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LESSONS FROM HISTORY

# The Wind-Chill Index

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This Lessons from History article about the wind-chill index (WCI) explores the historical polar and meteorologic literature relevant to the topic and presents unpublished work from 1939. Geographer Paul Siple (1908–1968) was a 6-time Antarctic explorer and scientist who invented and named the WCI in his doctoral dissertation at Clark University. Siple and Charles Passel (1915–2002) performed studies in Antarctica in 1940 that led to publication in 1945. This paper is often credited as the beginning of the WCI. Through years of critiques and revisions by others, these efforts evolved into the wind-chill equivalent temperatures (WCTs) used today. This essay explores the history, the science, and the overlooked originality, simplicity, and details of Siple's unpublished work. The remarkable similarity of the original chart to a current chart is shown by adapting and overlaying the 1939 WCI onto a current WCT chart with its times-to-frostbite data. The writings of Siple, Passel, and others provide an evocative supporting narrative to illustrate some of the problems of living in cold environmental conditions.

*Keywords:* Siple, Antarctica, weather, cold, frostbite, bioclimatology

Wind chill is a phenomenon caused by the effect of wind on heat loss from bare human skin, with a resultant increased rate of cooling and increased sensation of cold. Wind-chill indices and other tools are used in wilderness and nonwilderness weather reporting to warn people of cold weather hazards, particularly frostbite.[1] American geographer Paul Siple (1908–1968) invented the wind-chill index (WCI) in 1939. It was briefly adopted for polar and military purposes and is referred to here as the 1939 WCI. It is an index because it is a scale or chart that correlates clinical manifestations of cold with the environmental parameters of wind and temperature. In 1940, on another trip to Antarctica, Siple and Charles Passel (1915–2002) performed studies of the effects of wind and air temperature on humans. Their study was published in 1945.[2] This paper is the one usually cited for the creation of the WCI. This Lessons from History article explores the chronicle of the WCIs and related wind-chill equivalent temperatures (WCETs or simply WCTs). It examines the overlooked originality, simplicity, and details of the unpublished 1939 WCI and presents a remarkable comparison of the original and current charts.

Wind-chill terminology can be confusing. Wind chill is often used interchangeably with, or as an abbreviation for, any of several terms. SP 1945 WCI is used in this article to denote the heat loss rate measurements or the WCI of Siple and Passel. The SP 1945 WCI was employed and criticized for decades until it evolved into the WCTs. WCT may refer to an individual figure but, depending on context, may mean the whole structure of physics, calculations, and charted figures. When "the WCT" is presented on a chart that relates grades of danger, the term WCT index (WCTI) is correct but not always used. The term "old WCT" refers to any WCT or WCTI based on the SP 1945 WCI. The 2001 "new WCT" uses updated biophysical models. It predicts the risk of frostbite, so formally it is the "new WCTI" as described in the official report.[1] Despite this distinction, terms such as "new WCT," "2001 WCT," and "current WCT" are commonly used.

The convective cooling power of the wind has long been studied. A compilation of 89 early physics-laden references for experiments and calculations between 1912 and 1941 included terms such as comfort index, cooling power, cooling temperature, sensation scales, effective temperature index, and equivalent comfort conditions.[3] These were in the realm of mathematicians and other scientists. The emerging field that studied the interaction of human body temperature with the environment included leaders such as American biophysicist A. Pharo Gagge (1908–1993). In 1941, he proposed new units so that varying specialists could have a common system of communicating about thermal exchanges.[4] In an individual sitting/resting comfortably indoors at 21°C

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(70°F) and less than 50% humidity, 1 clo was the insulation value of everyday clothing and 1 metabolic equivalent of task (MET) was the metabolic rate of an average-size person at rest. Today's related MET is a ratio of the rate at which a person expends energy relative to the mass of that person while performing some specific activity compared to sitting/resting. Gagge et al. produced brief tables suggesting optimal temperatures and clothing requirements for comfort in indoor or outdoor conditions.[4] Siple and Passel cited the work of Gagge and the other forerunners.[2] The original MET and clo definitions were restated in 1966 with commonly used engineering terms and other changes at the US Army Research Institute of Environmental Medicine (USARIEM), whose mission statement includes the enhancement of health and performance through medical research.[5] Similarly, in 1966, the first institutional standards for comfortable temperature and airflow in the indoor thermal environment were published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, last revised in 2020.[6] The early studies laid some of the groundwork for a WCI, but a polar venue, a more memorable term, and popularization awaited.

Siple was a 6-time Antarctic explorer and scientist. At age 19, he was an American Eagle Scout selected from a national contest to accompany Richard E. Byrd, Jr (1888–1957) on his first expedition to Antarctica in 1928 to 1930.[7,8] Siple recorded that "the day we felt the cold most was one when the temperature was down fifty-five degrees [F] below zero [-48°C] and there was a wind of twenty miles an hour [32 $km \cdot h^{-1}$]. One could remain out of doors for only a few minutes."[7] These words were an inkling of his future career. On the second Byrd expedition (1933–1935), a member of the ice party keenly portrayed cold conditions as "the real agony of cold comes from the wind" and, more sharply, "like a knife drawn across the face."[9] Siple deemed it radically different from his previous trip to now be a supply officer and group leader, participate in biology experiments, head a 77-d exploration studying geology, glaciology, and biology, and have findings published in his name.[8,10,11] Afterward, he earned a doctorate in geography. Siple's naming of the "wind-chill index" and the rudimentary first formula is found in his unpublished dissertation of 1939.[12] It was only occasionally cited, and few details were published even by Siple himself.[2] The 1939 WCI was produced by simply multiplying the temperature in degrees below zero Celsius by wind speed (in $m \cdot s^{-1}$) and correlating the resultant product with the risks of cold outdoor travel. The results were chosen to be unitless, and the formula would never be so plain again. There had not been a known request for the dissertation until the time of this writing, according to the resource sharing librarian of Clark University Goddard Library (K Stebbins, October, 2020; personal communication). More features of Siple's early work are provided here. Near the conclusion of this paper is an adaptation of Siple's original work that shows a remarkable comparison of the 1939 WCI to a current WCT chart with its times-to-frostbite data.

Charles Passel (1915–2002) was a sedimentary paleontologist on the US Antarctic Expedition of 1939 to 1941, on which Siple was West Base leader. Passel went south to look for fossils in particular during 87 d of exploring by dogsled to map mountains. His contemporaneous diary *An Antarctic Journal* initially was limited to 200 personal copies and was not published until 1995 as the book *Ice*.[13] Siple's *90° South* is not a diary but an autobiographical memoir emphasizing his later trips to Antarctica.[8] Passel recalled in an interview that expedition meteorologist Arnold Court was occupied with collecting radiosonde data, so Passel was asked to help with a new experiment.[14] Passel attributed to Siple "the wind chill index and the background for his interest in the subject."[13,14] Returning home in 1941, Passel used his own Antarctic material for a master's degree in geology and served in the US Marine Corps.

Siple and Passel's experiments in Antarctica in 1940 made correlations "between atmospheric cooling rates and states of human comfort."[2] Final publication of their landmark 1945 paper was much delayed by the events of December 1941. During World War II, Captain Siple evaluated cold-weather clothing and later joined the US Army Office of Research and Development as a civilian scientist.[8,15] Siple devoted 26 pages in his dissertation to the Antarctic clothing of his era and in 1945 published an extensive paper on selection of winter clothing and gear that was supplementary to the WCI paper.[12,15] Modern materials have solved some of the problems of the older clothing. Siple's last trip to Antarctica began in 1956 at the US Amundsen-Scott South Pole Station as the inaugural science leader of the International Geophysical Year (IGY) 1957–1958. The history of the WCIs and WCTs continues forward from the 1940s with a return to Siple's 1939 WCI after that.

Leading up to the 1940/1945 study, Siple was aware of thermogenesis, insulation values of subcutaneous tissues, vasoconstriction, individual variability, and more, but early in his career he added a disclaimer that physiology textbooks should be consulted. He recognized that his original qualitative 1939 WCI represented "a real factor of climatic sensible temperatures to a certain extent, although it may not indicate the exact proportion of cooling effect. To calculate or measure the true cooling effect would entail a cumbersome process and would probably not give a much better picture of true wind-chill."[12] This would

prove to be a substantial understatement. He wrote that any scale needed to limit complicating factors such as humidity and solar gain. These were conveniently avoided in the dark and dry dead of Antarctic winter. Siple noted that the effects of insensible losses and clothing could be addressed in later corrections.[2] With knowledge of chamber experiments by the John B. Pierce Hygiene Laboratories and others, he and Passel proceeded in 1940 to quantitatively perform the carefully described "measurement of dry atmospheric cooling in subfreezing temperatures."[2] They would opine that, with a limited library in Antarctica, their methodology was not biased by knowledge of all previous studies.[2]

Siple set aside his elementary 1939 WCI in part because it did not actually measure heat loss.[2,8] Instead, in 1940 he constructed a "relative comfort thermometer" on a 10-m pole, stating that "I set up an experiment to try to measure the rate in time it took a small cylinder of water to freeze. Charlie Passel helped me measure accurately the exact length of time that the cylinder remained at the freezing point while it was letting up its heat of crystallization under nearly 100 different combinations of wind velocity and temperature."[8] An anemometer recorded wind speed.

Rather than a thermometer, a thermohm measured water and ice temperature by changes in electrical resistance through a platinum wire in the cylinder. A separate naked thermohm measured ambient air temperature. From observational "runs" at different temperatures and wind speeds made in the dark Antarctic winter in the absence of insolation (solar radiation) and ignoring any effects of evaporation or other factors, the data were recorded.[2] Siple and Passel measured the cooling rate of water freezing into ice in the cylinder, with attention to the time water remained at 0°C while freezing and giving up its heat of fusion. By knowing this property, time, the mass of water, and surface area, they calculated the SP 1945 WCI in units of $kcal \cdot m^{-2} \cdot h^{-1}$.[2]

The typically 3- or 4-digit WCI figure was neither a temperature nor did it resemble a temperature like the later WCTs. It needed a clinical relationship to have practical use. The inanimate test cylinder had no feelings, so the physics-based values correlated the cold sensations or manifestations of field parties with various wind and temperature combinations. For example, the SP 1945 WCI paper's Table 5 includes times elapsed to sudden pain and blanching of the cheek, known as frostnip.[16] Table 7 has a column of WCI numbers indexed with clinical descriptors in a second column. Table 7 is not titled as a wind-chill chart but as "stages of relative human comfort and environmental effects of atmospheric cooling."[2] The SP 1945 WCI values range from 0 to 100 ("nude sun-bathing possible") to 2600, including 2300 where "exposed areas of face will freeze within less than 1/2 minute."[2] A later reading of 3290 at the South Pole by Siple during the IGY in 1957 indicates "little chance for lengthy survival."[8]

Another example from the SP 1945 WCI Table 7 is a reading of 2000, signifying that "travel and living in temporary shelter becomes dangerous."[2] That closely echoes the words in Siple's different scale of 1939, where 500 indicates "conditions dangerous for travel or temporary shelter." As of 1945, there were 2 indices. One was the uncomplicated practical scale of 1939 still popular with the Antarctic services.[2,8] The other was the physics-based SP 1945 WCI.[2] The preliminary 1940 table of results made its way into polar, military, and climatology usage and publications.[14,17] The final form was published in 1945 and used for decades. Pragmatic rules of thumb were also commonplace. For example, military personnel in Alaska in 1964 were taught the "rule of 30s." At -30°F (-34°C) with a wind speed of 30 mph (13 $m \cdot s^{-1}$), there was risk of frostbite in 30 s according to a former US Army Specialist 4 (I. Coddington, December, 2020; personal communication).

In 1948, the aforementioned meteorologist Court focused on wind chill, stating that "no precise explanation or critical discussion of it and its method of computation has heretofore appeared."[17] Despite working with Siple in Antarctica in 1940, Court cited only the 1939 WCI but did not mention the graphs and tables. Instead, he focused on the physics-based SP 1945 WCI work, disagreed with the units, and rightly noted that the method did not consider the complex ways the human body exchanged heat with its surroundings. Court did compliment the study as the first performed at such low temperatures.[17] In a discussion section accompanying a 1951 report of 35 indoor workers' subjective sensations of the outdoors of Saskatchewan, Court audaciously declared that an objective numerical indicator would someday make such subjectivity unnecessary.[18]

In 1960, as displeasure with the SP 1945 WCI units continued, Siple recommended that the index be used "just as numbers," perhaps harkening back to what his 1939 WCI plainly did.[19,20] He continued defensively: "looking back, we perhaps made a rather too naive approach, and we may have made assumptions which were a little careless. From the practical standpoint, I think we evolved a schema that has been of some use."[19] It was useful, but modifications would come. The portrayal of the cooling effect of the wind would eventually be changed from the WCI to a different type of index that was more intuitively understood by regular users as a "feels like" temperature. Equivalent temperatures have been used for years to express various environmental conditions, but in the context here, WCTs are mathematically computed colder

temperature-like figures at which the cooling effect of the wind and cold on the exposed dry face is the same as if wind is not present.[1,20,21]

The US Department of Defense has long been interested in developing operational thermal indices.[1] In 1961, the US Army Armored Medical Research Laboratory (AMRL) at Fort Knox, Kentucky, consolidated with other laboratories into what is now USARIEM at Natick, Massachusetts. The AMRL's WCT chart of 1961 was based on the SP 1945 WCI and, despite its unrealistically cold results and awkward design, the AMRL chart was included in a 1963 textbook.[22] In 1967, the site of the US Air Force Arctic Aeromedical Laboratory at Ladd AFB, Alaska, became the Arctic Medical Research Lab, a subsidiary of USARIEM, at US Army Garrison Alaska, Fort Wainwright. A 1965 US Air Force Arctic Aeromedical Laboratory paper by Canadian biophysicist Charles Eagan identified problems with the AMRL WCT chart.[23] His WCT chart, while still based on SP 1945 WCI, had warmer WCTs than the AMRL version. It was much easier to use and, being indexed to degrees of danger, it was a WCTI. The source or formula of the chart in Eagan's paper was not stated. The US Army printed WCT charts on pocket cards.[23] Eagan would be recognized for his explanation that natural convection around the body produces a "wind" of 0.9 $m{\cdot}s^{-1}$ (2 $mi{\cdot}h^{-1}$) and that people in the cold outdoors do not stand still but move themselves or their limbs at about 1.8 $m{\cdot}s^{-1}$ (4 $mi{\cdot}h^{-1}$). Baseline wind velocity necessitated Eagan's correction of earlier WCTs.[23,24] The definition of walking speed was decreased to 1.3 $m{\cdot}s^{-1}$ (3 $mi{\cdot}h^{-1}$) in the 2001 WCT revision.[1]

In the 1970s, the use of WCTs began to supplant the SP 1945 WCI.[1,25] US National Weather Service (NWS) meteorologists began using WCTs in 1973 to describe comfort levels and contribute to forecasts and safety warnings according to a 2003 report by the US Office of the Federal Coordinator of Meteorological Service and Support Research (OFCM).[1] The history is obscure. It is likely that the NWS used both the SP 1945 WCI and the WCTs derived from it. The date and usage could not be fully corroborated so the term old WCT is used. Some weather sources still show the old WCT chart for comparison to the new one. The formula printed on the old WCT chart is the same as the one listed in a 1992 NWS operation manual so it must have been in use then.[21] It seems likely to have been in use before that because the old WCT values match those from Eagan's WCT tables II and III of 1965.[23] In the late 1970s Canada began using the SP 1945 WCI converted from $kcal{\cdot}m^{-2}{\cdot}h^{-1}$ to SI units of $W{\cdot}m^{-2}$ but some regions reported old WCT because WCTs resembled "regular" temperatures that were preferred over the WCI in user surveys.[1,25,26]

In the 1990s the SP 1945 WCI computation, and its continued heat flux basis of the old WCT, was once again under scrutiny for its seemingly impromptu initiation, lack of sound theoretical basis, and dubious experimentation.[20] Some of the many criticisms were that body heat production and transfer should have been considered; skin temperature was not constant as they assumed but fell when exposed, although vasodilatation could offset some of that; wind speed on a 10-m pole did not reflect the level of the face; a plastic water cylinder wall did not transmit heat like bare or clothed human skin and subcutaneous tissues or have proper surface area; wind speeds tested were limited or their cooling effects exaggerated; there was wide scatter or omission of some data points and inappropriate extension of parabola fit; the units were wrong; and more.[20,21,25,27] As additional scientists piled on, it was wondered if it was "time to bury the wind chill index rather than to praise it."[20]

That quip was from environmental physicist Randall Osczevski of Defence Research and Development Canada (DRDC), who measured heat loss from a head manikin in a wind tunnel to develop a mathematical model for new WCTs rather than the old WCTs based on the SP 1945 WCI data.[20,25] American biomechanical engineer Maurice Bluestein from the Purdue School of Engineering and Technology used an enclosed hollow cylinder to approximate a head. By using modern heat transfer principles, he found a numerical solution for a facial cooling model.[24,25,27] Despite the criticism of SP 1945 WCI, Osczevski in 1994 sympathetically wrote that "All the technical objections, valid as they may be, miss the point. Siple and Passel were not seeking a formula to calculate the heat loss of a clothed or a nude human body, or some small part of one. They were looking for and found a mathematical way to combine wind and temperature to create a scale that they could calibrate to consistently reflect how cold different combinations of those factors would feel."[20] A somewhat similar sentiment had been stated by a critic of a 1932 study: "too much mathematics and not enough experiment."[3] More pithy was a proverb offered by the anti-science, cold-ocean sailor and mountaineer H.W. Tilman (1898-1977): "Science is madness if common sense does not cure it."[28]

In 1999 a cold snap over Ontario made headlines with a dangerous WCI of nearly 1800 $W{\cdot}m^{-2}$. This was the WCI and unit of heat flux still used in some of Canada in 1999, rather than the WCT method.[1,25] It was just one event, along with many other concerns over the years, that led to a goal of making a new WCT chart that was more understandable, more recognizable, and more accurate than prior SP 1945 WCI-based WCT charts and that involved human studies to determine thresholds for the risk of frostbite.[1] The latter requirement made it a WCTI and better able to suggest the

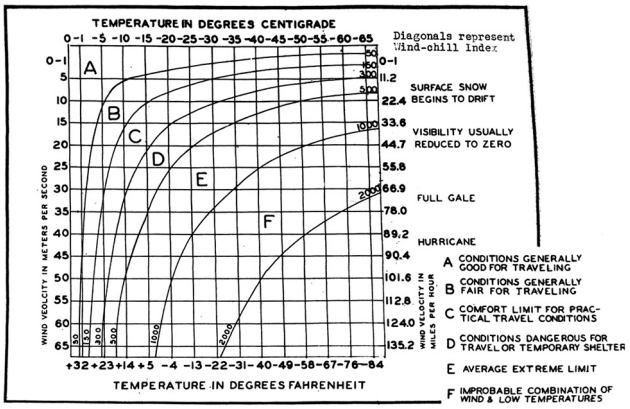


**Figure 1.** Original wind-chill index (WCI) chart from Figure 69 of Paul Siple's 1939 unpublished dissertation. Permission to reproduce this chart was granted by Clark University Goddard Library. The 1939 WCI was a 2- to 4-digit unitless number and not a temperature-like wind-chill equivalent temperatures number. Constant WCI values were displayed as curved lines (isopleths) across the figure and were correlated with observed or inferred temperatures and wind speeds. Between the WCI isopleths were bands of clinical risks, described in the legend, rating the suitability of being outdoors in the cold of Antarctica.

level of danger. The US Office of the Federal Coordinator of Meteorological Service and Support Research formed the Joint Action Group on Temperature Indices (JAG/TI) but primarily focused on cold to develop a new WCT. Participants included the Meteorological Service of Canada, DRDC, NWS, military, and other organizations and individuals. Multiple experimental models were examined, but ultimately the new 2001 WCT relied on the modeling of Osczevski and Bluestein. The site of cooling, chill sensation, and risk of frostbite was not the clothed whole body but the exposed dry face. The new 2001 WCT charts were implemented in the winter of 2001 to 2002.[1] The effects of humidity, evaporation, wet clothing, or solar gain were purposefully not included, although JAG/TI began a commission to study these issues in a universal thermal climate index.[1] Many such multivariable indices have been described and compared.[29,30]

The 2001 WCT numbers are not large heat flux numbers as used in the older WCI method and, except for extraordinary conditions, are only 2-digit calculated equivalent temperatures similar in appearance to ordinary air temperature readings. WCTs are not real temperatures. Although derived from units of temperature and wind, WCTs are expressed on charts only as degrees Celsius or Fahrenheit. Shaded areas on the charts indicate zones of frostbite risk limited to the exposed dry face.[1,31] WCT's popularity with the public was, and still is, a major part of its success and longevity as a weather tool, but the weather services of the United States and Canada began issuing extreme cold or other named watches, warnings, and advisories for some locations even in the absence of wind. There are various temperature and time thresholds for these depending on local or regional setting, populations at risk, suddenness or duration of hazard, and more. According to the NWS winter program coordinator, a future consolidation of watches, warnings, and advisories and other weather advice into one nationwide "seamless product suite" is intended for late 2022 (M. Muccilli, November, 2020; personal communication).

A return to 1939 and a closer examination of the past reveals many new details. Siple's 1939 dissertation was seldom cited by Court or others, and few or no specifics from the reference were given. It is not known how or if Siple's 525 pages, 16 tables, 156 maps, sketches, and photos, and 223 sources may have been communicated since signed by his advisors, the eminent geographers Samuel Van Valkenberg and T. Griffith Taylor.[12] Figure 69 from the 1939 dissertation is published here as Figure 1 possibly for the first time, or at least for the first time in many decades, with a new analysis.

On page 166 to 168 of his dissertation, Siple felt that "With so many factors to consider, no practical solution to the problem for quick computation and simple form will likely ever be invented… it seems therefore advantageous to use the simplest system."[12] The original 1939 WCI was described in 4 steps, beginning with Step 1 that identified the simple formula "C° x V = W-C," where he multiplied "temperatures in degrees of minus Centigrade [°C below zero] by wind speed in meters per second [$m \cdot s^{-1}$], the product of which I shall call the wind-chill index."[12] He chose to report the product as unitless. Step 2 was Siple's Table 12, not shown here, which did not list observations but only convenient round numbers for temperatures and wind speeds to perform the multiplication and develop a table. The multiplication product—the 1939 WCI—was applied to Steps 3 and 4, where it became meaningful.

Step 3 is shown in Figure 1 (Siple's figure 69). Along the axes are the same temperatures and wind speeds as in Siple's Table 12. Observed data points are plotted but not shown. Instead, curved lines of constant WCI values are drawn smoothly through the data points on the chart in a presumably best-fit manner, either by visual inspection or by an unrevealed method. Some, especially at higher wind speeds, were estimated by extrapolation.

Curved lines of constant values are called diagonals by Siple but are isopleths. For example, an isopleth for temperature is an isotherm and an isopleth for wind speed is an isotach. An isopleth for Siple's combination of temperature and wind speed is his 1939 WCI.

In Step 4, shown in Figure 1, Siple correlated his WCI with the level of discomfort and danger. Between the WCI isopleths he defined bands of risk that were a

surrogate for heat loss and the sensation of cold. In his Figure 69 legend, he rated the suitability of outdoor travel on foot or by dogsled in Antarctica:

- A: Conditions good for traveling (WCI 0–50)
- B: Conditions fair for traveling (WCI 50–150)
- C: Comfort limit for practical travel (WCI 150–300)
- D: Conditions dangerous for travel or temporary shelter (WCI 300–500)
- E: Average extreme limit (WCI 500–1000)
- F: Improbable combination of wind and low temperature (WCI 1000–2000)

This was not founded solely on his own experience. His personal WCI record while traveling was just over 400, but he amassed WCI values based on instantaneous, daily, seasonal or yearly past or contemporaneous meteorologic readings from 21 Antarctic stations, sledging parties, camps, or icebound ships.[12] The primary data were there, but he organized it into something new—the WCI.

Produced in Figure 2 are middle-range 1939 WCI isopleths plotted as an overlay onto a 2001 WCT chart adapted from the NWS and Meteorological Service of Canada.[1,31] The chart coordinates are in degrees Celsius, but the 1939 wind speeds had to be converted by the authors from $m \cdot s^{-1}$ to $km \cdot h^{-1}$. The underlying 2001 WCT chart's plotted digits are equivalent temperatures. Some further direction is needed to interpret what Figure 2 reveals because the overlay of the 2 charts visually presents 2 methods with different (but related) outcomes obtained using different approaches.

In Figure 2, the underlying 2001 WCT chart's shaded areas warn of the thermodynamically predicted 30-, 10-, and 5-min times-to-frostbite estimated separately from the WCTs.[1,31] To confirm these mathematical predictions, a small number of human volunteers had skin temperatures monitored for facial frostbite in an environmentally controlled wind tunnel, yielding a table of times whose large increments had a staircase appearance.[1] These uneven results were smoothed for the stylized 2001 WCT chart to display shaded zones of frostbite times.[1,31] It is these zones, not the WCTs, that are most useful for the chart overlay comparison.

The overlying 1939 WCI isopleths of green, yellow, and red lines in Figure 2 do not offer times-to-frostbite but are derived from a wealth of experientially obtained ratings of the safety of Antarctic travel or temporary shelter. The rating is fair (WCI 150), practical comfort limit (WCI 300), or dangerous (WCI 500). For example, the red 500 isopleth of 1939, although reflecting a different outcome (dangerous travel with frostbite or worse), offers a reasonable approximation of the perilous 5-min frostbite border of the 2001 WCT chart. The overlay shown in Figure 2 does not compare the 1939 WCI to the SP 1945

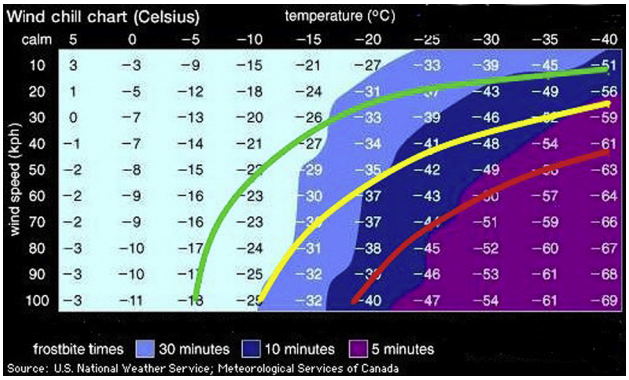


**Figure 2.** The middle range of Siple's 1939 wind-chill index chart isopleths has been placed as an overlay on a currently used 2001 wind-chill chart, adapted with permission from the US National Weather Service. The coordinates on the chart are temperatures and wind speeds. The digits are not temperatures but wind-chill equivalent temperatures. Shaded areas represent 30-, 10-, and 5-min frostbite warning zones. The overlying colored lines are 1939 wind-chill index isopleths of 150, 300, and 500 indicating the suitability of outdoor travel or temporary shelter as fair (green), comfort limit (yellow), or dangerous (red).

WCI or the old WCT chart but to a more accurate 2001 WCT chart currently in use. What is most remarkable about the overlay is that the middle range of Siple's original 1939 method, despite the obvious simplicity and limitations, closely parallels what is seen over 80 y later on the frostbite zones of the current WCT chart.

It does not take Antarctic-grade cold to feel or to be dangerously cold. Mountaineer-writer Frank Smythe advised with wit on the Himalayan peak Kangchenjunga: "In order to experience a really unpleasant form of cold, it is unnecessary to leave Great Britain."[32] Closer to sea level, British physiologist Griffith Pugh analyzed reports of hill-walkers who perished in hazardous conditions of wind, wetness, fatigue, and air temperatures as high as +10°C (+50°F).[33] Some of today's WCT charts start at that above-freezing ambient temperature where there is no frostbite but where wetness greatly contributes to heat loss and the risk of other cold injury and hypothermia.[1]

Siple's original 1939 WCI used below-freezing ambient temperatures and was a valuable guide in the dry cold and wind of Antarctica and elsewhere. The SP 1945 WCI was used for decades. There are other indices of thermal stress, such as the universal thermal climate index, that incorporate more parameters, but the WCI evolved into the 2001 WCT and continues as a commonly used cold weather guide that is popular with the public.[1,29,30] There are still concerns. For example, the more thermodynamically comprehensive 2001 WCT chart suggests the time for unprotected mid-cheek skin temperature to fall to a steady state with resultant risk of frostbite for the most

susceptible individuals.[1] Most people take less time than that to discern how cold it feels, but JAG/TI desired an objective endpoint in the 2001 WCT. Siple's modest original 1939 WCI did not give an immediate answer to the subjective question "How does it feel?" Instead, it gave valuable functional advice in a different way about the objective question "Is it safe to be outside?"

## Conclusions

This Lessons from History article has explored the environmental topic of the WCI first described by Paul Siple in his unpublished 1939 doctoral dissertation. Details of Siple's original WCI reveal his early insights and practical approach. Despite the obscurity, simplicity, or even naiveté of the 1939 work, an overlay of charts suggests that the 1939 WCI provides, in at least some of the range of conditions, a reasonably close approximation of the frostbite guidance of a current WCT chart. Siple's original idea has evolved and lives on as the 2001 WCT chart, but we think that in his own way and time, he may have been on the right track in the beginning.

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