RESEARCH FOCUS

Grapevine Winter Survival and Prospects in an Age of Changing Climate

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In the Northeast, bud and trunk injury related to cold temperatures is a recurring issue for producers. While management (eg. 'spare parts viticulture') can mitigate its impact, better understanding of the genetics of cold hardiness will improve management of existing cultivars and ultimately lead to improved grape varieties. White Springs Vineyard, Geneva, NY, December 2014.

Photo by Jason Londo.

Vines transition from active growth to dormancy by processes controlled by genes, but are greatly influenced by variation in weather conditions – even in the coldest part of the winter. My research program, known as the USDA Cold Hardiness Genetics Research Program, seeks to understand how a vine's genetics interact with climate variation to influence vine dormancy. Our studies of chilling requirements and bud-killing temperatures (LTEs) in wild and cultivated *Vitis* have revealed differences in how fast vines respond to temperature changes and how many chilling hours they require to break dormancy. More erratic swings in winter and spring temperatures associated with climate change may have a dramatic impact on the risk of winter injury and early budburst.

KEY CONCEPTS

- Cultivated grapevines are adapted to the Mediterranean and thrive in environments with mild winters and hot dry summers, so their ability to survive cold Northern winters is limited.
- Wild North American grapevine species are adapted to diverse environments, including severe winter conditions.
- Dormancy is when grapevines transition from green tissues susceptible to frost injuries to structures resistant to cold temperatures.
- Endodormancy is an early season state of dormancy where buds are more resistant to temperature fluctuations and will not burst if cut from the vine and placed in warm conditions.
- Ecodormancy is a later stage of dormancy where chilling fulfillment has occurred and buds are no longer resistant to temperatures changes. Canes will burst if placed in warm conditions.
- Supercooling is the mechanism used by the dormant grapevine bud to survive temperatures well below freezing. Extracellular water is allowed to freeze at warm temperatures outside the cell, preventing ice from forming within cells. The supercooling temperature is the same as the temperature at which 50% of dormant buds die.
- Climate change predications suggest the North and Northeast U.S. will experience generally warmer winters, but with greater potential for rapid swings in temperature (e.g. polar vortex).

Introduction. Cultivated grapevine (*V. vinifera*) was domesticated in the Mediterranean region and is thus adapted to a climate defined by hot dry summers and mild cool winters. Where grapes are grown in the North and Northeast United States, these climatic conditions do not occur. Instead, grapevines are challenged by warm, humid summers, and variable winter conditions ranging from mild and cool, to brutal and cold. As a result, the primary limiting factor for grapevine production of *vinifera* varieties in the North and Northeast is low winter temperatures.

As a perennial fruit crop, the grapevine defends its tissues against winter damage through the processes of dormancy and acclimation. These processes are influenced by climatic attributes that remain constant such as decreasing day length in the fall and winter, and also by attributes that vary from year to year, such as temperature fluctuations.

In addition, each grapevine variety (e.g. Riesling, Merlot, Concord) has a unique set of genes that allow that variety to respond to the surrounding environmental conditions. The primary focus of the USDA cold hardiness genetics research program is to understand how climate variation interacts with varietal genetics. The goal of this research is to determine how weather impacts vine dormancy, how temperatures increase or decrease vine hardiness, and methods of predicting and mitigating cold damage.

This information is critical for selecting appropriate breeding germplasm for new cultivar development. Our goal is to determine the specific response of each wild and cultivated variety when they are exposed to winter temperatures and to be able to quickly predict how the level of acclimation and the supercooling ability will change in response to temperature fluctuations in different species. Since wider fluctuations in midwinter temperature are predicted with a changing climate, it will be essential to select and breed with wild grapevines which are able to supercool to very low temperatures yet resist responding to rapidly changing temperatures.

Cold hardiness. Cold hardiness is a term used to describe the complex winter survival mechanisms of plants. Winter survival in grapevine is a multi-stage process that begins in the fall as day length shortens and temperature decreases. The initial cue for this change is the shift in daylight and day length, beginning a series of metabolic and genetic changes in the plant. Sometime after veraison (generally early September in New York), the grapevine begins the process of acclimation with the progressive ripening of the cane from green into brown periderm. During this period, the grapevine transitions from active growth with green, photosynthesizing leaves, into its dormant phase, where it becomes progressively more resistant to cold temperatures.

Endodormancy. As periderm advances down the cane from base to tip, the buds enter a state of dormancy called *endodormancy*, and become resistant to freezing damage. At this stage, buds are resistant to further development even when exposed to warm temperatures. As winter progresses and temperatures decrease, the buds gain greater freezing resistance (**Figure 1**) until the maximal limit of freeze resistance is achieved. Each grapevine variety has a different maximal freeze resistance point that changes from year to year, depending on the severity of winter.

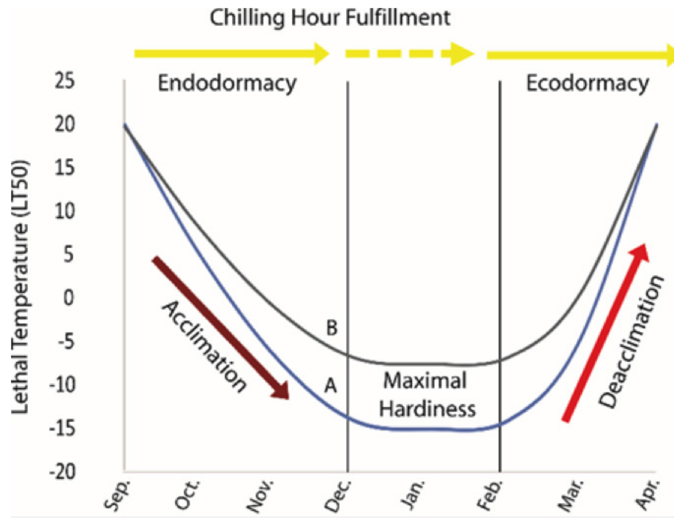


***Figure 1**: The lethal temperature (supercooling ability) of the grapevine buds decreases during early fall with the process of acclimation. During mid-winter the buds achieve maximal hardiness and supercooling ability. When winter temperatures being rising in late winter/early spring, the buds deacclimate at a faster rate than they acclimate and the lethal temperature rises. In cold years, A) supercooling ability is greater than in warm years B) The transition of endodormancy to ecodormancy occurs at the same time as supercooling ability changes.*

Chilling requirements. Remarkably, grapevines and other woody perennial plants are able to keep track of the amount of time they spend at a specific temperature range, in order to assure that they do not break bud before the conclusion of winter. This temperature range is thought to be between 0 and 10°C (32 to 50 °F). The number of hours at these temperatures that vines need to experience is called the *chilling requirement*. When vines have fulfilled their chilling requirement, buds become more responsive to warm temperatures and they are held in dormancy only by cold winter temperatures.

Ecodormancy. As vines fulfill their chilling requirement, they transition from being endodormant to a different state of dormancy called *ecodormany*, and will start to grow when exposed to warm temperatures. As temperatures begin to climb in late winter and early spring, the buds begin a process called deacclimation and they start losing freezing resistance. If temperatures are unseasonably warm, the buds can irreversibly deacclimate and lose freeze resistance in early spring. This process can also occur in early winter in some years—and vines can have increased risk of mid-winter damage if cold temperatures return. The final hurdle for grapevine buds to survive winter is to remain dormant long enough into spring to avoid frost damage.

Weather and the timing of budburst. Each variety has a different rate of growth and a different response temperature at which growth begins. All of the winter weather conditions leading up to this point play a major role in determining the date of budbreak. Cold, harsh winters tend to reduce chilling in dormant buds so they are less advanced into ecodormancy and less prone to burst. Warm and mild winters increase chilling and advance the buds to a state where bud burst is rapid. Once the buds have burst and green tissues are exposed, there is very little resistance to freezing and damage can occur at temperatures just below the freezing point. All of these processes are tied tightly to late fall-winter-early spring temperature patterns and thus are susceptible to disruption due to climate variation.

Supercooling and freeze resistance. The precise mechanisms that allow buds to survive temperatures far below the freezing point of water are not well understood. However, the general hypothesis is that the cells within the dormant bud dehydrate as much as possible in order to prevent ice crystals from forming inside the delicate membranes of the plant cell. Water outside the cell membrane can freeze at temperatures ~-5 °C (23° F) without damaging the cells, but the small amount of water left within the plant cell remains unfrozen. This process is called *supercooling*. It is thought that the grapevine bud uses a complex mix of defenses in order to supercool, including high sugar content to reduce freezing point, production of cryoprotectant proteins to stabilize membranes, mechanical ice barriers, and many other processes.

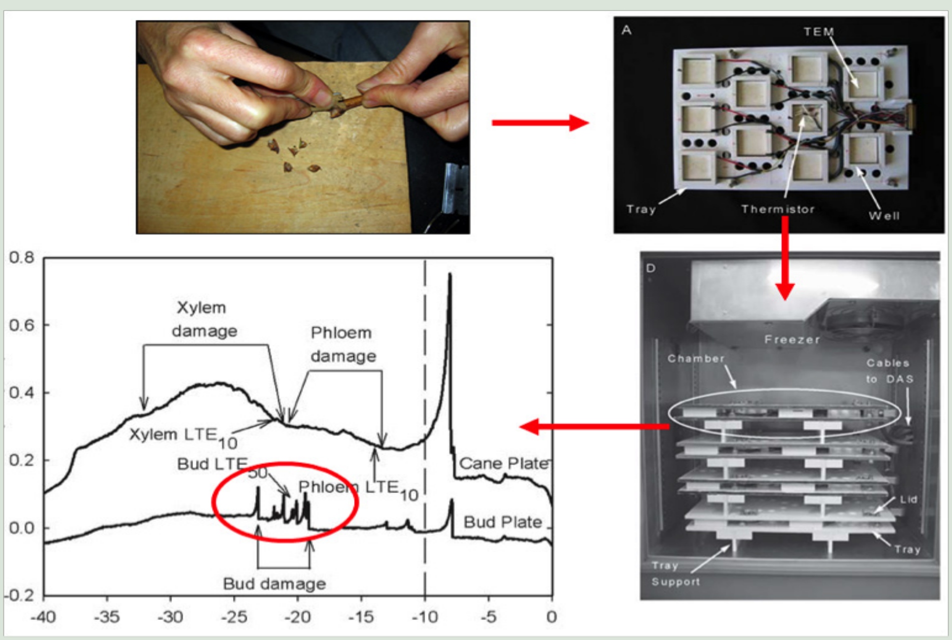
Measuring supercooling ability. The method for determining the supercooling ability of grapevine buds is called *differential thermal analysis* (DTA) (**see sidebar below**). The temperature where 50% of the buds on a vine are killed is called the LT_{50} and each grapevine variety (e.g. Riesling) has a slightly different LT_{50} temperature.

During the winter, the LT_{50} for each variety is not constant, but varies and is directly dependent on ambient temperatures during winter. If winter conditions are uniformly cold, the buds acclimate and supercool to deeper temperatures and are able to survive significant low temperature freeze events (**Figure1A**). However, if winter conditions are warm and mild, the buds have reduced acclimation and a warmer supercool point and are susceptible to bud injury at much warmer temperatures (**Figure1B**).

Variation in supercooling ability. Because they evolved in and were domesticated in the Mediterranean region, *V. vinifera* cultivars are best suited for locations with mild winters. Although they tend to be "cold-sensitive", *vinifera* cultivars do vary in their bud hardiness.

For example, Merlot and Syrah do not consistently survive the cold winters of the Midwest, North, and Northeast United States, and exhibit bud damage and death at temperatures around -18 °C (0 °F). Other varieties such as Riesling and Cabernet Franc typically do better at surviving the average Northern winter, with mid-winter bud-freezing LT_{50} temperatures down to -25 °C (-13 °F).

How Digital Thermal Analysis is Performed



From upper left: Dormant buds are removed from the cane at various times during the winter and placed within sample trays in a programmable freezer. Then the temperature is gradually reduced to -40 °C (-40 °F) while voltage is measured in each sample tray. The supercooling point (bud freezing temperature) is measured by a small change in voltage in the sample tray when the water within the bud cells freezes, releasing a small amount of heat called the Low Temperature Exotherm (LTE, circled area on graph). Thirty buds per collection are typically measured, and the median bud freezing temperature, or LT_{50} is then calculated.

Figure from Mills et al. 2006.

Wild North American *Vitis* species evolved in a more challenging winter climate and have a greater ability to acclimate and supercool. For example, the wild species *V. labrusca* (parent of Concord and Catawba) and *V. riparia* (parent of Marquette and Frontenac) can survive temperatures as low as -30 °C (-22 °F) and -40 °C (-40 °F), respectively.

In my research program, we used DTA analysis to examine midwinter bud hardiness of wild and cultivated *Vitis* from the USDA grape germplasm vineyard at Geneva over three dormant seasons. This collection encompasses wild *Vitis* spp from a wide array of climates. Northerly distributed wild grapes in the collection include *V. riparia* and *V. labrusca*, as well as the Chinese wild grapevine *V. amurensis*. Midwestern and Southern distributed species include *V. aestivalis*, *V. cinerea*, *V. rupestris*, and *V. vulpina*.

What I found is that the type of winter is at least as important as the genetic makeup of a grapevine variety. Three successive winters included a mild winter with frequent above-freezing episodes in midwinter (2012-2013), harsher midwinter low temperatures with alternating thaws (2013-2014) and a midwinter where temperatures were below freezing from January to March (2014-2015) (**Figure 2**). Since the LT_{50} level is dependent on both the genetics of the grapevine variety and the type of winter, the LT_{50} curve moves dynamically through the three winters.

Figure 2 shows that the midwinter LT_{50} for *V. vinifera* 'Riesling' is several degrees higher than the American hybrid cultivar Concord (with *V. labrusca* genetics). In addition, Concord LT_{50} values change more rapidly in response to temperature variations than Riesling LT_{50} values – the Concord curve is more wavy than the Riesling curve. This responsiveness can be problematic in hybrid cultivars as rapid deacclimation (loss of LT_{50} level) in response to warm weather can make the vines more likely to sustain damage if cold weather returns.

Supercooling ability is variable between wild grapevine species as well as between cultivated and hybrid grapevines. **Table 1** shows the average LT_{50} values for the last three years for wild, cultivated, and hybrid grapevines. In 2012-2013, there was a modest 3 °C (5 °F) difference between the highest (*V. amurensis)* and lowest (*V. cinerea*)

Table 1: *Variation in average LT_{50} values over the last three winters.*

Species	Dormant Season: Warm	Cold	Cold
	2012-2013	2013-2014	2014-2015
V. aestivalis	-24.96	-26.02	-25.63
V. amurensis	-23.05	-27.97	-27.81
V. cinerea	-26.00	-25.74	-25.89
V. labrusca	-24.71	-26.81	-26.50
V. riparia	-25.42	-28.91	-28.72
V. rupestris	-25.58	-27.63	-26.95
V. vulpina	-24.79	-26.12	-26.17
V. hybrid Concord	-27.21	-28.07	-27.39
V. hybrid Noiret	-25.43	-25.65	-25.33
V. vinifera Cabernet Franc	-23.22	-23.13	-23.22
V. vinifera Riesling	-24.63	-24.34	-24.50

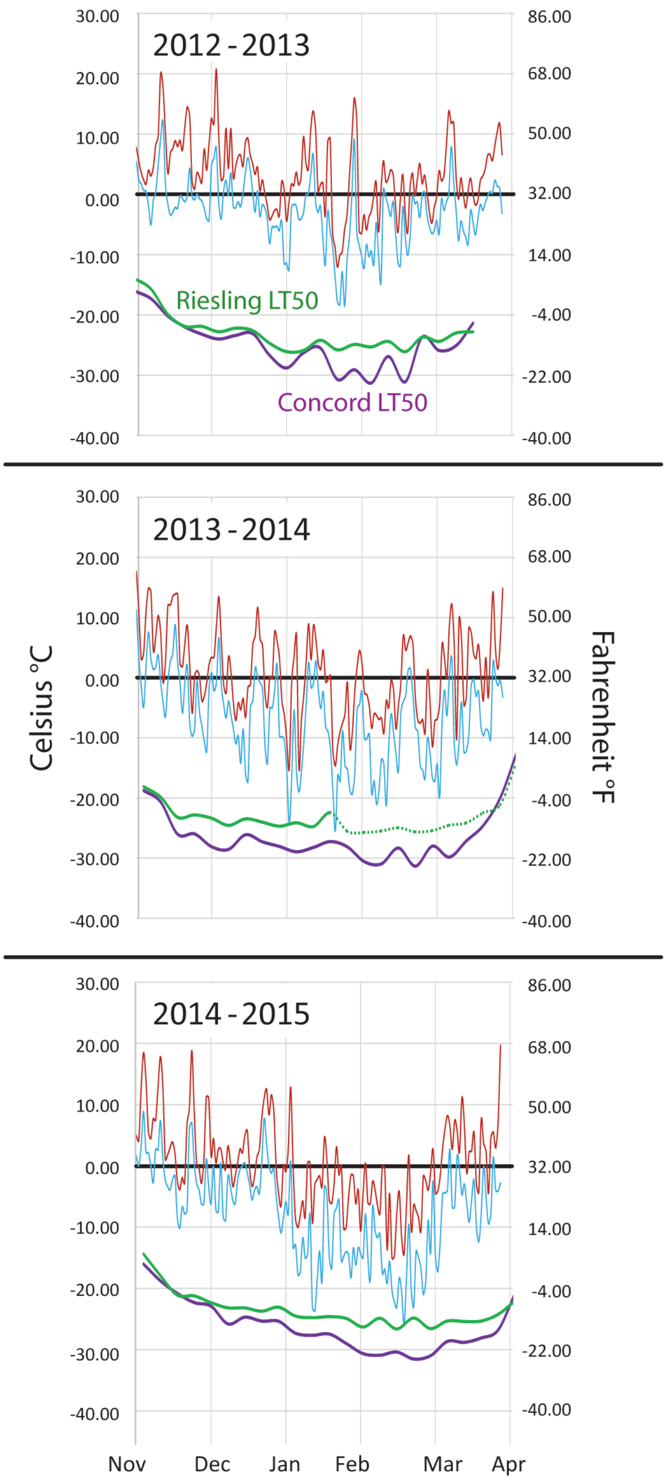


Figure 2*: Daily minimum and maximum temperatures at Geneva in the winters of 2012-2013, 2013-2014, and 2014-2015. Note that 2012-2013 had unseasonably warm temperatures spikes in January and March (budburst advanced by a month); 2013-2014 had fluctuating above and below freezing temperatures and two extreme lows (-25 C); and 2014-2015 had an extended period of below-freezing temperatures from January through the end of February. LT_{50} curves shown for V. vinifera Riesling and V. hybrid Concord. Dotted line for Riesling in 2013-2014 indicates the polar vortex cold even and subsequent vine damage.*

bud-freezing LT_{50}. In the colder 2013-2014 and 2014-2015 winters, there is still a 3 °C difference in supercooling, but the varieties with the highest LT_{50} (*V. hybrid* and *V. cinerea*) and lowest LT_{50} (*V. riparia*) were different. The interaction of genetics (variety) and environment (winter type) determine the level of supercooling observed in the field. You will also notice that the cultivated varieties did not vary as much between years. This is due to their more "sensitive" heritage as the cultivated grape's maximal bud hardiness is reached even in warm years.

Variation in chilling hours. I study chilling hour requirements in cultivated grape varieties to develop models of chilling and heating units, and predict the timing of budburst. I also study them on wild and hybrid grapevine varieties in order to understand the genetic components that determine endodormancy length. The goal of this research is to identify genes, which result in either short (low chill), or long (high chill), endodormancy. Dormant canes are collected from the field in late fall-early winter and placed into a cold room held at 4 °C so that chilling hours are maximized. After the buds are exposed to a specific number of hours of chilling, they are placed in a warm growing environment and observed to see how long it takes the buds to break (**Figure 3**). In the laboratory, the chilling requirement of each variety is determined when 50% of the buds in the experiment are seen to burst with 4 weeks of warm growing conditions. This data is used to then determine the minimal amount of chilling needed for a vine to have synchronous budburst in the field.

All species seem to respond to increases in chilling hours in the same way. As grapevines are exposed to increased chilling, they get faster and faster at bursting in warm conditions. Most *vinifera* varieties that grow in the Finger Lakes have a low chilling requirement, somewhere around 500-750 hours of chilling. The trends in the data suggest that wild species that have evolved in Northern climates (*V. riparia*, *V. labrusca*, *V. amurensis*), tend to have low chilling requirements (0-600). In contrast, species from more Southern distributions (*V. aestivalis*, *V. cinerea*, *V. vulpina*) tend to have high chilling requirements (1300-1700) (Londo and Johnson 2014) (**Figure 4**).

This pattern makes sense. Northern locations (low chilling requirement) have short growing seasons, a more abrupt transition between dormant and growing seasons, and fewer days in the 32-50 degree zone of chilling hours. More southern locations (high chilling requirement) have milder winters and more frequent fluctuations between moderate temperatures above freezing and freeze events. So in these regions, having a long chilling requirement would be the safest strategy. These adaptive strategies have formed over the long evolution of the different wild grape species.

Research Summary. Different grape species vary in both the depth of response to cold temperatures and the speed at which they respond. *V. vinifera* cultivars from a Mediterranean climate tend to respond more slowly, be less cold-hardy in midwinter, and break bud later than

Estimating Chilling Requirements

***Figure 3**: We estimate chilling requirement by forcing buds in the greenhouse after exposing them to varying amounts of chilling hours (see description Figure 3). The chilling requirement of each variety is determined when 50% of the buds in the experiment are seen to burst with 4 weeks of warm growing conditions.* Photo by Jason Londo.

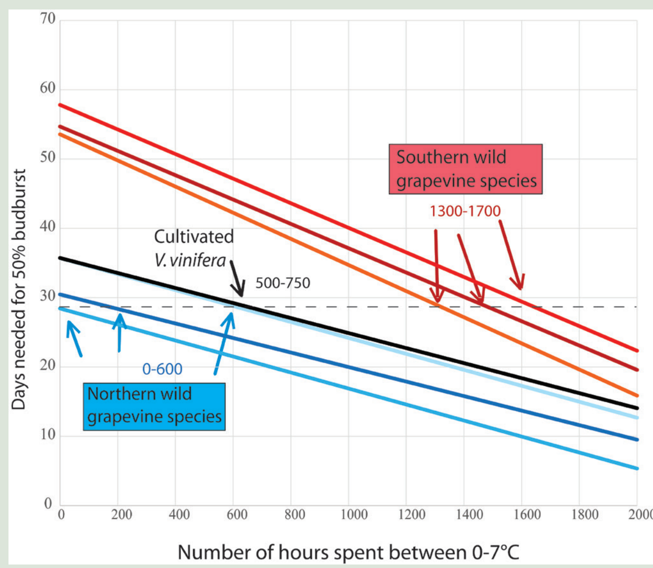


***Figure 4**: Chilling hours required for 50% budburst in 30 days for wild and cultivated grapevines. Range is 0 to 600 chilling hours for northern wild Vitis, to 500-750 for cultivated V. vinifera, and 1300-1700 for southern wild Vitis. Hybrids made between V. vinifera and either the low chill Northern species, or the high chill Southern species, will likely have intermediate chilling hours.*

wild grapes developed in Northern North America. Wild North American *Vitis* tend to reach lower LT_{50}s in midwinter. Chilling hour requirements to break dormancy range from 200 to 2000 hours – and are related to the climate in which the grapevines evolved. Northern collections of wild grapevines have lower chilling requirements than those collected in moderate southern climates.

Impacts of a Changing Climate. Will climate change affect dormancy and the risk of midwinter or spring cold injury? It is not possible to predict all potential effects, but warmer and more variable winter weather may increase the amount of chilling hours with temperatures between 0 and 10 °C (32-45 °F) in December and January, leading to more rapid deacclimation in the spring. The past several winters illustrate how cold versus warm winters may impact the future of grapevine production.

The last four winters were quite different both in extreme temperatures and temperature variation. Two of them (2013-2014 and 2014-2015) were very cold, harsh winters with polar vortex events and associated extreme low temperatures in the Great Lakes and Finger Lakes. *Vinifera* suffered severe winter injury in Michigan, Ohio, and Western NY, and less-severe, but significant bud injury in the Finger Lakes. Temperatures remained below freezing for much of the winter (Jan-early March). As a result, chilling hour accumulation in these cold years paused in midwinter and chilling requirements for *vinifera* varieties were not satisfied until late spring (**Figure 5**). Buds that were not damaged during midwinter burst in late April and avoided frost damage in the Finger Lakes.

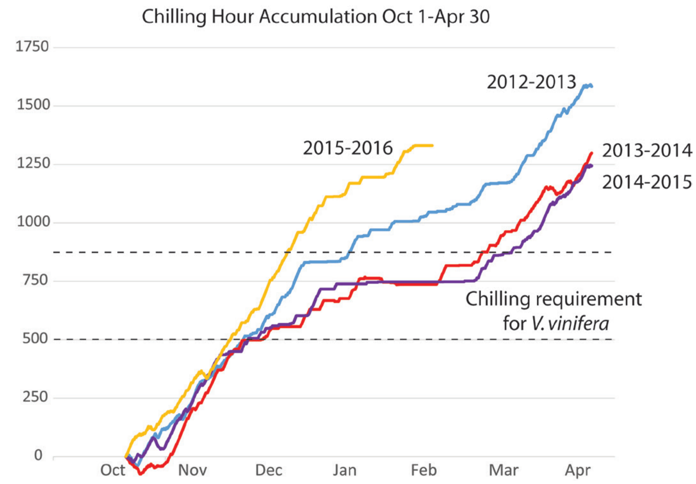
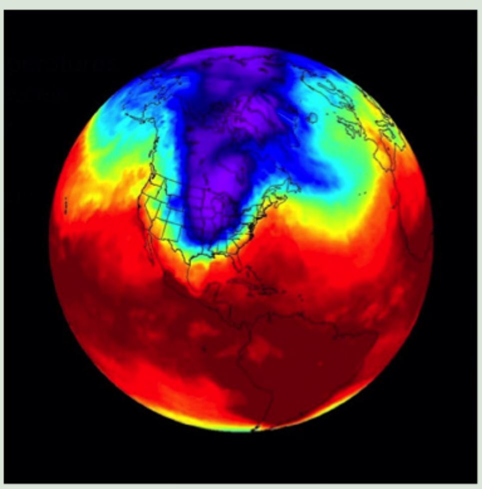
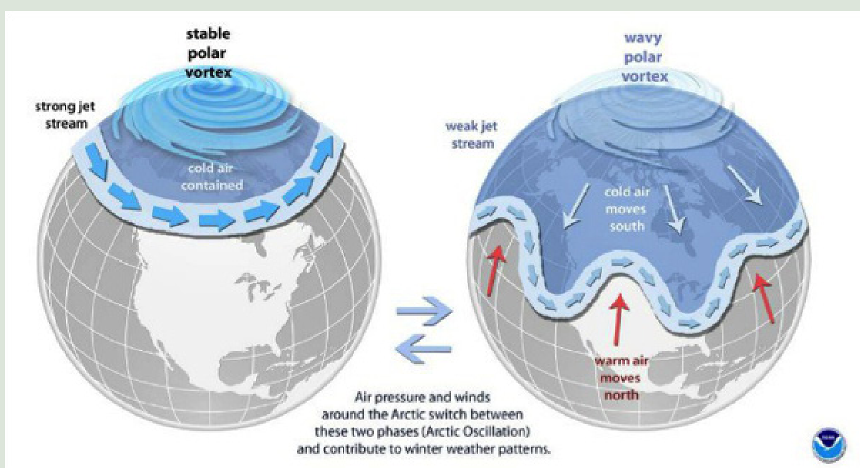


***Figure 5**: Cumulative hours of the last 4 winters in Geneva , NY, between 0-7°C (Utah Model). When temperatures are below freezing, chilling hours do not accumulate (flat line) and when conditions are excessively warm, chilling hours reverse. Excessive chilling in warm years (2012-2013, 2015-2016) makes vines more responsive to warm temperatures and increases risk of false spring and frost damage.*

Polar Vortex and Changing Climate





Climate change in the Midwest, North, and Northeast United States is predicted to increase winter temperatures by 2-3°C. This subtle warming is predicted to lead to more extreme weather fluctuations during winter and alterations in the dormancy cycle of grapevine. In the last 10 years, we have witnessed examples of these erratic weather patterns; the polar vortex events of 2013 and 2014, and the 2007 "Easter freeze". It is important to understand how climate warming, actually increases risk for severe cold events. Historically, strong winter temperature differences between the pole and equator creates a strong trade wind system across Northern North America. This strong system keeps cold air trapped at the poles during the winter (**left diagram**). However, as winter temperatures increase at the poles, the trade wind system loses strength and polar air can break out of the poles, dipping far to the south (**right diagram**). Grapevine damage from these events occur due to the combined effects of delayed or low acclimation from climate warming, with sudden shifts in temperature during midwinter and spring.

Images by NOAA.

In contrast, the winter of 2012-2013 and this winter, 2015-2016, started out as mild, warm winters with little time spent below freezing. As a result, the buds have experienced lots of time spent in the chilling hour temperature zone (**Figure 5**) and chilling hour accumulation in the field is much higher than in 2013-2014 or 2014-2015.

This year, chilling requirement for *vinifera* was satisfied in early/mid-winter (**Figure 5)**, which means that if warm temperatures were to occur and be sustained, bud burst would be likely. When this pattern last occurred in 2012-2013, temperatures were warm in early March followed by frost in late March/early April. As a result of the high chilling and warm spring, frost damage was observed on hybrid and wild grapevines. Currently (2015-2016), all *vinifera* buds have transitioned into ecodormancy in the field and are much more responsive to warm temperatures. Consequently, these vines will also be more responsive to early false springs and at risk to late spring frosts.

Early budburst and the 2012 growing season. The 2012 growing season is perhaps the most extreme example of the potential impact of early budburst. A week of temperatures in the 70s °F (21 °C) in early March led to the earliest budburst on record (March 27) for Concord grapes, followed by several frost episodes. The Concord crop suffered 40% freeze injury (Martin & Weigle 2012) and a 30% reduction in the overall crop. Economic losses were estimated at $28 million to the industry (Martin 2012). Will economic losses associated with milder winters and early spring temperatures become more common in the future?

The Future. Predictions of climate change suggest that both; milder, higher chilling winters with increased risk of frost damage, and more variable, polar vortex winters are likely to occur in the future. However, collaborative research between USDA and Cornell University in grapevine cold hardiness genetics is ongoing. Southern wild grapevine germplasm has already been identified with traits of long dormancy and slow deacclimation rates and Northern wild grapevine germplasm with traits for rapid acclimation and deep supercooling. Combining these traits and incorporating this knowledge into grapevine breeding programs now lead to a greater ability to mitigate climate challenges in the future.

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