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Preliminary results of an attempt to provide soil moisture datasets in order to verify numerical weather prediction models(*)

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Summary. — In the recent years, there has been a significant growth in the recognition of the soil moisture importance in large-scale hydrology and climate modelling. Soil moisture is a lower boundary condition, which rules the partitioning of energy in terms of sensible and latent heat flux. Wrong estimations of soil moisture lead to wrong simulation of the surface layer evolution and hence precipitations and cloud cover forecasts could be consequently affected. This is true for large-scale medium-range weather forecasts as well as for local-scale short-range weather forecasts, particularly in those situations in which local convection is well developed. Unfortunately, despite the importance of this physical parameter there are only few soil moisture data sets sparse in time and in space around in the world. Due to this scarcity of soil moisture observations, we developed an alternative method to provide soil moisture datasets in order to verify numerical weather prediction models. In this paper are presented the preliminary results of an attempt to verify soil moisture fields predicted by a mesoscale model. The data for the comparison were provided by the simulations of the diagnostic land surface scheme LSPM (Land Surface Process Model), widely used at the Piedmont Regional Weather Service for agro-meteorological purposes. To this end, LSPM was initialized and driven by Synop observations, while the surface (vegetation and soil) parameter values were initialized by ECOCLIMAP global dataset at 1km^2 resolution.

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1. – Introduction

The latent heat flux is an important term governing the surface energy balance in the presence of water, because it links the energy and water cycles. In fact, latent heat flux represents the energy needed for the evapotranspiration process, which can originate both from the evaporation of the bare soil and from the transpiration of the vegetation. Evapotranspiration is physically linked to the fraction of water contained in the upper layers of the soil in which plant roots are located. Evapotranspiration and soil moisture are thus both involved in the water budget, and errors in the specification of these parameters could have a deep impact on the model predictions.

However, the ground-based network, when aiming at quantitative estimates of these variables for larger scales (regional, continental, global), provides only coarse observations. Many studies have demonstrated the sensitivity of the surface energy budget and atmospheric fields to the formulation of land-surface processes, at virtually all spatial and temporal scales [11]. Many authors (for instance see ref. [20] for a review) attempted (successfully) to retrieve surface soil moisture, during the past two decades, using land surface schemes, or using directly screen-level meteorological observations, or both (see for instance ref. [16]).

The work described in this paper was done in the framework of the international project *COSMO* (COnsortium for Small-scale Modelling: see `http://www.cosmo-model.org` for details), whose objective is to develop, optimize and validate a meteorological hydrostatic limited area model, the “Lokal Modell” (LM), in order to use it operationally for meteorological forecasts as well as research model. One of the most important critical points is the optimization of the hydrological processes involving the terrestrial surface, aiming to the rainfall prediction improvement, and one of the inquired points is the check of the soil moisture supplied by aLMo, the Swiss version of LM. To this end, the method proposed was an independent soil moisture estimation on some pilot stations and its intercomparison with the aLMo predictions.

2. – The LSPM

LSPM, acronym of Land Surface Process Model, is a diagnostic 1D model developed at Turin University [1], and tested in many climatic conditions [2,21]. LSPM is a typical SVAT (Soil Vegetation Atmosphere Transfer) scheme developed to be used both as a “stand alone” model (in this case, a set of specific routines for the calculation of the input data is needed) and as the surface boundary subroutine of an atmospheric circulation model (in this case, input data should be provided by the atmospheric model itself). The LSPM parameterisations are reported in detail in ref. [14].

The schematic spatial structure of LSPM includes three main zones: the atmospheric layer above the vegetation (extending from a reference height to the vegetation canopy level), the vegetation layer (extending downward to the soil), and the soil layer. The hierarchy of the model allows a separation among soil, canopy and atmospheric layers. In the atmospheric layer, output variables are calculated as weighted averages between atmospheric and canopy components. The canopy is considered as a uniform layer (big-leaf) characterised by the following parameters: vegetation cover, height, leaf area index (LAI), albedo, minimum stomatal resistance, leaf dimension, emissivity and root depth. Soil temperature and moisture are calculated using multi-layer schemes whose main parameters are: thermal and hydraulic conductivities, soil porosity, permanent wilting point, dry volumetric heat capacity, soil surface albedo and emissivity. The user can select a variable number of soil layers: in this study, 6 soil layers were used. Each flux is partitioned according to the vegetation and snow fractional covers. The LSPM includes two subroutines for the long-wave and short-wave incoming radiation calculation (if observed radiation is unavailable, the cloud coverage is needed). The turbulent heat, water vapour and momentum fluxes are calculated by using the "analogue electric" scheme, in which the flux is expressed as a ratio between a generalised gradient (of temperature or moisture) and "resistances". LSPM can provide the values of each component of thermal and hydrological budgets in the soil, of the water balance in the planetary boundary layer and atmospheric turbulent fluxes. The snow is parameterised as a single layer. Being a diagnostic model, LSPM needs a number of boundary conditions for every time step, which are linearly interpolated by LSPM to the model time step. The input data used in this study to drive LSPM were: air temperature [K], atmospheric pressure [hPa], relative [%] or specific [kg/kg] humidity, total and low cloudiness [fraction of unity] or incoming solar radiation [W m^{-2}], longitudinal and latitudinal horizontal wind components [m s^{-1}] and total precipitation rate [mm s^{-1}]. The boundary conditions could be meteorological observations carried out at the synoptic stations of the World Meteorological Organisation, or measured by regional, national or international meteorological networks.

Among the LSPM output, the following variables were extracted and analysed in this study: soil temperature [°C] and moisture [kg m^{-2}] of the surface layer (10 cm), vegetation temperature [°C], net radiation [W m^{-2}], sensible, latent and soil-atmosphere heat fluxes [W m^{-2}].

3. – The model aLMo and the subroutine TERRA

The model aLMo is a prognostic non-hydrostatic limited area model, developed for operative numerical weather prediction and for several scientific applications at the mesoscale. It is the Swiss version of the "Lokal Modell" (LM), developed originally at the German Meteorological Service [12] and subsequently distributed to the member countries and modified according to the requirements of the local services.

The operative version of aLMo has a horizontal resolution of 7 km and 35 vertical atmospheric levels, and is based on the primitive equations, which describe compressible fluid in humid atmosphere. The subroutine of the model aLMo taking care of the processes in the surface layer is called TERRA, and describes processes analogous to those described by LSPM.

To calculate the soil volumetric content, both LSPM and the operative version of TERRA in aLMo use the *Darcy equation*:

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q_z}{\partial z} = \frac{\partial}{\partial z}\left[(D_{l\theta}+D_{v\theta})\frac{\partial\theta}{\partial z}\right] + \frac{\partial K}{\partial z} + \frac{\partial}{\partial z}\left[D_{vT}\frac{\partial T}{\partial z}\right], \tag{1}$$

where θ is the volumetric soil moisture, expressed in m^3 of water over m^3 of terrain, q_z is the water flux into soil, $D_{l\theta}$ and $D_{v\theta}$ are the hydraulic diffusivity coefficients for liquid water and water vapour, respectively, K is the hydraulic conductivity, D_{vT} represents the variation of the hydraulic diffusivity with the temperature profile and T is the soil temperature. TERRA considers a subset of five soil types extracted from the database of Clapp and Hornberger [6]. The discretisation of the soil levels, identical for the calculation of soil temperature and moisture in LSPM, is different in TERRA. In fact, soil temperature is calculated using a "forcing-restore" method, with three soil levels: the

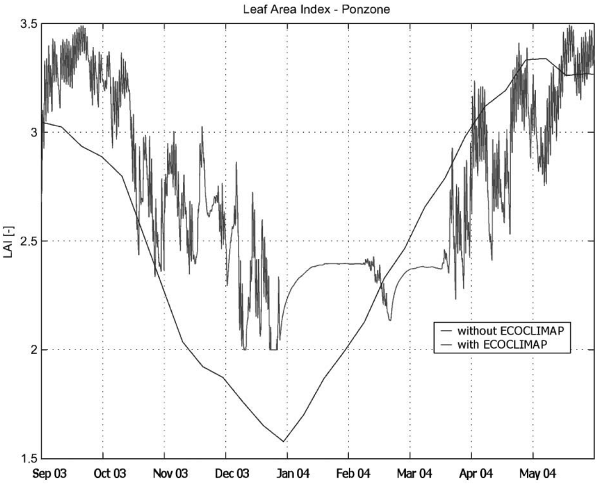

Fig. 1. – Example of the seasonal variation of leaf area index in the station of *Ponzone Bric Berton*, in the Po Valley, Northern Italy. The more stable line shows the values furnished by ECOCLIMAP, while the other one shows the LAI calculated according to the root zone temperature in the previous LSPM version.

surface one, a second layer of interface between the first and the third, and a deep level in which the temperature is considered as constant. As far as the soil moisture, instead, the number of levels has been selected equal to three in the operative version, but their depths are uncorrelated with those of the temperatures.

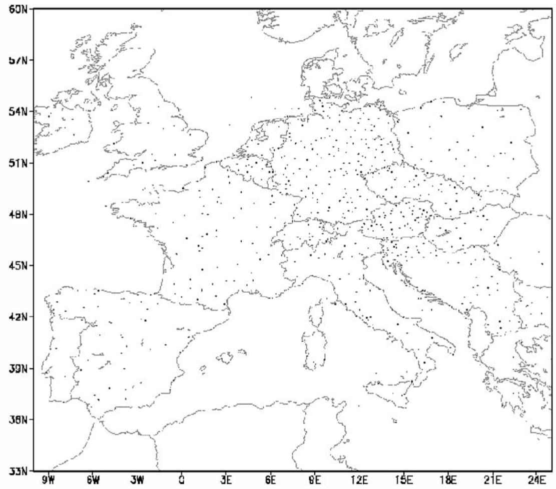

Fig. 2. – European synoptic stations considered in the present study.

4. – The ECOCLIMAP database and its implementation in LSPM

Some complete datasets of surface parameters, like that of Wilson and Henderson-Sellers [23], which has a resolution of 1°, or the ISLSCP-2 (International Satellite Land Surface Climatology Project), obtained combining observations from satellite in period 1982-1990, are already available. Nevertheless, the increment of the regional climatic model studies, and the increasingly greater resolution required for representing the smaller-scale phenomena, need an accuracy greater and greater in the determination of surface parameter values.

ECOCLIMAP is a new global dataset [17] with a resolution of 1 km^2, created with the aim to be used for the surface parameter initialisation in meteorological and climatic models. This database was constructed by mapping land cover at a resolution of 1 km^2 using some global databases and world maps [10,15]. The ground cover types were combined with global climatic maps [13] and with the *NDVI* (Normalized Difference Vegetation Index) index, deduced by NOAA satellite observations. Additional information for Europe was that coming from the projects FIRS (Forest Information from Remote Sensing [8], CORINE (COoRdination of INformation on the Environment [5] and PELCOM (Pan-European Land Cover Monitoring [18]. In this way, 125 ecosystems in the extra-European world, and 90 ecosystems in Europe, were found.

It was decided to use the database ECOCLIMAP in order to guarantee a more correct initialisation of the vegetation and ground parameters in the model LSPM. The parameters independent of the annual cycle (*percentage of clay and sand in the ground, minimal stomata resistance and root depth*) were defined at the beginning of the simulation. The other parameters (*surface emissivity, leaf area index, vegetation cover, vegetation albedo, and roughness length*), varying in the course of the year, were depending on the date.

It was necessary to introduce in LSPM some modifications in order to allow the calculation of some ECOCLIMAP parameters, because they do not have a direct correspondence with the LSPM ones.

As far as the *surface emissivity* is concerned, LSPM distinguishes between vegetation and bare soil emissivity. In the previous parameterisation, the latter was independent of the annual cycle, while the former was calculated according to the soil moisture and type. In the actual parameterisation, total emissivity is extracted from ECOCLIMAP, while the soil component is unchanged, and the vegetation component is calculated from the above two values.

Concerning the *soil type*, LSPM considers 14 types of ground: 12 are taken from Clapp and Hornberger [6], while the last two were added in Qian *et al.* [19]. The types of ground are determined from the percentages of sand, silt and clay furnished by ECOCLIMAP through the soil triangle [22].

In fig. 1, an example of comparison between the old and new parameterisation of the Leaf Area Index (LAI), one of the most important parameters in the calculation of the energetic budget, is shown. According to the old parameterisation, LAI varies between a wintertime minimum value and a summertime maximum value according to the mean root zone temperature.

5. – Setting for simulations and sensitivity experiments

The input data for the simulations with LSPM described in this section were the meteorological observations carried out at some European synoptic stations (Synop). The period selected was from 1 October 2002 to 31 August 2003. The synoptic stations

TABLE I. – *List of stations used in the paper, with their coordinates and the soil type code deduced from internal aLMo and ECOCLIMAP databases.*

WMO Code	Latitude	Longitude	Station name	Quote (m a.s.l.)	ECOCLIMAP soil type	aLMo soil type
06670	47.29 °N	8.32 °E	Zürich - Kloten	436	5 (loam)	3 (sandy loam)
10385	52.23 °N	13.31 °E	Berlin - Schönefeld	47	8 (clay loam)	5 (loam)
12375	52.10 °N	20.58 °E	Warszawa - Okecie	107	5 (loam)	1 (sand)
16059	43.13 °N	7.39 °E	Torino - Caselle	240	8 (clay loam)	8 (clay loam)

were selected in the area limited in longitude by the range $-10/+25°$ E and in latitude by the range $33/60°$ N (fig. 2).

A preliminary sensitivity analysis was performed on the 4 stations listed in table I, selected on the basis of geographic criteria in collaboration with the colleagues of the COSMO consortium.

Regarding aLMo model, the analysis of soil moisture calculated at the level of 10 cm in the soil was available from COSMO. The soil depths in LSPM were then chosen accordingly in order to evaluate soil moisture at the same level of 10 cm.

A particular care was reserved for the choice of the initial parameters inherent to vegetation and soil in LSPM (the model aLMo has its internal database for such data). The vegetation type of "short (10 cm) grass" was assumed, while other soil and vegetation parameters were taken from ECOCLIMAP database. The choice of the vegetation type (short grass) was based on the consideration that the selected stations were belonging to the WMO (World Meteorological Organization) network, and therefore their characteristics should respect some standard.

For some stations, the soil type founded in ECOCLIMAP was quite different from the aLMo one (see table I), thus two simulations were performed with LSPM. In the first simulation (hereafter referred to as *control run*), ECOCLIMAP soil type was used, while in the second one (referred to as *aLMo-soil run*) aLMo soil type was used.

For the intercomparison carried out in the next section, the soil moisture values of aLMo (which refer to the forecast at zero hours, *i.e.* the aLMo "analyses") were compared with the values diagnosed by LSPM at the same hour. It is necessary to remember here that LSPM is a model that diagnoses the soil moisture from the meteorological boundary conditions and from the vegetation and soil initial conditions, while aLMo is a prognostic

TABLE II. – *Mean errors (ME), biases (Bias) and root mean square errors (RMSE) of soil moisture (expressed in kg m^{-2}) between* LSPM *and* aLMo *simulations (intended as* aLMo *MINUS* LSPM*) referred to the aLMo-soil run (left) and to the control run (right).*

Station	ME	Bias	RMSE	ME	Bias	RMSE
	aLMo-soil run			control run		
Zurich	9.7	1.5	11.1	5.1	1.2	7.5
Berlin	2.7	1.1	6.5	3.9	−0.9	6.9
Warszawa	24.1	3.1	24.4	11.4	1.5	11.8
Torino	2.8	1.1	7.2	3.9	1.1	7.5

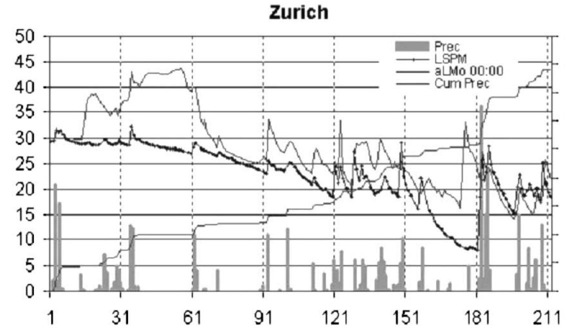

Fig. 3. – Soil moisture calculated in Zurich by LSPM (black line) in the *control run* and aLMo (grey line), left scale, in kg m^{-2}. Daily (grey histograms, left scale, in mm) and cumulated (thin line, right scale, in mm) precipitation is also shown. On the abscissa the day number (starting by 1 October 2003) is shown.

limited area model that estimates the meteorological observations and uses its routine TERRA to diagnose the soil moisture using its predicted fields.

To allow the comparison between the two models, the soil moisture was converted in the same unit. In fact, aLMo furnishes soil moisture in units of mass of water per unit area. LSPM, instead, calculates the relative degree of saturation (*i.e.* the ratio between the volumetric water content of the soil and its maximum value, or porosity). Thus, LSPM values were converted in mass of water per unit area using the formula

$$\rho = q \eta_{\mathrm{s}} \rho_{\mathrm{w}} \Delta z \,, \tag{2}$$

where ρ is the mass of water per unit of soil surface (kg$_{\mathrm{water}}$ m^{-2}), q the dimensionless degree of saturation, η_{s} the porosity, ρ_{w} the water density (1000 kg$_{\mathrm{water}}$ m^{-3}) and Δz the thickness of the soil layer (m). The values in all diagrams of the next sections and reported in table II are therefore expressed in kg$_{\mathrm{water}}$ m^{2}, or kg m^{2}.

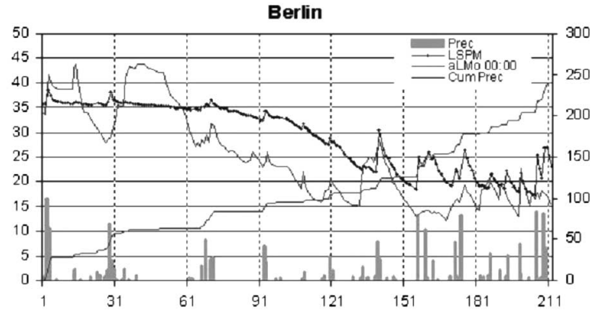

Fig. 4. – Same of fig. 3 but for Berlin.

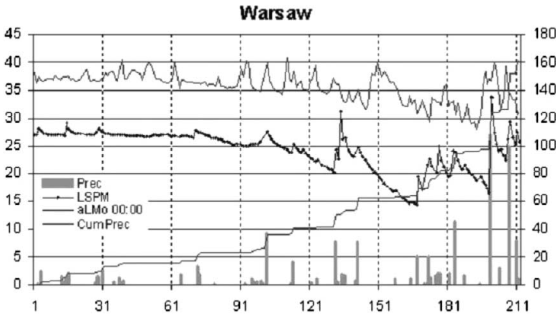

Fig. 5. – Same of fig. 3 but for Warsaw.

6. – Results

The intercomparison between the soil moisture values evaluated by LSPM (control run) and aLMo is reported for each station in figs. 3-6, together with the indication of the precipitation rate, useful to verify its impact on soil moisture. The statistical summary for both simulations (*control* and *aLMo-soil* run) is reported in table II.

In the station of Zurich (fig. 3), aLMo systematically overestimated LSPM. The overestimation was larger in the *aLMo-soil* run than in the *control* run, and in both runs was larger in winter 2002-3 and in April-May 2003. Both models showed a good behaviour during the precipitation events: the soil moisture peaks were almost concomitant. Instead, the discrepancy during winter 2002-3 was difficult to interpret. The values predicted by aLMo in the period October-December 2002 were too high for a wintertime period, as they approach the field capacity. If soil moisture equals the field capacity, the underground drainage should provoke a fast decreasing of the surface soil moisture, even if evapotranspiration is almost zero during wintertime. In addition, the possibility that the soil layer immediately underlying surface layer was frozen is difficult to verify. As reported in ref. [4], where several years of air and soil temperatures measured at Vercelli (Piedmont, North-West Italy) are presented, the first 26 cm of soil were never frozen even if screen-level temperature air was around −20°C, or if the monthly mean temperature was < 0°C. A possible explanation could be the presence, at the beginning of the simulation (October 1st, 2002), of a deep snow pack, which slowly melted in the following two months.

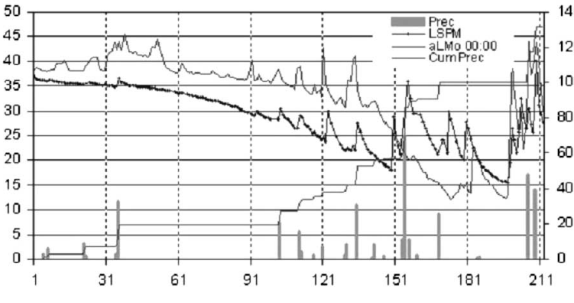

Fig. 6. – Same of fig. 3 but for Turin.

In the case of Berlin (fig. 4), the time trends of LSPM (control run) and aLMo are comparable (aLMo slightly underestimates LSPM in the *control* run, while in the *aLMo-soil* run, aLMo and LSPM almost equal), but also in Berlin, like in Zurich, there is an evident overestimation of aLMo in the period October-November 2002. In addition, sometimes, the soil moisture increment predicted by aLMo is larger than the quantity of water falling as precipitation (for instance, on 30 October, 2002).

In the station of Warsaw (fig. 5), the soil moisture predicted by aLMo systematically overestimated the values of LSPM (*aLMo-soil* run), even if the peaks were almost concomitant to the precipitation events. The aLMo soil moistures in the whole simulation period ranged in the interval 30–40 kg m^{-2}. Furthermore, the initialisation of the soil type as *sand*, according to the aLMo dataset, looked unreasonable, also because, for such kind of soil, a value of 40 kg m^{-2} for the soil moisture in the first 10 cm of soil was corresponding to the field capacity. It looked quite exceptional that, being the total precipitation of only 100 mm in the whole simulation period, soil moisture remained so close to the field capacity for 10 months. The ECOCLIMAP database prescribes for Warsaw a *clay loam* soil type (*loam* is certainly more capable to withhold moisture with respect to *sand*), and then the overestimation in the aLMo simulation *versus* the control run of LSPM was lower, but the mean difference was still 11 kg m^{-2}. Thus, the station of Warsaw had the worse agreement between the simulations.

In the station of Turin (fig. 6) the soil type of aLMo and ECOCLIMAP databases coincided (*clay loam* soil). Thus, the two simulations performed using LSPM were almost identical, and also did not differ too much from the aLMo simulation. Both models seem to answer well to precipitation episodes, except some cases in which aLMo soil moisture shows a peak in the absence of precipitation events (for example, in the period November 2002-January 2003). In particular, summer 2003 was recognized as really hot and dry by both models, and the soil moisture in the first layer of soil was constantly below the wilting point.

In conclusion, aLMo soil moisture seems to be in closer agreement with the one calculated by LSPM in the control run (*i.e.* when ECOCLIMAP was activated), except for the station of Berlin (in which, however, the difference between the two LSPM simulations is small). These results confirmed the fundamental importance of the acknowledgment of the ground and vegetation characteristics in order to evaluate the soil moisture.

7. – 2D maps on European territory

After the sensitivity experiments carried out in the four test stations, the next step was to run on the whole dataset, composed by the 902 synoptic stations (fig. 2). According to the previous experiment results, ECOCLIMAP was used to initialise soil and vegetation parameters. The simulation period was the same of the sensitivity experiments, *i.e.* from 1 October 2002 to 31 August 2003. After the simulation, a database containing all instant values of LSPM output variables was created. Each variable was subsequently weekly, monthly and tri-monthly averaged or cumulated, and displayed with the Cressman [7] interpolator (function *oacres*) of the graphic software *GrADS* (Grid Analysis and Display System). An example of these graphics is reported in figs. 7-10, in which soil temperature and moisture of the surface (10 cm) layer, and some components of the energy balance (sensible and latent heat fluxes), relative to the 2003 August, are displayed. The detailed analysis of the 2003 summer is out of the purposes of this paper (see for instance refs. [3] and [9]), but the main characteristics are here underlined.

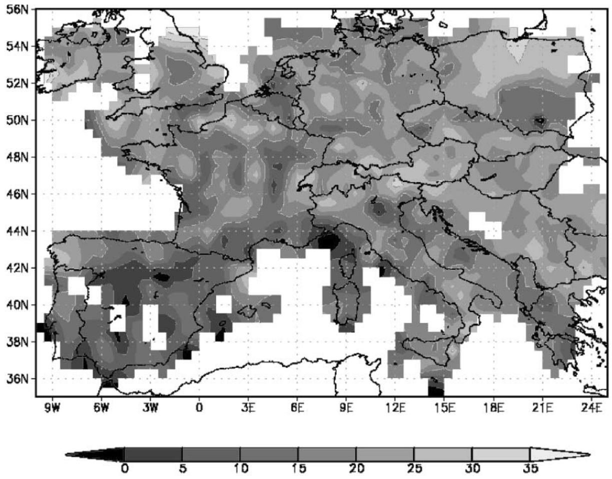

Fig. 7. – Surface (10 cm) soil moisture averaged during the month of August 2003, and expressed in kg m^{-2}. The values of all European synoptic stations shown in fig. 1 have been displayed using GraDS function "*oacres*".

Surface soil moisture (fig. 7) was unusually low (near or below the wilting point) over a great portion of the central and western European territory. This was perhaps due to the lack of precipitations in the spring and summer of 2003. Another evident feature was the presence of relatively high soil temperatures over the alpine area (fig. 8), in agreement with the observations of many updated records in the screen-level temperatures over the same area. The high temperatures and the low moistures in the soil were determinant factors for the partitioning of the net radiation, higher than normal, in sensible (fig. 9) and latent (fig. 10) heat fluxes. Particularly, the deficit in the soil moisture forced the latent heat flux to remain similar to (or sometimes to become lower than) its climatological

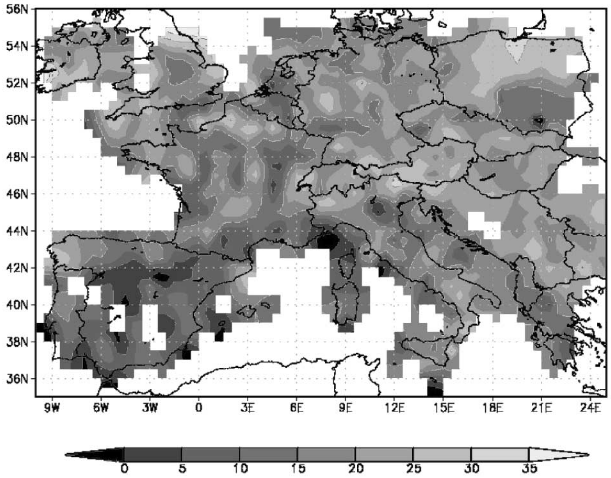

Fig. 8. – Same of fig. 7 but for the soil temperature, in °C.

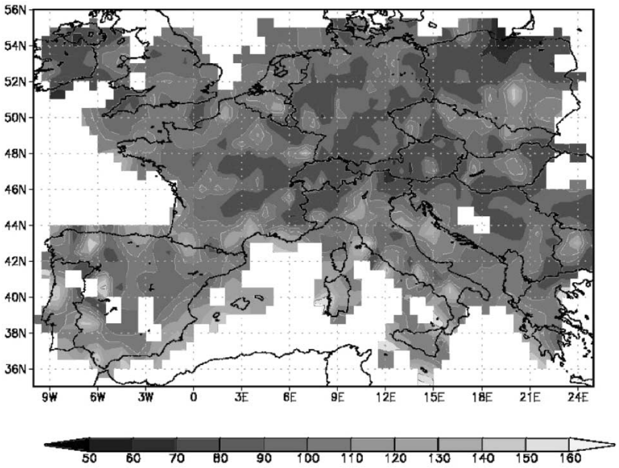

Fig. 9. – Same of fig. 7 but for the sensible heat flux, in W m^{-2}.

values. Thus, the sensible heat flux was larger and responsible for the lower atmosphere heating.

The confirmation of this interpretation can be seen in the map of the latent heat flux relative to the month of August 2003 (fig. 10). Over Piedmont and North-Western Italy, the values were of 40–50 W m^{-2}, with the exception of the areas covered by rice paddies and lakes, more humid than the adjacent zones, in which the latent heat flux peaked on 90 W m^{-2}, thus exceeding the sensible heat flux. The soil moisture in the first layer did not show a maximum in the same area, because of strong evaporation. As reported in refs. [3] and [4], in the above-mentioned areas, the screen-level temperature peaked 2–3°C less than the rest of Piedmont, confirming that, presumably, the evaporation from the humid zones (rice paddies, lakes) was a limiting factor for the daily thermal excursion.

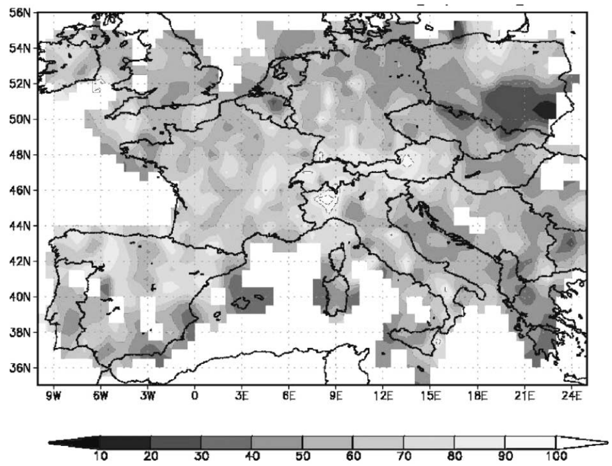

Fig. 10. – Same of fig. 7 but for the latent heat flux, in W m^{-2}.

This analysis could thus give a key for understanding the physical mechanisms which contributed to the growth and intensification of the heat wave of summer 2003. It was shown [9] that such episode only interested a limited portion of the world-wide territory, *i.e.* the central and Western Europe. Meteorologically, the summer trimester was characterised by an anomalous persistence of anticyclonic conditions over the area, in particular during the month of June and the first ten days of August, and it was preceded by insufficient rainfall conditions during spring. The insufficient soil moisture determined the weakening of the evapotranspiration. The combined effect of the anticyclonic conditions and low evapotranspiration strengthened the weakening of the cloudiness, provoking exceptionally high values of the sensible heat flux, which reflected in a heating of the low atmospheric layers and, in turn, depressed furthermore the evapotranspiration. This positive feedback was triggered by the persistence of the anticyclonic conditions, and persisted until the synoptic conditions were not favourable to its removal, *i.e.* until 12 August.

8. – Conclusions

In this paper, a preliminary method for the verification of soil moisture calculated by the mesoscale model LM was presented. This algorithm, instead of observations, used the output of a land surface model (the diagnostic model LSPM), operative at the Piedmont Regional Meteorological Service for simulations inherent to agrometeorology. LSPM was initialised by Synop observations, while the relative information of surface parameters (vegetation and soil) was taken from the global database ECOCLIMAP, at 1 km^2 of resolution. When LSPM was initialised with database the ECOCLIMAP, it was able to simulate the components of the energy and hydrologic budgets over Europe. The intercomparison with the values calculated by the limited area model aLMo version of the German "Lokal Modell", showed that, over the single stations, there were some significant discrepancies, due not only to the difference in the initialization of the surface parameters but also, more probably, to differences in the physical parameterisations. Further studies are thus necessary in order to better understand the causes of such differences. At the same time, it appears evident that the use of the database ECOCLIMAP for the initialisation of the surface parameters allows to create, through the use of LSPM, archives of data usually not measured (like temperature and moisture of soil and vegetation, and the components of the energy and hydrologic budgets), useful to validate limited area models or general circulation models. As example of application of this method, in the last section some considerations about some physical mechanisms which enhanced the exceptional and persistent heat wave of 2003 summer in Europe were presented.

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