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# Probabilistic analysis of Italian extreme winds : Reference velocity and return criterion

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**Abstract.** Applying and extending some preceding researches, this paper proposes a map of Italian extreme winds assigning the reference velocity, i.e., the wind velocity averaged over 10 minutes, at 10 m height, in a flat open terrain, with 50 years mean return period, depending on the site and the altitude. Furthermore, an objective criterion is formulated by which the actual values of the local wind velocity are given as a function of the reference velocity. The study has been carried out in view of the revision of the Italian Standards dealing with safety and loads and the introduction of the aeolic Italian map into Eurocode 1.

**Key words:** extreme velocity; meteorological station; probabilistic analysis; standards; wind load; wind map.

## 1. Introduction

The arrival of sophisticated methods for evaluating the actions and effects of wind on structures has made the availability of precise data of the basic wind speed progressively more important. The evolution of the international norm panorama and, particularly in Europe, of the structural Eurocodes, is a powerful incentive to formulate national wind maps which are more and more accurate and consistent with actual knowledge.

The authors have previously carried out a wide research program dealing, on one hand, with the subject of the probabilistic modelling of wind data bases (Lagomarsino *et al.* 1992, Solari 1996a, b) and, on the other, with the application of these methods to the evaluation of Italian extreme wind speeds (Ballio *et al.* 1991a,b, 1994). These latter are part of the activities planned by the Central Technical Service of the Superior Council of the Ministry of Works

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for the up-dating of the Italian standards on loads and safety ("Norme" 1996, "Istruzioni" 1996) and the introduction of the Italian wind map into Eurocode 1 (1994).

This paper is organised in two connected parts which reflect the evolutionary phases of the study. In the first part, using the data base of 69 meteorological stations, the map which assigns the reference wind velocity is determined. The second part proposes an objective procedure, defined "return criterion", by means of which it is possible to arrive, given the reference velocity, at the real local wind velocity.

The conclusions discuss the most meaningful aspects of the proposed procedure, the precision of the results obtained and the main innovations involved by this map with respects to the Italian tradition.

## 2. The map of extreme winds

Taking up the concepts set out by Ballio *et al.* (1991a), a data base acquired over a sufficiently extended period by a suitably sited station is defined as representative. Defined as reliable is a data base without errors. Defined as homogenous is a data base consisting of values referred to uniform conditions.

Starting from these premises and operating on representative and reliable data bases, defined as correct is a value $v_c$ of the wind speed averaged over the temporal interval $T$, measured by an anemometer placed at height $z$ above the ground in the point $P$ of a territory $\Delta$. Defined as transformed is a value $v_t$ of the wind speed averaged over $T_{ref} = 10$ minutes recorded by an ideal anemometer placed in $P$ at height $z_{ref} = 10$ m, $\Delta$ being indefinitely flat, uniformly open, with roughness coefficient $z_{oref} = 0.05$ m ("Eurocode 1" 1994). The reference velocity $v_{ref}$ is the value of the transformed velocity with mean return period $\bar{R} = 50$ years. A wind map is a model which enables to attribute a value $v_{ref}$ to every point $P$ of territory $\Delta$.

### 2.1. Acquisition, correction and transformation of velocity measurements

The following analyses are based on the direction and intensity measurements of the average wind speed over $T = 10$ minutes made by 42 stations of the Military Air Force and by 27 stations of ENEL (Italian Electric Power Company) judged to be representative (Ballio *et al.* 1991b, 1994). The first ones, recorded on magnetic tapes by the ITAV (Telecommunications and Flight Assistance Inspectorate), concern data acquired every three hours over time spans of several ten year periods. The second are referred to more limited periods but include all the values over successive 10 minutes.

Columns (1) to (10) of Table 1 report a list of the 69 stations examined indicating, for each one, the order number $n$, the authority to which it belongs, the type of measurement (2 corresponds to 144 daily readings averaged over 10 minutes; 1 indicates 8 daily readings averaged over 10 minutes, carried out every 3 hours; 0 is referred to the lack of one or more recordings among those carried out every 3 hours), the time interval $t_1$-$t_2$ of the available data, the latitude $\phi$, the longitude $\theta$, the altitude $a_s$ above sea level, the description of the site ($A$ = airport area, $C$ = city centre, $H$ = hilly zone, $I$ = small island, $L$ = littoral, $M$ = mountainous area, $P$ = plain, $R$ = promontory or isolated relief, $V$ = valley), the height $h$ of the anemometer above the ground. Fig. 1 illustrates the geographic distribution of the stations studied indicating the

Table 1 Basic data at selected meteorological stations

| Station (1) | $n$ (2) | Authority (3) | Measure (4) | $t_1$-$t_2$ (5) | Lat. $\phi$ (6) | Lon. $\Theta$ (6) | $a_s$ (m) (8) | Zone (9) | $h$ (m) (10) | $v^c_{ref}$ (m/s) (11) | $v^t_{ref}$ (m/s) (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ancona | 1 | ITAV | 0 | 51-73 | 43°37' | 13°31' | 103 | L | 10.5 | 26.1 | 26.8 |
| Aritzo | 2 | ENEL | 2 | 84-92 | 39°56' | 09°07' | 1065 | M | 15.0 | 32.2 | 33.8 |
| Aviano | 3 | ITAV | 0 | 51-73 | 46°02' | 12°36' | 128 | AP | 6.5 | 24.0 | 26.5 |
| Bari | 4 | ITAV | 1 | 51-73 | 41°08' | 16°47' | 34 | ALP | 20.0 | 23.3 | 20.8 |
| Bologna | 5 | ITAV | 0 | 51-73 | 44°32' | 11°18' | 36 | AP | 6.5 | 17.3 | 19.6 |
| Bolzano | 6 | ITAV | 0 | 51-73 | 46°28' | 11°20' | 241 | V | 10.5 | 16.7 | 21.9 |
| Cagliari | 7 | ITAV | 1 | 51-73 | 39°15' | 09°03' | 18 | ALP | 6.5 | 23.8 | 24.6 |
| Camigliatello | 8 | ENEL | 2 | 85-90 | 39°23' | 16°26' | 1195 | M | 15.0 | 32.7 | 33.3 |
| Campomarino | 9 | ENEL | 2 | 85-92 | 41°57' | 15°01' | 90 | P | 15.0 | 27.6 | 27.5 |
| Capo Bellavista | 10 | ITAV | 0 | 51-73 | 39°56' | 09°43' | 138 | LR | 12.0 | 38.0 | 27.9 |
| Capo Mele | 11 | ITAV | 1 | 63-73 | 43°57' | 08°10' | 220 | LR | 6.0 | 34.3 | 29.6 |
| Capo Palinuro | 12 | ITAV | 0 | 51-73 | 40°01' | 15°17' | 184 | LR | 24.0 | 39.1 | 26.6 |
| Catania | 13 | ITAV | 1 | 51-90 | 37°28' | 15°03' | 11 | AHP | 10.5 | 26.7 | 28.6 |
| Cingoli | 14 | ENEL | 2 | 84-92 | 43°22' | 13°11' | 790 | H | 15.0 | 36.8 | 39.2 |
| Cirras | 15 | ENEL | 2 | 80-86 | 39°51' | 08°32' | 5 | LP | 30.0 | 37.5 | 30.2 |
| Consalvi | 16 | ENEL | 2 | 91-92 | 40°05' | 18°28' | 100 | RL | 15.0 | 27.7 | 26.0 |
| Cozzo Spadaro | 17 | ITAV | 1 | 51-73 | 36°41' | 15°08' | 46 | RL | 10.5 | 27.6 | 28.7 |
| Enna | 18 | ITAV | 0 | 51-73 | 37°34' | 14°17' | 964 | CM | 47.0 | 30.4 | 27.7 |
| Faeto | 19 | ENEL | 2 | 89-92 | 41°18' | 15°10' | 930 | M | 15.0 | 35.8 | 37.9 |
| Filicudi | 20 | ENEL | 2 | 86-88 | 38°35' | 14°34' | 278 | I | 12.0 | 31.1 | 29.9 |
| Firenze | 21 | ITAV | 1 | 51-73 | 43°48' | 11°12' | 37 | AP | 17.8 | 25.3 | 24.9 |
| Fiume Santo | 22 | ENEL | 2 | 81-85 | 40°50' | 08°17' | 40 | P | 15.0 | 29.0 | 26.2 |
| Foggia | 23 | ITAV | 1 | 59-73 | 41°32' | 15°43' | 57 | AP | 6.5 | 25.7 | 27.3 |
| Frosolone | 24 | ENEL | 2 | 84-92 | 41°36' | 14°24' | 1363 | M | 15.0 | 42.7 | 44.3 |
| Garin | 25 | ENEL | 2 | 82-85 | 45°45' | 07°32' | 500 | V | 15.0 | 24.7 | 26.4 |
| Genova | 26 | ITAV | 1 | 63-73 | 44°25' | 08°51' | 2 | AL | 8.0 | 22.6 | 28.0 |
| Ginostra | 27 | ENEL | 2 | 84-88 | 38°48' | 15°10' | 130 | I | 12.0 | 30.2 | 28.4 |
| Grosseto | 28 | ITAV | 0 | 51-73 | 42°45' | 11°04' | 7 | AR | 6.5 | 24.3 | 27.6 |
| La Palascia | 29 | ENEL | 2 | 91-92 | 40°06' | 18°32' | 80 | LR | 12.0 | 32.9 | 24.6 |
| Le Porte | 30 | ENEL | 2 | 83-87 | 42°21' | 10°54' | 390 | I | 15.0 | 37.7 | 30.6 |
| Macerata | 31 | ENEL | 2 | 84-89 | 43°18' | 13°25' | 300 | H | 15.0 | 27.2 | 27.7 |
| Mazara | 32 | ENEL | 2 | 83-87 | 37°41' | 12°37' | 50 | LP | 15.0 | 30.4 | 25.2 |
| Messina | 33 | ITAV | 1 | 51-88 | 38°12' | 15°33' | 59 | CL | 19.0 | 21.1 | 26.0 |
| Milano Linate | 34 | ITAV | 1 | 51-73 | 45°27' | 09°16' | 107 | AP | 6.5 | 22.2 | 24.3 |
| Milano Malpensa | 35 | ITAV | 1 | 51-73 | 45°37' | 08°44' | 234 | AP | 10.0 | 23.4 | 25.2 |
| Monte Arci | 36 | ENEL | 2 | 80-92 | 39°48' | 08°45' | 789 | M | 15.0 | 33.0 | 33.4 |
| Monte Capellino | 37 | ENEL | 2 | 84-92 | 44°33' | 08°57' | 646 | M | 15.0 | 20.9 | 26.6 |
| Monte Cimone | 38 | ITAV | 0 | 51-73 | 44°12' | 10°42' | 2173 | M | 12.0 | 57.1 | 59.1 |
| Monte Paganella | 39 | ITAV | 0 | 51-73 | 46°09' | 11°22' | 2129 | M | 12.0 | 39.1 | 42.2 |
| Monte Terminillo | 40 | ITAV | 0 | 51-73 | 42°28' | 12°59' | 1875 | M | 6.0 | 54.1 | 64.9 |
| Napoli | 41 | ITAV | 1 | 51-73 | 40°51' | 14°18' | 88 | ALP | 6.5 | 27.5 | 28.3 |
| Olbia | 42 | ITAV | 1 | 51-69 | 40°55' | 09°30' | 2 | AL | 10.0 | 27.5 | 28.9 |
| Oriolo | 43 | ENEL | 2 | 86-92 | 40°04' | 16°27' | 685 | H | 15.0 | 30.5 | 31.7 |
| Pantelleria | 44 | ITAV | 1 | 51-73 | 36°49' | 11°58' | 191 | AI | 6.5 | 38.9 | 35.6 |
| Pescara | 45 | ITAV | 1 | 51-73 | 42°26' | 14°12' | 10 | ALP | 6.5 | 32.2 | 33.5 |
| Pian Rosá | 46 | ITAV | 0 | 51-73 | 45°56' | 07°42' | 3488 | M | 13.0 | 39.0 | 31.6 |
| Pianosa | 47 | ITAV | 0 | 51-73 | 42°35' | 10°05' | 15 | I | 20.0 | 44.0 | 47.1 |

Table 1 Basic data at selected meteorological stations (continuation)

| Station (1) | $n$ (2) | Authority (3) | Measure (4) | $t_1$-$t_2$ (5) | Lat. $\phi$ (6) | Lon. $\Theta$ (6) | $a_s$ (m) (8) | Zone (9) | $h$ (m) (10) | $v^c_{ref}$ (m/s) (11) | $v^t_{ref}$ (m/s) (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pisa | 48 | ITAV | 0 | 51-91 | 43°41' | 10°23' | 2 | AP | 6.5 | 24.4 | 24.7 |
| Ponza | 49 | ITAV | 1 | 51-73 | 40°55' | 12°57' | 184 | I | 8.0 | 33.7 | 30.2 |
| Potenza | 50 | ITAV | 1 | 51-73 | 40°38' | 15°48' | 843 | CH | 27.0 | 29.5 | 31.9 |
| Pradarena | 51 | ENEL | 2 | 86-92 | 44°17' | 10°18' | 1579 | M | 15.0 | 40.5 | 43.7 |
| Reggio Calabria | 52 | ITAV | 0 | 51-88 | 38°04' | 15°39' | 11 | AL | 10.0 | 24.0 | 27.4 |
| Rimini | 53 | ITAV | 0 | 51-73 | 44°02' | 12°37' | 12 | LP | 10.5 | 22.7 | 22.7 |
| Roma Ciampino | 54 | ITAV | 0 | 51-73 | 41°48' | 12°33' | 129 | AP | 10.5 | 27.7 | 28.7 |
| Roma Fiumicino | 55 | ITAV | 0 | 59-73 | 41°48' | 12°14' | 2 | ALP | 6.5 | 24.2 | 24.5 |
| Salcito | 56 | ENEL | 2 | 85-92 | 41°45' | 14°32' | 860 | H | 15.0 | 29.3 | 30.4 |
| Salina | 57 | ENEL | 2 | 85-89 | 38°35' | 14°49' | 283 | I | 12.0 | 40.5 | 32.7 |
| San Demetrio | 58 | ENEL | 2 | 86-92 | 39°34' | 16°21' | 630 | H | 12.0 | 35.9 | 38.8 |
| San Remo | 59 | ITAV | 1 | 51-63 | 43°49' | 07°49' | 113 | L | 10.0 | 27.7 | 29.3 |
| Santa Caterina | 60 | ENEL | 2 | 81-88 | 39°05' | 08°29' | 1 | LP | 15.0 | 31.3 | 25.1 |
| Tarvisio | 61 | ITAV | 0 | 51-73 | 46°30' | 13°35' | 778 | M | 11.0 | 21.0 | 23.3 |
| Torino | 62 | ITAV | 1 | 51-73 | 45°11' | 07°38' | 301 | AP | 6.5 | 21.9 | 25.7 |
| Trieste | 63 | ITAV | 0 | 51-73 | 45°39' | 13°45' | 8 | CL | 39.0 | 30.6 | 31.3 |
| Tuili | 64 | ENEL | 2 | 84-92 | 39°44' | 08°58' | 580 | H | 30.0 | 27.9 | 26.5 |
| Udine | 65 | ITAV | 0 | 51-73 | 45°59' | 13°02' | 93 | P | 6.5 | 21.2 | 24.6 |
| Venezia | 66 | ITAV | 1 | 61-73 | 45°30' | 12°20' | 2 | AL | 6.5 | 22.0 | 21.7 |
| Verona | 67 | ITAV | 1 | 51-73 | 45°23' | 10°52' | 67 | AP | 7.0 | 22.6 | 26.1 |
| Verrayes | 68 | ENEL | 2 | 82-85 | 45°46' | 07°33' | 1122 | M | 15.0 | 20.4 | 24.1 |
| Vetan | 69 | ENEL | 2 | 82-85 | 45°44' | 07°11' | 1680 | M | 15.0 | 26.7 | 31.5 |

order number. The low and high altitudes of the stations are defined applying the criteria later illustrated.

All the data acquired has been accurately corrected applying the methods illustrated by Ballio *et al.* (1991a). Moreover, suitable models of the roughness and topograghy of the territory surrounding the instruments have been implemented for each station. By means of these models ("Computer program" 1992) the corrected values of the average wind speeds have been converted into transformed values.

In this phase of the study the effects due to the altitude have not been considered.

## 2.2. Probabilistic analysis of the corrected and transformed data bases

The probabilistic study of the corrected and transformed data bases has been carried out applying two alternative methods, the asymptotic and process analysis (Lagomarsino *et al.* 1992, Solari 1996a, b).

Applying the asymptotic technique, the distribution function $F_M$ of the maximum yearly value of the average wind velocity is given by the extreme law of the first type (Gumbel 1958) :

$$F_M(v) = \exp\{-\exp[-a(v-u)]\} \qquad (v > 0) \tag{1}$$

where $v = v_c$, $v_t$ is the state variable of $V = V_c$, $V_t$; $V_c$, $V_t$ are the corrected and transformed

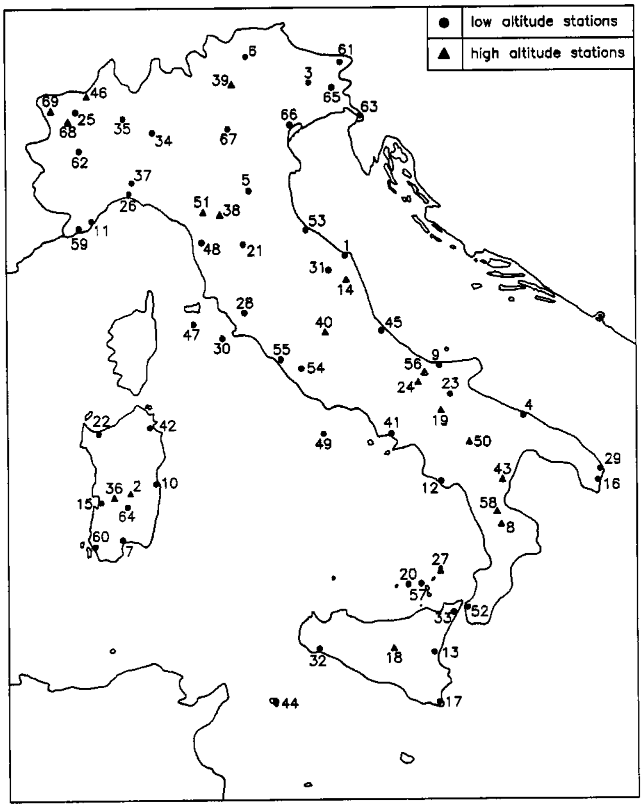


Fig. 1 Meteorological stations

average wind speeds; $a = a_c$, $a_t$, $u = u_c$, $u_t$ are the model parameters.

The process analysis considers the average wind speed as a stochastic stationary process (Gomes and Vickery 1977). Assuming as Poissonian the up-crossings of appropriately high velocity thresholds, the distribution function of the maximum yearly value of $V = V_c$, $V_t$ takes the form (Lagomarsino *et al.* 1992, Solari 1996b) :

$$F_M(v) = \exp\{-\lambda f_V(v)\} \qquad (v > 0) \tag{2}$$

in which $\lambda = \lambda_c$, $\lambda_t$ is the parameter of the extreme distribution; $f_V$ is the density function of the parent population expressed by the relationship (Solari 1996a) :

$$f_v(V) = P_o\, \delta(v) + (1 - P_o)\, \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \qquad (v \geq 0) \tag{3}$$

where $\delta(\,)$ is Dirac & operator; $P_o$ is the probability that $V = 0$; $k = k_c$, $k_t$ and $c = c_c$, $c_t$ are the distribution parameters.

The average wind velocity with mean return period $\bar{R}$ is deduced from the extreme distribution by setting $\bar{R} = 1/\ [1\text{-}F_M(v)]$. For $\bar{R} = \bar{R}_{ref}$, the asymptotic technique gives results whose accuracy increases with the number of years of the available data. It is simple and quick to use. Since $k$ parameter in Eq. (3) is usually greater than 1, it leads to estimates averagely prudential (Lagomarsino *et al.* 1992).

Process analysis guarantees solutions which are generally better than those given by asymptotic analysis, above all in correspondence with high mean return periods (Lagomarsino *et al.* 1992). Differently from this it is applicable, reliably, also when the data is limited to few years of measurement. Since one needs previous knowledge of the population density of the data, the calculations are markedly more burdensome.

Starting from this premise the statistical analysis of the 42 ITAV data bases has been carried out by the asymptotic technique. It is however important to note that, above all because of the three hourly recordings and sometimes because of the suspension of measurements in some synoptic hours, the ITAV records have relevant data gaps. Some preliminary evaluations (Bocciolone *et al.* 1993) indicate that these gaps lead to underestimations generally in the range from 5% to 10%. Analogous estimates (Lagomarsino *et al.* 1992) demonstrate that, for usual $k > 1$ values, the asymptotic analyses produce, with respect to process analysis, overestimates by an analogous amount. As more accurate evaluations are for the moment impracticable, it seems justified to conclude that the two effects mentioned above tend to compensate reciprocally. This on one hand validates the application of the asymptotic technique, on the other hand justifies the only slight usefulness of using more refined methods.

As for the probabilistic analysis of the ENEL records, rich in data but limited in time, the situation is completely different. These call, with rare exceptions, for process analysis.

Columns (11) and (12) of Table 1 summarise the results of the analysis giving, for each station, the values of the corrected average velocity $v^c_{ref}$ and the transformed average velocity $v^t_{ref}$ with $\bar{R} = 50$ years. Basically, $a$ and $u$ parameters in Eq. (1) are regressed by the resistant method (Hoaglin *et al.* 1983) applied to the first $r = 1$, 3 yearly maxima; the $\lambda$ parameter in Eq. (2) is estimated by counting the threshold up-crossing (Gomes and Vickery 1977); the $k$ and $c$ parameters in Eq. (3) are determined by the resistant method considering only the non zero values in the population. The full set of these parameters is reported by Ballio *et al.* (1991, 1994) and Bocciolone *et al.* (1993) together with detailed indications on the direction sectors of the extreme prevailing wind speeds.

The profoundly different significance of the analyses referred to corrected velocity and to transformed velocity is to be noted. The first express occurrence laws of real speed values which cannot be generalised to other contexts. The second give statistic estimates which, although fictitious, represent the point of departure for evaluating the effective wind speeds around the anemometer. In this study phase they are still tied to the altitude of the instrumented site.

### *2.3. Zoning and Italian wind map*

Starting from the $v^t_{ref}$ values in column (12) of Table 1, selected stations have been subdivided into two distinct classes: the first includes the stations sited near to sea level, the second the higher stations (Fig. 1). The demarcation limit between the lower and higher stations depends on where they are sited and will be discussed later.

The study of the $v^t_{ref}$ values of the stations at low levels indicates the existence of 5 geographic areas with different wind properties :

A) Valle d'Aosta, Piemonte, Lombardia, Veneto, Trentino Alto Adige, Friuli Venezia Giulia (excluding the Province of Trieste), Emilia Romagna;

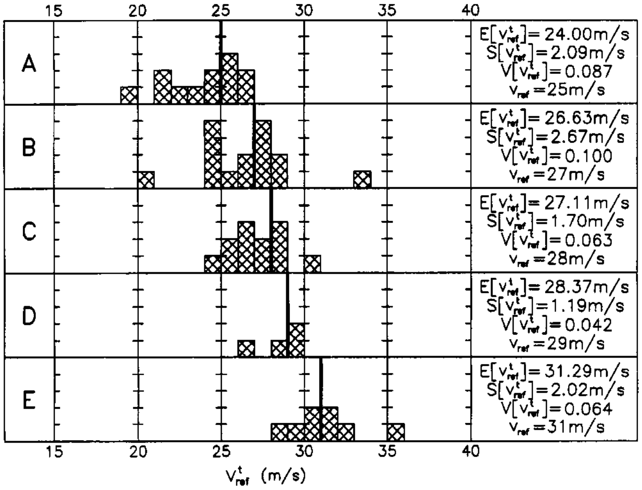


Fig. 2 Reference velocity at low altitude stations

B) Toscana, Umbria, Marche, Lazio, Abruzzo, Molise, Campania, Puglia, Basilicata, Calabria (excluding the Province of Reggio Calabria);
C) Province of Reggio Calabria, Sicilia, Sardegna;
D) Liguria;
E) Province of Trieste, Islands (excluding Sicilia and Sardegna).

Fig. 2 justifies the choice made showing, for each area, the histogram, the average $E$ [.], the standard deviation $S$ [.] and the variation coefficient $V$ [.] of $v^t_{ref}$. The same figure also shows, marked by a thick line, the representative values $v_{ref} = v_{ref,K}$ ($K = A, B, C, D, E$) attributed to the single areas.

Coherently with models established by Cook and Prior (1987) and "The assessment" (1989), the study of the transformed values of the reference velocity of higher stations shows a clear increase of $v_{ref}$ with the altitude. Notwithstanding the limited data, it also brings out 3 geographic areas characterised by different slopes of increase :

I) Alpine arc (excluding Liguria) ;
II) Liguria, Emilia-Romagna, eastern side of Sardegna ;
III) The Appenninines (excluding Liguria and Emilia-Romagna), Sicilia, western side of Sardegna.

Fig. 3 justifies this choice giving $v^t_{ref}$ in terms of altitude $a_s$. The values related to the different stations, grouped together with different symbols, tend to fall around three straight lines $v_{ref} = \alpha_J + a_s \beta_J$ ($J$ = I, II, III), each associated with a different area. Zone I, where the increase is less marked, corresponds to the Alpine arc protected from the wind mainly coming from Central Europe. Zone III, where the increase is maximum, includes the mountain zones, above all the Apennines arc and the western side of Sardegna, exposed to sea winds. Zone II groups the slopes with intermediate exposure.

The intersection in plane $v_{ref}$, $a_s$ of the 5 horizontal lines $v_{ref} = v_{ref,K}$ ($K = A, B, C, D, E$) with the three oblique lines $v_{ref} = \alpha_J + a_s \beta_J$ ($J$ = I, II, III) identifies the 9 zones into which Italy is divided (Fig. 4) :

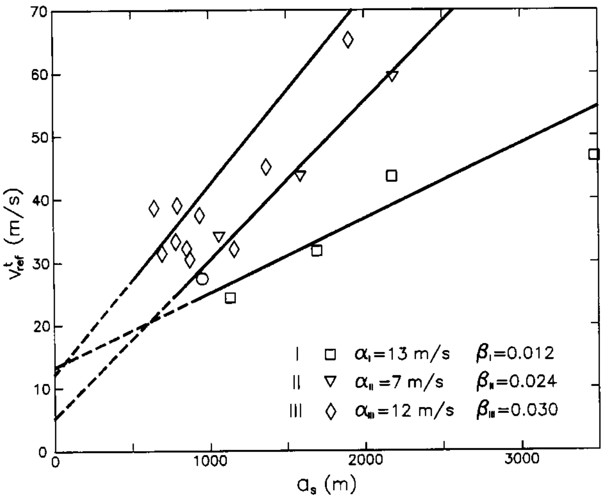


Fig. 3 Reference velocity at high altitude stations

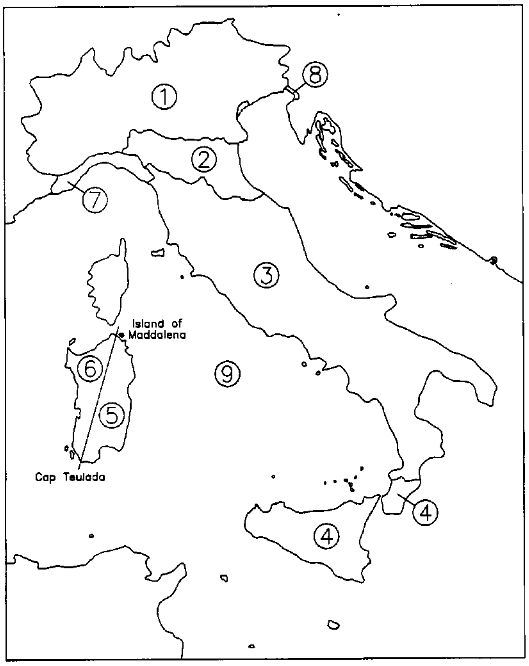


Fig. 4 Wind zoning

1) Valle d' Aosta, Piemonte, Lombardia, Trentino Alto Adige, Veneto, Friuli Venezia Giulia (excluding the Province of Trieste);
2) Emilia Romagna;
3) Toscana, Marche, Umbria, Lazio, Abruzzo, Molise, Campania, Puglia, Basilicata, Calabria (excluding the Province of Reggio Calabria);
4) Sicilia and Province of Reggio Calabria;

5) Sardegna (zone to the west of the line joining Cap Teulada with the Island of Maddalena);
6) Sardegna (zone to the west of the line joining Cap Teulada with the Island of Maddalena);
7) Liguria;
8) Provincia di Trieste;
9) Islands (except Sardegna and Sicilia) and open sea.

For each of these zones the reference velocity $v_{ref}$ is assigned by means of the law :

$$v_{ref} = v_{ref,o} \qquad \text{for } a_s \leq a_0$$
$$v_{ref} = v_{ref,o} + k_a\,(a_s - a_o) \qquad \text{for } a_s \geq a_0 \tag{4}$$

Table 2 Parameters of the wind zoning

| Zone | $v_{ref,o}$ (m/s) | $a_o$ (m) | $k_a$ (1/s) |
|---|---|---|---|
| 1 | 25 | 1000 | 0.012 |
| 2 | 25 | 750 | 0.024 |
| 3 | 27 | 500 | 0.030 |
| 4 | 28 | 500 | 0.030 |
| 5 | 28 | 750 | 0.024 |
| 6 | 28 | 500 | 0.030 |
| 7 | 29 | 1000 | 0.024 |
| 8 | 31 | 1500 | 0.012 |
| 9 | 31 | 500 | 0.030 |

Table 3 Exposure categories

| Exposure | $k_r$ | $z_o$ (m) | $z_{min}$ (m) |
|---|---|---|---|
| I | 0.17 | 0.01 | 2 |
| II | 0.19 | 0.05 | 4 |
| III | 0.20 | 0.10 | 5 |
| IV | 0.22 | 0.30 | 8 |
| V | 0.23 | 0.70 | 12 |

Table 4 Roughness classes

| Classes | Description |
|---|---|
| A | Urban areas in which at least 15% is covered with buildings and their average height exceed 15 m |
| B | Urban (except class A), suburban, industrial and wooded areas |
| C | Areas with diffuse obstacles (trees, buildings, walls, fences, ⋯); areas which cannot be defined by classes A, B |
| D | Areas without or with rare isolated obstacles (open country, airports, farmland, pasture, fenland or sandland, snow, ice, lake, sea, ⋯) |

Terrain roughness does not depend on topography and orography. Classes A, B apply to sites surrounded by this terrain in every direction for at least 1 km and however not less than 20 times the height of the structure.

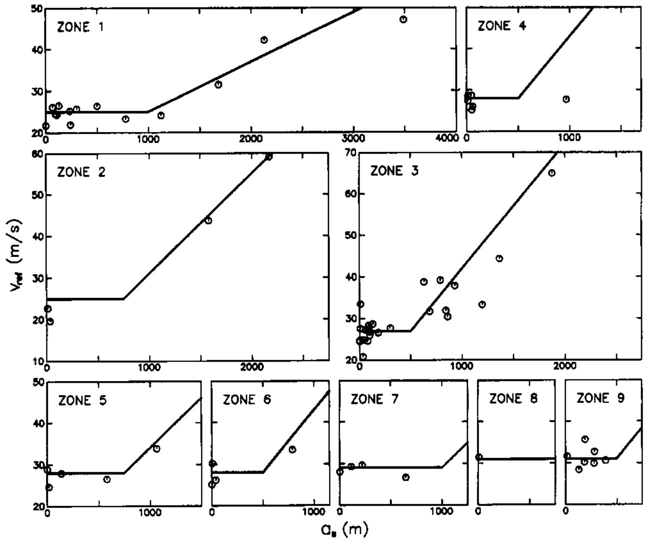


Fig. 5 Application of the wind map per each zone

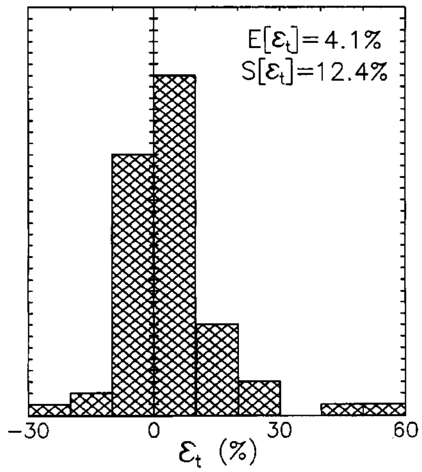


Fig. 6 Global errors due to the application of the wind map

in which $a_o$ is the altitude below which $v_{ref}$ is assumed as constant; $v_{ref,\,o}$ is the value of $v_{ref}$ for $a_s \leq a_o$ ; $k_a$ is the slope of the increment of $v_{ref}$ with $a_s$. The values of the parameters in Table 2 ("Norme" 1996, "Istruzioni" 1996, "Eurocode 1" 1994) are obtained with limited formal corrections by applying the procedure described above.

Fig. 5 shows, for the 9 zones into which Italy is divided, the level of approximation with which the map reproduces the transformed velocities. As can easily be seen, the available data leads to a reliable estimate for most of the country. However there are zones, especially at high altitudes, where the lack of information still forces recourse to qualitative extrapolations.

Fig. 6 testifies the complessive quality of the results achieved, showing the histogram, the mean value and the standard deviation of the error $\varepsilon_t = (v_{ref} - v^t_{ref}) / v^t_{ref}$ committed by applying the wind map over the whole country.

## 3. The return criterion

The return criterion is an objective method which makes it possible to evaluate, given the reference velocity, the real profile of the average wind velocity in terms of the local site characteristics. With the availability of the anemometric measurements used to formulate the map, the indispensable prerequisite of the return criterion is that of giving in reverse, with the maximum possible reliability, the starting data.

The calculation of the real profile of the average wind velocity requires, in principle, the institution of territorial models of the roughness and the topography of the terrain by which it is possible to evaluate, for every couple of the measured values of wind speed and direction, the couple respective of the profiles of wind speed and direction in the site studied. This approach requires the direct use of the original data bases, the knowledge and the detailed modelling of the conformation of the ground, the systematic use of directional probabilistic calculation. It is therefore applied, above all, to very important cases (Bocciolone *et al.* 1993, Ballio and Solari 1992, Lagomarsino and Solari 1995, Solari *et al.* 1998).

Against this, the traditional wind maps such as those proposed in the preceding section do not contain information about where the winds come from, a fact which excludes the possibility of deducing exactly the real velocity field. It however quite often happens, with the obvious exception of the coastal belt and partly of the relief, that the directional effects of wind play a minor role, at least in calculating the design velocity. If it is added that in many countries the roughness of the ground is a large scale parameter, it is easy to conclude that the attribution of schematic categories of roughness, eventually corrected in terms of the distance from sea, is a return criterion obviously approximated but reasonably reliable ("Eurocode 1" 1994).

The conformation of the terrain in Italy, surrounded on all sides by the sea, marked by high mountain chains, characterised by frequent and sudden roughness changes, drastically excludes this type of approach and neither allows the recourse to partial schemes. This is fully confirmed by the return criteria proposed by Finzi and Paris (1967) and Bartoli *et al.* (1995). The first (Finzi and Paris 1967), which inspired the Italian standards on wind previously in force ("Aggiornamento" 1982, "Istruzioni" 1982), set out when little was known on this matter, is pervaded by physical and engineering sense of rare depth; it takes account of the position of the site, of the distance from the sea and the altitude, without appreciating the roughness of the ground. The second (Bartoli *et al.* 1995), perfectly aligned with the most modern theories, examines the distance from the sea and the roughness of the ground while ignoring the geographic position and the altitude. Both lead to results which are marked by frequent lack of precision and notable uncertainties.

### 3.1. Formulation of the method

The return criterion illustrated below, inspired by a so-called inverse procedure, poses the objective of eluding the above problems while arriving at results which are simple and reliable.

N categories of exposure $e$ are defined ($e = 1 \cdots N$), initially associated only with terrain roughness. Each category is marked by a roughness length $z_o$, a terrain factor $k_r$ and a minimum height above ground $z_{min}$ ("Eurocode 1" 1994). Let $P$ be a site with reference velocity

$v_{ref}$, placed in a territory $\Delta$ indefinitely homogenous. The average velocity of the wind in site $P$ at height $z$ is given by the formula ("Eurocode 1" 1994) :

$$v^e_{ref} = v_{ref}\, c_t\, k_r \ln(z/z_o)\,; \qquad z \geq z_{min} \tag{5}$$

in which $c_t$ is the topography coefficient.

Eq. (5) is applied to all the instrumented sites and the value $v^e_{ref}$ at height $z=h$ of the anemometer, for $e$ vaying from 1 to $N$, is calculated. Comparing the real value $v^c_{ref}$ with the $N$ values $v^e_{ref}$, one obtains, site by site, the category of the exposure $e$ corresponding to the value $v^e_{ref}$ nearest to $v^c_{ref}$. The attribution of exposure most suitable to reproduce $v^c_{ref}$ is an effective return criterion associated to the five factors which best categorise the site : the local roughness, the geographic position, the distance from the coast, the altitude, the direction of the extreme prevailing winds.

The reliability of this criterion obviously depends on the amount of available data. This, in fact, is not a problem : the data can be augmented arbitrarily by instituting virtual sites marked by fictitious values $v^c_{ref}$, generated from the real values through transformation procedures like those discussed in "Computer program" (1992).

### 3.2. Application to the Italian territory

The application of the return criterion described in the previous paragraph to the Italian territory is carried out by defining 5 categories of exposure whose parameters are listed in table III. Four classes of terrain roughness described in Table 4 are also introduced. The

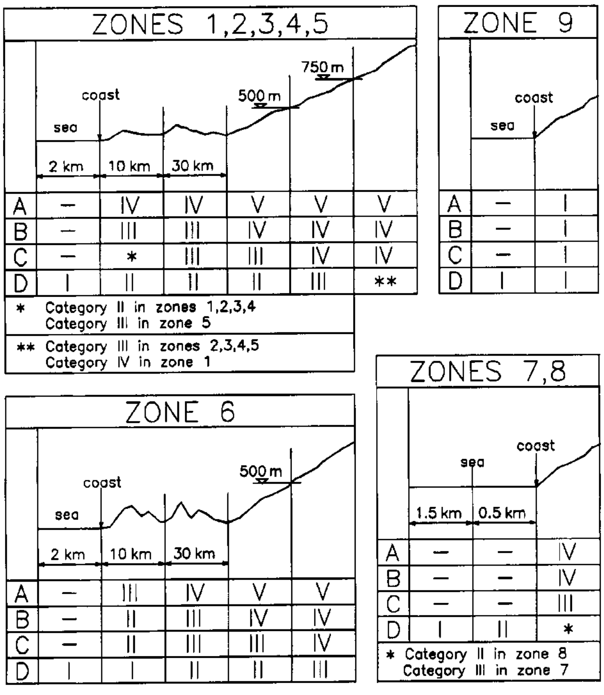


Fig. 7 Attribution criterion of exposure categories

Table 5 Errors due to the joint application of the wind map and the return crierion to each station and virtual site

| Zone | Station | $h$ (m) | $d$ (km) | Rough. | Exp. | $c_t$ | $v^c_{ref}$ (m/s) | $v^e_{ref}$ (m/s) | $\varepsilon_c$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Aviano | 6.5 | 55 | D | II | 1 | 24.0 | 23.1 | -4 |
| | Bolzano | 10.5 | 140 | C | III | 1 | 16.7 | 23.3 | 39 |
| | Garin | 15.0 | 200 | D | III | 1 | 24.7 | 25.1 | 1 |
| | & Milano A | 108.0 | 120 | A | V | 1 | 27.1 | 29.0 | 7 |
| | & Milano B | 98.0 | 130 | B | IV | 1 | 29.0 | 31.8 | 10 |
| | Milano Linate | 6.5 | 120 | D | II | 1 | 22.2 | 23.1 | 4 |
| | Milano Malpensa | 10.0 | 140 | D | II | 1 | 23.4 | 25.2 | 8 |
| | Monte Paganella | 12.0 | 130 | D | IV | 1 | 39.1 | 31.3 | -20 |
| | Pian Rosá | 13.0 | 180 | D | IV | 1 | 44.0 | 45.5 | 3 |
| | Tarvisio | 11.0 | 90 | C | IV | 1 | 21.0 | 19.8 | -6 |
| | Torino | 6.5 | 120 | D | II | 1 | 21.9 | 23.1 | 6 |
| | Udine | 6.5 | 35 | D | II | 1 | 21.2 | 23.1 | 9 |
| | Venezia | 6.5 | 0 | D | II | 1 | 22.0 | 23.1 | 5 |
| | Verona | 7.0 | 90 | D | II | 1 | 22.6 | 23.5 | 4 |
| | Verrayes | 15.0 | 200 | C | IV | 1 | 20.4 | 22.8 | 12 |
| | Vetan | 15.0 | 200 | C | IV | 1 | 26.7 | 28.5 | 7 |
| 2 | Bologna | 6.5 | 75 | D | II | 1 | 17.3 | 23.1 | 34 |
| | Monte Cimone | 12.0 | 45 | D | III | 1 | 57.1 | 56.6 | -1 |
| | Pradarena | 15.0 | 40 | D | III | 1 | 40.5 | 45.0 | 11 |
| | Rimini | 10.5 | 0 | D | II | 1 | 22.7 | 25.4 | 12 |
| 3 | Ancona | 10.5 | 0 | D | II | 1 | 26.1 | 27.4 | 5 |
| | Bari | 20.0 | 0 | D | II | 1 | 23.3 | 30.7 | 32 |
| | Camigliatello | 15.0 | 16 | D | II | 1 | 32.7 | 51.9 | 59 |
| | Campomarino | 15.0 | 4 | D | II | 1 | 27.6 | 29.3 | 6 |
| | Capo Palinuro | 24.0 | 0 | C | II | 1.23 | 39.1 | 39.0 | 0 |
| | Cingoli | 15.0 | 35 | D | III | 1 | 36.8 | 35.8 | -3 |
| | Consalvi | 15.0 | 2 | D | II | 1 | 27.7 | 29.3 | 6 |
| | Faeto | 15.0 | 55 | D | III | 1 | 35.8 | 40.0 | 12 |
| | Firenze | 17.8 | 75 | D | II | 1 | 25.3 | 30.1 | 19 |
| | Foggia | 6.5 | 30 | D | II | 1 | 25.7 | 25.0 | -3 |
| | & Foggia A | 50.0 | 30 | A | IV | 1 | 32.1 | 30.4 | -5 |
| | & Foggia B | 20.0 | 30 | B | III | 1 | 28.8 | 28.6 | -1 |
| | & Foggia D | 10.0 | 30 | D | II | 1 | 27.5 | 27.2 | -1 |
| | Frosolone | 15.0 | 55 | D | III | 1 | 42.7 | 53.0 | 24 |
| | Grosseto | 6.5 | 12 | D | II | 1 | 24.3 | 25.0 | 3 |
| | La Palascia | 12.0 | 0 | D | II | 1.10 | 32.9 | 30.9 | -6 |
| | Macerata | 15.0 | 20 | D | II | 1 | 27.2 | 29.3 | 8 |
| | Monte Terminillo | 6.0 | 90 | D | III | 1 | 54.1 | 55.9 | 3 |

Table 5 Errors due to the joint application of the wind map and the reurn crierion to each station and virtual site (continuation)

| Zone | Station | $h$ (m) | $d$ (km) | Rough. | Exp. | $c_t$ | $v^{c}_{ref}$ (m/s) | $v^{e}_{ref}$ (m/s) | $\varepsilon_c$ (%) |
|---|---|---|---|---|---|---|---|---|---|
| | Napoli | 6.5 | 2 | D | II | 1 | 27.5 | 25.0 | -9 |
| | Oriolo | 15.0 | 13 | D | II | 1 | 30.5 | 35.3 | 16 |
| | Pescara | 6.5 | 3 | D | II | 1 | 32.2 | 25.0 | -22 |
| | Pisa | 6.5 | 9 | D | II | 1 | 24.4 | 25.0 | 2 |
| | & Pisa B/1 | 50.0 | 5 | B | III | 1 | 31.0 | 33.6 | 8 |
| | & Pisa B/2 | 50.0 | 9 | B | III | 1 | 28.6 | 33.6 | 17 |
| 3 | & Pisa B/3 | 57.8 | 9 | B | III | 1 | 28.0 | 34.3 | 23 |
| | Potenza | 27.0 | 75 | B | V | 1 | 29.5 | 31.3 | 6 |
| | Roma Ciampino | 10.5 | 25 | D | II | 1 | 27.7 | 27.4 | -1 |
| | Roma Fiumicino | 6.5 | 2 | D | II | 1 | 24.2 | 25.0 | 3 |
| | Salcito | 15.0 | 51 | D | III | 1 | 29.3 | 37.9 | 29 |
| | San Demetrio | 12.0 | 18 | D | II | 1 | 35.9 | 32.2 | -10 |
| | Catania | 10.5 | 3 | D | II | 1 | 26.7 | 28.4 | 7 |
| | Cozzo Spadaro | 10.5 | 1 | D | II | 1 | 28.2 | 28.4 | 1 |
| 4 | Enna | 47.0 | 50 | A | V | 1 | 30.4 | 40.6 | 33 |
| | Mazara | 15.0 | 4 | D | II | 1 | 30.4 | 30.3 | 0 |
| | Messina | 19.0 | 1 | A | IV | 1 | 21.1 | 25.6 | 21 |
| | Reggio Calabria | 10.0 | 0 | D | II | 1 | 24.0 | 28.2 | 17 |
| | Aritzo | 15.0 | 50 | D | III | 1 | 32.2 | 35.6 | 11 |
| | Cagliari | 6.5 | 0 | D | II | 1 | 23.8 | 25.9 | 9 |
| 5 | Capo Bellavista | 12.0 | 0 | C | III | 1.60 | 38.0 | 42.9 | 13 |
| | Olbia | 10.0 | 7 | D | II | 1 | 27.5 | 28.2 | 2 |
| | Tuili | 30.0 | 15 | B | III | 1 | 27.9 | 31.9 | 14 |
| | Cirras | 30.0 | 1 | D | I | 1 | 37.5 | 38.1 | 2 |
| 6 | Fiume Santo | 15.0 | 1 | D | I | 1 | 29.0 | 34.8 | 20 |
| | Monte Arci | 15.0 | 16 | C | III | 1 | 33.0 | 36.7 | 11 |
| | Santa Caterina | 15.0 | 0 | D | I | 1 | 31.3 | 34.8 | 11 |
| | Capo Mele | 6.0 | 0 | C | III | 1.48 | 34.3 | 35.1 | 2 |
| | Genova | 8.0 | 0 | D | III | 1 | 22.6 | 25.4 | 12 |
| | & Genova A | 50.0 | 1 | A | IV | 1 | 29.8 | 32.6 | 10 |
| 7 | & Genova C/1 | 10.0 | 0 | C | III | 1.30 | 33.7 | 34.7 | 3 |
| | & Genova C/2 | 10.0 | 0 | C | III | 1 | 20.0 | 26.7 | 34 |
| | Monte Capellino | 15.0 | 25 | B | IV | 1 | 20.9 | 21.3 | 2 |
| | San Remo | 10.0 | 0 | C | III | 1 | 27.7 | 26.7 | -4 |
| 8 | Trieste | 39.0 | 0 | C | III | 1 | 30.6 | 37.0 | 21 |
| | Filicudi | 12.0 | 1 | | I | 1 | 31.1 | 37.4 | 20 |
| | Ginostra | 12.0 | 1 | | I | 1 | 30.2 | 37.4 | 24 |
| | Le Porte | 15.0 | 1 | | I | 1 | 37.7 | 38.5 | 2 |
| 9 | Pantelleria | 6.5 | 1 | | I | 1 | 38.9 | 36.3 | -7 |
| | Pianosa | 20.0 | 0 | | I | 1 | 39.0 | 40.1 | 3 |
| | Ponza | 8.0 | 0 | | I | 1 | 33.7 | 35.2 | 5 |
| | Salina | 12.0 | 1 | | I | 1 | 40.5 | 37.4-8 | |

choices here proposed, in part different from the schemes envisaged in the present version of Eurocode 1, have the aim of better reproducing the special characteristics of the Italian terrain.

Fig. 7 expresses the criterion of attribution of the exposure categories at the sites studied. Within itself it contains, in a simple but efficacious way, the main elements that appear separately, on a partial level, in the return criteria formulated by Finzi and Paris (1967) and Bartoli *et al.* (1995).

Among the numerous significant elements to be noted, one is that, apart from zones 6, 9, the use of marine exposure along the coastal strip is not envisaged. The imposition of this category would be like assuming extreme winds blowing from the sea, a situation which is only valid in zones 6, 9.

The attribution of high exposure classes to sites far from the sea or at high altitude independently on the real roughness of the terrain arises from the fact that the wind arrives in these zones after having estabilished its configuration over land with high average roughness. It also takes into account that the complessive topographic conditions can be related to equivalent sites with high roughness.

The assigning of category I to the small islands, whatever may be the local roughness of the site, is based on the principle that the wind arrives having stabilised its configuration over the sea. In the light of the little available data, this is reasonably prudent.

The assigning of category I to the sea strip in front of the coast has the double effect of establishing a correct exposure for off-shore type constructions and also to graduate the passage from coastal exposure to open sea.

Table 5 shows, for each 69 station examined and for other 11 virtual sites marked by the symbol &, the zone, the height $h$ of the real or virtual anemometer, the minimum distance $d$ from the coast, the roughness class, the exposure category, the topography coefficient $c_t$ calculated by means of Eurocode 1 (1994) (limited to simple topographic reliefs indicated with $R$ in Table 1), the real and virtual values of $v^c_{ref}$, the value $v^e_{ref}$ given by Eq. (5), the error $\varepsilon_c = (v^e_{ref} - v^c_{ref}) / v^c_{ref}$ due to the joint use of the wind map and the return criterion.

Fig. 8 illustrates the complessive quality of the result achieved, showing the histogram, the

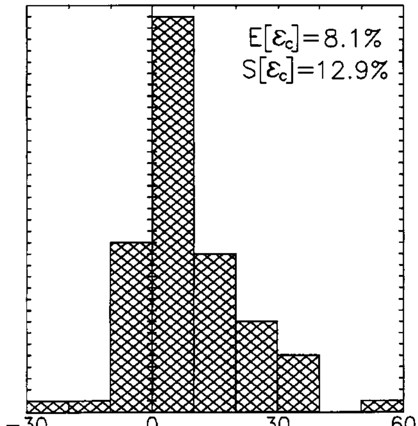


Fig. 8 Global errors due to the joint application of the wind map and the return criterion

mean value and the standard deviation of the errors $\varepsilon_c$ committed when applying this method to the whole of Italy.

As a further confirmation of the reliability of the method, it can be seen that the wind map and the return criterion proposed lead to estimates in excellent agreement with the values at present given by the wind maps of neighbouring countries ("Eurocode 1" 1994). France attributes values $v_{ref}$ between 26.0 and 27.5 m/s to the Mediterranean coast; imposing the use of marine roughness in the first 5 km from the sea, these are analogous to the value $v_{ref} = 29$ m/s assigned in Liguria, having excluded the exposure category I. In southern Germany $v_{ref} = 24.3$ m/s is assigned, in good agreement with value $v_{ref,o} = 25$ m/s of the Pianura Padana. Switzerland assumes $v_{ref} = 27.2$-$33.3$ m/s imposing a roughness equivalent to the IV Italian exposure category; taking into account the law of growth of $v_{ref}$ with $a_s$ and the criterion of attribution of exposure, these values are very close to those assigned to the Alpine arc. The value $v_{ref} = 30$ m/s used in Greece is not far from the values $v_{ref} = 27$-$28$ m/s of southern Italy and the Islands.

## 4. Conclusions

The analysis and the results discussed in this paper show clearly the role of the distance from sea and of the altitude in evaluation of wind speed. In a country like Italy, washed by the sea and divided by great mountain chains, this role is absolutely essential.

Although the anemometric data arriving from high altitude stations are still limited, there is a clear tendency for the wind speed to increase with altitude. This increase tends to take place, approximately, according to a linear law. The slope of the increment seems to depend quite closely on the position of the mountains with respect to the coast.

The calculation of real wind velocity given the local value of the reference velocity, traditionally carried out taking into account the roughness of the ground and possibly the presence of isolated topographical relief, cannot leave out the distance from sea and the altitude. The direction of the prevailing winds with respect to the coastline and the position of the mountain chains have an essential role.

The formulation of a return criterion aimed at reproducing the measured data starting from the wind map of reference velocity is the principal prerequisite of the model and leads to estimates of wind velocities affected by limited errors which are compatible with a macro-scale vision of the problem.

The comparison between the new Italian standard asset, which is identified with the proposed model, and the norms previously in force ("Aggiornamento" 1982, "Istruzioni" 1982), brings out a radical increase in the wind loads in high altitude sites, especially in the Appenine are, near the summits of isolated relief, and in the small islands. Not drastic but important increase are introduced in the Po Valley, in the Province of Trieste and, more generally, in sites without obstacles. In all remaining situations the actions of design wind remain the same or increase slightly. In very rough sites, such as city centres, design velocities can often be reduced (Ballio *et al.* 1994).

The increase of the design wind loads at high altitude sites deserves some more considerations. Although the available data fully confirms this tendency, it should be observed that most Italian high altitude meteorological stations are placed at the top of mountains, along ridges and however in exposed windy sites. It follows that more protected locations at the same altitudes could be characterised by lower values of the wind speed and thus subjected, using this map, to prudential wind loads. The studies at present carried out by the Climatological Group of the Meteo-Idrological Centre of Liguria Region (CMIRL) (Castino *et al.* 1998) should give a first contribution to a better understanding of this problem.

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