The History of Minimum Temperatures at the Arnold Arboretum: Variation in Time and Space

Michael S. Dosmann

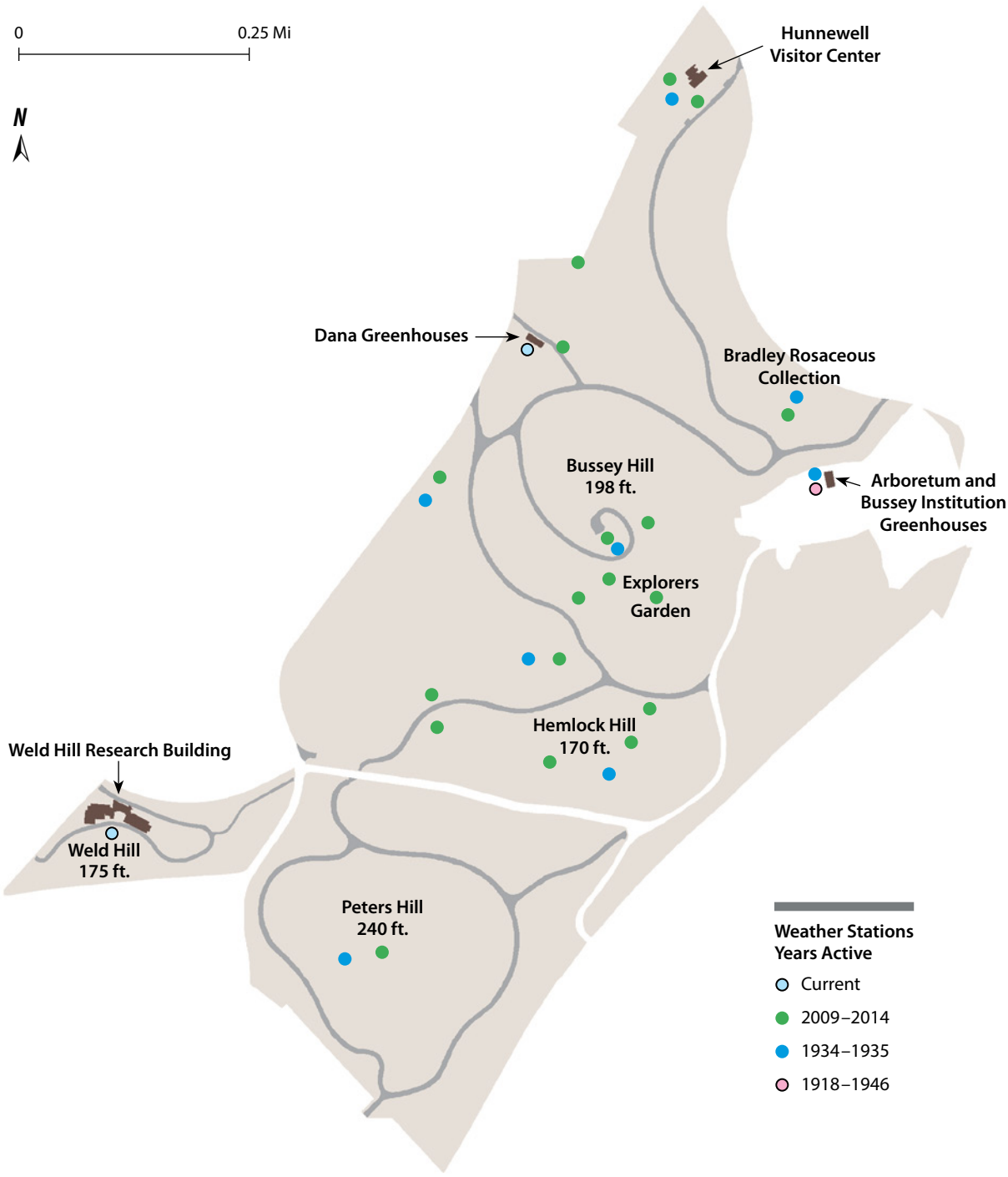
Given the original charge to cultivate "all the trees, shrubs, and herbaceous plants, either indigenous or exotic, which can be raised in the open air," it's not surprising that the Arnold Arboretum has long been interested in documenting local climate and weather, particularly as they relate to plant hardiness. Early publications such as *Garden and Forest* and *Arnoldia*'s predecessor, the *Bulletin of Popular Information,* are replete with notes of what did and did not survive New England's climate. *Arnoldia* continues that theme with annual summaries of the previous year's weather (see page 12 in this issue), often with notes on plant performance.

One of the most innovative projects linking plants and climate was Alfred Rehder's creation of the first Arnold Arboretum Hardiness Zone Map, which was published in the first edition of his *Manual of Cultivated Trees and Shrubs Hardy in North America* (Rehder 1927). On this map, Rehder divided the United States into eight different zones based on the average minimum temperature of the coldest month. Then, using information about what survived the winters in Boston and other regions, he assigned plants in his *Manual* to particular Arnold Arboretum zones of maximum hardiness. This novel application was further updated and improved by the Arnold Arboretum, and later inspired and gave rise to the hardiness zone map (see page 9) created and now perpetuated by the United States Department of Agriculture (USDA). (See Del Tredici 1990 for a broader review, as well as Dosmann and Aiello 2013 for a brief discussion on the 2012 version of the map and its application to plant acquisition and collections planning.) It is important to bear in mind that the zone parameters in the Arnold Arboretum scheme were different from those in the USDA's, thus giving rise to confusion about a species' cold tolerance, particularly when a species was simply said to be "hardy to Zone 6" without further clarification—was it the Arnold's Zone 6 (average annual minimum temperature -5 to 5°F [-20.6 to -15°C]) or the USDA's Zone 6 (-10 to 0°F [-23.3 to -17.8°C])?

The Arnold Arboretum map was last updated in 1971, and the now accepted industry standard, the USDA Plant Hardiness Zone Map, is based on the principle of average annual minimum temperature. Although other climatic factors (e.g., heat, rainfall, wind) certainly affect a plant's ability to survive in a given location, it is the minimum temperature in winter that is a primary driver of plant survival. The Arboretum lies within USDA Hardiness Zone 6. This means that in most winters we can expect a minimum temperature between -10 and 0°F, but it does not mean that temperatures lower than -10°F do not occur.

Just as the Arboretum has been curating plant data for almost 150 years, it has also been gathering and archiving weather data for nearly a century. Starting in 1918, William Judd, Arboretum propagator at the time, began to collect and record weather statistics on a daily basis. He collected these data near the greenhouse, which at the time was located near the former Bussey Institution and what is now the Massachusetts State Laboratory near the Forest Hills train station. Judd diligently recorded the data until his death in 1946, leaving us with a wonderful resource. In 1963, a new weather station was installed at the Dana Greenhouses (which had been constructed the previous year) and the Arboretum began to collect data again in earnest (Fordham 1970). In 2011, a new state-of-the-art weather station was erected at

Location of Weather Stations at the Arnold Arboretum of Harvard University

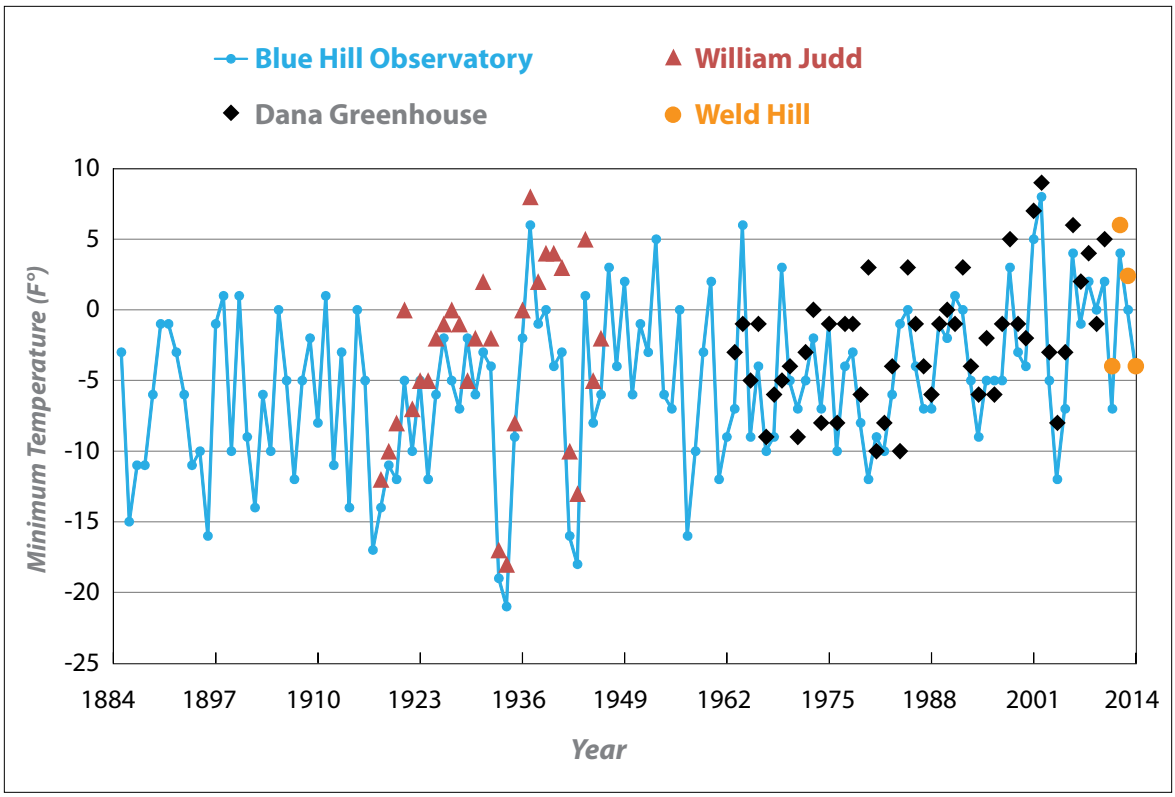


JORDAN WOOD

Over almost a century the Arboretum has acquired temperature data from three permanent stations (William Judd's measurements at the former Arboretum greenhouse [1918–1946]; the Dana Greenhouses; and the Weld Hill Research Building) as well as temporary stations set up by Hugh Raup (1934–1935) and, most recently, data loggers located throughout the grounds (2009–2014).

the Weld Hill Research Building, which, among other attributes, allows digital archiving of data and access via the web.

Although there is a 17-year gap between the end of the Judd period and the beginning of data collection at the Dana Greenhouses, the long-term collection has yielded volumes of information. One notable finding is the dramatic variability over time in the extreme minimum temperature events. The figure below depicts the temperatures from three Arboretum weather stations; I also included the annual minimum temperatures recorded at the Blue Hill Observatory (elevation 635 feet [194 meters]) in Milton, Massachusetts, some 8 miles south of the Arboretum. (Blue Hill Observatory has been collecting weather data since 1885 and is the oldest continuously operating weather observatory in the United States.) At the Arboretum, annual minimum temperatures have, by and large, stayed within the USDA Zone 6 range. However, there have been notable exceptions, including the bitter winters of 1933 and 1934 when Judd noted the thermometer hitting -17 and -18°F (-27.2 and -27.8°C), respectively. These were clearly Zone 5 (-20 to -10°F [-28.9 to -23.3°C]) winters, and the Arboretum documented the death of plants that could not tolerate that extreme. It has been thirty years since the Arboretum experienced a Zone 5 winter, and it was borderline (the Dana Greenhouse thermometer measured -10°F). Since then, annual minimum temperatures have remained in the Zone 6 range, with a number of years experiencing even warmer minimums. Are these due to climate change, or urban heat island effect? Perhaps a combination of both. Do these trends place the Arboretum in a new hardiness zone? I do not believe so. Even if 9 out of 10, or even 19 out of 20 winters never creep below 0°F (i.e., are in the Zone 7 range), all it takes is one Zone 6 winter to elimi-

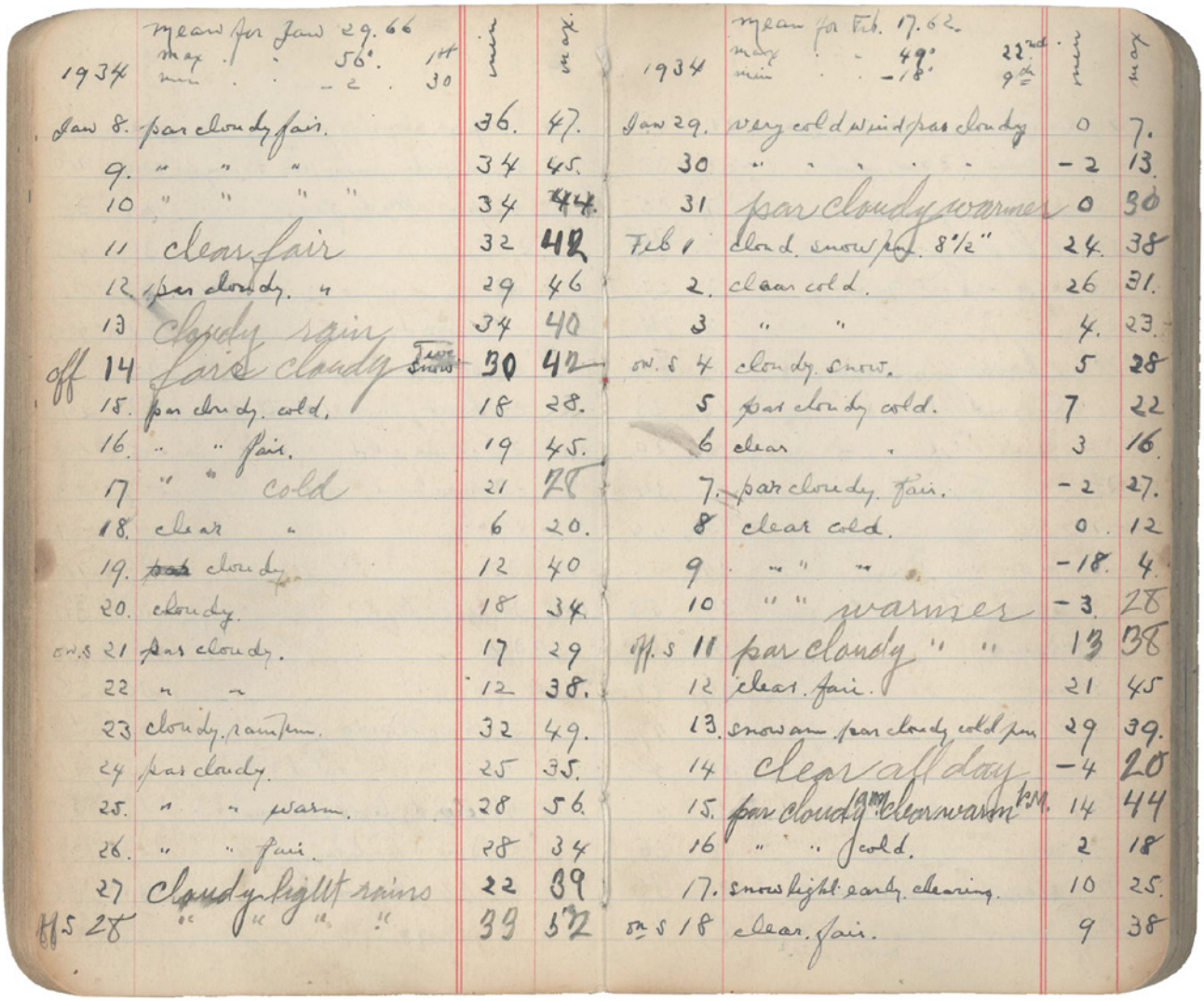


Annual minimum temperatures from the three permanent stations at the Arboretum, plus the annual minimum temperatures recorded since 1885 at the Blue Hill Observatory for comparison.

nate those plants unable to survive at those temperatures. It pays to be conservative when playing the hardiness game.

Location, Location, Location

In examining nearly a century of annual variation in minimum temperature at the Arboretum, one must bear in mind that those data were obtained from three separate and distinct locations, each with its own elevation and proximity to buffering buildings or canopies, as well as differences in aspect. And although we know that the present Weld Hill and Dana Greenhouse stations are sufficiently far away from buildings not to be influenced by them, we are not exactly sure where Judd's station was—it may have been somewhat protected. The Arboretum landscape comprises some 281 acres, with elevations that range from 44 feet (13.4 meters) above sea level in the Meadow by the Hunnewell Building to 240 feet (73.2 meters) on the summit of Peters Hill. Peters, Hemlock, and Bussey Hills each have their own character and microclimates distinct from surrounding areas.



ARCHIVES OF THE ARNOLD ARBORETUM

William Judd recorded daily weather notes, including maximum and minimum temperatures, from 1918 through 1946. The entry for February 9, 1934, (about half way down on the right) shows an extremely cold reading of -18°F.

ARCHIVES OF THE ARNOLD ARBORETUM

HARVARD FOREST, HARVARD UNIVERSITY

(Above) William Judd, longtime plant propagator at the Arboretum, working on cuttings in the former greenhouse (undated photo, probably from the 1930s).

(Left) Plant ecologist Hugh Raup had a long career at Harvard University, including serving as a research associate at the Arboretum and later as director of Harvard Forest.

These microclimates have been studied in the past, and also more recently. During the winter of 1934–1935, plant ecologist Hugh Raup conducted a study to document variation in minimum temperature, no doubt inspired by the bitter winters in the previous two years. As summarized by Al Fordham (1970), Raup set up eight stations across the Arboretum, with each station comprising a minimum-maximum thermometer. He then visited each station twice a day to record the maximum and minimum temperature that occurred for each site (one station on Peters Hill was stolen a month into the study, leaving us with data from just seven stations).

Even though this experiment lasted for only one winter and did not examine all of the undulations in topography, it confirmed the presence of a range of microclimates. According to Raup's measurements, the coldest temperatures for the winter occurred on January 28, 1935, a calm evening with no cloud cover that led to radiational cooling. During radiational

cooling, warm air is lost to the atmosphere and cools. This forms a temperature inversion, where the denser, colder air then settles into the exposed areas at the lower elevations, creating what are often referred to as frost pockets. On this evening, the average minimum temperature of Raup's seven stations was -18.6°F (-28.1°C), yet the range extended from a high of -7.5°F (-21.9°C) near the former greenhouse located at the Bussey Institution (now the site of the Massachusetts State Lab) to a low of -26°F (-32.2°C) in the shrub collection (now the home of the Bradley Rosaceous Collection). The flat area south of the Bussey Hill summit (now called the Explorers Garden) experienced a minimum temperature of -16.9°F (-27.2°C).

Finding Frost Pockets

Not long after I rejoined the Arboretum staff as Curator of Living Collections in 2007, I decided to repeat Raup's experiment using more modern technology and a greater number of stations. The goal was to again identify and confirm frost pockets as well as protected spots that the Arboretum might not be aware of. For instance, the Explorers Garden has long been exploited as a protected site, particularly the area along Chinese Path on the southwestern side where most of the plants in that collection have been grown. During radiational cooling, the dense cold air settles into the valley between Bussey and Hemlock Hills, leaving this area warmer. I was curious to know to what extent other areas of Bussey Hill—perhaps the eastern side—have the same moderating characteristics. This was particularly important to document because the Arboretum is running out of planting space in the crowded Explorers Garden. It would be wonderful to exploit other regions of Bussey Hill as well as other areas of the Arboretum for their moderating characteristics.

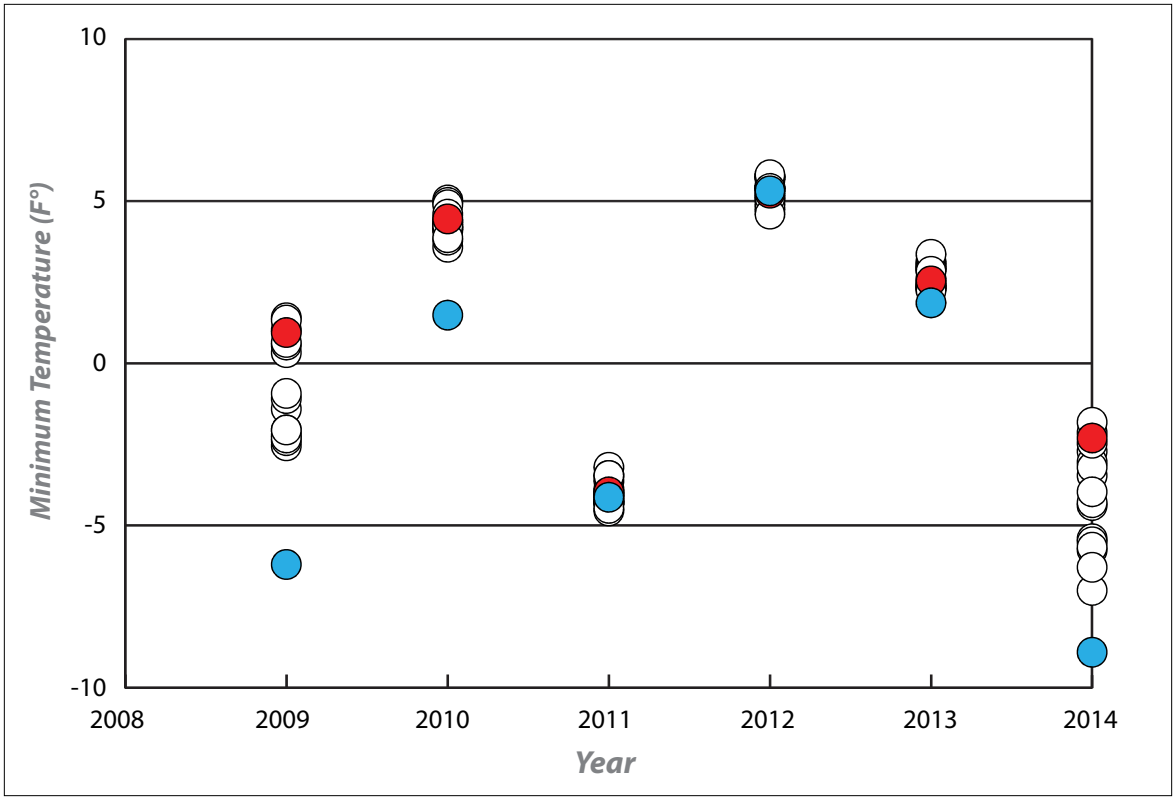
To achieve this task, I purchased some data loggers (Hobo U23 - Pro V2), small micro-meteorological stations that were programmed to record the temperature at 15-minute intervals. Each logger was enclosed in a plastic solar radiation shield, which ensured that the loggers would accurately record the air temperature and not heat up artificially on bright sunny days. The shields also kept out precipitation. The

MICHAEL S. DOSMANN

Curatorial assistant Jonathan Damery checks one of the data loggers that collect weather information throughout the Arboretum.

entire apparatus would normally be mounted to a post or a building just a few feet off the ground. However, I was a bit concerned that the loggers might suffer vandalism, like Raup's Peters Hill thermometer, particularly after many years. Thus we hung the loggers from tree branches about 10 feet (3 meters) from the ground using herbarium press straps and pieces of PVC pipe, effectively keeping the units out of the reach of curious passersby.

The loggers were deployed at 18 separate stations across the landscape (see map on page 3). Most of Raup's station descriptions were sufficient to identify the general area where they were located. New loggers were placed in the general vicinity for seven of Raup's sites; the one at the former Bussey Institution was not used because it is no longer part of the Harvard University enterprise. The remaining 11 stations were chosen for comparative purposes. For example, the station to the south of

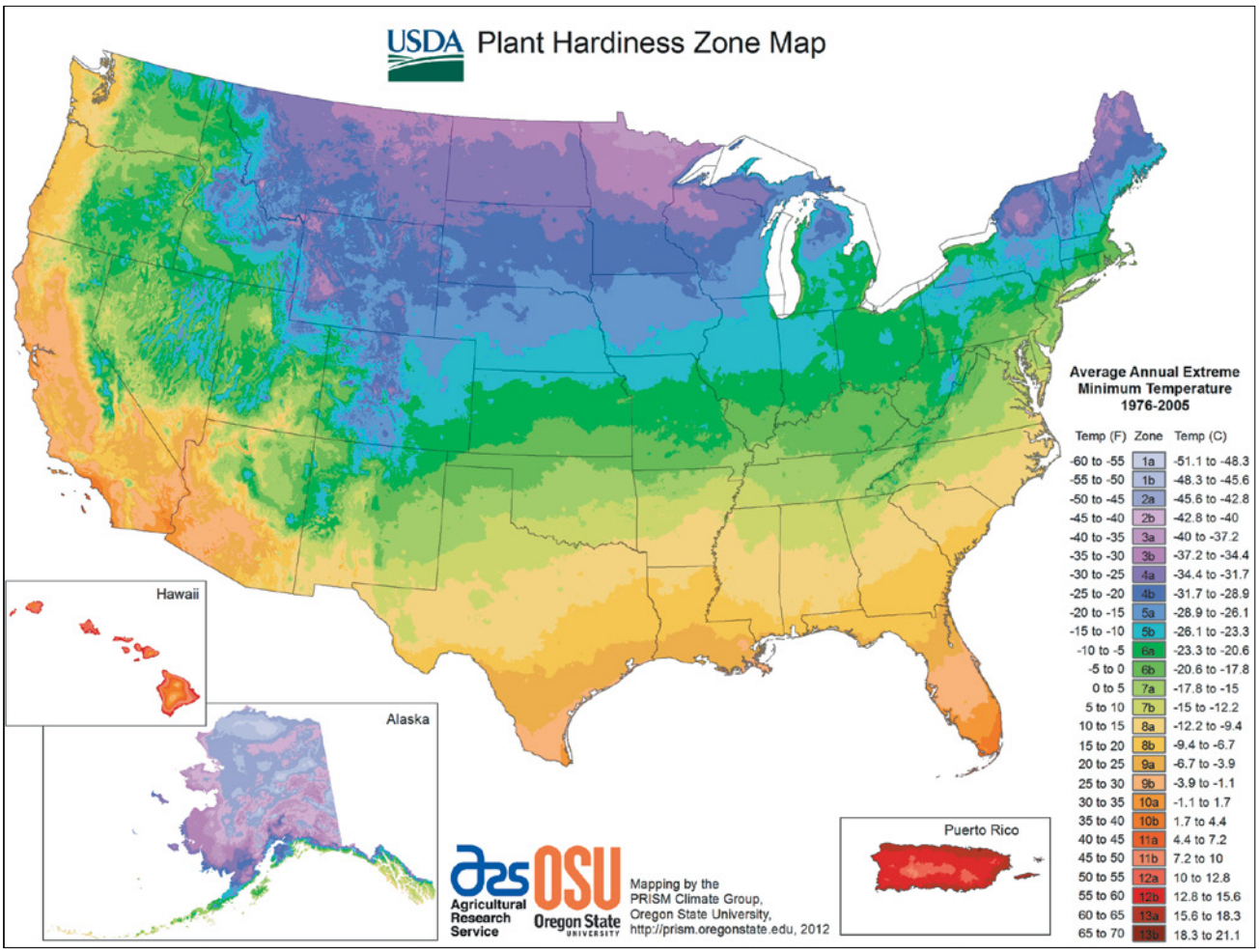


Annual minimum temperatures recorded for the winters of 2008–2009 through 2013–2014 at 18 monitoring stations across the Arboretum landscape. For readability, the individual stations are unlabeled; however, based on the 6-year average, the coldest (Bradley Rosaceous Collection) is shown in blue, and warmest (middle of Hemlock Hill) is shown in red. Cold-weather events of 2009, 2010, and 2014 are indicative of radiational cooling and the development of frost pockets, which led to great variation among stations.

the Hunnewell Visitor Center was paired with one behind the building, to assess the degree to which this site was protected. Raup had only one station on Hemlock Hill, at mid-elevation; we added stations at the summit and the bottom of the hill, in an east-west transect, as well as one in Rhododendron Dell, which lies in the valley between Hemlock and Bussey Hills. And to capture the possible variations in different exposures on Bussey Hill, loggers were placed on its summit and the edges of the Explorers Garden.

Curatorial staff visited each logger in spring to download the data from the previous winter and to provide some routine maintenance. The loggers performed quite well, with just a few anomalies. We are missing data for three separate loggers (one for one year, and two for another) when they stopped recording midway through winter. And on occasion there would be an aberrant spike or drop in temperature, much different from the readings 15 minutes before and after, so each logger's data were reviewed for consistency and the outliers tossed out. What I report upon here is just the minimum temperature recorded for each logger each year.

Although these data only refer to the previous six years and should be interpreted with caution, a few notable and fascinating trends cropped up (see figure above). To begin with, not just is there year-to-year variation in minimum temperature (which is obvious to anyone who has lived in New England!), but notice the variation among stations within a given year. In years 2009 and 2014, the absolute differences between the warmest and coldest stations were respectively 7.6 and 7.1°F (4.2 and 3.9°C)—a considerable spread, one that even spans multiple hardiness zones in 2009. In these events, the Arboretum experienced radiational cooling; the stations at higher elevations and in protected sites were warmer while those in the bottoms



of bowls—the frost pockets—had cold, dense air. Yet in other years, such as 2011–2013, the station minimum temperatures were all clustered together with only minor variation. Those years' coldest events occurred at times with ample cloud cover that prevented heat from escaping to the atmosphere, and perhaps windy conditions that ensured mixing of the air.

And, just where are these microclimates? Consistently, as it was in Raup's time, the Bradley Rosaceous Collection is the dependable frost pocket (note blue dots on page 8 figure). Cold air sinks down from the surrounding hills into this flat, low area. Across all years, the average warmest station was again the one sited on the middle of Hemlock Hill (note red dots on page 8 figure). However, numerous other stations in the Arboretum experienced rather similar temperatures year-in and year-out, and there was always another station warmer than the Hemlock Hill spot, so it is difficult to identify the most buffered microclimate. Other sites with moderated minimum temperatures are those clustered around the Bussey Hill summit and Explorers Garden (demonstrating that there is plenty of space to grow tender material), the area behind the Hunnewell Visitor Center (where we have already started to site a few tender plants), the summit of Peters Hill, the Centre Street beds, and the remaining two Hemlock Hill stations. It is worth noting that even if these stations have average minimum temperatures that place them within Zone 7, *all* stations in the Arboretum experienced Zone 6 minimum temperatures in 2011, as well as in 2014. Besides the Bradley Rosaceous Collection, what other frost pockets exist? The Juniper Collection, Rhododendron Dell, and the

open area southwest of the Hunnewell Visitor Center all have average annual minimum temperatures that place them in Zone 6.

Continuing Weather Data Collection

While it is tempting to draw major conclusions on six years of data, I'm not ready to create a new hardiness zone map of the Arboretum landscape just yet! The current USDA Hardiness Zone map relies on 30 years of thorough documentation; its 1990 predecessor used only 13 years of data and was deemed unreliable. So, perhaps after another 20 years of recording temperatures in the landscape, I'll feel more confident in creating such a map. Speaking of the future, we are looking into better technology

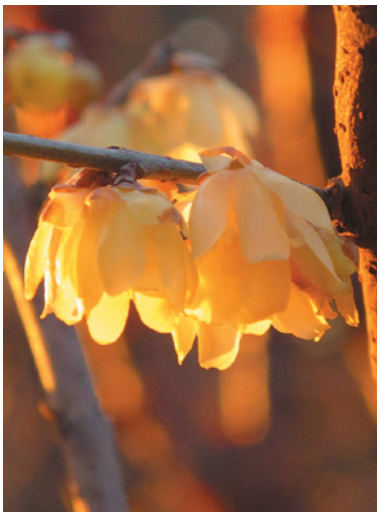
Right Plant, Right Place

The interplay between plant hardiness and microclimates has been well documented at the Arboretum. For example, many of the young cedars-of-Lebanon (*Cedrus libani*) grown from seeds collected in Turkey at the turn of the previous century were sited in a grove on Bussey Hill. Because the plants' hardiness was unknown, planting in this protected site provided some insurance in case the trees failed to survive elsewhere on the grounds. They grew with vigor, and this provenance proved to be fully hardy throughout the Arboretum and even in colder regions of North America. Other successes, like that of *Franklinia alatamaha*, were attributable to both site selection and keen horticultural practice (Del Tredici 2005). Not only was Bussey Hill the sweet spot for cultivation of this rarity, but the Franklin trees were also covered in mulch during the initial winters to ensure survival. Among recent accomplishments, the Arboretum has been able to successfully cultivate wintersweet (*Chimonanthus praecox*), generally known as a solid Zone 7 plant. In 2007, accession 236-98-A was finally planted in the Explorers Garden, and in March of 2010 it produced over a dozen cheerful yellow flowers. In 2012, a milder year, the fragrant flowers started to bloom in the middle of January and lasted for well over a month (for more see Yih 2014).

One thing to note is the difference between a plant's survival and actual performance. The ideal at the Arboretum is not just to grow plants that survive but that are healthy enough to reach mature size, or at least sexual maturity to produce flowers and fruits for study and enjoyment. A great example of this is *Stachyurus praecox*, which requires a favorable microclimate to perform best in New England. Although the species is able to survive—with occasional dieback—throughout the Arboretum, the flowers, which appear in very early spring, are particularly susceptible to low temperature damage. Thus, the plants growing in the Explorers Garden not only survive but consistently produce their unique pendent racemes of flowers.

LEFT TO RIGHT: KYLE PORT, MICHAEL S. DOSMANN, NANCY ROSE

Stachyurus praecox



Chimonanthus praecox

Franklinia alatamaha

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KYLE PORT

The weather station at the Dana Greenhouses, photographed by Arboretum plant propagator Al Fordham in the summer of 1969 (left), and the current state-of-the-art weather station located at the Weld Hill Research Building (right).

for data collection. This season we are experimenting with a new set of loggers. The originals, while excellent in some respects, were nearing the end of their lifespan and required too much additional care; we have retired them. As part of her research, Arboretum Putnam Fellow Ailene Ettinger deployed a new set of loggers across an even wider swath of the landscape. These pendent loggers (Hobo 8K-UA-002-08) are less intrusive in the landscape, easier to access and maintain, and are collecting temperature data at similar intervals.

As I hope this article has demonstrated, a single landscape like the Arboretum's is marvelously variable. The year-to-year variation in elements such as temperature can be quite significant, particularly when compared across the Arboretum's unique nooks and crannies. I not only find this fascinating as a scientist, but as a dedicated horticulturist I am excited that ongoing data collection and analysis will allow us to best match the plants curated in the Arboretum with their optimum locations.

Acknowledgements

The deployment and maintenance of the data loggers and subsequent data wrangling have been no small task, and I wish to call attention to the many who have assisted in the venture over the years. Erik Youngerman, Sue Pfeiffer, Abby Hird, Jonathan Damery, Sam Schmerler, Stephanie Stuber, Joyce Chery, and Kyle Port did a lot of the heavy lifting out in the landscape with the loggers and data. Jordan Wood created the wonderful map integrating the old and new stations. Will Buchanan spent countless hours in the library putting the Raup and Judd data into spreadsheet form. Lastly, Mike Iacono not only provided data from the Blue Hill Observatory but also gave valuable comments on an earlier draft of this article.

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