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Formation of Freezing Rain Events

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Ice storms can be devastating to trees and surrounding structures. Catastrophic tree failures from added ice weight, drag coefficient increases, and increased stiffness against the wind all conspire to damage or topple trees. A brief review of how ice storms form and spread is needed to help tree health care providers understand potential tree damage.

Precipitation Definitions

Ice storm is a generic name for a precipitation and wind event where freezing rain is a significant component. Officially, "freezing rain" is defined as liquid water drops with diameters greater than 0.5mm (~0.02 inch) which freeze upon impact with the ground or other structures, like trees, generating a glaze layer of ice. Surface objects must be at or below freezing, and the rain must be supercooled before impact. (Gay & Davis 1993) (Stuart & Isaac 1999) A "glaze" is defined as a clear layer of ice formed by supercooled water freezing on the surface of an object. (Lemon 1961)

"Freezing drizzle" are droplets less than 0.5mm (~0.02 inch) in diameter which freeze on contact forming an ice glaze. "Freezing precipitation" is a generic term which includes freezing rain and freezing drizzle. (Gay & Davis 1993) (Stuart & Isaac 1999) Falling ice pellets are officially termed "sleet." Unofficially, many people use the term sleet to represent a mixture of ice and liquid particles (mixed snow crystals, ice pellets, and rain). (Gay & Davis 1993) Here "freezing rain" will be used for liquid water drops of any size which freeze upon impact. An ice storm is a freezing rain event, although mixes of precipitation may occur. Other terms used for ice storms include silver thaws, blue northers, and freezing rain storms.

Ice Crystals

In many cases in Winter, precipitation at high elevations in clouds usually begins with ice crystals (snow). These ice crystals fall through miles of sub-freezing atmosphere and reach the ground as snow. Once formed, ice crystals do not change form, other than shrinking in size (sublimation) or growing in size. If air temperatures begin to increase as the ground surface is approached, ice crystals may completely melt and coalesce to form rain.

Ice particles can form in clouds in the following ways: (Huffman & Norman 1988)

1) water vapor deposited as ice onto freezing nuclei around 14°F to 4°F;
2) large supercooled drops freeze on nuclei up to 23°F.
3) pre-existing ice crystals act as freezing nuclei up to 32°F; and,
4) if no freezing nuclei are present, supercooled drops spontaneously freeze near -40°F.

Some clouds with temperatures between 14°F and 32°F, which have no large water drops or no ice crystals, are unlikely to form ice at all. This cloud form only contains supercooled water droplets. (Huffman & Norman 1988)

Layering

Different weather pattern can generate a number of combinations of air layers over a site – some warm layers and some cold layers. For example, cold arctic fronts can collide and be overtopped with moist warm fronts, or topography may trap cold temperature air layers near the ground overtopped by a warm layer. The temperature and thickness of each air layer can help determine the precipitation type which will been recorded at ground level.

Ice crystals falling through an elevated and thick warm layer melt. If this liquid water then falls through a cold (sub-freezing) layer, it could refreeze partially (graupel), completely (ice pellets), or the liquid could super-cool. Supercooled water occurs when liquid water temperature is lowered below freezing with no ice crystals or freezing nuclei present to initiate or form ice crystals.

Remember, pure water can theoretically supercool down to -40°F under the best conditions without forming ice. Usually droplets in the atmosphere can easily supercool to 4°F. (Lemon 1961) Cold clouds which are partially or wholly sub-freezing can contain supercooled water drops, ice crystals, or both. Ice does not always form at 32°F in pure water. (Huffman & Norman 1988)

First Type

Freezing rain precipitation can occur in two primary ways. The first (and most common = ~80%) is when a warm moist air mass overruns a cold surface layer. Figure 1 demonstrates air temperatures above the ground up to 5.6 miles. Close to the surface are sub-freezing temperatures. By 0.6 to 2.5 miles in height, air temperatures have reached a high mark and then fall back to sub-freezing levels as elevation increases. The warm "bump" is a warm front pushing over a cold layer of air near the ground.

Ice crystals formed at the top of clouds fall through a warm air layer which is warm enough and thick enough to completely melt the crystals. Figure 2 allows for a description of air temperature layers above the ground surface. As the warm front approaches, the cold freezing layer is over-topped by a warm, non-freezing layer. The warm layer bottom and top is where the 32°F threshold is passed.

The melted ice crystals are now rain which falls through a cold layer near the ground. The cold layer must be cold enough and thick enough to supercool the water, but not refreeze the droplets. The supercooled liquid water droplets then strike a cold surfaces <32°F on the ground. Upon striking the surface, supercooled water can either partially or completely freeze into ice. (Rauber et.al. 1994) (Rauber et.al. 2001) (Gay & Davis 1993) (Lemon 1961) (71) (Stuart & Isaac 1999) (Cortinas et.al. 2004) (Cortinas 2000) (Huffman & Norman 1988)

Warm Bulge

Another view of air layer temperatures is shown in Figure 3. This demonstrates the three air layer temperature zones: a high ice crystal formation zone, a warm melting zone, and a low sub-freezing zone. The presence of each of these zones, in both thickness and temperature variations, determine freezing rain precipitation occurrence.

Figure 4 attempts to show (but not to scale) how warm air of the warm front pushed through and over cold air covering a landscape. The over-lying warm air layer can be a hundred miles or more in front of the surface warm temperatures. As ice crystals begin to fall, the various layers (temperature and thickness) impact precipitation types. There is a unique and limited set of atmospheric and precipitation combinations which generate an ice storm.

Second Type

The second way freezing rain might occur (less common) is when air temperatures at cloud top and throughout the cloud are freezing but less than 14°F, leading to supercooled rain precipitation forming and falling (termed "supercooled warm rain process"). (Rauber et.al. 1994) (Rauber et.al. 2001) This second pathway is where water droplets coalesce in a cold layer without ice nucleating particles and are supercooled. (Rauber et.al. 2001) The supercooled warm rain process causes ice formation on surfaces when the supercooled cloud reaches to the ground. (Huffman & Norman 1988) Roughly 16-33% of freezing rain events do not have a warm layer overtopping cold air. (Huffman & Norman 1988) (Rauber et.al. 2001)

Developing Layers

A warm moist air layer over-laying a shallow sub-freezing air layer at the surface is responsible for most freezing rain formation. The thickness and temperature of each layer influences the type of precipitation which reaches the ground. (Cortinas 2000) For all conditions, an elevated humidity level supports freezing rain events. (Gay & Davis 1993)

With an on-coming warm front, the advancing upper level warm air layer moves forward over the cold surface layer. As the warm front gets closer, the elevated warm layer becomes thicker, melting some, most, or all of the snow crystals passing through, depending upon the warm air thickness. If the cold air layer near the ground is shallow, melted snow crystals will not refreeze. In a majority of Winter storms, without the combination of an upper warm air layer and shallow cold air layer with cold temperatures below freezing near the ground, only snow will occur. (Gay & Davis 1993) (Konrad 1998)

Thick & Thin

With a thin warm layer (as the warm front first approaches), at first only frozen precipitation occurs -- ice crystals or ice pellets. Figure 5 is a simple diagram showing a warm front cloud layer moving over the surface of the ground. As the front moves forward, precipitation transitions from snow through ice pellets and onto freezing rain. The freezing rain eventually loses its supercooled character and becomes rain.

A thin warm layer can begin to melt ice crystals, but not completely, and the lower cold layer beneath quickly refreezes any liquid water. For a number of ice storms, the minimum temperature in the cold layer was measured. Figure 6 shows the minimum temperatures in the cold layer during freezing rain events. Most freezing rain events had minimum cold temperatures between 18°F and 28°F. The depth of the cold layer is shown in Figure 7. Note as the minimum temperature in the cold layer warms, the cold layer thickness shrinks.

Warming the Cold

As the warm layer thickens, ice crystals falling through are now completely melted. Figure 8 shows the thickness of the warm layer above the cold layer. The warm layer depth continues to increase as its maximum temperature climbs. This is the result of the warm front pushing into the area. The maximum temperature in the warm layer during ice storms is given in Figure 9. Note the warm layer temperature runs between 38°F and 45°F for most ice storms. The warm layer is above freezing, but not greatly above.

As the warm front moves forward, the warm air layer aloft becomes thicker and the ground level cold layer thins out. Ice crystals entering the warm layer completely melt. The liquid water droplets from the warm layer now fall through the underlying cold layer and begin to supercool. If the cold layer is too cold or too thick, there will be a mix of liquid and frozen precipitation (sleet). As the supercooled droplets fall through the thinning cold air layer and do not refreeze, they strike sub-freezing ground structures and freeze upon impact. (Gay & Davis 1993) (Konrad 1998)

Approaching Supercool

Figure 10 provides a temperature profile side view of a warm front pushing in over cold air and the precipitation generated. If the air temperature between the top of the precipitation forming height and the ground remains significantly below freezing, the initial ice crystals (snow) remains frozen. As the middle layers of air become warmer, precipitation striking the ground shifts from a mix of solid and liquid to liquid. Supercooled liquid impacts are freezing rain.

One study showed the warm layer thickness must be at least 0.9 miles to completely melt the falling ice crystals. In addition, to keep the precipitation in a supercooled liquid form and not solid ice, the cold layer along the ground surface must be less than 0.8 miles of sub-freezing temperatures. (Stewart & King 1987) As the cold layer thickness increases, sleet is the most likely precipitation form. (Konrad 1998)

The cold layer temperature and thickness provides the supercooling and refreezing character to any precipitation. The minimum temperature of the ground-hugging cold layer can be significantly colder than measured at the ground surface by 3-5 degrees Fahrenheit. (Rauber et.al. 2001) Figure 11 shows the minimum temperature in the cold layer and the associated surface temperature. The temperature differential across the cold layer amounts to an estimated 2.5^{o}F to 9^{o}F, depending upon the temperature of the surface. The lowest temperature in the cold layer is always lower than the surface temperature.

Weather Generators

The specific weather patterns initiating ice storms are: 1) an arctic front (31% of ice storms); 2) cold air damming / trapping (24% of ice storms); and, 3) assorted patterns associated with interactions of an arctic front and anticyclone movements (43% of ice storms). The first pattern generates, by far, the longest duration ice storms. (Rauber et.al. 2001) The Atlantic Ocean, and especially the Gulf of Mexico, provide large amounts of warm moist air which can be pulled over sub-freezing surface layers, generating ice storm event conditions. (Cortinas et.al. 2004)

On weather forecast maps, warm front movement is represented by a line with half circles placed on the side of the line in which the front is moving. Figure 12 shows a view from above on a weather map where a warm front is pushing into an area from left to right. Just in front of the ground line of the warm front, bands of precipitation form. Freezing rain is usually a narrow band between snow and rain. Depending upon the movement, or lack of movement, and moisture content of the warm front, the band of freezing rain can last many hours or for just minutes.

Potential ice storm generating conditions are especially common with Winter warm fronts in the Southeastern United States (the longest duration ice storms), and in areas of the Appalachians where cold air is trapped (damned) in valleys along the Eastern slopes. (Gay & Davis 1993) (Changnon & Changnon 2002) (Changnon 2003) Mountain ridges and valleys set up conditions for freezing precipitation by holding sub-freezing temperature air masses close to the ground when covered with warm, moist air layers. (Cortinas 2000)

Precipitation

The precipitation amounts falling per hour (intensity) in ice storms have been: 0.01 inch (0.25mm) in 27% of all freezing rain events; <0.04 inch (<1.1mm) for 75% of all events; and, >0.3 inch (>7.62mm) in

0.3% of all events. The largest amount of freezing rain recorded in an hour was 0.72 inch (18.29mm) [1987 - Texas]. (Houston & Changnon 2007)

The state of any precipitation falling on the ground surface is dependent upon surface air temperatures. Figure 13 provides surface temperatures occurring for solid, liquid, and mixed precipitation. Solid precipitation has a broad temperature range even above freezing temperatures due to melting rates. Liquid precipitation is assumed as 46°F is surpassed. Freezing precipitation mixes, including freezing rain events, occur in a narrow band at and just below freezing.

Decision Guide

The precipitation form, solid, liquid, or freezing, depends upon a number of atmospheric conditions. Figure 14 shows a process pathway for predicting precipitation form. Key elements are cloud top temperatures, presence of a warm layer and its thickness, and presence of a cold layer and its thickness.

For most areas undergoing an ice storm, the precipitation form continues to change as the upper warm front advances. Usually precipitation type evolves from snow through ice pellets (sleet), then to freezing rain, and finally to rain. Mixtures of ice and water striking a sub-freezing surface accumulate differently than freezing rain alone. (Gay & Davis 1993) (Stewart & King 1987) (Cortinas 2000) In one study, other precipitation types mixed with freezing rain included: ice pellets 16% of the time; snow 13% of the time; and, freezing rain alone 71% of the time. (derived from Cortinas 2000)

Variations

Another way of appreciating the relationship between height and air temperature upon precipitation form is given in Figure 15. Note for freezing rain, at increasing height, temperature tends to drop then warms rapidly. For rain, the temperature line shows initial ice crystal beginnings and then a steady increase in temperature as the ground is approached, completely melting along the way. Snow begins as cold zone ice crystals and remains in that form until near 32°F. Sleet begins as ice and only partially melts before refreezing.

Rarely, cold front movements can lead to a reverse set of precipitation types: rain, freezing rain, sleet, and snow. (Gay & Davis 1993) When the surface cold layer is too deep or thick, or too cold in temperature, ice pellets form instead of freezing rain. (Yip 1995)

Temperature

The surface air temperatures (measured at ~6.5 feet above the ground) were found to range from: 31°F to 32°F during 39% of all freezing rain events; 28°F to 32°F in 71% of all freezing rain events; 14°F and 32°F in 85% of all events; and, less than 14°F in <1.5% of all freezing rain events. (Houston & Changnon 2007) (Cortinas et.al. 2004) (Cortinas 2000)

Figure 16 shows the temperature range along the ground surface where freezing rain occurs. Freezing rain events are concentrated where surface temperatures are between 14°FC and 34°F. In another way of examining surface temperatures during ice storms, Figure 17 provides the percent of freezing rain events and the surface temperature. Note 80% of the freezing rain events occur between 34°F and 30°F in this regional study.

Extreme Degrees

The lowest surface air temperature recorded for freezing rain was 2.9°F [1997 - Ohio]. The highest surface air temperature recorded for freezing rain was 41.7°F [1959 - Iowa], where the supercooled rain froze on sub-freezing ground surfaces, but quickly melted off. (Houston & Changnon 2007) (Cortinas 2000) Objects at the surface must be at or below 32°F for freezing rain to form ice, otherwise the precipitation is cold rain. (Gay & Davis 1993) In addition, the absolute temperature below 32°F does not change (increase) the amount of ice accumulated – only increasing precipitation amounts, or duration of the event, can increase ice accumulation. (Houston & Changnon 2007)

The surface temperature during freezing rain hours are usually measured at ~6.5 feet above the ground in an open area. Figure 18 shows the percent of freezing rain hours over a 74 year period and the surface temperature measured. Most freezing rain hours have occurred when surface temperatures were between 26°F and 33°F. Colder temperatures at the surface generates frozen precipitation, not freezing rain.

Summing Up

Generally, freezing rain events occur when surface air temperatures are around 30°F. Near this surface air temperature, there are insufficient active ice nucleating centers which prevent frozen precipitation (ice pellets) from forming. (Cortinas et.al. 2004) As surface air temperatures become colder, more ice crystals form and quickly grow, moving precipitation away from freezing rain into freezing sleet / ice pellets. (Cortinas 2000) Urban heat islands tend to have fewer freezing rain events than rural / open areas. (Gay & Davis 1993)

Duration

Most freezing rain events are short-lived, with 51% of events shorter than 2 hours and 47% shorter than one hour. Only 7% of all freezing rain events have lasted more than 5 hours, with the longest on record lasting 49 hours (1956 - Maine). (Houston & Changnon 2007) (Cortinas 2000) On the East side of the Appalachians, the duration of freezing rain events is greatly increased with only a small change in numbers of events. (Konrad 1998)

Freezing rain events usually occurred near sunrise, but did occur any time of day. (Cortinas 2000) A majority of freezing rain events occurred from December through March, but events from October through May have been recorded. (Cortinas 2000) Most (>97%) freezing rain events are categorized as light in intensity. (Houston & Changnon 2007) (Cortinas 2000) With light storm intensity, event severity increases with increased wind and extended duration. (Cortinas 2000)

Wind Speeds

Freezing rain event impacts on trees can be magnified by surface winds. Figure 19 provides one view of wind speeds in many ice storms. Note most wind speeds in this study were found to be below ~16 mph. Average wind speed during ice storms was found to be roughly 10 mph. Wind direction has also been examined, although wind direction during freezing rain events is dependent upon location in the nation. Across all freezing rain events in the nation, Figure 20 provides the wind surface direction which accompanied the ice storm. Winds from the North and Northeast were dominate.

Most (78%) freezing rain events have hourly wind speeds in the range of 9-13 mph. Only 3.8% of all freezing rain event hours had wind speeds of 23 mph or greater. (Houston & Changnon 2007) For freezing rain events generating greater than 0.1 inch of precipitation, 8.7% had wind speeds of 19 mph or greater, and 2.8% had winds speeds of greater than 25 mph. (Houston & Changnon 2007)

Figure 21 provides a view of how wind speed changes across freezing rain hours. Around 40% of all freezing rain hours have wind speeds of ~11 mph, with less than 5% of freezing rain hours showing wind speeds in excess of 23 mph. Another way to examine wind speeds within freezing rain hours is provided in Figure 22. This bar graph shows how most freezing rain hours have wind speed around 11 mph.

Conclusions

A typical freezing rain event lasts 3 hours, with surface temperatures ranging from 28°F to 32°F, generating less than 0.1 inch of precipitation, and with wind speeds less than ~11 mph. (Houston & Changnon 2007) It is the atypical or extreme ice storms which lead to massive tree loss and associated damage.

Citation:

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Selected Literature

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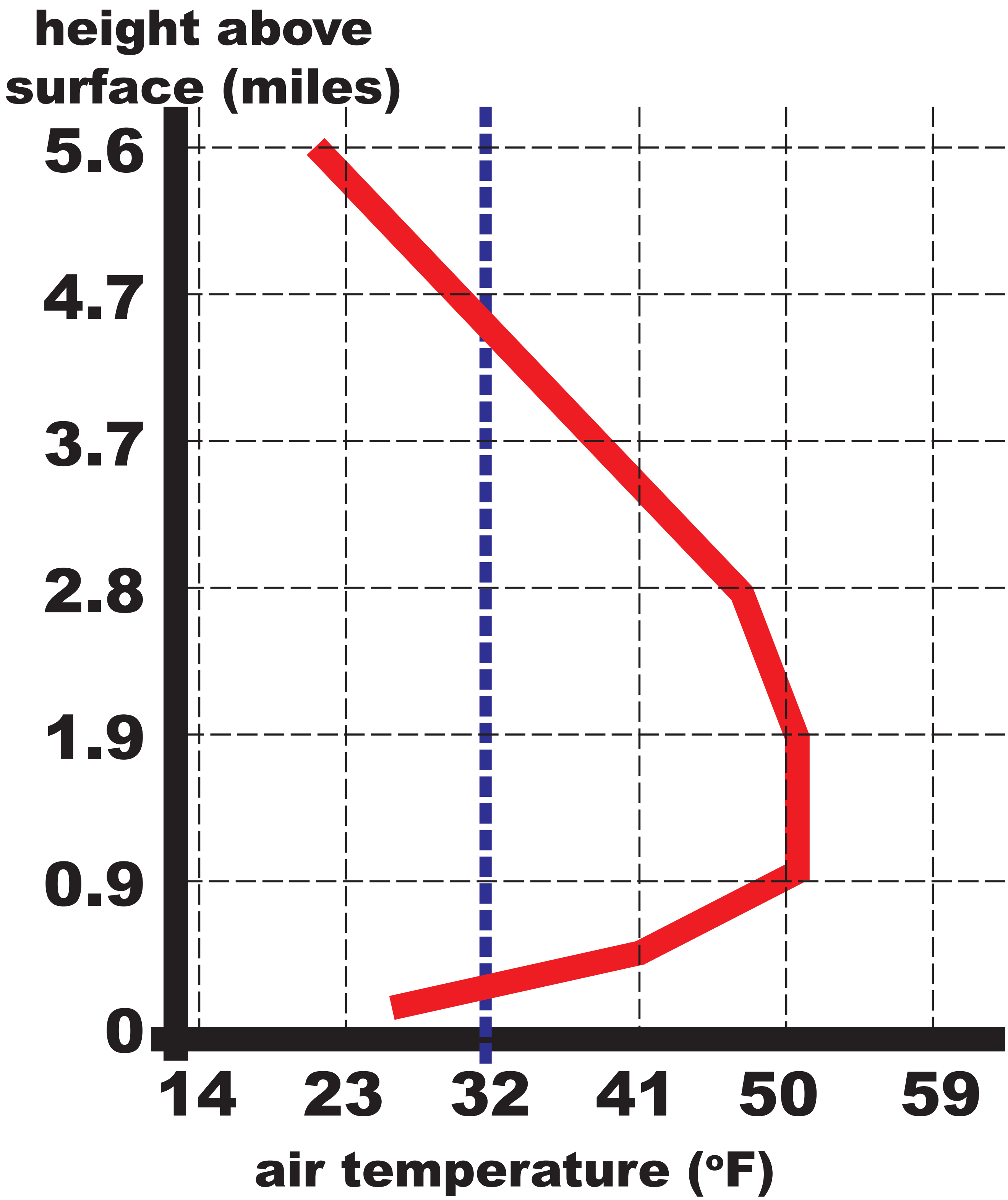

Figure 1: Air temperature at various heights above the surface during a freezing rain event. (derived from Cortinas 2000).

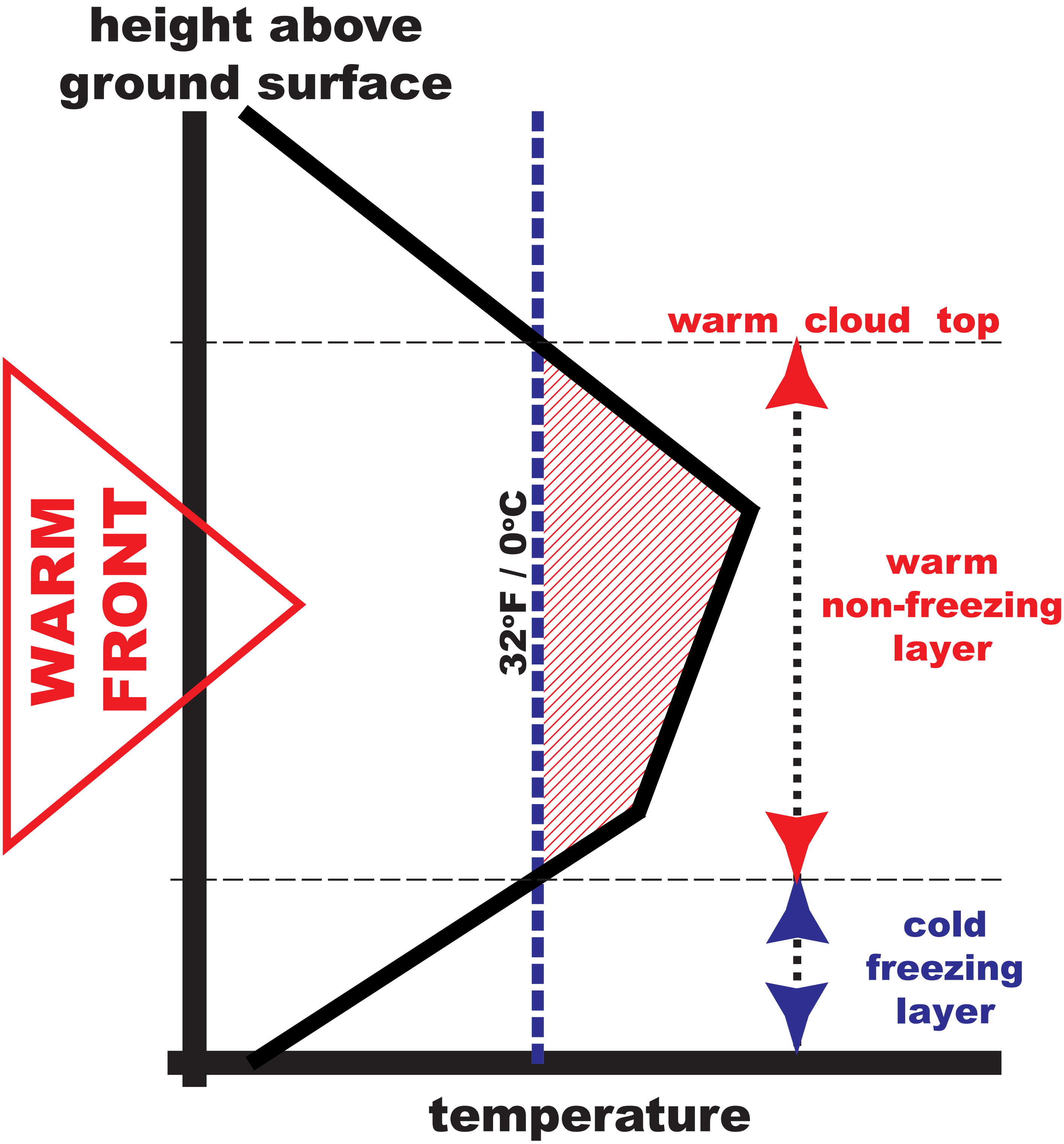

Figure 2: Basic atmospheric variables in ice storm events.
(derived from Huffman & Norman 1988).

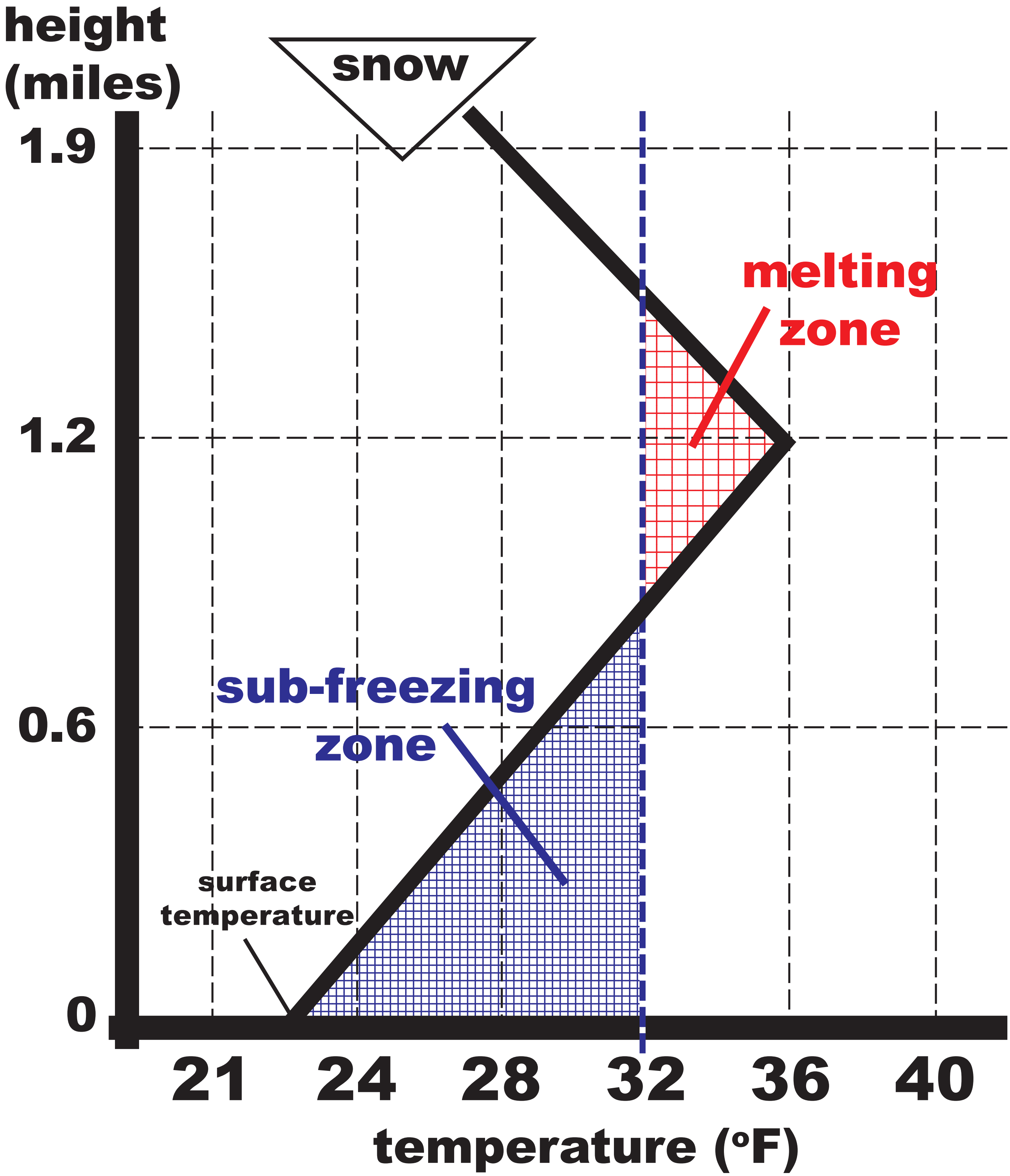

Figure 3: Idealized temperatures over a site generating freezing rain. (drived from Fikke et.al. 2008).

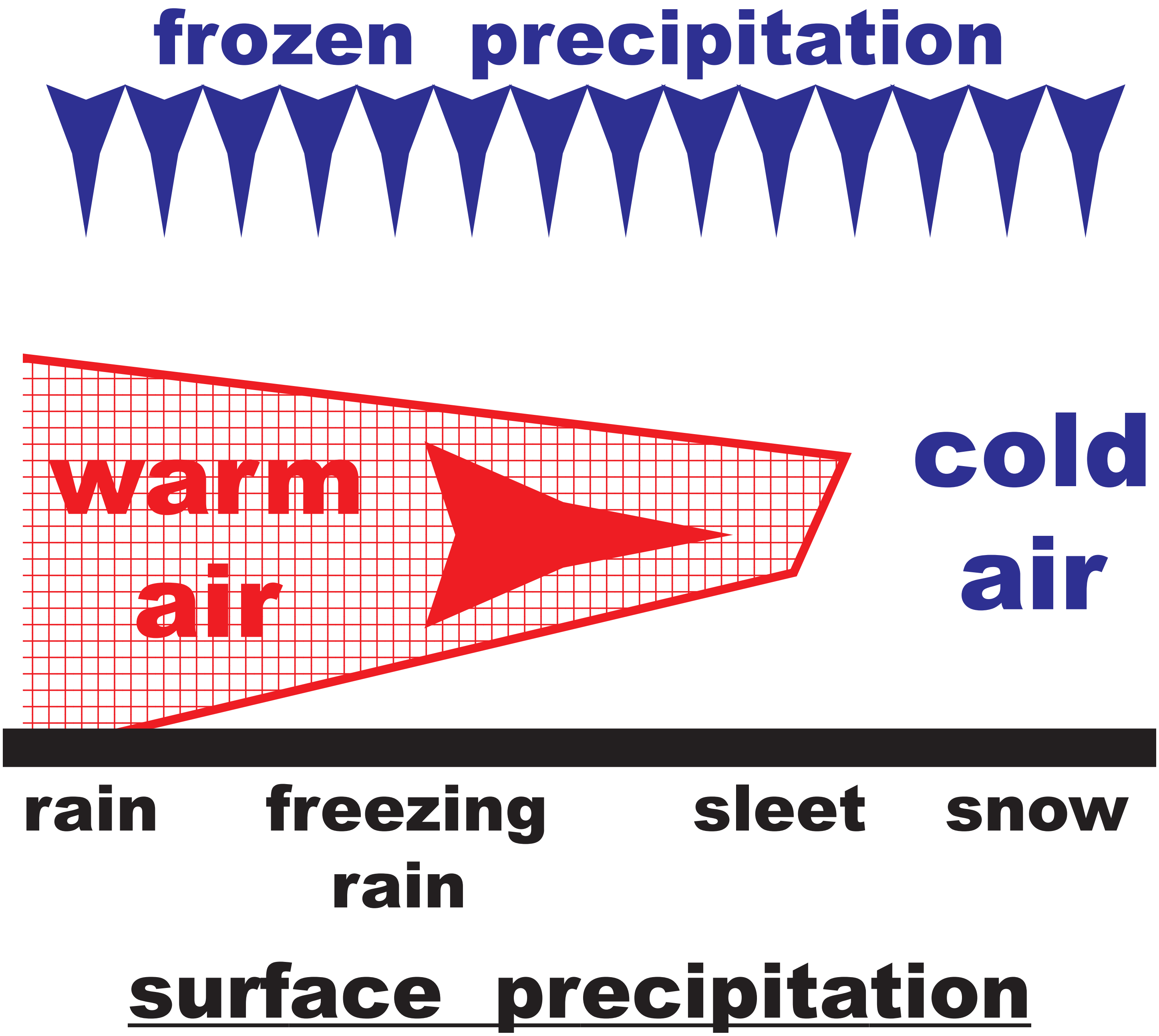

Figure 4: Precipitation types falling to ground as a warm front advances over cold air.

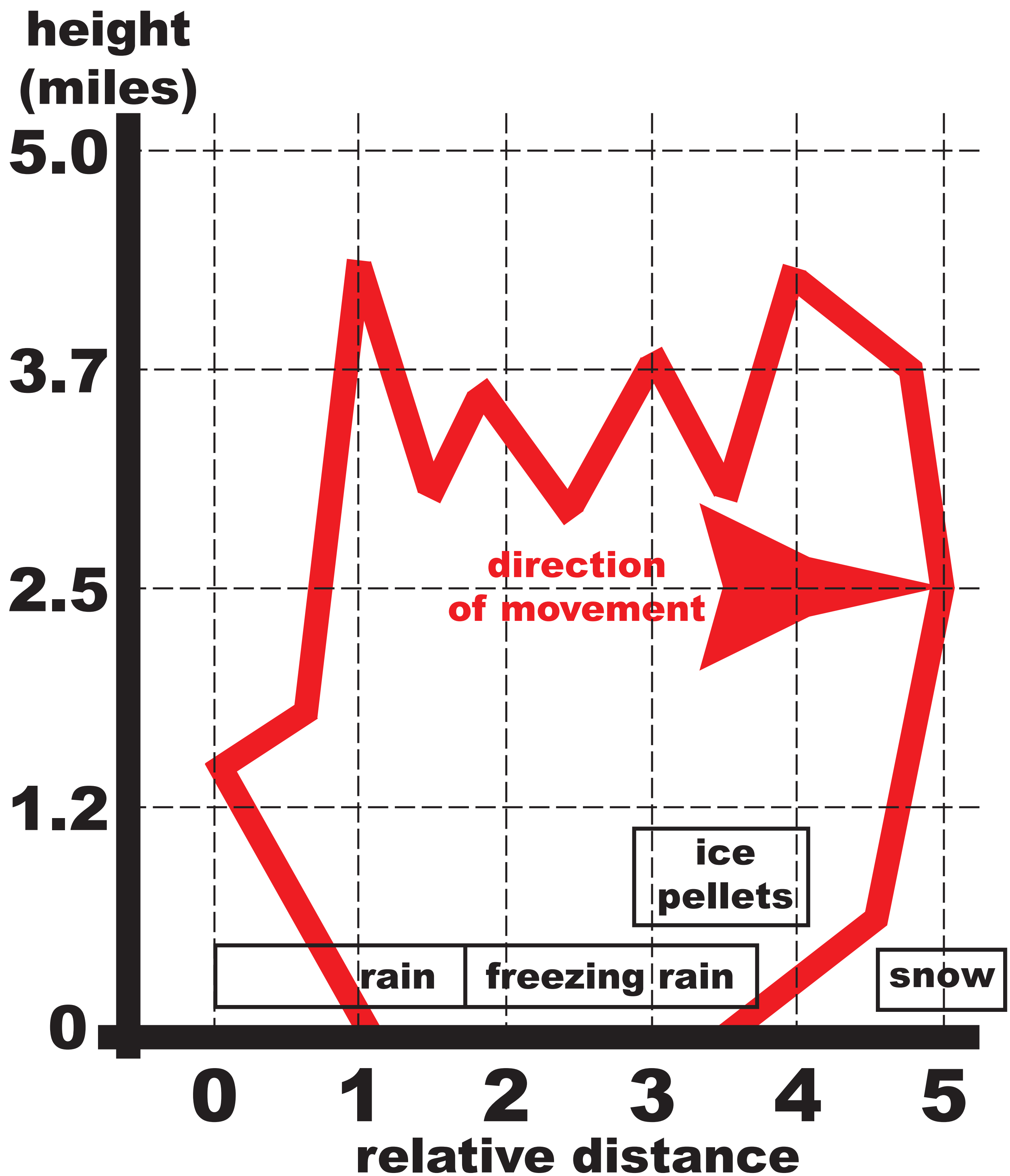

Figure 5: Diagram of awarm front moving over a sub-freezing surface layer and precipitation type generated at the surface.
(derived from Stewart & King 1987).

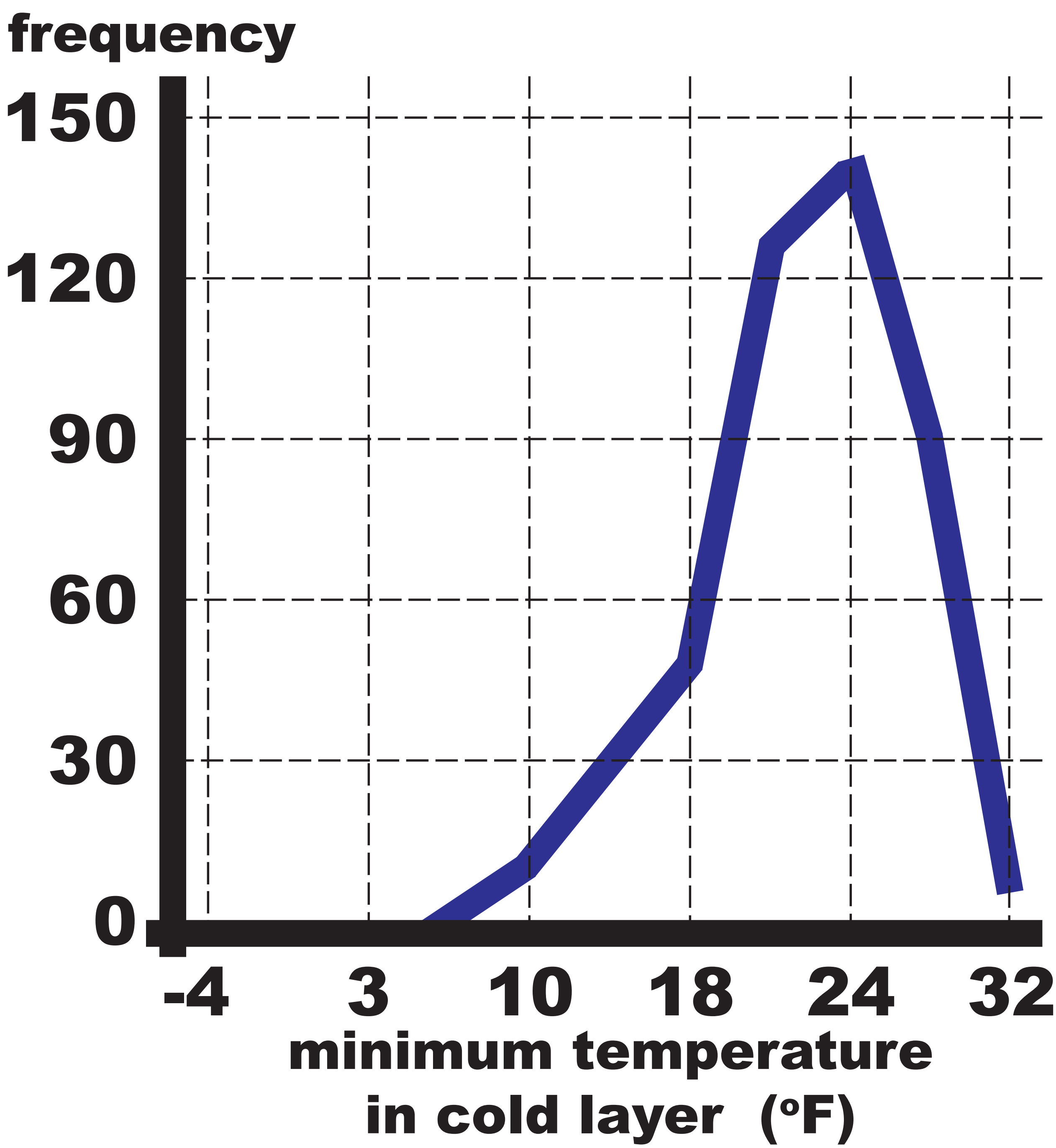

Figure 6: Minimum temperatures (°F) in a cold layer found during ice storms. (derived from Rauber et.al. 2001).

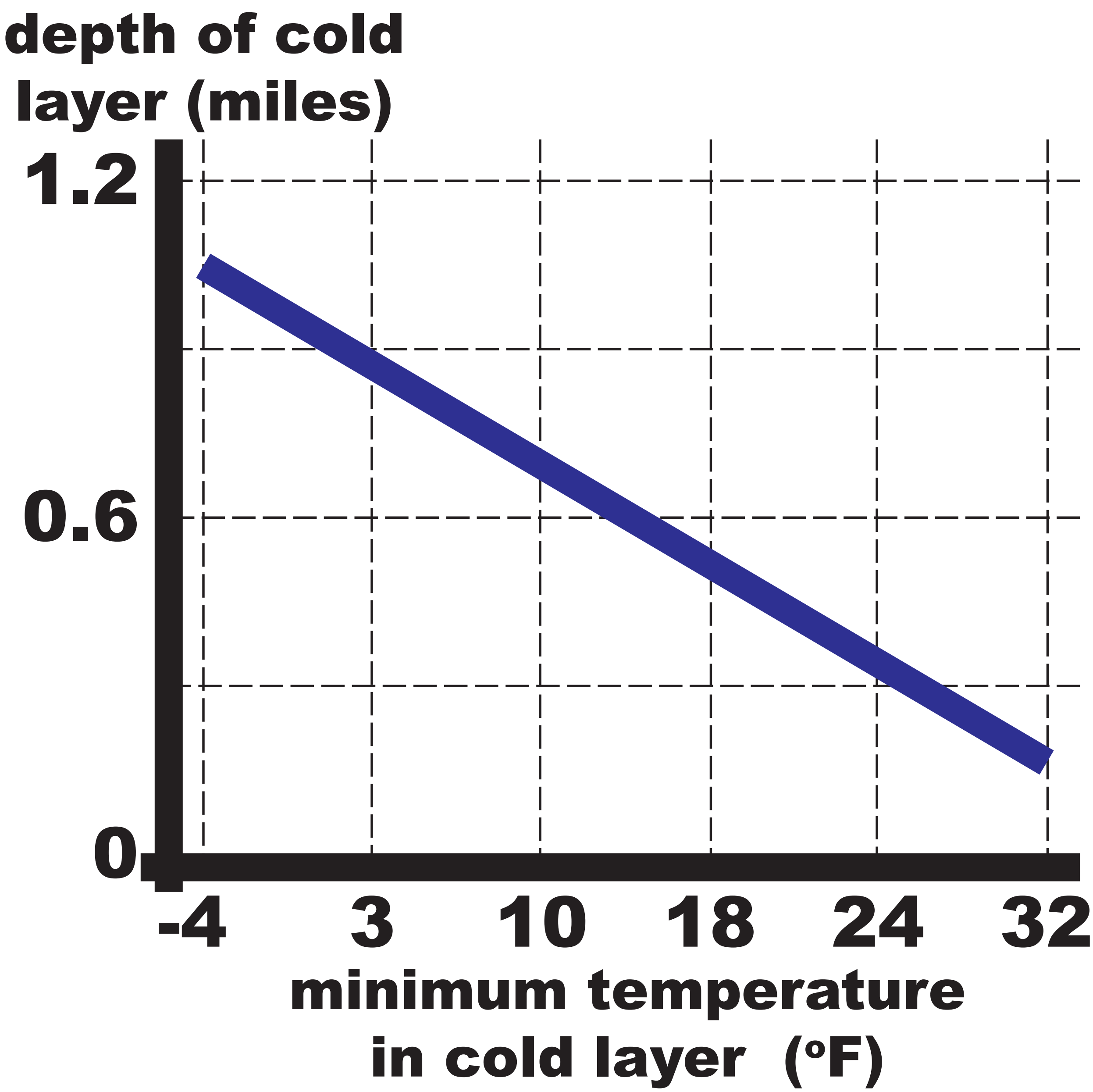

Figure 7: Minimum temperatures (°F) in cold layer and its thickness found during ice storms.
(derived from Rauber et.al. 2001).

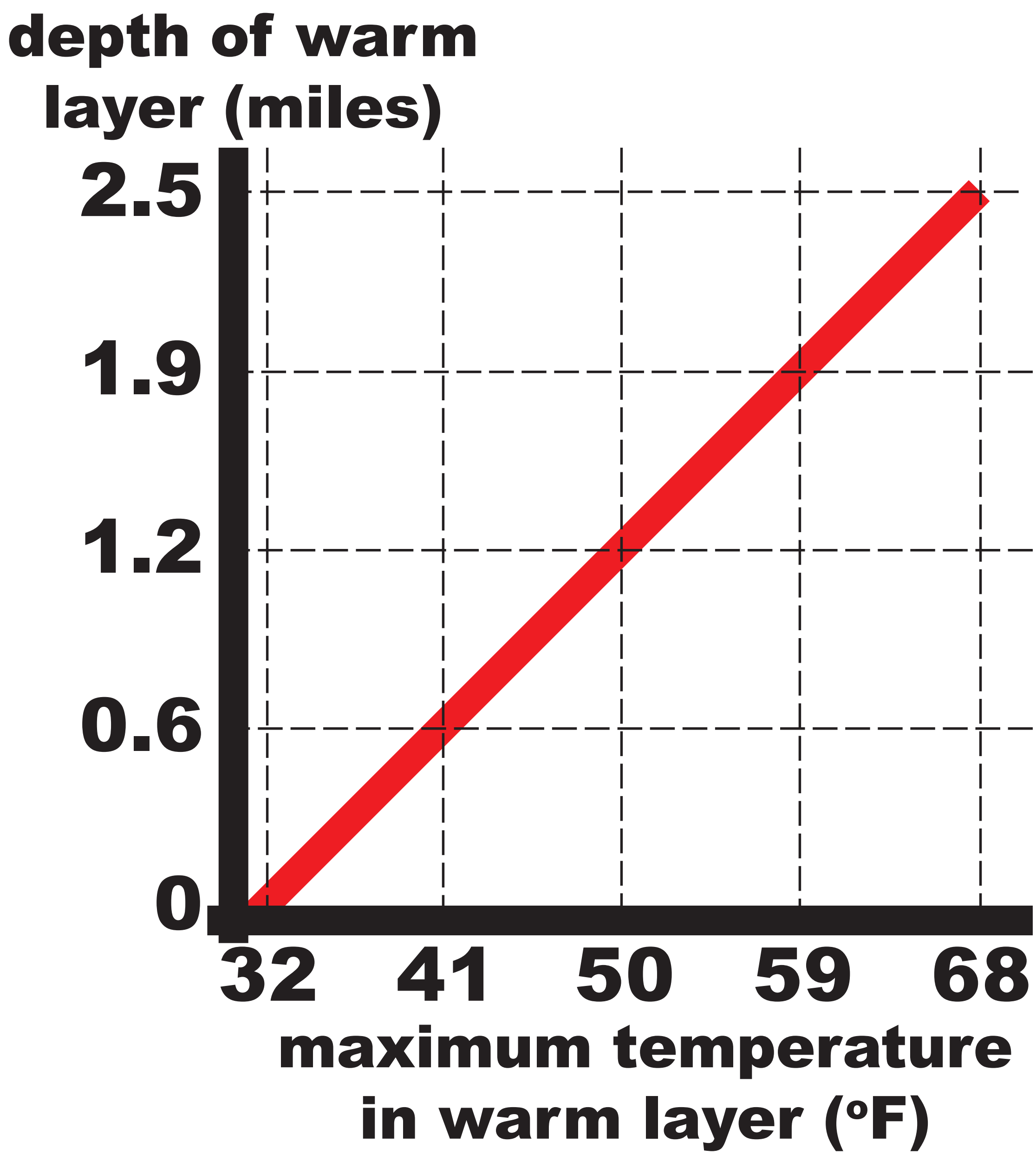

Figure 8: Depth of elevated warm layer in an ice storm and its maximum temperature. (derived from Rauber et.al. 2001).

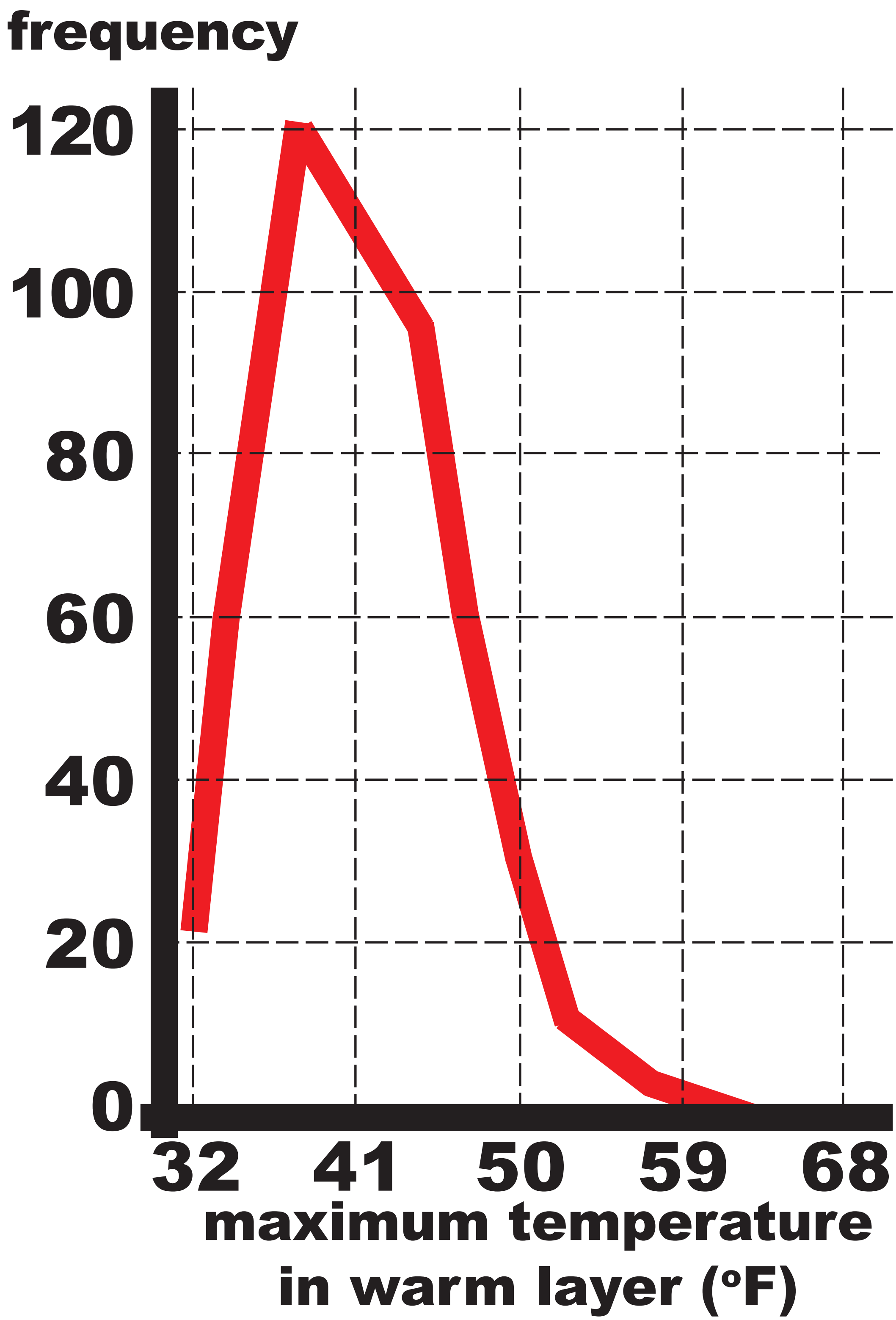

Figure 9: Maximum temperature found in an elevated warm layer in an ice storm. (derived from Rauber et.al. 2001)

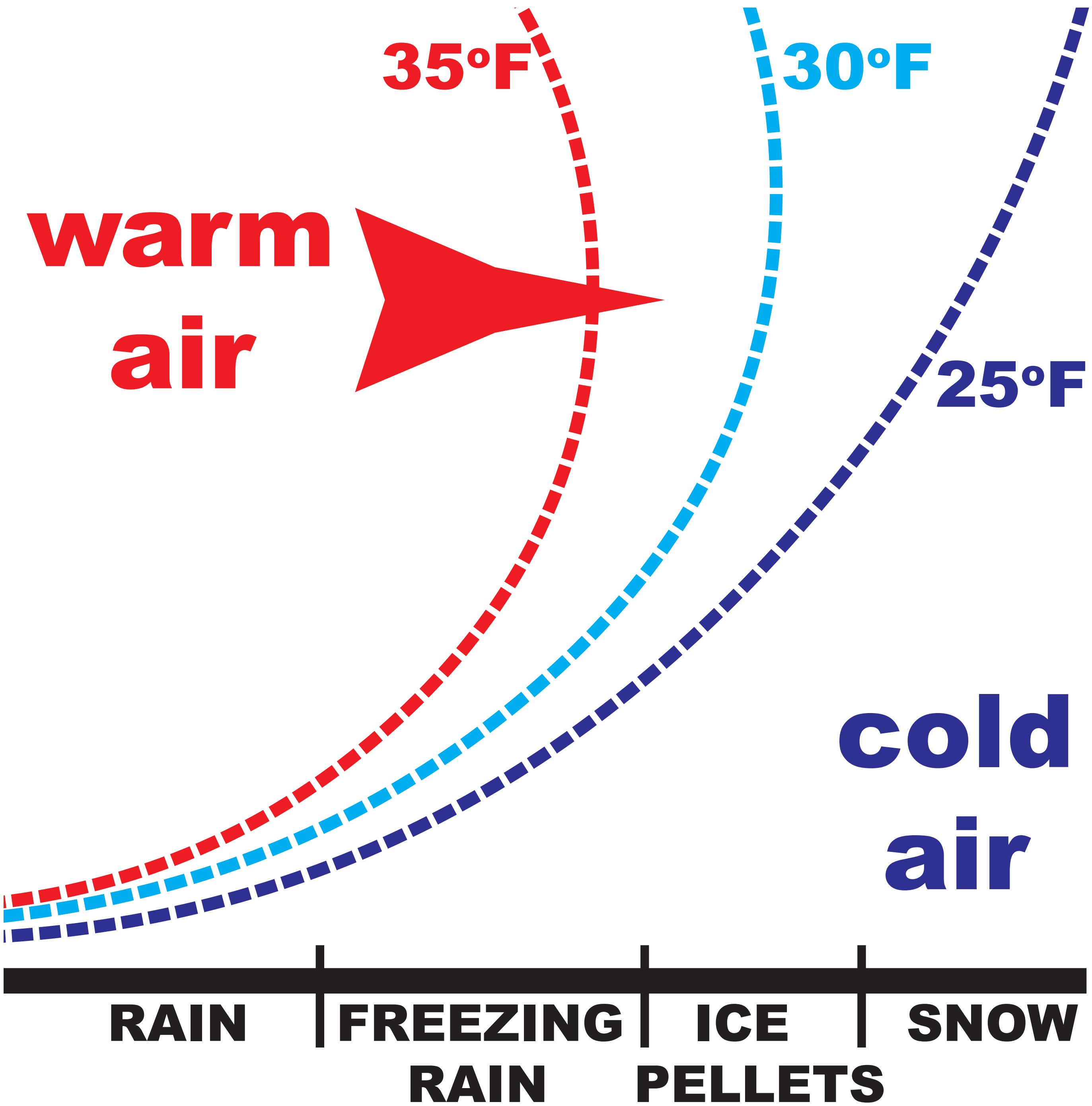

Figure 10: Diagram of advancing Winter warm front pushing over cold air with a list of expected precipitation.
(derived from Lemon 1961).

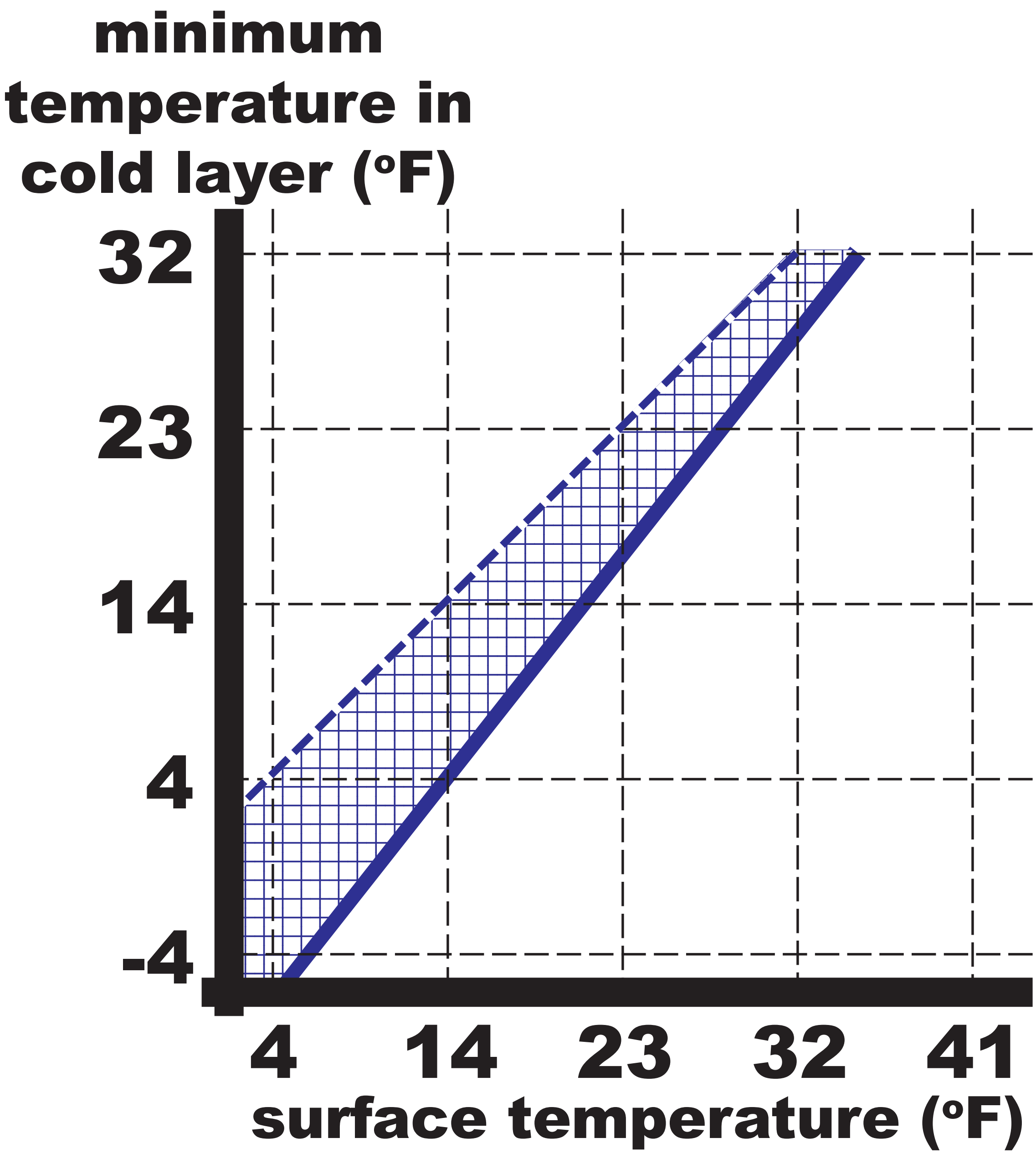

Figure 11: Difference between the minimum temperature in a cold layer and surface temperature. The dotted line shows where temperatures are the same, with the area between showing the temperature differential.
(derived from Rauber et.al. 2001).

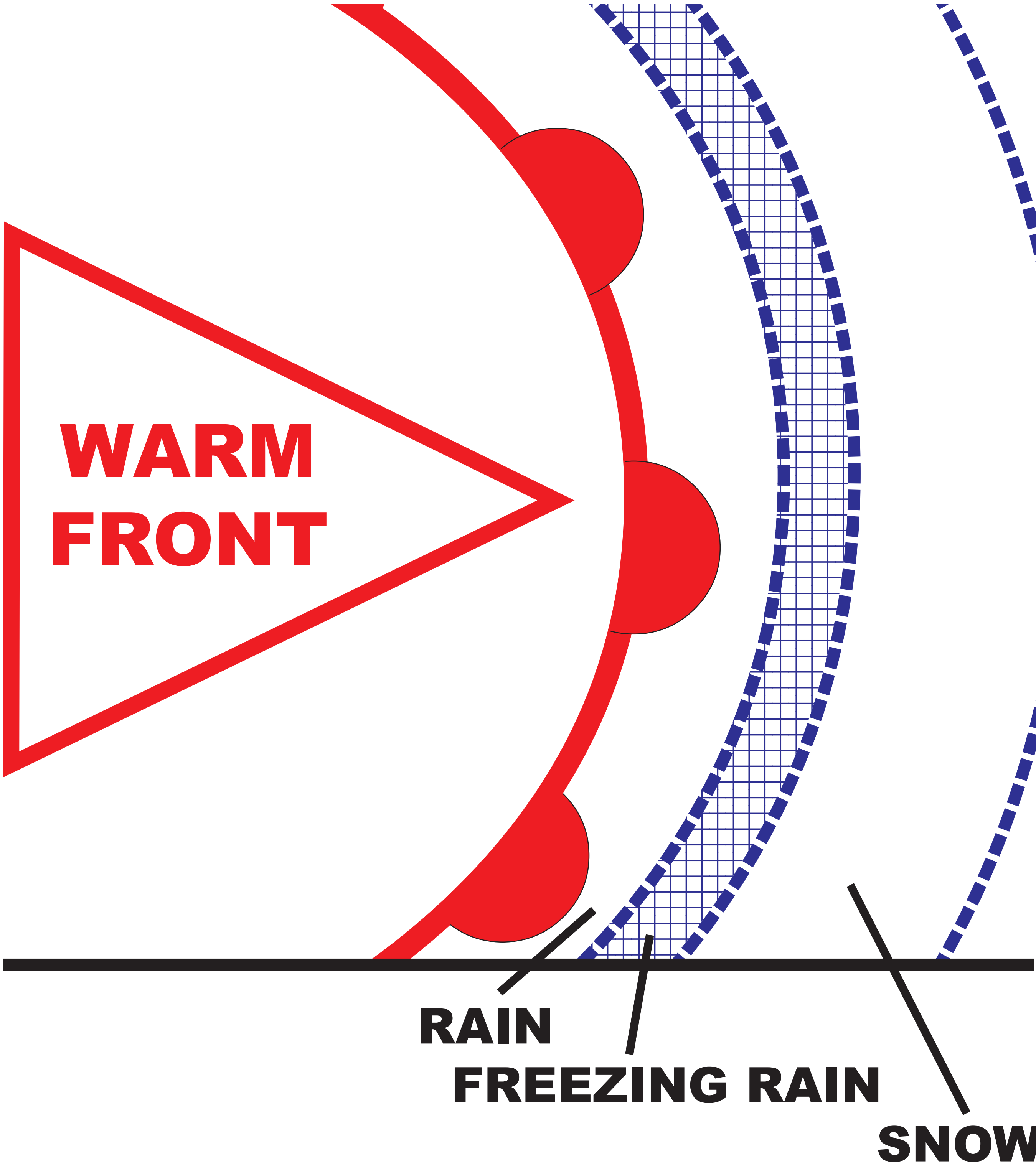

Figure 12: Precipitation bands in front of a warm front moving over subfreezing cold air.

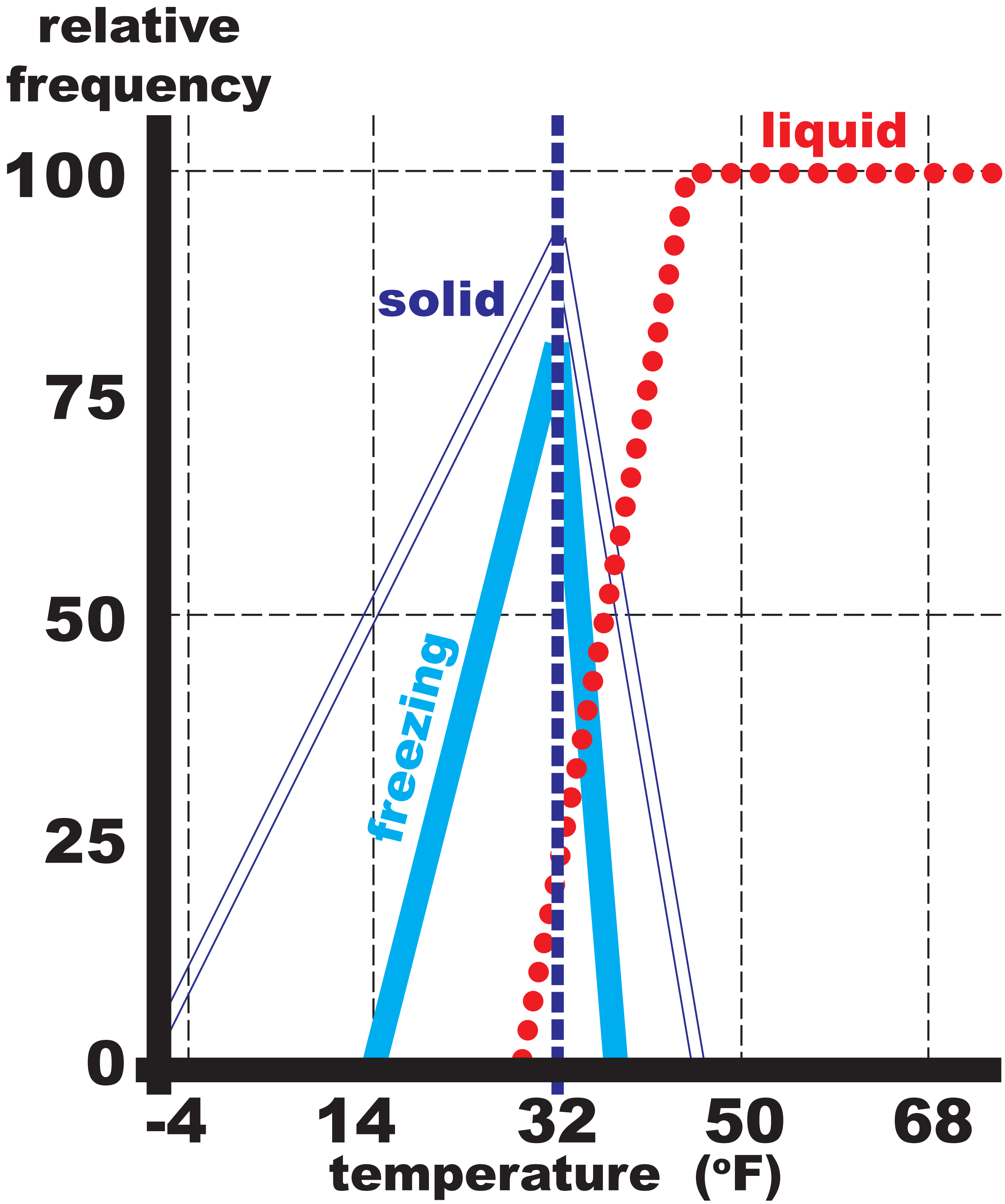

Figure 13: Surface air temperatures for solid, liquid, and freezing precipitation mixes. (derived from Huffman & Norman 1988).

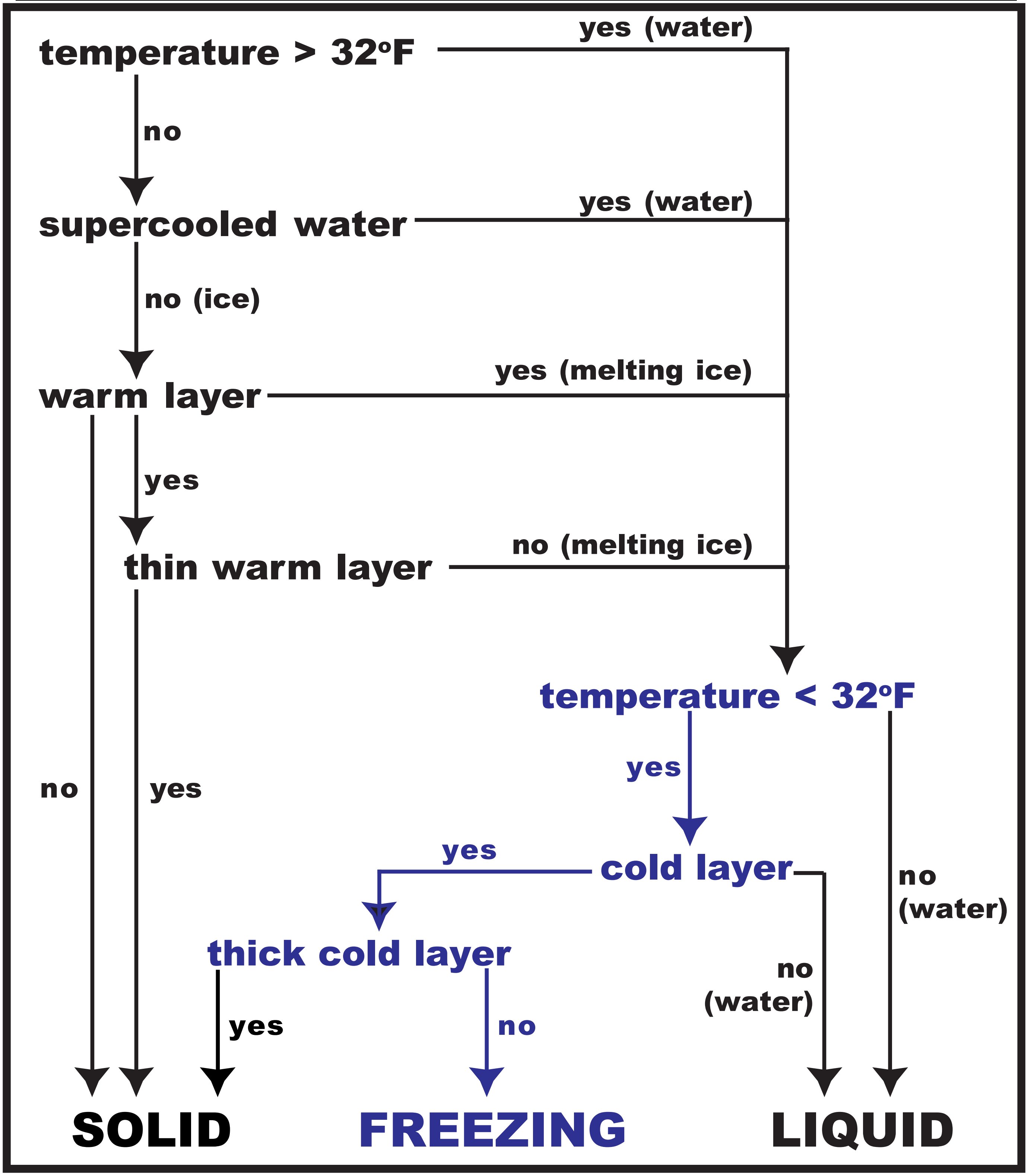

Figure 14: Decision pathway for precipitation forms starting at cloud top. (derived from Huffman & Norman 1988).

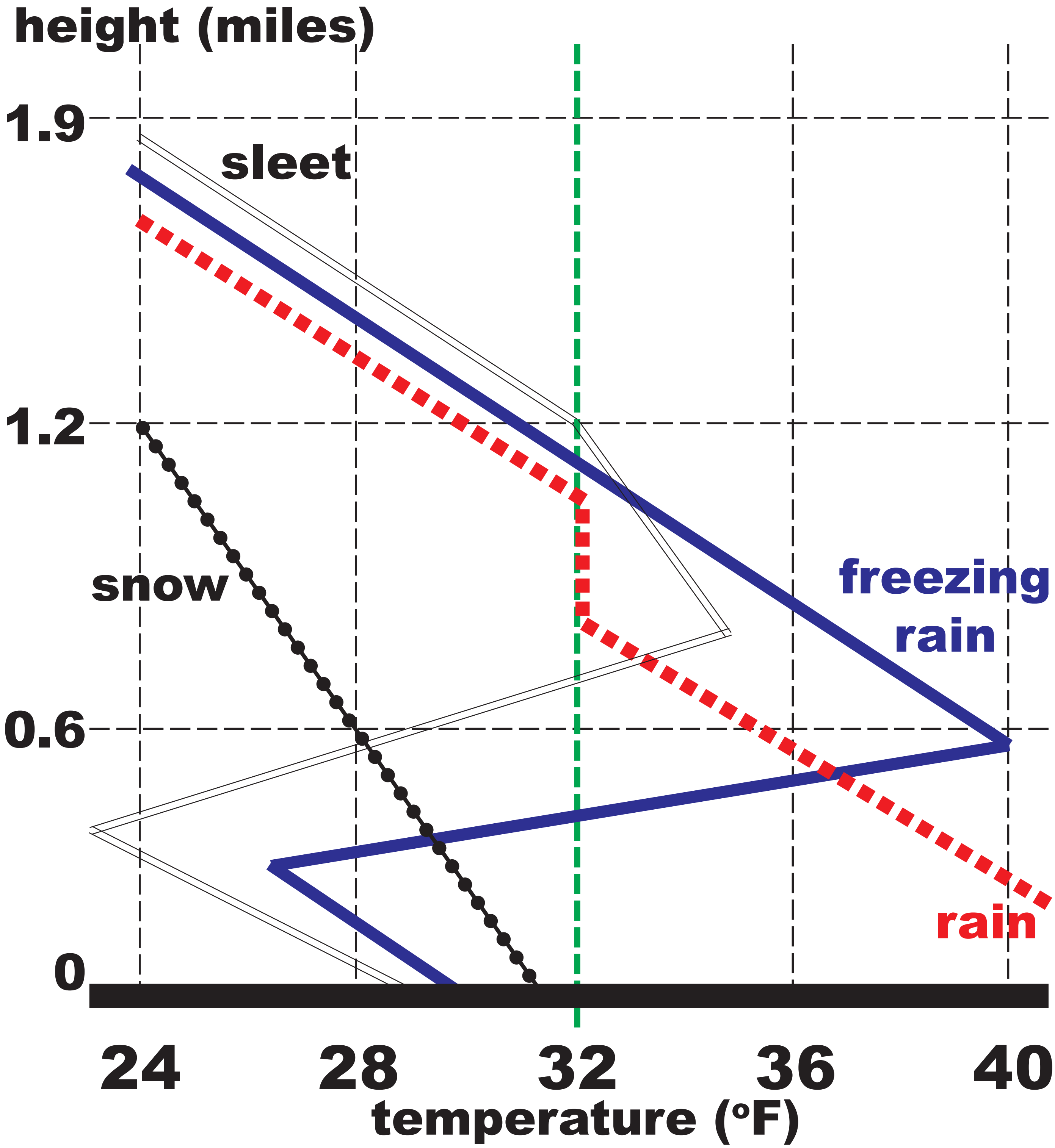

Figure 15: Air and surface temperatures leading to different forms of precipitation. (derived from Gay & Davis 1993).

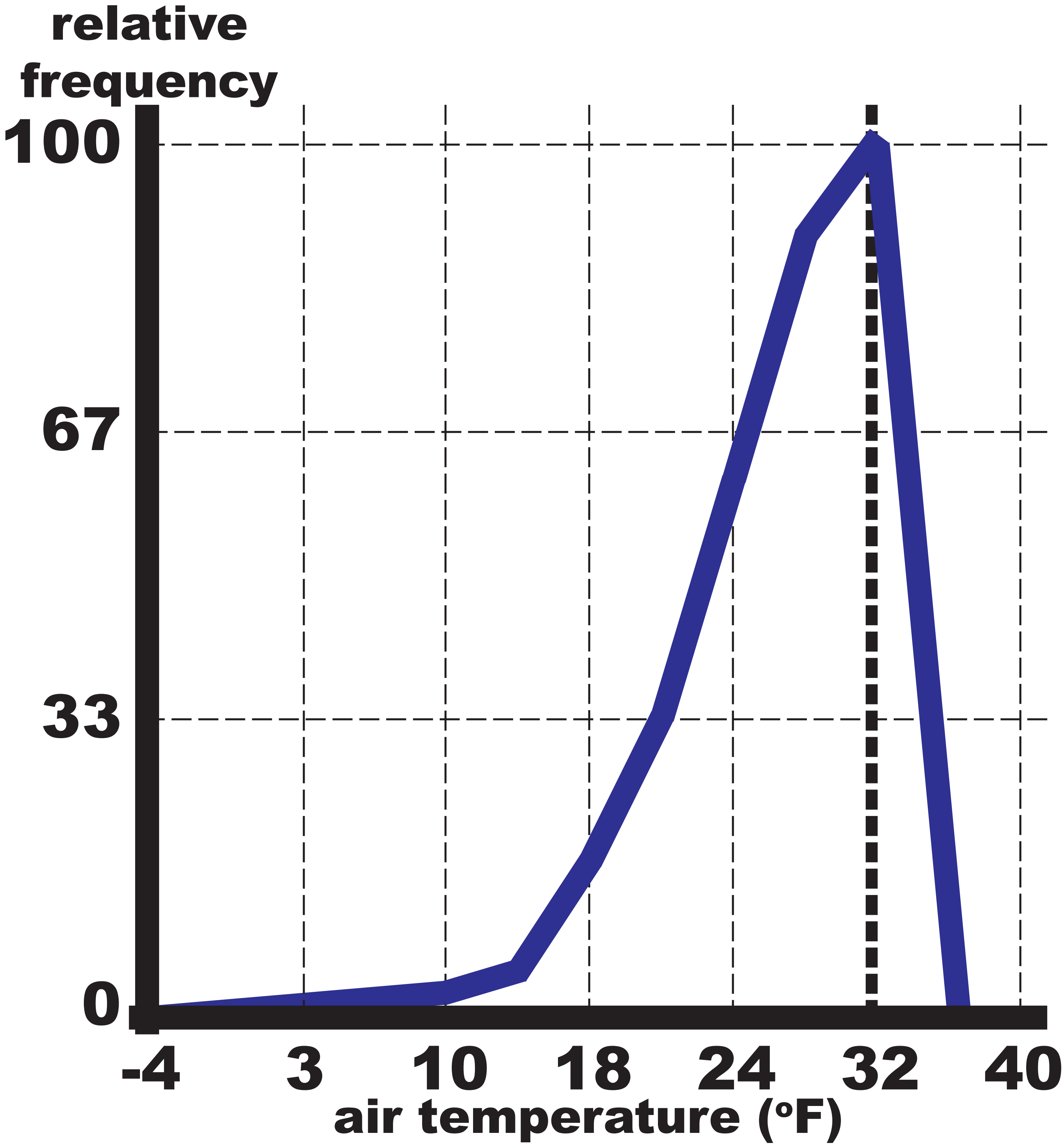

Figure 16: Air temperature at ~6.5 feet above the ground associated with freezing rain. (derived from Cortinas et.al. 2004).

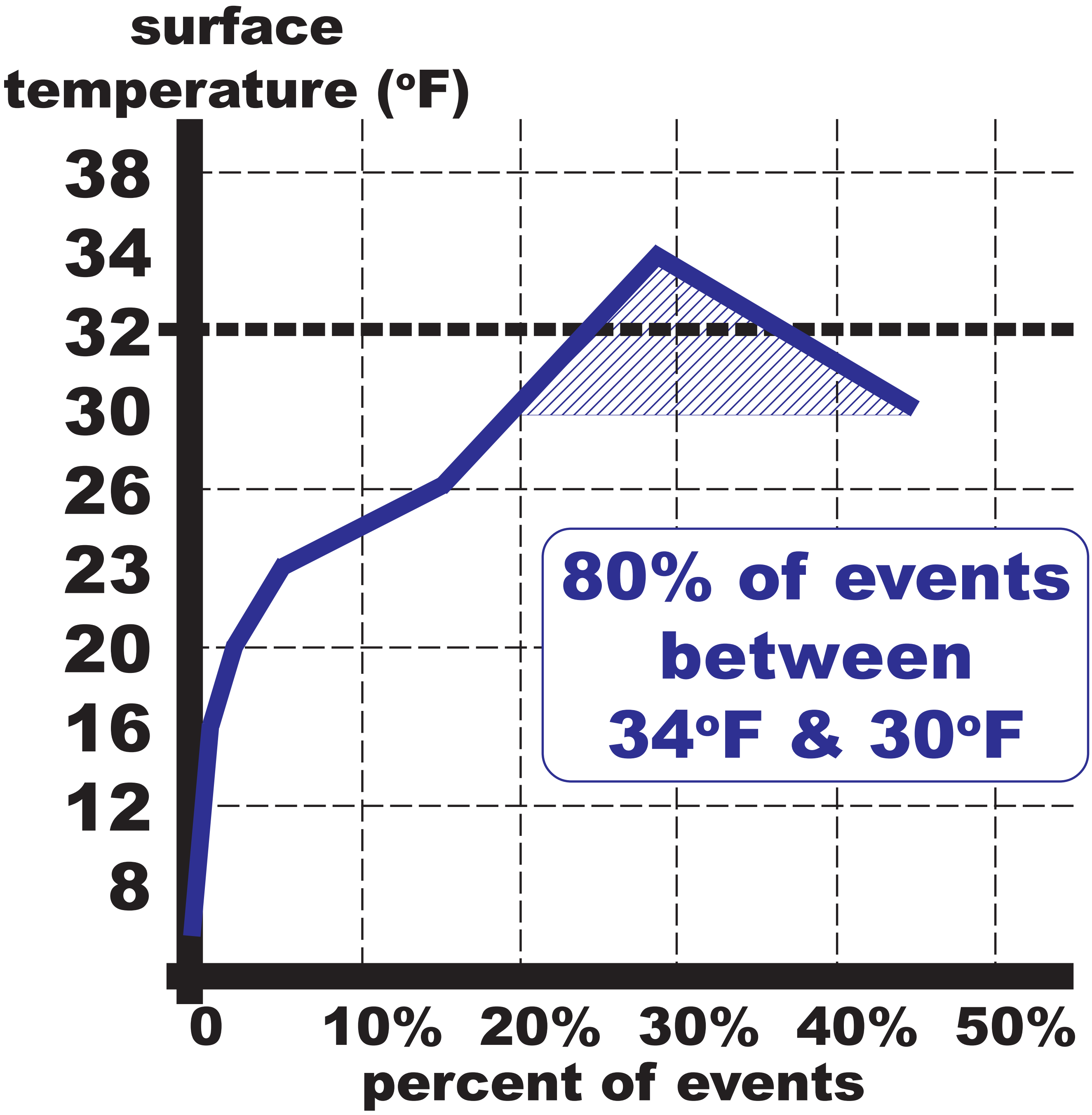

Figure 17: Surface temperatures during freezing rain events over a 15 year period (Great Lakes Region).
(derived from Cortinas 2000)

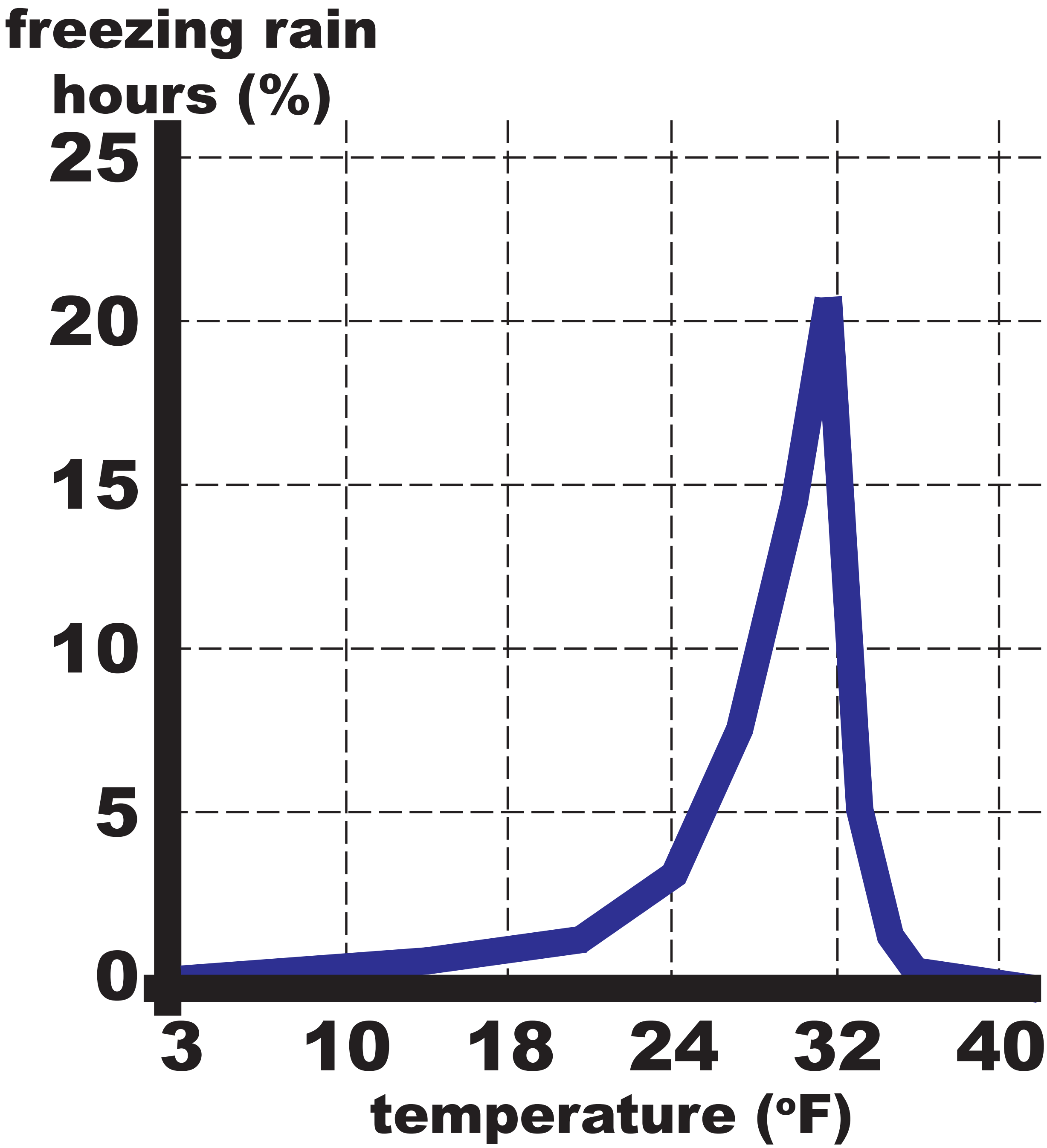

Figure 18: Surface temperatures taken at ~6.5 feet above the ground during freezing rain events over 74 years.
(derived from Houston & Changnon 2007)

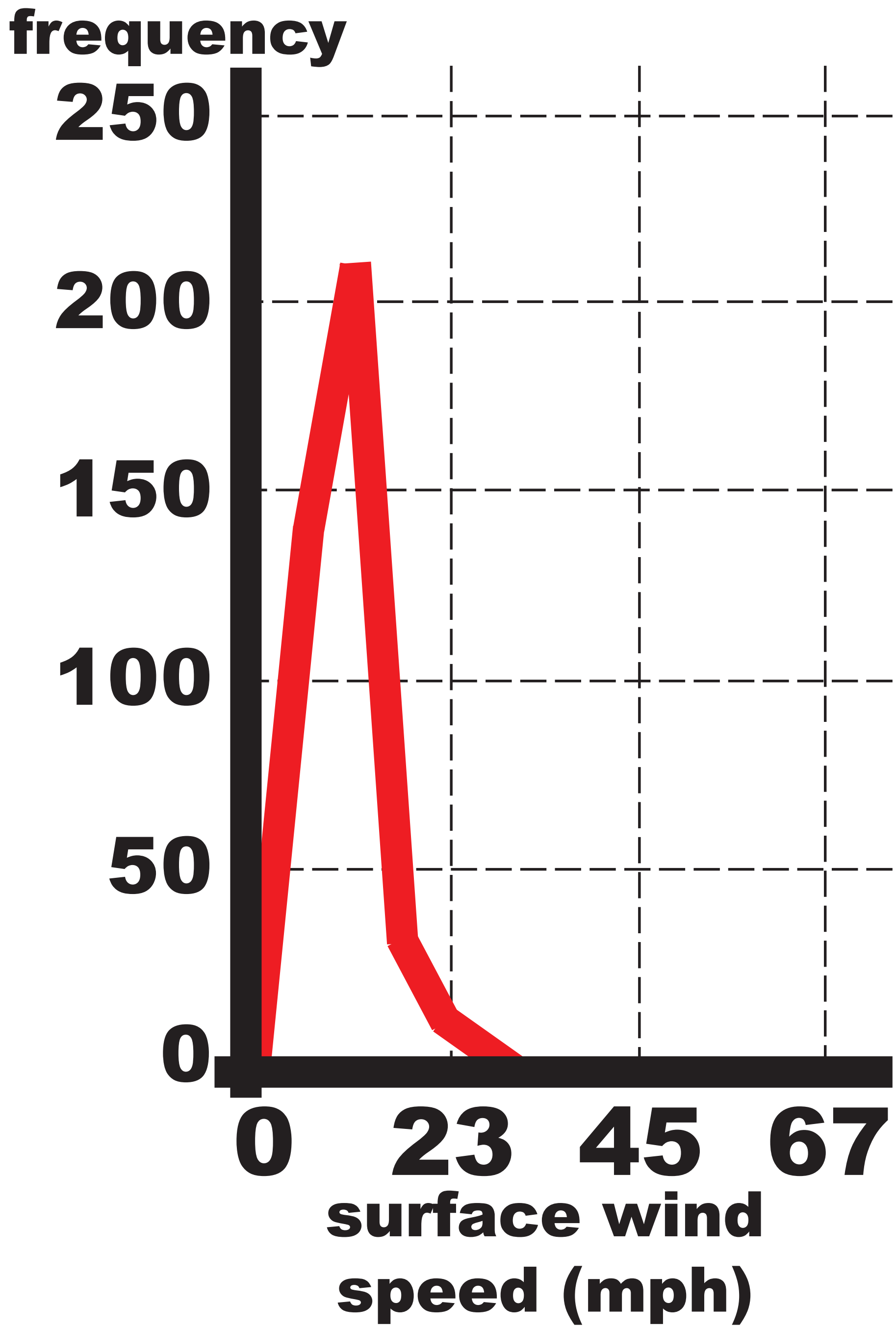

Figure 19: Ice storm wind speeds in miles per hour.
(derived from Rauber et.al. 2001)

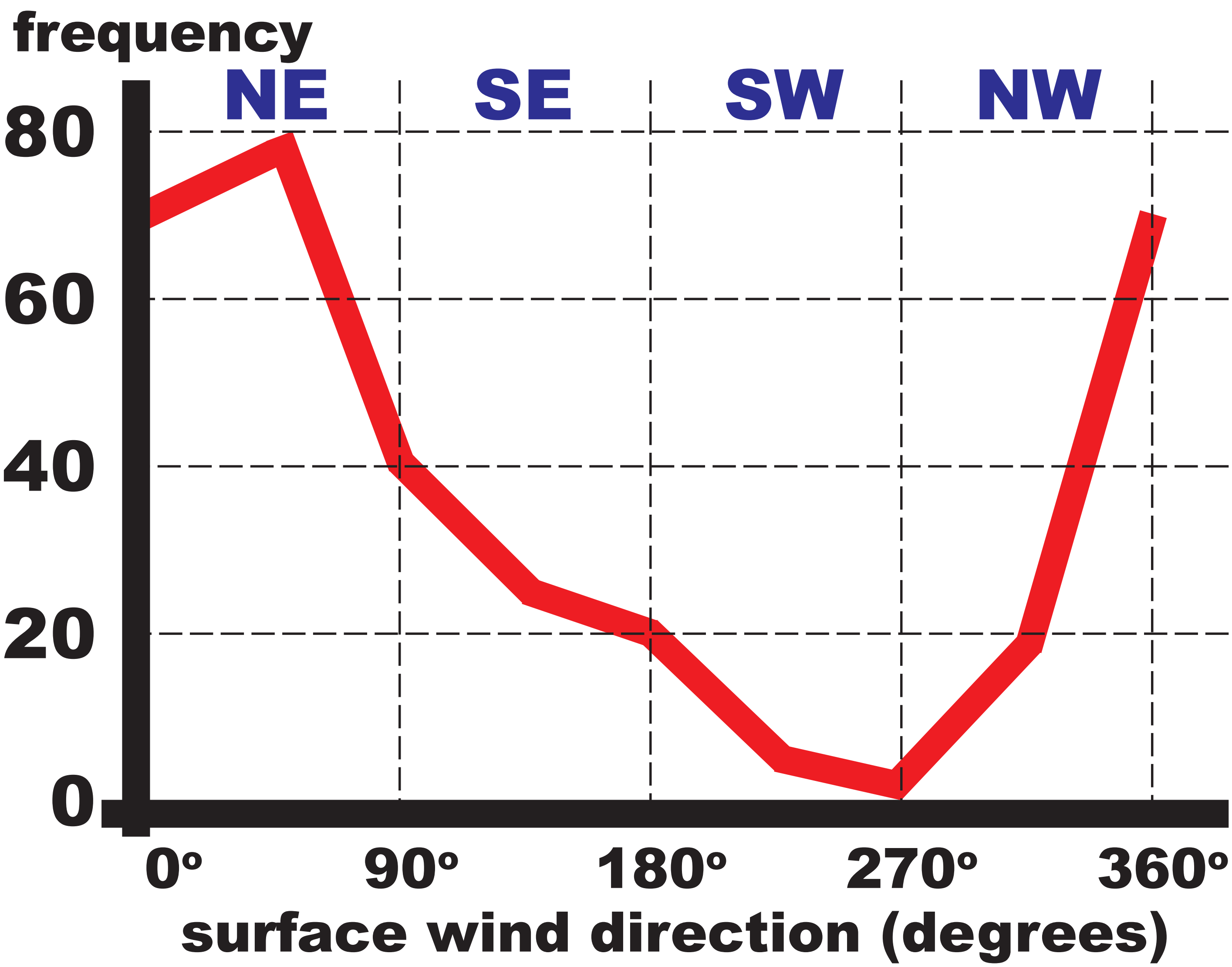

Figure 20: Ice storm wind directions in degrees.
(derived from Rauber et.al. 2001)

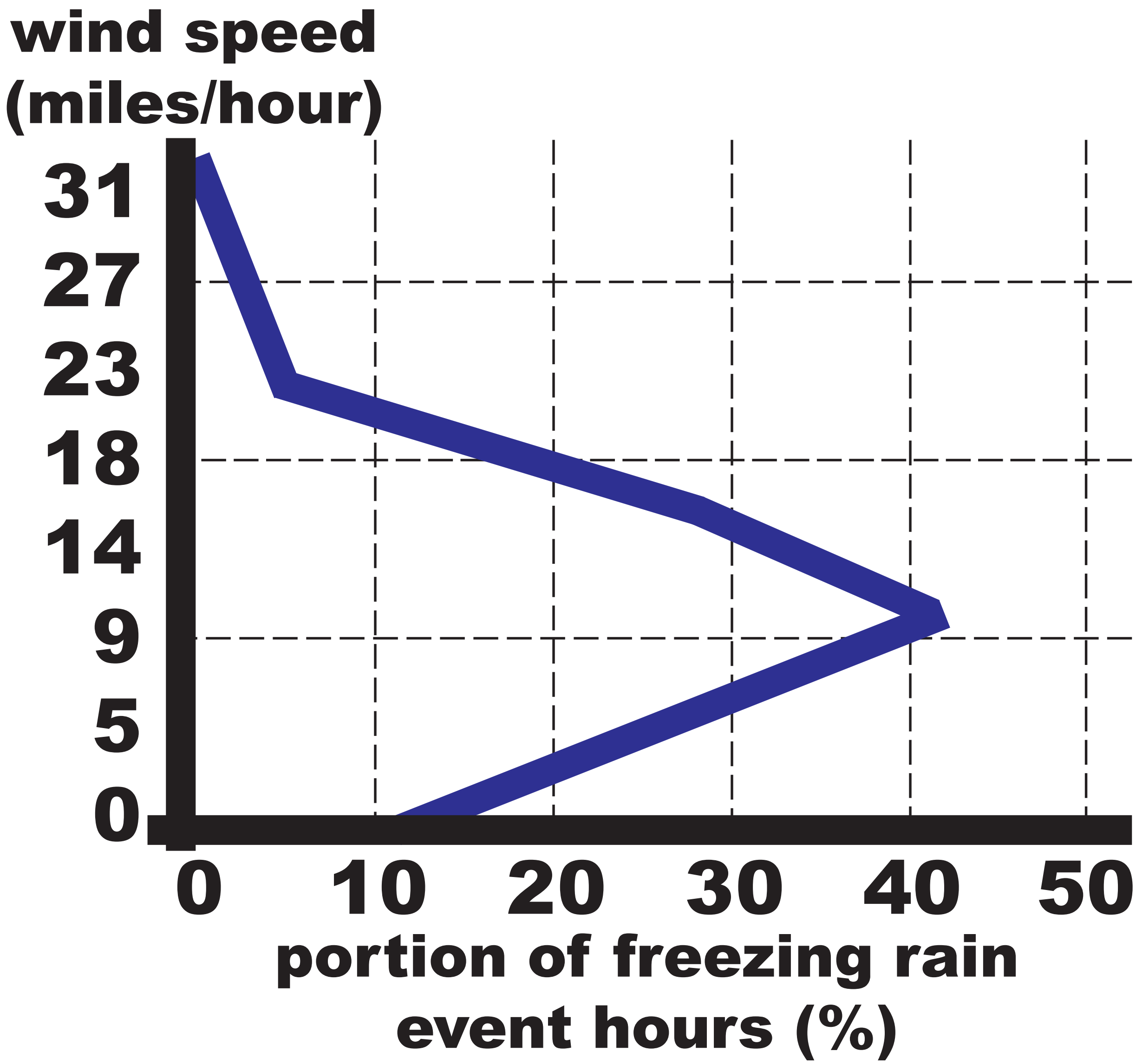

Figure 21: The percent of freezing rain hours with wind speeds of a given velocity for a 74 year period.
(derived from Houston & Changnon 2007)

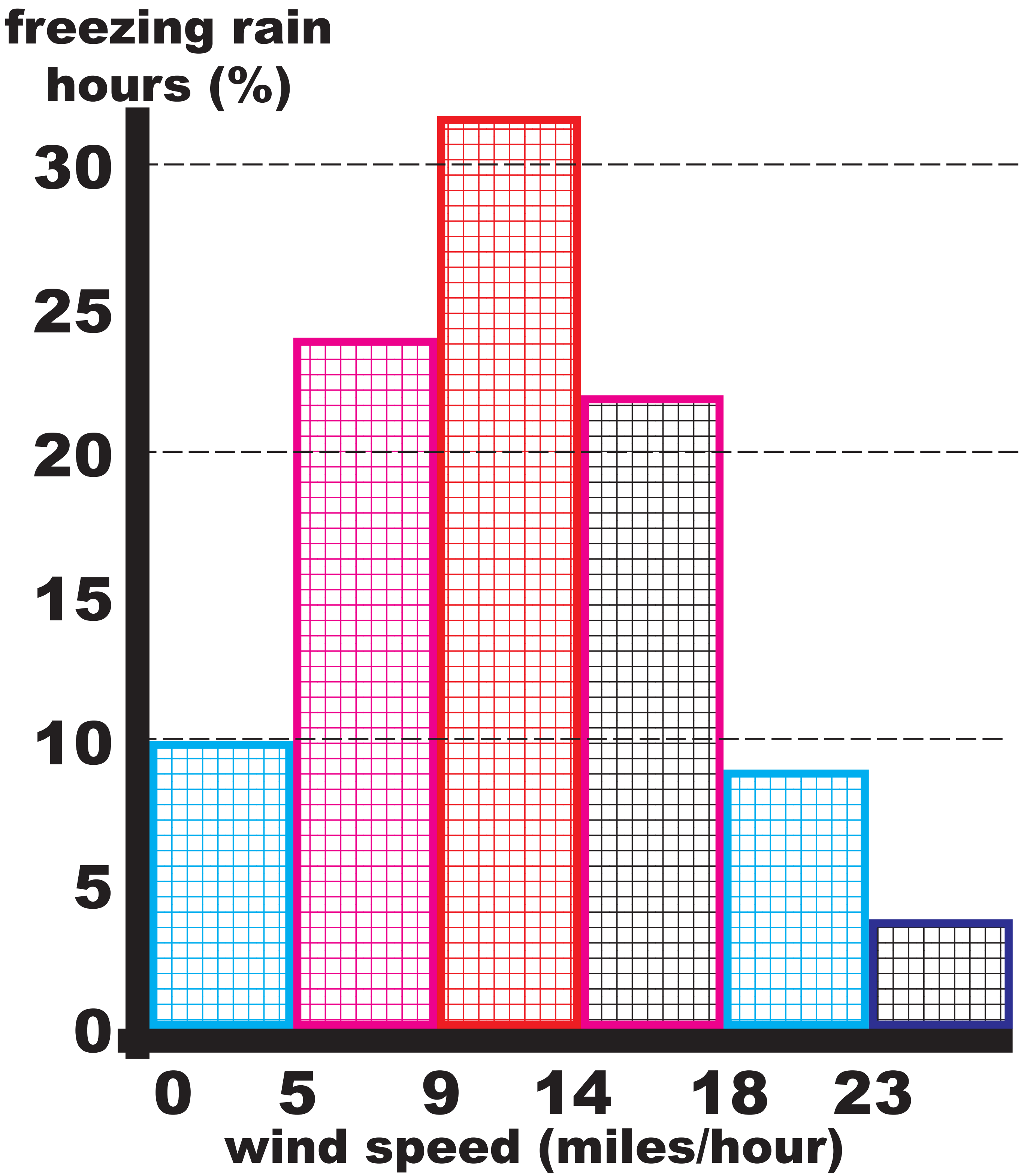

Figure 22: Frequency of wind speeds during freezing rain events. (from Houston & Changnon 2007).