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Statistical investigation on the relation between car accidents and warm katabatic winds(*)

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Summary. — The possible relationship between warm katabatic winds and human health and behaviour is analyzed; notwithstanding popular belief which is very positive about it, the connection has not been previously analyzed with the proper methods. We use a statistical model to address this question and our data suggest that the effects of warm katabatic winds in the Po Valley (Italy) can indeed be detected in the increase of car accidents.

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1. – Introduction

The influence of climate and severe weather on public health and economy is well known and presently of great concern in the international community [1]; what is less known and studied, instead, is the influence of single and apparently mild weather phenomena directly upon stress, morbidity and mortality in micro-organisms, plants, animals and humans.

Here we consider the possible social influence of a particular kind of wind, namely a warm katabatic wind, whose occurrence is characterized by a sudden and large change in several atmospheric parameters important in the metabolism of living beings: namely humidity and temperature.

A wind is called katabatic([1]) when it blows downhill along the slope of a mountain, a hill or a highland. It may be a cold wind that blows, for example, down the ice plains

(*) The authors of this paper have agreed to not receive the proofs for correction.
([1]) From a Greek word meaning "going downhill".

of Antarctica but also in more close and familiar places like central Europe (Mistral and Bora) or a warm wind that is well known in regions downwind of mountain ridges like, for example, the Rocky Mountains in USA (Chinook), or the Alps in Central Europe, but also in Argentina (Zonda), Japan, Middle East (Sharav), New Zealand and in many other places of the world. The rather frequent warm type of katabatic wind observed in the South Alps (Europe) area is called "foehn".

A foehn situation occurs when the air flow undergoes a precise thermodynamic transformation: air is first forced upward over the windward mountain slopes, cooling as it expands adiabatically. As the air cools its relative humidity increases till the level where saturation is reached and liquid water condensation is possible (such level is called cloud condensation level or CCL). In the further ascent the cooling rate is reduced due to the release of latent heat (it follows what is called a saturated-adiabatic transformation) and water can be released as precipitation. Loss of water content through precipitation is a necessary condition for the foehn mechanism to develop. In fact as the air flows downward over the lee slope, with less water content, it follows a shorter saturated-adiabatic backwards till a level where it becomes unsaturated. This level is located at a lower pressure value and a higher altitude than the windward CCL. From there it follows a longer-than-before dry-adiabatic down to the lee valley. The relative difference in length of the two adiabatic and two saturated-adiabatic transformations strongly affects the final state of the air so that the discharge of precipitation water results in a net warming and drying of the air at the end of the composite transformation.

A fohen situation, beside a low humidity content, is also characterized by high wind velocity. Both characteristics enhance the possibility of ion (aero-ions) formation in the atmospheric planetary boundary layer [2].

According to the literature [3, 4], high aero-ion concentration (especially positive) appears to be related to a number of health problems going from very mild psychological states (unhappiness) to enhancement of pre-existing mental pathologies or even to severe failures of internal organs, cardiovascular diseases, congestive headaches, chronic obstructive bronchopulmonary diseases characterized by asthmatic crisis, etc.

Due to the many possibilities of health problems and mechanisms of action, in the present study we have chosen to apply a statistical model to relate the presence of warm katabatic winds south of the Alps to a well-defined and unique social indicator, namely the number of car accidents in three freeways running along the region interested by such meteorological situation. On purpose we do not analyze whether the foehn affects the air ionization and then, in cascade, the health status, the driving capabilities and the number of car accidents. We take in consideration only the first and last link of all possible causal chains and evaluate only the likelihood that the two end phenomena are correlated.

2. – Materials and methods

The Alps encompass the Po Valley almost as an amphitheater wall with a continuous barrier, ranging in height from approximately 1500 m up to more than 4000 m that affects the winds coming from north-west, north and north-east; in such a topographically peculiar region where prevailing winds are north-westerly, foehn episodes are rather common (an average of approximately 40 per year in the interval considered). Car accidents data were taken from police reports on the three main freeways running in the central part of the Po Valley; namely: highway A-4, 400 km long and running in the direction W-E; highway A-8, 64 km long in the NW-SE direction; and highway A-9, 50 km long,

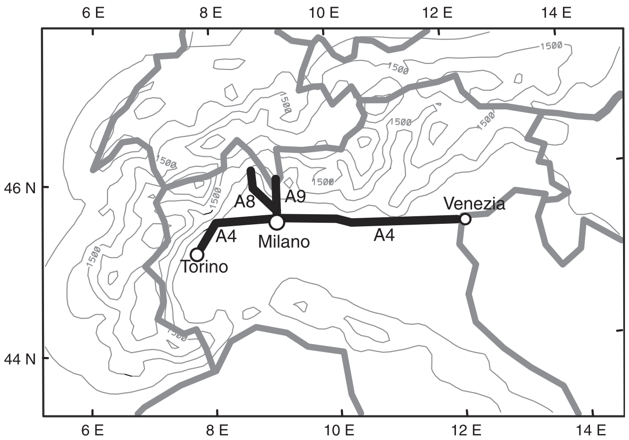

Fig. 1. – Map showing the Alps, the surrounding countries and the three highways whose car accidents have been used for the statistical model. Height contours are given every 500 m. The divide of the mountain range which acts as a semicircular "wall" for the Po Valley corresponds closely to the northern Italian borderline.

N-S direction (fig. 1).

The statistical analysis was made on meteorological and car accident(²) data gathered in the years 1997-2004. Only accidents with at least one reported injured person were considered. The meteorological parameters defining a foehn situation were extracted by the radiosonde profiles taken every 6 hours in the World Meteorological Organization network station placed close to the middle of the Po Valley (Station 16080 LIML, Milano, Italy).

While the daily frequency of car accidents is a relatively straightforward and non-ambiguous time series, a function stating the presence of a foehn condition needs some definition and a meaningful indicator for the presence of foehn must first be found. A preliminary study of the presence of a foehn situation has been done by examining: 1) the cloud distributions on satellite visible and infrared pictures, 2) large-scale meteorological analysis at 500 and 850 hPa and 3) radiosonde profiles averaged from surface up to 700 hPa. Such comparison has led to a criterion that is in accordance with previous studies (see for example the Mesoscale Alpine Programme web site: `http://www.map2.ethz.ch`); a foehn situation is present in the Po Valley, south of the Alps, if at least two of the following conditions hold within the lower layers of the atmosphere (from the surface up to 700 hPa):

i) mean relative humidity less than 30%,

ii) mean wind velocity greater than 10 m/s,

iii) mean wind direction in the range 270°–10°.

For the purpose of this study, an index that depends on wind velocity and relative humidity only was defined. The temperature dependence is embedded in the relative

(2) Source: ACI, Automobile Club d'Italia.

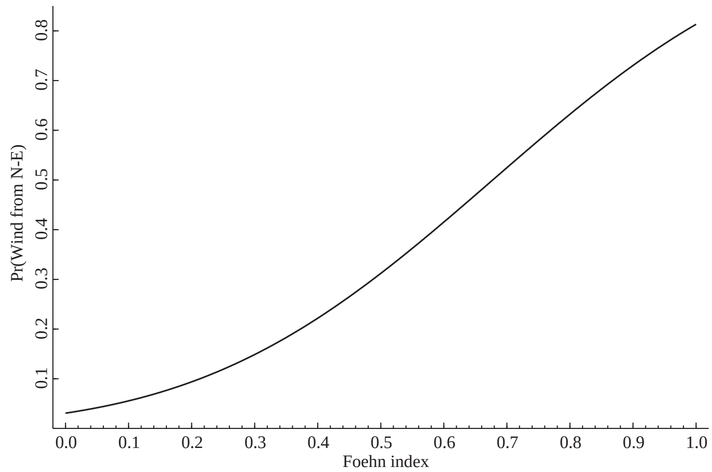

Fig. 2. – Probability of wind with mean direction in the range 270°–10° as a function of the foehn index.

humidity and so is the wind direction because, at least for the case of the Po Valley, any wind that comes from the two southerly quadrants (*i.e.* certainly not a foehn episode) will have a relative humidity much higher than 30%.

After some tuning a "foehn index", Fi, has been defined as a normalized non-dimensional number

$$Fi = 0.75 \cdot [1 - (RH - RH_{\min})/\Delta RH] + 0.25 \cdot (V - V_{\min})/\Delta V \,, \tag{1}$$

where RH is the relative humidity and V the wind velocity, both, as stated before, averaged between surface and the level at 700 hPa. The minimum values, $RH_{\min}$, $V_{\min}$, and the maximum variations ΔV, and ΔRH are all computed using the last 30 daily observations. In other words, they are 30-day moving minima and variations. Fi is linearly decreasing with humidity and linearly increasing with wind velocity with different weights; its time series was computed for the entire studied period for the daily mean relative humidity and wind velocity.

3. – Statistical model and results

First the statistical significance of Fi as an indicator of the actual presence of a foehn situation was tested through a statistical binary-response (Probit) model, where the binary wind direction variable (*i.e.* a variable which is one when condition iii) holds and zero otherwise), was modelled as a function of Fi. The hypothesis "the probability of the wind variable being one (wind from 270°–10°) increases with increments of the foehn index" could not be rejected at a significance level of 1%, and the estimated functional relation is plotted in fig. 2.

The distribution of the number of car accidents in a given period of time $(t - \delta, t]$ is well described by a Poisson distribution

$$p(x_t|\lambda_t) = \lambda_t^x \exp[\lambda_t]/x_t! \qquad x_t = 0, 1, 2, \dots, \tag{2}$$

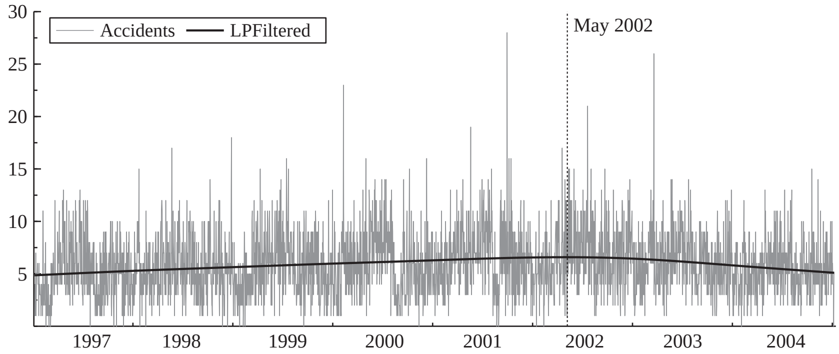

Fig. 3. – Raw and low-pass filtered time series of accidents.

where the parameter λ_t (mean) may depend on atmospheric, traffic or other conditions (time series models for this sort of data can be found in [5-7]). Since traffic is heavily dependent on the season and on the calendar-based organization of life (working days, holidays, etc.) the daily mean number of accidents λ_t has been let depend on dummy variables capturing week-days and months' effects (for example a Monday dummy is a variable that is 1 if day t is a Monday and zero otherwise, a January dummy is one if day t is in January and zero otherwise).

Other conditions that may keep the daily accident mean persistently high or low, such as periods of fog, prolonged rain storms, or social and cultural events in the area which last two or more days and attract huge numbers of vehicles in the three freeways under observation (for example trade-fairs and expositions), have been modelled through auto regression (today's number of accidents depends on yesterday's number of accidents).

In order to find out wether the number of accidents were trending or not, we filtered the data through a low-pass filter getting an approximately linear growth until April 2002 followed by an approximately linear decline starting from May 2002 (fig. 3).

Since the main goal of this study was to test the effect of the foehn in influencing the mean number of accidents, the model fitted to the daily car accidens time series $\{y_t\}$ is a Poisson process (a sequence of Poisson variates) with mean

$$\lambda_t = \boldsymbol{\beta}'\boldsymbol{x}_t + \phi(y_{t-1} - \boldsymbol{\beta}'\boldsymbol{x}_{t-1})\,, \tag{3}$$

where(3) $\boldsymbol{\beta}$ is a vector of coefficients to be estimated and

$$\boldsymbol{x}_t = \big(1,\ t,\ \mathbb{I}_{\{t\geq \text{May02}\}},\ t\mathbb{I}_{\{t\geq \text{May02}\}},\ \boldsymbol{d}_t',\ \boldsymbol{m}_t',\ Fi_t\mathbb{I}_{\{Fi>\xi\}}\big)'$$

is the vector of regressors, $\boldsymbol{d}_t$ a vector of daily dummies, $\boldsymbol{m}_t$ a vector of monthly dummies, Fi_t is the foehn index at time t, ξ is a threshold parameter to be estimated and $\mathbb{I}_{\{\text{condition}\}}$ is an indicator function assuming value 1 when the condition is true and zero otherwise(4).

(3) Any vector is meant as column vector and the symbol $'$ denotes transposition, thus, if $\boldsymbol{a}$ and $\boldsymbol{b}$ are conformable, $\boldsymbol{a}'\boldsymbol{b}$ is their internal product.

(4) Since the mean of a Poisson variate may only be positive, usually, instead of modelling λ_t directly, $\log \lambda_t$ is modelled as a linear function of the covariates. Nevertheless, since modelling

TABLE I. – *Maximum-likelihood estimates of the model with the foehn index.*

Parameter	Estimate	Std.Error	t-ratio	p-value
1	3.352	0.130	25.791	0.0000
t	0.001	0.000	7.735	0.0000
$\mathbb{I}_{\{t \geq \mathrm{May02}\}}$	6.302	0.906	6.955	0.0000
$t \cdot \mathbb{I}_{\{t \geq \mathrm{May02}\}}$	−0.003	0.000	−7.261	0.0000
March	1.345	0.182	7.383	0.0000
April	1.585	0.163	9.738	0.0000
May, June	2.299	0.152	15.143	0.0000
July	2.668	0.197	13.575	0.0000
September	1.089	0.167	6.526	0.0000
October	0.843	0.171	4.925	0.0000
November, December	0.532	0.134	3.965	0.0001
Monday, Thursday	0.627	0.098	6.377	0.0000
Friday	0.953	0.136	7.017	0.0000
Saturday	1.072	0.133	8.074	0.0000
Sunday	1.709	0.128	13.320	0.0000
ϕ	0.102	0.014	7.561	0.0000
ξ	0.774	0.029	26.561	0.0000
$Fi \cdot \mathbb{I}_{\{Fi > \xi\}}$	0.390	0.151	2.589	0.0096

For identifiability reasons the dummies for Wednesday and August (the day and month with the smallest mean number of accidents) have been excluded([5]); so the first component of $\boldsymbol{\beta}$, say β_0, represents the (marginal) mean number of car accidents in a Wednesday of August in the absence of foehn (or more precisely when $Fi < \xi$). The other components of $\boldsymbol{\beta}$ represent increments with respect to the Wednesday-August mean value β_0 due to the respective variables. The parameter ϕ is an auto-regressive parameter, and for causal stationarity must be in the open interval $(-1, 1)$. As argued in the former lines, ϕ is expected to be positive (a high (low) number of yesterday's accidents increases (decreases) today's accident mean number).

Inference on the model's parameters has been carried out through maximum-likelihood (ML) estimation and the results, after excluding variables not significant at 5%, are reported in table I. Some dummies have been given the same coefficient since in the estimation of the complete model they were not found significantly different. As the estimation of the threshold parameter ξ introduces discontinuities in the likelihood function, making numerical maximization non-feasible and invalidating the asymptotic properties of ML, the step function $f_\xi(Fi) = (Fi > \xi)$ has been approximated by a steep logistic function:

$$g_\xi(Fi) = \frac{1}{1 + e^{-c(Fi-\xi)}}\,, \tag{4}$$

λ_t allows for a more straightforward interpretation of the results, we modelled λ_t directly taking care of specifying the model in such a way that negative values of $\boldsymbol{\beta}'\boldsymbol{x}_t$ in the estimation phase were very improbable. As a result we did not incur any such problem.

([5]) Alternatively, but equivalently we could have excluded the constants, elements 1 and 3 of the vector $\boldsymbol{x}$.

where c is a large constant (we used $c = 500$).

The interesting result is that the mean of daily car accidents is increased by circa 0.4 times the value of the foehn index, when this is greater than 0.77, meaning that a strong foehn wind increases the expected daily accidents by a little less the 0.4 units. As the p-value shows (last column, last row of table I), the hypothesis that the foehn does not have any effect on the average number of incidents is rejected at any usual level.

Since statistical significance does not necessarily imply practical significance, and the latter is in many cases subjective, we let the reader reflect on the following figures. In the sample period the daily mean number of accidents is 5.9, and a strong foehn wind ($0.77 < Fi < 1$) comes with an expected increase of this number by some 5.1–6.6%. If we consider the magnitudes of the foehn index in the 8 years of our sample, the expected number of accidents that may be related to strong foehn episodes is circa 104, the 0.6% of the total (17113).

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