The Association between Two Windchill Indices and Daily Mortality Variation in the Netherlands

Anton E. Kunst, MA, Feikje Groenhof, MA, and Johan P. Mackenbach, MD, PhD

ABSTRACT

Objectives. The purpose of this study was to compare temperature and two windchill indices with respect to the strength of their association with daily variation in mortality in the Netherlands during 1979 to 1987. The two windchill indices were those developed by Siple and Passel and by Steadman.

Methods. Daily numbers of cause-specific deaths were related to the meteorological variables by means of Poisson regression with control for influenza incidence. Lag times were taken into account.

Results. Daily variation in mortality, especially mortality from heart disease, was more strongly related to the Steadman windchill index than to temperature or the Siple and Passel index (34.9%, 31.2%, and 31.5%, respectively, of mortality variation explained). The strongest relation was found with daytime values of the Steadman index.

Conclusions. In areas where spells of cold are frequently accompanied by strong wind, the use of the Steadman index probably adds much to the identification of weather conditions involving an increased risk of death. The results of this study provide no justification for the widespread use (e.g., in the United States) of the Siple and Passel index. (*Am J Public Health.* 1994;84:1738–1742)

Introduction

Exposure to low ambient air temperatures not only is uncomfortable but creates stress on the cardiovascular and respiratory system. People exposed during a short time to moderate cold show increases in heart rate, blood pressure, and blood viscosity.[1-5] Inhalation of cold air causes bronchoconstriction, especially among those with chronic obstructive lung disease.[6,7]

There is some evidence that exposure to low ambient air temperatures even creates a threat to human survival. For various countries, it has been shown that national death rates increase substantially during spells of cold.[8-13] This association can be attributed only to a small extent to influenza epidemics or to seasonal mortality variation.[14]

Nearly all studies on the association between exposure to cold and mortality have applied a simple exposure measure: outdoor air temperature. However, the effect of weather on the thermal balance of the human body is determined not only by ambient air temperature but also by a number of other meteorological factors such as solar radiation and wind speed.[1,2] Especially significant is the chilling effect of strong wind.

The combined effect of temperature and wind speed on heat loss of the human body has been expressed by a number of windchill indices.[15,16] Such indices may serve as indicators of weather conditions involving increased heat loss and, as a consequence, an increased risk of death. Therefore, when these indices exceed a preestablished threshold value, preventive actions can be initiated to protect the population groups most at risk.

The purpose of the present study was to assess the association between windchill indices and daily variation in mortality. The central question was whether daily variation in mortality is more strongly associated with windchill indices than with temperature.

Two windchill indices were considered, that of Siple and Passel and that of Steadman. Their indices were derived in entirely distinct ways. Siple and Passel estimated the heat loss corresponding to a specific combination of temperature and wind speed as the amount of time required for water in a cylinder of synthetic material to freeze when exposed to that combination of temperature and wind speed.[15,16] They derived windchill indices from these time intervals and from extrapolation of their results to temperatures above 0°C. It has been acknowledged that a cylinder of water probably cannot adequately represent the thermophysiology of a clothed and physically active human person. Nevertheless, mainly because of its ease of calculation, the Siple and Passel index is used by the meteorological offices of most countries.

Steadman constructed an elaborate theoretical model involving the clothing thickness needed to maintain the thermal balance of the human body in different situations.[17] His model includes a large number of parameters such as physical activity, solar radiation, wind speed, and ambient air temperature. Steadman derived simplified formulas for calculating windchill values corresponding to specific combinations of temperature and wind

The authors are with the Department of Public Health, Faculty of Medicine and Health Sciences, Erasmus University, Rotterdam, the Netherlands.

Requests for reprints should be sent to Anton E. Kunst, MA, Department of Public Health, Faculty of Medicine and Health Sciences, Erasmus University, PO Box 1738, 3000 DR Rotterdam, the Netherlands.

This paper was accepted March 30, 1994.

speed.[18] Because of the thorough theoretical foundation of Steadman's index, the meteorological offices of some countries (e.g., the United Kingdom and the Netherlands) choose to apply it in their weather forecasts.

Since Steadman's method approaches the thermal balance of the human body much more closely than the method of Siple and Passel, the Steadman index has the potential to predict more accurately the amount of physiological stress related to specific combinations of cold and wind speed. Unfortunately, no physiological experiment has compared the two windchill indices with respect to their accuracy in predicting heat loss and the ensuing physiological stress.

The ability of the Siple and Passel index to predict the frequency of health problems in the general population has been assessed in two studies. A Swedish study demonstrated an association between the Siple and Passel index and daily variation in hospital admissions for myocardial infarctions.[19] A British study found that monthly variations in hospital admissions for cerebrovascular disease were more strongly related to the Siple and Passel index than to temperature.[20] Neither study evaluated the Steadman index, and neither incorporated data on morbidity from other diseases or data on mortality.

In the study reported here, temperature and the two windchill indices were related to daily variation in both total mortality and mortality from a number of cardiovascular and respiratory diseases in the population of the Netherlands. The study encompassed the winter periods of the years 1979 to 1987. Since the Netherlands has a maritime climate, winters are not extremely cold, but there is considerable day-to-day variation in wind speed. In January, for example, the average temperature is 1.1°C (between-days SD = 4.7°C) and the average wind speed is 5.9 m/s (SD = 2.8 m/s).

Materials and Methods

Daily numbers of deaths by cause of death in the period 1979 to 1987 were supplied by the Netherlands Central Bureau of Statistics. Age- and sex-specific numbers of person-days at risk were obtained from the population registry.

Data on temperature (in °C) and wind speed (in m/s) were obtained for all days in the months of November, December, January, February, and March between December 1, 1978, and December 31, 1987. These data were collected by the Schiphol-Amsterdam airport weather station, which is centrally located in the Netherlands. For each hour of the day, temperature and wind speed values were obtained and windchill values calculated. A complex formula for windchill equivalent temperature presented by Dixon[16] was used in calculating the Siple and Passel index. The Steadman index was calculated by means of the following formula: $-0.52 + 1.04 \times \text{Temperature} - 0.65 \times \text{Wind}$.

This formula was derived from Steadman's formula for shade apparent temperature.[18] Both windchill indices are expressed as the still-air temperature (in °C) necessary to produce the same rate of heat loss as with the observed combination of wind speed and temperature.

The Siple and Passel index emphasizes the additional effect of wind more strongly than does the Steadman index.[16] As a consequence, temperature is less strongly related to the Siple and Passel index ($r = .73$) than to the Steadman index ($r = .93$). The two indices also differ in the strength of their associations with wind speed. In Dutch winters, wind is generally stronger during temperate periods; the correlation between temperature and wind speed is .35. The Siple and Passel index is inversely associated with wind speed ($r = -.35$), and the correlation between the Steadman index and wind speed is $-.02$.

The literature does not provide a clear answer to the question of whether mortality is related more strongly to daytime or to nighttime temperature. Therefore, we calculated temperature and windchill values as the average value over (1) all 24 hours of the day, (2) daytime only (7 AM to 7 PM), and (3) nighttime only (7 PM to 7 AM).

Data were also obtained on the incidence of influenza-like conditions. These data were registered on a continuous monitoring system covering 45 general practitioner offices from all parts of the Netherlands.[21,22]

The daily number of deaths was related to temperature and the windchill indices by means of Poisson regression analysis with control for influenza incidence and the long-term mortality trend. The regression model took into account lags in the effect of influenza incidence, temperature, and windchill on mortality by relating the number of deaths for a specific day to the average values of, respectively, influenza, temperature, and windchill over a lag period of 0 to 6 days.

Regression models were fitted with the GLIM computer package.[23] The strength of the association between mortality and a meteorological variable was assessed by means of the decrease in unexplained mortality variation caused by adding the meteorological variable to the basic regression model. That basic model included parameters on influenza incidence and the long-term mortality trend. In GLIM, the amount of unexplained mortality variation is measured in terms of *scaled deviance.* The decrease in scaled deviance caused by adding one meteorological variable to the regression model has a chi-square distribution with one degree of freedom. A decrease in scaled deviance by more than 3.84 units is statistically significant ($P = .05$).

Results

During the study period, 344 deaths occurred per day on average, with a standard deviation of 33 deaths. In terms of scaled deviance, the size of the daily mortality variation was 3204.5 units. The basic regression model, which included the long-term mortality trend and influenza incidence, was able to explain 32% of this mortality variation, leaving 2173.2 units of scaled deviance unexplained. Subtracting the number of degrees of freedom (1305, which, under the Poisson distribution, is equal to the amount of scaled deviance that can be explained by chance fluctuations in numbers of deaths), resulted in 868.2 units of unexplained mortality variation.

The first row of Table 1 presents the decrease in scaled deviance caused by adding to the basic regression model the 24-hour averages of temperature, the Siple and Passel index, and the Steadman index. Adding temperature to the regression model decreased the scaled deviance by 270.7, a highly significant value ($P < .001$) that represented a 31.2% decrease in unexplained mortality variation. The decrease associated with the Siple and Passel index was 31.5%, virtually the same as that for temperature. Only the Steadman index was able to explain more mortality variation than temperature (nearly 35%).

The remainder of Table 1 presents results of regression analyses in which the meteorological variables were calculated for daytime and nighttime periods. Again, daily mortality variation was more strongly related to the Steadman index than to temperature or the Siple and Passel index. The strongest association observed

TABLE 1—The Strength of the Association of Temperature and Windchill Indices with Daily Variation in Mortality

	Decrease in Scaled Deviance[b] (Reduction in Unexplained Mortality Variations, %)		
Period of Day[a]	Temperature	Siple and Passel Index	Steadman Index
Entire day	270.7 (31.2)	273.9 (31.5)	303.2 (34.9)
Daytime only (7 AM–7 PM)	284.4 (32.8)	268.5 (30.9)	305.6 (35.2)
Nighttime only (7 PM–7 AM)	251.5 (29.0)	273.4 (31.5)	293.2 (33.8)

[a]Period of day over which meteorological variables were measured.
[b]Decrease in scaled deviance caused by adding the respective meteorological variable to the basic regression model.

TABLE 2—Combination of Day and Night Values of the Steadman Index in One Regression Model

		Regression Coefficient (t Value)	
Regression Model[a]	Decrease in Scaled Deviance[b]	Day Value	Night Value
Basic + day value	305.6	−.007081 (17.54)	. . .
Basic + night value	293.2	. . .	−.006827 (17.18)
Basic + day value + night value	305.7	−.006591 (3.54)	−.000494 (0.27)

[a]The basic model plus the daytime and/or nighttime value of the Steadman index.
[b]Decrease in scaled deviance caused by adding the variable to the basic regression model.

TABLE 3—Combination of Temperature and the Steadman Index in One Regression Model

		Regression Coefficient (t Value)	
Regression Model[a]	Decrease in Scaled Deviance[b]	Steadman Index	Temperature
Basic + Steadman index	305.6	−.007081 (17.54)	. . .
Basic + temperature	284.4	. . . . . .	−.006678 (16.91)
Basic + Steadman index + temperature	305.7	−.006716 (4.62)	−.000371 (0.26)

[a]The basic model plus the daytime value of the Steadman index and/or temperature.
[b]Decrease in scaled deviance caused by adding the variable to the basic regression model.

was that between daily mortality variation and the Steadman index calculated for daytime hours.

These results raise the question of whether daytime values for the Steadman index are able to predict all of the mortality variation associated with wind speed and temperature or whether the prediction can be improved by using more extensive information. We present two extensions.

First, the nighttime value of the Steadman index can be added to the regression model containing the daytime value of this index. Comparison of the first and last rows of Table 2 shows that adding nighttime values to the regression model containing the daytime values results in an extra decrease in scaled deviance (305.7 instead of 305.6) that is minimal and statistically insignificant ($P > .05$). This is also illustrated with regression coefficients, although it should be taken into account that these coefficients are unstable as a result of strong collinearity between day and night values. Despite this collinearity, the regression coefficient for the day value retains its size and remains highly significant. The regression coefficient for the night value becomes very small and statistically insignificant.

Second, the daytime temperature can be added to the model containing the Steadman daytime value. Comparison of the first and last rows of Table 3 shows that adding temperature to the regression model containing the Steadman index results in an extra decrease in scaled deviance (305.7 instead of 305.6) that is minimal and statistically insignificant ($P > .05$). When control is made for the Steadman index, the regression coefficient for temperature is very small and not statistically significant.

In Figure 1, it is shown why mortality is more strongly related to the Steadman index than to temperature. The points refer to the average mortality level for days grouped according to wind speed and temperature. Mortality levels increase about linearly with decreasing temperature and, in addition, are higher with strong wind. The lines connect the corresponding mortality levels as predicted by the regression model containing the Steadman index. This index appears to be able to predict fairly accurately not only the effect of temperature on mortality, but also the effect of wind speed.

In Table 4, temperature and the windchill indices are compared with respect to the strength of their association with mortality from specific causes of death. Cardiovascular disease mortality, but not cerebrovascular disease mortality, was associated more strongly with the Steadman index than with temperature. For respiratory disease mortality, the improvement of the Steadman index over temperature was smaller than that for cardiovascular diseases.

Discussion

The purpose of this study was to compare temperature and two windchill indices with respect to the strength of their association with daily variation in mortality in the Netherlands. Mortality variation was not more strongly related to the Siple and Passel index than to temperature. A stronger relation was found with the Steadman index, especially for mortality from heart diseases.

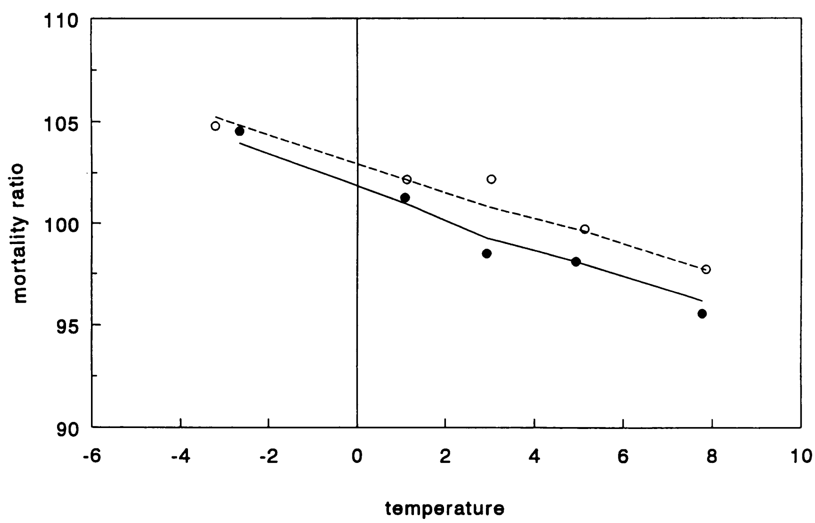
The finding that the Siple and Passel index does not perform better than temperature is perhaps not surprising. It suggests that the simple physical experiment on which this index was based—freezing of water in a cylinder—cannot adequately represent the thermophysiology of a clothed, physically active person exposed to cold and wind. In any case, our results do not provide justification for the practice (e.g., in the United States) of using the Siple and Passel index in weather reports aimed at the general population.

The Steadman index was derived purely theoretically. It has not been tested empirically for its ability to measure the amount of human discomfort or health risk inherent to specific weather situations.[15,16] Our results suggest that, at least with respect to death, the Steadman index accurately quantifies the amount of risk involved in specific combinations of temperature and wind speed.

Although daily mortality variation in the Netherlands was associated more strongly with the Steadman index than with temperature, the difference was small. The reason is that, in the Netherlands, temperature is strongly correlated with the Steadman index. For example, of the 326 days (one quarter of all days) with the lowest Steadman values, no less than 300 belonged to the 326 days with the lowest temperature values. This implies that hazardous weather situations in the Netherlands can be identified almost as accurately by temperature as by the Steadman index.

Thus, the Steadman index is mainly valuable when hazardous weather situations cannot be identified on the basis of temperature alone (e.g., when spells of cold are frequently accompanied by strong wind). Such weather conditions are rare in the Netherlands and in most of western Europe, where cold weather is usually associated with anticyclonic weather. In parts of North America, on the other hand, these conditions are less rare, and we expect that the Steadman index would add much to the identification of weather conditions involving an increased risk of death.

It is not certain, however, to what extent our results on the Netherlands can be extrapolated to countries with more extreme weather conditions. Before definite conclusions on the predictive power of the Steadman index are drawn, our study should be replicated in areas where cold frequently occurs together with strong wind. Supportive of our results are descriptive studies of blizzards in North America that have found that the combination of severe cold and strong wind increases mortality, especially that from heart disease.[24,25]



Note. Closed circles indicate observed mortality levels for days with wind speed lower than 5 m/s. Open circles indicate observed mortality levels for days with wind speed higher than 6 m/s. The solid and dashed lines represent mortality levels for days with low and high wind speeds, respectively, as predicted by the Steadman index. Temperatures are in °C. Wind speed and temperature values were calculated for a lag period of 0–6 days. Observed mortality levels are expressed as the ratio between the observed number of deaths and the number of deaths that, according to the basic regression model, could be expected on the basis of influenza incidence and the long-term mortality trend.

FIGURE 1—The association of mortality with temperature and wind speed: prediction by the Steadman windchill index.

TABLE 4—The Strength of the Association of Temperature and Windchill Indices with Daily Variation in Mortality from Cardiovascular and Respiratory Diseases

Cause of Death (ICD-9 Codes)	Average Daily No. of Deaths	Decrease in Scaled Deviance[a] (Reduction in Unexplained Mortality Variation, %): Temperature	Siple and Passel Index	Steadman Index
Ischemic heart diseases (410–414)	74	111.4 (25.0)	108.3 (24.3)	121.6 (27.3)
Cerebrovascular diseases (430–438)	35	70.4 (55.7)	49.7 (39.3)	67.2 (53.1)
Other cardiovascular diseases (390–459)	47	72.4 (18.8)	74.5 (19.3)	80.5 (20.9)
Pneumonia and influenza (480–487)	9	27.2 (14.3)	28.4 (15.0)	29.7 (15.7)
Chronic obstructive lung disease (490–496)	9	29.9 (48.4)	24.3 (39.3)	30.7 (49.7)

Note. ICD-9 = *International Classification of Diseases,* Ninth Revision.
[a]Decrease in scaled deviance caused by adding the variable to the basic regression model.

The Steadman index can, in addition, be useful for hypothesis testing. An example concerns the debate on the mechanism behind the association between cold weather and mortality. Whereas some have argued that this association is, to a large extent, due to confounding by seasonal factors or the incidence of influenza or other contagious respiratory diseases, others have argued that it mainly reflects a direct effect of heat loss on the cardiovascular and respiratory systems.[11,14,26–30] According to the latter hypothesis, it should be possible to explain the association between temperature and mortality by more accurate measures of heat loss, such as windchill indices. We indeed found that the association between temperature and mortality disappeared when control was made for the Steadman index. Our results therefore provide additional evidence for the hypothesis that cold-related stress is responsible for a major part of the increase in mortality during spells of cold.

This raises the question of which type of cold exposure causes the most deaths. The relevant exposure might occur indoors as a result of, among other factors, bad housing conditions, inadequate heating, and large temperature differences between rooms. However, a British study showed that the winter excess in mortality among elderly people living in well-heated institutions is as large as that among people living in other dwellings.[31] This suggests that exposure to cold during brief excursions outdoors is responsible for most cold-related deaths. According to the latter suggestion, one would expect that daytime but not nighttime values of the Steadman index are related to mortality. This is indeed what we found. These indications of the influence of outdoor exposure need verification in further studies, above all because such studies have the potential of demonstrating specific opportunities for the prevention of cold-related deaths. □

Acknowledgments

This study was financially supported by the Ministry of Welfare, Public Health and Culture, Rijswijk, the Netherlands.

References

1. Clark RP, Edholm OG. *Man and His Thermal Environment.* London, England: Edward Arnold; 1985.
2. LeBlanc J. *Man in the Cold.* Springfield, Ill: Charles C Thomas Publisher; 1975.
3. Keatinge WR, Coleshaw SRK, Cotter F, et al. Increases in platelet and red cell counts, blood viscosity, and arterial pressure during mild surface cooling: factors in mortality from coronary and cerebral thrombosis in winter. *BMJ.* 1984;289:1405–1408.
4. Keatinge WR, Coleshaw SRK, Easton JC, et al. Increased platelet and red cell counts, blood viscosity and plasma cholesterol levels during heat stress, and mortality from coronary and cerebral thrombosis. *Am J Med.* 1986;81:795–800.
5. Collins KJ. Low indoor temperatures and morbidity in the elderly. *Age Ageing.* 1986; 15:212–220.
6. Deal EC, McFadden ER, Ingram RH, et al. Esophageal temperature during exercise in asthmatic and nonasthmatic subjects. *J Appl Physiol.* 1979;46:484–490.
7. Schanning J, Finsen H, Lereim I, et al. Effects of cold air inhalation combined with prolonged submaximal exercise on airway function in healthy young males. *Eur J Respir Dis.* 1986;68(suppl 143):74–77.
8. Alderson MR. Season and mortality. *Health Trends.* 1985;17:87–96.
9. Rogot E, Padgett SJ. Associations of coronary and stroke mortality with temperature and snowfall in selected areas of the United States, 1962–6. *Am J Epidemiol.* 1976;103:565–575.
10. Bull GM, Morton J. Environment, temperature and death rates. *Age Ageing.* 1978;7: 210–224.
11. Anderson TW, Le Riche WH. Cold weather and myocardial infarction. *Lancet.* 1970;i: 291–296.
12. Bull GM. Meteorological correlates with myocardial and cerebral infarction and respiratory disease. *Br J Prev Soc Med.* 1973;27:108–113.
13. Wyndham CH, Fellingham SA. Climate and disease. *S Afr Med J.* 1978;53:1051–1061.
14. Kunst AE, Looman CWN, Mackenbach JP. Outdoor air temperature and mortality in the Netherlands: a time series analysis. *Am J Epidemiol.* 1993;137:331–341.
15. Driscoll DM. Windchill: the "brrr" index. *Weatherwise.* 1987;40:321–326.
16. Dixon JC, Prior MJ. Windchill indices: a review. *Meteorological Magazine.* 1987; 116(January):1–17.
17. Steadman RG. Indices of windchill of clothed persons. *J Appl Meteorology.* 1971; 10:674–683.
18. Steadman RG. A universal scale of apparent temperature. *J Climate Appl Meteorology.* 1984;23:1674–1687.
19. Ohlson C-G, Bodin L, Bryngelsson I-L, et al. Winter weather conditions and myocardial infarctions. *Scand J Soc Med.* 1991;19: 20–25.
20. Gill JS, Davies P, Gill SK, et al. Wind-chill and the seasonal variation of cerebrovascular disease. *J Clin Epidemiol.* 1988;41:225–230.
21. Sprenger MJW, Mulder PGH, Beyer WEP, et al. Impact of influenza on mortality in relation to age and underlying disease, 1967–1989. *Int J Epidemiol.* 1993;22:334–340.
22. Bartelds AIM. *Continuous Morbidity Registration, Monitoring Network of the Netherlands.* Utrecht, the Netherlands: NIVEL; 1987.
23. Baker RJ, Nelder JA. *GLIM Manual, Release 3.* Oxford, England: Numerical Algorithms Group; 1987.
24. Faich G, Rose R. Blizzard morbidity and mortality: Rhode Island, 1978. *Am J Public Health.* 1979;69:1050–1052.
25. Glass RI, Zack MM. Increase in deaths from ischaemic heart-disease after blizzards. *Lancet.* 1979;1:485–487.
26. Macfarlane A. Daily mortality and environment in English conurbations 1: air pollution, low temperature, and influenza in Greater London. *Br J Prev Soc Med.* 1977;31:54–61.
27. Bainton D, Moore F, Sweetnam P. Temperature and deaths from ischaemic heart disease. *Br J Prev Soc Med.* 1977;31:49–53.
28. Bull GM. The weather and deaths from pneumonia. *Lancet.* 1980;i:1405–1408.
29. Bowie C, Prothero D. Finding causes of seasonal diseases using time series analysis. *Int J Epidemiol.* 1981;10:87–92.
30. Marshall RJ, Scragg R, Bourke P. An analysis of the seasonal variation of coronary heart disease and respiratory disease mortality in New Zealand. *Int J Epidemiol.* 1988;17:325–331.
31. Keatinge WR. Seasonal mortality among elderly people with unrestricted home heating. *BMJ.* 1986;293:732–733.