

Mapping of *Alternaria* and *Pleospora* concentrations in Central Italy using meteorological forecast and neural network estimator

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Received: 21 December 2011 / Accepted: 16 May 2012
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Abstract Airborne particles (pollens and fungal spores) are recognized as important causes of allergies and many other pathologies whose main symptoms are usually associated with respiratory problems. In addition, these particles seem to be responsible for clinical symptoms of oculorhinitis and bronchial asthma. Many authors showed how pollen and spore concentrations are critically linked to meteorological conditions, while other studies investigated the possibility to estimate these concentrations through meteorological parameters. So, many different approaches have been proposed, and one of the most sophisticated is based on the use of a complex artificial neural network architecture. Once the neural device is calibrated using simultaneous time series of observed meteorological parameters and airborne biological

particles, it is straightforward to use the Neural Network to predict spore concentrations using operational Limited Area Meteorological Model. In a previous work, it has been shown that the MM5 meteorological model developed by National Center for Atmospheric Research and Pennsylvania State University can be coupled with the above-cited neural predictor to provide a good prediction of *Alternaria* and *Pleospora* spore in the location of L'Aquila (Central Italy). Following the same approach, this work aims to provide the mapping of spore concentration over a wide area covered by high-resolution meteorological prediction in Central Italy. The complex patterns of fungal spore concentrations in selected areas will be described, and the high temporal variability of such fields will be discussed as well. The possibility to infer useful information from the predicted pattern of spore concentrations is discussed, as an example it appears that for people suffering from allergy to fungal spores is more comfortable to spend summertime close to the east coast of Italian Peninsula respect to the west coast. A further step of this work may easily lead to an operational use of the model for supporting the clinical management of allergies and for establishing a preventive strategy in agriculture to avoid unsafe and useless pollution of atmosphere, crops and fields.

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Keywords Aerobiological monitoring · *Alternaria* ·
Artificial neural network · Fungal spores prediction ·
Pleospora

1 Introduction

Cultivated areas and natural vegetation constitute a paramount source of fungal spores and pollen grains. Agricultural operations are considered the most important sources of organic dusts and bio-aerosols in rural areas; the allergies conidial spores of the fungus are thought to be released from crops during harvesting, permitting fungal spores to disperse to the nearby areas (Abdel Hameed 2005).

In the last few years, the relationship between spore concentrations and meteorological variables has been recognized by several authors for different geographical domains. Mitakakis and Guest (2001) showed the presence of *Cladosporium* and *Alternaria* in Australian peaks in spring and summer and increased *Leptosphaeria* and *Ganoderma* air concentrations mainly toward summer and autumn. Hjelmroos (1993) and Giner and Carrión García (1995) recognized that no simple relationship can be established between single meteorological variables and fungal spores concentrations. More specifically, Burch and Levett (2002) demonstrated that increases in temperature, dew point and surface air pressure are strongly correlated with increases in spore concentrations, but no single predicted weather variable is correlated with the occurrence of spore plume. Stennett and Beggs (2004) correlated daily average, minimum and maximum temperature, dew point temperature and air pressure with *Alternaria* concentrations. Hollins et al. (2004) analyzed two different time series of *Cladosporium* conidia observed in England and Wales. Their results demonstrated that the number of days in summer when the *Cladosporium* spores are above the allergenic concentration is positively correlated with regional temperature and negatively correlated with precipitation for both sites over the study period. The link between climatic factors and the daily content of certain fungal spores in the atmosphere was studied by Sabariego et al. (2000). They found that *Alternaria* and *Cladosporium* are significantly correlated with temperature and hours of sunlight, while *Ustilago* shows positive correlation indices with relative humidity and negative indices with wind speed. Herrero et al. (1996) have shown a positive correlation between daily minimum temperature and *Cladosporium* spores concentration, while they are found a positive correlation with maximum temperature and a negative correlation with

precipitation for *Alternaria*. Grinn-Gofroń and Mika (2008) found that spore concentrations are positively correlated with the minimum temperature, for some spore types, they also found a significant correlation between concentrations, relative humidity and rain. Rodríguez-Rajo et al. (2005) concluded that the weather factor displaying the strongest positive correlation with mean daily spore counts was temperature. Oliveira et al. (2009) showed as the spring–autumn spores (*Coprinus*, *Didymella*, *Leptosphaeria* and *Pleospora*) exhibited negative correlations with temperature and positive correlations with both relative humidity and rainfall level; on the contrary, late spring–early summer spores (*Alternaria*, *Cladosporium*, *Epicoccum*, *Ganoderma*, *Stemphylium* and *Ustilago*) exhibited positive correlations with temperature and negative correlations with both relative humidity and rainfall level. Recio et al. (2011) demonstrated that weekly values of the atmospheric concentration of *Alternaria* spores can be predicted from the expected maximum temperature.

Recent publications are examining the impacts of climate change on aeroallergens and related allergic diseases. A review of such studies has been reported by Bernard et al. (2001) and Beggs (2009), and these authors also show evidences of increasing concentrations of *Alternaria* spores. An increasing long-term trend of *Alternaria* spore levels, probably linked to climate change, has been also reported by Corden et al. (2003). All these studies suggest that monitoring and forecasting spore concentrations will become increasingly important in the framework of climate change.

Besides the possibility to efficiently estimate the spore concentrations from meteorological variables, a possible important application could be the prediction of these concentrations from meteorological forecast. Diseases determined by fungi can cause economic losses, and so chemical treatments are applied depending on meteorological conditions or plant development stages (Staub 1991; Rodríguez-Rajo et al. 2005). In fact, an accurate forecasting spore concentrations over a wide geographical area could drive local authorities to limit the use of fungicide treatments in agricultural activities avoiding unsafe and useless pollution of atmosphere, crops and fields (Frenguelli 1998). These treatments are usually applied in fixed year time but, as stated above, the critical correlation between spore concentrations and meteorological conditions has been long recognized

by many authors. The major peaks of such concentrations are therefore reasonably expected to occur in different periods for different years depending on the specific meteorological condition especially during spring and summer seasons. In this paper, we will show in Sects. 3 and 4 as the timing of fungicide treatments in agricultural activities is critical to get effective results.

Understanding the fluctuations of spore concentrations in the clinical management of allergies may be important, too. Mari et al. (2003) show that 19 % of the allergic population reacted to at least one fungal extract by mean of the skin test. The sensitization to *Alternaria* in patient with respiratory allergy has been investigated by Gioulekas et al. (2004) observing a positive skin reaction to fungal spores for more than 30 % of asthmatic patients. A similar study was carried out by Bartra et al. (2009), and they find that patients sensitized to these fungal spores were affected more frequently by asthma. All these studies suggest that an accurate prediction of spore concentrations could be very important to the possibility to establish a preventive and appropriate strategy for allergy sufferers, encouraging, for example, the patients affected by oculorhinitis and bronchial asthma to spend the critical periods in locations where the spore concentration peaks are expected to be lower. As an example of possible application, we will demonstrate, in Sect. 3, as for people suffering of allergy is more comfortable to spend summertime close to the east coast of Italian Peninsula than on the west coast.

From these considerations, it is straightforward to develop applications allowing the prediction of the future spores concentration level from observed or predicted meteorological data. In the last few years, this possibility has been investigated by many authors. A first simple model for the fungal spores prediction was calibrated by Stephen et al. (1990), and they combined an estimated diurnal rhythm with a simple one-parameter time series model, providing a short-term forecast. More recently, an autoregressive approach has been adopted by Escuredo et al. (2011) to test three different models to optimal treatment timing on a potato crop. An approach based on the artificial neural network has been adopted by Astray et al. (2010) to predict the atmospheric *Alternaria* spore content in Northwest Spain, and a similar approach has also been used by Grinn-Gofroñ et al. (2011) to create forecasting models useful in the

prediction of aeroallergens. These authors demonstrated that the concentrations of *Cladosporium* and *Alternaria* spores can be predicted with quite good accuracy from meteorological conditions and air pollution recorded 3 days earlier.

This paper has a similar and, maybe, more ambitious aim than the above-cited ones, and it follows the preliminary phases in the development of the numerical model discussed in the papers of Angelosante Bruno et al. (2007) and Tomassetti et al. (2009). We show how the application of the neural approach on the same discrete grid of the meteorological model allows to retrieve the complete map of *Alternaria* and *Pleospora* spores concentrations in the geographical domain simulated by the meteorological model. Analysis of such maps is discussed showing how the combination of meteorological forecast and the neural predicting model allows to evidence the high spatial and temporal variability of spore concentrations.

The paper is organized as follows: in the next section, a short resume of the predicting numerical model is given including a quick description of MM5 meteorological model and a description of complex Neural Network approach adopted to predict the fungal spores; a short synthesis about results of the previous works is also reported in this section. In the third section, the predicted spatial and temporal distributions of *Alternaria* and *Pleospora* spore concentrations are illustrated and extensively discussed. In the final section, we stress how the reported maps may represent a first indication for allergy sufferers and also how the maps discussed in Sect. 3 may be useful to carry out rational fungicide treatments in agriculture.

2 Materials and methods

2.1 The numerical model for fungal spore prediction

The previous works of Angelosante Bruno et al. (2007) and Tomassetti et al. (2009) showed that the *Alternaria* and *Pleospora* spores concentration can be estimated from observed meteorological variables using a complex recurrent neural network model. Once the neural network model has been calibrated using observed meteorological variables and the corresponding observed spores concentrations, the

neural model can be forced using predicted meteorological conditions to estimate the future concentrations of spores. In this section, we quickly recall the basic description of the predicting numerical model built by coupling neural fungal spore estimators and MM5 meteorological model. A more complete description of the model and its validation can be found in the cited references.

Angelosante Bruno et al. (2007) showed that a recurrent artificial neural network (ANN hereafter) architecture can be trained to map the complex relationship between meteorological condition and spore concentrations. The neural architecture used for this purpose is usually referred to as Elman recurrent Network (Elman 1990) and is schematically shown in Fig. 1.

The input layer is set with the values of daily minimum, maximum and average temperature, the total accumulated precipitation, the daily average for relative humidity and wind speed. It is also assumed that the spore concentrations depend on other heterogeneous seasonal factors and, in order to take into account those factor, a sinusoidal function of julian day is also considered (Daylight in Fig. 1). The number of neurons in the hidden layer is established with the constraint that the total number of weights of the network must be one order of magnitude lower

with respect to the number of training patterns used to calibrate the network. This condition is usually adopted to avoid problems of overtraining with respect to the simple multi-layer perceptron (for a more general reference, see Hecht-Nielsen 1991); in order to provide ANN input layer with homogeneous information, the input variables are normalized using a linear function of maximum and minimum values, more specifically, each of the input variable V listed in Fig. 1 is normalized according to:

$$V_N = \frac{(V - V_{\min})}{V_{\max} - V_{\min}}$$

being $V_{\min}$ and $V_{\max}$ respectively the minimum and maximum observed value for the variable V in the whole time series; the value V_N is actually used to set the neuron in the input ANN layer, and it corresponds to 0 when V assumes its minimum value and 1 when V assumes its maximum value. The recurrent ANN architecture (Elman 1990) allows to implement a sort of dynamical memory and then, in our application, the concentration of fungal spore is not simply determined by the input pattern in a single day, but by a temporal sequence of meteorological patterns. To train the neural device, a modified version of Jetnet package (Lombladd et al. 1992) has been used, with respect to the original version of the package discussed by Lombladd et al. (1992), and the possibility to use the recurrent neural architectures has been implemented. Angelosante Bruno et al. (2007) showed as such architecture is able to estimate with high accuracy the concentrations of *Alternaria* and *Pleospora* from the meteorological variables.

Spore concentrations and meteorological variable measurements were recorded in L'Aquila (Italy) from January to October 2004. L'Aquila is located in Central Italy at latitude 42.355°N and longitude 13.395°E, and at about 700 m above sea level. The site is inland and situated at the southwest foothills of the Gran Sasso peak (2,912 m a.s.l.). The landscape is made up of oak wood (*Quercus pubescens*), pine wood (*Pinus nigra*) and a community of pastures. Typical communities along the rivers are willows (*Salix* sp.) and poplars (*Populus* sp.). Invasive plants are present in the surroundings in the whole region of Central Italy, especially in the uncultivated fields, road, path margins and dumps. For the application discussed below, it is important to notice that similar vegetation

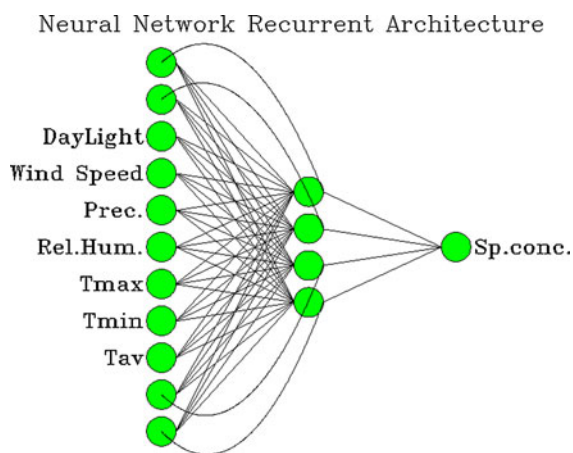


Fig. 1 Schematic view of recurrent neural network used for fungal spore prediction and estimation, input variables are daylight, daily minimum ($T_{\min}$), maximum ($T_{\max}$) and average temperature (T_{av}), the total accumulated precipitation (P_{rec}) and the daily average for relative humidity ($Rel.Hum$) and wind speed. The output variable ($Sp.conc.$) is the spore concentration

scenarios can be found in the whole geographical domain selected for spore concentration mapping (see Fig. 3 and related discussion), except for the areas very close to the east coast and the areas around Rome (42.89°N–12.48°E) that are strongly urbanized.

The time series of spore concentrations used for the calibration of the model has been collected using a Lanzoni VPPS 2000 Hirst volumetric sampler (Hirst 1952) that was installed 20 m above ground level. Melinex tape impregnated with a 2 % silicon solution was used as trapping surface. Average daily spore concentration estimations (spores/m⁻³) were carried out from January to October 2004: the spores were identified under a Leica light microscope at 4,000× magnification on the basis of morphological characteristics; the counting procedure of the conidia followed the model proposed by Mandrioli et al. (1998). The concentration of *Alternaria* spores is observed to increase from early April with the maximum peaks (around 80 m⁻³) occurring during the summer months, while the maximum concentration of *Pleospora* spores (about 40 m⁻³) occurred during April, with only a few spikes observed during summer months. The meteorological data needed for the training of the ANN were provided by Cetemps Center of Excellence of University of L'Aquila, the set of data includes observations, at hourly time step, of temperature, wind speed, precipitation, air-relative humidity. To make these data suitable for the calibration of the model, the daily average has been calculated for each variable and, for temperature time series, the maximum and minimum for each day are also considered.

The statistical analysis of ANN performances reported by Angelosante Bruno et al. (2007) showed the ability of the proposed technique to provide an excellent estimation of *Alternaria* spores with an average error of about 4 m⁻³ and also better performances for what concerns the estimation of *Pleospora* concentration.

Tomassetti et al. (2009) investigated the possibility to use the trained ANN to predict the future spore concentration from the meteorological forecast. In order to validate this hypothesis, the authors analyzed the performances of the neural model for the period from January to October 2004 using, as input, the daily average meteorological parameters predicted by a meteorological model instead of the observed meteorological variables.

The meteorological model used in this work is the non-hydrostatic version of the NCAR/Pennsylvania State University Mesoscale Model MM5 (Dudhia 1993). A complete description of the model is beyond the scope of the present paper, and a complete reference is given in Grell et al. (1994). The configuration adopted for the operational activities in Central Italy uses 24 unevenly spaced σ levels. All the simulations are driven by the ECMWF (European Centre for Medium-range Weather Forecast) global analyses; forecast and boundary conditions are upgraded every 6 h, and no data assimilation is done during the operational runs. Figure 2 shows the model triple nested domain used in the experiments. The outer domain covers Italy and the surrounding regions at a grid interval of 27 km; the intermediate domain covers Central Italy at a 9-km grid interval, while the innermost domain encompasses the Abruzzo region at a 3-km grid interval.

The different domains are nested in a two-way mode, as described, for example, by Zhang et al. (1986). The MM5 model in the above-described configuration is used for operational forecasts (Palolucci et al. (1999), Kain and Fritsch (1990) and Troen and Mahrt (1986)). MM5 performance in reproducing thermally driven circulation in a region of complex topography with different planetary boundary layer (PBL) parameterizations has been investigated by Bianco et al. (2006), while Tomassetti et al. (2003)

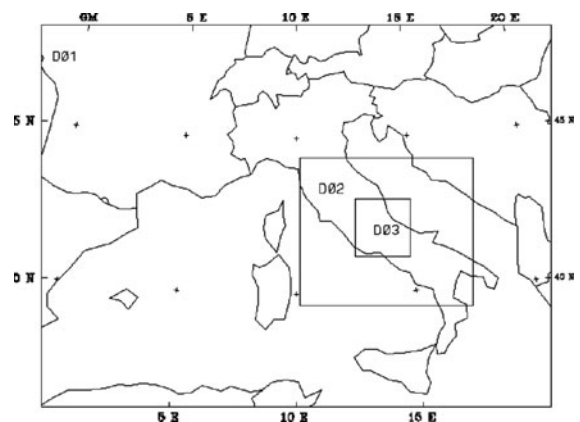


Fig. 2 Schematic view of three nested domains used for operational meteorological forecast in Abruzzo region with MM5 mesoscale model. The outer domain covers Italy and the surrounding regions at a grid interval of 27 km; the intermediate domain covers central Italy at a 9-km grid interval, while the innermost domain encompasses the Abruzzo region at 3-km horizontal resolution

demonstrated the ability of the model to efficiently simulate the effects of land-use change on the hydro-meteorological cycle in the same Abruzzo Region whose simulation is used in the present paper. Every day the first 24-h of a 72-h operational simulation, the main meteorological fields at ground level are archived at hourly time step, and such archive is used for the fungal spores mapping discussed in the next sections.

The validation of main ground-level meteorological parameters used as input of the neural model has been reported in Tomassetti et al. (2009) where the differences in the observed and predicted time series have been analyzed. We have resumed here the main results showed in the cited work: the sequence of minimum temperature is quite well reproduced by the model, while the daily maximum is lightly underestimated with respect to observed values. In fact, the bias is negligible for minimum temperature, and it is found to be -2.5°C for maximum temperature, the root mean square error (RMSE hereafter) is found to be around 3°C for both the minimum and maximum temperature time series while the correlation coefficient is over 90 %. The average temperature variability is well reproduced by the meteorological model with a small underestimation around 1.5°C , the RMSE is around 2°C and correlation is above 97 %. The meteorological prediction of relative humidity is affected by a systematic error of about 5 %, while the correlation is around 50 % and the RMSE is 14.2 %. Nevertheless, also for this field, the seasonal variability is reasonably well reproduced, and the occurrence of the seasonal major peaks is also well captured. The bias for the rainfall time series is negligible (less than 1 mm/day), while the RMSE is 4.3 mm/day. For ground wind speed, the bias is about 1.5 m/s and the RMSE is 3.0 m/s. For relative humidity, wind speed and daily precipitation, the correlation coefficients between observed and predicted time series are around 50 %.

Tomassetti et al. (2009) also showed that predicted meteorological time series can be used to estimate with a reasonable level of accuracy the concentration of *Alternaria* and *Pleospora* fungal spores; for each considered time series, the BIAS is always negligible (no systematic errors occur in the predictions), while the RMSE was always small if compared with the intrinsic variability of concentrations, more specifically the RMSE was around 3.5 for both the considered fungal spores carrying out a prediction 5 days in advance.

All these results lead to the possibility to predict the spatial distribution of *Alternaria* and *Pleospora* fungal spores in the whole geographical domain simulated by the meteorological model. Although the calibration of the model has been carried out using a time series of observations obtained in a single location, we expect that the neural device gives reasonable results in the selected domain because the genus *Alternaria* and *Pleospora* comprising species that are ubiquitous cosmopolitan. *Alternaria* (*Deuteromycetes*), occurring in soil, air and even in aquatic habitats, being maximum in air because of its occurrence as saprophytes as well as leaf spot parasites on various crops (Srivastava and Wadhwani 1992). *Pleospora* is a genus of ascomycete fungi, ascospores are mostly found on leaves and stems of herbaceous plants, while a few species are found on trees (Hanlin 1990). Therefore, in the topographic region examined, we expect that the differences in vegetation covers and land use patterns does not significantly affect the distribution of the spores.

In the next sections, we will discuss the results obtained for the two different considered fungal spores. The predictions are carried out using the meteorological fields predicted by MM5 model in the innermost domain of Fig. 2; such geographical domain, shown in Fig. 3, covers a large part of Central Italy between Adriatic (east) and Tyrrhenian (west) seas, including the whole Lazio and Abruzzo Regions; the false colors of Fig. 3 correspond to different heights on sea level ranging from zero up to more than 2,000 m for the two major peaks located in the Abruzzo Region; only a small portion, the area is covered by mountains, in fact more than 50 % of the selected geographical domain is characterized by a height above seal level ranging from 300 to 1,000 meters and more than 30 % of territory is situated between 0 and 300 m above sea level. Land-use information can be deduced from United States Geological Survey (USGS) Global database, the same database adopted by MM5 model, details can be found in Grell et al. (1994); most of the area shown in Fig. 3 is characterized by dryland crops (about 50 %) and irrigated crops (20 %), forests and crop-wood mosaic cover the rest of area while only a small portion of the selected geographical domain is strongly urbanized.

The annual trend of main meteorological variables affecting the concentration of spore has been analyzed for the geographical domain selected for this study. The portion of Central Italy shown in Fig. 3 is

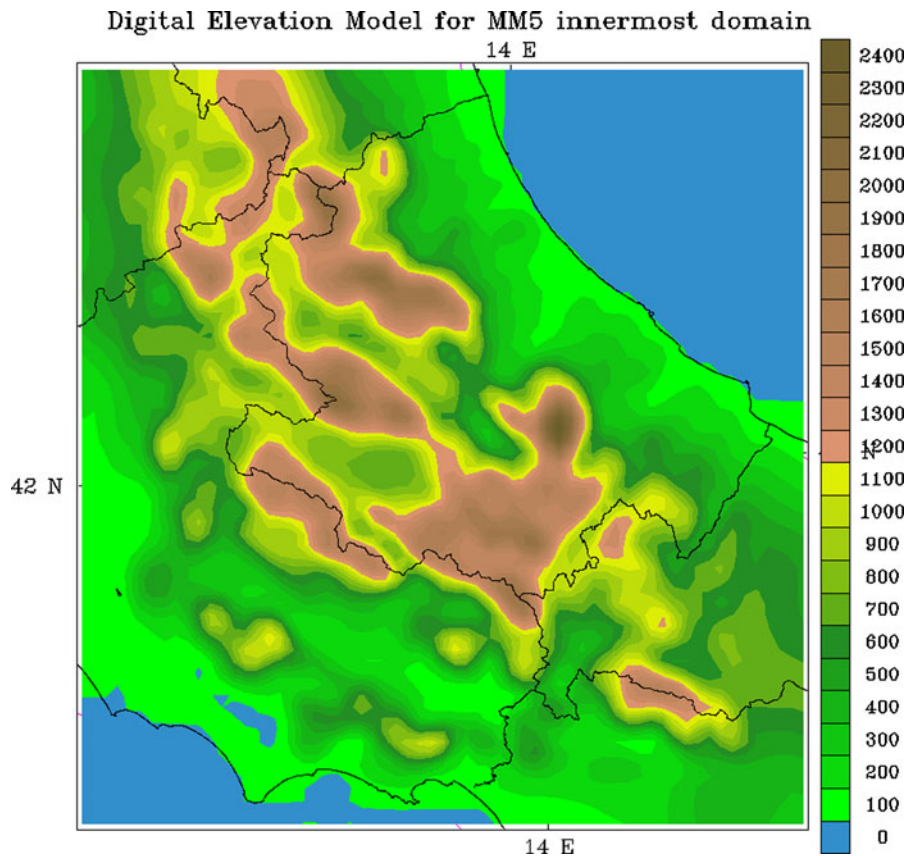


Fig. 3 The digital elevation model for the innermost geographical domain of MM5 meteorological model, the domain covers a large part of Central Italy between Adriatic (east) and Tyrrhenian (west) seas including the whole Lazio and Abruzzo

Regions; the false colors correspond to different heights on sea level ranging from zero up to more than 2,000 m for the major peaks located in the Abruzzo Region. *Black lines* refer to administrative boundaries of Italian regions

characterized by daily average temperatures ranging from 4 to 10 °C during winter months to 18–22 °C; during summer months. The major peaks of precipitation are observed during fall months with average value around 0.5 cm/day during October and November; summer months are characterized by weak precipitation with the average value around 0.2 cm/day, and intermediate situation is observed during wintertime. Average ground-level air-relative humidity reaches a maximum around 85 % during wintertime and a minimum around 70 % during summer months. No significant changes in the average ground wind speed are observed during the year cycle, average values are always around 3 m/s. All these climatological data are obtained analyzing the file of daily meteorological forecast for the last 15 years.

Black lines are also reported in the Fig. 3 showing the administrative boundaries of Italian regions. For

the discussion of the next sections, it has to be known that the Lazio Region is located in the western side of the map, and it is characterized by an almost flat territory, while a more complex orography is observed in the Abruzzo Region located in the eastern part of the geographical domain.

3 Results and discussion

3.1 Spatial and temporal distribution of *Alternaria* spores in Central Italy during the 2004 year

The archive of meteorological forecast carried out with MM5 model discussed in the previous section has been used to produce maps of *Alternaria* and *Pleospora* spores daily concentrations for year 2004 in the

whole geographical domain simulated by the meteorological model.

Meteorological variables are predicted by MM5 model in a regular equally spaced horizontal grid of 67×64 cells, the resolution of the grid is 3 km, the geographical domain simulated in the meteorological forecast is represented in Fig. 3. For each grid point, we extract from the archive the sequences of daily minimum, maximum and average temperature, the daily average wind speed, daily average relative humidity and the daily accumulated precipitation. Such sequences of daily meteorological parameters are then used as input for the neural network-based model described in the previous section to obtain the sequence of prediction of *Alternaria* spore concentrations. The same process is then re-iterated over all the grid points of MM5 domain to obtain a complete set of spores maps, the whole set of calculated data corresponds to $67 \times 64 \times 365$ estimations.

These data can now be plotted representing the daily predicted distribution of *Alternaria* spores; in this paper, we limit the analysis to a single year (2004), in fact, it has to be recalled that the calibration of the neural estimator (Angelosante Bruno et al. 2007) has been carried out using observed data collected in a single location (L'Aquila, 42.355°N, 13.395°E). We then assume that the observed meteorological sequences used to calibrate the neural device are actually representative of the meteorological variability within the whole geographical domain of Central Italy considered here, but only for the selected year.

Detailed analysis of maps obtained with above-described procedure shows high spatial and temporal variability of *Alternaria* concentration; according to observed time series (Angelosante Bruno et al. 2007), main peaks of concentrations during summertime and especially during the first half of August are observed.

A significant sequence of maps of Fig. 4, where we report the estimated concentration of *Alternaria* spores from August, 4 to August, 7 2004. For this Figure, and for Figs. 5, 7 and 8 as well, the different color indicates a different level of spores concentrations, the higher concentrations (red color) are around 80 spores/m³ for *Alternaria* and 40 spores/m³ for the *Pleospora* whose results are discussed in the next section.

From Fig. 4, we see that a further indirect validation of the neural-forecast spore estimator is that the major peaks of *Alternaria* concentration are predicted

in adjacent areas, in other words, similar meteorological conditions lead to similar *Alternaria* spore concentrations. The sequence of maps also shows the high temporal variability of the concentration (in fact, this is also evident from the observed time series discussed by Angelosante Bruno et al. 2007). In the first 2 days of this sequence, the concentrations are close to zero or negligible while a rapid increase of such concentrations occurs in the two next days when peaks of 80 spores/m³ are observed in significant parts of the selected geographical domain.

No simple relationship seems to exist between the increasing of *Alternaria* concentrations and the orography, since a comparison between Fig. 3 and the last two panels of Fig. 4 leads to conclude that the major peaks of *Alternaria* concentrations are located in the mountainous zones of Abruzzo during August 6 while these peaks moved westward toward the area of lower altitude in the following day. Nevertheless, the higher peaks of concentration of *Alternaria* appear to occur with higher frequency in flat zones than in mountainous areas, as an example from the sequence shown in Fig. 5, we observe a rapid growth of concentrations in the flat zone of Lazio region, while such concentrations appear negligible in the most part of Abruzzo Region. From the maps reported in Figs. 4 and 5, we also deduce that a rapid depletion of spores concentration seems to occur with a time lag of a day, as it is clear comparing the last panel of Fig. 4 (August 7), with the first panel of Fig. 5 (August 8). Panels of Figs. 4 and 5 also show that concentrations are always around maximum (70–80 spores/m³) or minimum values (0–15 spores/m³), no significant zones of the domain are characterized by intermediate concentration around 50 spores/m³.

The results shown in Figs. 4 and 5 have been resumed in Table 1 where the percentage of the selected domain characterized by level of concentration above different threshold values is reported for each day considered in the cited figures; such percentage has been calculated considering only the inland grid points of domain. During the selected days, the percentage of spore concentration always remains above the minimum threshold of 10 spores/m³ in a significant part of the domain, while higher-level peaks are observed in a wide area only for 2–3 days.

Maps shown in Figs. 4 and 5 have also been produced for every day of year 2004. A systematic analysis of these maps allows to conclude that major

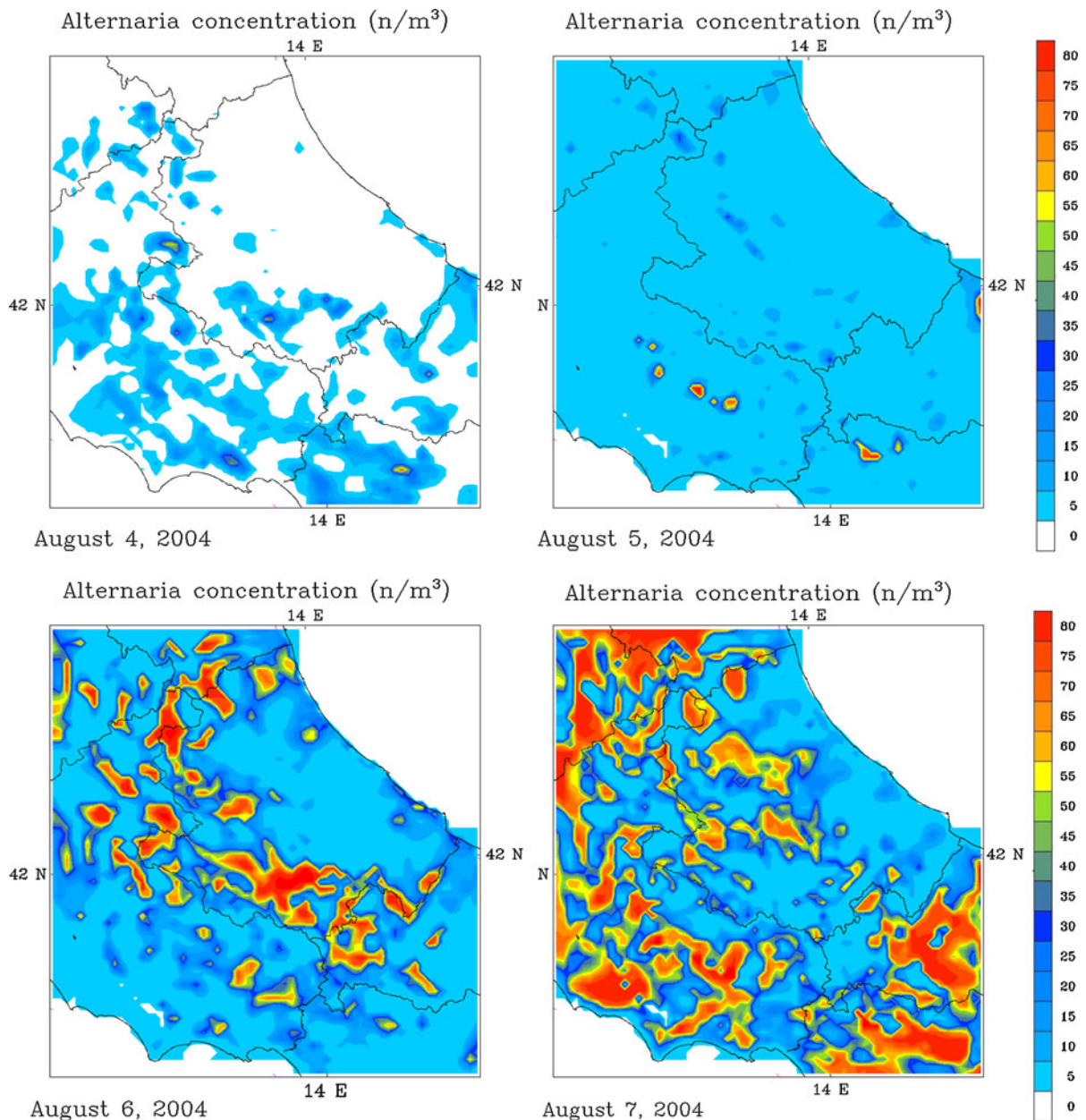


Fig. 4 Distribution of *Alternaria* spores as predicted by neural network model forced with meteorological forecast maps. The spatial distributions are shown for the days from August 4 to August 7, 2004

peaks of *Alternaria* are mainly observed during the first period of August, while the concentrations are never greater than 40–50 spores/m³ during the rest of the year, more specifically such concentrations appear to be negligible until the end of May, and the average values are below 20 spores/m³ during June, July and September.

In order to provide more suitable information for establishing a preventive strategy for allergy sufferers, it could be important to establish a detailed statistic about the frequency of events characterized by high concentration values. To this aim, we defined three different threshold values, and we calculated the number of days characterized by a concentration of

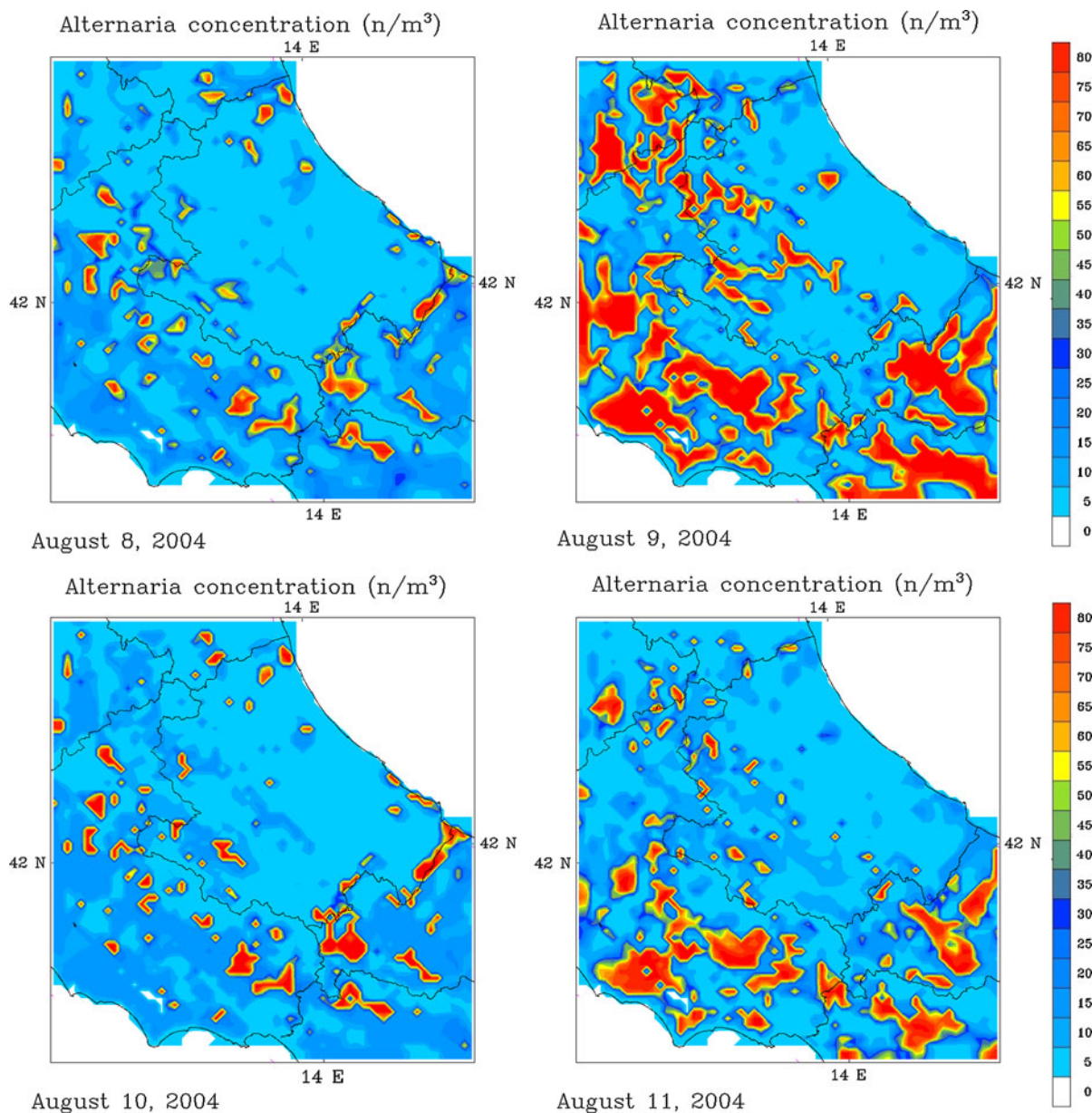


Fig. 5 Same as Fig. 4, but in this case, the sequence between August 8 and August 11, 2004 is shown

Alternaria greater than such threshold for each grid point of the domain. According to the concentration calculated for the maps above discussed, these thresholds are 20, 30 and 40 spores/m³. The results are summarized in Fig. 6.

Panels of Fig. 6 report the map of percentage of days in 1 year characterized by an average concentration of *Alternaria* spores greater than 20 spores/m³ (left panel), 30 spores/m³ (central panel) and 40 spores/m³ (right

panel). A first evidence is that the choice of threshold does not significantly change the maps while the events characterized by high spores concentrations appear to be more localized in the flat areas of Lazio and more specifically (see also Fig. 3) in the flat internal zone. From this analysis, it is also evident that areas closer to the east coast of Italian peninsula are not significantly affected by persistent events characterized by high *Alternaria* spores concentration. A first general

Table 1 Percentage of territory having concentrations of *Alternaria* spore greater than various threshold, the percentages are calculated from the maps shown in Figs. 4 and 5

Days	Thresholds (N/m ³)			
	10	20	40	50
August 4	7	1	0	0
August 5	2	1	1	0
August 6	30	21	12	10
August 7	50	40	29	23
August 8	24	10	7	5
August 9	38	28	24	22
August 10	30	7	6	6
August 11	27	17	13	12

It is evident the high temporal variability of the concentrations

conclusion of the analysis discussed in this section is that for people sensitized to fungal spores is more comfortable to spend summertime close to the east coast of Italian Peninsula respect to the west coast.

3.2 Spatial and temporal distribution of *Pleospora* spores in Central Italy during the 2004 year

The same analysis described in the previous section for *Alternaria* has been carried out for *Pleospora* spores. The numerical approach is absolutely the same with the only difference that the neural estimator is

different because it was calibrated to predict *Pleospora* instead of *Alternaria* spores.

In this case, the analysis carried out for the whole year 2004 year shows the highest concentration during the first half of April, and the first occurrence of high concentrations is represented in the panels of Fig. 7 where the maps of spatial distribution are shown for the days from March 30 to April 2, 2004. Also in this case, the spore concentrations rapidly increase within 1 day between March 30 and March 31, but a first difference with respect to the evolution of *Alternaria* spores is that highest values of concentration last for few days. Areas covered by the highest peaks appear to be more homogeneous, and they cover most of the considered geographical domain. For the *Pleospora* spores, the occurrence of high concentration seems to show a closer relationship with the orography of geographical domain. It can be recognized, as an example, as zone with higher altitude (compare maps of Fig. 7 with the Digital Elevation Model shown in the Fig. 3) is not significantly affected by high value of concentration, on the contrary in the area closer to the sea *Pleospora* concentrations remains around the maximum value for many days.

Figure 8 reports the sequence of concentration maps from April 3 to April 6 2004, as for the *Alternaria* spores, *Pleospora* spores are rapidly depleted in a large area within 1 day. Similar considerations emerge carrying out a detailed analysis for all the days of the year. A first conclusion is that also

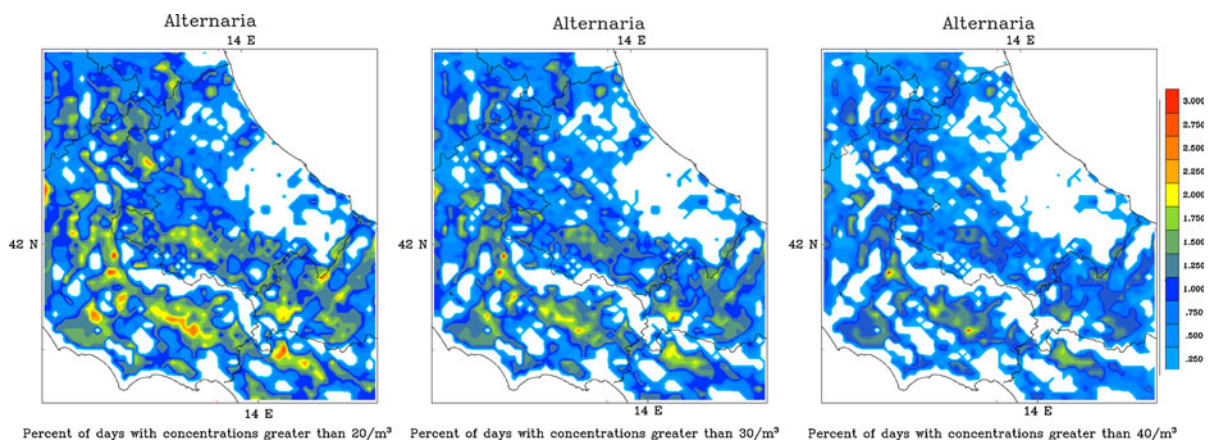


Fig. 6 The panel shows the percentage of days in 1 year having a concentration of *Alternaria* spores greater than 20 spores/m³ (left panel), 30 spores/m³ (central panel) and 40 spores/m³ (right panel). The red color corresponds to a percentage around 3, namely about 10 days in a year with concentrations greater

than the threshold, green spots correspond to the areas where we expect about 6 days with concentration greater than the threshold; finally blue tones correspond to areas where the frequency of high spore concentrations appears to be negligible (1 or 2 days in 1 year)

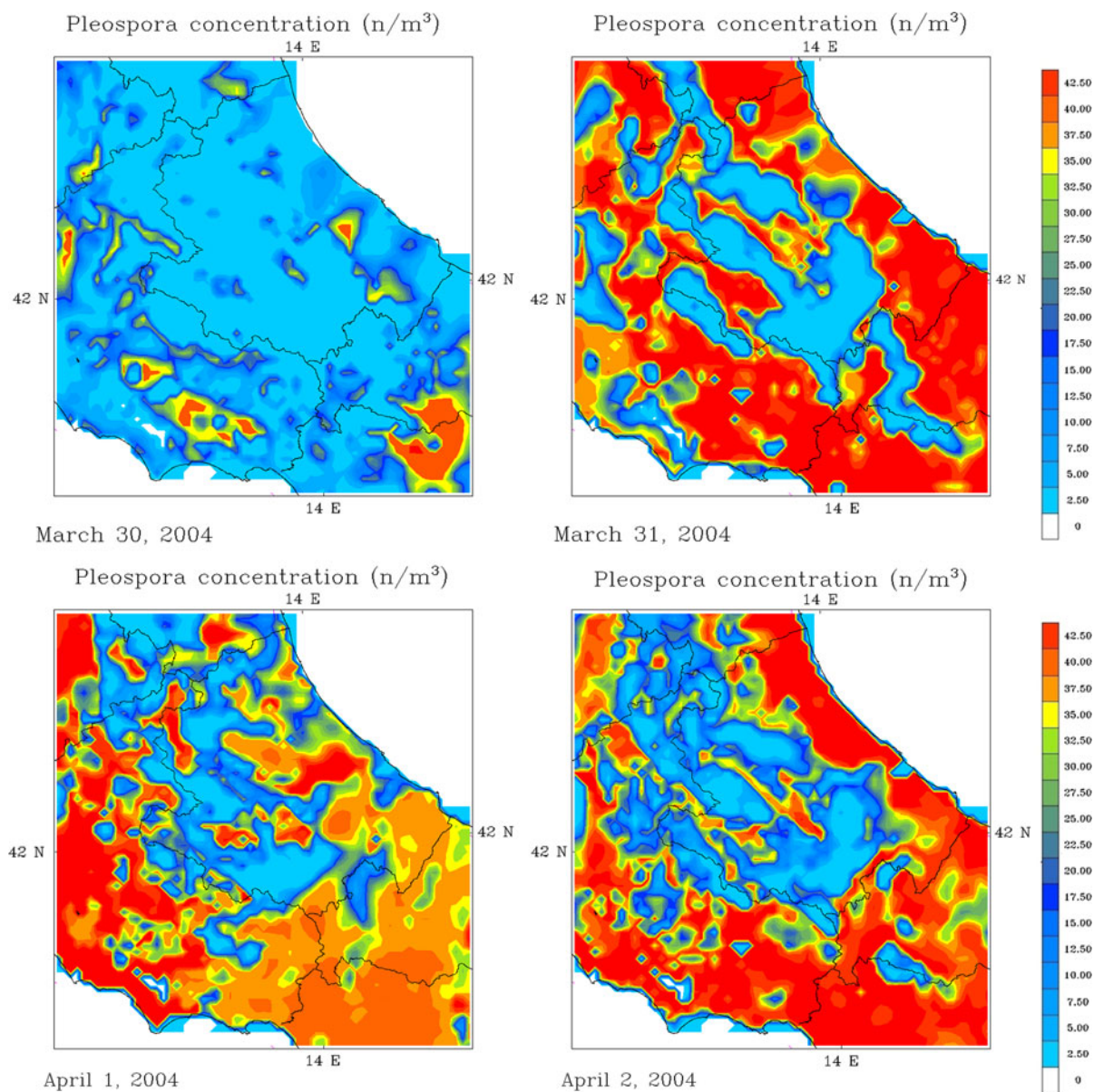


Fig. 7 Distribution of *Pleospora* spores concentration as predicted by neural network model forced with meteorological forecast maps. The spatial distribution is shown for the days from March 30 until April 2, 2004

Pleospora is characterized by a strong temporal variability while the spatial distribution appears more homogeneous with respect to the *Alternaria* spores distribution. Nevertheless, the highest peak of concentration of the *Pleospora* occurs more frequently in areas close to coasts.

Also for the *Pleospora* spores, the results shown in Figs. 7 and 8 have been resumed in Table 2 where the percentage of the selected domain characterized by

level of concentration above different threshold values is reported for each day considered in the cited figures; the table shows that for 6 consecutive days with a significant part of the domain (10–36 %) affected by high concentrations of *Pleospora* spores.

Maps reported in Figs. 7 and 8 have also been produced of each day of the year 2004; an overall analysis of such maps allows to conclude that highest peaks of concentration are reached in a wide area

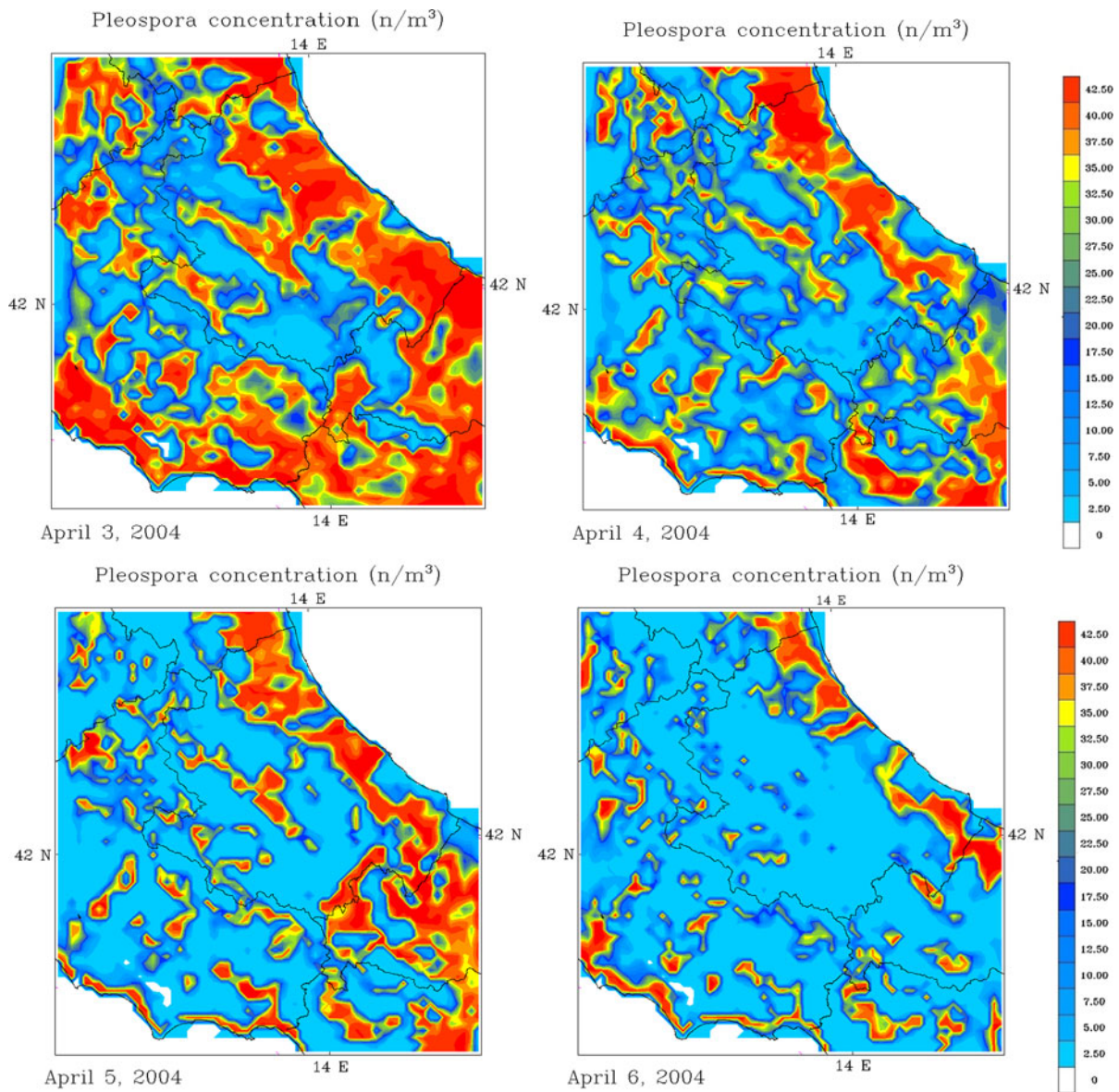


Fig. 8 Same as Fig. 7 but for the days from April 3 to April 6, 2004

during the months of March and April, while similar peaks of concentrations are observed only in limited areas during the months of January, February and May. The same concentration also appears limited to values around 10–15 spores/m³ during the month of September.

Also for *Pleospora* we calculated the annual probability to have concentration greater than different thresholds and results are reported in Fig. 9 where panels refer to the map of the probability to have daily

average concentrations greater than 20, 30 and 40 spores/m³, respectively. An overview of such maps clearly indicates a significant lower probability to have higher concentration in internal areas with respect to areas closer to the coast. Moreover, it results that, in the considered geographical domain, about 20 % of days in a year are characterized by serious (40 spores/m³) level of *Pleospora* concentrations, while the probability to have high concentrations of *Alternaria* has been found to be only around 3 % and in a limited

Table 2 Percentage of territory having concentrations of *Pleospora* spore greater than various threshold, the percentages are calculated from the maps shown in Figs. 7 and 8

Days	Thresholds (N/m ³)			
	10	20	30	40
March 30	20	12	7	0
March 31	61	56	51	36
April 1	66	59	50	15
April 2	63	54	46	30
April 3	58	50	42	22
April 4	46	36	25	10
April 5	35	30	25	13
April 6	23	18	13	6

High concentration (40 spores/m³) of *Pleospora* affects more than 10 % of the selected domain for all the considered days except for March 31

area of the considered geographical domain (see Fig. 6 and related discussion).

As quickly mentioned above, in this paper, we limited the analysis to a small region of Central Italy; within this region, it is reasonable to consider that the relationship occurring between spore concentration and meteorological variables remains the same. However, fungi are cosmopolitan, but the spore concentration may vary over different areas depending on weather conditions but also on vegetation type and geographical region, as a consequence, we expect that the same neural approach discussed in this paper can be applied to any geographical domain after a recalibration of the neural device allowing to take

into account the specific characteristics of such region; such recalibration can be easily carried out using local spores and meteorological observed time series, the process of recalibration can be done with the same software developed for the application discussed in this paper; the source software will be provided from the author for any no-profit application.

4 Conclusion

A neural device was calibrated with observed time series of spores concentrations and meteorological variables; in this work, we showed the possibility to use the neural model to predict the spatial distribution of *Alternaria* and *Pleospora* spore concentrations from the map of meteorological variables predicted by a meteorological model. In this preliminary study, the data for the whole year 2004 have been analyzed; specific maps of spatial distribution have been produced for the days corresponding to the highest peak of *Alternaria* and *Pleospora* spore concentrations.

The systematic analysis of time series of the map concentration allowed to locate areas that are more subject to high value of *Alternaria* and *Pleospora* concentration and to point out the high spatial and temporal variability of both fungal spores.

Such high variability suggests a possible operational use of the numerical model described in this paper for establishing an adequate strategy for appropriate use of fungicide treatments in agriculture avoiding unsafe and useless pollution of atmosphere,

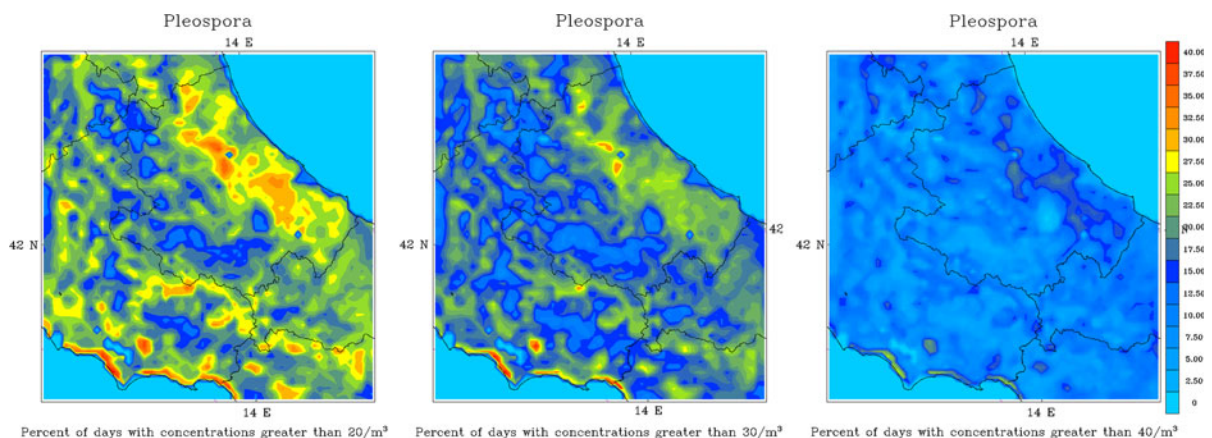


Fig. 9 The panel shows the percentage of days in 1 year having a concentration of *Pleospora* spores greater than 20 spores/m³ (left panel), 30 spores/m³ (central panel) and 40 spores/m³ (right panel)

crops and fields. At the same time, an operational preventive strategy leads to seriously limited costs of treatments and agricultural losses. As an example, a treatment of the crops appears totally ineffective if carried out on April, 5 2004 (see Fig. 8 and related discussion); on the contrary, the same treatment could have led to effective results if it had been carried out just a few days in advance. At the present time, the sophisticated meteorological models and the increasing computing power offer a robust platform to predict with few days in advance the main meteorological parameters with a good accuracy and, therefore, the operational use of the neural model described in the present paper appears straightforward.

Understanding the fluctuations of spore concentrations may be also of value in the clinical management of allergies. An operational use of the neural model described in this paper will lead to the possibility to establish a preventive and appropriate strategy for allergy sufferers, encouraging, for example, the patients affected by oculorhinitis and bronchial asthma to spend the critical periods in locations where the spore concentration peaks are expected to be lower. As an example of possible application, we demonstrated in Sect. 3 that to spend summertime close to the eastern coast of Italian Peninsula is more comfortable for people sensitized to fungal spores.

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