CHEMICAL ENGINEERING TRANSACTIONS

VOL. 107, 2023

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Bohong Wang, Petro Kapustenko

ISBN 979-12-81206-07-6; **ISSN** 2283-9216

DOI: 10.3303/CET23107080

Local Scale Wind Regime Changes and their Consequences on Sustainability in the Carpathian Basin (Hungary)

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The Carpathian basin is facing significant threats to its unique biogeography and the sustainability of its human society due to climate change. While studies have extensively analyzed temperature and precipitation changes, little attention has been given to the analysis of wind regime changes despite their potential correlation with diverse climatic effects. This paper presents a comprehensive analysis of long-term observational wind data at both local and regional scales of the basin. The study aims to identify trends in wind speed and direction and raises some implications for sustainability aspects such as forest health, agricultural potential, and availability of wind energy. To track the decadal trends in wind speed, two indexes were utilized: the number of calm days and the number of windy days. In addition to traditional wind roses, fine changes in wind direction distribution were visualized using heat maps. The dominance of local winds was also examined through aggregated wind roses. Our research findings reveal that contrary to predictions and reanalysis data, there has been a noteworthy rise in wind resources in the Hungarian Great Plain, accompanied by a decrease in the number of calm days. It is evident that there are variations among different geographical regions within Hungary regarding changes in wind regimes. These trends have the potential to impact current dominant climatic influences, leading to possible modifications in climate change patterns and necessitating a reassessment of main forest and agricultural species.

1. Introduction

Climate change is a widespread issue that has significant consequences for ecosystems and economies around the world. While the direct and indirect effects of rising temperatures, increasing aridity, and extreme weather events have been widely acknowledged (IPCC, 2022), changes in wind patterns have received less attention. However, understanding fluctuations in wind speed and distribution can serve not only as indicators for predicting wind energy resources (Jung and Schindler, 2022) and energy mixes (Cipolletta et al., 2023) but also for assessing multiple dimensions of sustainability. Modifications in wind regimes directly impact the dispersal of air pollution and arthropod species (Gu et al., 2018).

Across Europe, a strong decrease in wind resources is predicted (Carvalho et al., 2021). The Carpathian Basin (Pannonian Basin), characterized by the confluence of Atlantic (oceanic), Mediterranean, and continental climates, boasts remarkable climatic and ecological diversity. This intricate balance maintains a heightened level of vulnerability (Bede-Fazekas et al., 2017) and gives rise to varying prevailing wind patterns across the basin's regions.

Regional climate models anticipate a more pronounced temperature increase in Hungary compared to the global average. Projections indicate that the southern regions will experience the most significant warming, while the northwestern corner and the Transdanubian Mountains are expected to be relatively less affected (Kovács and Jakab, 2021). The weakening of Atlantic-alpine effects may lead to reduced precipitation in western areas, potentially impacting forest health, while a stronger Mediterranean influence could amplify winter warming, facilitating the spread and overwintering of subtropical pests and vectors.

While the future climate of the region remains heavily reliant on wind patterns, prior wind regime investigations in Europe have primarily focused on alterations in wind energy resources (Jung and Schindler, 2022) and have predominantly employed reanalysis data such as ERA-5 (Hersbach et al., 2023). Detailed wind analyses at a

Paper Received: 07 June 2023; Revised: 02 August 2023; Accepted: 02 November 2023
Please cite this article as: Rácz É.V., Környei L., 2023, Local Scale Wind Regime Changes and their Consequences on Sustainability in the Carpathian Basin (Hungary), Chemical Engineering Transactions, 107, 475-480 DOI:10.3303/CET23107080

small spatial scale, encompassing assessments of wind direction shifts and local variations, have been notably lacking from this region. This paper introduces a comprehensive, long-term study utilizing observational data to elucidate regional trends in wind speed and directional changes on a small and regional scale. Additionally, we present flexible wind speed trend indices and generalizations of the concept of calm days (Manders et al., 2012). Besides traditionally used wind roses, we apply novel methodologies to detect subtle alterations in wind direction, as well as potential shifts in dominant wind regimes.

2. Data and methods

Data were downloaded from the freely available databases: 50-year-data (1973-2022) from NOAA Hourly Observational Database (NOAA, 2023), while more detailed 20-year-data (2002-2021) from The Hungarian Meteorological Service OMSZ (2023). From 80 stations located in the Pannonian basin (including ones outside but nearby Hungary) of the NOAA database, only 23 had regular records from 1973 without considerably missing wind data. However, the data was highly inhomogeneous.

Daily average wind speeds were calculated to get a homogenous time series. Trends of monthly, yearly, and more yearly data were investigated compared to the average daily mean wind speeds (Avg50) for each location. Daily maximum wind speed data were determined for the time series of each location.

Trends were investigated visually, and linear fitting with statistical parameter calculation was performed by Wolfram Mathematica. The extent of decadal change of maximum wind speed was characterized using categories (Figure 1a).

Two kinds of indexes were defined to describe windiness. In this paper, a calm day is defined as a day with a daily maximum smaller than a threshold wind speed. As in our long-term dataset, the scale of measurement was at first 1 m/s, later 0.5, and recently 0.1 m/s (intervals vary by location). Thresholds smaller than or equal to 1 m/s cause large bias in older data. Therefore, 2 m/s, 3 m/s, and 4 m/s were considered as thresholds, and trends in the number of yearly calm days were studied by linear fitting.

The other index was the number of windy days in a year, where windy days are defined as days with a daily average larger than a threshold (e.g., 2 m/s, 3 m/s, 4 m/s). Trends of the number of windy and calm days were also investigated and categorized (Figure 1b).

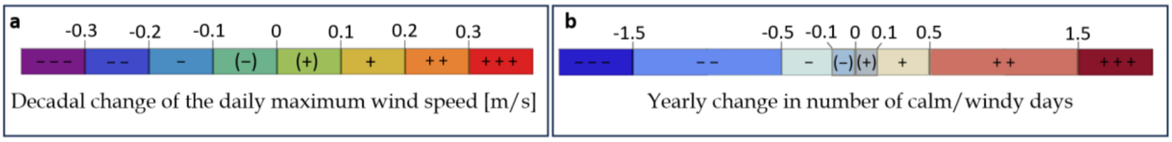

Figure 1: Limits of categories of changes used in windspeed trend investigations

From OMSZ data the hourly average wind speed and direction was extracted and processed. All invalid data and data marked missing were deleted from the database, and no other method was used to handle them. Wind direction trends were investigated using yearly histograms. To eliminate noise in the data, 60 bins of the same size were used. As wind speed highly influences the amount of air transported from the specified direction, weighing is used to determine the wind direction distributions.

As the local climate in the Carpathian Basin is heavily influenced by three main wind directions, it is plausible to analyze the proportional influence of these winds. For that, the 20-year time series of the wind directions were analyzed for each measurement point. Wind direction data is available for the years 2002-2021 on an hourly basis in a 1° resolution, which is given in degrees from north (0°) to east (90°), south (180°) and west (270°). Besides per-year statistics, both decades, 2002 to 2011 and 2012 to 2021, are investigated. The following four methods are used to describe evolution and change in wind direction:

- A yearly weighted histogram was employed to describe wind direction distribution for each year using 60 sectors, starting with the sector 0°-5. Wind speeds were utilized as weights. Changes in frequency were examined by plotting the data on a heat map.
- A decadal weighted histogram was calculated with the same 60-sector analysis for both decades and compared on a heat map.
- The traditional wind rose was used to visualize the distribution of decadal wind speed and direction for both decades.
- A 4-sector analysis was conducted using a decadal weighted histogram with four sectors for both decades 2002-2011 and 2012-2021. Four sectors, north (315° - 44°), east (45° - 134°), south (135° - 224°) and west (225° - 314°) were used. To describe the change in wind direction, the change in frequency was

calculated in percentage points. A map was created to see spatial similarities in changes of wind speed directions among different locations.

3. Results

3.1 Regional wind speed trends

Considerable regional differences were observed in both 50-year and 20-year data. Results of 50-year data are summarised in Table 1. After the highest peak of Hungary (Kékes) the windiest locations (highest Avg50 values) are in the North and West corner of the Carpathian Basin. Daily average wind speed shows significant trends in most cases (for intervals of categories, see Figure 1.). Wind speed trends are described by the slope of the fitted line in percent increase or decrease of wind speed per decade. Daily average wind speed in the 50-year-long term (WS50) seems to be increasing in the Little Hungarian Plain (North-Transdanubia). An example of the latter is shown in Figure 1a. However, negative trends of WS50 were observed in the windiest regions of Hungary, such as the Alpine Foreland (West Hungary) and higher locations of the Northern Mountains. A notably significant and unexpected increase in daily average wind speeds was observed in locations situated in the middle of the Great Hungarian Plain, particularly in Szolnok and Nyíregyháza.

Daily maxima show a significant increase in most locations. The number of calm days (daily maximum≤2 m/s) tends to decrease almost everywhere (e.g., Békéscsaba – Figure 2b). For thresholds other than 2 m/s, the number of calm days shows a similar tendency.

The number of windy days (daily average≥3 m/s) increased in the last 50 y in the Little Hungarian Plain, in some parts of the Great Plain, and at Lake Balaton but strongly decreased at the western border of the county.

*Table 1: Comparison of wind speed trends in 50 y NOAA data. Signs and abbreviations: Avg50 – average of daily mean wind speed (m/s), WS 50 – wind speed trend of daily averages (% per decade), Daily Max – trend of daily maximum wind speed for categories see Figure 1a, Calm Days – trend of yearly number of days with daily mean wind speed ≤2 m/s; Windy Days: trend of number of days with average wind speed ≥3 m/s. (+)/(-): slightly increasing/decreasing; +/-: increasing/decreasing; ++/-- strongly increasing/decreasing; ns: not significant; significant * p<0.01, ** p<0.001*

Location	Region	Avg50	WS 50	Daily Max	Calm Days	Windy Days
Bratislava	Little Hungarian Plain (N)	3.33	+6.4%**	++**	–**	++**
Eisenstadt	Little Hungarian Plain (NW)	3.25	+2.4%**	+**	–**	+++**
Győr	Little Hungarian Plain	2.67	+3.2%**	+++**	– –**	+*
Pápa	Little Hungarian Plain	2.97	+5.0%**	+++**	– – –**	++**
Hurbanovo	Little Hungarian Plain	2.87	-0.6%*	(+)**	–**	ns
Sopron	Alpine Foreland	3.69	-9.2%**	(–)**	ns	– – –**
Szombathely	Alpine Foreland	3.00	-7.2%**	–**	ns	– – –**
Nagykanizsa	South-Transdanubia	2.03	-1.9%**	(–)**	ns	++*
Siófok	S-Transdanubia (Balaton)	3.44	+5.0%**	++**	– –**	++**
Pécs	South-Transdanubia	3.00	ns	+**	–*	ns
Ferihegy	Budapest	3.20	+0.9%*	ns	–**	ns
Pestszentlőrinc	Budapest	2.57	-5.6%**	–**	ns	– – –**
Szolnok	Great Hungarian Plain	2.67	+12.3%**	+++**	– – –**	+++**
Kecskemét	Great Hungarian Plain	3.10	-3.4%**	+**	–**	ns
Baja	Great Hungarian Plain	2.03	-8.9%**	–**	+*	– – –**
Szeged	Great Hungarian Plain	3.19	-0.8%**	+**	–**	*–
Békéscsaba	Great Hungarian Plain	2.79	ns	++**	– –**	ns
Debrecen	Great Hungarian Plain	2.85	+4.5%**	++**	– – –**	++**
Nyíregyháza	Great Hungarian Plain	2.91	+11.3%**	+++**	– – –**	+++**
Orodea	Great Hungarian Plain	2.94	+2.1%**	–**	–**	ns
Kékes	Northern Mountains (Peak)	4.12	-4.4%**	–**	–**	ns
Miskolc	Northern Mountains (Valley)	1.96	+6.3%**	+**	ns	ns
Kosice	Northern Mountains	3.24	-4.3%**	–**	ns	+**

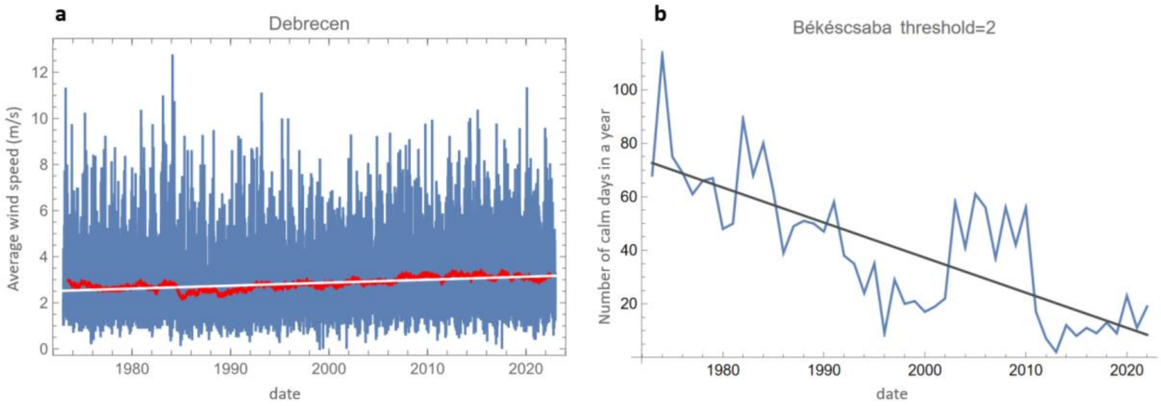

Figure 2: Examples of 50-y wind speed data from stations located in the Hungarian Great Plain. a: Fitted line to daily average wind speeds from Debrecen station (Middle Hungarian Great Plain) (white line) with a moving average of 365 days window (red curve). The daily average wind speed data are plotted in blue. Parameters of the fitted line: slope=-1.31107 p=0.0000 b: Fitted line to the number of calm days (i.e., #(daily maximum ≤ threshold =2 m/s) in a year) from Békéscsaba station (South East Hungarian Great Plain).

3.2 Regional wind direction trends

In order to examine wind directions, we selected data from multiple stations to demonstrate different patterns in the change of wind direction. The behavior of these changes varied across locations, ranging from minimal shifts to more noticeable ones. We will showcase the methodologies employed at the Agárd station, where a systematic and significant alteration in wind direction can be observed (Figure 3). Changes in the wind direction distribution are more prominent. Two dominant wind directions in the earlier decade were north-northwest and east-northeast, both of which started changing direction starting around 2012 to northwest and northeast, respectively. A significant decrease in the wind speeds is also observable on the wind roses.

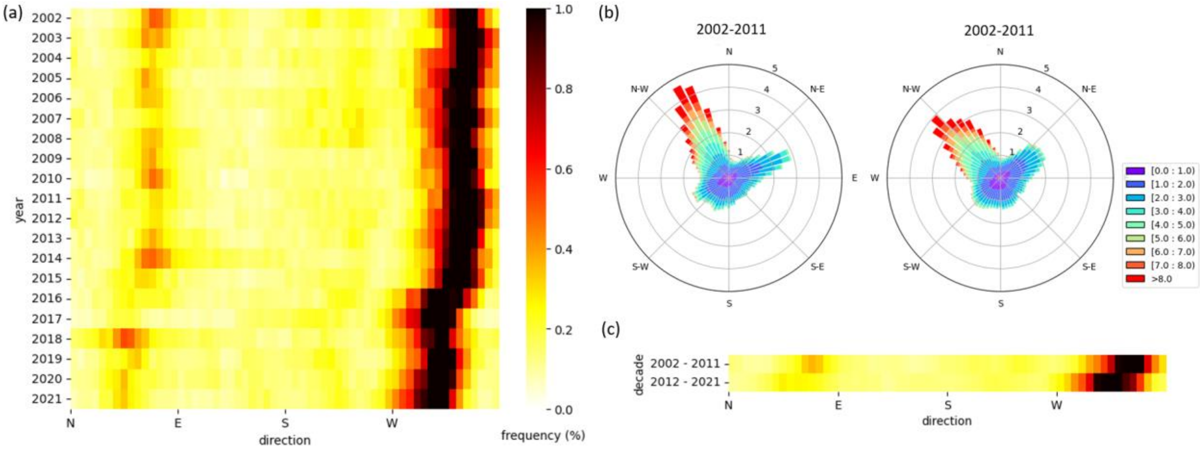

Figure 3a (left): (a) Yearly weighted wind direction histogram heat map of Agárd weather station from 2002 to 2021. (b): Decadal wind direction and speed frequency of Agárd weather station shown on wind roses. (c): Decadal weighted wind direction histogram heat map of Agárd weather station.

It is a reasonable question if the changes observed in the specific locations are results of local effects or if a more systematic change in the wind directions can be observed across the country. To summarize and compare changes in the behavior of local wind speed, we conducted a 4-sector analysis using data from all available stations. The results are presented in Figure 4.

Upon analyzing the wind direction changes on the map, it is clear that these effects tend to cluster in specific local regions. The highest change occurs predominantly in the Bakony and Börzsöny Mountains. In the Little Hungarian Plain, there is a noticeable decrease in western wind dominance, with northern winds becoming more prevalent. However, changes are less significant in western Hungary as well as the eastern and southern parts of the Great Hungarian Plain. It's worth noting that there are some exceptions; for example, at stations like Agárd and Sátoraljaújhely, these changes appear to be more pronounced compared to neighboring stations.

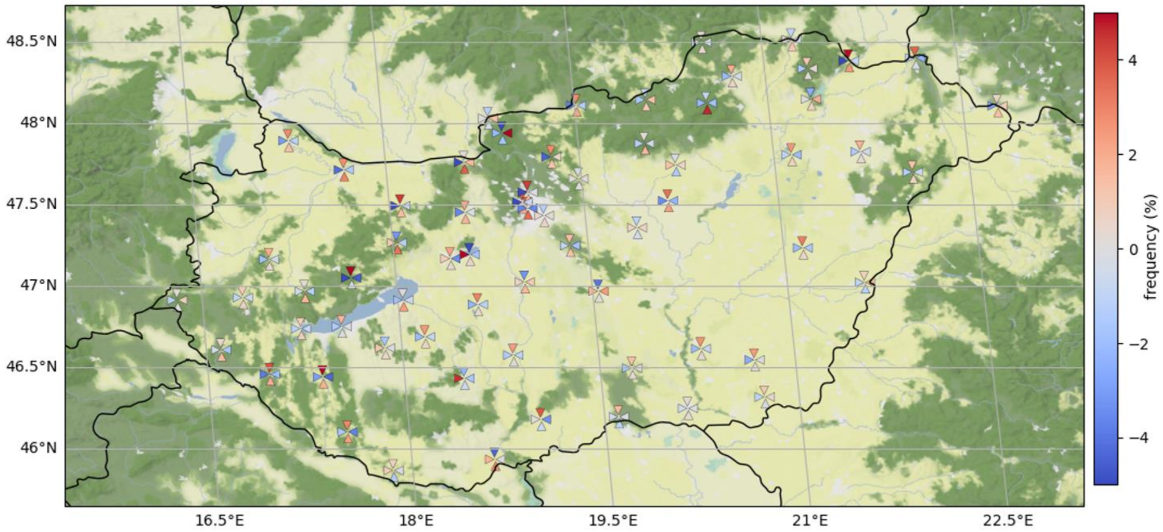

Figure 4: Changes in the percentual distribution of the weighed wind direction for various measurement stations in Hungary using the fourth method.

4. Discussion

The previous results suggest that change in wind speed and direction is localized to specific regions. Also, there are some points where change is exceptionally high, like in the Bakony mountains, or distinct from its surroundings, like Agárd. It is reasonable to assume that changes in wind direction affect changes in the local climate as well. These results do raise some questions. Is there a way to describe climate change more accurately? What will be the effects of changing wind speed on other aspects of the climate, such as temperature and humidity? How does this affect the sustainability of Hungary's agriculture? Observing the Little Hungarian Plane, as the northwestern wind turns north-northwestern, the humidity of the incoming wind will not change. However, the temperature will decrease. The decline in the prevalence of westerly and easterly winds could suggest a decreased impact from Atlantic and continental climates, potentially favoring Mediterranean influences. This shift may have implications for agricultural crops and local vegetation.

Increasing windspeed over the lakes (Balaton) may mitigate the warming of the water by stirring it up. Further investigation of seasonal variability may be needed to specify this result. The number of calm days is also an important index from the point of view of air pollution, as calm, warm days favor smog formation.

The fact that the number of calm wind days is uniformly increasing almost everywhere is consistent with the wind speed increase we have observed and the variability growth predicted by the models.

However, our data contradict the general decrease in wind speed predicted for Central Europe (Carvalho et al. 2021). Increasing trends in wind speed and the number of windy days in the northwest affect those areas where the most wind power plants are in Hungary, therefore enhancing wind power production. Although our wind speed data are 10 m height records, according to Peterson and Hennessey (1978), wind power law can be calculated. A sufficient understanding of climate change components, such as trends of wind, water, and solar radiation resources, is needed for planning further increases in the share of renewable energy (Cipolletta et al., 2023).

There is a significant but not very strong weakening of westerly winds in the western part of Transdanubia, indicating a possible connection to the absence of precipitation-bringing Atlantic-alpine air masses. However, for a more direct link between wind regime change and the mass mortality of beech in Zala County (Lakatos and Molnár, 2009) the directional analysis of the longer time dataset is also needed.

5. Conclusions

Our examination of wind speed data from the Carpathian Basin spanning 1973-2022 has unveiled previously unknown regional variations in trends. A noteworthy rise in wind speed across numerous locations over the last fifty years was unforeseen. The most significant decrease in wind speed occurred in elevated windier locations such as the Alpine Foreland and Kékes. The daily maximum values showed an overall increase in line with the

rise in wind speed, although the negative effect on daily maxima was less pronounced when wind speed decreased. The number of calm days demonstrated a significant decrease, while windy days became more frequent in areas experiencing higher wind speeds. These findings bring up the possible loss in wind energy potential in Alpine Foreland, but it might be compensated by the increase in the Little Hungarian Plain.
Using heat maps as a visual representation for analyzing the distribution of wind direction on an annual basis has proven to be a novel and effective approach in detecting even subtle changes over relatively brief periods of time. Aggregated wind roses indicate shifts in prevailing winds, which might disrupt the equilibrium of Hungary's three main climate regimes driven by wind patterns.
For a more definitive conclusion, further investigations are needed, such as aggregated wind rose analysis of the longer time series data. In addition to conducting similar investigations using longer-term data, factoring in seasonal variations may provide a more comprehensive understanding of the impacts of wind regime changes and unveil new questions regarding their interactions with other climatic factors. This avenue of research holds the potential to deepen our insights into this complex dynamic and guide future exploration in this field.

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