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Report on Wind Chill Temperature and Extreme Heat Indices: Evaluation and Improvement Projects

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FEDERAL COORDINATOR
FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

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REPORT ON

WIND CHILL TEMPERATURE AND EXTREME HEAT INDICES: EVALUATION AND IMPROVEMENT PROJECTS

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FOREWORD

The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) is an interdepartmental office established under the Department of Commerce National Oceanic and Atmospheric Administration (NOAA) to ensure the effective use of United States (U.S.) federal meteorological resources by leading the systematic coordination of operational weather requirements, services, and supporting research among the federal agencies. Fifteen federal departments and agencies are currently engaged in meteorological activities and participate in the OFCM's coordination and cooperation infrastructure. In addition to providing a coordinating infrastructure, the OFCM prepares operations plans; conducts studies; responds to special needs, inquiries and investigations; and conducts forums to address national meteorological topics.

Over the last several years, numerous articles on the inaccuracy of the wind chill index were published in scientific journals, business journals, and newspapers. In response to convincing scientific evaluation, as well as public critique, of the current North American wind chill indices, NOAA's National Weather Service and Environment Canada's Meteorological Service of Canada decided to upgrade their wind chill indices and to evaluate the heat indices for possible improvement. They requested assistance in this endeavor from OFCM.

To that end, the OFCM interagency Committee for Environmental Services, Operations and Research Needs formed the Joint Action Group for Temperature Indices (JAG/TI) as the result of discussions on temperature indices at the American Meteorological Society's 12th Conference on Applied Climatology, May 8-11, 2000, and during the Environment Canada's Internet Workshop on Windchill, April 3-7, 2000, along with the recommendations and reports of known experts. The JAG/TI was charged with evaluating the existing temperature indices (wind chill and extreme heat) and determining if changes to the operational indices were required.

This OFCM report describes the U.S. and Canadian project to jointly evaluate NOAA's National Weather Service, Environment Canada's Meteorological Service of Canada and U.S. Department of Defense operational temperature indices, to work together on any upgrades and/or replacements, and to implement these changes as necessary.

Samuel P. Williamson
Federal Coordinator for Meteorological
Services and Supporting Research

EXECUTIVE SUMMARY

REPORT ON

WIND CHILL TEMPERATURE AND EXTREME HEAT INDICES: EVALUATION AND IMPROVEMENT PROJECTS

Introduction. Over the last several years, there have been many articles on the inaccuracy of the wind chill index which were published in scientific journals, business journals, and newspapers. Convincing scientific evaluation, as well as public critique, of the current United States (U.S.) and Canadian weather services' wind chill indices based on the 1945 Siple & Passel Index led to the services' decision that an upgrade of the indices was needed. As a result of increasing federal agencies' concern, the Office of the Federal Coordinator for Meteorological Services and Supporting Research's (OFCM) Committee for Environmental Services, Operations and Research Needs (C/ESORN) formed a special group during the summer of 2000 called the Joint Action Group for Temperature Indices (JAG/TI). The JAG/TI's purpose was to evaluate the existing wind chill and extreme heat formulas in light of recent knowledge, and determine if changes were needed. The goal of JAG/TI was to upgrade and standardize the indices used for determining temperature extremes, with the first task of the group focused on the current wind chill temperature indices. Standardization of indices among the meteorological community is important so an accurate and consistent measure is provided and the public safety is ensured.

The Chairperson of the JAG/TI was appointed from the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). The JAG/TI representatives and participants were from several U.S. federal agencies (U.S. Air Force (USAF), U.S. Army Corps of Engineers (USACE)/Engineer Research and Development Center (ERDC)/Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Research Institute for Environmental Medicine (USARIEM), Department of Energy (DOE), NOAA (NWS and the National Climatic Data Center (NCDC)), Federal Aviation Administration (FAA), Federal Highway Administration (FHWA), U.S. Department of Agriculture (USDA), and the Federal Emergency Management Agency (FEMA)), Canadian national ministries (Environment Canada (EC)/Meteorological Service of Canada (MSC) and Defence Research and Development Canada/Defence and Civil Institute of Environmental Medicine (DRDC, formerly DCIEM)), the academic research community (Indiana University-Purdue University in Indianapolis (IUPUI), University of Delaware, and University of Missouri), and the International Society of Biometeorology (ISB).

The Canadian ministries, the academic research community, and the ISB participants were included in the JAG/TI activities because of their involvement in the review of the wind chill models conducted via the EC and World Meteorological Organization sponsored Internet Workshop on Windchill, held the week of April 3, 2000. This workshop produced comments and discussions from experts and the public world-wide. The OFCM, NWS and other U.S. professionals also participated in the workshop.

Through a series of workshops held from October 2000 through November 2002 and email discussions, the JAG/TI reviewed research and public comments on wind chill indices, initiated a replacement wind chill index project, and implemented the results for the 2001-2002 winter season. The following is a summary of this work.

Overview of JAG/TI Work and Results. The review of the results of the EC/MSC Internet Workshop, current literature (Kessler 1993, 1995; Bluestein 1998; Quayle and Steadman 1998; Maarouf and Bitzos 2000; Osczevski 1995a,b and 2000a,b; Quayle et al. 2000), and invited presentations by subject experts led JAG/TI members to agree that the current NWS and MSC methods to determine wind chill overstated the effect of the wind, made people think it feels colder than it really is, and fooled the public into thinking they could withstand colder temperatures than reality. In addition, the review recommended revising the indices because they were too cold, especially at very cold temperatures and high wind speeds, and they did not apply well to situations of actual temperatures above freezing. A comparative study of several indices demonstrated that at least three other indices outperformed the current NWS and MSC indices, and that these other indices produced consistent results (Quayle et al. 2000). Noted problems with the NWS and MSC indices included: radiative and convective heat losses were not modeled separately, thermal resistance of the skin was ignored, the assumed skin temperature was too warm, and the wind speed used was measured at a height of 33 ft (10 m) instead of the average height of a human face (Santee et al. 1994; Schwerdt 1995; Bluestein 1998).

To correct these known problems, the JAG/TI members and participants agreed to have IUPUI and DRDC develop a new wind chill temperature (WCT) index (WCTI) based on their recently published new wind chill models. The new model used wind, air temperature, and solar radiation as the environmental factors in the wind chill formula and used the human face for evaluating wind chill impact since it is the part of the body most often exposed to severe winter weather. The JAG/TI also agreed to have human studies conducted at the DRDC facilities in Canada to help verify the new WCTI. Infrared and heat sensor measurements were used to measure the skin temperature of human subjects in various environmental conditions which may produce wind chill effects. The OFCM, CRREL and DRDC provided the funding for this research and development of the new wind chill index. Transition into the weather services' operations was accomplished with NWS and MSC existing resources. The human studies were completed in June 2001 and the results used to correct the preliminary WCTI algorithm. Solar radiation calculations and associated charts could not be completed by the MSC and NWS deadlines for transition and implementation for the winter season 2001/2002.

The completed WCTI algorithm and the results of the human studies were presented to the JAG/TI at the August 2-3, 2001, meeting at DRDC in Toronto, Canada. The group recommended the new WCTI for implementation by NWS, MSC and DOD. NWS and MSC agreed to and did implement it on November 1 and October 31, respectively, for the winter season of 2001-2002. DOD also agreed to implement beginning in November. These agencies also asked for threshold values for frostbite, which could be added to their web sites. During September and October 2001, DRDC continued their frostbite research, used the human studies' results to develop threshold values for "time to frostbite," and subsequently provided the data to the JAG/TI members to be included in the WCTI.

Specifically, the new WCTI:

- uses wind speed corrected to a height (5 ft or 1.5 m) that represents the height of an average adult's face;
- is based on a human face model;

- incorporates modern heat transfer theory (heat loss from the body to its surroundings, during cold and breezy/windy days);

- uses a walking speed of 3 mph (4.8 km h^{-1} or 1.3 m s^{-1});

- uses a consistent standard for skin tissue resistance; and

- assumes the worst case scenario for solar radiation (clear night sky).

<u>WCT Index Algorithms</u>. The initial iterative WCT algorithms were submitted to the NWS and MSC for transition into their central and forecasters' computers. Subsequently, the weather services asked for non-iterative equations that would best represent the final WCT data points since iterative procedures overwhelmed their forecasters' computers, and therefore, would have jeopardized operational implementation of the new WCTI. As a result, the researchers ran the model over 800 times with different combinations of wind speed and air temperature, and then performed a multiple regression analysis of the results. The following were the resulting algorithms:

In English units, $WCTI = 35.74 + 0.6215T - 35.75V^{0.16} + 0.4275TV^{0.16}$
where T is the air temperature in °F and V the wind speed in mph at 33 ft elevation.

In metric units, $WCTI = 13.12 + 0.6215T - 11.37V^{0.16} + 0.3965TV^{0.16}$
where T is the air temperature in °C and V the wind speed in km h^{-1} at 10 m elevation.

The equations use observed wind speed at 33 ft (10 m) to generate WCT corrected to the height of the face. For these equations, the wind speed at the level of the face in "calm" conditions is assumed to be the walking speed of 3 mph (4.8 km h^{-1} or 1.3 m s^{-1}). As a result, the WCT should equal the air temperature at this "calm" wind speed. These equations were used to prepare the WCTI charts. On the request of MSC and NWS, the charts were modified to identify wind chill temperatures that might be expected to produce frostbite on exposed skin in 30 min or less, in the most susceptible (95th percentile) of the population, and for a worst case scenario (night time clear). The resulting WCTI charts were given in degrees Fahrenheit (EF; NWS) and Celsius (EC; MSC) and were derived from the appropriate WCT equation. If the wind is measured at face level, the wind speed should be multiplied by 1.5 to use the equation or chart.

<u>Future</u>. It is expected that the new WCTI will be periodically reviewed and upgraded as science progresses. The following are several areas that will be pursued by JAG/TI. The JAG/TI agreed to delay incorporation of solar radiation effects to allow the researchers to finish determining the correct adjustments for solar radiation (i.e., the impact of sun) for a variety of conditions, including day time clear, day time cloudy, and night time cloudy. For the WCTI, research and development will continue for the solar radiation and frostbite models. Full analysis of the human studies will be used to refine the frostbite model. In addition, the marine spray part of the studies will be evaluated for possible application of the WCTI for maritime warnings.

JAG/TI will continue to focus on addressing standardization of the heat indices of both U.S. and Canada, moving towards a North American standard, and if possible, an international standard. This process will be in collaboration with a commission of international experts that were brought together by the International Society of Biometeorology (ISB) for the development of a Universal Thermal Climate Index (UTCI), known as ISB Commission 6 (ISB C6). Its purpose is to build on the EC/MSC Internet Workshop discussions and recommendations towards an internationally accepted UTCI. The JAG/TI members, EC/MSC, and U.S. academia, as well as other well respected experts on thermal indices and pertinent country representatives, are participating in the on-going ISB C6's meetings and discussions. ISB C6 has set a goal to produce a UTCI within two to three years.

ACKNOWLEDGMENTS

The Joint Action Group for Temperature Indices (JAG/TI) is a subgroup of the Committee for Environmental Services, Operations and Research Needs (C/ESORN), under the Office of the Federal Coordinator's Interdepartmental Committee for Meteorological Services and Supporting Research. In August 2000, this Group was charged with evaluating the existing temperature indices for wind chill and extreme heat. The group determined that changes to the indices were needed, and then coordinated and implemented a new Wind Chill Temperature Index (WCTI). The following scientists and engineers' contributions to the JAG/TI work are gratefully acknowledged:

- Ms. Esther Atkins, National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), Silver Spring, Maryland (former Chairperson, JAG/TI)
- Mr. Myron Berger, NOAA, NWS, Silver Spring, Maryland
- Dr. Maurice Bluestein, Purdue School of Engineering and Technology, Indiana University-Purdue University at Indianapolis, Indiana
- Dr. Michel Ducharme, Defence Research and Development Canada (DRDC) , Defence and Civil Institute of Environmental Medicine, Toronto, Ontario, Canada
- Ms. Katrina Frank, Center for Climatic Research, University of Delaware, Newark, Delaware
- Dr. Edwin Kessler, University of Oklahoma, Norman, Oklahoma
- Dr. Anthony Lupo, Department of Soil and Atmospheric Science, University of Missouri, Columbia, Missouri
- Mr. Abdel Maarouf, EC, MSC and Co-Chairman of the International Society of Biometeorology Commission 6, Toronto, Ontario, Canada
- Mr. Larry Nicodemus, NOAA, National Environmental Satellite, Data, and Information Service (NESDIS), National Climatic Data Center (NCDC), Asheville, North Carolina
- Mr. Ed O'Lenic, NOAA, NWS, National Centers for Environmental Prediction, Climate Prediction Center, Camp Springs, Maryland
- Mr. Randall Osczevski, DRDC, Toronto, Ontario, Canada
- Mr. Gary Phetteplace, U.S. Army Corps of Engineers Engineering Research and Development Center's Cold Regions Research and Engineering Lab (CRREL**),** Hanover, New Hampshire
- Mr. Robert Quayle, NOAA, NESDIS, NCDC (Retired), Asheville, North Carolina
- Mr. Richard Schwerdt, NOAA, NWS (Retired), Kansas City, Missouri
- Mr. Joseph Shaykewich, Environment Canada (EC), Meteorological Service of Canada (MSC), Toronto, Ontario, Canada
- Col. David Smarsh, Ph.D., U. S. Air Force Weather Liaison to NOAA, Washington, DC
- Ms. Jill Derby Watts, Center for Climatic Research, University of Delaware, Newark, Delaware

Funding for the development of the replacement WCTI was provided by DRDC, OFCM, and CRREL. NWS, DOD, and MSC used existing resources for implementation of this WCTI in their respective weather service operations.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

Table **Page**

CHAPTER 1

INTRODUCTION

1.1 Introduction. The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) and Environment Canada's (EC) Meteorological Service of Canada (MSC) issue forecasts, warnings and advisories for extreme temperatures that could affect public safety, as their primary concern is the protection of life and property. The United States (U.S.) Department of Defense (DOD) also issues warnings on extreme temperatures to the military community. The effects of extreme temperatures are increased by the interaction between temperature and other atmospheric parameters, such as wind and humidity. This interaction led to the development of equivalent temperature or thermal indices which represent the effect of various atmospheric parameters on temperature or energy levels. These indices are used by forecasters to determine when to advise the public on restricting their behavior or changing their activities. Two types of indices are used by the NWS, DOD and MSC: wind chill and extreme heat.

Over the last several years, numerous articles on the inaccuracy of the wind chill index were published in scientific journals, business journals, and newspapers. Convincing scientific evaluation of the current U.S. and Canadian weather services' wind chill indices led to the services' decision to first upgrade their wind chill indices and to evaluate the heat indices for possible improvement. The weather services requested assistance in this endeavor from the NOAA Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM).

This OFCM report describes the U.S. and Canadian project to jointly evaluate NWS, MSC and DOD operational temperature indices, to work together on any upgrades and/or replacements, and to implement these changes as necessary.

1.2 Definitions.

1.2.1 What is "Wind Chill"? One of the principal modes of heat transfer from an object is convection to the surrounding air. Convective heat transfer increases significantly with increasing air velocity. Thus a person is cooled at a faster rate under windy conditions than under calm conditions, given equal air temperature. Wind chill is a concept that relates the rate of heat loss from humans under windy conditions to an equivalent air temperature for calm conditions. The wind chill temperature (WCT) is an equivalent air temperature equal to the air temperature needed to produce the same cooling effect under calm conditions. Thus, it is not actually a temperature, but rather an index that helps relate the cooling effect of the wind to the air temperature under calm air conditions. It is important to remember that the wind will not cause an exposed object to become colder than the ambient air. Higher wind speeds will only cause the object to cool to the ambient temperature more quickly.

1.2.2 What is an Extreme Heat Event or Heat Wave? An extreme heat event or heat wave is a period of excessive daytime and nighttime heat in association with high humidity relative to geographic location and time of year. This definition would be coupled with the specific criteria in use (temperatures, humidity, duration, etc.) which may vary from location to location (Adams 1997).

1.3 Wind Chill Historical Background. The concept of a wind chill temperature was first quantified from experiments performed in 1941 by U.S. Army Major Paul Siple and geographer Charles Passel while wintering over in Antarctica. They measured the cooling rate of water in a container left hanging outside and developed a temperature index for wind chill based on this data. After the publication of their results (Siple and Passel 1945), the wind chill concept has enjoyed widespread use in describing the combined severity of wind and low air temperature on humans.

In 1973, NWS meteorologists began using WCT to describe human comfort level and, more significantly, to warn of the risk to human safety with regard to expected cold weather conditions. These wind chill forecasts and warnings were expressed in equivalent temperatures (EF). Shortly thereafter, MSC also began using the Siple and Passel Index by including wind chill information in their public weather forecasts as a cooling rate in watts per square meter (W m^{-2}). A table of WCT values was created as a public health tool to reduce the number of cases of hypothermia, frostbite, and other cold-related injuries. It warned people who had to be outdoors of the need to dress more warmly than the temperature alone might indicate.

In recent years, however, the index had come under increasing attack because it could promote the opposite result by leading people to believe that they have experienced more severe temperatures than they really have. During the 1990's, numerous researchers expressed concern about using Siple and Passel based indices for the human condition (Kessler 1993; Osczevski 1995a; Schwerdt 1995; Bluestein 1998; Quayle and Steadman 1998). Unlike simple containers of water, humans produce heat metabolically and conserve heat through vaso-constriction and with body fat and clothing. Not only were Siple and Passel's experiments conducted with wind speeds less than 26 mph (12 m s^{-1} or 42 km h^{-1}), but they fitted their data with a parabolic equation which gives a meaningless result when wind speeds are less than 4 mph (1.8 m s^{-1} or 6.4 km h^{-1}) and more than 55 mph (25 m s^{-1} or 88.5 km h^{-1}). During the last several years, there have been discussions about possible improvements to these wind chill indices and a general agreement has arisen that improvements should be made in this formula. As a result, a number of factors had to be studied before formulating a new one (Phetteplace and Mulhern 2001).

1.3.1 OFCM Committee for Environmental Services, Operations and Research Needs (C/ESORN). During the spring of 2000, the issues with the NWS operational wind chill index were brought to the attention of C/ESORN. At the April 4, 2000 meeting, C/ESORN requested a briefing by NWS on the status of their wind chill and extreme heat programs. The NWS manager for the temperature indices program presented an overview of the current NWS wind chill and extreme heat warning programs. Based on the scientific reports (Kessler 1993; Schwerdt 1995; Quayle and Steadman 1998) on the inaccuracies of the wind chill index, NWS was considering updating their operational wind chill index but had not decided how this would be accomplished. The NWS requested assistance in this endeavor from OFCM in obtaining cooperation from other agencies.

An invited expert, Dr. Edwin Kessler of the University of Oklahoma, provided his evaluation of the NWS temperature index for wind chill (Kessler 1993) at the C/ESORN meeting. First, it was felt that current indices had become a cultural phenomena, which were presented to the public with overreaction by the media, and perhaps the wind chill index was not serving the public as well as it could be. Second, four recent studies (Osczevski 1995a,b; Schwerdt 1995; Quayle and Steadman 1998; Bluestein and Zecher 1999) all agreed that the original study used to devise the wind chill index does not accurately portray the equivalent temperature resulting from wind chill effects on humans. The NWS wind chill index was based on an Antarctica experiment (Siple and Passel 1945) and appeared to give temperatures with errors 10 to 15 degrees Fahrenheit too cold. The NWS index was also used when the temperature is above freezing which can result in wind chill temperatures below freezing. Third, it was suggested that Canada and the U.S. use the same reporting framework. Canada also used the Siple and Passel index but reported in W m^{-2}. These values were then related to a table that gave a qualitative indicator of the wind chill effect on humans. The U.S. was using an equivalent temperature in ^{E}F, as did most of the media; even Canadian media converted the W m^{-2} to an equivalent temperature. In summary, it was recommended C/ESORN:

- scientifically revise the tables;
- unify U.S. and Canada procedures;
- provide no wind chill data above freezing;
- distribute the equivalent table of Apparent Temperatures (ATs) only to knowledgeable people, not to the public; and
- use text warnings and advice or a qualitative guidance on behavior and suitable clothing.

Recognizing a large meteorological community interest in apparent temperatures, the Committee recommended reaching a consensus on temperature indices, developing a path to update the indices as soon as possible, and obtaining agency support for this work. OFCM and NWS representatives participated in a panel discussion on the wind chill index at the American Meteorological Society (AMS) Conference on Applied Climatology, May 10, 2000. In addition, several C/ESORN meeting attendees also participated in the Internet Workshop on Wind Chill Index sponsored by EC. Information from the AMS panel recommendations and the Internet Workshop discussions were provided to C/ESORN, which were reviewed and discussed. The resulting action was the formation of the Joint Action Group for Temperature Indices (JAG/TI).

1.3.2 Overview: EC Internet Workshop on Windchill and International Society of Biometeorology (ISB) Commission 6. The Internet Workshop attempted to address four questions regarding temperature indices: 1) how much meteorology should be incorporated, 2) what units should be used, 3) how should the indices be harmonized, and 4) how should wind chill values be communicated to the public. These were not resolved at the workshop because of the numerous diverging views by the experts. It was felt that the work was unfinished but more progress could be made on completing the work with additional coordination (Maarouf and Goessl 2001). A direct result of this workshop was the formation of the ISB Commission for the development of a Universal Thermal Climate Index (UTCI), known as ISB Commission 6 (ISB C6), in July 2000. The ISB C6 membership consists of international experts, many of which participated in the EC Internet Workshop. This Commission is endorsed by the World Meteorological Organization (WMO), under the umbrella of the WMO-ISB collaborative Memorandum of Understanding to address the concept of developing and employing an internationally accepted UTCI. The Commission was also seeking the collaboration of the World Health Organization (WHO). This UTCI would apply to the full spectrum of temperatures, from extreme cold to extreme heat. Both the U.S. and Canada are members of this Commission and the JAG/TI. Development of a single

UTCI is the Commission's goal but the Commission recognizes the need for more than one index, depending upon local circumstances. The rationale for one global index will be carefully examined since not all scientists or governments are likely to see the benefit of a standardized index as opposed to their own preferred and local practices.

1.3.3 Overview: Wind Chill Panel, AMS 12th Conference on Applied Climatology, May 10, 2000. The panel discussion on wind chill temperatures at the AMS Conference on Applied Climatology included presentations by known experts and developers of temperature indices. Graphical comparisons of the various indices were presented which clearly pointed out that the Siple and Passel index was noticeably colder than all the other indices. The overall consensus of the AMS panel was that the current operational Siple and Passel based indices should be revised because they generate values that are too cold, especially at cold temperatures and high wind speeds, and do not apply to temperatures above the freezing level.

1.4 Joint Action Group for Temperature Indices (JAG/TI). Based on the results of the AMS Conference and the EC Internet Workshop, the C/ESORN formed the JAG/TI to continue the indices discussions, evaluate the existing wind chill formulas, and determine if changes were needed.

1.4.1 Purpose. The purpose of the JAG/TI is to promote cooperation among federal agencies sharing interest in and responsibility for current and programmed activities affected by apparent temperatures, to evaluate the existing equivalent/apparent temperature indices for wind chill and extreme heat, to determine if changes to the indices were needed, and to recommend changes to more effectively represent apparent temperatures resulting from a combination or interaction of cold or heat and other atmospheric effects such as wind and humidity. Specifically, the JAG/TI was tasked with: (1) the responsibility for planning and executing strategies and projects to address deficiencies, (2) coordinating a thorough scientific review of research, practices, and procedures pertaining to the use or development of temperature indices, and (3) coordinating any changes to the official Wind Chill Index, Heat Index or other indices. The goal of the JAG/TI was to upgrade and standardize internationally, or at least standardize between the U.S. and Canada, the indices used for determining temperature extremes.

1.4.2 JAG/TI Membership and Participants. The JAG/TI membership and participation was formed with representatives from several U.S. federal agencies (U.S. Air Force (USAF), U.S. Army Corps of Engineers (USACE)/Engineer Research and Development Center (ERDC)/Cold Regions Research and Engineering Laboratory (CRREL), U.S. Army Research Institute for Environmental Medicine (USARIEM), Department of Energy (DOE), NOAA (NWS and the National Climatic Data Center (NCDC)), Federal Aviation Administration (FAA), Federal Highway Administration (FHWA), U.S. Department of Agriculture (USDA), and the Federal Emergency Management Agency (FEMA)), Canadian national ministries (Environment Canada (EC)/Meteorological Service of Canada (MSC) and Defence Research and Development Canada/Defence and Civil Institute of Environmental Medicine (DRDC, formerly DCIEM)), the academic research community (Indiana University-Purdue University in Indianapolis (IUPUI), University of Delaware, and University of Missouri), and the International Society of Biometeorology (ISB).

CHAPTER 2

SCIENCE REVIEW AND RECOMMENDATIONS

2.1 Introduction. The JAG/TI members agreed to address both the wind chill and heat indices and to evaluate them through workshops, email discussions, and solicitation of recommendations from outside the committee. Five workshops and meetings were held from October 2000 through November 2002. The first workshop was devoted to discussions on the wind chill index, the second devoted to status of the WCTI project and discussions on the heat indices, the third devoted to the review of the human studies and to the finalization of the WCTI, and the fourth a review of the solar radiation calculation and continuation of science review of heat indices. The fifth meeting was held to review further development and/or improvement to the WCTI, and to review possible heat index changes. This chapter presents a summary of the JAG/TI science review, a brief summary of operational programs in the U.S. and Canada, and recommendations and guidance towards the development of a new wind chill temperature and heat index.

2.2 Science Review. The first task of the JAG/TI was to review the results of the EC Internet Workshop, scientific reports and papers on various operational and research indices, the AMS Panel on evaluation of wind chill temperature indices, the results of the 1996 NOAA Heat Wave Workshop, reports on the development of a relative heat factor, and current temperature indices in operations. Descriptions of other indices from European countries and Australia were examined but the group found that it was difficult to directly compare programs outside of the U.S. and Canada to the United States. These differences result in the underlying science in the models. The Europeans work focuses on models which included a complete heat budget, whereas others (e.g., U.S. and Canada) uses simple "facial cooling" models which could provide adequate warning of the effects of wind chill. One possibility was to have two complementary indices: one index based on the properties of the environment and the second follow-on index that tied the temperature to what one should wear using the first equation as input. The group decided to press ahead with the review, summarize the desired indices characteristics, and then analyze the most promising indices as to how they meet these characteristics. This review is presented below.

2.2.1 Summary of EC Internet Workshop on Windchill. The Internet Workshop on Windchill was conducted April 3-7, 2000 and was hosted by the MSC (Maarouf and Goessl 2001). There were six sessions held producing comments and discussions from experts and the public around the world (Windchill Science, Windchill Indices, Current Reporting of Windchill, Communication Issues, International Collaboration, and a last day Panel Discussion). The workshop objectives were to review the science, evaluate the usefulness of the index, discuss the most accurate and acceptable ways of disseminating information and warnings, and to develop recommendations for rigorous experimental research including international harmonization and standards. During this activity, numerous recommendations to upgrade or replace the current commonly used Wind Chill Index were made because this Index tended to be at least 10 degrees Fahrenheit too cold and was used inappropriately for temperatures above freezing. EC determined that the way to move forward was to collaborate with efforts for the adoption of an international program, focus on terminology in the short term, implement program changes in an internationally consistent way, and educate their public on any changes to the existing program.

2.2.2 Osczevski Index. The Osczevski model (Osczevski 1995a,b; Osczevski 2000a,b) is based on facial cooling and was developed at DRDC. DRDC is Canada's center of expertise for research and development in human performance and protection, human-systems integration and operational medicine. The Osczevski wind chill index incorporates the environmental parameters of air temperature, wind, and a solar radiation correction, with heat transfer theory, human comfort and risk of frostbite. DRDC conducted experiments at the testing facilities to determine whether wind chill was a whole body experience or a local cooling effect or a combination. The theory was that cooling was mostly felt on the facial area. For example, if you open an umbrella and shade your face you will feel colder than without the umbrella. One of the devices used to evaluate this theory was a Thermal Manikin Head (TMH) which is a computer-controlled, multi-zone device built to assess the thermal insulation of headgear. Using this device, one can break down the loss of heat from four separate zones (face, crown, back of head, and narrow zone at the contact point of hats). Future development will add a zone for the center of face where most frostbite occurs. The DRDC's testing facilities includes climatic chambers in which clinical trials with the TMH and volunteers are conducted.

2.2.3 Siple and Passel Index. Siple and Passel (1945) conducted an experiment in Antarctica. The data obtained was used to develop their index. The equipment used consisted of water-filled plastic cylinders which were exposed to the cold wind of Antarctica at various temperatures. Siple and Passel recorded the time to freeze the water over a range of temperatures from -9ºC (15.8EF) to -56ºC (-68.8EF) and wind speeds from calm to 43.2 km h^{-1} (12 m s^{-1} or 26.8 mph). The experimental data were scattered, some of the most distant observations were subjectively thrown out, and the best fit line (parabolic) was applied to the remaining data. The extremes of wind were not accounted for or included in the chart. If they were included, the fitted line wouldn't make sense after 50 mph (80.5 km h^{-1} or 22.3 m s^{-1}), since it would imply that the wind chill decreases above 50 mph. Their graph calls the best fit line the cooling rate, but it was really the heat transfer co-efficient. The index was not intended nor should it have been extrapolated beyond a 50 mph wind or Siple's experimental observations. In spite of all this, the index has served the community quite well by getting the public to protect oneself in cold and windy conditions (Maarouf and Bitzos 2000).

2.2.4 Bluestein and Zecher Index. Bluestein and Zecher (1999) developed a new wind chill index based on the Siple and Passel Index. They found that Siple and Passel had not taken into account the resistance of the container used in their experiments. This addition dramatically changed the results of Siple and Passel Index temperatures. It appears that their index had also exaggerated the effect of heat transfer. The new index used a mathematical approach for a full adult head model, with heat loss from the exposed surfaces and temperature and wind considered as the environmental factors. Solar radiation and the effect of light winds on heat transfer from the upwind side of a cylinder were not considered.

2.2.5 Perceived Temperature and the Physiological Equivalent Temperature Indices. Two other indices developed by German scientists were reviewed. Both of these indices incorporated a heat budget model of a standard or average human body to calculate equivalent or perceived temperatures to express thermal comfort. The Perceived Temperature (PT) index

(Jendritzky et al. 2000) is a comfort climate index based on a reference environment related to the public's perception of heat or cold. The Physiological Equivalent Temperature (PET) (Hoeppe 1999) based the calculations of comfort on how indoor temperatures are perceived and the wearing of office work clothes. It enables the public to compare the integral effects of complex thermal conditions outside with their experience indoors. Both models take into account all variables of the thermal environment in a physiological relevant way.

2.2.6 Steadman's Climate Index. The Steadman climate index (Steadman 1994) is a fully clothed body model that accounts for effects of temperature, wind, radiative heat, and relative humidity. The main advantage for the U.S. using the Steadman's index would be that the NWS already uses a modified Steadman's index (which only accounts for temperature and humidity). This would allow the blending together of both heat and cold indices. At the time of the first JAG/TI workshop there was some concern that the algorithms for the Steadman's index were not available since the NWS derived their modified Steadman index from plotting the values and applying a regression analysis to the data (Rothfusz 1990). Subsequently, it was learned that the algorithms could be provided. This would allow more standard atmospheric variables to be included in the future.

2.2.7 Comments and Information From University of Missouri-Columbia. Comments were provided by Dr. Anthony Lupo, University of Missouri-Columbia. Several points were made regarding the development and implementation of a new WCTI. First, more complex models could be used with the advancement of computers. Second, the Steadman model had a few advantages over other indices: more comprehensive, compatible with the current NWS heat index, and it could be easily programmed into existing computer models. Third, base the index on standard bare skin due to the complexities of approximating a clothed model. Also, the whole body should be considered or approximated. Fourth, continue the current NWS practice of warning on extremes because it gets people's attention easier and of using an equivalent or apparent temperature. Fifth and last, continue research in both physiology of human response and in the communication aspects of a thermal environment.

2.2.8 Comparative Study. Quayle et al. (2000) has presented a comparative review of the most common, environmentally based, wind chill indices (Steadman Climate Index, the Bluestein and Zecher Index, the Osczevski (1995b) Index, and the Siple and Passel Index as used by NWS (Rothfusz 1990)). The review demonstrated that the first three indices' values were similar and that all three outperformed the NWS operational index (see Fig. 2-1). The differences between Osczevski's and Bluestein and Zecher's indices were the amount of exposed body part, the inclusion of solar radiation, and how the still conditions are handled. Osczevski's index was a full face model, used a standard person's walking pace for still conditions, and included a set value for radiation, while Bluestein and Zecher's index was a full head model with no solar radiation considered and with still winds equal to 4 mph (6.4 km h^{-1} or 1.8 m s^{-1}). Bluestein and Zecher's model tended to be slightly colder than Osczevski's model, which appeared to be related to solar radiation considerations and the handling of still conditions. Osczevski and other models originally used a wind speed in still conditions set at 4 mph because the standard cup anemometer stopped at this speed and most people tend to be in motion when outside. Steadman's model used a whole body model represented by a cylinder, added more environmental variables, and incorporated clothing assumptions.

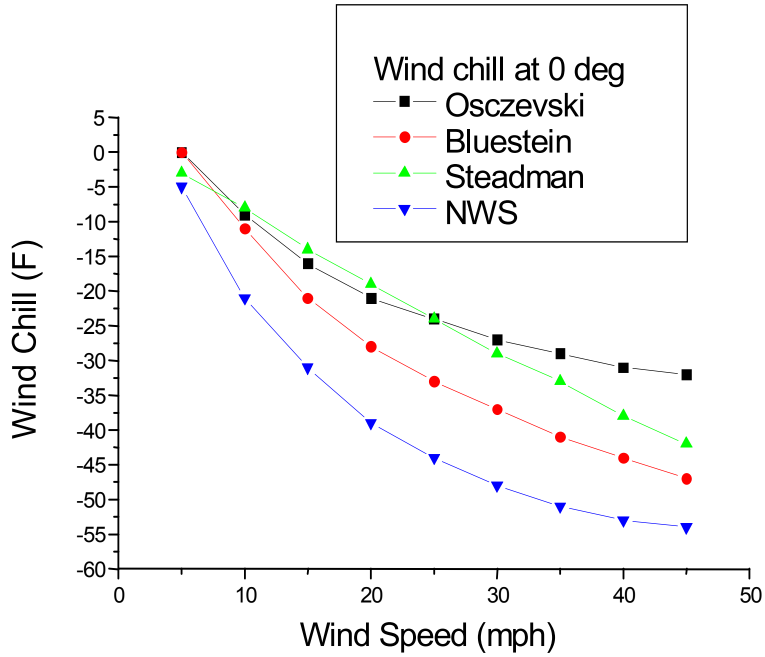

Figure 2-1. The figure shows the differences in the various wind chill equivalent formulations at an air temperature of 0EF (adapted from Quayle et al. 2000).

2.2.9 Comments on upgrading the NWS wind chill program. Schwerdt (1995) evaluated wind chill variations by latitude and region, and on occurrence of frostbite. The report brought out the need to look at injuries occurring outdoors resulting from cold weather and the relation between injury rate and wind chill. Two concerns were discussed: 1) there were no specific NWS standards governing the relation between the onset of frostbite and wind chill, only guidelines for when wind chill is dangerous, and 2) the NWS wind chill index and guidelines needed improvement (NWS 1992). Schwerdt also reported on early 1970's Russian experiments conducted by Adamenko and Khairullin (1972). These were conducted on unprotected human skin under various combinations of wind speed and air temperature, and showed that frostbite can occur at about -10EF (-23.3EC) with wind chill, that acclimation to climate did not change the threshold for frostbite occurrence, and that the higher the wind speed, the faster the skin will freeze with only wind speed varying and no accounting for sunny weather. As a general rule, based on user feedback through the years and the Russian research, the accepted NWS threshold for potentially dangerous wind chill conditions was a wind chill of about -20EF (-28.8EC). This appeared to be a reasonable value overall for the issuance of wind chill warnings, as long as one realized that more positive wind chill values could still cause frostbite on exposed body parts.

2.2.10 U.S. Army Overviews of Temperature Related Research. The U.S. military uses wind chill to provide specific guidance for various cold weather activities. The sources for these guidelines are often undocumented, and may be derived from unofficial, experience-based sources. One example is an Individual Safety Card, GTA 5-8-12 (USA 1999) which included both heat and cold guidance based on indices. The incorporation of this wind chill information into military doctrine made transition to a new wind chill index more difficult and emphasized the need for widespread and frequent public education efforts.

2.2.10.1 U.S. Army Corps of Engineers/Engineering Research and Development Center (ERDC)/Cold Regions Research and Engineering Lab (CRREL). The CRREL was interested in the JAG/TI work as it related to developing cold weather performance factors for soldiers which could be used in models and simulations. DOD was required to run simulations on how material will perform in various environments. CRREL tried to put more human factors into the simulations as decisions were made based on the results of the simulations. This was important because the losses in cold situations outnumber the losses to the enemy. Objective force concepts were dependent on light equipment but soldiers were more susceptible to cold than equipment. The impacts of cold consisted of limited manual dexterity and task efficiency, diminished cognitive functions, and emotional changes. The key was to relate environmental state to body state using heat balance equations. Several historical examples support this idea. Napoleon's army lost two-thirds of its soldiers in the Russian campaign due, in part, to the cold. During the Russian/Finnish conflict, the Russian army was hurt because of the cold. In World War II, Germany invaded Russia but became bogged down and extensively weakened by the winter cold. CRREL has a simplified model which could use the human studies data from DRDC for a benchmark.

2.2.10.2 U.S. Army Research Institute of Environmental Medicine (USARIEM)/ Biophysics and Biomedical Modeling Division. USARIEM interests in the JAG/TI work involve the integration of weather into modeling efforts. USARIEM research areas include the environment, physiology and medicine (hot and cold, complex models, altitude, clothing/biophysics, solar radiation input, and predictive modeling), and occupational health and performance (soldier performance, injury, biomechanics, nutrition, and animal studies). The two USARIEM groups with programs most relevant to weather index issues were the Biophysics and Biomedical Modeling Division (biometeorology, clothing and modeling) and the Thermal and Mountain Medicine Division (heat and cold physiological effects).

Military models were developed for military populations who must conduct operations while exposed to extreme heat or cold conditions. There was a need within the military for models that go beyond heat indices to take into consideration solar radiation input, acclimatization, body size, activity roles, and clothing to predict thermal state. A Heat Strain Decision Aid was developed using complex physiological models to provide guidance for a narrowly focused population. Model outputs included the change in core temperature, maximum exposure time and an optimal work-rest cycle for minimizing heat casualties. Some of the modeling methods applications were linked with a miniature environmental sensor suite to produce a hand-held Heat Stress Monitor. Another product was the MERCURY program that combines heat and cold models and weather data from a grid to predict soldier thermal status, and display it graphically. The Warfighter Physiological Status Monitoring was an entirely different approach that utilizes up to 16 independent sensors to monitor soldier physiological status in real time. Other equipment or facilities available at USARIEM included copper manikins, sectional hand and foot models for measuring clothing insulation, an immersion pool, and weather instrumentation to measure solar radiation.

2.2.11 NWS National Centers for Environmental Prediction (NCEP), Climate Prediction Center's (CPC) Excessive Heat Index and Forecast. A new NWS heat index and forecast product was implemented in June 2000. It was originally designed to give the likelihood for occurrence of a heat wave (defined as three hot days out of five with a daily average heat index of 85EF (29.4EC). The heat index is a simple regression model based on the warm end of the Steadman apparent temperature scale and uses temperature and humidity observations. As a starting point, CPC decided to use the 500 hPa height and 850 hPa temperature forecasts as predictors in the excessive heat forecast model. CPC has skill in forecasting 500 hPa heights and 850 hPa temperatures in the 6 to 10 day time frame and some skill in the 8 to 14 day time frame. In addition, the Medium Range Forecast (MRF) model ensembles, consisting of 20 runs or members of the model, are also heavily used in the regression model. The ensemble member results are combined to produce a smooth mean field. The biggest flaw of ensembles appears to be the result of excess smoothing which reduced the amplitude of the response. The regression model did reasonably well on predicting the phase of an event and CPC was able to follow most events, although the amplitudes were insufficient. The Texas heat wave of 2000 was not well captured because it was mainly a surface event with the drought and lack of soil moisture enhancing the heat wave effects. CPC has a soil moisture data set to train the model, and the future intent will be to improve the model with this training set by adding soil moisture as a predictor. In addition, there were some persistent biases that showed up in the MRF which were corrected by the addition of a Kalman filter. The main CPC product sent to the WFOs has been the probability field of a heat wave occurring in the 6 to 10 day window, which gave a forecast of the highest expected heat wave. This product appeared to be difficult for the public and some meteorologists to understand and to relate to the physical world. Another more user-friendly product on CPC's web site was obtained from contouring the probability product to show a maximum value of the heat index product. This was depicted on a U.S. chart as apparent temperatures and shaded. Individual stations could be selected to get temperature values, observations and climate values. Directly distributed to WFOs, the U.S. Threats Assessment depicted potential threats as highlighted areas on U.S. maps and included heat waves. These forecasts were prepared every day with the weekend product fully automatic and the remainder of the week the forecasts had human intervention. These heat index products were discontinued in mid-fall 2000, and CPC worked over the winter to improve them based on the information and data collected during the summer of 2000. These products are now regularly procuded by CPC daily from May through September.

2.2.12 Development of a Universal Relative Comfort Index. At the University of Delaware with funding from NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) National Climatic Data Center (NCDC), several graduate students are working on a relative comfort index, where relative relates to accounting for different locations. The work is based on the Weather Stress Index (WSI) developed by Kalkstein and Valimont (1986) where apparent temperature varied from mean apparent temperature and was adapted to regional applications. The new relative comfort index is based on Steadman's Apparent Temperature (AT)

Index, regional temperature means, and prolonged exposure or consecutive day effect. It represents the percent difference from the mean conditions. The imbedded heat index uses Steadman's updated algorithms (Steadman 1999) for this project. A daily stress value is calculated. The model uses U.S. Surface Airways reports which have wind speed, temperature, dew point temperature, and information to calculate solar radiation. This comfort index incorporates: consecutive day effect, maximum and minimum AT, mean cloud cover (10 a.m. to 6 p.m.), cooling degree days, and 30 years of data at 240 first order stations. This research is focused on the summer/high heat application to various locations. A winter side will be worked on later and will represent the opposite end of the index. Possible applications are for the NCDC climate atlas, public health initiatives, and problems related to animal stress.

At the first workshop, Ms. Jill Derby Watts (University of Delaware) presented an overview of her Master's thesis work on developing a new relative comfort index (Watts and Kalkstein 2002). The WSI used 40 years of data, the results were smoothed, and the real-time data was compared to the mean temperature. The relative results were presented as a percent of real-time temperature compared to the mean temperature. Comparative evaluations of the WSI's summer and winter algorithms, Steadman's outdoors and with sun (year around) algorithm, and the current NWS index have been completed. Comparisons showed the NWS index had noticeably different results from the rest of the indices. For instance, NWS did not appear to handle the situation well when cold temperatures existed and/or when the wind was calm. All the results appeared to agree during the afternoon in the summer. The new relative index will include using a daily mean relative stress value to account for several hours of exposure/day, which will cause an adverse effect. This should help account for consecutive days impact on regular human health. Incorporation of the cooling degree-day aspect was also done since the amount of cloud cover impacts both day and night temperatures. Possible applications for this work include the development of a U.S. comfort index climatology which could be presented as a climate atlas and would have values for all first order weather stations across the United States. It would account for means, variances, and temporal and spatial differences. Another area the index could be used for was within the public health sector as implementation information for health warnings and advisories.

2.2.12.1 Effects of Temperature on Livestock. During the second workshop, Ms. Katrina Frank reported on another aspect of this research effort at the University of Delaware. Her graduate study was looking at the effects of extreme temperatures on livestock production. Live stock managers and agricultural experts noted that animal food intake was affected by extremes of heat and cold. The relationship between air temperature and livestock production was well established. There was a zone where the animals were comfortable and thresholds where production began to decline. This can be quantified because the animals will not produce as much milk or eggs and their eating patterns change when the environment changes. Temperature, relative humidity, wind, number of consecutive days, available shade, and precipitation were taken into account when determining how much food would be eaten and converted to growth or production by animals. For instance, at -10EF (-23.3EC) ranchers needed to add 7 to 8 lbs (3.2-3.6 kg) of hay per cow and 4 to 5 lbs (1.8-2.3 kg) of grain per cow to fill their energy needs to maintain body weight. If the threshold was wrongly predicted, there would be either feed consumed when not needed resulting in additional costs or not enough feed resulting in weight loss or decrease in production of milk or eggs. Both would result in decreased profits for the owner. To limit feed waste, the rancher needed to decrease the amount of feed because the cattle eat less during extreme heat conditions and increase feed during extreme cold conditions to maintain cattle weight. Another aspect considered was the animals' hair or feathers which can provide insolation. The condition of the cow's hair needed to be evaluated, which was also a function of exposure to the environment, especially wind and precipitation. In general, state agriculture departments develop food intake tables that use the NWS wind chill and heat index output, a percentage adjustment for the environment, and adjustments for hair condition to determine the recommended food amount per day for animals such as cows. The project was based on developing a comprehensive means to accommodate all the factors in a table or index that is easily applied by the livestock manager. Another reason that livestock managers needed to know the temperature extremes would be for the transport of animals, where one was more concerned about mortality issues.

2.2.13 NOAA Heat Wave Workshop, September 18-19, 1996. The JAG/TI reviewed the action items and proceedings from the NOAA Heat Wave Workshop of September 18-19, 1996 (Adams 1997). The workshop was held as a result of the Chicago heat wave and was co-sponsored by the CDC and the EPA. One of the purposes of this workshop was to discuss what had occurred during the 1995 Chicago heat wave, which killed 465 people, and to outline steps to help prevent that type of high mortality from occurring in future heat waves. This included developing a better warning system for heat waves; suggesting state and local intervention programs, such as the provision of shelters and assistance to the elderly and others by health officials and emergency managers; and meteorologists, health professionals, and others conducting research into identifying the pertinent environment, medical and social factors. As a result of the workshop, NWS has loosened operational application of weather service procedures, developed local criteria for the WFOs, and produced some informational brochures on extreme heat safety. The overall policy recommendations have not been accomplished, including the establishment of a task force. One encouraging aspect is the reorganization of NWS Headquarters, which resulted in more personnel to address this program and other types of policy issues. The new CPC product is in partial answer to the research recommendations (see section 2.3.3.1). Funding was still being sought for the recommended comparison work that University of Delaware and the NWS wanted to conduct. The changing or updating of the NWS heat index was not a part of this workshop's discussions. The workshop focus was on improving the types of public warnings and public response. The JAG/TI Canadian participants pointed out that there were no Canadian cities that suffered a heat wave at the same time as Chicago. The biggest difference between Chicago and nearby Canadian cities was the nighttime cooling in the Canadian cities that was not experienced in Chicago.

2.3 Descriptions of NWS and MSC Operational Programs.

2.3.1 NWS Wind Chill Program. Prior to November 2001, the NWS index was based on the work of Siple and Passel who conducted heat loss rate research in the Antarctic immediately prior to World War II (Siple and Passel 1945). As a result of their research, Siple and Passel developed the basic empirical formula used for determining the wind chill index. In 1973, the NWS adopted this formula to produce a wind chill index for alerting the public of possible hazardous conditions. This index used the rate of body cooling based on cooling of water, did not account for sun or the lack thereof, and used the wind velocity at 10 m (33 ft) height. The NWS basic policy for producing wind chill warnings and advisories was described in their Operations Manual (NWS 1992) under Winter Weather Warnings Chapter C-42. Current NWS policy on wind chill products can be found at the following web site: http://www.nws.noaa.gov/directives. It provided the worst case criteria for wind chill warnings and referred to Regional NWS Operations Manuals for specifics of how the program is implemented in the field. Each NWS Region established a modified set of criteria for warnings based on regional and local consideration.

Wind chill warnings and advisories were used to alert the public of dangerous or life-threatening wind chill conditions. A Wind Chill Warning was issued when WCTs become life threatening. A Wind Chill Advisory was issued when WCTs become dangerous and, if caution is not exercised, could lead to life-threatening situations. Issuance criteria of Wind Chill Warnings and Wind Chill Advisories were locally defined.

2.3.2 MSC Windchill Program. The Canadian Windchill Index was also based on the Siple and Passel (1945) Index. The wind chill program was established in the late 1970's. The index values were reported in units of W m^{-2}. Using this Index, MSC produced forecasts and issued warnings on wind chill dangers. Their warning criteria also varied by region.

With Canadian Ministerial commitment to review the wind chill program, EC's objective was to reconcile clients' needs for information with the science. MSC decided to review the basic science on wind chill temperature determination and to communicate with the public through a public opinion survey. This survey showed how the public used the information and what were their concerns. This review was compiled and published by MSC before the Internet Workshop (Maarouf and Bitzos 2000). MSC determined that the science information would be obtained by doing a literature review, a science assessment, physiological assessment, working groups, and workshops. MSC was unable to do clinical tests because funds were not yet available. National and MSC working groups were formed to work on the review of science. As mentioned earlier, the MSC sponsored a one week Internet Workshop on Windchill in April 2000 that was very successful. The workshop continued the review of the science, evaluated the usefulness of the index, discussed the most accurate and acceptable ways of disseminating information and warnings, and worked towards recommendations for rigorous experimental research and international harmonization and standards. Progress on these recommendations were constrained by budgetary restrictions, cross-border compatibility concerns, and the formation of a special commission to look at the issues of thermal indices. MSC determined the way to move forward was to collaborate with efforts for the adoption of a renewed international program, focus on terminology in the short term, and implement program changes in an internationally consistent way.

2.3.3 Excessive Heat Programs. The heat wave that Chicago experienced in 1995 resulted in more than 400 human deaths (Adams 1997). Although there did not appear to be any major problems identified with the present heat indices in U.S. or Canada, these two North American indices do not result in the same values for the same conditions, which is confusing for the public. In addition, the NWS WFOs have identified wind as a parameter that makes a difference, and therefore, should be an additional factor in determining the AT during extreme heat instances. Another major reason for upgrading the heat index would be to replace old technology with better scientifically based equations that used more of the known affecting parameters. Public pressure to upgrade the heat index is not prevelant at this time, but could occur if there was another severe heat wave episode like the 1995 heat wave in Chicago. This situation allows for the slow movement on updating the heat index to ensure that a better, improved index would be adopted.

2.3.3.1 NWS Program. NWS issues outlooks, watches and warnings using a version of Steadman's index (Steadman 1979a,b), represented as a table called the NWS Heat Index. The last incorporated update to this table and to the NWS operational program was in 1992. NWS WFOs' computers use a NWS derived regression algorithm (Rothfusz 1990) to approximate the table. The derived algorithm appears to be unstable at the lower end and it doesn't take into account the number of days that the excessive heat existed, cool nighttime temperatures, and regional acclimation. A table on the NWS web site describes the NWS Heat Index. In the NWS Operations Manual, there are descriptions of the effects of extreme heat, effects of humidity and the minimum criteria for issuing advisories and warnings. An Advisory is issued when the daytime high AT reaches 105EF (40.6EC) or above with nighttime lows at or above 80EF (26.7EC). A Warning is issued under extreme conditions, exceeding those conditions for an advisory. The specific values or thresholds are determined by the NWS Regional Headquarters. Two NWS regions do not issue advisories and warnings: Pacific and Alaska Regions. Eastern, Southern, Western and Central Regions issue advisories and warnings, and each Region sets regional criteria to accommodate any adjustments. These criteria are used by the WFOs to decide whether or not to issue a heat advisory.

The NWS extreme heat forecast guidance product was first officially issued during the summer of 2000 by the CPC. It was developed from a training set of observed data, a linear regression fit of 500 hPa heights and 850 hPa temperature fields, and approximated algorithms of the NWS Heat Index (modified Steadman's Apparent Temperature Index). This was combined with NCEP's MRF model and the MRF ensemble model output to produce a prediction of apparent temperatures. CPC found the following problems with the product: the MRF ensembles were not very good at forecasting extremes (tends to under forecast), the training data were not good or complete (needs soil moisture), and the linear regression fit was unstable. CPC added soil moisture, replaced the regression fit with the use of 1000-500 mb thickness, 1000-850 hPa thickness, and 1000 hPa height fields, used Steadman's Index table instead of approximate algorithms, and improved the look of the products by the 2001 summer season.

2.3.3.2 MSC's Humidex. The Canadian heat index, Humidex, has been used for about 22 years. Humidex uses temperature and relative humidity to determine how hot the weather feels to any person. The reports are in degrees Celsius and considered significant if the temperature are greater than 30EC (86EF) and the Humidex value is greater than 40EC (104EF). In addition, a scale of discomfort splits the Humidex from 29º to 54ºC (84.2 to 129.2EF) into several discomfort levels. In general, the Humidex values tend to be higher than the U.S.' heat index values, except at the extreme end, where they tended to be slightly lower. Excessive heat advisories are issued by the MSC in only two provinces, Ontario and Quebec.

2.4 Science Review Results. After reviewing the NWS operational requirements, the JAG/TI members determined that the federal government's responsibility was to address temperature extremes and safety, not necessarily what clothing the public should wear or for public comfort.

2.4.1 WCTI. The most important function of a wind chill program was to address safety and cover the most extreme situations (bare skin). Comfort factors could also be considered, but as a secondary function. This led to a wind chill index that would be based on environmental factors as the prime scientific input to the index algorithm. The results of the comparison studies led the JAG/TI members to agree that the NWS Wind Chill Index produced wind chill temperatures that were too cold, creating a false sense of actual air temperatures in nearly windless conditions by the public. The JAG/TI members and participants agreed that a new WCTI should be science-based by addressing proper heat transfer aspects, including appropriate environmental parameters, and be easily explainable to the public. This has been accomplished in many of the existing indices, including Osczevski, Bluestein and Zecher, the PT, and the PET indices. Although more comprehensive by taking into account many more environmental factors, Steadman's model included varying aspects of how one is clothed and used a full average body model, which added complexity to the model. Osczevski's and Bluestein and Zecher's indices both use a bare skin model while the other models use a standard clothed human body model. For the comfort factor, the PT and PET models might work, if clothing amounts were precisely defined and could vary, and other parameters were easily turned on and off. These physiological models assume an average or standard body. This could cause a problem resulting from the physiology of a body, since it changes from person to person and depends on size, shape, weight, circulation factors, etc. On the other hand, the JAG/TI decided that a face didn't vary much from one individual to the next and was a sensitive "instrument" that would normally be exposed, with the most cold felt on the face. With the use of the face model, one didn't have to account for clothing nor need to define a "standard" human. Other threshold temperatures, including those above freezing, were also considered important. Some temperatures were used to determine when to open homeless shelters because of concerns about hypothermia (e.g. Tampa, FL used a wind chill temperature of 44EF (6.7EC)), and others were used by power companies to determine the public's need for additional power. The workshop participants suggested these uses may be better addressed by ISB C6 development.

The group summarized the desired index characteristics in Table 2.1. They also completed an analysis of how some indices fulfill these index characteristics. There were other indices and studies mentioned (e.g. Israel and Russia) which were not included, because full descriptions of them were not readily available to the workshop participants. The JAG/TI members and participants recommended that U.S. and Canada use the same indices. Next, the group agreed that the primary use of the index was to provide warnings to the public about potentially harmful temperatures. With public safety the paramount goal, public comfort would be next consideration on the list.

For wind chill, the overall consensus of the JAG/TI was that the operational Siple and Passel (1945) based wind chill indices used by NWS and MSC should be revised as the first task because the indices generate values that are too cold, especially at cold temperatures and high wind speeds. After detailed discussion of each index, the group decided to recommend a combination of Bluestein and Zecher's (1999) and Osczevski's (1995 a,b) indices, with an addition of a solar radiation calculation, for the replacement WCTI.

2.4.2 Heat index. The JAG/TI members agreed there did not appear to be any major problems identified with the present heat indices in U.S. and Canada. The major reason for upgrading the heat index is to replace old technology with better scientifically based equations that use more of the known affecting parameters and to have the U.S. and Canada use the same index. Two areas that need to be addressed are: 1) these two North American indices did not result in the same values for the same conditions, which was confusing for the public, and 2) the NWS WFOs identified wind as a parameter that makes a difference, and therefore, should be added as another environmental parameter. Public pressure to upgrade the heat index was not present at the time, but could occur if there was another heat wave episode like the 1995 heat wave in Chicago. This current situation allowed for the slow movement on updating the heat index to ensure that a better, improved index would be adopted.

Although the JAG/TI members recommended waiting for the results of the ISB C6 discussions on a UTCI before making judgment on heat index improvements or replacement, a preliminary evaluation of indices was completed. The following were recommended to be included as input to the heat index: solar radiation (based on cloud cover and type, latitude and longitude), temperature, humidity, and wind. Precipitation is another parameter to consider but it was not in some of the indices. Soil moisture will be added to the numerical weather forecast model of apparent temperatures from satellite observations but was not currently considered appropriate for the index. How many days extreme heat has existed and whether or not there are cooling nights need to be taken into account, since the effects of a heat wave are not instantaneous but cumulative. Another variable shown to be important was the time of occurrence within the season. This may be related to acclimatization or mortality. The JAG/TI members thought that acclimatization might be hard to incorporate as part of an index, but including this as a forecaster adaption may be possible. There were also differences from the European weather services on how to address the problem (comfort and extremes/safety) and between instantaneous and cumulative values. For instance, the wind chill value is instantaneous and the extreme heat value is cumulative, but for both of these, the weather services in Canada and U.S. warn on the extremes that could affect public safety. Tentatively, the JAG/TI members agreed to the following heat index characteristics:

- the index should be capable of regional adaption by the forecaster and acclimatization may be possible;

- smog would not be a component, but kept separate;

- the output should be temperature based in degrees C or F;

Table 2-1. Summary of index characteristics recommended by the JAG/TI.

Meteorological Parameters		Exposed body / clothes	Other model considerations	Requirements (in order of importance)	Operations	Research & Development
temperature	at human height (hh); Heat-temps. for both day and night	amount of time exposed; Heat - number of consecutive days and cooling nights	Based on heat transfer theory	1. Extremes - public safety; heat stroke, frostbite, death	Cold: Interim O and B&Z combination Heat: See what ISB recommends	Cold: add radiation Heat: add wind and radiation calculations
wind	wind speed adjusted to hh	skin/body temperature is greater than or equal to air temperature	Regional criteria or thresholds	2. Comfort - what to wear, stay inside, find shelter	one index, if possible, but could have more than one with a transition or buffer zone between heat and wind chill	Continue tests and development of national and regional criteria
humidity	for heat it is major effect For wind chill a lesser effect	steady state conditions assumed and defined	product = apparent/ equivalent/perceived temperature in degrees C and/or F; forecast of apparent temperature	3. forecast for steady state conditions for worst case; range of use if not continuous	Cold: Temp and Wind Heat: Maintain current operations until decide how to use ISB recommendations.	add radiation, clouds; R& D for hypothermia, precipitation, soil moisture
solar radiation	use cloud cover and type, latitude, and longitude	WCT - no clothing, covering of face Heat- Not sure how to handle	WCT-combine O and B&Z indices; Heat-Participate in and rely on recommendation of the ISB Commission 6	4. Common units for Canada and U.S. - degrees preferred	Plan upgrade of both countries for the same cold and heat season with cold first (Oct/Nov 2001)	time of occurrence within the season
precipitation	let forecaster add for now	time of occurrence within the season - include as forecaster adaption	understandable by forecasters and users	Did not decide on whether to address hypothermia. No stated requirement.	If change, must educate public and other users about new index and how to use	Develop public education; determine need for hypothermia warnings
soil moisture	heat/address in FCST only (CPC)					

- consecutive high temperature days and cooling nights should be considered;
- temperature, humidity, solar radiation, and wind speed should be included as input;
- a simple heat index chart for use by local forecasters and the public is preferred, with possibly a more complicated version for the numerical weather forecast product;
- for now, no soil moisture and precipitation should be used as input to the index, although the NWS CPC is planning to use soil moisture in their forecast model; and
- proper air mass handling and turbidity should be part of the NWP forecast model guidance products, but not as input to the index used by the forecaster.

2.5 **<u>Wind Chill Temperature (WCT) Advanced Development Guidance.</u>** The JAG/TI members agreed to the following recommendations for the advanced development of WCTI:

- The new wind chill index should be based on an algorithm that was scientifically defendable, reasonable, understandable, and simple; on obtaining its basic input from existing environmental observations; on experimental data and not human comfort; and on heat budget theory. This index could be used by others as input to "comfort" indices that included clothing concerns. Associating the wind chill index with the environment allows a step further into the interpretation of human comfort.
- Having an internationally agreed upon index was preferable, but at least there should be an agreement between the U.S. and Canada on using a common index. The group recommended that the output should be the same in both Canada and the U.S., and be an equivalent temperature. In addition, the members recommended that both countries switch to the new index at the same time. This consistency aspect was seen as important for the U.S. and Canada because of the movement of the public between the two countries.
- At the initial stage, wind, air temperature, and solar radiation should be the environmental factors used. As further research progresses on how to handle other environmental parameters, the results could be incorporated into this simple index.
- The uncovered frontal cylinder or face should be used to represent the bare skin human model, since it represented the worst case and tended to be uncovered. The nose, chin and ears were the most likely parts of the body to feel the cold and freeze first.
- The Bluestein and Zecher and Osczevski indices should be combined and should include the addition of a radiation calculation. In addition, DRDC has a testing facility where testing of a new index algorithm could be accomplished, if funding is

available. These scientists agreed to work together on developing a common wind chill index. Their indices were recommended for the following reasons:

< were the closest to the environment;

< made the least assumptions;

< were based on bare skin that is exposed first;

< could be operational in a relatively short period of time;

< did not depend on body characteristics;

< could be implemented anywhere;

< used parameters that are available in standard environmental observations;

< could have a radiation calculation added scientifically; and

< were reasonably simple and could be explained to and understood by the public.

- The output product should be an equivalent or AT in both degrees Fahrenheit and Celsius, with warnings issued for extremes only. Limited user surveys in the U.S. on wind chill index information and more extensive surveys in Canada favored the use of equivalent or apparent temperatures and warning on extremes.

- Public education should be conducted prior to and after the implementation of the new index. This education should stress that this change to the current index was an improvement on the old index and incorporated more information.

CHAPTER 3

WCT INDEX ALGORITHM ADVANCED DEVELOPMENT, VERIFICATION, AND VALIDATION

3.1 <u>Introduction.</u> From the formation of the JAG/TI in the fall of 2000, all participants were anticipating how their agency could incorporate recommended improvements to their temperature indices as quickly as possible. As a result, the JAG/TI built into their approved advanced research development recommended deadlines for finishing various aspects of the development, including provision of algorithms and completion of verification and validation. Some of these deadlines were adjusted as the research activities progressed. The first JAG/TI goal was to upgrade or replace the WCTI for the 2001/2002 winter season. Funding for the development project was provided by DRDC, OFCM, and CRREL, with project management provided by OFCM. Reports on the WCTI advanced development, verification, human studies and reverification of the WCTI were provided to JAG/TI by IUPUI and DRDC during the February 14-15 and August 2-3, 2001 workshops.

3.2 <u>Advanced Development and Verification Report.</u> After the first JAG/TI Workshop in October 2000, DRDC and IUPUI began working together on a consensus approach to developing an index based on their existing indices (Bluestein and Osczevski 2002). This new WCTI would be easily utilized by weather forecasters. At the February 2001 Workshop, DRDC and IUPUI reported that their plan was to conduct human studies in the July/August 2001 time frame, with the index ready by October 1, 2001, for the winter season. In addition, twelve human volunteers were needed for the studies. MSC said they would assist with the provision of volunteers. The proposed time frame for the development project was a concern to the group because of the lead time needed to complete internal NWS and MSC coordination, public notification of changes (at least 60 days), public education on the replacement index, and necessary reprogramming of the computers used by forecasters before the start of the 2001-2002 winter season. As a result, the group requested provision of the basic theoretical algorithms and assumptions by May 2001. This would permit MSC and NWS to begin developing the computer software programs and the public education package ahead of time. The group agreed that a mid-May 2001 time slot for the human studies would be better than July/August 2001 for completing the project development work. The preliminary index algorithm was needed by early June (later revised to July10th) for development of software changes to the NWS Advanced Weather Interactive Processing System (AWIPS). The final index algorithm was required by both NWS and MSC no later than August 2, 2001 to ensure adequate time for the final software changes and for coordination and public comment before the start of this year's winter season.

3.2.1 WCT Parameters. The adult face, modeled as the front half of a vertical cylinder, was used as the area affected by the wind since the face was usually exposed to the cold weather. An appropriate frontal diameter, 180 mm, was used for the model. The cylinder's length was of little consequence in considering heat loss from the surface to the air.

A typical walking speed was assumed to be 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}). This value was obtained from published studies of pedestrians crossing streets at intersections. As a worst case, it was assumed that the person would be walking into the wind. This walking speed was added to the wind speed for the actual conditions to determine the effect of the wind chill.

DRDC reported that the solar radiation calculation requested by the JAG/TI to be included in the new index was more difficult to do than originally thought. The members recommended using another method such as the Klima-Michel-Model (KMM), and that KMM modelers would be requested to forward their algorithms. The University of Munich, Germany, has radiation measurements and a radiation algorithm used in the KMM. This was provided to DRDC.

3.2.2 Theoretical Calculations. A steady state condition was assumed for the initial calculations. This required a determination of the skin temperature that would result in the same heat loss rate from the interior or core of the body to the skin as from the skin to the outside air. Heat transfer between two points equaled the temperature difference between the points divided by the resistance to heat flow in that path. This resistance was equivalent to the "R" factor utilized in insulation materials. Heat travels outward from the body to the skin by conduction with conduction resistance dependent on the skin temperature. The heat then travels from the skin to the air by convection and radiation. Both processes involve resistance that was again affected by the skin temperature. Since the skin temperature was not known a priori, an iterative mathematical procedure was required to determine the resistance, and thus, the heat transfer rate. In this procedure, a skin temperature was assumed and the heat transfer equations were solved for the actual air conditions yielding a closer approximation to the actual skin temperature. This result was then used in a repeated solution to the equations until the skin temperature converges to a steady value, providing the final steady state heat transfer rate.

These values of heat loss rate and skin temperature were then used with an assumed wind speed of 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}) to determine what air temperature (the WCT) yielded the same loss rate. This also required iteration since the change in the air temperature from actual to WCT modified the convection and radiation resistances.

The iterative calculation was carried out on a computer, using an Excel^{tm} spreadsheet. It resulted in WCT values for temperature ranges of +45E to –50EF and +10E to –50EC versus wind speeds of 3 to 60 mph and 5 to 80 km h^{-1} (or 1.34-26.8 m s^{-1}) at increments of 5 degrees (F or C), 5 mph and 5 km h^{-1} (or 1.3 m s^{-1}).

3.3 <u>Validation of WCT Algorithms Through Human Studies.</u> While the index development process followed established heat transfer theory, human studies were done to validate the various parameters, including body temperature, skin temperature, and skin resistance, and how these change with time of exposure. The DRDC thermal chamber and wind tunnel facility was chosen by the JAG/TI because it had well-established facilities for such tests and DRDC agreed to partially fund the trials. DRDC conducted the experiments with human volunteers. The results of these trials were used to determine tissue resistance, an essential variable in the mathematical modeling and to validate the theoretical algorithm.

Six men and six women volunteered to be subjects of these studies. These subjects were capable of continuously walking at a moderate rate for 90 min, and were generally more fit than the general population. They ranged in age from 22 to 42 years with a mean of 33 years. The mean Body Mass Index (BMI) was 25.2, which is ideal for the general population from a health standpoint, but is lower than the average BMI of the general population of North America. The

BMIs of the subjects ranged from 18.5 to 32.5. Their percent body fat, measured at four points by calliper, ranged from 18.5 to 32.5% with a mean of 19.6%. The subjects were instrumented with thermocouples to measure the temperatures of the skin of the nose, forehead and both cheeks and ears. Internal temperature was measured with a rectal thermistor. Very thin transducers (RdF 20457-3) were used to measure the heat flow from the cheeks and forehead. At each of three air temperatures, 50EF (+10EC), 32F (0EC) and 14EF (-10EC), the subjects walked on a treadmill for 90 min at 3 mph (1.34 m s^{-1} or 4.8 km h^{-1}), facing into an artificially generated wind of 4.5, 11 or 18 mph (2, 5 or 8 m s^{-1}; 7.2, 17.7, or 29 km h^{-1}). In each experiment, the wind speed was initially set at 4.5 mph (2 m s^{-1} or 7.2 km h^{-1}) and was stepped up to the other two values at 30 min intervals. Skin temperatures were continually monitored to ensure that frostbite did not occur.

The following modifications were made to the initial heat transfer equations as a result of these studies. Over a wide range of temperature and wind speeds, steady state deep body temperature depended on the intensity of exercise and not on the weather. As a result, a body temperature of 38EC (100.4EF) rather than 37EC (98.6EF) was used in the model. This was based on the measurements from the volunteers who were walking at a moderate speed. It was also found that the cheeks usually were the coldest areas of the face, and therefore, should be used for the worst case skin condition. This necessitated a modification to the convective heat transfer calculation. The convective heat transfer component of the computer model was also modified to represent the heat transfer from a location on a cylinder corresponding approximately to the location of the cheek, at a 50E angle from the forward stagnation point. The convective heat transfer coefficient at this angle was equal to the average for the front 160E of a cylinder at any wind speeds that were likely to be encountered. Skin resistance was found by dividing the heat loss rate at the cheek by the temperature difference between the body (38EC or 100.4EF) and the cheek. This yielded a range of resistance values for the 12 subjects. Based on worst case conditions, the skin resistance representing the 95th percentile was used, i.e., the resistance greater than 95 percent of the observed values from the subjects in the trial. Higher resistance was associated with lower skin temperatures and a greater risk of frostbite. There was a tendency for the higher resistances to be associated with subjects who had higher BMIs. While the thermal resistance of the cheek of an individual varied with skin temperature, no correlation was evident for a population. The model was therefore changed to have a constant tissue resistance that corresponded to the 95th percentile value obtained from the experiments. The thermal resistance of the body at skin temperatures near or below the freezing point of skin (-4.8EC or 23.4EF), defined by Danielsson (1996), could not be determined in these human studies because of ethical considerations. Experimental conditions in some subjects did not result in a steady state skin temperature and heat flow from the subjects' cheeks because of Cold Induced Vasodilation (CIVD), which occurs at painfully cold skin temperatures. In CIVD, surface blood vessels open up to allow warm blood to flow from the interior of the body to the skin. This mechanism serves to protect the skin from freezing especially when the body core is warm, but might not occur if the body's temperature is subnormal. One concern with CIVD was that it can make identification of patterns difficult.

3.4 <u>WCT Algorithms - Revalidation and Reverification</u>. The initial iterative equation for the WCTI was modified based on the results of the human studies, which required they be revalidated and reverified. In addition, NWS and MSC tried to run the iterative equation on their central and forecaster computers, but soon discerned that it overwhelmed the resources of the smaller computers. This could have jeopardized the implementation of the WCTI. As a result, NWS and MSC requested, and JAG/TI approved, the researchers develop a non-iterative equation for the WCTI.

3.4.1 Revalidation and Reverification Report and Discussion. DRDC reported that the trial results picked up the variation of reaction among the test subjects and noted that the younger subjects demonstrated more reaction than the older subjects. The studies tentatively suggested that physically fit people might tend to have low skin resistance, and therefore, high heat transfer from the inner body to their skin resulting in higher skin temperatures. Additionally, less fit people might have high skin resistance with low heat transfer which prevented the warming of the skin layer. Those people who have a low transfer rate cannot keep their extremities sufficiently warm to avoid freezing of the skin layer and will be more at risk for experiencing wind chill effects. The group decided to use this case since the weather services issue warnings for frostbite and the worst-case scenario. As a result, the resistance factor in the worst case was determined to be 0.09 m^2 K W^{-1}.

It was hypothesized that the high resistance individuals may fare better in hypothermia instances because their core body heat would not be drained as fast as those with higher transfer rates. Previous studies have shown that heavier people lose less heat than thinner people. The group noted that the wind chill should be a heat transfer coefficient based on the convective heat loss due to wind, and that simplified resistance is a function of temperature. If resistance was large then there was a greater temperature gradient across the barrier. Therefore, total resistance was related to the body and convection.

The wind speed effect was not as significant as the skin resistance in the upper wind speeds. The biggest effect occurs with the gentle breezes. Therefore, the new formula was in error at zero wind speed, where the equivalent temperature should equal the air temperature because zero values were not used in the regression. As a result, the recommended starting point for the index was at 5 mph (2.2 m s^{-1} or 8 km h^{-1}), not zero mph or calm winds. The NWS recommended the chart begin at 3 mph (1.3 m s^{-1} or 4.8 km h^{-1}) which was the NWS forecast breakpoint for light and variable or calm wind conditions and the JAG/TI accepted this recommendation. Wind speed was calculated at the face level by applying a two-thirds correction factor to the observed wind speed, which was added to the walking speed to obtain an estimate of the wind speed affecting the face. It was noted that the heat transfer coefficient was proportional to the square root of the wind speed.

DRDC next discussed the results using charts and diagrams. The first chart compared the results of the new index to the old index. The results of the human studies were also presented. As previously mentioned, the twelve subjects ranged from 22 to 42 years in age, from 10 to 27% body fat, and from 18.5 to 32.5 BMI. The wind chill chart incorporated a minimum wind speed of 3 mph, equal to walking speed. The algorithm was run out to 200 km h^{-1} (124.3 mph or 55.6 m s^{-1}) and the regression equation seemed to fit the model calculations reasonably well over the whole range.

The effect of solar radiation was a complex problem due to the number of parameters involved: latitude, longitude, elevation, cloud cover, time of day, and day of year. Development work on incorporating the solar radiation effects could not be completed in time to meet the weather services' operational implementation deadlines. JAG/TI decided that the initial calculation of the WCT would be based on wind alone with a solar radiation factor to be added later.

3.4.2 WCTI Equations. After making the necessary corrections indicated from the human studies, the researchers ran the iterative model over 800 times with different combinations of wind speed and air temperature. Subsequently, a multiple regression analysis of the results was performed and Equations 3.1a and 3.1b were found to best fit the data. These equations corrected the observed wind speed at 33 ft (10 m) to the height of the face. The wind speed at the level of the face in "calm" conditions was assumed to be 3 mph (4.8 km h^{-1} or 1.3 m s^{-1}). As a result, the WCT should equal the air temperature at this "calm" wind speed. These equations were used to prepare the WCTI charts which were submitted to JAG/TI for review. The weather services requested the charts be modified to identify wind chill temperatures that might be expected to produce frostbite on exposed skin in 30 min or less, in the most susceptible (95th percentile) of the population, and for a worst case scenario (night time clear). This frostbite parameter helped to establish new warning and advisory criteria. The literature suggested that 95% of the population will experience frostbite at a skin temperature of -7.8EC (18EF). Although, about 1-2% of the population might experience it at -1EC (30.2EF) and 5% may be affected at -4.8EC (23.4EF). The resulting WCTI charts (see Tables 3.1 a and b) were given in degrees Fahrenheit and Celsius, and were derived from the appropriate WCT equation. If the wind was measured at face level, the wind speed should be multiplied by 1.5 to use the equation or chart.

$$\mathbf{WCTI=35.74 + 0.6215T-35.75V^{0.16} + 0.4275TV^{0.16}} \qquad \mathbf{3.1a}$$

or

$$\mathbf{WCTI=13.12 + 0.6215T-11.37V^{0.16} + 0.3965TV^{0.16}} \qquad \mathbf{3.1b}$$

where WCTI is the wind chill temperature index, T and V are the air temperature in units of degrees Fahrenheit and wind speed in mph, respectively (3.1a), or degrees Celsius and km h^{-1}, respectively (3.1b).

3.4.3 Frostbite. DRDC continues to work on a time-dependent frost point model. A cylindrical model with 25 layers of concentric circles is being used. Each layer has thermal resistance, heat capacity, and temperature associated with it. Total thermal resistance is spread over 25 layers and adds up to 0.05. Heat is moved from warm to cold. The model is based on a dynamic model of the face and uses a finite difference approximation technique. The preliminary model calculations gave initial times to occurrence of frostbite under certain winds and air temperatures. Based on the best fit to the model results, equations 3.2a and b would be used on the NWS AWIPS computers and in DOD documents, but the equations are only valid when the frostbite time is less than or equal to 30 min and the wind speed is greater than 16 mph (7.2 m s^{-1} or 25 km h^{-1}) and less than or equal to 50 mph (22.3 m s^{-1} or 80.5 km h^{-1}). These results were also provided as a chart (see Table 3.2a and b). Table 3.2b is used by MSC and is on their web site for public use. NWS incorporated the frostbite times into the NOAA Wind Chill Chart (Table 3.3). DOD produced Wind Chill Charts for 3 heights of the anemometer (5, 15, and 33 ft or 1.5, 4.6, and 10m; Tables 3.4a-c) because of various military operational instrument packages. They also incorporated the frostbite times into their Wind Chill Charts.

$$\mathbf{Ft = ((-24.5 \times ((0.667 \times (V10 \times 8/5)) + 4.8)) + 2111) \times (-4.8 - ((Tair - 32) \times 5/9))^{-1.668}} \qquad \mathbf{3.2a}$$

or

$$\mathbf{Ft = ((-24.5 \times ((0.667 \times V10) + 4.8)) + 2111) \times (-4.8 - Tair)^{-1.668}} \qquad \mathbf{3.2b}$$

where Ft is the frostbite time in minutes, Tair and V are the air temperature in units of degrees Fahrenheit and wind speed in mph > 16 measured at a height of 33 ft, respectively (3.2a), or degrees Celsius and km h^{-1} > 25 measured at a height of 10 m, respectively (3.2b).

One may note in Table 3.3 that there are several cases where the same wind chill value occurs in different frostbite zones. DRDC found that the wind is a greater factor in time to cooling and frostbite than it is in the steady state equivalent temperature. The time to frost point depends on the integrated heat flow, which is very high when the skin is warm, especially if windy, and becomes lower as the skin cools. The WCT depends on the value of the heat flow after the skin has cooled as low as it is going to go, so it is not surprising that there appears to be inconsistency. It should be kept in mind that frostbite will not actually occur when the air temperature is above the freezing level. It will take greater than two hours for frostbite to occur from the freezing level down to 10EF even with high winds of up to 50 mph (80.5 km h^{-1} or 22.3 m s^{-1}; see Table 3.2a).

3.5 <u>Summary Discussion</u>. Freezing cold injury can occur anytime temperatures (air or surface) fall below freezing (32EF and 0EC). However, the likelihood and severity of injury increases with prolonged exposure to lower temperatures and greater relative wind speed, where wind speed may be a combination of actual wind speed, walking speed, and/or vehicle speed. Wind chill is not just a property of the environmental conditions, but of the faces being cooled by it. Cheek thermal resistance varies considerably among individuals. In the human studies, it varied by more than a factor of two. As a result, cheek temperatures in wind, in general, will differ from person to person.

Individuals will feel different degrees of coldness at the same combination of wind and temperature, since the perception of wind chill depends on the skin temperature. Those with high thermal resistance cheeks will have colder faces than those with lower thermal resistance cheeks. The wind chill equivalent temperature for individuals with high thermal resistance cheeks should be relatively high compared to that of individuals having low thermal resistance cheeks. The wind chill equivalent temperature depends on the heat transfer rate, which in the high thermal resistant individual will be relatively low because of the higher internal thermal resistance. However, those individuals with low thermal resistance will feel the cold less because of higher facial skin temperatures. Thus, individuals for whom the wind chill equivalent temperature should be milder, the high thermal resistance group, will perceive the weather to be colder. This apparent paradox calls into question the utility of wind chill equivalent temperatures. In spite of this, once individuals have experienced the range of wind chill and recalibrated the temperature scale to their own sensations, the scale will be useful to them in that they will know what to expect.

Some individuals have leveled criticism at the previous wind chill equivalent temperature scale because the cold equivalent temperatures do not feel the same as a real temperature of that magnitude in still air that they have previously experienced. This criticism will still be heard, because the new scale was not derived for their faces but for the faces of the 95th percentile of cheek thermal resistance. Incidentally, while the population with high thermal resistance is at greater risk of frostbite, they are at lower risk for hypothermia.

Several cautions apply to the use of the WCT model and tables. The exact effect of cold exposure due to wind chill on an individual will vary depending on the type and level of activity, length of exposure, moderating effects of clothing, partial shelter from the wind, solar radiation, and overall physical state of the individual. The model was not designed to determine hypothermia effects since it is based on facial cooling, not on the whole body's temperature cooling. Frostbite will not occur when the air temperature (T) is above freezing (T>32EF or 0EC). In addition, wind chill does not apply to inanimate objects. The only effect that wind will have on inanimate objects is to shorten the time to cool to the actual air temperature.

Table 3.1a The new Wind Chill Temperature (WCT) Index chart, with T = Air Temperature in EC and V = Wind Speed in km h^{-1} at 10 m elevation.

Temperature (EC)

Wind (km h^{-1}) / **Calm**	**10**	**5**	**0**	**-5**	**-10**	**-15**	**-20**	**-25**	**-30**	**-35**	**-40**	**-45**	**-50**
10	8.6	2.7	-3.3	-9.3	-15.3	-21.1	-27.2	**-33.2**	**-39.2**	**-45.1**	**-51.1**	**-57.1**	**-63.0**
15	7.9	1.7	-4.4	-10.6	-16.7	-22.9	**-29.1**	**-35.2**	**-41.4**	**-47.6**	**-53.7**	**-59.9**	**-66.1**
20	7.4	1.1	-5.2	-11.6	-17.9	-24.2	**-30.5**	**-36.8**	**-43.1**	**-49.4**	**-55.7**	**-62.0**	**-68.3**
25	6.9	0.5	-5.9	-12.3	-18.8	–25.2	**-31.6**	**-38.0**	**-44.5**	**-50.9**	**-57.3**	**-63.7**	**-70.2**
30	6.6	0.1	-6.5	-13.0	-19.5	-26.0	**-32.6**	**-39.1**	**-45.6**	**-52.1**	**-58.7**	**-65.2**	**-71.7**
35	6.3	-0.4	-7.0	-13.6	-20.2	-26.8	**-33.4**	**-40.0**	**-46.6**	**-53.2**	**-59.8**	**-66.4**	**-73.1**
40	6.0	-0.7	-7.4	-14.1	-20.8	-27.4	**-34.1**	**-40.8**	**-47.5**	**-54.2**	**-60.9**	**-67.6**	**-74.2**
45	5.7	-1.0	-7.8	-14.5	-21.3	–28.0	**-34.8**	**-41.5**	**-48.3**	**-55.1**	**-61.8**	**-68.6**	**-75.3**
50	5.5	-1.3	-8.1	-15.0	-21.8	-28.6	**-35.4**	**-42.2**	**-49.0**	**-55.8**	**-62.7**	**-69.5**	**-76.3**
55	5.3	-1.6	-8.5	-15.3	-22.2	**-29.1**	**-36.0**	**-42.8**	**-49.7**	**-56.6**	**-63.4**	**-70.3**	**-77.2**
60	5.1	-1.8	-8.8	-15.7	-22.6	**-29.5**	**-36.5**	**-43.4**	**-50.3**	**-57.2**	**-64.2**	**-71.1**	**-78.0**

Frostbite may occur in 30 minutes or less

WCT (EC) =13.12 + 0.6215T – 11.37$V^{0.16}$ + 0.3965T$V^{0.16}$

Table 3.1b The new Wind Chill Temperature (WCT) Index chart, with T = Air Temperature in EF and V = Wind Speed in mph at 33 ft elevation, which is corrected to 5 ft via the equation.

Temperature (EF)

Wind (mph)

Calm	40	35	32	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	27	25	19	13	7	1	-5	-11	-16	**-22**	**-28**	**-34**	**-40**	**-46**	**-52**	**-57**	**-63**
10	34	27	24	21	15	9	3	-4	-10	-16	**-22**	**-28**	**-35**	**-41**	**-47**	**-53**	**-59**	**-66**	**-72**
15	32	25	22	19	13	6	0	-7	-13	**-19**	**-26**	**-32**	**-39**	**-45**	**-51**	**-58**	**-64**	**-71**	**-77**
20	30	24	20	17	11	4	-2	-9	-15	**-22**	**-29**	**-35**	**-42**	**-48**	**-55**	**-61**	**-68**	**-74**	**-81**
25	29	23	19	16	9	3	-4	-11	-17	**-24**	**-31**	**-37**	**-44**	**-51**	**-58**	**-64**	**-71**	**-78**	**-84**
30	28	22	18	15	8	1	-5	-12	**-19**	**-26**	**-33**	**-39**	**-46**	**-53**	**-60**	**-67**	**-73**	**-80**	**-87**
35	28	21	17	14	7	0	-7	-14	**-21**	**-27**	**-34**	**-41**	**-48**	**-55**	**-62**	**-69**	**-76**	**-82**	**-89**
40	27	20	16	13	6	-1	-8	-15	**-22**	**-29**	**-36**	**-43**	**-50**	**-57**	**-64**	**-71**	**-78**	**-84**	**-91**
45	26	19	15	12	5	-2	-9	-16	**-23**	**-30**	**-37**	**-44**	**-51**	**-58**	**-65**	**-72**	**-79**	**-86**	**-93**
50	26	19	14	12	4	-3	-10	-17	**-24**	**-31**	**-38**	**-45**	**-52**	**-60**	**-67**	**-74**	**-81**	**-88**	**-95**
55	25	18	14	11	4	-3	-11	**-18**	**-25**	**-32**	**-39**	**-46**	**-54**	**-61**	**-68**	**-75**	**-82**	**-89**	**-97**
60	25	17	13	10	3	-4	-11	**-19**	**-26**	**-33**	**-40**	**-48**	**-55**	**-62**	**-69**	**-76**	**-84**	**-91**	**-98**

Frostbite may occur in 30 minutes or less

$$\text{WCT (EF)} = 35.74 + 0.6215T - 35.75V^{0.16} + 0.4275TV^{0.16}$$

Table 3.2a Time to occurrence of frostbite (5% risk of frostbite) in minutes or hours (h) and English units.

Air Temperature (EF)

Wind (mph)

Calm	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	>2h	>2h	>2h	>2h	31	22	17	14	12	11	9	8	7
10	>2h	>2h	>2h	28	19	15	12	10	9	7	7	6	5
15	>2h	>2h	33	20	15	12	9	8	7	6	5	4	4
20	>2h	>2h	23	16	12	9	8	8	6	5	4	4	3
25	>2h	42	19	13	10	8	7	6	5	4	4	3	3
30	>2h	28	16	12	9	7	6	5	4	4	3	3	2
35	>2h	23	14	10	8	6	5	4	4	3	3	2	2
40	>2h	20	13	9	7	6	5	4	3	3	2	2	2
45	>2h	18	12	8	7	5	4	4	3	3	2	2	2
50	>2h	16	11	8	6	5	4	3	3	2	2	2	2

Table 3.2b Time to occurrence of frostbite (5% risk of frostbite most susceptible segment of the population) in minutes and metric units.

Air Temperature (EC)

Wind (km/h)

Calm	-15	-20	-25	-30	-35	-40	-45	-50
10	x	x	22	15	11	8	7	6
20	x	x	14	10	7	6	5	4
30	x	18	11	8	6	4	4	3
40	42	14	9	6	5	4	3	2
50	27	12	8	5	4	3	2	2
60	22	10	7	5	3	3	2	2
70	18	9	6	4	3	2	2	2
80	16	8	5	4	3	2	2	1

x = Frostbite unlikely

Frostbite possible in 2 minutes or less	1
Frostbite possible in 3 to 5 minutes	3
Frostbite possible in 6 to 10 minutes	6

Table 3.3 NOAA Wind Chill Chart with "time to frostbite" indicated (adapted from Tew et al. 2002).

Wind Chill Chart

Temperature (°F)

Wind (mph)	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Calm																		
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	29	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Frostbite Times: 30 minutes; 10 minutes; 5 minutes

$$\text{Wind Chill } (^\circ F) = 35.74 + .06215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Table 3.4a DOD Wind Chill Chart with frostbite times for an anemometer height of 5ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 5 foot anemometer height (handheld)

Wind Speed (mph) \ Temperature (°F)	Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
	5	35	29	23	17	11	5	-1	-8	-14	-20	-26	-32	-38	-44	-50	-56	-62	-68	-74
	10	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	-83
	15	30	23	17	10	3	-3	-10	-16	-23	-30	-36	-43	-50	-56	-63	-69	-76	-83	-89
	20	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
	25	27	20	13	7	0	-7	-14	-21	-28	-35	-42	-49	-56	-63	-70	-77	-84	-90	-97
	30	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	-100
	35	25	18	11	4	-3	-10	-17	-24	-32	-39	-46	-53	-60	-67	-74	-82	-89	-96	-103
	40	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
	45	24	17	9	2	-5	-12	-20	-27	-34	-42	-49	-56	-64	-71	-78	-86	-93	-100	-107
	50	23	16	9	1	-6	-13	-21	-28	-36	-43	-50	-58	-65	-72	-80	-87	-95	-102	-109
	55	23	15	8	1	-7	-14	-22	-29	-37	-44	-52	-59	-66	-74	-81	-89	-96	-104	-111
	60	22	15	7	0	-8	-15	-23	-30	-38	-45	-53	-60	-68	-75	-83	-90	-98	-105	-113
	65	22	14	7	-1	-8	-16	-24	-31	-39	-46	-54	-61	-69	-76	-84	-92	-99	-107	-114
	70	21	14	6	-1	-9	-17	-24	-32	-40	-47	-55	-62	-70	-78	-85	-93	-100	-108	-116
	75	21	13	6	-2	-10	-17	-25	-33	-40	-48	-56	-63	-71	-79	-86	-94	-102	-109	-117

Risk of frostbite within | *30 minutes* | *10 minutes* | *5 minutes*

23 Jan 02

Table 3.4b DOD Wind Chill Chart with frostbite times for an anemometer height of 15 ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 15 foot anemometer height

Temperature (°F)

Wind Speed (mph) / Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
5	36	30	24	18	12	6	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-65	-71
10	33	27	20	14	8	1	-5	-11	-17	-24	-30	-36	-43	-49	-55	-61	-68	-74	-80
15	31	24	18	11	5	-2	-8	-15	-21	-28	-34	-41	-47	-54	-60	-67	-73	-80	-86
20	30	23	16	10	3	-4	-10	-17	-24	-30	-37	-44	-50	-57	-64	-70	-77	-84	-90
25	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
30	28	21	14	7	0	-7	-14	-21	-28	-35	-41	-48	-55	-62	-69	-76	-83	-90	-97
35	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-85	-92	-99
40	26	19	12	5	-2	-9	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80	-87	-94	-101
45	25	18	11	4	-3	-10	-18	-25	-32	-39	-46	-53	-61	-68	-75	-82	-89	-96	-103
50	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
55	24	17	10	2	-5	-12	-20	-27	-34	-41	-49	-56	-63	-71	-78	-85	-92	-100	-107
60	24	16	9	2	-6	-13	-20	-28	-35	-42	-50	-57	-65	-72	-79	-87	-94	-101	-109
65	23	16	8	1	-6	-14	-21	-29	-36	-43	-51	-58	-66	-73	-80	-88	-95	-103	-110
70	23	15	8	0	-7	-15	-22	-29	-37	-44	-52	-59	-67	-74	-82	-89	-97	-104	-111
75	22	15	7	0	-8	-15	-23	-30	-38	-45	-53	-60	-68	-75	-83	-90	-98	-105	-113

Risk of frostbite within *30 minutes* *10 minutes* *5 minutes*

23 Jan 02

Table 3.4c DOD Wind Chill Chart with frostbite times for an anemometer height of 33 ft.

New Wind Chill Chart in Fahrenheit and MPH

Use this chart for winds from 33 foot anemometer height

Wind Speed (mph)	Temperature (°F)																			
	Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
	5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63	-69
	10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72	-78
	15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77	-83
	20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81	-88
	25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84	-91
	30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87	-94
	35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89	-96
	40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91	-98
	45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93	-100
	50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95	-102
	55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97	-104
	60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98	-105
	65	24	17	10	2	-5	-12	-19	-27	-34	-41	-49	-56	-63	-70	-78	-85	-92	-99	-107
	70	24	16	9	2	-6	-13	-20	-27	-35	-42	-49	-57	-64	-71	-79	-86	-93	-101	-108
	75	23	16	9	1	-6	-13	-21	-28	-36	-43	-50	-58	-65	-72	-80	-87	-95	-102	-109

Risk of frostbite within	*30 minutes*	*10 minutes*	*5 minutes*

23 Jan 02

CHAPTER 4

WCT INDEX: TRANSITION FROM ADVANCED DEVELOPMENT TO OPERATIONS

4.1 <u>Introduction</u>. The transition of the new WCTI into operations was handled within the JAG/TI through approved actions and coordinated activities. Notification of the new WCTI was sent by the Federal Coordinator to federal agencies in mid-September 2001. The purpose of this memorandum was to officially notify the federal agencies of the new recommended WCTI, to provide the Index's algorithms and charts, and to provide a summary of the JAG/TI project through an attached executive summary. Other documentation of these activities and decisions were provided to federal agencies by their C/ESORN and JAG/TI representatives and through distribution of the JAG/TI meetings' Record of Actions. Education of the meteorological community and general public was also critical to the success of the WCTI. The JAG/TI activities are summarized in Table 4.1.

4.2 <u>Agencies' Implementation</u>. Each weather service implemented the new WCTI and frostbite equation according to their agency procedures, which are summarized in this section.

4.1.2 National Weather Service (NWS) Implementation. The NWS implemented the new WCTI on November 1, 2001 (Nelson at al. 2002b; Tew et al. 2002). The implementation process involved three key steps which were AWIPS integration, operations integration and public education.

4.1.2.1 AWIPS Integration. In order to begin the WCTI implementation process, the new WCTI algorithm was first inserted into AWIPS. The AWIPS programs and products that use the new wind chill equation are: the Hourly Weather Roundup (HWR), the Interactive Forecast Preparation System (IFPS) products, and the Display 2-Dimensional (D2D) application.

- The HWR is composed of two software applications which summarize hourly observations from both land and marine stations. These observation summaries are disseminated over the NOAA Weather Radio as well as the NOAA Weather Wire Service (NWWS). The NWWS product is in a tabular format, with each row representing a station, and each column represents a weather element, such as temperature and wind. The WCTI value will be found in the "Remarks" column whenever the temperature, wind, and wind chill index exceed user-defined thresholds.

- The IFPS products affected by the change in the wind chill index include the Zone Forecast Product and the Revised Digital Forecast.

- Hourly WCTs can be displayed on a map background of choice on D2D within AWIPS. These observations may also be animated.

The WCTI equation with frostbite thresholds was released to all NWS WFOs in October 2001. The software changes were transmitted to each WFO through an AWIPS maintenance release by the Office of Operational Services, and the installation was monitored by the Network Control

Facility. The installation was completed before the implementation date of November 1 at all sites. The installation of the WCTI was included in the AWIPS software release 5.1.1.1.

4.1.2.2 Operations Integration. The NWS issues Wind Chill Outlooks, Wind Chill Watches, Wind Chill Warnings and Wind Chill Advisories to provide the public advance notice of dangerous or life threatening wind chill conditions. To implement the new WCTI and frostbite times, the NWS changed warning and advisory threshold values to better reflect the new index and updated national and regional policy documents to reflect the changes.

4.1.2.3 Public Education. The NWS developed an extensive education effort to inform their customers and partners about the new WCTI. The list of the educational activities included:

- issuing a public information statement on September 1, 2001 to inform the public of the upcoming change to the NWS wind chill program;
- developing and publishing the WCTI chart with frostbite times shaded on NWS web pages and the updated winter storm brochure;
- organizing mailings and seminars targeting local media, emergency managers, city and school officials;
- participating in interviews, resulting in numerous wind chill articles published in newspapers, magazines, and brochures;
- fielding several television and radio interviews; and
- establishing the NWS Wind Chill web page, which includes the NOAA WCTI chart and calculator, at: http://www.nws.noaa.gov/om/windchill.

4.2.2 Meteorological Service of Canada (MSC). The MSC began using the new WCTI in their forecasts on October 2, 2001, but did not have the formal implementation ceremony until October 30, 2001 (Shaykewich et al. 2002). The formal implementation ceremony, which was attended by most major media networks in Canada, took place at the DRDC site of the human trials. The equation was incorporated into the winter guidance and into the Scribe auto-generated forecast bulletin preparation program before the start of the use of the new index. MSC wrote a short Standard Operating Procedure document for use by the forecasters that was available upon start-up. It included national guidance on format and terminology as well as on climate region specific thresholds for reporting on wind chill for inclusion in a forecast and for the issuance of warnings. All of this required finalization of the WCTI by mid-August, when the initial notice was issued. Although MSC does not have a required notification time to adhere to, they do have an understanding with the media to notify them six weeks ahead of any changes. In fact, MSC worked with several media outlets during the human trials and afterward to help publicize the change and educate their public. As part of the media coverage and from the filming of the trials, Discovery Channel and The Weather Network in Canada broadcast 30 minutes of interviews, equipment, trials, and trial results.

During August 2001, MSC worked on training, more detailed talking points, information for outreach, possible questions and answers, climatology, and the relation of the old index to the new index. MSC also produced educational products for children, updated brochures, and wallet cards to reflect the new WCTI. These were distributed widely and made available via their web site. MSC developed an extensive web site which provides information on the wind chill index, including the scientific basis, April 2000 Workshop documents, the update process, an on-line downloadable wind chill calculator, equations for the WCTI and frostbite times, educational documents, charts and tables, fact sheet, and links to other JAG/TI agencies. Their web site address is: http://www.windchill.ec.gc.ca/.

4.2.3 Department of Defense (DOD).

4.2.3.1 United States Air Force (USAF) and United States Army (USA) Implementation. The USAF and USA began implementation of the WCTI and Minutes to Frostbite equation at worldwide locations on November 1, 2001. The USAF Director of Weather, Policy Division issued an announcement to Air Force and Army units on October 17, 2001. The USA Office of Surgeon General sent guidance to Army units on December 17, 2001. Subsequently, the information on the new WCTI and frostbite was publicized, distributed, adapted for use, included in models and weather systems, and references and publications were updated. Articles were released by the Air Force Weather Agency Office of Public Affairs to the *Air Force News* on October 26, 2001 and appeared on Air Force Radio News on October 29, 2001. The new index was introduced by several other media through safety articles, disaster preparedness briefs, and internal newsletters. The new index was also available for downloading at several military web sites.

For worldwide adaption of WCTI and Minutes to Frostbite information, an additional eight charts were created to convert to metric units, correct for the different wind measuring heights (5, 15, and 33 ft or 1.5, 4.6, and 10 m), and extend the equations from wind 45 mph (72.4 km h^{-1} or 20 m s^{-1}) to 60 mph (96.6 km h^{-1} or 26.8 m s^{-1}). To accomplish this extension, the USAF requested, and DRDC agreed, to rerun the WCT and Frostbite models to obtain new data values. The new charts were completed in January 2002 and distributed shortly thereafter to both the military and JAG/TI members.

Automating the new WCTI and Minutes to Frostbite equations into Air Force Weather systems will be accomplished as new versions of software are created. The WCTI was included in the March 2002 software upgrade for Air Force Weather's forecast display work station, the New Tactical Forecast System. Weather models will also be updated with the WCTI as visualization output is programmed.

As identified or reviewed, military publications will be updated with the new WCTI and Minutes to Frostbite information. For example, the Air Force Surgeon General plans to include the information in the Air Force Pamphlet 48-151, *Thermal Injury*. The USA Research Institute for Environmental Medicine (USARIEM) has already incorporated the new information into their update of the Technical Note: *Sustaining Health and Performance in Cold Weather Operations,* published in October 2001.

4.2.3.2 United States Navy (USN) and United States Marine Corps (USMC) Implementations. The USN Commander, Naval Meteorology and Oceanography Command (CNMOC) forwarded the WCTI to its subordinate commands in November 2001. Since that time, copies of the WCTI have been posted on the CNMOC Operational Support Web (both classified and unclassified sites). In addition, the WCTI will be incorporated in the next version of the Automated Surface Observing System (ASOS) software release; the Navy has installed ASOS at its airfields.

The USMC also incorporated the WCTI in support of USMC operations worldwide during November 2001. The USMC meteorology and oceanography personnel introduced the new index to all the warfighting commands of the Marine Air Ground Task Force. The new index was also made available for downloading at several USMC military web sites.

The WCTI will be included as a new requirement into automated observing and recording weather systems as new versions of the software are fielded. The new WCTI will be updated in publications when identified or reviewed.

4. 3 <u>Summary of JAG/TI Implementation Actions.</u> The first phase of the project covered a science review, group decisions and implementation process to update the existing U.S. and Canadian wind chill indices by the JAG/TI. The group initiated the research activity, solicited funding support, and established a time line for delivery of the new WCTI. As the project progressed, the group approved adjustments to this time line, monitored the research activity, conducted ongoing coordination with the researchers and funding agencies, and reviewed project reports by the researchers. The final form of the WCTI algorithm was obtained by the NWS and MSC at the beginning of August 2001 and implemented into their forecast centers and forecast offices' computer software. This was accomplished on September 1, 2001. DOD also obtained the WCTI by August and completed their internal coordination with the various military branches' medical and operational hierarchy.

The JAG/TI assisted agencies with the development of educational packages by arranging for the DRDC human studies to be filmed by CRREL. This also helped document the JAG/TI index verification process. Copies of the film were provided to the weather services and OFCM. In addition, a poster on the WCTI implementation (Mulherin and Phetteplace 2001) was distributed to the JAG/TI participants for use in publicizing the WCTI change. MSC also provided their educational package on CDROM and video tapes to NWS and OFCM along with additional pictures of the human studies tests. The JAG/TI members were interviewed for television reports and articles on the new index that appeared in various newspapers across the nation and in professional journals such as "Weatherwise."

The OFCM provided several documents on the WCTI project to assist in the public and federal agencies education process, including an executive summary, papers for professional meetings, media talking points, and point papers. OFCM posted the executive summary on their web site under Special Projects at: http:\\www.ofcm.gov\.

In addition, contacts were made with the Centers for Disease Control and Prevention (CDC) on updating their web site to refer to or reflect the new WCTI. CDC then set up on their web site a link to the NWS wind chill link. Office of Safety and Health Administration was also contacted to ask them to participate in future JAG/TI meetings and activities, and to update their manuals, handbooks, and relevant web sites to reflect the new WCTI.

Table 4.1 JAG/TI ACTIVITIES 2000-2002

October 2000

- Held first JAG/TI Workshop:
  - < reviewed the wind chill science and indices,
  - < reviewed existing NWS and MSC wind chill indices,
  - < agreed to have Dr. Bluestein and Mr. Osczevski develop a replacement WCTI,
  - < agreed to participate in the on-going discussions of ISB Commission 6 on UTCI, and
  - < made decision to provide position papers on wind chill and heat indices to ISB Commission 6 on JAG/TI.

February 2001

- Held second JAG/TI Workshop:
  - < reviewed the progress of the research,
  - < approved continuation of WCTI development project,
  - < revised project delivery schedule as needed, and
  - < reported on sources for project funding.
- Sent JAG/TI position paper on wind chill to ISB Commission 6.

April 2001

- DRDC and IUPUI provided tentative iterative algorithms for the new WCTI to NWS and MSC for development of and integration into weather forecaster's tools software.
- Sent JAG/TI position paper on heat indices to ISB Commission 6.
- JAG/TI members made decision to delay solar radiation inclusion in the WCTI until at least 2002.

May/June 2001

- Conducted human trials at DRDC with 12 volunteers to verify wind chill index values.
- Three JAG/TI members represented the JAG/TI and participated in the ISB Commission 6 meeting in Germany.
- CRREL filmed human trials for use with other public education material and for verification purposes.

July 2001

- The WCTI algorithm was delivered by July 10.
- Experts completed the evaluation of the new index by July 27, 2001.
- First draft of report on JAG/TI activities complete, to be reviewed at the August meeting of the JAG/TI.

July/August 2001

- NWS and MSC began integration into their workstation computers and development of the public education package.
- The trials recommended some minor changes to the WCTI, adjustments to the WCTI were accomplished by August 3 and provided to weather services.
- As part of the educational process, abstracts on JAG/TI activities and the new WCTI were submitted for presentation at National Weather Association (NWA) and at the annual American Meteorological Society (AMS) meeting.

August 2001

- Third JAG/TI Workshop held August 3 and 4 at DRDC, Toronto, Ontario, Canada:
  - < viewed DRDC wind tunnel and climate chamber where human studies were conducted,
  - < reviewed project status and implementation plans of the weather services,
  - < decided to recommend new WCTI for operational implementation,
  - < MSC, DOD, and NWS requested "time to frostbite" chart and algorithm from researchers, and
  - < reviewed draft document of JAG/TI activities.
- NWS and MSC started internal weather services education process, public/private coordination, and development of media products.

September/October 2001

- The researchers drafted a report on the results of the human studies and development of the WCTI and provided it for inclusion in JAG/TI report document.
- JAG/TI agencies reviewed and commented on draft researchers' report.
- NWS and MSC completed development of education package.
- NWS and MSC finished workstation computer software development.
- NWS issued Public Announcement Statement on new WCTI.

- NWS and MSC began education of forecast offices and public on how to use new WCTI.
- Federal Coordinator, OFCM, notified federal agencies about the new recommended WCTI.
- OFCM gave a presentation on the new WCTI at NWA annual meeting.
- DRDC developed "time to frostbite" algorithm and table, and delivered it in early October to JAG/TI members for approval and implementation.

September through November 2001

- DOD coordinated internal approval to implement new WCTI and education package.

October 31 2001

- Official Implementation of new WCT by Canada MSC.

November 1 2001

- Official Implementation of new WCT by United States NWS.

November-December 2001

- Researchers began development of solar radiation calculations/algorithms for possible addition to the WCTI.
- OFCM contacted CDC to update their web site to reflect the new WCTI.

January 2002

- OFCM, NWS, and MSC presented papers/posters on new WCTI at the AMS annual meeting.
- Fourth JAG/TI Workshop (January 18 and 19):
    - researchers reported the status of the solar radiation calculation development project which included expressing concerns about using it in WCTI because of the complex nature of solar radiation,
    - as a result of implementation deadlines and the scientific complexity, the solar radiation parameter incorporation, which JAG/TI approved for inclusion in the new WCTI, was postponed to be accomplished during the next couple of years,
    - discussed how to evaluate WCTI operation,
    - JAG/TI members began a more detailed review of the extreme heat and solar radiation problems, and
    - JAG/TI members recommended the University of Delaware do an expanded Heat Stress Factor test in 10 cities and recommended MSC and NWS participate and provide an evaluation of the Factor to the JAG/TI.
- OFCM contacted OSHA to ask them to update their references to wind chill and to ask them to participate in JAG/TI activities.

November 2002

- JAG/TI and ISB C6 members presented papers/posters on new WCTI at the co-convened 15th AMS Conference on Biometeorology and Aerobiology/16th International Conference of Biometeorology in Kansas City, MO.
- Fifth JAG/TI Workshop (November 1 and 2), joint with the ISB C6:
    - reviewed further development of improvement to the WCTI; changes will be implemented prior to the 2003-2004 winter season, and
    - reviewed and discussed heat index changes; recommended postponing changes until compartive model results are available from ISB C6.

CHAPTER 5

FOLLOW-ON DEVELOPMENT AND EVALUATION

5.1 <u>Introduction</u>. The JAG/TI is continuing to work with Canada to implement fully compatible programs for temperature indices, including the heat index and temperature ranges that fall between the extremes. This chapter describes several areas that the JAG/TI will focus on in the future.

5.2 <u>WCT Index Follow-on Development</u>. It is expected that the new WCTI will be periodically reviewed and upgraded as additional human data becomes available and as science progresses. Several areas are under consideration for inclusion in any overall WCTI improvements: solar radiation correction, time to frostbite, refinements in both the resistance factor and changes due to the effects of wind and human position (e.g., calm winds, location of winds measured, sitting versus walking), and the effects of "wet" conditions (for fishing or marine transportations).

5.2.1. Status of Solar Radiation Correction Research. The task of providing a solar radiation correction is complex due to the effects of terrestrial extremes and interacting atmospheric physics. There are several variables to consider, including angle of sun, day of year, latitude, elevation, vapor pressure, air temperature, and cloud cover. Cloud cover complicates the calculation by adding in radiation and reflectance of the clouds and subtracting out some of the solar radiation, depending on the type of clouds, total sky coverage, and cloud thickness. Another variable to consider is the albedo of the surface on the ground; for example, snow has a high albedo depending on the extent and depth of coverage. Information provided on the German calculation for solar radiation was reviewed but was not specific enough to calculate the solar radiation factor.

One objective of the WCTI was to warn the public about a hazard or worst case scenario. The danger with adding the solar radiation correction is that it would no longer be the worst case. A conservative stance would be to not include solar radiation. A paper by Danielsson (1996) stated solar radiation could add 5° to 10°C (9-18EF) to temperatures, although his results were based on the Antarctic environment. Also, the effect of solar radiation would level off as wind increased and lead to the significant effect being from the wind.

An actual solar radiation measurement would be the best situation, but most instrument packages currently used do not include this capability. Observations from the NWS are sent in hourly and daily but do not include a solar radiation measurement. Some of the newer instrument packages and observation sites report solar radiation, including the DOE's Atmospheric Radiation Measurement (ARM) sites used for global climate change research and the planned new sites for the NCDC Climate Reference Network. The ARM sites measure several types of radiation and the data is available. JAG/TI members are assessing whether the data can be used in the development of the solar radiation calculation.

The JAG/TI also agreed to delay the incorporation of solar radiation effects to allow the researchers to finish determining the correct adjustments for solar radiation (i.e., the impact of sun) for a variety of conditions, including day time clear, day time cloudy, and night time cloudy. DRDC and IUPUI will continue their project work, with assistance of the rest of the members of JAG/TI, to develop a process for identifying the effect of solar radiation on the WCT. In the meantime, a statement is included on the WCTI charts and accompanying information saying when there are no clouds and the sun is bright, the temperatures will be warmed by 5 to 10°C (9-18EF).

5.2.2 Status of "Time to Frostbite" Research at DRDC. Although a preliminary description, algorithm, and chart of the time to frostbite was provided by DRDC, a more detailed description for any set of conditions is forthcoming. DRDC has measured the resistance factor R at 0.05 with the work on walking humans, versus the 95th percentile R value of 0.091 that was used in the calculation of the wind chill equation. It is suggested that this value be updated in the equations to better represent the population. It is planned that the WCTI will be updated for the 2003-2004 winter season for the new time to frostbite based on the DRDC research.

Problems arise from using the WCTI above freezing in the temperature range where the WCT ends up being below freezing, implying that frostbite might occur. In reality, frostbite will not occur unless the actual air temperature is below freezing. The WCTI charts and descriptive information indicate that no frostbite occurs above an air temperature of 32EF (0EC).

5.2.3 Other areas of improvements. Several other factors can be considered in the improvement of the WCTI. The effect of sitting/standing (resting), as well as walking, should be determined for the wind chill. This might be more useful since people (elderly and young) sit or stand at bus stops in the cold weather, rather than walk and move around. The worse case scenario might actually be people sitting. A lower R value would lower the wind chill temperature. Ethnic origin is another area which could be studied.

The effects of "wet" conditions on wind chill should be addressed. This would be important for industries such as fishing or marine transportation (freezing spray).

5.3 Status of Heat Index Update. The JAG/TI is currently focusing on addressing standardization of the heat indices of both the U.S. and Canada, moving towards a North American standard, and if possible, an international standard. This process will be in collaboration with NOAA NESDIS sponsored research at University of Delaware and with the ISB C6. JAG/TI members are participating in the ISB C6 development of a new UTCI for the full range of temperatures.

5.3.1 Report from 2002 Workshops. The weather services have reviewed the use of their heat indices for replacement or upgrade. For the 2002 summer season, NWS NCEP Hydrometeorological Prediction Center began using the current NWS Heat Index and NCEP's model input to forecast short range excessive heat areas. Current NWS WFO warnings for maximum heat index are done once a day during an event and are based on exceeding a threshold value which is applied regionally. EC/MSC gets hourly observations and issues advisories as needed. NWS and MSC both agreed they needed algorithms that can be calculated within a reasonable time and computer space. The military uses a hand held computer to measure temperature and then gives a recommendation on clothing and activity. They specify standard clothing, type of person, proposed activity, and walking at a slow pace. The military also uses a safety briefing to give out relative warnings on heat and cold extremes. These warnings are based on the Wet Bulb Globe Temperature and OSHA, USDA, and military standards.

Heat index values may be easier to forecast because one could use model output for necessary inputs that are not readily available in current observations, such as solar radiation, convection, and evaporation. A central site could do the calculation by producing a grid with needed parameters (e.g., T, Td, and radiation) and predict core temperatures in the short time frame needed to meet safety margins. The problem then becomes on how to evaluate the model output and on whether current operational indices have been evaluated. One method of evaluation includes the use of the number of injuries and death numbers (decreased or increased numbers), but the statistics are not always available in a timely manner. Another method is to do a comparison of models by looking at the basic parameters and then compare how these parameters are handled, such as evaporation, temperature and radiation. The group agreed to evaluate what is currently in use and suggest any improvements. This led to the need to do a scientific evaluation of Steadman's model (currently used by NWS and other countries), including understanding how winds and solar radiation are handled. Although the JAG/TI did conduct limited comparisons in their earlier meetings, the group agreed it would be worthwhile to readdress this in more detail. After a review of Steadman's later work, it was decided that a more rigorous approach should be taken. Statistics on mortality and morbidity were investigated, though no standard data were available at this time.

5.3.2 Heat Stress Index Research. The University of Delaware is currently conducting research on a new heat stress index (HSI; Watts and Kalkstein 2002). The HSI is a relative measure of how bad an extreme heat incident is for a given location, current weather and climatology. The calculations are based on several climatological factors by city, cloud cover, air temperature, and the Steadman Apparent Temperature Index. The results are expressed in a range from 1 to 10, where 10 is the worst case and the most dangerous to the public. Several experiments were conducted in the summers of 2001 and 2002, the results are currently being evaluated. The JAG/TI agreed that there needs to be more rigorous scientific analysis and experimental testing before a recommendation for operational use is made.

5.4 ISB Commission 6 Progress. The ISB C6 is aware of the JAG/TI work with temperature indices. The Commission had questioned the JAG/TI as to why the U.S. and Canada could not wait until the Commission finished its work before establishing a new wind chill index. As a result of the Commission questions, two U.S. position papers were written and provided to the ISB C6. The papers covered the JAG/TI decisions on the wind chill temperature and heat indices (Appendix B) and the current public debate on the wind chill index problems. These papers pointed out the importance for the ISB C6 members to understand that their recommendations would be for the global environment including North America, and that North America was looking to the Commission for further advice on improving its programs at both ends of the temperature scale. On the extreme heat side of the temperature scale, the current U.S. and Canadian indices differ by several degrees for the same situation, and therefore, both countries look forward to using the Commission guidance to remedy the situation and improve the extreme heat program. Subsequent to reviewing the papers, the Commission recognized the need for the U.S. and Canada to go ahead with the work on wind chill, appreciated the provision of the papers, and welcomed the JAG/TI position on heat index.

In December 2000, the Commission requested a number of modeling groups to produce values from their respective models for intercomparison. On-going discussion centered on the differences in how the models handled solar radiation. Another discussion topic was on acclimation. In addition, a paper called "Looking for a Universal Thermal Climate Index (UTCI) for Outdoor Applications" which described the KMM model was written (Jendritzky et al. 2001). The KMM has a radiation calculation based on temperature, relative humidity, wind, and cloud cover and type, which is being evaluated for use in the future as part of the WCTI.

Following this work and subsequent discussions, the Commission reached decisions on how to proceed in the development of the UTCI. The whole body model will be used, but will also produce effects for the extremities. The average walking speed for the "at risk" population will be 4 km h^{-1} (2.5 mph or 1.1 m s^{-1}; ISO Standard). Wind speed observed at 10 m (33 ft) will be reduced to 1.1 m (3.5 ft; two-thirds of 10 m wind) and assumed to blow at 90 degrees to the walking subject. These were compromises between normal assumptions of the heat and cold indices. There was a lengthy discussion on the wind direction and walking speed, since the U.S. and Canada had agreed to using the wind blowing directly at the face, and in calm winds, a walking speed of 3 mph (4.8 km h^{-1} or 1.3 m s^{-1}). In addition, there were discussions on handling of the radiant fluxes. The Commission has decided to use mean radiant temperature. There will be four inputs: air temperature, water vapor pressure, radiant temperature, and wind speed. The output will be used for frostbite, extreme heat, and hypothermia.

Initial model output on preliminary experiments are due to the C6 in the near future. These will be reviewed and results shared with the JAG/TI. In addition, the JAG/TI and ISB C6 will continue discussion on model evaluation for use in the development of a new UTCI. The Commission members felt there was no urgency to produce the index quickly and established a goal of producing the UTCI over the next two to three years.

5.5 <u>Summary of Future Tasks.</u> The following are several tasks to be addressed by OFCM's JAG/TI over the next several years:

- evaluate the new WCTI in terms of public acceptance and use;
- continue the research into solar radiation calculations so that a solar radiation correction can be added to the temperature indices;
- continue research and model development for "time to frostbite";
- address the extreme heat end of the temperature scale, and improve, develop or adopt a heat index to be used in both the U.S. and Canada;
- evaluate the results of the test of the University of Delaware HSI for possible operational implementation;
- assess whether the ISB C6 results can be scientifically adopted in an operational setting;
- develop the ability to effectively communicate any results or improvements to the end-user; and
- evaluate the human study data on the marine spray simulation for possible use with the WCTI for maritime warnings.

APPENDIX A

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APPENDIX B

U.S. POSITION PAPERS ON TEMPERATURE INDICES

PROVIDED TO THE ISB COMMISSION 6

OFFICE OF THE FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH (OFCM)
COMMITTEE FOR ENVIRONMENTAL SERVICES, OPERATIONS AND RESEARCH NEEDS (C/ESORN)
JOINT ACTION GROUP FOR TEMPERATURE INDICES (JAG/TI)

UNITED STATES POSITION PAPER: WIND CHILL TEMPERATURE INDEX

Background. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) of the National Oceanic and Atmospheric Administration, United States Department of Commerce, is an interdepartmental office established to ensure the effective use of federal meteorological resources by leading the systematic coordination of operational weather requirements, services, and supporting research among the federal agencies. Fifteen federal departments and agencies are currently engaged in meteorological activities and participate in the OFCM's coordination and cooperation infrastructure. In addition to providing a coordinating infrastructure, the OFCM prepares operations plans, conducts studies, and responds to special inquiries and investigations.

For over a year, there has existed public controversy over the current U.S. and Canadian wind chill indices which are based on the Siple & Passel Index. Within the OFCM structure, the Committee for Environmental Services, Operations, and Research Needs formed the Joint Action Group for Temperature Indices (JAG/TI). The purpose of the JAG/TI is to promote cooperation among Federal agencies sharing interest in and responsibility for current and programmed activities affected by apparent temperatures and to recommend changes to more effectively represent apparent temperatures resulting from a combination or interaction of cold or heat and other atmospheric effects such as wind and humidity. Specifically, the JAG/TI is responsible for planning and executing strategies for addressing deficiencies and for reviewing practices and procedures pertaining to the use or development of temperature indices and coordinating any changes to the official Wind Chill Index, Heat index or other indices as needed. The goal of the JAG/TI is to upgrade and standardize internationally, or at least standardize between the U.S. and Canada, the index used for determining temperature extremes.

Discussion. The JAG/TI held a workshop on October 12 and 13, 2000, to begin addressing the temperature index controversy. This first meeting included reviews of reports, papers, and other workshop results on evaluating the current state of wind chill temperature indices. The heat indices will be addressed in future meetings.

The first activity reviewed was a workshop sponsored by the Meteorological Service of Canada (MSC) (Environment Canada (EC)). The one week Internet Workshop on Windchill in late spring produced comments and discussions from experts and the public around the world. Its objectives were to review the science, evaluate the usefulness of the index, discuss the most accurate and acceptable ways of disseminating information and warnings, and work towards recommendations for rigorous experimental research and international harmonization and standards. MSC determined that the way to move forward was to collaborate with efforts for the adoption of an international program, focus on terminology in the short term, implement program changes in an internationally consistent way, and educate their public on any changes to the existing program.

The second activity reviewed was the AMS Applied Climatology Conference Panel Discussion on Wind Chill Temperatures which was attended by several JAG/TI members. The overall consensus of the AMS Panel was that the current operational Siple & Passel based indices should be revised because they generate values that are too cold, especially at cold temperatures and high wind speeds, and do not apply to temperatures above the freezing level.

Also reviewed was the current U.S. National Weather Service (NWS) method for determining the wind chill apparent temperatures.. The NWS Operations Manual has a general description of the program, provides the worst case criteria for wind chill warnings, and refers to Regional NWS Operations Manuals for specifics of how the program is implemented in the field. Each NWS Region establishes a modified set of criteria for warnings based on regional and local atmospheric parameters. The NWS plans to rely on the JAG/TI meetings and workshop to provide a recommendation on how to update or replace the current Siple & Passel based index. Before NWS changes a public program, they are required to give a minimum 60 day notification to the public and private companies, including provision of public education on the program change. In addition, internal NWS coordination and approval of the change will need to be completed before the public is notified.

Mr. Robert Quayle provided a comparative review of the most common, environmentally based, wind chill indices (Steadman, Bluestein & Zecher, Osczevski, and Siple & Passel as used by NWS) which demonstrated that the first three indices' values were similar and that all three outperformed the NWS operational index. The differences between Osczevski and Bluestein's indices are the amount of exposed body part, the inclusion of solar radiation, and how the still conditions are handled. Osczevski's index is a full face model and includes a set value for radiation, while Bluestein's index is a full head model with no radiation considered. Bluestein's model tends to be slightly colder than Osczevski's model which appears to be related to radiation considerations and the handling of still conditions. Osczevski and other models use a wind speed in still conditions set at 4 mph because the standard cup anemometer stops at this speed. If Bluestein's index is changed to use a face model and add radiation or Osczevski's to Bluestein's head model and the radiation value is not added, the temperatures would be nearly the same. Steadman's model uses a whole body model represented by a cylinder, adds many more environmental variables, and incorporates clothing assumptions. The new (June 2000) operational NWS Heat Index is based on the warm end of the Steadman Apparent Temperature scale but uses only temperature and humidity.

Results. After reviewing the U.S. NWS operational requirements, the JAG/TI members determined that the U. S. Federal government's responsibility was to address temperature extremes and safety, not necessarily what clothing to wear or public comfort. The most important function of a wind chill program was to address safety and cover the most extreme situations (bare skin). Comfort factors could also be considered, but as a secondary function. This leads to an index that is based on environmental factors as the prime scientific input to the index algorithm. The results of the comparison studies led the JAG/TI members to agree that the current NWS wind chill index produced wind chill temperatures that were too cold, creating a false sense of temperatures by the public. A new index should be science-based by addressing proper heat transfer aspects, include appropriate environmental parameters, and be easily explainable to the public. This has been accomplished in many of the indices, including Osczevski, Bluestein & Zecher, Hoeppe, and

Jendritzky et al. models/indices. Although more comprehensive by taking into account many more environmental factors, Steadman's model appears to be complicated and may not be able to get all of the required environmental factors from standard atmospheric observations. Osczevski's and Bluestein's indices both use a bare skin model while the other models use a standard clothed human body model. For the comfort factor, the Hoeppe and Jendritzky et al. models might work if clothing amounts were precisely defined and could vary, and other parameters were easily turned on and off. These physiological models may have a basic assumption problem resulting from the physiology of a body, which changes from person to person and depends on size, shape, weight, circulation factors, etc. On the other hand, a face doesn't vary much from one individual to the next and is a sensitive "instrument" that is normally exposed, with the most cold felt on the face. Use of the face model means one doesn't have to account for clothing nor need to define a "standard" human.

Recommendations. The JAG/TI members agreed to the following recommendations:

1. The new wind chill index should be based on an algorithm that is scientifically defendable, reasonable, understandable, and simple; obtain its basic input from existing environmental observations; be based on experimental data and not human comfort; and be based on heat budget theory. This index could be used by others as input to "comfort" indices that include clothing concerns. By associating the wind chill index with the environment, those who wish to go a step further into the interpretation of human comfort could do so.

2. Having an internationally agreed to index is preferable, but at least there should be an agreement between the U.S. and Canada on using a common index. The group recommends that the output should be the same in both Canada and the U.S., and be an equivalent temperature. In addition, the members recommended that both countries switch to the new index at the same time. This consistency aspect was seen as important for the U.S. and Canada because of the movement of the public between the two countries.

3. At the initial stage, wind, air temperature, and solar radiation should be the environmental factors used. As further research progresses on how to handle other environmental parameters, the results could be incorporated into this simple index.

4. The uncovered frontal cylinder or face should be used to represent the bare skin human model, since it represents the worst case and tends to be uncovered. The nose, chin and ears are the most likely part of the body to feel the cold and freeze first.

5. The Bluestein's and Osczevski's indices should be combined and should include the addition of a radiation calculation, for the following reasons: their indices

- are the closest to the environment,
- have made the least assumptions,
- are based on bare skin that is exposed first,
- could be operational in a relatively short period of time,
- do not depend on body characteristics,
- can be implemented anywhere,
- use parameters that are available in standard environmental observations,
- could have a radiation calculation added scientifically, and
- are reasonably simple and could be explained to and understood by the public.

In addition, Mr. Osczevski has a testing facility where testing of a new index algorithm could be accomplished, if funding is available. These scientists have agreed to work together on a common index.

6. The output product should be an equivalent or apparent temperature in both Fahrenheit and Centigrade degrees, with warnings issued for extremes only. Limited user surveys on wind chill index information in the U.S. and more extensive surveys in Canada favor the use of apparent temperatures and warning on extremes.

7. Public Education should be conducted prior to and after the implementation of the new index. This education should stress that this change to the current index is an improvement on the old index and incorporates more information.

Note: The JAG/TI found that it was difficult to directly compare programs in Europe to U. S. because, in general, the Europeans tended to advise the public on what they should wear and are tied to physiology, while the U.S. warned the public of environmental dangers and kept their index tied to a property of the environment. This difference may have resulted from North America experiencing more extremes of temperatures and environment than Europe has experienced. One possibility is to have two complementary indices: one index based on the properties of the environment and the second follow-on index that ties the temperature to what one should wear and that uses the first equation as input.

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COMMITTEE FOR ENVIRONMENTAL SERVICES, OPERATIONS AND RESEARCH NEEDS (C/ESORN)
JOINT ACTION GROUP FOR TEMPERATURE INDICES (JAG/TI)

UNITED STATES POSITION PAPER: HEAT INDEX

Background. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) of the National Oceanic and Atmospheric Administration, United States Department of Commerce, is an interdepartmental office established to ensure the effective use of federal meteorological resources by leading the systematic coordination of operational weather requirements, services, and supporting research among the federal agencies. Fifteen federal departments and agencies are currently engaged in meteorological activities and participate in the OFCM's coordination and cooperation infrastructure. In addition to providing a coordinating infrastructure, the OFCM prepares operations plans, conducts studies, and responds to special inquiries and investigations.

Within the OFCM structure, the Committee for Environmental Services, Operations, and Research Needs formed the Joint Action Group for Temperature Indices (JAG/TI). The purpose of the JAG/TI is to promote cooperation among Federal agencies sharing interest in and responsibility for current and programmed activities affected by apparent temperatures and to recommend changes to more effectively represent apparent temperatures resulting from a combination or interaction of cold or heat and other atmospheric effects such as wind and humidity. Specifically, the JAG/TI is responsible for planning and executing strategies for addressing deficiencies and for reviewing practices and procedures pertaining to the use or development of temperature indices and coordinating any changes to the official Wind Chill Index, Heat index or other indices as needed. The goal of the JAG/TI is to upgrade and standardize internationally, or at least standardize between the U.S. and Canada, the index used for determining temperature extremes.

Discussion. As a follow-on to the October JAG/TI workshop, the JAG/TI members and participants met on February to review the U.S. and Canadian heat indices and programs. This meeting included reviews of weather services programs, reports, papers, and other workshop results on the extreme temperature indices. The following paragraphs review the current U.S. and Canadian operational heat indices and warning programs and the University of Delaware research efforts.

a. Environment Canada. The Canadian heat index, Humidex, has been used for about 22 years. Humidex uses temperature and relative humidity to determine how hot the weather feels to any person. It reports in degrees C and is considered significant if the temperature is greater than 30° C and the Humidex value is greater than 40° C. There is also a scale of discomfort which splits the temperatures from 29° to 54° C into discomfort levels. In general, the Humidex values tend to be higher than the U.S. heat index, except at the extreme end where they tend to be slightly lower.

Advisories are issued by the Meteorological Service of Canada in only two provinces, Ontario and Quebec.

b. U.S. National Weather Service (NWS). NWS issues outlooks, watches and warnings using a version of Steadman's index, represented as a table. The last incorporated update to this table and to the NWS operational program was in 1992. NWS Weather Forecast Offices' (WFOs) computers (AWIPS) use a U.S. derived regression algorithm to approximate the table, although it appears to be unstable at the lower end. It also doesn't take into account the number of days that the extreme heat has existed, cool night time temperatures, and regional acclimation. In addition, there is a table on the NWS web site which describes in words the heat index. In the NWS operations manual, there are descriptions of the effects of extreme heat and humidity. three NWS regions do not issue advisories and warnings: Western, Pacific, and Alaska. Eastern, Southern, and Central Regions do issue advisories and warnings, and have each set regional criteria to accommodate adjustments. These criteria are used by the WFO's to decide whether or not to issue an advisory.

The NWS heat extreme forecast product was first officially issued last summer by the NWS National Centers for Environmental Prediction (NCEP) Climate Prediction Center (CPC), was developed from a training set of observed data, a linear regression fit of 500 mb heights and 850 mb temperature fields, and approximates the algorithms of the NWS Heat Index (modified Steadman's Apparent Temperature Index). This was combined with NCEP's Medium Range Forecast (MRF) model, and the MRF ensemble model output to produce a prediction of apparent temperatures. CPC has found following problems with the product: the MRF ensembles were not very good at forecasting extremes (tends to under forecast); the training data were not good or complete (needs soil moisture); and the linear regression fit was unstable. CPC plans to add soil moisture; replace the regression fit with the use of 1000-500 mb thickness, 1000-850 mb thickness, and 1000 mb height fields; use Steadman's Index table instead of approximate algorithms; and improve the look of the products by the 2001 season.

c. University of Delaware. At the University of Delaware, several graduate students are working on a relative comfort index, where relative relates to accounting for different locations. The U.S. National Climate Data Center (NCDC) has provided funding and the Steadman algorithms (circa 1998) for this project. This relative comfort index is based on Steadman's Apparent Temperature (AT) Index, regional means, prolonged exposure or consecutive day effect, and represents the percent difference from the mean conditions. A daily stress value is calculated. The model uses U.S. Surface Airways reports which have wind speed, temperature, dew point temperature, and information to calculate solar radiation. This comfort index incorporates: consecutive day effect, max/min AT, mean cloud cover (10 am to 6 p.m.), cooling degree days, and 30 years of data at 275 first order stations. Currently, work is focused on the summer/high heat application to various locations. A winter side will be worked on later and would represent the opposite end of the index. Possible applications are for the NCDC climate atlas, public health initiatives, and problems related to animal stress. Another aspect of this research effort is a graduate study of the effects of temperatures on livestock production. Live stock managers and agricultural experts have noted that animal food intake is affected by extremes of heat and cold. The relationship between air temperature and livestock production is well established. There is a zone where the animals are comfortable and thresholds where production begins to decline. This can be quantified because the animals will not produce as much milk or eggs and their eating patterns change. Temperature, relative humidity, wind, number of consecutive days, available shade, and precipitation have to be taken into account when determining how much food will be eaten and converted to growth or production by animals. For instance, at -10^o F ranchers need to add 7 to 8 lbs of hay per cow and 4 to 5 lbs of grain per cow to fill their energy needs to maintain body weight. If the threshold is wrongly predicted, there will be expending of feed when not needed or not enough feed which results in weight loss or decrease in production of milk or eggs. Both will result in decreased profits for the owner. To limit feed waste, the rancher would need to decrease the amount of feed because the cattle eat less during extreme heat conditions. Another aspect considered is the animals hair or feathers which can provide insolation. The condition of the cow's hair needs to evaluated, which is also a function of exposure to the environment, especially wind and precipitation. In general, state agriculture departments develop food intake tables that use the NWS wind chill and heat index output, a percentage adjustment for the environment, and adjustments for hair condition to determine the recommended food amount per day for animals such as cows. The project is based on developing a comprehensive means to accommodate all the factors in a table or index that is easily applied by the livestock manager. Another reason that livestock managers need to know the temperature extremes would be for transport of animal, where one would be more concerned about mortality issues.

Recommendations. The JAG/TI members agreed there did not appear to be any major problems identified with the present indices in U.S. or Canada. The major reason for upgrading the heat index is to replace old technology with better scientifically based equations that use more of the now known affecting parameters. Two areas that needed to be addressed are: these two North American indices do not result in the same values for the same conditions, which is confusing for the public, and the U.S. WFOs have identified wind as a parameter that makes a difference. Public pressure to upgrade the heat index is not present at this time, but could occur if there was another heat wave episode like the 1995 heat wave in Chicago. This current situation allows for the slow movement on updating the heat index to ensure that a better, improved index is adopted. The JAG/TI members recommended waiting for the results of the ISB Commission 6 discussions on a universal temperature index before making judgment on heat index improvements or replacement.

The JAG/TI members did recommend that the following be included as input to the heat index: solar radiation (based on cloud cover and type, latitude and longitude), temperature, humidity, and wind. Precipitation is another parameter to consider but it is not in some of the indices. This may need to be accommodated by the forecasters. Soil moisture will be added to the U.S. forecast model of apparent temperatures from satellite observations but is not currently considered appropriate for the index. How many days extreme heat has existed and whether or not there are cooling nights need to be taken into account, since the effects of a heat wave are not instantaneous but cumulative. Another variable shown to be important is the time of occurrence within the season. This may be related to acclimation or mortality. This might be hard to incorporate as part of an index, but including this as a forecaster adaption is possible. There are also differences of how to address the problem (comfort and extremes/safety) and between instantaneous and cumulative values. For instance, the wind chill value is instantaneous and the extreme heat value is cumulative but for both of these the meteorological services in Canada and U.S. warn on extremes for public safety.

Specifically, the JAG/TI members agreed to recommend for consideration by the ISB Commission the following concerning heat index:

- the index should be capable of regional adaption by the forecaster but not acclimatized;
- smog would not be a component but kept separate;
- the output should be temperature based in degrees C or F;
- consecutive high temperature days and cooling nights should be considered
- temperature, humidity, solar radiation, and wind should be as included input;
- a simple heat index chart for use by local forecasters and public is preferred, with CPC NWP forecast product more complicated;
- for now, no soil moisture and precipitation should be used as input to index, although CPC is planning to use soil moisture as input in their model; and
- proper air mass handling and turbidity should be part of the NWP forecast model guidance products but not as input to forecaster held index.

Perspective. For the extreme heat and the in-between comfort range, NWS and EC are very much interested in the recommendations of the ISB Commission 6. The JAG/TI perspective is North America is approaching the update of temperature indices incrementally. As a first step, the JAG/TI is planning to improve upon the U.S. and Canadian current wind chill program by adopting the results of the Dr. Maurice Bluestein and Mr. Randall Osczevski's collaboration. These results will be used to design the public education and actual operational program for the coming winter (2001-2002). This will allow them to make a significant improvement in the program.

Our operational public programs have been criticized for the inaccurateness of the wind chill index, and deadlines exist for installing an update before the next winter season. This ties into the mission of the weather services to enhance the safety of the public by advising them of adverse weather. We need to get on with the best science as soon as possible. With the movement to a temperature scale in Canada, making incremental improvements in the future should be relatively easy. Increased public awareness of the wind chill errors and public pressure are pushing the U.S. and Canada to fix it now, not later. The JAG/TI members agree that it would be better to incorporate as many of the known improvements as possible in our first change, which will result in major improvements to the operational program. Other changes recommended by the ISB can be inserted incrementally in the near future. This project is a compromise in the middle of the complexity range of indices, between the U.S./Canadian indices and the more complex German indices. The U.S. and Canada have a slightly different perspective for the wind chill program than the approach of the ISB Commission 6. Their services warn for the worst case scenario and are not oriented to a climate based index approach for wind chill. The U.S. and Canada were definitely interested, long term, in the recommendations of the commission and in using these results for updating or replacing our indices that cover the rest of the temperature scale. The U.S. and Canada will be looking to the results of the ISB Commission June meeting to improve our program in subsequent years. The JAG/TI will examine the results of the ISB Commission 6 meeting from the perspectives of:

- differences from our interim improvement to our wind chill temperature index programs;
- the ability to adopt those results scientifically in an operational setting;

- the ability to effectively communicate those results/improvements to the end-user; and
- specifically, the requirement to address the extreme heat end of the temperature scale.

The JAG/TI members think it is extremely important that the ISB Commission 6 members understand that their recommendations would be for the global environment including North America, and that North America is looking to the Commission for further advice on improving its programs at both ends of the temperature scale. On the extreme heat side of the temperature scale, the current U.S. and Canadian indices differ by several degrees for the same situation, and therefore, both countries look forward to using the Commission guidance to remedy the situation and improve the extreme heat program. On the cold side of the temperature scale, North America is taking some initial steps to rectify the major obvious shortcomings in the program that are in the public's eye and will be looking to the Commission for advice on further improvements.

APPENDIX C

ACRONYM AND ABBREVIATION LISTING

-A-

AMS	American Meteorological Society
ASOS	Automated Surface Observing System
AT(s)	Apparent Temperature(s)
AWIPS	Advanced Weather Interactive Processing System

-B-

BMI	Body Mass Index

-C-

C	Celsius
C6	Commission 6 (ISB)
CDC	Centers for Disease Control and Prevention
C/ESORN	Committee for Environmental Services, Operations and Research Needs
CIVD	Cold Induced Vasodilation
CNMOC	Commander Naval Meteorology and Oceanography Command
CPC	Climate Prediction Center
CRREL	Cold Regions Research and Engineering Laboratory

-D-

D2D	AWIPS Display 2-Dimensional
DCIEM	Defence and Civil Institute of Environmental Medicine
DOE	Department of Energy
DRDC	Defence Research and Development Canada

-E-

EC	Environment Canada
EPA	Environmental Protection Agency

-F-

F	Fahrenheit
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
Ft	Frostpoint Time

-H-

h	hour(s)
hPa	hectopascal
Humidex	Canadian heat index
HWR	AWIPS Hourly Weather Roundup

-I-

IFPS	AWIPS Interactive Forecast Preparation System
ISB	International Society of Biometeorology
IUPUI	Indiana University-Purdue University at Indianapolis

-J-

JAG/TI	Joint Action Group for Temperature Indices

-K-

K	temperature in Kelvin
KMM	Klima-Michel-Model
km h^{-1}	kilometers per hour

-M-

m^2 K W^{-1}	meters squared times degrees Kelvin per watt
m s^{-1}	meters per second
mph	miles per hour
MRF	Medium Range Forecast model
MSC	Meteorological Service of Canada

-N-

NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NWR	NOAA Weather Radio
NWS	National Weather Service (U.S.)
NWWS	NOAA Weather Wire Service

-O-

OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
OSHA	Office of Safety and Health Administration

-P-

PET	Physiological Equivalent Temperature
PT	Perceived Temperature

-R-

R	resistance factor used in insulation materials

-T-

T or Tair	air temperature
Td	dewpoint temperature
TMH	Thermal Manikin Head

-U-

USA	U.S. Army
USACE	U.S. Army Corps of Engineers
USAF	U.S. Air Force
USARIEM	U.S. Army Research Institute of Environmental Medicine
USMC	U.S. Marine Corps
USN	U.S. Navy
UTCI	Universal Thermal Climate Index
US or U.S.	United States

-V-

V	wind speed

-W-

WCT	Wind Chill Temperature
WCTI	Wind Chill Temperature Index
WFO(s)	Weather Forecast Office(s)
WHO	World Health Organization
W m^{-2}	watts per meter squared or watts/$meter^2$
WMO	World Meteorological Organization
WSI	Weather Stress Index

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