Climate Variability and Socioeconomic Consequences of Vermont's Natural Hazards: A Historical Perspective

The climate of Vermont has been described as changeable, with inherent variations. . . . Today, in the face of inherent climate shifts and enhanced greenhouse gas effects, understanding the role of climate variability becomes critical.

By LESLEY-ANN DUPIGNY-GIROUX

Over the last three centuries, Vermonters have lived with, learned from, and come to love the weather and climate around them. In turn, the relentless march of the seasons, each with its own series of weather events, has shaped our activities and the landscape. From the completion of the state's constitution during a severe thunderstorm in 1777[1], to the necessity-driven creation of recipes during the January 1998 ice storm, weather and climate have greatly influenced the socioeconomic fabric of our lives.

The climate of Vermont has been described as changeable, with inherent variations. Climate variability refers to the natural fluctuations that occur in hydroclimatological variables such as precipitation and temperature patterns, storm tracks, and frequency at a number of time scales (annual, decadal, centennial, and even millennial). Such naturally occurring variations make it difficult to distinguish long term trends in the climate record. Our knowledge about the climate around us is ever improving, although actual observations of climatic parameters remain somewhat limited. The interaction and inter-relatedness between the weather (i.e., daily temperatures, storms, precipitation) and climate (e.g. the recurring patterns of droughts and floods) on human activities and vice versa has long

Vermont History 70 (Winter/Spring 2002): 19–39.

been documented in Vermont. Samuel Williams first published *The Natural and Civil History of Vermont* in 1794, followed by Zadock Thompson's *Natural History of Vermont* in 1853, and *Lectures on Milk, Fertilization, Birds, Insects, Forestry, How to Foretell Storms, etc.* by Dr. Hiram A. Cutting in 1884. In the twentieth century, numerous accounts by naturalists, meteorologists, and climatologists, including F. E. Hartwell (1922), Arthur Stone (1929) and David Ludlum (1985) have greatly enriched our understanding of the complexities of the state's weather and climate.[2]

These complexities are highlighted by considering some well-known facets of life in Vermont. In general, Vermont enjoys equally distributed precipitation due to the convergence of storm tracks in New England originating in the northwest, west, and Gulf of Mexico. This implies that the cloud shield affects much of the region, making it one of the cloudiest places in the U.S. Two well-known climate singularities observed in Vermont include the January thaw and Indian summer. A climate singularity refers to a meteorological event that tends to occur on or around a well-defined date. Meteorologists now believe the January thaw occurs around the twenty-first of January. When F. E. Hartwell wrote his article about Vermont's weather for *The Vermonter* in 1922, the mild period could occur at any time from the final week in December to the middle of February. Then, as now, thaws have been known to remove all of the snow cover from the Lake Champlain valley, but do not tend to occur during severe winters.[3] Recently, pronounced thaws were observed in 1995 and 1996.

Today, in the face of natural climate shifts and enhanced greenhouse gas effects, understanding the role played by climate variability becomes critical. Changes in climate regimes could have adverse impacts on tourism, forestry, and water resources in Vermont. In particular, there is growing concern about the ability of farmers to adapt to increasing climate variability. In quantifying the impact of climate variability, individual events, and weather extremes on the state's economic activities over the past century-and-a-half, this account differs from earlier accounts in its focus on natural hazards. Severe weather, droughts, and flooding are all examples of naturally occurring phenomena that pose hazards or risks to human beings. It is the intersection between exposure to the risk by vulnerable populations that leads to a natural disaster. This emphasis on hydroclimatic hazards (and not geologic ones) will augment David Ludlum's synopsis of Vermont's weather[4] by highlighting the temporal and spatial underpinnings of climatic phenomena that have helped to shape Vermont's society and economy during the recent past.

Hazards in Vermont

Vermont is susceptible to a number of hydrometeorologic natural hazards ranging from temperature extremes, drought, flooding, flash flooding, tornadoes, and damaging winds, to severe thunderstorms, winter storms, and forest fires. Many of these phenomena are either made up of several hazards or are associated with additional ones. For example, lightning and hail often accompany severe thunderstorms. Winter storms can include snowstorms, blizzards, and icing events.

Every hazard has seasonal characteristics. For example, winter and spring flooding can result from ice jams or sudden thaws, whereas during the fall, tropical cyclone remnants can bring copious amounts of precipitation. Each hydroclimatic hazard also tends to occur in temporal cycles, and thus, some have been more frequently observed during some decades but not others. When this cyclical nature of extreme weather events is considered in conjunction with evolving patterns of population growth, land use practices, and economic development, we observe varying impacts on life, limb, and property over the course of Vermont's history.

Flooding, with Special Reference to Tropical Cyclones

One of the most pervasive hazards that impinges upon and marks the Vermont landscape is flooding. Flooding can be categorized as one of two types: flash flooding, which has a rapid onset of six hours or less from the time of the initiating event; and flooding that has a more gradual onset. Rarely does a year elapse without a flooding event of a significant magnitude being reported in at least one of Vermont's fourteen counties or perhaps statewide, making this the number-one hazard across the state. Between 1955 and 1999, floods accounted for $16.97 million in damage annually.[5] In recent decades, 1973 ($422 million) and 1984 ($115 million) stand out as notable for extreme amounts of flood damage.

The causal factors that lead to flooding are strongly seasonal in nature and include the arrival of consecutive large storms, snowmelt, ice jams, rain on frozen ground, wet antecedent soil conditions, and the passage of tropical storms or hurricane remnants. In the case of rain on frozen ground, downward percolation is inhibited, leading to surface runoff, as occurred during the ice storm of January 1998. Runoff due to lack of infiltration also occurs when the ground is already saturated from previous precipitation or a rising water table.

Large precipitation totals can be associated with a number of factors, including frontal systems. In Vermont, the combination between frontal characteristics (such as orientation and speed) and complex topographic barriers such as the Green Mountains and Taconics produces enhanced precipitation totals (also known as the orographic effect). The Montgomery flood of July 15, 1997 is a good example of orographic enhancement of the effects of a backdoor cold front (that moved from east to west) interacting with tropical moisture that was guided around the northern spine of the Green Mountains by the upper level (jet stream) flow. In the towns of Montgomery, Montgomery Center, Lowell, and Wolcott at least 6 inches of rain fell in less than six hours. Roads and bridges were washed out and homes were swept away. Along the Missisquoi River, North Troy recorded a new record peak flow value that exceeded the 100-year recurrence interval. The 1997 flooding at Montgomery points to another Vermont characteristic: repeat occurrences of certain types of hazards. Prior to 1997, the Montgomery/Jay Peak area was also affected in June 1993, while the Lamoille River in the adjacent watershed overflowed in August 1995. Repeat flooding was also observed in Underhill in 1998 and 2000.

Ice jams can occur during winter or spring and cause water accumulations that produce flooding upstream. If the ice jam breaks free, then downstream flooding occurs, as was the case in Montpelier on March 11, 1992. As the floodwaters rose to seven feet in the business district, 400 families and major businesses were affected. Montpelier is particularly prone to flooding given its location in the Winooski River valley just upstream from the confluence with the Dog River. Throughout its history, the capital city has been the site of flood damage, including extraordinary freshets (defined by the *Glossary of Meteorology* to encompass flooding due to either rain or melting snow) in July 1811 and July 1830. The floods of July 1859 and October 1869 produced heavy losses and claimed several lives. Early residents of Montpelier used the high water marks left on trees by the freshets as reminders against building too close to the water's edge.[6]

About a century-and-a-half ago, Zadock Thompson noted that "very little damage is ever done by hurricanes or hail. The crops oftener suffer from an excess, than from a deficiency of moisture, though seldom from either."[7] By the early twentieth century, however, the arrival of tropical cyclone remnants had become a double-edged sword. The precipitation accompanying these systems often has helped to reverse or end an existing drought. This happened in August 1988 with the arrival of Tropical Storm Chantal, again in October 1995 with Hurricane Opal, and most recently with Hurricane Dennis and Tropical Storm Floyd in 1999.

The opposite of this beneficial addition of moisture occurs when, instead of being parched dry, the landscape is already moist to saturated as a result of previous rainfall. Under these conditions, tropical remnants have produced widespread, and at times, catastrophic flooding. For example, the Great Flood of 1927 resulted from record rainfall totals produced by tropical storm remnants on November 3, following October precipitation totals that were already 50 percent above normal. As this decaying storm tracked directly along the spine of the Green Mountains, streams rose so rapidly that there was little time for warning. The Winooski River rose 40–45 feet above its normal level, causing land and settlement along the river to bear the brunt of the estimated $30 million in economic losses. The 1927 flood was greater than the 100-year flood on many rivers and remains today as the flood of record at many gauging stations. Eighty-four of the eighty-five fatalities during this New England-wide flood occurred in Vermont. In addition, thousands of dairy cows and other farm animals drowned. Rich topsoil on farmland either washed away or got buried under infertile silt, such that no crops could be produced for many years.[8] Montpelier remained isolated for days and Waterbury for weeks. The flood disrupted communications across the state and with the outside world, producing a "black triangle."

One positive highlight of the 1927 flood was the survival of the Chittenden Dam near Rutland, which did not overflow, despite the copious precipitation. Although some dams washed away in other parts of the state, the ones that did not (e.g. the Deerfield River) pointed to the usefulness of such structures as flood control measures. In 1929, the *Report of Advisory Committee of Engineers on Flood Control* recommended that "the only feasible method of diminishing flood flows in Vermont consists in constructing reservoirs for power use."[9] The resulting flood control plans took advantage of New Deal programs such as the Civilian Conservation Corps (CCC).[10] Today, attention has shifted to the wise use of floodplains as a prevention strategy, including buy-outs, improving municipal transportation infrastructure, and building flood resistant structures.[11]

The Great New England hurricane of 1938 (ranked category 3 on the Saffir-Simpson scale for hurricane intensity) arrived on September 21, following significant rainfall a few days earlier between September 12 and 20. Between September 17 and 20 alone, over 6 inches of rain fell, only to be followed by similar amounts during the hurricane itself. On some rivers (e.g., Black, Williams, Saxtons, West), peak flows exceeded both the 1927 and 1936 floods. Winds wrapped around the central low pressure to arrive from the northeast bringing salt-laden seawater and seabirds including puffins and albatrosses, which were left floundering in fields and swamps across Vermont in the aftermath.[12] The state reported almost $4.4 million in highway and bridge damage, especially in the areas around Brattleboro, Ludlow, Woodstock, Middlebury, and Rutland. Farm losses from the wind and water stood at $7.6 million, while tremendous wind speeds led to the loss of about half of the state's sugar maples. The havoc wreaked by hurricane-related winds was repeated most recently with the arrival of Tropical Storm Floyd on September 15–17, 1999. After surviving moderate losses ($1 million) as a result of the 1998–1999 drought, the apple industry suffered approximately $3 million in damages in the wake of this storm.[13]

Tropical cyclone remnants need not produce the catastrophic flooding of November 1927 or September 1938. Throughout the twentieth century, other cyclones have produced flooding of varying magnitudes and extents, as well as wind-related damage. Table 1 lists the tropical cyclones or their remnants that moved directly over Vermont. It should be noted that, in addition to these landfalling storm systems, the rainbands associated with the outer fringes of a decaying tropical cyclone can also produce significant damage. The 1938 hurricane was notable in that it followed a track very similar to the famous 1815 hurricane. The 1950s was a particularly active decade for hurricane activity. Of note

TABLE 1 Tropical Remnants that Made Landfall In/Proximate to Vermont

Name	*Year*	*Month, Day*
	1927	November 3
Great New England	1938	September 21
# 2	1949	August 29–30
Hurricane Baker	1952	September 1–2
Hurricane Carol	1954	August 31
Tropical Storm Brenda	1960	July 30
Hurricane Donna	1960	September 12
Tropical Storm Doria	1971	August 28
Hurricane Belle	1976	August 9–10
Hurricane David	1979	September 6–7
Hurricane Frederic	1979	September 14
Hurricane Gloria	1985	September 27
Tropical Storm Chris	1988	August 29
Hurricane Hugo	1989	September 22–23
Hurricane Bob	1991	August 19
Hurricane Opal	1995	October 5–6
Hurricane Bertha	1996	July 13
Hurricane Fran	1996	September 8–9

were Hurricanes Edna and Hazel in 1954. Hazel tracked from the Carolinas all the way to the city of Toronto in Ontario, with wind gusts of over 70 mph and considerable tree losses in the Burlington area. In 1955, two category-3 hurricanes (Connie and Diane) affected New England. In 1960, the flooding from Tropical Storm Brenda was confined to the extreme southeast of Vermont, while Hurricane Donna six weeks later produced little flooding. In October 1962, Tropical Storm Daisy's remnants caused leaves to be stripped from trees, leading to clogged drains and urban flooding. The remainder of the 1960s was relatively quiescent. The next major event, Tropical Storm Doria's remnants arrived in August 1971, causing landslides, road washouts, and bridge damage in the southeast. In June 1972, the winds from Hurricane Agnes felled trees and caused utility failures, blocked roads, and other property damage.[14]

In the winter, flooding can occur due to rain on frozen ground, ice jams, and snowmelt. The depth of the snowpack and the rapidity of its ablation (melting) are important factors in determining the severity of snowmelt-related flooding. At times, rain on snow assists in the ablation of the snow by the transfer of latent heat. This happened in March 1936 when a snowpack with water equivalents of 2–10 inches covered much of the state, the ground was frozen, and the streams covered with ice. The ice jam flooding on the Winooski River that devastated Montpelier in March 1992 was caused by rainfall and snowmelt. Similarly, above-normal temperatures on April 1, 1998 combined with excessive snowmelt to produce flooding on Lake Champlain as it rose to over 100 feet. Flood stage on Lake Champlain in Burlington is 101.88 feet, while the lowest level on record is 92.04 feet.

Apart from ice jams and snowpack ablation, freezing rain and frozen ground conditions can also produce flooding scenarios. During the first week of January 1998, a series of freezing events affected southeastern Canada and northern New England, including Vermont. During this Great Ice Storm of '98, Grand Isle and Franklin counties were particularly hard hit. Record-breaking rainfall combined with snowmelt to produce flooding on January 8 along the Otter Creek in Rutland and the Black River in Coventry. Ice jams along the Sleepers River washed away a bridge. Electricity pylons collapsed under the weight of the accumulating ice, and extended power losses led to financial ones as milking operations were disrupted around the state. Forest health issues came to the fore as crown loss, bole breakage, and other injuries, all of which are consequential in their own right, became even moreso in the face of subsequent attacks by disease and insects. Only one fatality occurred in Vermont, as a resident of the town of Milton, who was critically injured on January 8, 1998, lost his final battle on May 22, 1999.

Freezing rain and glaze conditions are inherent features of the climate in northern New England and occurred fairly frequently in the 1960s. These events resulted in school and business closings, tree injury, and hazardous travel. In December 1969, a multi-type event took place that is comparable in scope to the Great Ice Storm of 1998. This event began as a nor'easter on December 26–28, bringing 45 inches of new snow to Waitsfield and 1.5–3 feet elsewhere. Adding to a major snowstorm of a few days earlier, snow drifts ranged from 6–30 feet high, so that only snowmobiles were functional. As the precipitation changed to freezing rain in the Northeast Kingdom and the Connecticut River valley, forest injury and utility line damage became marked, leaving some customers without electricity for a week or more. Farmers lost thousands of gallons of milk as the lack of power translated into a lack of storage options or transportation opportunities.[15]

Thus, flooding in Vermont can occur during any season and produce a variety of geophysical and socioeconomic impacts. Flooding scenarios are often enhanced by the state's complex and rugged topography, antecedent moisture characteristics, and the tendency for flood-producing storms to stall or stagnate over preferred locations.

A Note About Flash Flooding

In addition to the effects of flooding, we must also consider flash flooding. These rapid onset events often result from stagnant or slow-moving thunderstorms as well as from the passage of a series of thunderstorms over the same geographic area. Such high-intensity and often long-duration events produce copious amounts of precipitation in a short period of time. These precipitation amounts can quickly exceed bank-full stages along rivers and streams, trigger mass movements (such as landslides and mudslides), sweep away unattached structures (e.g. trailer parks), and carve new channels.

Urban development and recreation activities, antecedent soil conditions, and ground cover type exacerbate flash flooding. Vermont's steep V-shaped valleys help to constrain the flow, creating remarkable depths of flow at tremendous speeds. As far back as 1853, Zadock Thompson noted these topographic characteristics along the Winooski, Lamoille, and Missisquoi rivers, such that by default, roads could only be constructed along the open valley floors, making them susceptible to flooding damage.[16] In the aftermath of the 1927 flood, Arthur F. Stone observed that, not only did the roadways, bridges, culverts, and other built features encroach on streams in these valleys, but the secondary growth and other vegetation that had replaced Vermont's primeval forests following clear cutting were inadequate to promote the infiltration and percolation necessary to delay runoff.[17] Today, over 70 percent of the state is now forested, but the encroachment of the built environment on streams and rivers still plays a crucial role in flooding episodes. This increasingly familiar scenario was repeated in late June 1998 (the third major flooding episode of that summer) when a stationary front stalled, allowing a series of thunderstorms to train across central Vermont. The already swollen rivers quickly overflowed onto adjacent roadways and developed urban spaces, leading to the evacuation of the towns of Lincoln and Bristol on July 2.

Timing can significantly affect the consequences of flash floods. Many of the frontal systems that affect northern Vermont are spawned at night. In addition to the difficulty of warning the vulnerable populations of the impending danger, many of these storms were enhanced by the steep slopes over which they passed. Examples include the Montgomery floods of July 15, 1997, as well as the northern Vermont flooding on 19 and 27 June, 1998.

Droughts

In Vermont, there is a saying that one extreme follows another. This is especially true for the hydrological extremes of floods and droughts, and examples abound. Extraordinary heat and drought followed the yearlong snow and frost of 1816. Drought-like conditions that had been in place since at least April preceded the November 1927 flood. The September 1938 hurricane brought relief from the severe drought of the 1930s. More recently, flash flooding in the northern portions of the state in August followed the statewide drought in the spring and summer of 1995. The statewide flooding of June/July 1998 gave way to the drought of 1998/1999.

Very severe droughts are rare in Vermont. They tend to affect the entire state and span a number of years. Prior to the 2001–2002 episode, the droughts of the mid-1960s were the most severe and long-lasting ones to afflict the state in the last fifty years. The years 1963, 1964, and 1965 were the second, third, and fourth driest years since records began in 1895, while 2001 was the fifth driest. Less severe droughts are relatively common and more localized in extent.

As a drought progresses, various socioeconomic sectors are affected. The 1998–1999 drought caused problems for individuals, utilities, agriculture, tourism, and other economic sectors that depend on surface or subsurface water supplies. An estimated $30 million in hay and pasture was lost statewide by the end of 1999. In the western counties of Addison, Chittenden, and Rutland, which were among the hardest hit, farmers suffered corn production losses estimated at $2,249,520, $29,586 and $664,290 respectively.[18] Christmas tree farms lost 50 to 100 percent of the seedlings or transplants set in 1999.[19] Some crops and plants, however, benefited from the warm, dry conditions. These included berries and grapes, which grew larger and sweeter than normal, while hot weather crops such as tomatoes, cucumbers, and non-silage corn ripened early and in abundance.

It should be noted that the effects of a precipitation shortfall cascade through the landscape, affecting the surface soil moisture, streams, and groundwater in that order. The hydrologic impacts of a given drought become increasingly evident as an episode evolves. During the 1998–1999 drought, record low streamflows and groundwater levels were observed at a number of U.S. Geological Survey (USGS) sites and wells across the state by the end of August 1999. While many individual drinking water wells also had run dry by this time, the water quality issues that were present during the 1994–1995 drought were absent. The summer of 1995 was a time of water conservation in many communities, while others, such as the towns of Newbury and Barre City, brought in water supplies by truck.[20] Such conservation measures were not required during the 1998–1999 event due to the timing of the water shortages and the reversal of the drought in the fall of 1999. Record low streamflows and dry wells were also a feature of the 2001–2002 drought, which when combined with the magnitude of the deficits, raises some concern for the nature of the recharge of the state's aquifers.

Across state forests, a total of 85,000 acres (34,425 ha) showed the effects of the 1998/1999 drought with such symptoms as leaf scorch, leaf yellowing, and early leaf color. Some deciduous trees began changing color by mid-August and the fall foliage color in the Northeast Kingdom was described as "subdued."[21] Several species, such as red and sugar maple, are susceptible to drought, and leaf scorch was evident in urban trees across Chittenden County.

Thunderstorms

A thunderstorm is a storm that contains thunder and lightning. According to the National Weather Service, Vermont and northern New York experience about twenty-five thunderstorm days annually. At times thunderstorms may be associated with wind gusts, torrential rainfall, and hail. A severe thunderstorm (defined by the National Weather Service as one with 3/4-inch hail and surface wind gusts of 50 knots) is also capable of producing flash floods and tornadoes. When thunderstorms form in a line along or ahead of a cold front, these are classified as a squall line. Thunderstorms that form in winter can be associated with snowfall, which some refer to as thundersnow. Each of the thunderstorm-related events (lightning, strong wind, hail, flash flood, and tornadoes) is itself a natural hazard that can cause property and crop damage as well as loss of life. One of the most memorable thunderstorm outbreaks in Vermont occurred between May 21–31, 1968, when thunderstorms, lightning, hail, and high winds were observed across the state. Although Vermont escaped the $133 million in flooding damage that occurred in New Jersey, this severe weather outbreak was beneficial in that it helped to reverse the drought that had gripped much of the northeast in the mid-1960s.[22]

Tornadoes

One of the concomitant hazards of severe thunderstorms is the spawning of a tornado. Historically, tornadoes were reported in Rutland on September 19, 1787, and again on May 3, 1790. Since 1950, tornadoes have struck every county except Grand Isle, Caledonia, and Washington for an annual average of $241,600 in damage in 1999 dollars.[23] Many of these tornadoes tend to be weak (F0 or F1 on the Fujita Scale, used for ranking tornadoes based on the damage caused and their speed of rotation). Between 1960 and 1969 alone, one waterspout on Lake Champlain and ten tornadoes were observed across the state.

Tornado damage tends to be localized. Some recent examples include barn destruction in Cambridge and apple orchard demolition in Bennington on June 24, 1960; timber, tree, and farm silo damage in St. Albans on June 13, 1961; roof damage, twisting or uprooting of trees, and some electric power loss in southeastern Windsor County on July 9, 1962. On August 7, 1970 a tornado at St. Albans injured seven in a camp home and demolished buildings. A rare F2 tornado, observed in Colchester on August 8, 1983, packed winds of 59 mph recorded at the Burlington International Airport and unofficial winds of 80 mph. It capsized aircraft at the Champlain Airport and snapped trees 100 feet tall.[24]

Tornadoes that form ahead of a cold front are often steered by southwesterly winds and move in a northeasterly direction. Those that hit Vermont are no exception. In some cases, tornadoes are not spotted, but rather inferred from the type and orientation of the resulting damage. Such cases occurred in Swanton on October 31, 1965 and near the Burlington International Airport on August 9, 1972, where a narrow path of destruction 0.1 mile long was reported.

Tornado sightings were frequent in the 1960s, less so during the 1970s, and rather rare in the 1990s, when only two were observed. Of these, the most recent occurred in Bennington County on May 31, 1998, producing $630,000 in property damage and power outages that affected about 8,000 customers for two to three days. Prior to that, the September 3, 1993 tornado that touched down in Orleans and Essex counties destroyed a Christmas tree farm as well as 70–80 acres in a maple orchard worth $50,000.[25]

Tornado outbreaks refer to a family of tornadoes that tend to form along a squall line. Such outbreaks can either be spawned by the same thunderstorm or by several thunderstorms over a period of time (more than two hours) and an extended spatial extent (more than 100 km). One example of the former scenario occurred on May 20, 1962, when three tornadoes formed from the same thunderstorm cell in Franklin and Orleans counties. On July 9 of the same year, another cell spawned at least two more tornadoes in southeastern Windsor County. In the first case, a barn, silo, and new trailer home were destroyed and tree damage was observed on both occasions.[26]

Hail

The F2 tornado that swept across Bennington County on May 31, 1998 was accompanied by 1.75-inch diameter hail that produced $20,000 in property damage. Like lightning, hail is a thunderstorm-related hazard that has produced significant property and crop damage through the years. Farmers have sometimes called hail the "white plague," because entire fields of crops can be destroyed in minutes.[27] Apples are one of the crops most susceptible to hail damage. As far back as July 15, 1799, accounts tell of devastating thunderstorms in the Connecticut towns of Lebanon, Bozrah, and Franklin, which destroyed not only apples but also apple trees due to heavy rains, winds, and hail as large as 7 inches in circumference.[28] Hailstones destroyed entire apple orchards in May and June 1959, as well as on July 10, 1966 in southern Vermont and two days later in the counties of Addison, Rutland, and Bennington. On June 25, 1983 a three-minute hailstorm in Cornwall damaged over 500 acres of apple crops, causing growers to label it as the worst storm in ten years.[29]

Hailstones have flattened entire hay fields (e.g., the tornadic thunderstorm in Highgate Springs on June 13, 1961) as well as cornfields from Grand Isle to Morrisville on August 18, 1969. In addition, large acreages of potatoes were also lost in the towns of Albany and Craftsbury on July 21, 1964.[30]

On the same day as the hailstorm in Cornwall, another one, which produced 1-inch diameter stones, prematurely ended a hot air balloon event in Quechee, forcing balloonists to make emergency landings. Overall, hail damage to property in Vermont has been estimated to be on the order of $111,000 between the beginning of 1993 and the end of March 2001.[31]

Lightning

Lightning is an electrical discharge within a cloud, between clouds, or from a cloud to the ground. While cloud-to-ground lightning only accounts for about 20 percent of all lightning strikes, this type has been the most detrimental to life and property across the state. Between January 1, 1993 and March 31, 2001, approximately $1,611,000 in lightning-related property damage occurred. Next to flooding, lightning strikes have accounted for a disproportionate share of hydrometeorological-related fatalities in Vermont since the 1960s. At least nine people have died in lightning-related incidents. Others have sustained burns and other injuries. Dairy cows and other livestock have been killed; barns have burned down completely; and communications facilities have been impaired on a number of occasions including June 15, 1972 and July 21, 1983, when emergency services personnel were forced to use back-up supplies.[32]

June 18–24, 2001 was designated as National Lightning Awareness Week around the U.S. One of the most important messages of this campaign is that lightning not only strikes in conjunction with a thunderstorm, but away from it as well. This occurs when positive lightning originates in the cirriform anvil at the top of a thunderstorm. This type of lightning is particularly dangerous because it can strike up to 5–10 miles away from the storm, and its lengthy duration ignites forest fires more easily.[33] The threat of forest fires is heightened when large amounts of debris accumulate under dry atmospheric conditions, as occurred when the drought of 1998–1999 followed the Ice Storm of January 1998.

Winds

Damaging winds can occur at any time of the year, can gust to more than hurricane speeds (74 mph) and can be classified as one of three types. One category, Shirkshires, are gravity or fall winds that gain speed from being funneled through the Valley of Vermont, located in southwest Bennington County between the Green Mountains and the Taconics.[34] During one such event in the county on March 12–13, 1962, wind gusts of up to 81 mph produced widespread, extensive damage. One of the rare wind-related fatalities occurred when a man who was trying to open a door against the wind went into heart seizure.[35]

Very strong winds are also associated with thunderstorms when downward moving air (called a downdraft) strikes the ground and moves out laterally to form a downburst. Downbursts are examples of straight-line winds that can exceed 100 mph and produce damage that is reminiscent of a tornado. Microbursts are downbursts of 4km or smaller in size, while macrobursts are larger than 4km. When microbursts reach the ground and continue moving outward, they become a gust front. Downbursts in combination with gust fronts have caused tree damage, flattened crops, and downed power lines. Often, these damaging winds occur along with other hazards, such as hail.

During the winter, strong winds can accompany snowstorms, blizzards, and icing events. On April 3–7, 1975, during the worst storm of the 1974–1975 season, record snowfall that was heavy and wet combined with very strong winds to damage trees and take down power lines. Statewide, high winds and glaze on February 15, 1967 broke glass panes, communications antennae, and signs, and took down trees.[36]

One atmospheric pattern that is conducive to windstorms occurs in advance of a cold front when the associated low pressure system is moving to the north and west of Vermont. At the same time, high pressure exists over the Canadian Maritimes. As air moves from the area of high pressure to the area of low pressure, the strength of the resulting wind usually depends on the gradient (or difference in pressure values between the two). Vermont's complex topography is conducive to creating downslope winds and/or strong winds that have been funneled through narrow mountain passes. On January 27, 1996 windstorms of this sort produced air flow of 95 mph at Cambridge, damaging a school roof; 68 mph winds at Jericho, also resulting in roof damage and; 67 mph at Waltham.[37]

Winter Storms

Despite such tongue-in-cheek comments as "Vermont has only two seasons: winter and July,"[38] snowfall in its many varieties, sources, and durations has been both a boon and a bane to the state. Winter sports industries (especially skiing) and various components of the agricultural sector definitely reap benefits from this form of precipitation, although not without several caveats. A number of systems or scenarios produce snowfall, including lake-effect and lake-enhanced snows off Lake Champlain, mountain-induced events, nor'easters and blizzards, and frontal events. For a winter storm to develop, three key ingredients need to be in place. The first is moisture so that clouds and precipitation can form. Secondly, this moist air must be uplifted in some way so that condensation can initiate the cloud formation. Such uplift is provided by warm and cold fronts, as well as by topographic barriers such as mountains. Third, cold air must be present between the clouds and the ground to ensure that the precipitation falls as either snow or ice.

Just as Lake Champlain produces a moderating effect on the temperatures of the Champlain Valley so that the growing season there is longer than in other parts of the state, so too it influences snowfall. Alexander Tardy has found that most of the time, the lake's influence is limited to low clouds and flurries once an Arctic airmass has moved through.[39] At the other end of the spectrum, however, snowstorms on Lake Champlain can reduce visibility to zero and produce over 12 inches of snowfall.

Nor'easters (also called northeasters) are intense low-pressure systems that develop or intensify along the North American eastern seaboard between December and March. Moving northeastward along the coast, these systems are accompanied by very strong winds, heavy snowfall, and at times, sleet. The nor'easter of December 26–28, 1969 produced 1.5–3 feet of snow statewide and 45 inches at Waitsfield. The state was declared a disaster area. Snowdrifts were 6–30 feet high, halting all traffic except by snowmobile. Forests and utility lines were devastated, while roofs collapsed in both urban and rural areas. Power outages on dairy farms led to the disposal of thousands of gallons of milk, due to a lack of transportation or storage.[40] This situation would be repeated twenty-nine years later during the ice storm of January 1998, when such losses contributed to the statewide total of $5.8 million in property damage. More recently, the winter of 2000–2001 was marked by four nor'easters between December 31 and March 31. Although the financial losses did not approach the 1969 storm, the later nor'easters in the 2000–2001 season set new snowfall records (e.g., 22.9 inches at Burlington on March 5–6), with the wet, heavy snow breaking branches and leading to telephone and power outages.

Blizzards are common occurrences in Vermont. True blizzards are dry, powdery snow events that are accompanied by low temperatures and strong winds (34.5 miles per hour or 15.3 metres per second) that can reduce visibility to a few metres. The Great Blizzard of March 1888 was actually preceded by a blizzard on January 25–26. Roads were blocked and businesses closed in Strafford for three days, while ten trains were stranded between Shelburne and Charlotte by huge drifts. Peak winds of 47 mph and 42 mph were recorded at Brattleboro and Northfield respectively. This storm would be followed by the unforgettable Blizzard of March 1888 during which deep snowfall, extreme temperatures, and gale force winds converged. Snowfall totals exceeded 40 inches over much of the southern counties, while at Danville, only 12 inches of snow was measured. The temperatures dipped as low as 6°F.[41]

In the twentieth century, one of the worst blizzards in the state's history occurred on December 29–31, 1962. Gale-force winds accompanied the 2–30 inches of snow that fell over the thirty-six-hour period, clogging highways and slowing air and rail transportation. The high winds and bitter cold led to a number of frostbite reports and froze water pipes around the state. Stores, offices, schools, and even ski operations closed, in some cases all week. Transportation hindrances would also be a by-product of the Blizzard of 1993, another memorable event. Property losses from this storm totaled over $500,000 including a barn that collapsed in Craftsbury and statewide power outages that affected nearly 3,000 customers. In terms of its broad geographical extent, the Blizzard of 1993 rivals the Great mid-February snowstorm of 1958, the Great Snowstorm of January 1831, the Cold Storm of January 1857, and the Eastern Blizzard of 1899.[42]

Apart from these memorable storms, a few additional observations are notable. As mentioned above, one extreme frequently follows another. For example, the September 1999–January 1, 2000 period was the least snowy on record at Burlington, while April 2000 became the second snowiest April on record. Another observation revolves around the fact that, during some winters (e.g., April 1967), snow squalls associated with thunder are especially common. In other years, large snowfalls in October or November have led some ski resorts to open early, as was the case in November 1965 and 1968. In the latter year, 10–20 inches of snowfall on November 7 and 8 precipitated early openings, but the addition of two feet of snow on November 10 forced the closure of roads like State Route 9. Several thousand skiers were marooned with insufficient food and accommodations.[43]

The transportation sector frequently bears the brunt of severe winter weather. In the modern era, no mode has been spared. Repeated snowstorms in January and February 1960 led to the closure of Lake Champlain on February 14. Occasionally, heavy snow makes for difficult clearing and removal, at times stranding motorists who have abandoned their automobiles. Holiday air travel has also been disrupted.

The winters of 1968–1969 to 1971–1972 were the snowiest on record dating back to the 1800s. At Burlington, the previous snowfall record of 132 inches was set in 1886–1887. The final total for the 1970–1971 winter was 145.4 inches.[44] The 122.5 inches received during the 2000–2001 winter exceeds the 1968–1969 (96.3 inches), 1969–1970 (104.6 inches) and 1971–1972 (108.9 inches) seasons. Prior to the 1970–1971 season, the 1965–1966 season held the record for the highest snow total in the twentieth century at 111.7 inches. It is significant to note that this latter record occurred at a time when much of the state was locked in a multiyear drought. During these especially snowy winters repair personnel and line crews used snowmobiles and snowshoes as a mode of transport. New snow removal equipment also debuted during this time and annual budgets for winter maintenance were accordingly adjusted to better handle snow removal in the post-1970 era.[45]

During particularly snowy winters, the threat of snowmelt-related flooding in March or April is heightened. By late March 1971, the water content in the snowpack was twice the normal value in some areas. In addition, some rivers were at 160 percent and 185 percent of their normal discharges. Under those conditions, officials predicted that only 1.9 inches of rain would be needed to produce a flash flood.[46]

In addition to winter recreation, another economic sector that is heavily dependent on snowfall is the sugar maple industry. A blanket of snow during the winter protects the roots of these trees, making it easier for them to extract soil water when temperatures rise and the sap begins to flow. The latter occurs when the internal tree temperature rises above freezing, which corresponds to air temperatures of 35°–40°F. Even though the 2000–2001 winter season provided excellent root cover, the thermal factor was absent, as has been observed over the last four to five winters.[47] Along with the 1987 maple syrup season, the 275,000 gallons produced in 2001 ranked as the second lowest production total since records began in 1916. The 1970–1971 record-breaking snow season yielded the lowest maple syrup totals (240,000 gallons) on record.[48] Table 2 shows the vagaries of maple syrup production over the last eight years. The 1998 figure reflects the aftermath of that year's ice storm.

Temperature Extremes

Climatologists use a thirty-year period to compute statistics of the mean temperatures, precipitation, and other parameters for a given re-

Table 2 Maple Syrup Production in Vermont, 1994–2000

Year	*Total (thousands of gallons)*
1994	435
1995	365
1996	550
1997	395
1998	360
1999	370
2000	460
2001	275

Source: Vermont Department of Agriculture, Food & Markets.

gion. One of the noteworthy characteristics of Vermont's climate is the tendency to stray above or below these expected values, a statement that was as true in 1922 as it is today.[49]

Extremes in temperature and the seasonality of these extremes are important to both individuals as well as economic activities. During the summer, both extreme cold and extreme heat can be observed. The former is associated with frost, which can be detrimental during the growing season. Extremely high temperatures can occur when a high-pressure system (under which air is descending towards the earth's surface) develops and intensifies over the state. Under such conditions, the potential for a heat wave exists. A heat wave is a period of three or more consecutive days during which the diurnal maximum temperature meets or exceeds 90°F. In Burlington, the average number of days per year with above 90°F temperatures is six. In 1999, a drought year, this figure climbed to nineteen. Extreme maximum temperatures are often observed during drought years, and in many cases, the records that are broken were long standing and set during previous droughts. It should be noted that a heat wave can be either a boon or a bane depending upon the time of year and the antecedent conditions. For example, the hot conditions of August 1996 followed a cool, wet summer, thereby providing an extra boost for plants.

In the fall, both abrupt cold snaps and record warmth can be observed, where the latter tends to be associated with southerly flow. Similarly in winter, both extreme cold and record warm conditions occur. The winter of 1933–1934 was particularly cold and the lowest temperature ever recorded for the state (−50°F) occurred at Bloomfield on December 30, 1933. Prior to this, extreme cold temperatures were widespread on January 4 and December 18, 1835, with −40°F at Montpelier and White River, −38°F at Bradford, −30°F at Rutland and −26°F at Burlington.[50]

Following the winter of 1933–1934, more than 20 percent of the apple trees in Vermont were eliminated, although this figure was less than 2 percent for the Macintosh variety. Temperature is a very important variable in promoting apple growth. The dwarf trees introduced in the 1860s lacked the winter hardiness needed to be truly viable in Vermont. In 1868, the first Macintosh tree, a transplant from Ontario, was planted in Newport. The severe winter of 1917–1918 destroyed almost all of the Baldwin and other strains. Only the Macintosh variety survived, and it remains the dominant strain grown today.[51] In 2001, temperature fluctuations in the spring produced a different loss. Daily maxima of at least 90°F followed by minima on the order of 20°F accelerated the flowering of the apple blossoms, which were then killed by the low nighttime temperatures.[52]

One of the most prolonged cold episodes lasted from January 18 to February 3, 1969. Diurnal maxima were below 0°F. Water mains and other connections froze and burst in record numbers across the state. Since then, extreme cold has been recorded in February 1993 and again on January 19, 1997. In both cases, cold dense air moving out from an Arctic high pressure system caused temperatures to plummet. Daytime highs in 1993 were 10°F, while the minima were −5°F.[53]

An interesting pattern is that these cold episodes tend to follow (and sometimes precede) severe snowstorms. In some cases, cold dense, subsiding air in high pressure systems quickly follows the passage of cold fronts that are associated with a given winter storm. In others, cold waves (surges of cold air), which originate over Hudson Bay, move across northern Vermont fairly frequently in the winter.[54] Examples include one of the state's worst blizzards on December 29–31, 1962, near blizzard conditions on January 30–31, 1966, the 8–18 inches of heavy, wet, clinging snow received on November 14–15, 1972, and the Great Ice Storm of 1998.

The variability in temperature extremes would not be complete without mentioning 1816, "the year without a summer." In April 1815, Mt. Tambora on the Sumbawa Island of Indonesia erupted, spewing 150 km^3 of ash into the air that reached well into the stratosphere at a height of about 28 miles (44 km). The dust and aerosols thus produced and dispersed affected global climate for up to two years. The northern hemisphere, especially New England and Europe, were particularly affected, and accounts of the hardships suffered were preserved by farmers such as James Winchester and Benjamin Harrison of Bennington. The severe winter of 1815–1816 gave way to a warm, dry April that turned into a backward spring, a cold, snowy summer, and an early fall. The month of May was dry and cold and although the start of June promised warmth (90°F on June 5), the series of cold spells that would keep Vermont and much of New England in their grip through September and onwards arrived on June 6. As the maximum temperatures dropped to 40°F, snow began. Snowfall continued through June 8 with accumulations of 12 inches at Montpelier and 18 inches at Cabot, accompanied by severe frost that froze standing water and killed all but the hardiest crops, such as oats.[55]

Dry, windy conditions continued into July and August. Although rain fell in other parts of New England, Vermont received no relief. Some enterprising farmers built bonfires around their cornfields and salvaged some of the crop. On August 21, a killing frost decimated more potato, corn, and bean crops. The cold drought continued into September, accompanied by forest fires. Staples were destroyed. Livestock starved due to lack of forage and later due to lack of hay in the winter. Money was scarce and it was difficult to import food due to the condition of the roads. The years 1816–1817 were marked by famine, but 1816 will remain infamous for the phrase, "eighteen hundred and froze to death."[56] Thus tested, many people emigrated from Vermont and New England in the wake of the year without a summer.

Conclusion

The human and physical landscapes of Vermont have been and continue to be shaped by the vagaries of our weather and climate. The manifestations of certain events (e.g., shirkshires) are native to the state and occur as a function of the state's complex topography. In turn, the topography has dictated to some extent the way in which infrastructure (in particular, roads) has developed, thereby setting the stage for vulnerability to flooding. Many of the most devastating floods, droughts, winter storms, and temperature extremes have been related to regional, and at times, hemispheric patterns and changes. Atmospheric fluctuations have long fascinated human beings and repeatedly proven a number of Vermont weather truisms such as "when the mountain roars, close your doors." Given the cyclical nature of hazards and the inherent variability of the climatic system, perhaps we should remember that for Vermont, it is normal to be abnormal.

Notes

[1] Ira Allen, *The Natural and Political History of the State of Vermont* [1798] (Rutland, Vt: Charles E. Tuttle Company, 1969), 63.

[2] Zadock Thompson, *Natural History of Vermont, with Numerous Engravings and an Appendix* (Burlington, Vt: Zadock Thompson, Stacy & Jameson printers, 1853); Hiram A. Cutting, *Lectures on Milk, Fertilizations, Birds, Insects, Forestry, How to Foretell Storms, etc.,* (Montpelier, Vt: Watchman Journal Press, 1884); F. E. Hartwell, "The Climate and Weather of Vermont," *The Vermonter-The State Magazine* 27, no.9 (1922):211–214; Arthur Stone, *The Vermont of Today with Its Historical Background, Attractions and People* (New York, NY: Lewis Historical Publishing Company, Inc., 1929); David M. Ludlum, *The Vermont Weather Book,* [1985] 2nd ed. (Montpelier, Vt: Vermont Historical Society, 1996).

[3] Hartwell, "Climate and Weather of Vermont": 212.

[4] Ludlum, *Vermont Weather Book.*

[5] ESIG, *Extreme Weather Sourcebook 2001* [book on-line]. Accessed 13 June 2001. Available from http://www.esig.ucar.edu/sourcebook/index.html.

[6] Stone, *Vermont of Today,* 160–161.

[7] Thompson, *Natural History of Vermont,* 13

[8] Stone, *Vermont of Today,* 163.

[9] Report of Advisory Committee of Engineers on Flood Control, *Journal of The House of the State of Vermont, Biennial Session* (Montpelier, Vt: Capital City Press Printers, 1929), 40.

[10] Gregory Sanford, 1 June 2001.

[11] Vermont Agency of Natural Resources, *Options for State Flood Control Policies and a Flood Control Program* (Waterbury, Vt: Department of Environmental Conservation, Water Quality Division, 1999).

[12] Kendall Wild, "New England's '38 Hurricane Left a Trail of Ruin in Vt.," *The Sunday Rutland Herald and the Sunday Times Argus,* 18 September 1988, Section E.

[13] Maria Elena Garcia, 25 June 2000.
[14] *Storm Data* (Monthly Publication of the National Climatic Data Center), July 1960, October 1962, August 1971, June 1972.
[15] *Storm Data,* December 1969.
[16] Thompson, *Natural History of Vermont.*
[17] Stone, *Vermont of Today,* 159.
[18] Michael Toussaint, July 2001.
[19] Jeffery Carter, August 1999.
[20] Vermont Agency of Natural Resources, "Water Supply and Quality." Accessed on 13 June 2001. Available from http://www.anr.state.vt.us/env96/ed961011.htm
[21] Sandra Wilmot, November 1999.
[22] *Storm Data,* May 1968.
[23] ESIG, *Extreme Weather Sourcebook 2001.*
[24] *Storm Data,* June 1960, June 1961, July 1962, August 1970, August 1983.
[25] *Storm Data,* September 1993, May 1998.
[26] *Storm Data,* May 1962, July 1962.
[27] C. Donald Ahrens, *Meteorology Today: An Introduction to Weather, Climate and the Environment,* 5th ed. (St. Paul, Minn.: West Publishing Company, 1994).
[28] Ray Helenek. "Terrible Hail Storm." Accessed 13 June 2001. Available from http://www.nws.noaa.gov/er/btv/html/NCO_Internet/JUL00_Issue/links_folder/terrible_hail.htm
[29] *Storm Data,* May 1959, June 1959, June 1983.
[30] *Storm Data,* June 1961, July 1964, August 1969.
[31] *Storm Data,* June 1983; National Climatic Data Center, Storm Events Database. Accessed 13 June 2001. Available from http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvents~storms
[32] *Storm Data,* June 1972, July 1983.
[33] National Weather Service, Lightning Safety. Accessed 13 June 2001, Available from http://www.lightningsafety.noaa.gov/science.htm
[34] Ludlum, *Vermont Weather Book,* 9.
[35] *Storm Data,* March 1962.
[36] *Storm Data,* April 1975, February 1967.
[37] Paul Sisson and Charles McGill, "Green Mountain Windstorms." Accessed 10 October 2001. Available from http://www.nws.noaa.gov/er/btv/html/projects/downslope/index.html
[38] Hartwell, "Climate and Weather of Vermont," 211.
[39] Alexander Tardy "Lake Effect and Lake Enhanced Snow in the Champlain Valley of Vermont." Accessed on 13 June 2001. Available from http://www.nws.noaa.gov/er/buf/abstracts/tardy.htm
[40] *Storm Data,* December 1969.
[41] Ludlum, *Vermont Weather Book,* 162–169.
[42] *Storm Data,* December 1962, March 1993; Ludlum, *Vermont Weather Book,* 172–175.
[43] *Storm Data,* November 1965, November 1968, April 1967.
[44] "Yea, We Did It! Wow! Most Snow Ever Here" *Burlington Free Press,* 22 March 1972.
[45] " '71 Storms Break Record," *New England Telephone Green Mountaineer,* 25 March 1971.
[46] Brenda Morrissey, "Officials Map Strategy to Handle Damaging Floods, If They Develop," *Burlington Free Press,* March 1971.
[47] MariaFranca Moreselli, 31 March 2001.
[48] Lisa Rathke, "Bad Year for Vt. Maple Syrup," *Burlington Free Press,* 20 June 2001, 6A.
[49] Hartwell, "Climate and Weather of Vermont," 212.
[50] Thompson, *Natural History of Vermont,* 9.
[51] Maria Elena Garcia, 25 June 2000.
[52] Jim West, "Frosty Apples," *Vermont Times,* 11, no.23 (6 June 2001).
[53] *Storm Data,* February 1969, February 1993, January 1997.
[54] *Storm Data,* December 1962, January 1966, November 1972.
[55] Sylvester L. Vigilante, "Eighteen-Hundred-and-Froze-to-Death," in *Mischief in the Mountains,* eds. Walter R. Hard and Janet C. Greene (Montpelier, Vt: Vermont Life Magazine, 1970), 97–101.
[56] Vigilante, "Eighteen-Hundred-and-Froze-to-Death," 100–101.