A physically based regional rainfall frequency analysis: application to a coastal region in Northern Italy

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ABSTRACT

Regional frequency analysis provides a good tool for the reduction of the uncertainties on the annual probability of exceedence of rare hydrological events. Some regional frequency analysis methods rely on the concept of homogeneous region, a region where the random variable under analysis can be described by the same parent distribution. The heuristics methods used for the homogeneous region definition can be improved through the use of some underlying physics and of the experimental evidence on the characteristics of the extreme rainfall events. The results of the research on Mediterranean storms of the last fifteen years is used here to define a method for homogeneous region definition in the North-Western Mediterranean. The analysis of the experimental evidence on Mediterranean storms, on their triggering factors and characteristics scales is used to define the method for the choice of homogeneous region and for the spatial variability characterization of the rainfall index . An application of the proposed method is also shown, based upon the two component extreme value distribution (TCEV) and follows a hierarchical procedure for parameter estimation.

1. INTRODUCTION

The estimation of the return period T of rare hydrological events, such as extreme floods and rainfall, is one of the most common problems in civil and environmental engineering. For large values of T, the evaluation of the related quantile Q(T) and its dependence on T, can be affected by non acceptable uncertainties for design purposes, if we rely only on a observed time series of length n<<T. The compensation of the lack of enough extended time series can be performed using all the available hydrological data on a geographical area, applying regional frequency analysis techniques and therefore increasing the value of n [Versace et al., 1987].

Let $Y(\mathbf{x},t)$ describe in space and time the stochastic hydrological process of concern, with CDF $F_Y(y)$: a general expression for an estimate of any distribution parameter Z is:

$$Z(\mathbf{x}) = \mu(\mathbf{x}) + W(\mathbf{x}) + \varepsilon(\mathbf{x}) \qquad (1)$$

where $\mu(\mathbf{x})$ is large scale deterministic term; $W(\mathbf{x})$ is spatial random field with $E[W(\mathbf{x})]=0$, and $Var[W(\mathbf{x})]=\sigma_w^2$; $\varepsilon(\mathbf{x})$ is random estimation error with $E[\varepsilon(\mathbf{x})]=0$ and $VAR[\varepsilon(\mathbf{x})]=\sigma_\varepsilon^2$.

If we can define a region S where $\mu(\mathbf{x})= \mu_0$ and $\sigma_w^2 << \sigma_\varepsilon^2$ then we can assume for Z the simplified expression:

$$Z(\mathbf{x}) = \mu_0 + \varepsilon(\mathbf{x}) \qquad (2)$$

that is the observed spatial variability of the estimated distribution parameters is due to sample variability only. In this case S is defined as a *homogeneous* region for the estimated parameter. A hierarchical application of this model, based on the TCEV distribution [Rossi et al. 1984] has been proposed by Fiorentino et al. [1987] and Gabriele and Arnell [1991]. The procedure allows the identification of the regions where the parameter:

$$K_T = \frac{E[Y(x,t,T)]}{E[Y(x,t)]} \qquad (3)$$

is unique, with T= return period.

The dimensional distribution of $Y(\mathbf{x},t)$ is then obtained using for the rainfall index $E[Y(x,t)]$ a more general expression of (2)

$$E[Y(\mathbf{x},t)] = \mu(\mathbf{x}) + \varepsilon(\mathbf{x}) \qquad (4)$$

and using a linear regression analysis to characterize $\mu(\mathbf{x})$ over suitable morphological and climatological parameters.

Several techniques have been proposed for the identification of the homogeneous regions [see Nathan and McMahon, 1990; Cavadias, 1990; Gabriele and Arnell, 1991] and index rainfall evaluation. Such techniques, although mathematically robust, fail to give a physical interpretation of the phenomena that cause either a proposed region to be homogeneous or the scale factor to be rapidly variable in space. Particularly useful for the phenomenological interpretation of the parameters spatial variability is the use of a parent distribution which parameters have a clear physical meaning. The TCEV distribution has parameters that can be easily related to the rainfall process characteristics and then to the meteorology of the hydrological extremes.

This study shows how the use of the experimental evidence on the characteristics of the extreme events provides important elements for the correct definition of the spatial variability of the parent distribution parameters, both in terms of homogeneous regions and index rainfall variability. The regional frequency analysis with the proposed method is performed here for the coastal region of northern Thyrrenian sea.

2. A METEOROLOGICAL APPROACH FOR THE DEFINITION OF THE HOMOGENEOUS REGIONS.

2.1 The TCEV distribution.

The need of taking into account the occurrence of extraordinary rainfall events lead to the formulation of a Two Component Extreme Value distribution (TCEV) proposed by Rossi et al., [1984]. This distribution is currently interpreted as the distribution of a process characterized my the mix of two distinct independent populations: i) the medium component and ii) the extreme component. The form of the TCEV is:

$$F_X(x) = \exp\left[-\Lambda_1 e^{-x/\theta_1} - \Lambda_2 e^{-x/\theta_2}\right] \qquad (5)$$

where Λ_i (i=1,2) is the averaged annual number of the elements of the ith component, while θ_i (i=1,2) represents the expected value of each population.

The parameters of the distribution show then a clear physical meaning and, as mentioned before, it is an essential characteristic of the probabilistic model, when we operate in a homogeneous region framework.

2.2 The storm features.

Under the hypothesis that the TCEV distribution is suitable to be used as parent distribution for Annual Rainfall Maxima (ARM), the analysis of the experimental evidence on heavy impact weather provides information for homogeneous region definition . In fact if the meteorological mechanism that produces heavy rainfall in a particular region is the same, it is very likely that the magnitude and relative importance of the medium and extreme component and, as a consequence, the TCEV parameters, are the same.

Various atmospheric circulation patterns have been observed in the Mediterranean that in some cases can produce heavy rainfall such as frontal systems of Atlantic origin, tropical-like cyclones [Reale and Atlas, 1998; Reale, 1998], polar lows. The source of humidity has been also identified either in the Mediterranean area or in the Intertropical Convergenze Zone. The presence or the absence of the European blocking condition (a strong high pressure cell over central Europe) can affect also the evolution of the potentially dangerous meteorological conditions: blocking over the Balkans slows down the displacements of the fronts, potentially increasing the amount of rainfall released over the same area [Conti et al. 1994].

From the morphological point of view the Mediterranean is characterized by large areas with steep coastal orographic chains with average elevation often above 1000 m a.s.l. Such a morphology interacts at various scales with all these different atmospheric circulation patterns, producing sometimes heavy rainfall.

In any case the common feature observed during extreme rainfall events in the northwestern Mediterranean is the presence of a southwesterly moist air flow. When it impacts the coastal orography, in case of atmospheric instability, it produces strong convection upstream the orographic chain. Figure 2.1 shows an example of such a kind of circulation. Observe the presence of a high pressure over central Europe.

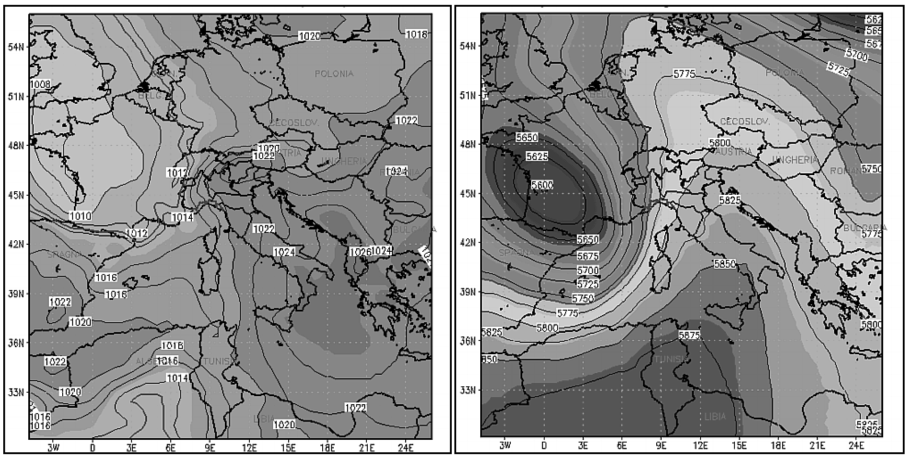

Figure 2.1: Lower atmosphere circulation for the flood event of September 1992 occurred over the Liguria region (Northwestern Italy). The left panel reports the sea level pressure field and the right one the geopotential height at 500 hPa. Observe the isobars oriented along the north-south direction, producing air flow toward the northern Mediterranean coast line.

For such a meteorological conditions the IR geostationary imagery show the development of cloud structures with low top IR radiance temperature [Lanza and Conti, 1995; Bolla et al, 1996], currently interpreted as areas of strong convective activity. The spatial scales of the observed structures are of the order of few thousand of square kilometers. They develops in the upstream side of the coastal orography, extending in the downstream side at least for the characteristic depth of the atmospheric layer concerned by the phenomena. An example of such a cloud structures is reported in figure 2.2.

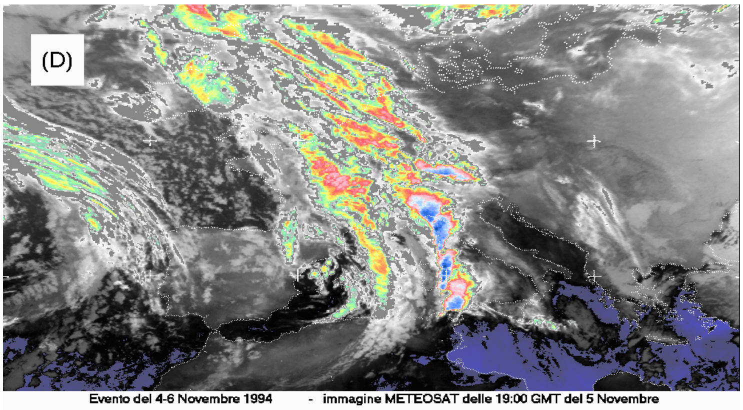

Figure 2.2: example of cloud pattern produced by convection during an extreme rainfall event of 5-6 November 1994 over northwestern Italy. Several convective clouds (light blue) have been observed.

At several raingauges in the “shadow” of such a cloud strtuctures, the observed total rainfall depth frequently exceed 1/5-1/3 of the total annual average precipitation. In the event of figure 2.1 total rainfall depths ranging from 350-450 mm/24h have been observed. This are very large values if compared to the total annual average precipitation that ranges from t 1000 to 2000 mm/year. The analysis of the ground observations relative to the extreme convective events occurred in northwestern Italy in the decade 1984-1994, reported in table 2.1, shows that the annual rainfall maximum is often produced by such a kind of events. The result is in agreement with the analysis made by Llasat et al. [1996] for Catalonia and southern France, that shows the convective origin of extreme rainfall in the region.

The common features of the extreme rainfall events allows to assume that the parent distribution is the same on the region where this kind of phenomena are observed. This gives a very useful information for the definition of the homogeneous regions.

3. REGIONAL FREQUENCY ANALYSIS WITH HOMOGENEOUS REGION APPROACH: A CASE STUDY.

This paragraph focuses on the definition of homogeneous regions for short-duration (up to 24 hours) ARM in the Riviera, a coastal area of northern Italy presenting steep orographic chains with average elevation of about 1000 m and the water-divide running parallel 30-50 km from the coast. The TCEV distribution [Rossi et al., 1984] has been chosen as regional parent distribution. The maximum likelihood (ML) procedure for estimating regional TCEV parameters (hereafter TCEV-ML) has been applied [Gabriele and Arnell, 1991]. The performance of the proposed method, hereafter referred as Meteo-morphological, has been validated using different definitions of the homogeneous regions.

Year		d=1 hrs		d=3 hrs		d=6 hrs		d=12 hrs		d=24 hrs	
		h(mm)	T (yrs)	h(mm)	T (yrs)	h(mm)	T (yrs)	h(mm)	T (yrs)	h(mm)	T (yrs)
84	Calice al Cornoviglio	46	7	85	15	94	7	100	5	111	2
84	Levanto	52	8	108	30	111	10	114	5	140	3
84	Genova Università	93	70	122	30	128	10	-	-	-	-
85	Airole	19	1	51	5	81	10	101	10	112	5
85	Bestagno	35	7	57	8	79	10	109	15	117	5
85	Centrale Argentina	21	2	58	10	83	20	105	15	115	7
91	Viganego	63	10	163	130	175	50	185	20	188	5
91	Valle Tane	36	10	78	50	135	200	215	650	251	300
92	Bolzaneto	61	10	73	5	171	50	316	270	345	100
92	Genova Università	62	10	169	160	226	180	417	>1000	450	500
92	S.Eusebio	60	10	153	90	226	170	359	600	369	130
92	Sella di Savona	92	200	271	>1000	365	>1000	475	>1000	522	>1000
93	Genova Università	92	70	122	30	245	300	321	300	343	100
93	Pontecarrega	80	30	142	60	238	250	364	650	384	170

Table 3.1: rainfall depth observed at several raingauges during the extreme convective events of the last ten years. The observations often represent the annual rainfall maximum and the associated return period (retrieved from the regional frequency analysis) is very high.

3.1 The Meteo-Morphological approach.

Under the meteorological conditions described in paragraph 2.2. the combined observation of METEOSAT IR imagery and ground observations shows the formation of convective structures which typical diameter is of the order of about 50km. High resolution limited area model outputs confirm this observation as shown in figure 3.1.

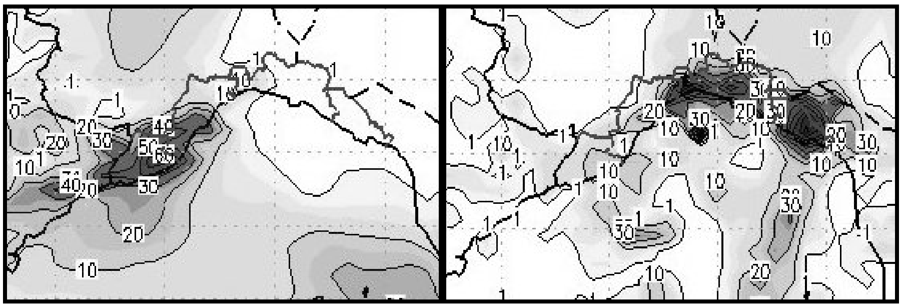

Figure 3.1: rainfall field produced by high resolution LAM relative to two extreme rainfall events occurred over northern Italy. The rainfall field extension are coherent with the convective structures observed by METEOSAT IR sensor.

In the hypothesis that homogeneity in the meteorology of the high impact weather generates homogeneity in rainfall distribution, an homogeneous region extended all along the coastline and about 50 km wide has been considered. The location of the raingauges belonging to the region is reported in figure 3.2 (top left panel). The results of the homogeneity test are reported in tables 3.1 and 3.2. The hypothesis of homogeneity cannot be rejected for any of the considered durations. In order to state that this homogeneity is effectively produced by the similar meteorology of the extremes in the area a validation is needed. In fact the extension of the homogeneous region can be larger than the area interested by the convective phenomena driven by orographic uplift, invalidating the basic assumption of the method. Some control hypotheses has been then formulated and tested using the same procedure.

3.2 The Control Hypotheses.

The homogeneous region of the meteo-morphological case has been extended towards the plains of the Po river valley, in order to test if homogeneity is effectively produced by the meteorology. In fact if the extended region, that exceed the average extension of the convective structures produced by the orographic uplift of moist air masses, resulted homogeneous then the basic hypothesis of the meteo-morphological approach would fail. The results of the homogeneity test are reported in table 3.1 and 3.2. Since for the coefficient of variation CV the homogeneity test fails, the extended region has been subdivided into different subregions in order to test if the spatial variability of the distribution parameters can be explained in different ways. The following hypotheses has been then tested:

a) an unique extended homogeneous region for skewness (CS) and coefficient of variation (CV) ;
b) an unique homogeneous region for CS and two subregions for CV: eastern+western (b1) and central (b2);
c) an unique homogeneous region for CS and two subregions for CV: windward (c1) and leeward (c2).

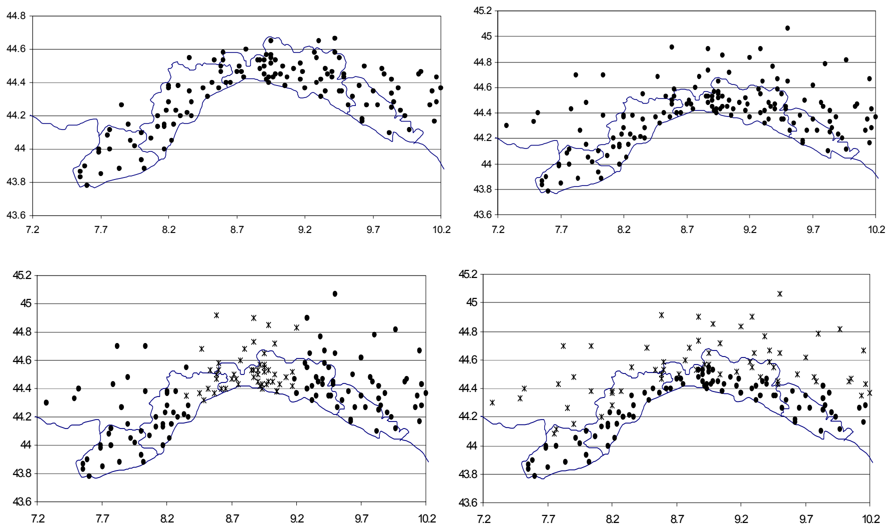

Figure 3.2: meteo-morphological hypothesis (top left) and control hypotheses for the homogeneous region definition. The hypotheses are: hypothesis a) top right; hypothesis b) bottom left; hypothesis c) bottom right respectively.

Region	Sample χ^2 (CS)					$\chi^2_{0.025,n}$	n
	1 h.	3 h.	6 h.	12 h.	24 h.		
Unique (a),(b1+b2),(c1+c2)	9.0	6.9	8.2	4.6	6.2	16.0	7
Unique (meteo-morph.)	5.6	5.0	12.4	8.7	7.6	16.0	7

Table 3.2: χ^2 test for the skewness coefficient CS for different hypotheses of first level homogeneous regions. Bold means χ^2 test failure. All the hypotheses do not fail the test, but the meteo-morphological approach gives globally better results.

As tables 3.1 and 3.2 show, none of the control hypotheses passes the homogeneity test. This is an important validation of the meteo-morphological method, suggesting further observational studies to validate the homogeneous region definition on a phenomenological basis in other Mediterranean regions.

Region	Subregion	Sample χ^2 (CV)					$\chi^2_{0.025,n}$	n
		1 h.	3 h.	6 h.	12 h.	24 h.		
Unique (a)	Unique (a)	11.5	10.7	**18.9**	**20.3**	**16.8**	14.5	6
Unique (b)	Eastern+western (b1)	10.8	8.2	4.2	6.8	10.8	14.5	6
	Central (b2)	10.0	**16.8**	**19.6**	**27.2**	**24.8**	14.5	6
Unique (c)	Windward (c1)	**15.6**	5.3	10.4	7.6	7.8	14.5	6
	Leeeward (c2)	11.7	**16.6**	10.9	8.9	11.4	14.5	6
Unique (met-morph)	Unique (met-morph.)	14.0	4.7	11.8	7.9	10.0	14.5	6

Table 3.3: χ^2 test for the coefficient of variation CV for different hypotheses of second level homogeneous sub-regions. Bold means χ^2 test failure. All the empirically defined hypotheses, if analyzed globally, fail the goodness-of-fit test for the given level of significance. As in the case of CS χ^2 test, the meteo-morphological method gives globally the best results.

4. RAINFALL TRIGGERING BY OROGRAPHIC UPLIFT: A SIMPLE MODEL FOR INDEX RAINFALL ESTIMATION.

4.1 The model.

For the index rainfall characterization a more complex model than the "homogeneous region" approach must be used, due to its high spatial variability. In this case eq. (4) is used, with a linear regression analysis such that:

$$\mu_j(x) = \gamma + \sum_i \beta_i x_{i,j} \qquad (6)$$

where $x_{i,j}$ are the values at the location j of some suitable meteorological and morphological parameters that describe $\mu(x)$ spatial variability.

Using the simple scheme for cumulus convection proposed by Georgakakos and Bras [1984] and other authors [Seo and Smith, 1992; French and Krajewsky, 1994], the rainfall depth over a defined time interval, $R_{\Delta t}$, can be related to some meteorological variables. We assume also that some dynamical and morphological factors affect $R_{\Delta t}$, then we have:

$$R_{\Delta t} = R_{\Delta t}\left[p_0, T_0, T_d, w_z\right] \qquad (7)$$

where p_0, T_0 and T_d are respectively the surface pressure, air and wet bulb temperature; w_z represents the vector of the dinamical-morphological factors affecting convection.

In order to individuate the components of w_z a simple dynamic scheme of orographic uplift of moist air masses has been used. In this scheme the magnitude of the displacement of the air parcel from its initial conditions, due to the mechanical uplift, can be identified as a very important factor for convective rainfall production, under the assumption of atmospheric instability. We assume that this factor is characterized by the vertical velocity produced by the uplift and the mean elevation of the water divide. Using a simplified scheme of irrotational two-dimensional uncompressible flow, confined between the tropopause and the ground surface and modeling the latter as a Fourier series, the analytical solution for the velocity field is given for each component of the series (Marchi and Rubatta, 1981). The vertical velocity is then:

$$v_{z_i} = UA_i \frac{2\pi}{L_i} \frac{\operatorname{sh}\frac{2\pi}{L_1}(Z_0 - z)}{\operatorname{sh}\frac{2\pi}{L_i} Z_0} \cos\frac{2\pi}{L_i} x \qquad (8)$$

where A_i,L_i represent the i^{th} component amplitude and wavelength respectively; U is the horizontal wind speed; z is the elevation and Z_0 is a scale length representative of the troposphere thickness. Averaging the process at slope scale for z=0 and neglecting the effects of second and higher order components, we obtain the averaged vertical velocity in the wind direction:

$$\langle v_{z=0} \rangle = UA_1 \frac{4\pi}{L_1^2} \cdot \int_{-L_1/4}^{L_1/4} \cos\frac{2\pi}{L_1} x \cdot dx = 2U\frac{A_1}{L_1} = 2Us \qquad (9)$$

The averaged elevation of the water divide is quantified, following this scheme, by the parameter $e=A_1/L_1$. Eq. (7) becomes then:

$$R_{\Delta t} = R_{\Delta t}\left[p_0, T_0, T_d, U, s, e\right] \qquad (10)$$

Assuming that: i) $\mu_{\Delta t} \propto E[R_{\Delta t}]$; ii) $f(p_0,T_0,T_d,U,s,e)=f(p_0)f(T_0)f(T_d)f(U)f(s)f(e)$; iii) $\delta_M \ll \delta_D \ll \delta_s$, where f(.) represents the PDF, $\mu_{\Delta t}$ represents the index rainfall and δ_M, δ_D, δ_s represent the spatial scales of variation of the meteorological variables PDF parameters, the analysis domain and the morphological variables PDF parameters respectively, then the index rainfall is given by:

$$\mu_{\Delta t} = \mu_{\Delta t}\left(\bar{s}, \bar{e}\right) \qquad (11)$$

where $\bar{s}, \bar{e}$ represent the expected values of s and e at a given location respectively.

This means that the vector **x** in eq. (6) has the components $\mathbf{x} = \left(\bar{s}, \bar{e}\right)$.

4.2. The case study.

The values of **x** have been calculated within the homogeneous region identified in paragraph 3 using the 30” resolution USGS DEM, using wind direction ranging from 20° to 50° clockwise the south-north oriented direction. The linear regression has been performed on the observed index rainfall for 1 hour duration ARM. The results are shown in table 4.1. Best results are obtained for wind directions among 40° and 45°. In this case the model explains 60% of the observed index rainfall spatial variability.

θ	20°	30°	35°	40°	45°	50°
R^2	0.19	0.38	0.51	0.60	0.61	0.49
ρ	0.44	0.62	0.72	0.78	0.78	0.70

Table 4.1: statistics of the linear regression of the index rainfall vs. local slope and water divide elevation. Results are reported for different values of the wind direction θ. Best results are obtained for $40° < \theta < 45°$, where the model explains the 60% of the variance (estimate provided by R^2 statistics) and correlation ρ between observed and evaluated values is around 0.8.

5. CONCLUSIONS.

The procedure presented in this paper is based on the knowledge of the characteristics of the Mediterranean storms emerging from remote sensing data and meteorological models. It provides the criterion for the identification of the regions where homogeneity in frequency distribution of the extreme rainfall may apply, relying on the concept that the latter is produced by homogeneity in the meteorological characteristics of the extreme events. The method, applied to the Italian Riviera provides a physical explanation on how the homogeneity in frequency distribution produces over the selected region.

The spatial variability of the index rainfall is also explained using the simple, physically based model for atmospheric convection driven by orographic uplift. The model allows to identify, on a physical basis, the morphological factors that affects the index rainfall spatial variability, as confirmed by the results of the analysis applied to the Italian Riviera. For surface wind directions consistent with the most frequent ones observed during storms it explains up to 60% of the spatial variability of the index rainfall and the wind directions that allows

The methodology presented here can provide then a complete set of tools for regional frequency analysis of hydrological variables in the Mediterranean, through a multidisciplinary approach involving meteorology and remote sensing. An extension of the analysis to a larger area of the Thyrrhenian coast is under consideration.

6. REFERENCES

Bolla, R., Boni, G., La Barbera, P. L., Lanza, L., Marchese, M., and Zappatore, S., The tracking and prediction of high intensity rainstorms, *Remote Sensing Reviews*, 14(1-3), 151-184, 1996.

Cavadias, G., The canonical correlation approach to regional flood estimation, in Regionalization in Hydrology, 191, pp. 171-178, IAHS, 1990.

Conti, M., Lanza, L., and Siccardi, F., Predictability of heavy rainfall patterns over the southern european region. storm 93 and GNDCI recent research experiences, in Proc. of Int. Work. on Flood and Inundations related to large hearth movements, Trento, Italy, 1994.

Fiorentino, M., Gabriele, S., Rossi, F., and Versace, P., Hierarchical approach to regional flood frequency analysis, in Regional Flood Frequency Analysis (V.P. Singh ed.), D. Reidel, Dordrecht, Holland, 1987.

French, M.N. and Krajewski W.F. A model for real time quantitative rainfall forecasting using remote sensing. 1. Formulation". *Water Resour. Res.*, 30(4): 1075-1083. 1994

Gabriele, S. and Arnell, N. W., A hierarchical approach to regional flood frequency analysis, *Water Resour. Res.*, 27(6), 1281-1289, 1991.

Georgakakos, K.P. and Bras, R.L. A hydrologically useful station precipitation model. 1. Formulation. *Water Resour. Res.*, 20(11): 1585-1596, 1984

Lanza, L. and Conti, M., Cloud tracking using satellite data for predicting the probability of heavy rainfall events in the mediterranean area, *Surveys in Geophys*., 16(2), 163-181, 1995.

Llasat, M., Ramis, C., and Barrantes, J., The meteorology of high-intensity rainfall events over the west mediterranean region, *Remote Sensing Reviews*, 14(1-3), 51-90, 1996.

Nathan, R. J. and McMahon, T. A., Identification of homogeneous regions for the purpose of regionalisation, *J. Hydrol.*, 121 , 217-238, 1990.

Reale, O. and Atlas, R., A tropical-like cyclone in the extratropics, available as ICTP preprint IC98007, 1998.

Reale, O., Tempeste autunnali sul mediterraneo: inquadramento sinottico-dinamico ed aspetti previsionali in un general circulation model, CNR-GNDCI, puble n. 1862 (in Italian), 3-18, 1998.

Rossi, F., Fiorentino, M., and Versace, P., Two component extreme value distribution for ood frequency analysis, *Water Resour. Res*., 20(2), 847-856, 1984.

Seo, D.-J. and Smith J.A. Radar-based short-term rainfall prediction". *Journal of Hydrology*, 131(1992), 341-367.

Versace, P., Ferrari, E., Gabriele, S., and Rossi, F., Valutazione delle piene in Calabria, IRPI Geodata - In Italian, 1987.