

# Recent Changes in Wind Chill Temperatures at High Latitudes in North America

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## **Abstract**

Afternoon wind chill temperatures at fifteen Alaskan and northern Canadian stations in the months October through April have increased in most months and at most stations in the period 1953-1993 (that is, “apparent temperatures” have become warmer). Many monthly means increased by more than 5° C over the period. Though increases in air temperature had a dominant effect on increases in wind chill temperature, decreases in wind speed generally contributed to the wind chill temperature increases. The largest and most persistent positive trends in wind chill temperature were in Alaska and western Canada, with negative and smaller positive trends in central, eastern, and northern Canada. As a result of the trends, humans outdoors in the afternoon have experienced an “apparent” warming even larger than the warming indicated by the air temperature trends.

## **1. Introduction**

North American high latitudes have warmed considerably in the last five decades. Mean annual temperatures have increased by about 2° C in Alaska (National Assessment Synthesis Team, USGCRP, 2000) and more than 1° C in the western two-thirds of northern Canada (Zhang et al., 2000) during that period. One of the impacts of this warming is its effect on human comfort, and here we assess that effect on outdoor activities during the cold season. The effect of the warming on human outdoor activities must include some consideration of wind, since the combination of

wind and temperature produces an “apparent temperature”, that is, a value that indicates what the exposed areas of a human body actually experience. Wind chill temperature is such a value.

Wind chill temperature has been used for several decades as a measure of discomfort and potential danger for humans. It can be defined as the temperature that would, with no wind, produce a heat loss from human skin equivalent to the loss produced by the ambient air temperature and ambient wind. The formulation of wind chill temperature currently in use is based on the work of Siple and Passel (1945, hereafter S&P), who empirically determined the rate of heat loss from water in a plastic container in a variety of wind and temperature conditions in Antarctica.

The use of the S&P formulation of wind chill temperature, though widespread and popular, has been the subject of some criticism (Kessler, 1993; Steadman, 1971; Osczevski, 1995; Bluestein, 1998). Steadman (1971), Osczevski (1995), Osczevski (2000), Bluestein (1998), Bluestein and Zecher (1999), and Quayle and Steadman (1998) employed both theoretical and empirical methods to more accurately calculate heat loss and wind chill temperature. All of the above research indicated that wind chill values derived using the S&P method were generally more extreme than those based on the other approaches. Nevertheless, in spite of the controversy surrounding the use of the S&P method for calculation of wind chill temperature, that method has been used by the United States National Weather Service and the Meteorological Service of Canada, although in Canada the wind chill has been reported as both a temperature and a rate of heat loss (in  $W/m^2$ ). Because of the continued and familiar use of the S&P method of wind chill temperature calculation, and because we are simply examining trends over time, we employ it in

this analysis. Subsequent to the development of the results of this paper, an improved wind chill temperature formula was developed by a special group formed by the U. S. Office of the Federal Coordinator for Meteorological Services and Supporting Research. This new formula will be implemented by the U. S. and Canadian meteorological services during fall, 2001 (National Weather Service, 2001).

## **2. Data and Methods**

Hourly wind speed and temperature data from early to mid-afternoon (a period when outdoor activity is common) from fifteen North American (six Alaskan and nine Canadian) stations located between 55° N and 75° N were used in this analysis (see Figure 1). The data were part of the North American synoptic station dataset described in Groisman et al. (2000), and the period of record is 1953 through 1993. Data homogeneity is difficult to assess, as station metadata are either absent or poorly documented. In Alaska there were some station moves, along with changes in anemometer height (P. Groisman, personal communication). The degree of homogeneity of the Canadian stations is not known. Though it is possible that some station changes may have affected the results for individual stations, the overall pattern of change that we describe is unlikely to have been influenced by such factors.

The hours used ranged from 1200 local time through 1500 local time; the hour used for each station depended on availability of data for the given hour for the full period of record. Of the fifteen stations, twelve had data for 1400, one for 1200, one for 1300 and one for 1500. A station was included only if, for all months for the full period of record, at least 75% of all selected hours in the month had both temperature and wind speed.

For each hourly observation used, wind chill temperature was computed according to the S&P formula:

$$\text{WCT} = 0.045(5.27W^{0.5} + 10.45 - 0.28W)(T - 33) + 33, \quad (1)$$

where WCT is wind chill temperature in °C, W is wind speed in km/hr and T is dry bulb temperature in °C. When W is less than 7 km/hr, equation 1 produces a WCT which is greater than T. In these cases we set WCT=T. As W surpasses 88 km/hr, equation 1 actually produces increasing WCT; therefore, for the very small number of wind speeds in excess of 88 km/hr (17 observations over all stations), the value of 88 km/hr was used for W. Monthly means of T, W, and WCT were computed for October through April, the months during which wind chill temperatures would have a significant impact. Means of T, W, and WCT were also computed for the full period of October through April. For each of the months and for the October-April period trends in T, W, and WCT were calculated. Data were available for five of the six Alaskan stations (all but Bettles) for the period 1949-1997. Monthly means and trends for those stations were also computed for the longer period. All trends were calculated using ordinary least squares (OLS) regression. Inspection of all time series plots indicated that outliers, which can produce large errors in OLS trends, did not present a problem, and that the trends were gradual and not representative of sudden changes in values

Since the new wind chill temperature formula became available prior to final revision of this paper, monthly trends were also calculated for the 1953-1993 period using the new formula:

$$\text{WCT} = 13.1267 + 0.6215T - 11.3612V^{0.16} + 0.3961TV^{0.16}, \quad (2)$$

where WCT, W, and T are as defined for the S&P formula (equation 1).

### 3. Results

Table 1 lists the trends in S&P wind chill temperature, dry bulb temperature, and wind speed. Of the 105 monthly WCT trends (fifteen stations x seven months) 76% were positive (i.e. “apparent temperatures” got warmer over the period of study). Figure 2 shows the geographical pattern of trends. The largest positive WCT trends occurred in December, January, March and April, with some stations in each of those months showing WCT warming of 7° C or greater over the 41 year period. 47% of the warming trends in those months were significant at the .05 level. Ten of the fifteen stations showed WCT warming in at least five of the seven months, with Annette Island, King Salmon, and Yakutat warming in every month. For the full October-April period 13 stations had positive WCT trends, seven of which were significant at the .05 level.

October and November had the largest number of stations with negative WCT trends. Only one month for one station (February at Iqaluit) showed WCT cooling that was significant at the .05 level (about 7° C over the 41 year period). Only Resolute and Iqaluit showed WCT cooling in at least four months (Figure 2).

To assess the reasons for the trends in WCT, we examined trends in temperature and wind speed. 66% of the monthly trends in T were positive, while 64% of the monthly trends in W were negative. As a first approximation, one would expect to see mostly positive WCT trends, since both increases in temperature and decreases in wind speed produce higher wind chill temperatures. However, the non-linearity of the WCT formula makes extremely non-trivial any mathematical assessment of the degree to which a trend in WCT is the result of either the T trend or the W trend. Nevertheless, some reasonable relationships between the trends in WCT and those in T and W can be deduced by the use of Table 2. For example, for a positive trend in

WCT, if the T trend is positive and the W trend is negative (both of which contribute to an increase in WCT), the cause of the WCT trend is a combination of the trends in T and W.

Likewise, for a positive trend in WCT, if the T trend is positive (which contributes to an increase in WCT) and the W trend is positive (which contributes to a decrease in WCT), the cause of the WCT trend can be attributed to T. The combinations +/-/+ and -/+/- would not be expected, and they did not occur. Most of the increases in WCT were related to an increase in temperature, or a combination of lower wind speeds and higher temperatures. These results are color-coded in Figure 2.

Table 3 shows that temperature had an effect in 83% (82%) of the cases of positive (negative) WCT trends and that temperature was the sole effect in 28% (43%) of those cases. From Table 1 only 15% of all months had a T trend opposite in sign to its corresponding WCT trend.

October, November, and February had the largest number of negative WCT trends, and, where WCT increased in those months, the trends were smaller. All Alaskan stations had positive WCT trends significant at the .05 level in December. Those stations retained positive trends into January, but the larger and more significant trends in January appear in western Canada (Figure 2). Most stations in Alaska and western Canada had positive WCT trends in February, though the trends were smaller than those in January. Those stations had increased positive trends in March, with trends at eight of the stations significant at the .05 level. In April the significant positive trends were all in western Canada. In general, the western part of the study area had the most (and the most significant) positive WCT trends, while the more eastern and northern stations had either more negative trends or smaller positive trends. Iqaluit, the station farthest

east in the study area, had positive WCT trends only in October and November and also had negative T trends in all seven months.

The 49 year (1949-1997) WCT trends for the five Alaskan stations (not shown) exhibit statistics similar to those for the 41 year trends with the trends for the 1953-1993 period being, in general, larger than the trends for the 1949-1997 period.

The trends computed using the new wind chill equation (not shown) were quite similar to the trends computed using the S&P formula. Only five monthly trend values had different signs, and all of those were small trends. The magnitudes of the great majority of new wind chill temperature trends (both positive and negative) were smaller for positive trends and larger for negative trends, most by about  $0.1^{\circ}$  to  $0.3^{\circ}$  C/10 yr. Thus, even though there can be large absolute differences in the wind chill values derived using the two methods, the differences in the wind chill temperature trends were quite small. The overall spatial and temporal patterns of the two sets of trends were also quite consistent.

#### **4. Conclusions**

Afternoon wind chill temperatures at Alaskan and northern Canadian stations in the months October through April have increased in most months and at most stations in the period 1953-1993 (that is, “apparent temperatures” have become warmer). Most of the increases in wind chill temperature have been due to a combination of temperature increases and wind speed decreases, though a large number of wind chill temperature increases are due solely to increases in temperature. In the 27% of station-months with wind chill temperature decreases, 43% are due solely to decreases in temperature.

The largest and most persistent positive trends in wind chill temperature were in Alaska and western Canada, with negative and smaller positive trends in central, eastern, and northern Canada. This is consistent with the fact that most positive wind chill temperature trends corresponded to positive temperature trends, and temperature trends decreased eastward and northward from Alaska across Canada. At both Iqaluit and Resolute most wind chill temperature trends were negative.

In 71% of the cases with positive trends in wind chill temperature, the trend in wind speed had an effect. So, even though increases in temperature had a dominant effect on increases in wind chill temperature, decreases in wind speed generally contributed to the increases in wind chill temperature. Indeed, 64% of all monthly wind speed trends were negative, and some stations exhibited 1953-1993 wind chill temperature increases in some months which were 2° to 3° C greater than corresponding temperature increases. As a result, humans outdoors in the afternoon have “felt” a warming even larger than the warming indicated by the temperature trends over the last five decades.

The warming at high latitudes since the 1950s is well documented; the decrease in wind speeds is not. Two questions arise: Are the processes that produced the substantial warming also responsible for the decreases in wind speed? Will the projected future warming at high latitudes be accompanied by further decreases in wind speed, producing an “apparent” warming in the cold seasons greater than the “actual” warming?

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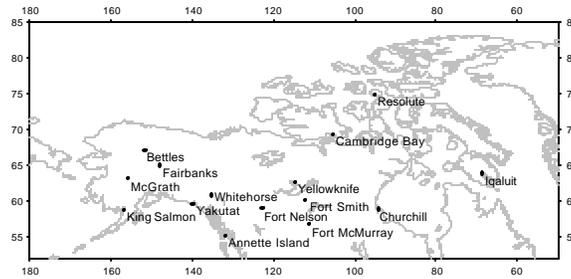


Figure 1. Stations used in the study.

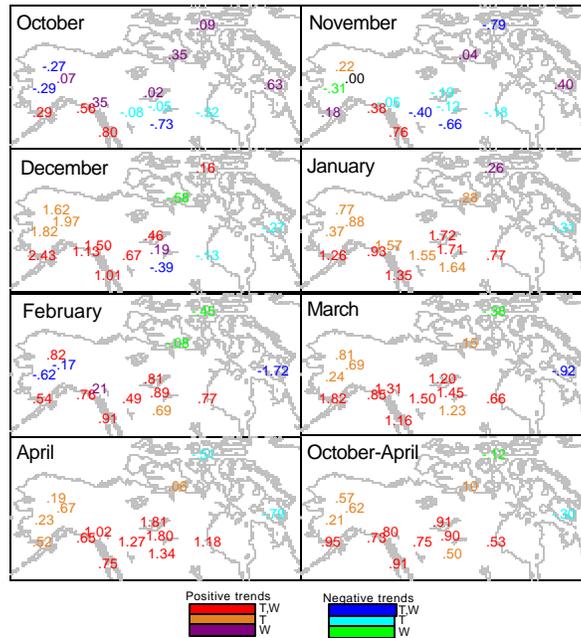


Figure 2: 1953-1993 trends in mean wind chill temperature ( $^{\circ}\text{C}/10 \text{ yr}$ ). Trends are color coded for positive/negative and for whether temperature (T), wind speed (W), or both (T,W) are responsible for the trends. See Table 2.

Table 1: 1953-1993 trends in mean S&P wind chill temperature (WCT), dry bulb temperature (T), and wind speed (W) for the months of October through April and for the seven month period of October to April. Units for WCT and T are °C/10 yr; units for W are km hr<sup>-1</sup>/10 yr. Values in bold type are significant at the .05 level. Values in bold and underlined are significant at the .01 level.

|                     | Oct          |              |                     | Nov         |             |              | Dec         |              |                     | Jan         |              |              |
|---------------------|--------------|--------------|---------------------|-------------|-------------|--------------|-------------|--------------|---------------------|-------------|--------------|--------------|
|                     | WCT          | T            | W                   | WCT         | T           | W            | WCT         | T            | W                   | WCT         | T            | W            |
| Annette Island, AK  | <b>0.80</b>  | 0.17         | <b><u>-2.11</u></b> | <b>0.76</b> | 0.16        | <b>-1.76</b> | <b>1.01</b> | 0.30         | <b><u>-1.89</u></b> | <b>1.35</b> | 0.65         | <b>-1.30</b> |
| Bettles, AK         | -0.27        | -0.16        | 0.16                | 0.22        | 0.25        | 0.08         | <b>1.62</b> | <b>1.75</b>  | 0.39                | 0.77        | 0.84         | 0.24         |
| Fairbanks, AK       | 0.07         | -0.05        | -0.17               | 0.00        | 0.02        | -0.02        | <b>1.97</b> | <b>1.96</b>  | 0.15                | 0.88        | 0.99         | 0.39         |
| King Salmon, AK     | 0.29         | 0.04         | -0.55               | 0.18        | -0.03       | -0.37        | <b>2.43</b> | <b>1.85</b>  | -0.07               | 1.26        | 0.91         | -0.26        |
| McGrath, AK         | -0.29        | -0.12        | 0.32                | -0.31       | 0.01        | <b>0.81</b>  | <b>1.82</b> | <b>1.78</b>  | <b>0.50</b>         | 0.37        | 0.47         | <b>0.58</b>  |
| Yakutat, AK         | <b>0.56</b>  | 0.12         | <b>-1.23</b>        | 0.38        | 0.02        | -0.86        | <b>1.13</b> | 0.46         | <b>-1.14</b>        | 0.93        | 0.47         | -0.57        |
| Cambridge Bay, Can. | 0.35         | -0.08        | -0.67               | 0.04        | -0.16       | -0.23        | -0.58       | 0.30         | 1.08                | 0.28        | 0.23         | 0.00         |
| Churchill, Can.     | -0.32        | -0.50        | <b>-0.84</b>        | -0.18       | -0.68       | <b>-1.40</b> | -0.13       | -0.47        | -0.58               | 0.77        | 0.50         | -0.34        |
| Fort Nelson, Can.   | -0.08        | -0.18        | -0.06               | -0.40       | -0.49       | 0.01         | 0.67        | 0.49         | -0.10               | <b>1.55</b> | <b>1.41</b>  | 0.00         |
| Fort Smith, Can.    | -0.05        | -0.36        | <b>-0.78</b>        | -0.12       | -0.38       | -0.49        | 0.19        | -0.08        | -0.36               | <b>1.71</b> | <b>1.38</b>  | -0.17        |
| Iqaluit, Can.       | 0.63         | -0.10        | -1.63               | 0.40        | -0.09       | -0.64        | -0.27       | -0.78        | -0.99               | -0.31       | -0.76        | -0.75        |
| Resolute, Can.      | 0.09         | 0.00         | -0.07               | -0.79       | -0.21       | 0.48         | 0.16        | 0.04         | -0.20               | 0.26        | -0.10        | -0.68        |
| Fort McMurray, Can  | -0.73        | -0.59        | 0.18                | -0.66       | -0.52       | 0.09         | -0.39       | -0.22        | 0.27                | <b>1.64</b> | <b>1.72</b>  | 0.49         |
| Yellowknife, Can.   | 0.02         | -0.26        | <b>-0.72</b>        | -0.19       | -0.34       | -0.42        | 0.46        | 0.02         | -0.59               | <b>1.72</b> | 1.02         | -0.64        |
| Whitehorse, Can.    | 0.35         | -0.06        | <b>-0.93</b>        | -0.05       | -0.23       | -0.54        | 1.50        | 1.02         | -0.55               | 1.57        | 1.40         | 0.11         |
|                     | Feb          |              |                     | Mar         |             |              | Apr         |              |                     | Oct-Apr     |              |              |
|                     | WCT          | T            | W                   | WCT         | T           | W            | WCT         | T            | W                   | WCT         | T            | W            |
| Annette Island, AK  | 0.91         | 0.36         | -1.37               | <b>1.16</b> | <b>0.60</b> | <b>-1.19</b> | 0.75        | 0.38         | -0.86               | <b>0.91</b> | 0.35         | <b>-1.40</b> |
| Bettles, AK         | 0.82         | 0.55         | -0.08               | 0.81        | 0.93        | 0.39         | 0.19        | 0.32         | 0.28                | 0.57        | 0.61         | 0.22         |
| Fairbanks, AK       | -0.17        | -0.17        | 0.10                | 0.69        | 0.81        | 0.42         | 0.67        | 0.56         | 0.01                | 0.62        | <b>0.62</b>  | 0.12         |
| King Salmon, AK     | 0.54         | 0.26         | -0.38               | <b>1.82</b> | <b>1.35</b> | -0.40        | 0.52        | 0.53         | 0.19                | <b>0.95</b> | <b>0.68</b>  | -0.20        |
| McGrath, AK         | -0.62        | -0.39        | 0.27                | 0.24        | 0.42        | 0.58         | 0.23        | 0.21         | 0.10                | 0.21        | 0.32         | <b>0.42</b>  |
| Yakutat, AK         | 0.76         | 0.28         | -0.82               | <b>0.85</b> | 0.59        | -0.25        | 0.65        | 0.48         | -0.23               | <b>0.73</b> | 0.34         | -0.69        |
| Cambridge Bay, Can. | -0.08        | 0.58         | 0.83                | 0.15        | 0.64        | 0.94         | 0.06        | 0.00         | 0.15                | 0.10        | 0.27         | 0.31         |
| Churchill, Can.     | 0.77         | 0.23         | -0.84               | 0.66        | 0.31        | -0.62        | <b>1.18</b> | 0.43         | <b>-1.47</b>        | 0.53        | 0.03         | <b>-0.96</b> |
| Fort Nelson, Can.   | 0.49         | 0.28         | -0.19               | <b>1.50</b> | <b>1.14</b> | -0.30        | <b>1.27</b> | <b>0.99</b>  | -0.21               | <b>0.75</b> | <b>0.54</b>  | -0.14        |
| Fort Smith, Can.    | 0.89         | 0.64         | -0.21               | <b>1.45</b> | <b>1.08</b> | -0.40        | <b>1.80</b> | <b>1.29</b>  | -0.56               | <b>0.90</b> | <b>0.53</b>  | <b>-0.46</b> |
| Iqaluit, Can.       | <b>-1.72</b> | <b>-1.43</b> | 0.17                | -0.92       | -0.73       | 0.15         | -0.79       | <b>-0.93</b> | -0.55               | -0.30       | <b>-0.64</b> | -0.74        |
| Resolute, Can.      | -0.45        | 0.09         | 0.55                | -0.38       | 0.27        | 0.75         | -0.51       | -0.31        | -0.16               | -0.12       | 0.02         | 0.01         |
| Fort McMurray, Can  | 0.69         | 0.66         | 0.26                | <b>1.23</b> | <b>1.24</b> | 0.47         | <b>1.34</b> | <b>1.09</b>  | -0.06               | 0.50        | 0.50         | 0.21         |
| Yellowknife, Can.   | 0.81         | 0.61         | -0.05               | <b>1.20</b> | 0.79        | -0.37        | <b>1.81</b> | <b>1.11</b>  | <b>-1.00</b>        | <b>0.91</b> | 0.46         | -0.57        |
| Whitehorse, Can.    | 0.21         | -0.15        | -0.59               | <b>1.31</b> | 0.69        | -0.80        | 1.02        | 0.44         | <b>-1.15</b>        | <b>0.80</b> | 0.42         | -0.58        |

Table 2. Relationships between trends in wind chill temperature (WCT), dry bulb temperature (T), and wind speed (W). The first three columns are the possible combinations of signs of trends. The fourth column indicates which of the trends in T and W is responsible for the trend in WCT.

| WCT | T   | W   | WCT trend due to |
|-----|-----|-----|------------------|
| +   | +   | -   | T,W              |
| +   | +   | 0/+ | T                |
| +   | 0/- | -   | W                |
| -   | -   | +   | T,W              |
| -   | 0/+ | +   | W                |
| -   | -   | 0/- | T                |

Table 3. Causes of trends in wind chill temperature (WCT). Percents of positive and negative wind chill temperature trends attributed to temperature (T) alone, wind (W) alone, and both (T&W).

|     | + WCT trends | - WCT trends |
|-----|--------------|--------------|
| T   | 28           | 43           |
| W   | 16           | 18           |
| T&W | 55           | 39           |