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A new meteorological pressure index to support a sustainable nuclear energy programme

M. Giardina *, P. Buffa

Department of Engineering, University of Palermo, Viale delle Scienze-Parco d'Orléans, 90128 Palermo, Italy

A R T I C L E   I N F O

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A B S T R A C T

Today, the evaluation of a site for innovative nuclear installations represents a fundamental step in supporting the implementation of a sustainable nuclear power program. One major concern is the potential for radioactive releases and their effects on the biosphere, particularly on human health. To address this issue, a new Meteorological Pressure Index (MPI) has been developed to identify sites with resilience capacity in terms of transport phenomena correlated to natural wind actions on a regional scale. The MPI utilizes a fuzzy approach that combines data on 3D wind speed, direction, and frequency, providing maps that are useful in the site selection process. The application of MPI in the Sicily region of Italy has allowed to identify bordering areas that that are more affected by efficient air mass transport mechanisms. Consistency analyses have been conducted among MPI maps, observed wind distributions using wind rose charts, and stagnation S and recirculation R factors. The results confirm the MPI's ability to aggregate meteorological data on a regional level, making it a suitable tool when compared to disaggregated data that may not always provide a comprehensive viewpoint.

1. Introduction

Among the aspects considered crucial in evaluating the suitability of a site for nuclear installations, the characteristics of the site and its environment play a key role as they can influence the transfer of released radioactive material on both humans and the environment. If the evaluation determines that the site is unacceptable, any identified deficiencies cannot be mitigated by design features, site protection measures, or administrative procedures, and the site will be deemed unsuitable (International Atomic Energy Agency, 2019).

It is important to note that planned releases of radionuclides within prescribed limits from nuclear power plants can occur during normal operation. While plants are designed to prevent accidental releases, it is necessary for the Environmental Impact Assessment (EIA) to consider the possibility of such releases and their potential impact on humans and the environment (Basri et al., 2016; Fischer et al., 2019; Musyoka and Field, 2018). The analysis of atmospheric dispersion of radioactive material should consider the region's orography, land cover, and meteorological features. This includes parameters such as wind speed and direction (International Atomic Energy Agency, 2019). If possible, long term meteorological data for nearby locations shall be obtained, evaluated for quality and used.

Therefore, conducting studies that provide a thorough and accurate understanding of the interplay between climate conditions, environmental characteristics, and anthropogenic impacts is essential to facilitate decision-making processes (Abudeif et al., 2015; Giardina et al., 2017; Giardina and Buffa, 2018; International Atomic Energy Agency, 2014; Woo et al., 2022).

In this context, it can be effective to have a tool able to generate maps that highlight the most suitable sites in terms of meteorological resilience capacity with respect to the environmental impacts of nuclear installations. These maps can then be compared with other thematic maps (archeologic protection sites, seismic hazard map, etc.) to provide a comprehensive assessment.

As part of a collaboration between Regional Agency of Environmental Protection in Sicily (ARPA) and Department of Engineering, University of Palermo, research activities allowed to develop a new meteorological pressure index (MPI) which proves to be useful in identifying geographical areas on a regional scale that exhibit resilience capacity in terms of transport phenomena linked with natural wind actions (Giardina et al., 2019, 2018).

The MPI utilizes a fuzzy approach to integrate data on 3D wind speed, direction, and frequency. It creates maps that are useful for identifying neighboring areas on a large scale, which exhibit

* Corresponding author.
E-mail address: mariarosa.giardina@unipa.it (M. Giardina).

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environmental similarities in terms of 3D wind fields. Specifically, the MPI distinguishes between high rates of atmospheric interchange zones and no interchange zones.

Since wind variability is important for a variety of applications, several studies have focused on this subject. The vertical wind profile is an important parameter that affects various meteorological processes across all scales, ranging from micro to synoptic and planetary scales (Nair et al., 2022). In the study by Zheng and Sun (2016), the impact of vertical wind shear on the intensity and organizational mode of mesoscale convective systems is examined. The results included the fact that the near-surface wind speed and precipitation amount increased with increased vertical wind shear, and heavy precipitation appeared after the strongest wind. In (Papadopoulos et al., 2012; Soukissian and Sotiriou, 2022) the significant role of the wind field over the Mediterranean during the extreme cooling events is highlighted and studied.

In nuclear field, another fundamental aspect concerns the rainfalls analysed by numerous studies for the deposition evaluations after Fukushima accident (Fang et al., 2022; Sato et al., 2020, 2018; Zhuang et al., 2023). Zhuang et al. (2023) highlighted that the wind transport showed substantial influence on the removal of atmospheric 137Cs, and it was nonnegligible even during periods in which wet deposition was dominant. Other authors highlighted the importance of the good representation of the wind field resulted in the reasonable simulation of the distribution of deposition amount to different areas of Fukushima Daiichi Nuclear Power Plant (Sato et al., 2020).

All the above touched-upon subjects highlight the importance of having a methodology aimed at identifying the efficient performance of the 3D wind field and, as a result, identifying potential sites for nuclear installations where further fundamental investigations can be carried out, such as studying precipitation events or extreme events.

An application of MPI in the Sicily region, Italy, as a case study, has been conducted to identify zones that exhibit a natural predisposition to withstand environmental pressures. Furthermore, consistency analyses have been performed, comparing the MPI maps with observed wind distributions from various coastal and near-coast stations using wind rose charts. Additionally, stagnation S and recirculation R factors, as proposed in (Allwine and Whiteman, 1994), have been considered, and results have been compered and discussed.

2. Fuzzy logic and fuzzy operations

Fuzzy logic and Fuzzy sets (Zadeh, 1992) have found an important role in different fields (Casamirra et al., 2009; Kentel and Aral, 2007) and applications can be found also in different meteorological and environmental analyses (Abdourahamane and Acar, 2019; Liu et al., 2009).

The success of this approach is that it allows to deal with problems characterised by imprecise phenomena or to model experiences defined by linguistic expressions (Buffa et al., 2021; Castiglia et al., 2010; Castiglia and Giardina, 2011).

As well known, classic set theory is based on bivalent logic and a shortcoming of this approach is its inability to come to grips with the issue of uncertainty and imprecision.

On the contrary, let Ω be a collection of fuzzy objects (i.e., universe of discourse) whose elements are denoted by x; a fuzzy subset A in Ω is characterized by a membership function $f_A(x)$ that associates x in Ω with a real number in interval [0,1]. Function $f_A(x)$ is the membership degree of x in A. The most common fuzzy membership functions are triangular or trapezoidal.

Zadeh (1992) suggested for operations on fuzzy sets, minimum operator for intersection and maximum operator for union:

$$CB \equiv ax, fACB(x)n|xIXefACB(x) = \min[f_A(x), f_B(x)] \tag{1}$$

$$AEB \equiv ax, fAEB(x)n|xIXefAB(x) = \max[f_A(x), f_B(x)] \tag{2}$$

The combination of these two operators is generally used for the definition of fuzzy if-then rules, i.e. the fuzzy inference system (FIS) characterized by the following main steps:

- fuzzification process to model variables into fuzzy sets;
- construction of FIS, based on if-then rules where fuzzy logic operations are used;
- defuzzification process to return from fuzzy numbers to crisp value.

Table 1
Linguistic terms and input fuzzy sets related to Wind Speed, WS [m/s].

Linguistic value of WS [m/s]	Fuzzy linguistic number $(x_1; x_2; x_3)$; $(x_1; x_2; x_3; x_4)$*	Weight, p_{WS}
Very Low (VL)	(0; 1.5; 3.3)	0.2
Low (L)	(1.5; 3.3; 6)	0.4
Medium (M)	(3.3; 5.5; 7; 10)	0.6
High (H)	(6; 9.5; 11; 14)	0.8
Very High (VH)	(10; 14; 100;100)	1

*Triangular and trapezoidal fuzzy numbers are indicated with (x_1, x_2, x_3) e (x_1, x_2, x_3, x_4), respectively.

Table 2
Linguistic terms and input fuzzy sets related to Wind Frequency, WF [%].

Linguistic value of WF [%]	Fuzzy linguistic number $(x_1; x_2; x_3)$; $(x_1; x_2; x_3; x_4)$	Weight, p_{WF}
Very Low (VL)	(0; 0; 5; 10)	0.2
Low (L)	(5; 10; 15)	0.4
Medium (M)	(10; 15; 20)	0.6
High (H)	(15; 20; 25)	0.8
Very High (VH)	(20; 25; 100; 100)	1

An example of fuzzy *if-then* rule is reported below:

Rule R_j: ***If*** x_1 *is* A_{1j} ***and*** … ***and*** x_n *is* A_{nj} ***then*** y *is* B_j j = 1, 2,…m (weight of the rule, w_j) (3)

where A_{ij} and B_j are input and output linguistic variables of universes of discourse Ω, respectively, and w_j is the importance degree of the rule, in the range [0,1].

The if-part of the rule "x_n is A_{nj}" it's called antecedent, or assumption, while the then-part of the rule "y is B_j" it's called consequent.

The parameter w_j in Eq. (3) gives the weight attributed at j^{th} rule if compared to the other rules in the FIS system and allows the analyst to attribute an importance level to each rule.

If min–max inference is used in Eq. (3), Eq. (1) is employed in if parts of the rule (i.e., intersection) and Eq. (2) is used to aggregate output fuzzy sets (i.e., union) after cutting output membership functions at the minimum values of the antecedents (Giardina et al., 2014; Kundu, 1998).

Moreover, if Eq. (3) is used with the attribution of w_j, the consequent function B_j is modified as follow:

$f_j^*(x) = \max\{w_j f_j(x); \text{for } j = 1, 2,..m\}$ (4)

Final step is the defuzzification process that consists of averaging fuzzy outputs into a single decision (i.e. crisp value):

$$\text{Crisp} = \frac{\int x\, f^*(x)\, dx}{\int f^*(x)\, dx} \tag{5}$$

where f*(x) is calculated by Eq. (4) (Giardina et al., 2014).

2.1. MPI index

Fuzzy classification is a process that allows to group elements that have the same characteristics in a fuzzy set. As stated above, it corresponds to assigning a membership function that indicates whether an element is a member of a class, given its fuzzy classification predicate.

For MPI index calculation, two fuzzy indicators are classified (Tables 1 and 2):

Table 3
Linguistic terms and output fuzzy sets related to MPI index.

Linguistic value of MPI [-]	Fuzzy linguistic number $(x_1; x_2; x_3)$; $(x_1; x_2; x_3; x_4)$	Weight, p_{MPI}
Very Low (VL)	(0; 0.1; 0.2)	0.111
Between Very low and Low (VL_L)	(0.1; 0.2; 0.3)	0.222
Low (L)	(0.2; 0.3; 0.4)	0.333
Between Low and Medium (L_M)	(0.3; 0.4; 0.5)	0.444
Medium (M)	(0.4; 0.475; 0.525; 0.6)	0.556
Between Medium and High (M_H)	(0.5; 0.6; 0.7)	0.667
High (H)	(0.6; 0.7; 0.8)	0.778
Between High and Very High (H_VH)	(0.7; 0.8; 0.9)	0.889
Very High (VH)	(0.8; 0.9; 1;1)	1

- wind speed (WS) [m/s];
- percentage of wind frequency (WF) [%].

WS is classified considering the Beaufort scale, based on observed effects of wind speeds on sea or land (Barua, 2005; Giardina et al., 2019).

To give an example, numbers 1 through 3 in Beaufort scale are related to wind speed in the range 0.0 ÷ 3.3 m/s, with effects between "calm" and "light breeze", therefore, fuzzy classification in terms of linguistic label is "Very Low" (VL), with triangular membership function and mean value of 1.5 m/s (Table 1).

WF linguistic distribution is based on five classes, considering frequency of 5% as a lower limit of WF set, identified with label "Very Low", and frequency of 25% as an upper limit of WF set, identified with label "High" (Table 2). This takes into to account common frequency scores used in wind rose chart.

MPI linguistic distribution is based on a domain of nine labels to extend the semantic relations of natural languages used by experts in this field (Table 3).

Details about the fuzzy approach used to do fuzzy if-then rules is described in the following section.

2.1.1. Example of determination of fuzzy rule-based system for MPI index

The fuzzy model is based on a FIS of 25 rules defined for each of the layers that schematize the vertical wind field. To do this, weights of each linguistic term are evaluated by assuming linear hypothesis:

$$p_{WS}p_{WF}p_{MPI} = i/k i = 1, 2k \tag{6}$$

where k is the number of language variables of WS, WF and MPI (see Tables 1–3).

FIS is determined taking into account the linear weights of input fuzzy variables, reported in Tables 1 and 2, the relative importance R_{WS} and R_{WF} attributed to WS and WF by the analyst, and linear weights of output fuzzy variables, reported in Table 3.

In this paper, for the first layer that defines the vertical structure of the atmosphere, it is assumed $R_{WS} = 0.5$ and $R_{WF} = 0.5$. For subsequent two vertical layers, it is assumed $R_{WS} = 0.4$ and $R_{WF} = 0.6$. That's because of frictional drags that have low impact on WS values in higher vertical layers compared to frictional drags in the first layer (or ground level), consequently, low differences of WS can be observed in higher vertical layers and neighboring zones. Therefore, WF is the meteorological parameter that better follows reciprocal exchanges among bordering cells.

The following example provides a comprehensive understanding of the determination of the FIS (Fuzzy Inference System) rule for the MPI index. This is achieved by referring to Tables 1 through 3.

Let us take $R_{WS} = 0.5$ and $R_{WF} = 0.5$, and weight p_{MPI} calculated as follows:

$p_{MPI} = R_{WS}\, p_{WS} + R_{WF}\, p_{WF}$ (7)

Based on Eq. (7), it is possible to identify the following rule:

Rule: ***If*** WS is VL with $p_{WS} = 0.2$ ***and*** WF is M with $p_{WF} = 0.6$ ***then*** MPI is *Between Low and Medium* (L_M) with $p_{MPI} = 0.444$ (8)

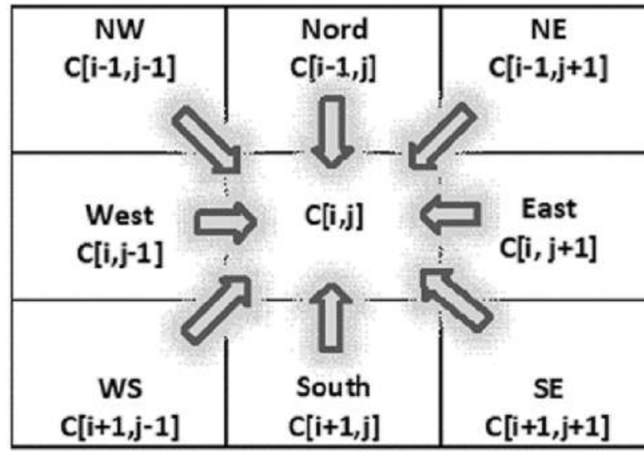


Fig. 1. Schematization of cell c[i,j] for computing MPI[i,j].

Detailing the content of the above rule, by using Eq. (7), mathematically it happens that $p_{MPI} = 0.5x0.2 + 0.5x0.6 = 0.4$. This value is close to MPI label defined as Between Low and Medium (L_M) (Tab. 3) with weight $p_{MPI} = 0{,}444$.

Once FIS rules are known, min–max inference is used to combine input fuzzy sets into output fuzzy sets. Defuzzification step is carried out by using Eq. (5).

For definition of resilience maps, MPI index is calculated in each cell neighboring of a generic cell c[i,j] of the grid, as represented in Fig. 1. Sum of the results is attributed to c[i,j]. This allows to take into account two main factors: c[i,j] receives meteorological pressure from the nearby cells; wind directions (i.e., direction bins related to height cells: North, NE, East, SE, South, SW, West, and NW) that with more frequency affect c[i,j] (Fig. 1).

Finally, MPI map is created by using the sum aggregation method of MPI indexes evaluated for each of the layers.

2.1.2. MPI classification by using CALMET simulation

For MPI index calculation, wind speed and frequency results obtained by CALMET simulations (Martorana et al., 2021; Scire et al., 2000) of the vertical profile of the atmosphere divided into three layers (z = 10, 20, 40 m) are used.

CALMET is a meteorological model that develops hourly wind and temperature fields on a three-dimensional gridded modelling domain, and two-dimensional fields of turbulent parameters.

FIS rules are developed, i.e. 25 rules for each of the three layers with which vertical structure of the atmosphere is schematized. The following steps are used to evaluate MPI for cell c[i,j]:

- read velocity and frequency wind data calculated by CALMET for the eight cells adjacent to the cell c[i,j] (Fig. 1);
- use data as inputs in FIS;
- evaluate MPI for each of the eight cells adjacent c[i,j];
- sum of MPI results and assign the result to c[i,j].

Finally, MPI normalization procedure is done by using a distribution in ten quantiles:

$$\mathrm{IPM}\,[i,j] = \begin{cases} \begin{array}{ll} 0 \text{ if IPM } Q^{0.2} & 5 \text{ if } Q^{0.6} \le \mathrm{IPM} < Q^{0.7} \\ 1 \text{ if } Q^{0.2} \le \mathrm{IPM} < Q^{0.3} & 6 \text{ if } Q^{0.7} \le \mathrm{IPM} < Q^{0.8} \\ 2 \text{ if } Q^{0.3} \le \mathrm{IPM} < Q^{0.4} & 7 \text{ if } Q^{0.8} \le \mathrm{IPM} < Q^{0.85} \\ 3 \text{ if } Q^{0.4} \le \mathrm{IPM} < Q^{0.5} & 8 \text{ if } Q^{0.85} \le \mathrm{IPM} < Q^{0.9} \\ 4 \text{ if } Q^{0.5} \le \mathrm{IPM} < Q^{0.6} & 9 \text{ if } Q^{0.9} \le \mathrm{IPM} < Q^{0.95} \\ & 10 \text{ if IPM} \ge Q^{0.95} \end{array} \end{cases} \tag{9}$$

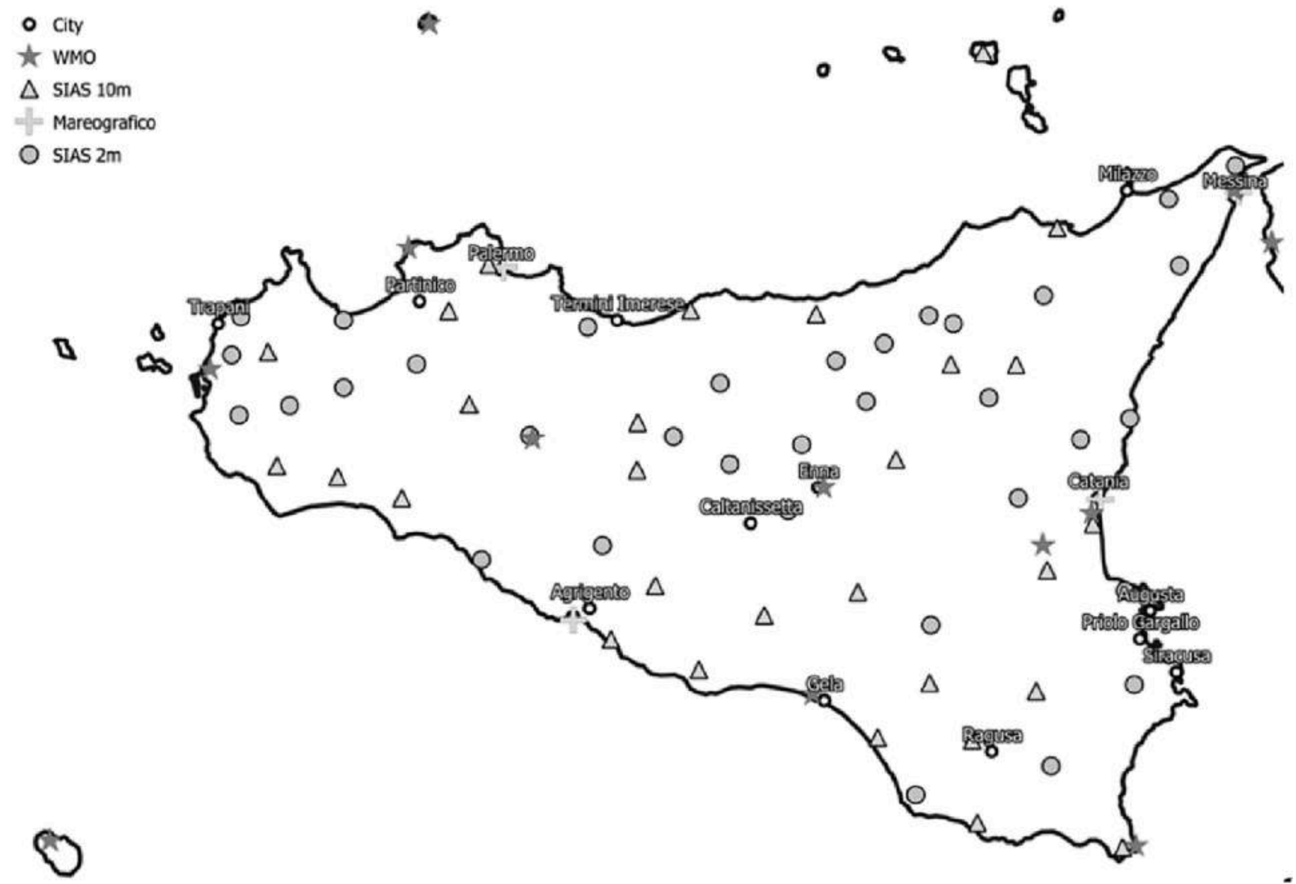


Fig. 2. Network stations used for simulations performed by CALMET model.

where Q_n is n-th quartile of the data set (e.g. $Q^{0.5}$ corresponds to the median of data set). Note that MPI index is approximately normally distributed.

3. Application of MPI in a case study and results

Sicily is in the middle of the Mediterranean Sea and experiences hot, dry summers and mild winters with hardly any frost.

Because of its position, this region is in a transition area between the dry and arid climate typical of North Africa and the more temperate climate of central Europe. In summer, moist convective phenomena lead to thunderstorms that affect the inland areas, where temperatures can reach high values. In autumn, the seas surrounding Sicily are normally perturbed by cyclones that originate from interactions between air masses with different temperatures which contrast with the high temperature of the sea water.

Sicily is known for its characteristic winds. For example, the sirocco is a hot and dry wind that blows from the south or southeast, originating in the Sahara Desert. It can bring dusty conditions and increase temperatures significantly. The mistral is a strong north-westerly wind that affects the western coast of the island.

It's important to note that in literature it is highlighted the importance of considering the mean wind field as a crucial meteorological factor in understanding and predicting specific weather phenomena and atmospheric processes, contributing to a more comprehensive understanding of synoptic-scale weather patterns (Hartten et al., 2018). Extending the time interval to multiple years in the evaluation of MPI can be useful to obtain a more accurate view of synoptic-scale weather patterns. While short-term weather events are often characterized by fluctuations and variability, analyzing over a longer period allows for the identification of climate trends and anomalies. Of course, MPI can also be used to conduct subsequent analyses on annual averages, providing insights into the characteristics of a specific area.

3.1. Details of CALMET simulations

CALMET is a diagnostic computer model that produces detailed three-dimensional fields of meteorological parameters based on surface and upper air measurements, digital land use data, digital terrain data and prognostic meteorological data. The wind field module uses a two-step approach to evaluate the wind fields:

- step 1, an initial guess wind field is adjusted for kinematic effects of terrain, slope flows, and terrain blocking effects to produce a first wind field;
- step 2, an objective analysis procedure allows to introduce, into the wind field results obtained in step 1, observational data of surface and upper air measurements, specified by the user in input. This produces the final wind field.

Reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF) have been downloaded for the same period and processed by using the FORCAL pre-processing software (Martorana et al., 2021). The FORCAL tool extracts and converts data provided by ECMWF, calculates the meteorological missing variables, and sets results in the format accepted by CALMET. The reanalysis datasets were utilized as the initial guess wind field (step 1) in the CALMET simulations.

Moreover, observed data of temperature, relative humidity, wind direction and speed from 80 measuring stations covering the whole Sicily region are employed (Fig. 2).

In detail, measurements from 12 stations of the World

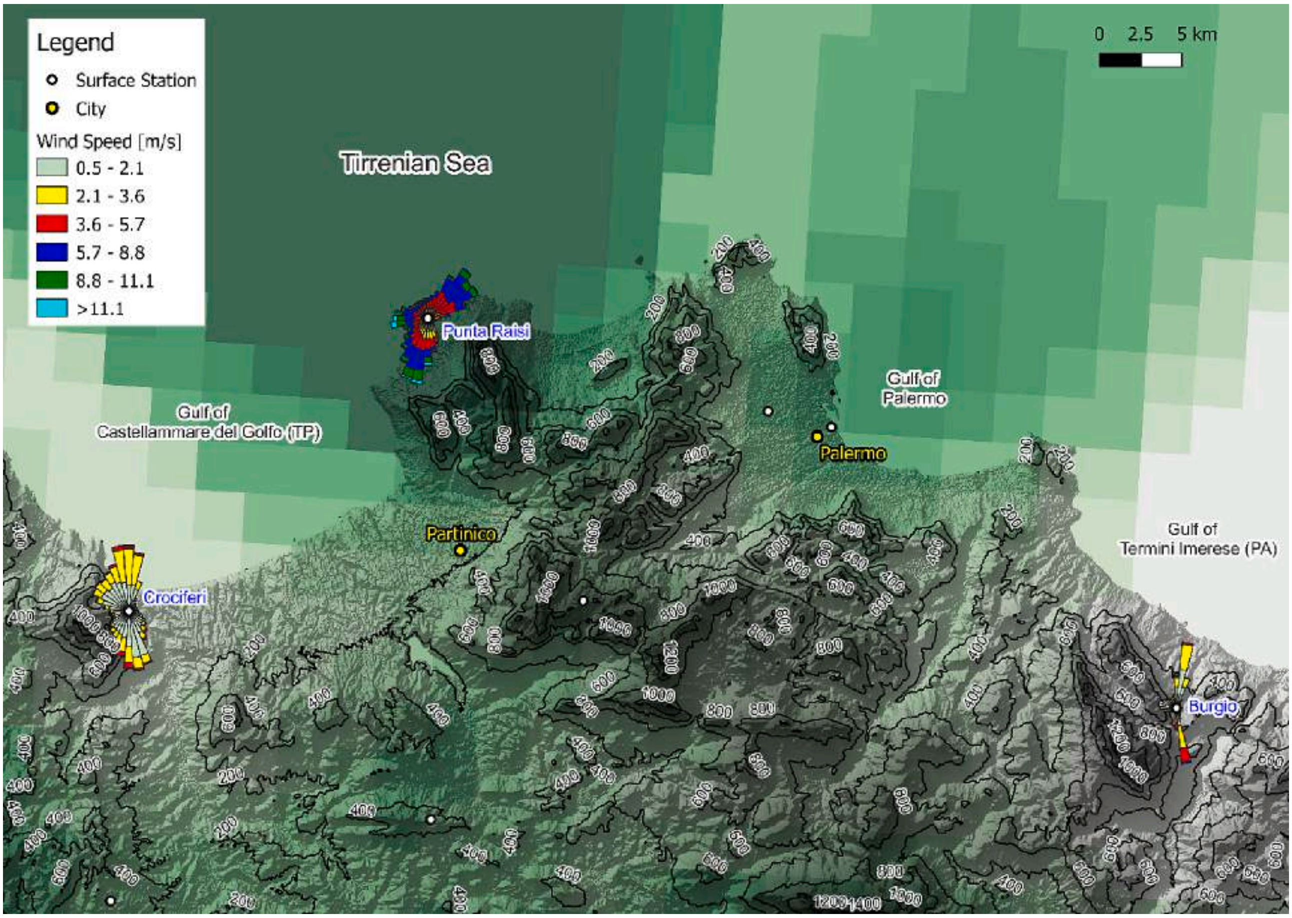


Fig. 3. Location of Crociferi, Palermo and Burgio stations on the north coast of the Sicily.

Metereological Organizzation (WMO) at 10 m height above ground level (star points in Fig. 2), and 4 stations of Mareografic at 10 m height above ground level and near the coast are used (cross points in Fig. 2). For a total coverage of the Sicily region, data from on-surface stations of Servizio Informativo Agrometeorologico Siciliano (SIAS) at 2 and 10 m above the ground level are considered. In Fig. 2 stations at 10 m are shown by triangle points, at 2 m by circle points.

The profilometric data are provided by an upper-air station of the Servizio Meteorologico dell'Aeronautica Militare sited near the Trapani Birgi airport.

The computing domain covers an area of 73.700 km^2 extending to a territory that comprises the entire region of Sicily and the smaller islands, with cell resolution of 3x3 km.

A lot of attention is paid to choosing the parameter called TERRAD (Terrain Adjustment, expressed in km), specified by the user. Terrain features, such as mountains, valleys, hills, and coastal areas, can significantly affect the flow and distribution of atmospheric variables like wind speed, wind direction, temperature, and precipitation. By using TERRAD, the CALMET model allows the consideration of the distance used in computing the kinematic effects, the slope flow effects, and the blocking effects on the wind field. Analyses performed by the QGIS software regarding ridge-to-ridge distances across hills of neighboring cells allowed an evaluation of the TERRAD value of 2.5 km. Other parameters are set according to the guidelines reported in (Bridgers, 2016; Irwin, 1998; Irwin, 1998; Bridgers, 2016; Martorana et al., 2021).

To determine the accuracy of the simulated wind speeds, we have evaluated the index of agreement (AI) (Willmott et al., 1985) that measures how well the variability in the model simulations matches observed data. AI can vary between 0 and 1, with 1 representing a perfect agreement of wind speeds at all grid points. In mesoscale model applications, a value of AI greater than 0.5 is considered to be typical for a successful simulation of wind speed.

AI results in our work have range from 0.6 to 0.7, demonstrating the good performance of the simulations.

MPI index is evaluated by using three-dimensional wind data calculated by CALMET with hourly time step for ten years, from 2010 to 2019, to obtain a more consistent set of results.

For the entire examined domain, the MPI classification has been conducted as described in section 2.2.2, utilizing all simulated data from 2010 to 2019. MPI maps have been generated to identify neighboring areas on a large scale that demonstrate contrasting levels of air interchange zones, ranging from high rates to no interchange.

3.2. *Consistency analyses between MPI map and observed wind distributions at different coast and near-coast stations*

Generally, high wind intensity in coastal areas is characterized by local phenomena that periodically move air masses from the sea to the coast and from the coast to the sea (land-sea breeze). Therefore, these situations can have a large impact on the spatial and temporal distribution of the winds and determine to a large extent the dispersive ability of the atmosphere.

To determine if MPI modelling allows to capture these effects, investigations are performed by comparisons of MPI maps with observed wind distributions from some coast and near-coast stations by using wind rose graphical charts and stagnation S and recirculation R factors, as proposed in (Allwine and Whiteman, 1994).

3.2.1. *Description of station sites used for validation*

Fig.s 3 through 5 show topography maps of some territories in Sicily,

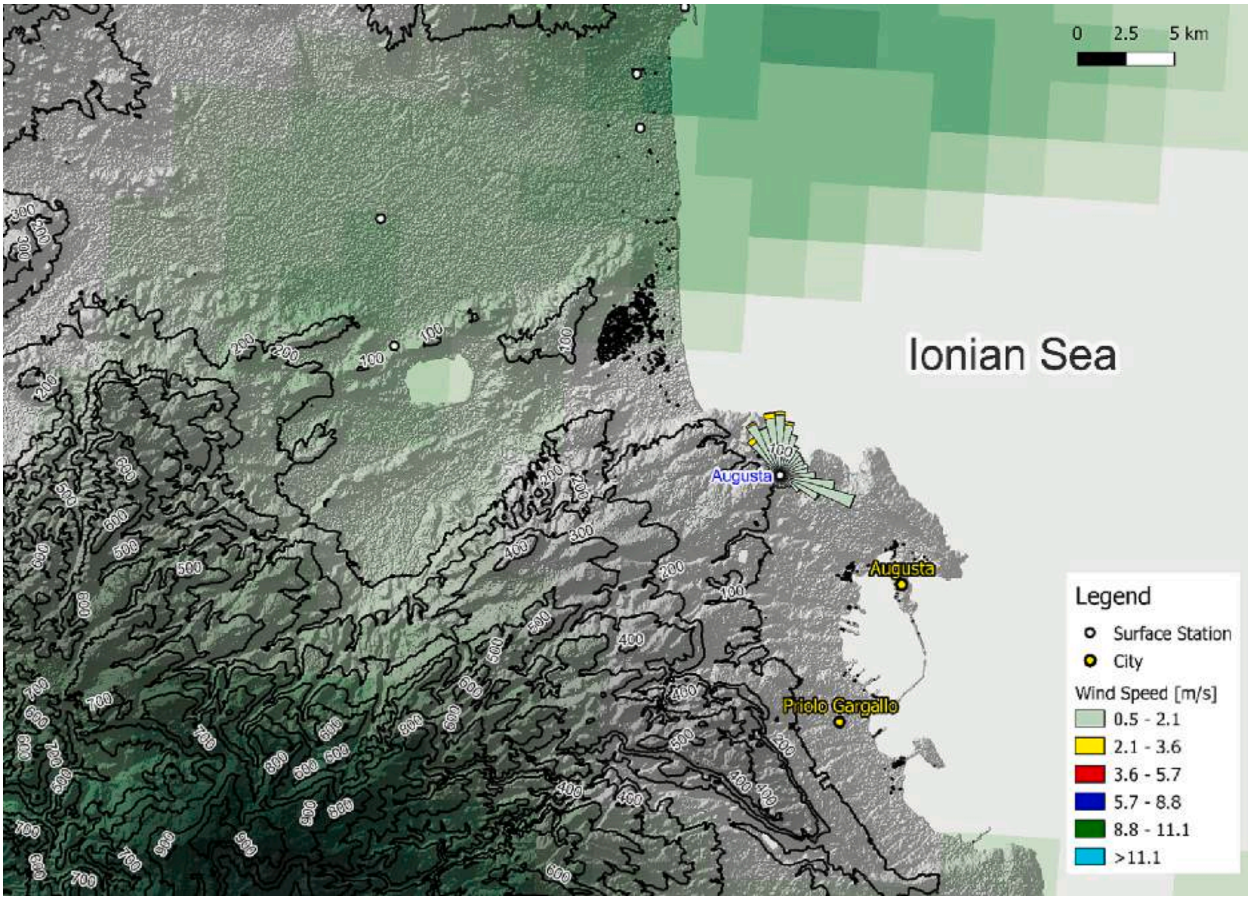


Fig. 4. Location of Augusta station on east coast of the Sicily.

isolines of elevation above mean sea level (MSL) [m], results of normalized MPI index distributions, and location of Crociferi, Palermo, Burgio (Fig. 3), Augusta (Fig. 4), and Fulgatore (Fig. 5) weather stations, used to study wind patterns by using wind rose diagrams. MPI data is represented by different shades of green colour that show the quantiles from 1 to 10 by Eq. (9).

Crociferi, Palermo and Burgio stations are located on the north coast of the Sicily and face the Tyrrhenian Sea (Fig. 3).

In particular, Crociferi station is in the Castellammare del Golfo, a large and deep natural inlet that stretches from Capo Rama to Capo San Vito, near San Vito Lo Capo town in the province of Trapani.

Palermo station is located near Falcone-Borsellino Airport, approximately 35 km from the city center of Palermo, finally Burgio Station is located near Termini Imerese power station, a gas-fired power plant in the province of Palermo.

Augusta station (Fig. 4) is placed on the east-side of the Sicily coast, facing the Ionian Sea. It is near the petrochemical industries (Gela, Ragusa, Siracusa and Augusta) that cover a large area from Siracusa to Ragusa cities. These plants are considered to be the largest in Europe, with numerous oil and chemical refineries and energy production companies. The station site is located in a coastal mountainous area (Climiti Mountains) with elevations between 50 and 570 m. The shape of the vertical cross section of the Climiti Mountains constitutes a cliff barrier, the top part is more or less flat and is furrowed by numerous gullies bordered by more or less developed rocky walls.

Lastly, Fulgatore station (Fig. 5) is situated in the west hinterland of the Sicily (about 15 km from the western coastline), between Trapani and Marsala cities. The territory around the site is characterized by mix of rolling hills and flat valleys.

3.2.2. *Stagnation A and recirculation R factors*

S factor measures the straight-line transport of an air parcel from the selected transport time. Values close to zero are associated to almost stagnant conditions (no winds and thus no transport). R factor allows to identify transport and extended local horizontal recirculation. Values approaching 0 indicate straight-line transport while values approaching 1 mean that the air parcel returned to its.

These factors are computed according to Allwine and Whiteman (1994) as:

$$S_i = T\sum_{j=1}^{i+p} \langle U \rangle_j \tag{10}$$

$$R_i = 1 - \frac{L_i}{S_i} \tag{11}$$

$$L_i = \sqrt{X_i + Y_i} \tag{12}$$

resultant transport distance with

$$X_i = T\sum_{j=1}^{i+p} \langle u \rangle_j \tag{13}$$

north–south transport distance

$$Y_i = T\sum_{j=1}^{i+p} \langle v \rangle_j \tag{14}$$

east–west transport distance

where U is the wind speed at 10 m above ground level, u and v are the west-east and south-north components of wind, T is the averaging interval of the observed data, i = 1,2,…,N − p, N is the total number of

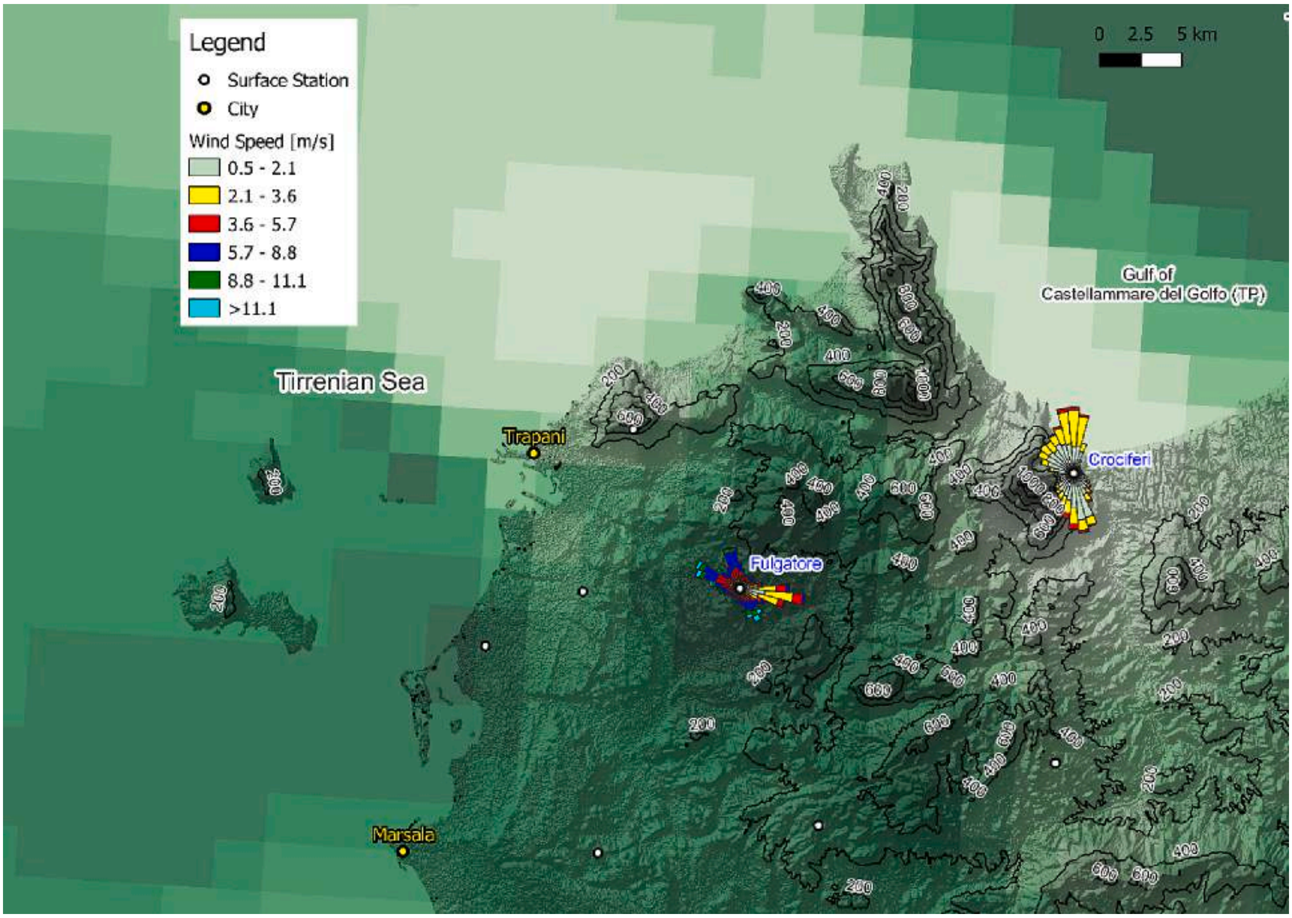


Fig. 5. Location of Fulgatore station in Sicily west hinterland.

series data points and p = τ /T − 1 with τ the selected transport time, and L_i the resultant transport distance.

Fig.s 6 and 7 report stagnation S and recirculation R factors for some of examined observed data.

It's worth noting that, as highlighted in (Allwine and Whiteman, 1994), S would be a correct measure of transport in an ideal homogeneous wind field. However, as homogeneous wind fields are not normally experienced in real situations, especially in complex terrain, integral measures of transport are not true measures of the transport of a plume, but rather should be considered as characteristics of the flow at the measurement point.

Therefore, wind roses diagrams, S and R factors allow to experience wind characteristics at the measurement point, whereas MPI index allows comparisons of bordering cells in the territory with similar or different behaviours in terms of 3D wind fields, by providing as much information as possible about resilience capacity related to transport phenomena at regional level.

3.2.3. Discussion about results

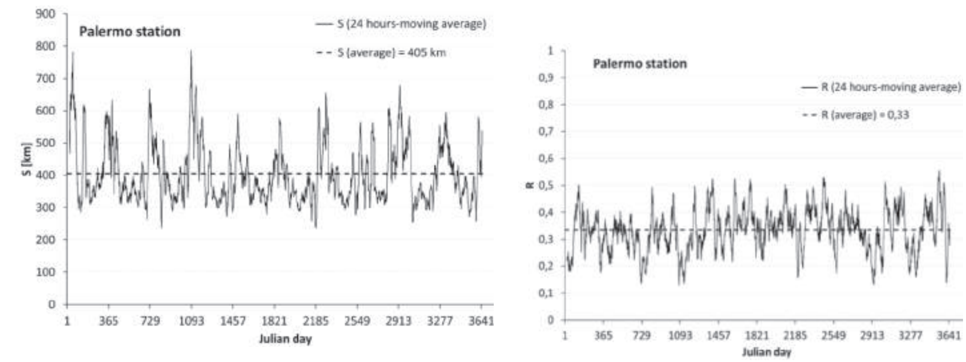
Note that wind roses diagrams of Figs. 3 through 5 and R an S distributions of Fig.s 6 and 7 are evaluated for ten years, from 2010 to 2019, as done for MPI index.

The wind roses of Crociferi, Palermo and Burgio stations in Fig. 3 provide the distribution of the prevailing wind speed and direction as outlined below:

- For Crociferi station, wind directions are scattered between north and south with low wind speeds (highest frequencies are for wind speed classes 0.5 ÷ 2.1 m/s and 2.1 ÷ 3.6 m/s). The orography of the western shore of the Castellammare del Golfo is characterized by mountains with peaks that approach 1000 m (Figs. 3 and 5), and this gives barrier winds that in turn generate a mountain-parallel wind, however of low speed;
- For Palermo station, the winds tend to blow predominantly from north-east and south-west directions (about 15% frequency). These conditions are associated with wind speeds in the range of 3.6 ÷ 11 m/s. The orography and the geographical location right on the tip of the Punta Raisi promontory is of significant influence on these observations;
- Burgio station is blocked by the surrounding land which is more conducive to the development of sea breezes. Wind directions are scattered between north and south-east, with speeds of low intensity (highest frequency is for wind speed class 2.1 ÷ 3.6 m/s). The highest frequency of the north direction (sea breeze) is about 20% but it is characterized by low-speed intensity.

The wind fields for Augusta station tend to blow predominantly from north and south-east directions (Fig. 4). Wind speeds in the range of 0.5 ÷ 2.1 m/s, with highest frequency of about 6% from south-east, are observed. We recall that Augusta station site is bordering the Climiti Mountains. Similar conclusions, given for observed data of Crociferi and Burgio stations, can be drawn for this site.

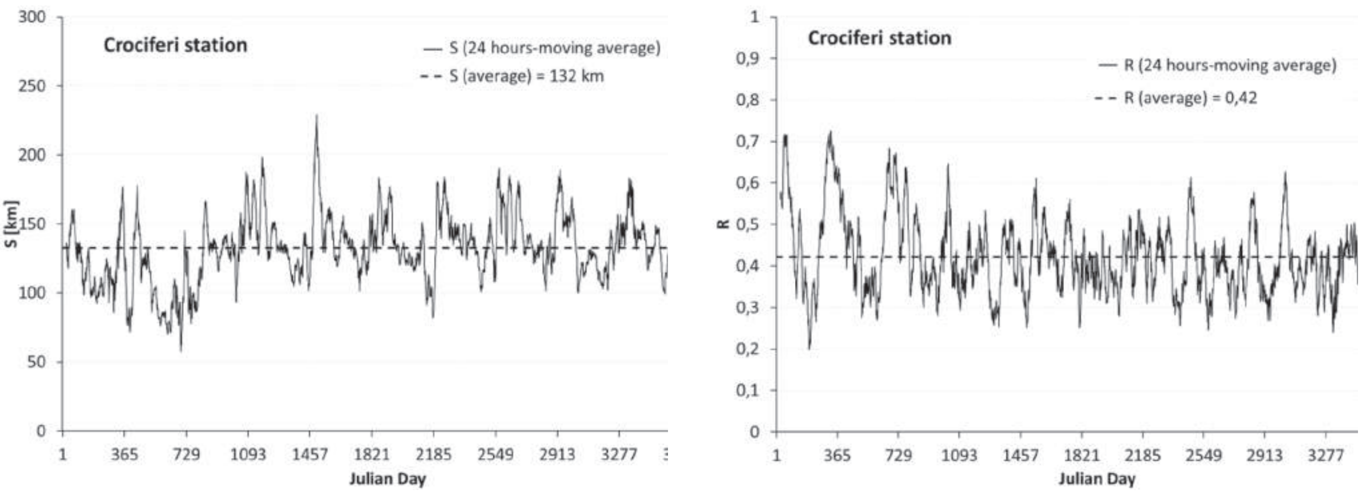
To learn more about observed data behaviors of Crociferi, Burgio and Augusta stations, wind roses based on seasonal variations as well as diurnal and nocturnal distributions were examined. The results highlight that in winter and autumn the prevailing wind speeds are relatively low (less than 2.0 m/s), while in the other seasons speed classes between 2 and 4 m/s prevail. Therefore, if recirculation by land-sea breeze phenomena occur, these are characterized by low speed intensity and short duration.



(a)

(b)

Fig. 6. Stagnation S (a) and recirculation R (b) factors evaluated for ten years, from 2010 to 2019, by using observation data.



(a) (b)

Fig. 7. Stagnation S (a) and recirculation R (b) factors evaluated for ten years, from 2010 to 2019, by using observation data from Crociferi station.

For Fulgatore station (Fig. 5), the winds tend to blow predominantly from the north, east, south-east, and north-west directions (highest frequency of about 10%) and speed intensity in the range 2.1 ÷ 11 m/s. The station is located in a place with low complex and not very varied topography that facilitates wind flows, in the absence of obstacles.

R and S factors are evaluated by observation data from the examined stations for the whole period under consideration. Since diurnal thermally driven flows (mountain-valley winds, slope winds, and land-lake breezes) are frequently expected in these areas, a selected transport time of 24 h for the calculations has been chosen.

Fig. 6, which report results for Palermo station, shows highest values for stagnation and recirculation factors that highlight an improved air transport processes compared to Crociferi station. This result is consistent with the wind roses distribution examined in Fig. 3.

Analysing MPI index distributions, it can be seen that the areas in front of the beaches of Palermo city and the territories around Fulgatore stations, in province of Trapani, are located in zones where MPI index results show very high values (dark green areas in Figs. 3 and 5).

As described in section 2.2.2, MPI normalization procedure is done by using a distribution in ten quantiles and the results obtained for these areas fall within quantiles from 8 to 10. The groups of MPI index values, that are splitted into these quantiles, derive by rules of the FIS system involving combination of WS and WF fuzzy indexes in the classes "Medium", "High" and "Very High''. This highlights a high-level of air mass exchange among bordering cells (Fig. 7).

Very different considerations can be found for areas where Crociferi, Burgio (Fig. 3) and Augusta (Fig. 5) stations are located. For these territories, the groups of MPI index values are splitted into quantiles from 1 to 2 involving combination of WS and WF fuzzy indexes in the classes "Very Low", "Low".

All results confirm the capacity of the MPI fuzzy model to aggregate meteorological data on a regional level, providing to be a suitable tool compared to disaggregated data that are not always practical or feasible to be translate in a single viewpoint.

4. Conclusions

The siting process for a nuclear installation starts on a regional basis and each step is focused on selecting potential sites and candidate sites. Consideration of environmental issues early in the site selection process of nuclear power programmes should result in a selected site that is acceptable with regards to the environmental and socioeconomic impacts, with no other site significantly superior.

These considerations for environmental protection and the environmental analysis typically include the protection of air, water, cultural resources. etc and, in this context, the wind fields are an important factor which provide information about transport and dispersion capability of the territory.

The great spatial and temporal fluctuation at regional scale of this meteorological factor requires that wind parameters be measured and analysed in many different locations, to perform deep studies. In this respect, wind rose graphics give a succinct view of how wind speed and direction are typically distributed at a site (characteristics of air flows at the measurement point). However, these data become difficult to interpret in the site selection process at regional scale, moreover there's no way to identify areas with high rates of air interchange against zones without any interchange (i.e. with low resilience in respect to pollution phenomena).

Meteorological pressure index (MPI), developed in the framework of previous research projects, allows to create geographical maps in which to identify neighbouring areas that are characterized by environmental similarities in term of 3D wind fields and so with resilience capacity in terms of air transport phenomena connected to wind actions.

It is worth noting that MPI map can provided additional data if it is overlapped to maps relevant to areas classified as sites of community interest of Natura 2000 (Council Directive 92/43/EEC), archeologic protection sites, seismic hazard map or other data of specific geographical constraints.

The MPI approach has been tested through a case study conducted in the Sicily region of Italy. The aim of the study was to identify geographical areas where there are significant variations in the long-term climate state of the wind field. To calculate the 3D wind field for MPI, the CALMET model was used, utilizing observed meteorological data from 80 measuring stations that cover the entire Sicily region.

Consistency analyses among MPI maps, observed wind distributions at different coast and near-coast stations by using wind roses charts, and stagnation S and recirculation R factors, as proposed in (Allwine and Whiteman, 1994), are performed.

The results confirm the capacity of the MPI fuzzy model to aggregate meteorological data on a regional level, providing to be a suitable tool compared to disaggregated data that are not always practical or feasible to be translate in a single viewpoint.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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