CHILLING WINDS AND THEIR DIRECTIONAL DISTRIBUTION IN TWO CLIMATOLOGICALLY DIFFERENT REGIONS OF ESTONIA

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Wind chill equivalent temperature was used to characterize human thermal comfort during Nordic winter season. Directional distribution of winds associated with uncomfortable weather was composed for two climatologically different Estonian regions, represented by coastal Vilsandi and continental Jõhvi stations. Cases with wind-chill equivalent temperature < –10 °C, which could be classified as 'uncomfortable or worse', were investigated. Additional thresholds were used to measure weather risk. Classical prevalent wind directions in Estonia, W, SW and NW, bring warm air in winter from the North Atlantic, while winds from the East-European plain (NE, E and SE) are associated with cold air. The eastern prevalence was stronger when a lower threshold was used. Traditional protection from prevalent directions may not be beneficial to protect from cold winds. A directional approach may find several applications, such as building, agricultural, landscape or settlement planning.

Keywords: thermal comfort, wind distribution, wind chill, Estonia

INTRODUCTION

The term "human thermal comfort" is often applied to describe how weather and climate impact our wellbeing. The term describes a person's mental or psychical state of mind, and is usually referred to in terms of whether someone is feeling too hot or too cold. Since there can be no accurate definition or formula for what a person feels like, thermal comfort is quite a subjective measure. Most often, air temperature is used as a comfort indicator, while over the past century a growing number of more complex indices (e.g. Epstein and Moran 2006, Blazejczyk et al 2012, Freitas and Grigorieva 2015 for overview) have been developed in an attempt to give a measure of how comfortable an average person feels based on the interaction of several weather variables. More often rather the opposite is addressed – the attention is on human thermal discomfort or risk. In the countries that regularly experience cold weather, a probably most commonly used measure of human outdoor comfort during cold months is "wind-chill" (Court 1948, Dixon and Prior 1987), which combines effect of low air temperature and wind speed. The difference between the (measured) actual air temperature and the (calculated) wind-chill equivalent temperature (WCT) quantifies the influence of wind on heat loss.

Thermal discomfort rather than threat is examined in the current research – we look at the cases, which can be classified as uncomfortable or worse. Estonian climatic conditions are under investigation – a temperate humid climate with fairly severe winters. The country is situated in a climatic transition zone between marine and continental conditions, with very variable weather. Especially during the cold half-year atmospheric circulation, primarily cyclonic activity, plays crucial role in weather conditions (Jaagus 2006, 2013, Jaagus and Kull 2011). Therefore the people here experience a wide range of possibly uncomfortable conditions: from bitter cold to wet and windy in winter and almost tropical hot to cool and chilly in summer, while in transition seasons "too cold" rather than "too warm" is generally considered uncomfortable. In this work the "too cold" side of the problem is examined and the cases are analyzed, which are not just straightforwardly cold, but which are thermally uncomfortable because of the cooling effect of the wind. We shall call those the chilling wind.

The purpose of the research is to compile the relative frequency of unpleasantly cold conditions by wind direction in Estonia. We aim to distinguish wind directions, which are associated with the most uncomfortable winter outdoor conditions. The results could be taken into account in urban and landscape planning to decrease winter discomfort.

MATERIALS AND METHODS

Meteorological data

All data originate from the meteorological network of Estonian Weather Service. Meteorological data for 1981-2003 are used. Although longer meteorological time series exist, the choice was made based on the homogeneity of measurements: in 1981 anemorhumbometers were introduced in Estonian stations instead of old wind vanes, while in 2003 automatic measurements began. Air temperature, wind speed and direction data from measurements at 00, 03, 06, 09, 12, 15, 18 and 21 GMT were used. Wind direction data were allocated into 16 rhumbs.

Although Estonian territory is small, we have quite remarkable climatic differences between coastal and continental parts of country. Two meteorological stations were chosen to represent those differences. Vilsandi (58°22´58´´ N, 21°48´51´´ E) has maritime climate, since it is situated on western coast of Estonian archipelago and is open to the sea. The proximity of sea causes milder conditions compared to mainland area – warmer in winter and cooler in summer – as well as later arrival of spring and autumn. The highest mean yearly temperature in Estonia has been recorded in Vilsandi (8.3 ºC in years 1975, 1989 and 2000). From the other side, being widely open to cyclonic activity from the Baltic Sea, Vilsandi is also the stormiest station in Estonia, with 20 stormy days a year (wind speed over 15 $m.s^{-1}$), most of them in winter and autumn. Jõhvi (59°19´44´´ N, 27°23´54´´ E) in the eastern part of Estonia and, according to the climatic classification of Estonia based on its air temperature regime (Jaagus and Truu 2004), represents continental climate region with practically no climatic effect of the Baltic Sea.

Wind chill equivalent temperature (WCT)

WCT is calculated using air temperature and wind speed. The calculated value represents the chill effect of wind on the skin, indicating the equivalent temperature on a colder day with only very calm wind with the same loss of body heat. The "new" wind chill index (Bluestein and Zecher 1999, Osczevski and Bluestein 2005) is applied, which is today broadly accepted and used in many countries, including Canada, United Stated, United Kingdom and Iceland. In this work air temperature (T) is indicated in ºC and wind speed (v) in $m.s^{-1}$.

$$WCET=13.12+0.6215*T-1.37*(v*3.6)^{0.16}+0.3965*T*(v*3.6)^{0.16}$$

Although sun can raise WCT by 5-10 degrees, it is not accounted for due to local effects. The formula is developed for a temperature range between -46 and +10 °C and for wind speeds at 10 meters high between 1.3 and 49.0 m.s^{-1}. Accordingly, only suitable observations are used in the analyses. Formula is based on the loss of warmth by an average person walking at a speed of 4.8 km.h^{-1}, wearing winter clothing. The behavior of WCT, as a function of wind and temperature (Figure 1, calculated from the abovegiven formula) for cold weather, reflects the common observations that people tend to feel more stressed on windy and cold days. As the air temperature falls, the chilling effect of any wind that is present increases.

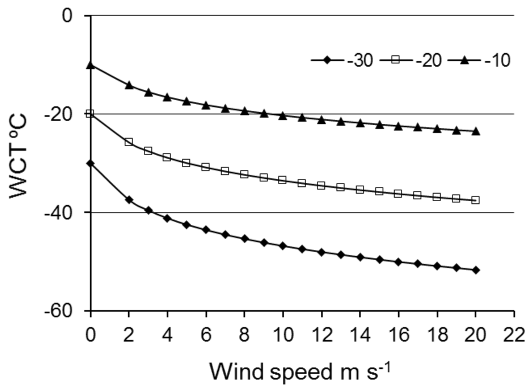

Figure 1. Behavior of WCT as a function of wind and temperature. Lines with diamond, square and triangle are evaluated at air temperature of -30 ºC, -20 ºC and -10 ºC, respectively.

The following analyses was organized in two main sections: (1) determining the cases which can be described as "uncomfortable or worse" and (2) drawing directional wind-roses of such cases.

There are several absolute categories defined for the wind-chill thresholds. According to Canadian program (CWCP), WCT between –10 and –27 °C is considered as 'uncomfortable', between –28 °C and –39 °C as 'increasing risk' and below that there are further risk categories. The Canadian threshold of discomfort (–10 °C) was applied, since their winter temperatures are comparable to those of Estonia. Discomfort rather than risk is discussed in this paper, therefore all cases are included that can be classified as uncomfortable or worse (WCT < –10 °C). Further, a lower threshold of WCT < –20 °C was included, which is a practically used limit, when school may be cancelled for smaller children in urban areas in Estonia. Additionally, observations with WCT < –27 °C as 'increasingly risky' were investigated. To define the situations in which wind increases the feeling of cold, additional filtering was applied to exclude cases when the difference between ambient temperature and WCT was < 5 °C.

RESULTS

Climatology of WCT

The absolute lowest WCT values within the observed period were in January 1987: –45.6 and –41.2 °C at Jõhvi and Vilsandi, respectively. The ambient temperatures for such low values were also very low: –31 and –27 °C with 3 and 7 m.s^{-1} wind, respectively.

The cycle of the average daily minimum WCT for November–March presents apparent difference between marine and continental regions (Fig. 2). Daily minimum WCT values were detected for each day from November to March and moving 15-day mean daily minimum WCT was plotted. For that, the averages of the minimums were first derived for every day in the year from 23 annual observations. Greater difference in average minimum values appered in autumn and winter, when coastal climate remains milder; those differences tend to diminish towards spring, which starts earlier in mainland.

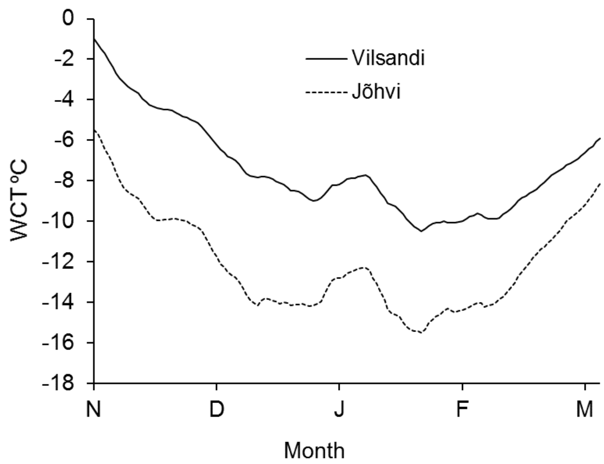

Figure 2. Centered moving 15-day mean daily minimum wind chill temperatures at two locations from November to March, derived from observations in 1981-2003.

Jõhvi also had considerably higher number of uncomfortable days, well in accordance with its climatic location (Table 1). Below-freezing WCT could occur in both stations in all months except the three summer months (JJA), while uncomfortable (< –10 °C) WCT occurred during October–April (November–April at Vilsandi) with the highest average occurrence in January-February. Really cold conditions (WCT < –27 °C) have occurred in Estonia between November and March, with very few observations in November and March. In November WCT < –27 °C was only observed once at Jõhvi, with –28°C on 30 November 1991. At milder Vilsandi such increasingly risky WCT only occurred on average once a year, in January–February.

In addition to obvious difference between the two stations, there was also high year-to-year variability. For instance, in 1990 there was only one uncomfortably cold day at Vilsandi, while the maximum number of such days in a year has been 104 (Jõhvi in 1985 and 1987).

Table 1. Average number of days per month on which the minimum WCT was below certain thresholds.

	Threshold	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Jõhvi	-10	16.0	26.5	29.2	18.7	18.3	13.3	2.2
	-20		1.3	4.1	6.1	7.7	1.8	
	-27		0.1	1.0	2.3	2.3	0.4	
Vilsandi	-10		2.0	7.6	8.9	11.3	6.2	0.5
	-20			0.2	2.2	2.7	0.3	
	-27				0.6	0.7		

The 5th and 25th percentiles of daily minimum WCTs (Table 2) confirm considerable differences between locations. In Jõhvi the values are lower for all the five observed months, reflecting its continental location far from the sea. Vilsandi proves much milder, with even the 5th percentile remaining quite moderate. February was the most uncomfortable month for both stations. At Vilsandi, March was comparable to December, while inland in March the spring starts usually earlier and temperatures had already became warmer.

Table 2. WCTs corresponding to 25 % of the minimum WCTs.

Station	Percentile	Nov	Dec	Jan	Feb	Mar
Jõhvi	25th	–10.8	–16.6	–17.6	–20.8	–13.5
	5th	–19.8	–25.3	–28.6	–29.8	–20.4
Vilsandi	25th	–5.6	–9.8	–10.9	–13.7	–9.0
	5th	–10.6	–15.9	–22.1	–23.3	–15.0

The 25th percentile of daily minimum WCT, corresponding to 25 % of the coldest cases, can also be exploited a relative threshold to mark a limit between 'comfortably cool' and 'unpleasantly cold'. Relative is used here in a context that the value of the threshold differs in different locations and different months, involving an acclimatization effect. For example, the 25th percentiles for November displayed in Table 2 mean that < 25 % of all November observations have WCTs lower than the observation in question and hence implies that the thermal situation experienced at that moment probably feels uncomfortable. Similarly, the 25 % threshold in February means that < 25 % of all February observations have WCTs lower than the one in question; however, due to the different thresholds of discomfort in November and February, 'uncomfortable' in November would probably be considered 'comfortable' in February. Likewise, different thresholds exist in different locations (see Table 2). It should be emphasized that the thus allocated cases do not represent all situations when a person would feel chilly; they describe situations, when thermal feeling is below the '25 % of the coldest' limit. Additionally, the 25th percentile can be considered to define risky situations.

While in March and November those "relative" threshold of discomfort was not very different from the general threshold (–10 °C), during the winter months the 25 % threshold was much lower at the continental stations. Therefore, if trying to define the limit that defines 'discomfort' for people, the local acclimatization effect should be considered even for a small territory. While the threshold of discomfort, WCT < –10 °C, seems indeed reasonable to use in November and March and for coastal/island locations also throughout the winter, for mainland locations it is quite possible that, due to the acclimatization effect, people would not experience WCT of –10 °C as uncomfortable and a lower threshold would be more suitable in defining discomfort.

Probability of discomfort

Identifying occurrence probability (Fig. 3) of uncomfortable or risky weather is significant, since by estimating its occurrence we could decrease its damage and effects in future, specifically for athletes and people interested in winter sports who encounter cold climate more than others. The probability of uncomfortable weather was considerably different between the stations. For instance, the probability of daily minimum WCT < −10 °C was 0.6 at Jõhvi – i.e. uncomfortable conditions every other day are likely during the three winter months for Estonian mainland. At Vilsandi the same level probability was 0.3. The risk-defining threshold of WCT –27 °C had a probability of 0.06 and 0.01 at Jõhvi and Vilsandi, respectively. In March and November (not included in Fig. 3), this probability was of course lower – but there was still a corresponding 40 and 20 % probability of uncomfortably low temperatures in March; and 30 and 7 % in November.

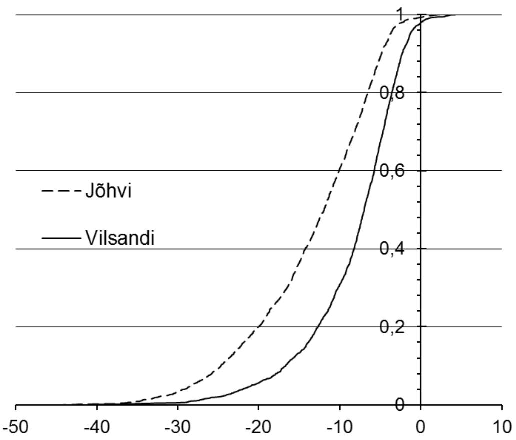

Figure 3. Probability of WCET being below given value.

WCT and wind distribution

Directional wind-roses were composed for different WCT thresholds together with the distribution of moderate and strong winds (over 5 m.s–1). For the three winter months (DJF) (Fig. 4) there was a strong general prevalence of southerly winds at Jõhvi, which may be (partly) influenced by the fact that the station is widely open to the south while westerly winds are to some extent blocked by a building. The southern dominance was also seen in the distribution of chilling winds. However, for lower thresholds (colder cases), a secondary maximum appeared and increased in importance for an easterly direction.

At Vilsandi, strong and moderate winds blew predominantly from the western-southwestern directions during winter. The uncomfortable weather (WCT < –10 °C) in winter months was most often related to easterly winds and another, smaller, peak occurred around SE-SSE. Compared to the distribution of moderate and strong winds (over 5 m.s–1), the chilling winds shape was quite the opposite – the stronger winds came from westerly directions, and easterly directions had a minimum of moderate and strong winds. W, SW and NW winds were at minimum in cold wind distribution, being related to warmer air from the North Atlantic. Generally, for both stations, the lower the threshold, the more an easterly (E, NE and SE) prevalence was manifest. Such easterly cold is strongly related to cold continental air masses from the East European Plain.

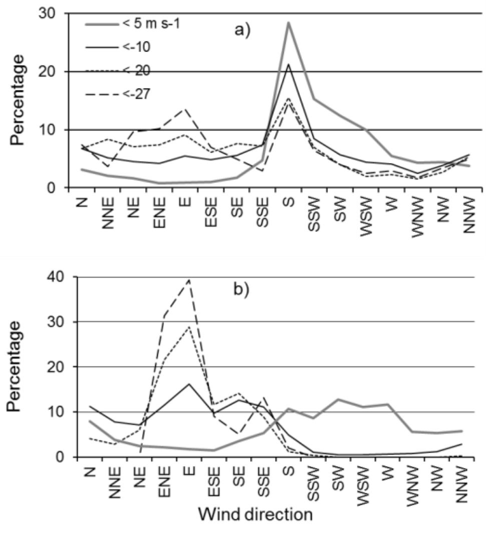

Figure 4. Distributional distribution of moderate and strong winds (< 5 m.s-1) and winds associated with WCT below given thresholds at Jõhvi (a) and Vilsandi (b) for winter period (December, January, February).

Spring and autumn were represented by March and November in this study (Fig. 5). Although extremely cold events are rare during those months, uncomfortable conditions are still very common. In November, uncomfortably cold weather was again obviously related to easterly winds at Vilsandi. From the other side, there were no observations with WCT < –20 °C at Vilsandi in November, which reflects its milder climate and also the fact that winter generally begins later here due to the warming effect of the Baltic Sea. At Jõhvi, the very cold cases were very strongly related to ESE winds. In March, the cold wind pattern was not as clearly and unambiguously expressed for the –10 °C threshold. At Vilsandi, generally easterly and northerly directions prevailed, at Jõhvi the southerly direction was very dominant. Very cold weather tended to be more related to northerly winds (NNE to NNW) in both stations.

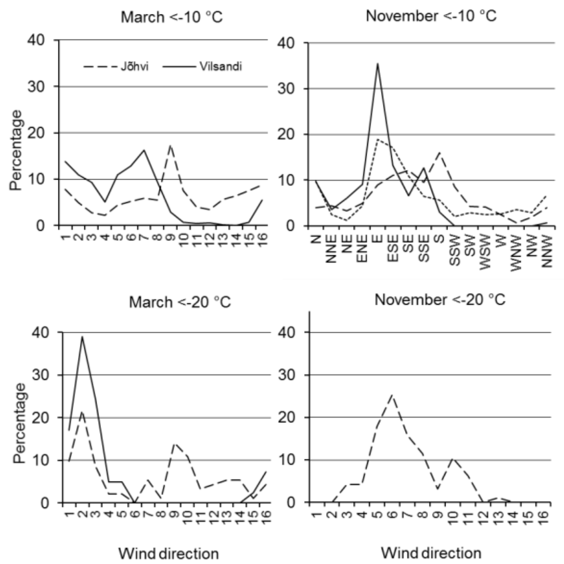

Figure 5. Distributional distribution of winds associated with WCT below given thresholds for March and November months.

Wind-driven discomfort

Further analyses included the cases when thermal discomfort was strongly influenced by wind, i.e. uncomfortable cases (WCT < –10 °C), with the difference between ambient temperature and WCT being ≥ 5 °C (Fig. 6). At Jõhvi, again, there was a dominant southerly direction throughout all months, with another peak in March from NW and another in November around SE. Vilsandi showed an easterly dominance, with another peak around SE, while there were practically no chilling winds from SW to NW. In November, an easterly peak was especially dominant at Vilsandi.

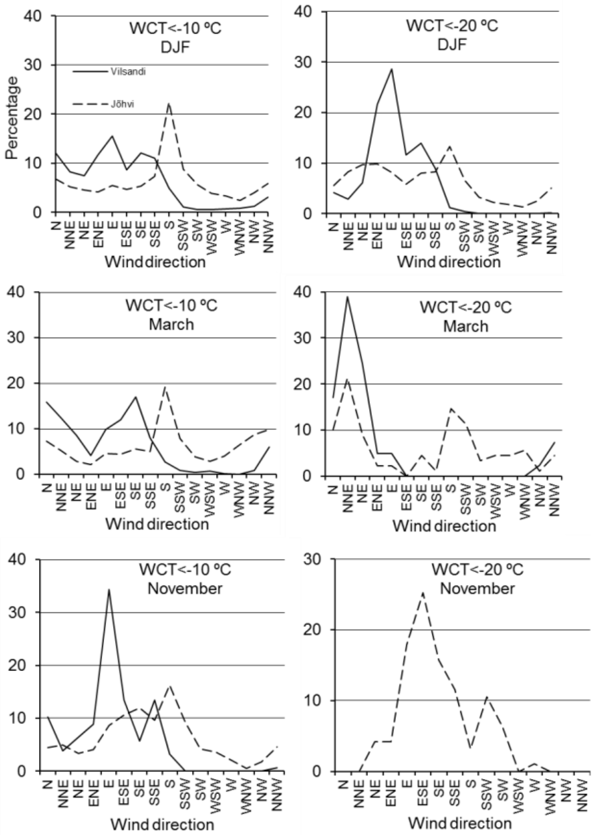

Figure 6. Distributional distribution of winds associated with conditions, when uncomfortable weather is caused by wind, for two different thresholds.

DISCUSSION

Wind speed, and especially wind direction, determines the general character of weather conditions. Historically, the wind field in Estonia has been treated as practically directionally homogeneous with a slight prevalence of southerly, westerly and south-westerly winds (Kull and Steinrucke 1996, Miętus 1998). This anisotropy stems from the domination of a large-scale westerly airflow at these latitudes and the basis of this assumption is that the majority of the classical wind-roses (that equally account for all wind measurements notwithstanding wind speed) are almost circular, with a slight prevalence of wind from certain directions (Kull and Steinrucke 1996, Soomere and Keevallik 2003). It has also been acknowledged, that the angular distribution of for moderate and strong winds (over > 5 m.s^{-1}) has a significant minimum for easterly winds (Soomere 2001, Soomere and Keevallik 2001, 2003, Keevallik and Soomere 2009). Such knowledge is very important for wind farm or harbor planning, but from the point of view of human thermal comfort, the strongest winds do not necessarily produce the strongest chilling effect. Instead, warmer air in Europe generally comes from the west, from the ocean, and colder air from the east. In winter, the stronger winds can thus rather bring warmer weather. For instance, winter and spring warming in Estonia (Jaagus 2006, 2013) has been shown to be related to significant intensification of westerlies and south-westerlies in winter (Jaagus and Kull 2011).

This pattern was clearly confirmed in this study for Estonia. Generally winds from W, SW and NW brought warm air from the North Atlantic, while winds arriving from the East European plain (NE, E and SE) were associated with cold air. It was shown that the most uncomfortable outdoor conditions are not necessarily related to the dominant wind directions. So, when urban planners or landscape architects traditionally use only the basic knowledge of prevalent western-southern winds (e.g. Nurme 2012), optimal protection from uncomfortable weather conditions may not be met. Instead/in addition, eastern directions should be addressed in urban planning to decrease winter discomfort.

Blazejczyk et al. (2012) reasoned that 'cold' indices represent better human thermal balance. This makes strongly sense for Estonia, since cold-related discomfort is much more common and undesirable here than hot-related discomfort. Although wind chill is not observed for 'dead' objects such as buildings or water pipes, wind can cool objects faster to the air temperature. Also the cooling effect of wind should be considered when planning objects that will be used by humans or animals. Therefore, while the traditional use of wind chill has been for human biometeorology, the directional approach may find several additional applications, such as urban planning (Li et al. 2007, Szucs 2013, Hong and Lin 2015), agricultural planning (Segnalini et al. 2011, Van laer et al. 2014) or landscape work. Over the past few decades, making outdoor spaces attractive to people, and being ultimately used by them, has been increasingly recognized as a goal in urban planning and design (e.g. Gehl and Gemzøe 2004, Maruani and Amit-Cohen 2007, Li et al. 2007, Brown 2010). That goal would gain from considering directional information concerning the frequencies of various combinations of wind and temperature, such data have further uses in the planning of sites and settlements to provide a better environment during the cold season. Among the benefits are improved pedestrian comfort, greater use of the spaces around buildings and better prospects for establishment of vegetation of various types (Prior and Keeble 1991, Brown 2010).

Acnowledgement

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