Implications of a Climate-Changed Atmosphere on Cool-Climate Viticulture

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(Manuscript received 10 June 2018, in final form 8 March 2019)

ABSTRACT

The impact of anthropogenic global warming on viticulture has been thoroughly studied. However, many of the climate projections are limited by the resolution of the models that cannot resolve mesoscale weather patterns, which heavily influence grape production. In this work, data were gathered from the National Center for Atmospheric Research wherein a high-spatiotemporal-resolution ($4\text{ km} \times 4\text{ km}$, 1 h) Weather Research and Forecasting (WRF) Model was run from October 2000 to September 2013 over North America using observed data, and again using the atmospheric chemistry of CMIP5 ensemble mean of the RCP8.5 greenhouse gas emission scenario, creating a pseudo-global warming (PGW) model. Such models are capable of resolving the mesoscale influences that most climate models cannot. Contrasting the observed results to the PGW results allows users to compare “what happened” to “what could have happened.” This analysis was applied to four cool-climate viticultural regions in the United States: two in Michigan, one in upstate New York, and one in Oregon. In the PGW run, hours exposed to extreme heat ($>32^{\circ}\text{C}$) increase by orders of magnitude. Growing season degree-day (GDD) accumulations increase between 783 and 1057 base 10°C in comparing the models, while growing season average temperatures increase between 4.05° and 5.53°C . Precipitation patterns were also studied. The four regions would no longer classify as “cool climate” and would see growing seasons similar to some of the most productive warm-climate wine-producing regions. The authors consider the opportunities and challenges presented by the potential climate shift for cool-climate and warm-climate viticultural regions.

1. Introduction

Cool-climate viticulture occurs in a region where the average growing season temperature, calculated between the months of April and October, is reported in the range of 13° – 15°C (Jones et al. 2010). These cooler-climate areas typically accommodate grape varieties of the *Vitis vinifera* species that are more cold resistant while also being more able to mature fruit with reduced warm summer temperatures and a short season (Gladstones 1992). In particular, grapevines planted in such a climate must be cold hardy to withstand typical temperatures of -18°C during the winter (Zabadal et al. 2007). As the vines come out of dormancy in spring, newly formed buds must avoid temperatures below -1°C in order to prevent potential frost damage, which can limit the potential fruit production of the season (Zabadal and

Andresen 1997; Schultze et al. 2016a). After avoiding damaging temperatures in the winter and spring periods, the vines must contend with extreme or fluctuating temperatures during the summer. While most grape varieties have at least some tolerance to extreme heat, varieties traditionally grown in cool-climate viticultural regions of the world are very sensitive to frequent extreme high temperature events. Grape quality is affected by solar radiation and rainfall, frost intensity and duration, temperature variability, and humidity levels during the growing season: temperatures of 25° – 30°C , wind speed of less than 4 m s^{-1} , and relative humidity of between 60% and 70% are fundamental for efficient vine photosynthetic activity and consequently fruit maturation (Hunter and Bonnardot 2011).

Worldwide, there are a number of cool-climate viticultural regions: the Mosel or Baden regions in Germany, the Champagne region of France, Christchurch region of New Zealand, Hobart region of Australia, and the Innsbruck region of Austria. All those regions currently

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have, or had in recent decades, average growing season temperatures between 13° and 15°C (Gladstones 1992; Hall and Jones 2009; Jones et al. 2010). The climate greatly affects what wines grow and how they taste and in “cool climate” regions there is an industry specialization in varieties like Riesling, Chardonnay, Pinot Noir, Pinot Gris, Pinot Blanc, and Sauvignon Blanc. Michigan, New York, and Oregon are cool-climate regions of the world and they share the same viticultural focus on those varieties, with Riesling been the most planted variety in Michigan and New York, while Pinot Noir is the most widely planted variety in Oregon. The reason is that certain wine varieties will not fully ripen if grown in a cool climate (e.g., Grenache and Cabernet Sauvignon). Instead, cool-climate regions plant more white wine varieties and elegant or aromatic reds (e.g., Pinot Noir, Merlot). The climate impacts the sensory attributes of the wines, and white wines from cool climates tend to have higher acidity and more lemon–lime aromas, and are typically lower in alcohol with a very light body; those are the wine styles of Michigan, New York, and Oregon wines.

Each of these regions is currently undergoing a warming trend, which is a response to recent global climate change (Hayhoe et al. 2008; Chang and Jung 2010; Andresen et al. 2012). Hence, the possibility of alterations to grapevines’ phenology, physiological metabolism, yield, and fruit quality is a reality. Vegetative and reproductive vine performance is highly dependent on interconnected effects of CO₂, temperature, water availability, and mineral nutrition, impacting photosynthesis, respiration and carbon transport, yield level, and fruit quality. In the field of viticulture, the concept of *terroir*, or “land characteristics,” features climate as one of its main components (van Leeuwen et al. 2004; Sommers 2008). Any long-term trend in climate has an impact on vine performance in every region of production across the globe. Numerous papers have been published on climate impact on grape and wine production with data sources going as far back as the fifteenth century (Cook and Wolkovich 2016). Moreover, researchers are regularly updating the literature with new data from recent climate model runs, with the goal of establishing trends in climate change that will impact the world’s vines (Schultz 2000; Jones et al. 2005; Fraga et al. 2012; Dunn et al. 2015; Bonfante et al. 2018). Cool-climate viticulture has not experienced similar levels of research, but recent papers have shown that changes to these cooler regions may be occurring faster than their equatorial counterparts. The results generally find that the cool-climate viticultural regions of the world reflect the bedrock climatic change concept of Arctic amplification in that poleward areas are responding to climatic change at a faster rate than the world’s equatorial regions.

(Jones et al. 2005; Schultze et al. 2014; Holland and Smit 2014; Molitor et al. 2014; Schultze et al. 2016b).

These climate change–wine interaction studies are useful in applying the projections of a climate-changed atmosphere on some aspect of the production of wine grapes. Most studies rely on either global climate models (GCMs) or downscaled regional climate models (RCMs) to provide the forcing data for whatever application they are using. GCMs and RCMs are very useful in this setting as they provide status and trends from which conclusions can be drawn. However, even the most downscaled models are still limited by a coarse spatiotemporal resolution. Many global-scale models use spatial resolutions as large as 100 or 200 km in grid size. In some cases, a RCM with a significantly smaller spatial scale can be nested in to a GCM, but very often the model run is still limited by a coarse monthly or yearly temporal scale (Liang et al. 2006; Fronzek and Carter 2007; Tian et al. 2017). Considering such spatiotemporal limitations, conclusions for wine grapes are useful but limited.

With this issue considered, in this manuscript the authors used the National Center for Atmospheric Research’s (NCAR’s) recently released high spatiotemporal Weather Research and Forecasting (WRF) Model run over much of North America (Rasmussen and Liu 2017), which was run on an hourly time scale at a 4 km × 4 km grid resolution from 1 October 2000 to 30 September 2013.

While the time scale is limited to only the past, users are able to compare a observed dataset from a weather model to another dataset from the same weather model with a simulated atmosphere with more greenhouse gases, specifically, the atmospheric chemistry projected by the RCP8.5 scenario of the CMIP5 suite of climate models. Such a high spatiotemporal scale allows users to explore mesoscale influences that cannot typically be resolved by larger-scale climate models, allowing finer-scaled analysis to be done in various related fields. The reanalysis of the time frame for the growing seasons between 2001 and 2012 (2000 and 2013 did not include full seasons) allowed for the calculation of the potential differences between the observed run and the simulated run, and performing the model at such a high spatiotemporal resolution allowed for a direct comparison of “what happened” to “what could have happened” while framing the changes from a viticultural perspective.

In particular, the objective of this research was to examine the effects of an atmosphere with a changed chemistry similar to what is likely to occur within the forecasted CMIP5 RCP8.5 greenhouse emission scenario, comparatively, for different cool-climate viticultural regions. By using the high spatiotemporal resolution WRF Model data, the authors have been able to compare observed data from October 2000 to September 2013 with an

FIG. 1. (top) Location maps, (middle) elevation maps, and (bottom) climographs for the four study regions: (left) southwest Michigan (SWMREC) and northwest Michigan (NWMHRS), (center) the Finger Lakes, and (right) Corvallis.

atmosphere with more carbon dioxide, more water vapor, and other simulated changes to atmospheric chemistry. As mentioned previously, GCM and RCMs are limited in how they can be applied to such a resolution-dependent concept as viticulture. The authors derive agriculturally significant variables and compare the observational model run to the simulated atmosphere run. For comparative reasons, we examine the differences in four cool-climate viticulture regions and draw conclusions for the current viticultural landscape and reason a potential future in a climate-changed world.

2. Study sites, data, and methods

a. Study sites

The four regions in this study (southwestern Michigan, northwestern Michigan, the Finger Lakes in New York, and the Willamette Valley in Oregon) have

distinct climates (Fig. 1). Western Michigan's wine-producing regions, broken in to two regions are classified as Dfa and Dfb Köppen climates (Köppen 1900; Geiger 1965), while the Finger Lakes region is classified solely as a Dfb. Oregon's Willamette Valley is classified as Csb climate, although microclimate influences arising from topographical differences can allow for small pockets of cooler climates. However, with regard to viticulture, all of these regions are cool climates by definition.

Large bodies of water influence temperatures by moderating extreme temperatures. For example, in Michigan, the Great Lakes, and in particular Lake Michigan, heavily influence the climate of the region (Andresen and Winkler 2009). Winter temperatures do not typically drop far below -18°C for considerable lengths of time thanks to the thermal inertia of the lake. Only when Lake Michigan fully freezes over do temperatures consistently drop

down to the point of endangering the vines. It has happened as recently as the winter of 2014, but previously had not happened since the winter of 1978 (Assel et al. 2002, 2013). In spring, temperatures are lower with closer proximity to the lake, which delays the bud burst phenological stage of grapevines. This is crucial when trying to avoid exposure to frost events (temperatures below -1°C) in the late spring months (Howell 2001). In summer, the lakes serve to suppress cloud formation for the benefit of grapevine photosynthesis, while in fall the warmth of Lake Michigan allows the growing season to extend in to mid- or late October (Schultze et al. 2014).

The Finger Lakes region of New York experiences a similar environment with their proximity to Lake Erie, Lake Ontario, and the eponymous lakes of the region where the large bodies of water aid in the moderation of temperatures. However, winter temperatures typically are lower than in Michigan as Lake Erie more frequently freezes over than Lake Michigan. Vines must be buried in snow during the winter to prevent exposure to dangerous cold-damaging temperature of this region (Zabadal et al. 2007). While the region experienced a decline in wine production in the 1970s and 1980s (Newman 1992), it is currently expanding in acreage as summer temperatures have risen over the recent decades (Adams 2006).

The Willamette valley is impacted by its proximity to the Pacific Ocean. However, unlike in Michigan or New York, elevation change and the dynamics of an orographic rain shadow also have an influence on region. For this reason, most vineyards are located on the leeward side of the Oregon Coastal Range clustered on the eastern side of the valley (Gladstones 1992). Location on the leeward side provided protection from moist air, allowing for greater sunshine hours in what would otherwise be a climate that is too wet and too cool for sustainable viticulture. Extreme winter cold damaging temperatures are rare in Willamette valley, and monthly precipitation rates are different from Michigan and New York. While Michigan and New York get more rain in summer, Oregon gets the majority of its precipitation in the late fall and winter months (Jones and Goodrich 2008).

b. Data

Gridded weather data were obtained from a joint operation between the NCAR and University Corporation for Atmospheric Research (UCAR). The high-resolution WRF simulations of current and future climate of North America suite model is run at a 4-km resolution for the entire continental United States (CONUS) region with an hourly time step from October 2000 to September 2013. Such a high spatiotemporal

scale allows the model to resolve convection style events as well as mesoscale influences including mountains and complex water–land interactions that a larger-scale model could not. Two simulations were performed: 1) a retrospective simulation utilizing observed data from the October 2000–September 2013 dates and 2) a future climate sensitivity simulation modified by the adding atmospheric chemistry changes reflected in the CMIP5 RCP8.5 with a high emissions scenario. These changes to the atmosphere, projected by 2100 by the RCP8.5 scenario, include a carbon dioxide concentration of 1380 ppmv and a global temperature rise of at least 3°C (Riahi et al. 2007; van Vuuren et al. 2011). This second simulation, the “pseudo-global warming” (PGW) scenario contains an atmosphere with more carbon dioxide, more water vapor, and represents an already “climate changed” atmosphere (Rasmussen and Liu 2017). Comparison of the two model runs, allows a user to compare actual conditions with simulated conditions where atmospheric chemistry has altered the processes. The authors required an entire year of data for analysis to be completed, so the years 2000 and 2013 were omitted, leaving the full years between 2001 and 2012 to be studied. By comparing the two, one can examine the effects of climate change directly by measuring differences between the observed past and the simulated past terms of in temperature, precipitation, or frequency of extremes over the studied time.

The creation of this dataset has allowed the application of climate model data to be applied down to smaller-scale human–land interactions such as viticulture. As mentioned previously, climate model data has been applied several times in multiple research to wine grapes, but most models were limited in their capacity because of resolution constrains (Stock et al. 2004; Ruml et al. 2012; Hannah et al. 2013). Viticulture relies on the concept of terroir, which is something that global-scale, or even regional-scale, climate models cannot resolve. The hybridization of a high-resolution weather model using climate model projections could allow a field like viticulture a better understanding of the impact of climate variability on terroir, which may give growers a perspective on what may need to be done to adapt in the future. In fact, this approach could allow the evaluation of weather extremes and it could examine differences over the course of a growing season or between seasons, to improve our understanding of the interaction between vine growth and development and climate conditions. Moreover, by comparing the PGW scenario to the observed model run, it would be possible to compare real-life conditions to a climate-changed world and how it may influence something as small-scale dependent as viticulture.

The point data were extracted from the two larger high-resolution WRF Model runs for two variables—1) air temperature and two meters and 2) accumulated gridscale precipitation—at four points: 1) southwest Michigan (42.08°N, 86.3555°W), 2) northwest Michigan (44.8831°N, 85.6777°W), 3) the Finger Lakes (42.7338°N, 76.6591°W), and 4) the Willamette valley (44.5077°N, 123.4575°W). While these sites are located in American viticultural areas (AVAs) that are relatively large in area, these exact point locations were chosen because of their proximity to a weather station with a reliable dataset. The Willamette valley station was chosen to represent areas found near elevations where wine grape production is more common (on the leeward side of the Coastal Range). The Corvallis location, specifically, was chosen because of its nearby long-term weather station located at the city's water bureau. At all four sites, wine grape production presently occurs nearby.

c. Methods

The point data were compared between the observed WRF Model run and the simulated PGW model run at the four study sites for both the temperature and precipitation variables. For temperature, daily maximum highs and lows were calculated for each day. This allowed for the examination of extremely hot ($>32^{\circ}\text{C}$) and extremely cold days ($<-18^{\circ}\text{C}$) over the study time. These temperature thresholds were chosen because of the potential damage they can cause to white wine grapes, which are more cold hardy and less heat tolerant than their red counterparts (Zabada et al. 2007). Calculating the daily temperature max and minimum ($T_{\max}$ and $T_{\min}$, respectively) also allowed for the calculation of growing degree-days (GDD) over the course of a growing season. The growing season was assumed to be from 1 April to 31 October, which follows the tradition wine grape growing season in the Northern Hemisphere (Keller 2010). In this case, a basic GDD calculation using a base of 10°C was utilized:

$$\text{Daily GDD} = \frac{T_{\max} + T_{\min}}{2} - 10^{\circ}\text{C}. \quad (1)$$

It was also possible to calculate the average growing season temperature over the same time period.

For precipitation, accumulations were calculated over the growing season months. Of particular interest were the months of August, September, and October, which are the months when the phenological stage of veraison (starting of grape maturation) and fruit ripening has likely taken place. Heavy rains after veraison are known to negatively impact season yields via fruit rot and disease pressure (Sabbatini and Howell 2010). Out-of-season

precipitation was also considered. Snowpacks are important at the four sites, although for potentially different reasons. A snowpack in Michigan or New York is critical for protecting the root system and lower trunks from extreme cold during extreme events in winter (Zabada et al. 2007). The snowpack in Oregon is critical for water availability during the very dry summer months.

Data from the high-resolution observed WRF Model run were compared to local weather station data for the four study sites. In Michigan, data were compared with two Michigan State University Enviroweather mesonet stations, located at the Southwest Michigan Research and Extension Center (SWMREC) in Benton Charter Township and the Northwest Michigan Horticultural Research Station (NWMHRS) in Bingham Township. Data for the Finger Lakes region were compared to the Aurora Research Farm in Aurora, New York. The Willamette valley's data were compared to a weather station at the Corvallis Water Bureau. Data from the Finger Lakes and Willamette valley sites were obtained from the Global Historical Climatology Network (GHCN) acquired from the National Centers for Environmental Information's (NCEI's) online data system. This approach allowed for a check of the validity of the observed model run.

3. Results

a. Observed run validity

The WRF Model data were very accurate in terms of replicating real-world point observations (Table 1) in relation to temperature. WRF estimated temperatures over the growing season were typically within 0.5°C of the point observations over the growing seasons between 2001 and 2012. Only in a few exceptions, the WRF Model missed extremely hot or extremely cold days, and those exceptions were likely a function of disaggregating continuous data down to a singular point source where microclimate influences on the location of the station may have influenced the point source in a way that could not have been detected by the gridded model. It was deemed that the WRF Model was an accurate replicator of real-life data for temperature.

Precipitation data from the WRF Model were also compared to the real-world observations (Table 2). While the differences remain relatively high between the two sources, the WRF Model was deemed acceptable as an analog of precipitation data if measured in terms of trends (percentage change from aggregated average) rather than a direct comparison of values. This is likely because of the uneven nature of precipitation

TABLE 1. Differences in average GST (°C) and GDD base-10°C accumulation between real-world observations and observed WRF Model data for the 2001–12 growing seasons.

Growing season	SWMREC		NWMHRS		Finger Lakes		Corvallis	
	ΔT	ΔGDD	ΔT	ΔGDD	ΔT	ΔGDD	ΔT	ΔGDD
2001	0.31	24	-0.22	-79	0.55	107	0.16	28
2002	0.21	-5	-0.66	-142	0.83	342	0.28	211
2003	0.17	-38	-0.59	-156	0.53	57	-0.56	-75
2004	0.30	-7	-0.14	-82	-0.21	56	-0.57	-111
2005	0.47	31	0.02	-72	1.46	41	-0.56	-116
2006	0.57	48	-0.27	-111	0.13	13	-0.40	-48
2007	0.73	91	-0.21	-106	0.52	86	-0.56	-114
2008	0.46	42	-0.17	-104	1.01	371	-0.03	5
2009	0.46	26	-0.11	-89	0.49	150	1.25	212
2010	0.73	84	0.22	-50	0.54	96	-0.73	-115
2011	0.81	127	-0.24	-77	0.66	116	-0.71	-88
2012	0.82	139	-0.22	-99	0.92	162	0.21	2
Avg	0.50	47	-0.22	-97	0.62	133	-0.19	-18
St dev	0.23	54	0.23	29	0.42	113	0.59	118

over space. Precipitation examined from point data will typically vary from precipitation assumed over a gridded area. Point data can overestimate data in some areas, and underestimate in others depending on the general landscape, thus comparing day-to-day precipitation amounts between the real-world observations and the WRF was not performed. As such, it was deemed appropriate to explore the trends for precipitation rather than compare the data on a day-to-day basis.

b. Comparison of extreme weather events

Maximum temperature, minimum temperature, hours of extreme heat ($>32^{\circ}\text{C}$), hours of extreme cold ($<-18^{\circ}\text{C}$), and days of extreme precipitation ($>50\text{ mm}$) were calculated over the study time between the two models. The $>32^{\circ}$ and $<-18^{\circ}\text{C}$ thresholds were chosen because of the fact that prolonged exposure to these temperatures can damage grape vines traditionally grown in cool-climate viticultural regions, either during the growing season or winter. The $>50\text{-mm}$ threshold was chosen because any day above this accumulation was experiencing an abnormally heavy precipitation event. Such events can cause damage directly or indirectly (through ensuing disease or fruit rot) to grape clusters of any variety.

The results in extreme events between the observed WRF run and the PGW run are displayed in Table 3. Between the two runs, the PGW model shows that all extreme events happen at a rate that suggest the four regions have undergone drastic changes to their climates. Maximum experienced temperatures rise at all stations between 5.93° and 7.54°C , while minimum experienced temperatures rise at all stations between 6.57° and 11.27°C between the observed WRF run and the PGW run.

The number of hours of extreme heat and extreme cold changed in a similar manner. The number of hours of extreme heat between the observed WRF run and the PGW run rise at an astonishing rate. The number of hours of exposure to temperatures above 32°C at Corvallis in the PGW run is nearly 13 times higher than in the observed WRF run, while at SWMREC extreme heat hours increase by 26 times. These numbers suggest a heavily changed climate but are small in comparison to the rise in extreme heat hours in the Finger Lakes and NWMHRS regions. The number of extreme cold hours ($<-18^{\circ}\text{C}$) change similarly. In the Finger Lakes region, extreme cold hours are reduced by nearly 75%, while in Michigan there is nearly a 97% drop at both locations in hours with temperatures below -18°C . The Corvallis location never recorded an

TABLE 2. Comparison of precipitation amounts (mm) between the real-world point observations and the observed WRF Model run for the growing seasons (Apr 1–Oct 31) from 2001 to 2012.

Growing season	SWMREC	NWMHRS	Finger Lakes	Corvallis
2001	46	135	61	105
2002	121	161	-181	260
2003	62	127	101	149
2004	94	-72	-94	86
2005	211	-52	62	237
2006	186	55	-33	608
2007	287	-1	65	138
2008	112	-43	-129	76
2009	64	46	-270	468
2010	67	66	-107	150
2011	110	53	-432	159
2012	301	117	-234	449
Avg	138	49	-99	240
St dev	88	78	162	174

TABLE 3. Comparison of extreme weather events [maximum temperature ($^{\circ}\text{C}$), minimum temperature ($^{\circ}\text{C}$), hours of extreme heat ($>32^{\circ}\text{C}$), hours of extreme cold ($<-18^{\circ}\text{C}$), and days of extreme precipitation ($>50\text{ mm}$)] between the observed WRF run and the PGW run for the study period between 2001 and 2012.

	SWMREC	NWMHRS	Finger Lakes	Corvallis
WRF run				
T_{max}	39.95	36.39	37.18	39.38
T_{min}	-31.25	-31.93	-32.25	-14.06
Extreme heat	126	6	19	45
Extreme cold	690	1218	649	0
Extreme precip	2	4	11	31
PGW run				
T_{max}	45.89	43.16	44.72	45.76
T_{min}	-24.03	-22.11	-20.98	-7.49
Extreme heat	3344	1468	1851	572
Extreme cold	21	39	185	0
Extreme precip	13	10	17	32

hour below the extreme cold threshold in either model run, thus its extreme hours total remained unchanged. The number of heavy precipitation events ($>50\text{ mm}$) increased at all locations between the observed WRF run and PGW run. While the magnitude of the change may not be as large as the extreme temperature events, the increases suggest that heavy precipitation events occur more frequently in an atmosphere with more greenhouse gases, which confirms the trend linking global warming and extreme precipitation events found in the general literature (Easterling et al. 2000; Allan and Soden 2008; Fischer and Knutti 2015).

Closer inspection of distinct meteorological events can also display the differences between the observed WRF Model run and the PGW model run allowing for the analysis of mesoscale weather patterns (Fig. 2). Figures 2a(1) and 2a(2) display the differences in model outputs for a heat wave that occurred in July 2011 in Michigan. Figure 2a(1), the observed WRF Model, shows a total of 46 h that would classify as “extreme heat” at the southwest Michigan location and a maximum temperature experienced at 36.4°C . The numbers rise to 88 extreme heat hours and a maximum experienced temperature of 44.4°C in the PGW run. A similar, though less dramatic rise is also seen at the northwest Michigan location, though this may be due to its location on peninsula surrounded by cooler waters. Figures 2b(1) and 2b(2) display two separate heavy precipitation events. On 11 June 2004, the observed WRF Model accumulated 31.9 mm of rain in southwest Michigan, while PGW run projects 66 mm of rain. Northwest Michigan, on 4 October 2002 saw an accumulation of

21.2 mm in the observed model run. Yet, in the PGW run, the location saw an accumulation of 92.1 mm, a more than fourfold increase.

c. Comparison of temperature-derived variables

Figure 3 contains a visual of the difference between the observed WRF Model run (solid line) and the PGW model run (dashed line) for SWMREC in southwest Michigan. It is clear that GDD accumulation and growing season temperature are vastly higher in the PGW model run. The graphs are nearly similar in trend, which is logical, in that the same weather events are being experienced albeit under different atmospheric chemistry conditions. Considering that, only the SWMREC graph is shown (Fig. 3). This was done for brevity, as the NWMHRS, Finger Lakes, and Corvallis graphs show the same graphical trend. Table 4 displays the numerical differences for all points.

The growing degree-day accumulation from April to October of each of the 12 study years is shown to be between 783 and 1057 units higher in the PGW run compared to the observed WRF run. The standard deviations of each stations years were also calculated and compared between the two runs. The PGW run shows that the variability of GDD accumulation from year-to-year increases in an atmosphere with higher greenhouse gases. Table 4 also shows the difference in growing season average temperatures. It is reasonable to assume the GDD and growing season temperature (GST) should be closely related, but the relationship is not perfect. Northwest Michigan registers the biggest different in temperature between the WRF Model run and the PGW run but registers the third highest difference in GDD accumulation. In all cases, the climates of these cool-climate viticultural regions are warmer and more variable in temperature during the growing season.

d. Comparison of precipitation-derived variables

As previously mentioned, precipitation variables between the models had some issues scaling from point to gridded data. However, in comparing the gridded observed WRF Model run to the PGW model run, a status and trends comparison is possible between the two models. As such, precipitation accumulation over three times were examined: total growing season precipitation, January and February precipitation, and August and September precipitation. Total growing season precipitation gives an estimate of the total rainfall that grapevines would likely experience between the months of April and October, while August and September precipitation totals the precipitation during the months after the veraison phenological

FIG. 2. Maps of a heat wave from 16 to 23 July 2011 at both Michigan sites including (top) the number of hours experiencing extreme heat hours ($>32^{\circ}\text{C}$) and the maximum temperature during the timeframe for [a(1)] the WRF-observed model and [a(2)] the PGW-model run and (bottom) precipitation amounts during heavy rainfall events for [b(1)] the WRF-observed model and [b(2)] the PGW-model run.

stage when most grape varieties prefer drier conditions. January and February precipitation were included as an analog to potential winter precipitation. Winter precipitation is important in all four locations either as insulation from potentially dangerous cold temperatures (both Michigan locations and the

Finger Lakes) or as the second half of the region's rainy season (Corvallis). By viewing these accumulations as a percentage of the calculated average, potential trends for precipitation can be explored. Table 5 displays the potential changes to precipitation to the region.

FIG. 3. Comparison of the observed WRF Model run (solid) and the PGW model run (dashed) for growing degree-day accumulation (GDD base 10°C ; April–October) and average growing season temperature ($^{\circ}\text{C}$) at SWMREC.

TABLE 4. Difference (diff) in average values between the two models calculated as PGW model minus observed WRF Model over the 12 growing seasons.

	SWMREC	NWMHRS	Finger Lakes	Corvallis
GDD diff	1057	1001	1026	783
St dev diff	25	21	44	35
GST diff	5.4	5.53	5.37	4.05

A positive number in Table 5 reflects a higher value in precipitation in the PGW run than the observed WRF run. For total growing seasonal precipitation, there does not appear to be a strong trend in Michigan while it appears to be somewhat drier in the Finger Lakes region (-5.6%) and somewhat wetter in the Corvallis region ($+6.8\%$). However, winter precipitation in Michigan and the Finger Lakes regions appears to increase dramatically, particularly in the northwestern region of the Lower Peninsula of Michigan ($+65.6\%$). Corvallis, in the second half of its rainy season, appears to get slightly more precipitation. This trend is reversed when considering late growing season precipitation. The two Michigan regions appear to get somewhat more precipitation while the Finger Lakes region appears to get somewhat less end season precipitation. However, Corvallis receives a significantly higher amount of late season precipitation ($+43.2\%$) in the PGW run scenario.

4. Discussion and conclusions

a. Implications for cool-climate viticulture

A warming trend in cool-climate viticulture with an increased variability brings both challenges and opportunities for the grape industry. This warming trend could allow for the introduction of alternative grape varieties, drastically improving the limited availability of cool-climate *Vitis vinifera* cultivars. Varieties such as Merlot, Cabernet Sauvignon, and Syrah, which require warmer climates, would likely thrive. Traditionally, season-to-season variation is significantly high in cool-climate viticulture regions of the United States. Seasonal variation may remain high, but the addition of significantly warmer growing seasons would ensure that these regions would not need to contest with years of exceptional cold in the winter, or cool summers that could limit production. This is seen in Table 3, where extreme cold ($<-18^{\circ}\text{C}$) hours in the PGW run drop to virtually zero in comparison to the real-world observations, and in Table 4, where growing season temperature differences increase by at least 4°C .

TABLE 5. Percentage change (%) in average totaled precipitation between the PGW run and the observed WRF run for the total growing season (April–October), January and February only, and September and October only.

	Season	Jan–Feb	Sep–Oct
SWMREC	0.0	16.3	7.5
NWMHRS	-0.7	65.6	4.0
Finger Lakes	-5.6	36.8	-3.7
Corvallis	6.8	2.1	43.2

Perhaps most striking about the PGW run is the projected GDD accumulation compared to the observed WRF results (Table 4). Thermal heat accumulations increase between 63% and 77% in the PGW run compared to observations. For perspective, Table 6 compares the observed WRF run and the PGW run average GDD accumulations with results from Jones et al. (2010). The increase in thermal heat accumulation brings the four cool-climate viticulture regions, which are comparable to other traditionally white-wine-producing regions of the world in the observed WRF run, up to GDD rates that are similar to some of the warmest wine-producing places in the world. Notably, the results show that Corvallis would see GDD accumulations close to the accumulations experienced in Napa Valley, while the Finger Lakes and southwest Michigan regions would see accumulations warmer than what is seen currently in places like southern Spain. While it should be noted that the PGW run results are the by-product of the CMIP5 RCP8.5 greenhouse gas emission scenario and are thus trending toward the higher end of potential global warming scenarios, these results show a radically different landscape for viticulture.

Even if grapevines have a large potential to adapt to changes in the environment, higher temperatures will not necessarily translate into improved crop yield or enhanced fruit quality, as temperature does not have a linear relationship with those parameters. Increased weather variability would almost certainly limit that option. Variability between seasons affects yield and fruit quality at harvest because of extreme weather events. In all four regions, extreme heat, and extreme precipitation events appear to increase (Table 3). The number of hours in extreme heat ($>32^{\circ}\text{C}$) increases by orders of magnitude for each of the four regions. New varieties would likely be introduced that would be able to survive in such weather, but older, cooler varieties, may not, especially classical cool-climate white aromatic varieties (e.g., Sauvignon Blanc, Gewürztraminer, Pinot Gris), will have a reduced varietal characteristic under the pressure of extreme heat.

TABLE 6. GDD accumulations of the four cool-climate viticulture regions compared to other wine-producing regions [data after Jones et al. (2010)]. One asterisk indicates the observed WRF run, and two asterisks indicate the PGW run.

Region	Country	GDD	Region	Country	GDD
Champagne	France	923	Southwest Michigan*	United States	1677
Baden	Germany	1056	Porto	Portugal	1684
Corvallis*	United States	1057	Corvallis**	United States	1840
Burgundy	France	1118	Napa Valley	United States	1883
Northwest Michigan*	United States	1304	Lodi	United States	2211
Valtellina Superiore	Italy	1335	Northwest Michigan**	United States	2305
Finger Lakes*	United States	1551	Jerez-Xeres-Sherry	Spain	2343
Walla Walla	United States	1558	Finger Lakes**	United States	2576
Vinho Verde	Portugal	1677	Southwest Michigan**	United States	2734

Precipitation trends are also a cause of concern. Extreme precipitation ($>50 \text{ mm day}^{-1}$) events increased at all locations in our research (Table 3). Such events can cause erosion and could be associated with severe weather that could damage the vines or their fruit. Overall, seasonal trends in precipitation are mixed. Table 5 shows that seasonal precipitation is not likely to change much in any region. Upon closer inspection, there are positives and negatives from monthly trends. Increased precipitation in January and February in the Michigan and Finger Lakes locations suggests that winter precipitation will still be available to protect the vines in the coldest months. However, increased precipitation in September and October at the Michigan and Corvallis regions could be problematic. The change in precipitation patterns could aggravate the problem of fruit technological maturity, increasing the potential of cluster rot complex problem at harvest (Sabbatini and Howell 2010). With an increase of 43.2% in September–October precipitation rates, the Corvallis region will need to be particularly aware of the precipitation issues that can plague an end season yield.

b. Implications for global wine production

Considering the fact that the four regions would undergo profound changes in the PGW run, one must ask what this may mean for global viticulture. These cool-climate viticultural regions would not be able to be called “cool climate” any longer. These regions would see similar climates to some of the great wine-producing areas across the globe opening up new potential markets and sources. Yet these places are not unique, as there are a number of other places worldwide that fall under the classification of “cool climate” viticulture. Northern France, Germany, Austria, Switzerland, Tasmania, Patagonia, and western Canada are just a sample of the areas with similar climates that would experience changes on the same order as our study regions. These new regions would be subject to the same new opportunities as well as the same potential difficulties.

In these cool regions, shifts in climate would bring shifts in phenology. Earlier bud bursts and later harvests would be consequences of a warmer world (Schultze et al. 2014; Molitor et al. 2014; Meier et al. 2018), but the effects would not be all positive. Vine morphological and physiological traits change during vegetative and reproductive stages. The duration of each stage differs according to each grapevine variety and is tied to the thermal conditions of each region. Climate change can potentially influence phenology, vine development, vine yield, and quality. Temperature trends in viticultural regions show that the growing season mean temperatures have increased globally by about 1.3° – 1.7°C from 1950 to the present. Several studies have already noted earlier phenological events of the grapevines. Advances in the phenological events are resulting in spring frost events that destroy crops, or they result in fruit ripening during a warmer period, which has strong negative impacts on fruit and wine (Jones and Davis 2000; Rigby and Porporato 2008; Bock et al. 2011; Webb et al. 2012; Schultze et al. 2016a). Climate change projections for the twenty-first century are expected to have important impacts on viticulture, as changes in precipitation patterns also will increase risks of pests and diseases. Wine-making regions under extremely hot temperatures or heat waves may lead to a significant increase in the risk of organoleptic degradation and wine spoilage. Under a warmer climate, higher temperatures may inhibit the development of color compounds (i.e., the formation of anthocyanin), thus reducing grape and wine color and increasing volatilization of a variety of aroma compounds. Several wine grapes of the world are also expected to face adverse conditions of water scarcity, as regions become excessively dry for high-quality wine production and unsuitable for grapevine planting without irrigation. Despite the projected increases in precipitation, which can be favorable to pests and diseases (e.g., downy mildew), the warming in cool-climate regions will potentially benefit the planting of a wider range of varieties.

However, all viticultural regions will be subject to global warming. Regions that currently classify as “warm” or “hot” will also see a trend in rising temperatures and GDD accumulation. Where this may be seen as a benefit in a cool-climate region, it may be problematic elsewhere. Increasing temperatures will likely affect grape quality on a region-by-region basis, pushing these areas either to, or beyond, their optimum temperatures (Jones et al. 2005). To adjust, these regions will need to introduce new varieties or change their viticultural practices. Increased water demand will almost certainly be an issue for such regions (Webb 2006), and the cost of water could be prohibitive in some areas. Extreme heat events, already an issue in some wine-grape-producing regions, will likely increase in frequency similarly to what is seen in this study. White et al. (2006) found that increases in extreme heat will likely be detrimental to future wine production in the United States. In these cases, areas that are already “warm” or “hot” will be pushed to the limit or beyond their viability before major changes come to grower practices.

As mentioned previously, the PGW run is based on an atmospheric chemistry stemming from the RCP8.5 greenhouse scenario, which could be considered to be the “business-as-usual” scenario. It is, by nature, an extreme scenario whose utility is that it gives a picture of what could happen should greenhouse gas emissions not begin to slow down in the twenty-first century. The results of this paper reflect these extreme changes. Realistically, and hopefully, these changes do not come to pass, but showing these results extends the concept that climate change is reflected not just in ice caps or sea levels, but also in vines and fruit (Aono and Kazui 2008; Cook and Wolkovich 2016).

c. Conclusions

The goal of this study was to explore the difference between the observed weather conditions and the potential weather conditions of a climate-changed world, and how that might impact viticulture. The contrast between the real-world observed WRF run and the pseudo-global warming model run is remarkable. The four cool-climate viticultural regions are radically changed in terms of average temperatures and frequency of extreme events. The results regarding viticulture are mixed. Higher temperatures will allow these regions to be less concerned with extreme temperatures in winter and more certain that summer temperatures will be adequate for growth. However, expansion of extreme events (extreme heat, extreme precipitation) may limit those gains. New varieties will likely be introduced, but the selection of varieties will be important as the climate will continue to shift in the coming

decades. In all four cases, the landscape of viticulture will have changed greatly should these greenhouse gas emission projections be realized.

The study was limited, particularly regarding precipitation, because of the nature of spatially continuous data versus point data. Temperature data were found to be sufficiently accurate but, because of the nature of precipitation, it was difficult to resolve point data (from mesonets, etc.) to the model’s gridded data. Having a single point reading of precipitation and comparing a $4\text{ km} \times 4\text{ km}$ grid where interpolation methods were used likely obfuscates rainfall events, as the highest points of rainfall are not typically resolved by the grid. As such, the conclusions about precipitation could not be as strong as initially hoped for. This study was also limited to the use of the RCP8.5-simulated greenhouse gas emission scenario as the projected atmospheric chemistry used in the pseudo-global warming model run. The results of the PGW run are based with atmospheric chemistry found at the end of the scenario, which is projected in the later decades of the twenty-first century. With that in mind, the PGW run GDD accumulations and precipitation shifts observed here should not be seen until late in the century. Yet the transition to a warmer climate is already under way, and changes by the 2030s or 2050s will likely continue on pace somewhere between the range of the RCP2.6 and RCP8.5 scenarios. Considering that, it would be interesting to see what potential changes could occur on the $4\text{ km} \times 4\text{ km}$ grid in another RCP scenario. However, by viewing these projections through the lens of a model that can resolve mesoscale processes, it is clear that even if emissions fall short of the RCP8.5 projections, wholesale changes are imminent for the field of viticulture.

Changes in temperature and precipitation trends are a common occurrence in viticulture. Of the major components of terroir (soil, topography, varietal, climate), climate is the only one that changes both over space and time. Moving forward, new site selection tools that will take in consideration climate trends will be pivotal to manage expanding regions. From a viticultural perspective, the great research challenge of the future will be to have good predictions of future climate scenarios and develop adequate viticultural strategies to avoid potential problems and to allow growers to properly take advantage of new opportunities. This will require the climate research community to continue to develop tools such as the model used in this study, because projections of a potential climate allow growers to adequately prepare for what may come in the future.

Acknowledgments. The authors thank University of South Alabama Geography student Mike Jeffries for

his invaluable help in downloading and processing the raw data. They also thank the reviewers for their help in making this paper better. There were no external funding sources for this paper.

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