Fog in the Po valley: some meteo-climatic aspects

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FOG IN THE PO VALLEY: SOME METEO-CLIMATIC ASPECTS

NEBBIA IN VAL PADANA: ALCUNI ASPETTI METEOCLIMATICI

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Abstract
Fog is an relevant meteorological phenomenon with important effects in transportation, human health and agriculture. A phenomenological description with a review of the mechanisms of onset and evo-lution of fog was presented and associated with some climatological data referred to the plain of the Po valley. The decrease of the frequency and persistence of fog in the 20 last years was also discussed and associated with determinants at macroscale (changes in circulation) and microscale (changes in lad use). The effect of fog on vegetation was also discussed.

Keywords: fog climatology, land use, weather types, dew.

Riassunto
La nebbia è un fenomeno meteorologico con effetti di rilevo sui trasporti, la sanità e la stessa agricoltu-ra. Una descrizione della fenomenologia di questa meteora è presentata assieme ad una review sui meccanismi di genesi ed evoluzione del fenomeno. Dati sulla climatologia della nebbia in area padana sono altresì presentati e discussi. Il decremento della frequenza e persistenza della nebbia in ambito padano registrato negli ultimi 20 anni è presentato e discusso alla luce dei determinanti a macroscala (cambiamenti circolatori) e a microscala (cambiamenti nell'uso del suolo). L'effetto della nebbia sui vegetali spontanei e coltivati è altresì discusso.

***Parole chiave**: climatologia, nebbia, uso del suolo, tipi di tempo, rugiada.*

Introduction
Fog is a microscale phenomenon (Munn, 1966; Oke, 1978), which means that it is directly influenced by the presence of the earth's surface and responds to surface forcings (evapotranspiration, heat transfert, pollutant emission, airflow modification induced by the terrain) with a timescale of about one hour or less (Stull, 1997). Furthermore fog is influenced by a wide range of meteorological scales, from macroscale (e.g. dynamic anticyclones) to the mesoscale (e.g. mesoscale precipitation areas).
The terminology adopted in this paper is defined by international agreement and reported in the manuals of World Meteorological Organisation (WMO, 1996) and in particular:
- **visibility** is defined as the greater distance at which an object of specified characteristics can be seen and identified with the unaided eye in any particular circumstances or, in the case of night observations, could be seen and identified if the general illumination were raised to the normal daylight level.
- **haze** is a suspension of very small, non-aqueous, solid particles (smoke, dust, etc.) which produce a milky appearance of the sky. For synoptic purposes the term is used when the particles are sufficiently numerous to give the air an opalescent appearance. There is no upper and lower limit to the horizontal visibility in the presence of which haze may be reported.
- **Mist** and **fog** are a state of obscurity in the surface layers of the atmosphere which is caused by suspended microscopic water droplets or wet hygroscopic particles. The term of mist is used when there is such obscurity and the associated visibility exceeds 1 km and is lower than 5 km; the term of fog is associated with visibility less than 1 km.

Fogs are generally classified according to the physical process which produces saturation or near-saturation of the air. Examples are radiation fogs, advection fogs, upslope fogs and evaporation fogs.
Relevance of fog in agrometeorology can be referred to many aspects. Firstly, the presence of fog enhances the persistence of liquid water on vegetal organs (Richards, 2004), with important phytopatological effects on (i) cryptogams that needs liquid water for particular phases of their cycle of infection (e.g.: peronosporacee like Plasmopara viticola) or cryptogams which evolution is enhanced by high levels of relative humidity. The direct effect of fogs on satisfaction of water needs of crops is usually insignificant due to the very low level of deposition of water produced by this hydrometeor.
Fog has also relevant effects on climatic risk of frost,

Tab. 1 – Scheme of the characters of some phenomena reducing visibility
***Tab. 1** – Schema dei caratteri di alcuni fenomeni che limitano la visibilità*

Pheno-menon	Italian term	WMO international code	Horizontal visibility (m)
haze	Caligine	05	undefined
mist	Foschia	10	1000-5000
fog	Nebbia	Codes from 40 to 49	100-1000
thick fog	Nebbia fitta	Codes from 40 to 49	<100

due to the changes produced in energy balance of canopies. In particular, natural fog is known to provide protection against freezing, so artificial fogs have also been studied as possible methods against freeze damage. Fog lines that use high pressure lines and nozzles to make fog droplets have been reported to provide excellent protection under calm wind conditions. Similarly, fogs created by vaporising water with jet engines has been observed to provide protection (Snyder, 2001).

MICROPHYSICS OF FOG

Fog is a multiphase systems, with a presence of gas, liquid droplets and solid particles. This system is subject to chemical and physical transformations that involve many different atmospheric components and pollutants (Fuzzi, 1993).

In analogy with clouds, the genesis of fog is the result of a process of condensation of water vapour on minute atmospheric particles (condensation nuclei). The efficiency of particles as fog condensation nuclei is quite different in function of their hygroscopic properties that in their turn are function of chemical composition, shape and dimension.

The chemical and physical characters of the multiphase system are the result of some different kinds of phenomena. First of all, at the onset of fog, the insertion of condensation nuclei in droplets - heterogeneous nucleation – influences significantly the initial chemical com-

Tab. 2 – values of visibility and liquid water content (LWC) in a specific case (Fea, 1988).

Tab. 2 *– Visibilità e contenuto in acqua liquida (LWC) in un caso specifico (Fea, 1988).*

Visibility (m)	LWC g/m^3
400	0.05
20	10

Tab. 3 – relation between visibility and fog produced by the drop of air temperature to 1°C below the dew point Td (Fea, 1988).

Tab 3 *– Relazione fra visibilità e nebbia prodotta dal calo della temperatura dell'aria a 1°C al di sotto del punto di rugiada Td (Fea, 1988).*

Td (°C)	Visibility (m)
- 30	1600 (mist)
- 20	800
- 10	400
0	250
+ 10	170
+ 20	100
+ 30	60

Tab. 4 – influence of number of condensation nuclei on fog droplet characters (number, radius, relative number) (Neuberger, op.cit. from Mammarella, 1970).

Tab. 4 *– influenza del numero di nuclei di condensazione sulle caratteristiche delle goccioline della nebbia (numero, raggio, numero relativo) (Neuberger, op.cit. da Mammarella, 1970).*

Condensation nuclei / mm^3) (N)	Radius (micron)	Fog droplets droplets / mm^3 (n)	Relative number (n/N - %)
3	5.6	3	100
25	3.1	10	40
45	2.4	28	62
75	2.1	40	53
175	2.0	54	31
350	1.8	58	17
3000	1.6	80	3

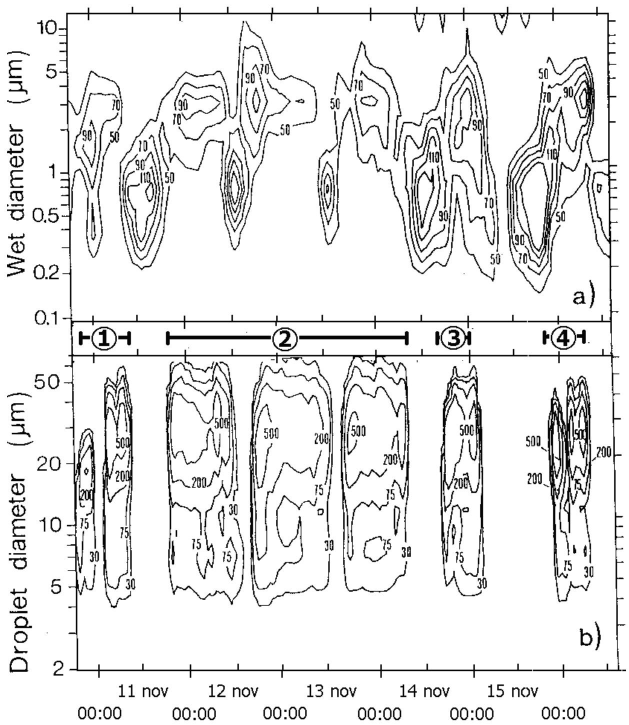

Fig. 1 – Time evolution of Aerosol Size distribution ASd (dM/dlog D, in μg m^{-3}) and Droplet Size distribution DSd (dV/dlog D, in mm^3 m^{-3}) at ground level in GCE experiment. The duration of the fog episodes is shown by the horizontal bars in the middle of the figure (Fuzzi et al. 1992). Example of lecture: at noon on 11 november Asd (upper part of the figure) have a peak value of 130 μg m^{-3} at 0.75 μm of diameter; 12 h later, due to the high humidity in the fog, the peak in aerosol mass had shifted up to 3 μm. The same applies for DSd – lower part of the figure).

Fig. 1 *– Evoluzione nel tempo della distribuzione dimensionale degli aerosol ASd (dM/dlog D, in μg m^{-3}) e delle goccioline DSd (dV/dlog D, in mm^3 m^{-3}) a livello del suolo nell'esperimento GCE. La durata degli episodi di nebbia è indicata dalle barre orizzontali nel mezzo della figura (Fuzzi et al. 1992). Esempio di lettura: a mezzogiorno dell'11 novembre ASd (upper part of the figure) ha un picco di 130 μg m^{-3} a 0.75 μm di diametro; 12 h dopo, per l'alta umidità delle nebbia, il picco nella massa dell'aerosol si è spostato a 3 μm. Ad analoghe valutazioni si presta l'andamnto della DSd – in basso nella figura).*

position of droplets. Later on, particles that persist in the interstitial spaces among droplets are gradually incorporated in the liquid phase droplets due to some different phenomena like Brownian diffusion or inertial impact. Also gaseous components and, in particular, trace atmospheric elements, can be included in the droplets with an equilibrium point defined by the Henry law. The result of these processes is the intermediate composition of droplets but other changes will be observed due to the chemical reactions in liquid phase that take place into the droplets (e.g.: SO_2 oxidation reactions are enhanced in the liquid phase than in the gaseous one).

The result of these processes are fog droplets with a final composition of droplets that can be very different than the initial one; the final consequence is that the evaporation of droplets at the end of fog phenomenon liberates in the atmosphere particles and molecules different to respect to that initially included in the fog system.

It should be borne in mind that fog is not just saturated water, but air which contains an amount of liquid water sufficient to reduce the horizontal range of visibility to 1000 m or less. The visibility is primarily a function of the amount of liquid water, but it also depends on the size of the droplets and the pollution. It is known that the liquid water content (LWC) in fogs may vary between 0.05 and 10 g/m^3. In Tab. 2 are presented the visibility and the LWC in a specific case (Fea, 1988).

These data show that a relatively low atmospheric content in liquid water value is sufficient to obtain a significant reduction of visibility. From a very high number of observation carried out by Radford (Fea, 1988) was derived the following empirical equation that correlates visibility to LWC:

$$\text{Visibility} = 50 * 1/(\text{LWC}^{3/4})$$

where visibility is expressed in m and LWC in g/m^3.

In Tab. 3 is presented the horizontal visibility associated with the fog produced by a drop of air temperature to 1 °C below the dew point (Tab. 3).

These data highlight that the unusual condition of fog produced in presence of higher temperatures can generate very thick fogs.

Number and diameter of fog droplets are influenced by the number of condensation nuclei, as shown by experimental data presented in Tab. 4. From these data can be deduced that the fog droplets born in environments with high presence of condensation nuclei can differ significantly from those formed in lower presence of nuclei.

Other data about number and radius of fog droplets are presented in Sutherland et a. (1996); besides Tampieri e Tomasi (1976) have developed a modelling approach to these quantities founded on a gamma statistical istribution.

A detailed study of the fog system in the Po valley, with the elucidation of the principal physical and chemical processes and the most important parameters which control the chemical composition of the fog and the exchanges of material among the atmospheric reservoirs of the system, was the subject of the Ground based Cloud Experiment (GCE) that was part of the E.U. research program EUROTRAC (Heintzenberg, 1992). The evolution of aerosol mass distribution and the droplet volume distribution at ground level over four fog episodes analysed during the GCE experiment is presented in Fig. 1.

SYNOPTIC AND MESOSCALE CONDITIONS FAVOURABLE TO FOG IN THE PO VALLEY

Fog represents a frequent phenomenon in the Po valley during the fall-winter season. In high pressure and clear sky conditions, the orography of the valley, which is surrounded on three sides by the high mountain ranges of the Alps and Apennines, favours the establishment of strong temperature inversions with the formation of widespread fogs (Cantù, 1987). Depending on the meteorological conditions, fog can either be a local phenomenon or extended over the whole valley (figure 2).

A first synoptic determinant of fog events in the Po

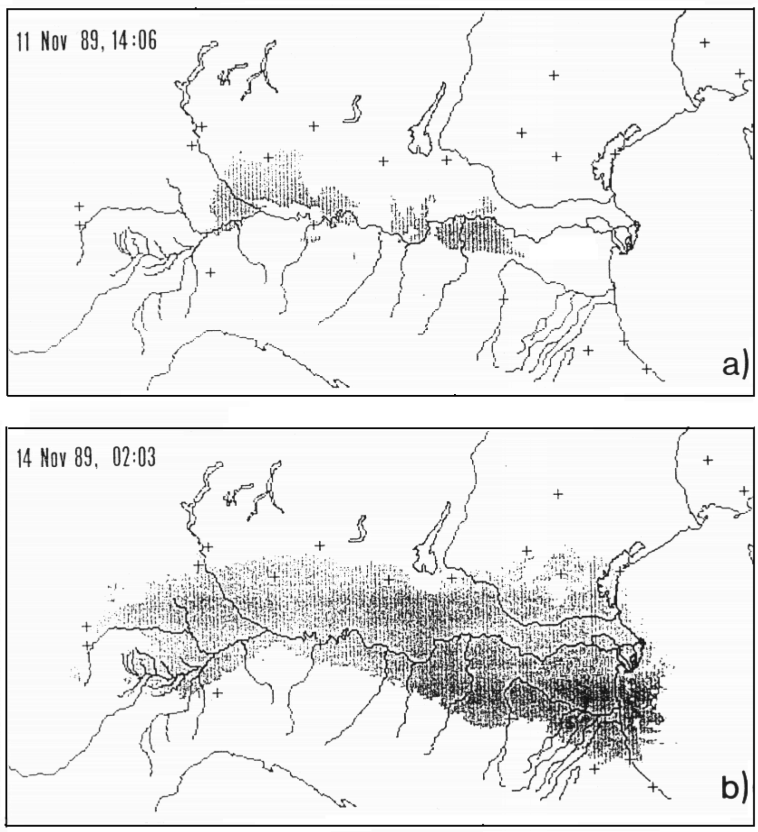

Fig. 2 – examples of local (a) and extended fogs (b) in the Po valley. Maps based on satellite multispectral data from NOAA/AVHHR (Fuzzi *et al.*, 1992).

***Fig. 2** – esempi di nebbia locale (a) ed estesa (b) in Val Padana. Mappe basate su dati multispettrali da satellite NOAA/AVHHR (Fuzzi* et al., *1992).*

Fig. 3 – Cold lake with fog extended to the whole Po valley in October 1997. The picture shows that fog even infiltrates the alpine valleys of the Po tributaries (source: NASA - Photo #: NASA6-703-44).

Fig. 3 – *Lago freddo con nebbia estesa all'intero bacino del Po nell'ottobre 1997. La foto mostra che la nebbia si insinua anche in numerose vallate alpine degli affluenti del Po* (source: NASA - Photo #: NASA6-703-44).

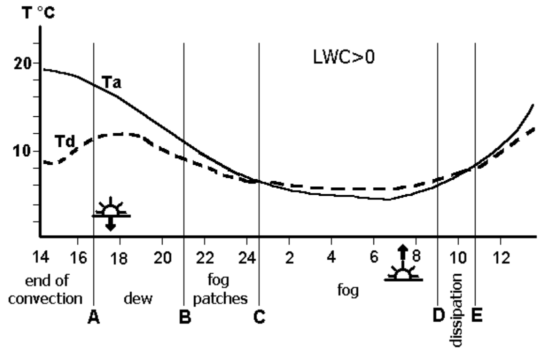

Fig. 4 – phases of evolution of radiative fog (at the base of the figure are presented the phenomena and the references to thermal profiles of fig. 5).

Fig. 4 *– fasi di evoluzione di una nebbia radiativa (alla base della figura sono indicati i fenomeni e i riferimenti ai profili termici di fig. 5).*

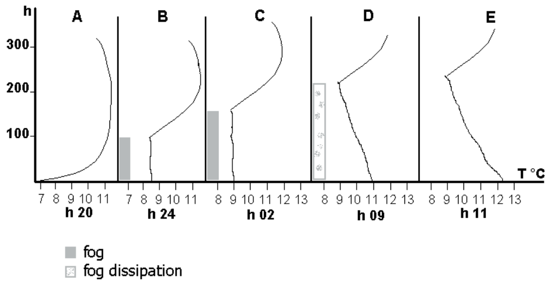

Fig. 5 – evolution of vertical thermal profile and fog layer in the event of figure 4.

Fig. 5 *– evoluzione del profilo termico verticale e dello strato nebbioso nell'evento di fig. 4.*

Fig. 6 – Stratus nebulosus. The layer of stratus has a uniform base as it intersects the foothills.. Except for this feature, there is little structure to the cloud., besides the semi-tranparent area where the sun is almost visible – Colorado, Boulder, 20 february 1986 h.15.55 (WMO, 1987).

Fig 6 *- Stratus nebulosus; si osservi la base uniforme all'intersezione delle colline; al di fuori di ciò è arduo cogliere altre strutture nella nube, ad eccezione dell'area semi-trasparente in vicinanza del disco solare – Colorado, Boulder, 20 febbraio 1986 h.15.55 (WMO, 1987).*

river plain is represented by <u>dynamic anticyclones</u>, which produce a very high static stability of the air mass in the boundary layer and the presence of an anticyclonic inversion of temperature in the lower levels.
Furthermore an important synoptic trigger for the persistent fogs typical of late fall and winter is represented by the <u>irruption of polar continental air</u>, very cold and dry, coming from the centre of the Eurasia (Siberian area). This phenomenon (named *european winter monsoon* by some climatologists) is favoured by the orographic structure of the Po valley (a basin opened towards the East).
Once entered, this air mass can persist in the Po valley for a relatively long period, cooling progressively for radiation and humidifying gradually from below (Fea, 1988).

Tab. 5 – some meteorological factors associated with the scheme of evolution of the radiation fog episode presented in this paragraph.

Tab. 5 – *Alcuni fattori meteorologici associati con lo schema di evoluzione dell'episodio di nebbia radiativa illustrato in questo paragrafo*

Factor	Elements that act on this factor	Physical effects of this factor
Cloud free sky	Anticyclonic conditions	Radiative cooling – ground thermal inversion
Dry air in upper layers	Anticyclonic conditions	Radiative cooling – ground thermal inversion
Moist air in lower layers	Advection of humidity, wet surfaces, rivers, lakes, channels	Saturation – liquid water genesis
Wind calm	Anticyclonic conditions, presence of natural or artificial obstacles	The mixing of atmospheric layers is inhibited and colder / moister air is persist close to the soil. The role of mixing is ambivalent: a total absence of wind inhibit the formation of fog; strong wind can destroy the fog layer
Cold soil	Autumn and winter season	The heat cession from the interior of soil to the surface doesn't compensate the radiative cooling.

Another synoptic contribution to fog events is the inflow of polar maritime air, moist and mild, from Atlantic area. This phenomenon is important when Po valley is directly influenced by the occidental circulation (westerlies).

A SCHEME OF FORMATION AND DISAPPEARANCE OF FOG

On the base of the behaviour of air temperature (Ta) and dew point (Td) is possible to describe the evolution of fog defining the three successive phases of onset, consolidation and dissolution (Fig. 4).

Fog onset

The schema is referred to the onset of radiation fog and is effective in presence of the favourable factors listed in Tab. 5.

We can present the following temporal sequence for the formation of radiation fog in a winter day with the presence of factors listed in Tab. 5:

1. During cloud and fog free daytime periods, the heating of the soil surface by the solar radiation causes a moisture loading of the boundary layer. In coincidence with the daily thermal maximum (that in stable conditions is reached at about 2 p.m. in winter) Td decrease due to vertical mixing;
2. 2.after the daily maximum, Ta presents a gradual decrease towards the nocturnal thermal minimum (that in stable conditions is reached at sunrise);
3. At sunset Td shows a little increase due to the prosecution of evaporation from soil in presence of a drastic fall of vertical mixing;
4. After sunset a light lowering of Td is produced by the soil cooling with the formation of dew, phenomenon that sometimes gives a delay in the onset of fog;
5. At 9 p.m. the reduction to about 1°C of the difference Ta-Td measured in the standard meteorological screen was coupled to a first appearance of shallow ground fog;
6. At 00 is reached the saturation (Td=Ta) and a well structured field appears.

Tab. 6 – atmospheric phenomena associated to fog evolution at S.Pietro Capofiume (FE) in the period 10-17 novembrer 1988.

Tab. 6 – *Fenomeni atmosferici associati all'evoluzione della nebbia a S.Pietro Capofiume (FE) nel periodo 10-17 novembrer 1988.*

1.	Advection to the observation point of already existing fog layers developed elsewhere
2.	Advection of humid or dry air
3.	Advection of cold or warm air
4.	Subsiding dry air in a dynamic anticyclone (A)
5.	Supersaturation (H)
6.	Turbulent mixing in the surface layer (first 10 – 20 m above ground) due to a very shallow low level jet (I1)
7.	Turbulent mixing in the boundary layer (from 20 to 50 m above ground (I2)
8.	Radiative cooling of soil (negative net radiation flux) with development of a ground temperature inversion (L)(Q)(U)
9.	Radiative heating of surface by solar radiation (positive net radiation flux) (P)
10.	Radiative cooling near the fog top (O)
11.	Radiative heating of ground surface due to the thermal radiation of the fog layer (M)
12.	Humidification due to vertical mixing with transport of water vapour from the boundary layer layer into the surface layer (N)
13.	Humidification from moist soil and open water surfaces (R)
14.	Vertical expansion of the fog field (T)
15.	Very strong fluctuations of temperature and humidity (V)
16.	Irregularity of the fog top (X)

Fog consolidation

A further lowering of 2°C of Ta in presence of saturation is associated with a gradual thickening of fog.

Fog dissolution

Radiative fogs have their maximum frequency in the night and they clear up in the morning, after sunrise.

Tab. 7 – classification of fogs on the base of producing and dissipating processes.
Tab. *7 – classificazione delle nebbie in base ai processi di genesi e dissoluzione.*

FOG-PRODUCING PROCESSES	FOG-DISSIPATING PROCESSES
Evaporation 1. from rain that is warmer than the air (rain-area fog or frontal fog) 2. from water surface that is warmer than the air (steam fog)	**Sublimation or condensation** 1. On snow with air temperature below 0°C 2. On snow with air temperature above 0°C (melting snow)
Cooling 1. due to adiabatic upslope motion (upslope fog) 2. due to radiation from the underlying surface (radiation fog) 3. due to advection of warmer air over a colder surface (advection fog)	**Heating** 1. Due to adiabatic downslope motion 2. Due to radiation absorbed by the fog or the underlying surface 3. Advection of colder air over a warmer surface
Mixing Vertical mixing (e.g.: important in upward expansion of fog layers)	**Mixing** Vertical mixing (e.g.: important in dissipating fogs and producing low stratus)
Advection of fog layers Fog layers generated abroad and advected on the reference area	**Drying** Subsidence of dry air in a dynamic anticyclone

The dissipation and disappearance of fog is the consequence of the evaporation of the whole liquid water due to the energy given by sun. This phenomenon is described by thermal profiles in Fig. 5, that show the gradual erosion of the surface inversion.
The effect of solar radiation on the disappearance of radiation fog is attenuated due to the strong albedo of the fog top. The consequence is that thick fog layers can persist for the whole day; on the contrary the dissolution of thin fog layers can be characterised by an increase of the horizontal visibility near the surface associated with the genesis of low clouds (*Stratus nebulosus*) that gradually dissipates upwards (Fig. 6).
A more detailed description of the microscale structure of fog events in the Po valley fog was obtained in recent experiments. For example the field campaign of the project EUROTRAC - subproject GCE analysed five fog events that happened in the period 10-17 november 1989 in the monitoring site of San Pietro Capofiume (FE)). During the period a huge, blocking anticyclone developed and persisted over central Europe and due to the cloud free atmosphere the radiative cooling in the nights caused a temperature inversion favouring fog formation in the Po river valley.
For the analysis (Wobroch et a., 1992) were considered temperature, relative humidity, wind speed and direction and shortwave radiation at the ground level and at different levels on a meteorological tower of 51 m. These data were integrated with:
- Liquid water content (optical probes FSSP-100 and liquid water indicator PVM100);
- synoptic maps of temperature and geopotential at different heights;
- remote sensed data from 3D doppler sodar system and from AVHHR NOAA.

The different micrometeorological phenomena in GCE experiment that were directly related to onset, evolution and dissipation of fog (Fuzzi et al, 1992) are listed in Tab. 6.
In complex, on the base of mechanisms of fog formation observed in the GCE experiment, four principal types of fog are classified:

1. radiation fog (event 1 of Fig. 1);
2. advected fog (entire event 2, second part of event 1, 2nd period of event 4);
3. fog formed on site due to advection of moisture (event 3, first period of event 4);
4. fog formed on site due to advection of cold air (event 5).

The disappearance of the fog fields was associated to two principal mechanisms:

1. solar radiation in the morning and the subsequent heating of the surface and the adjacent layers;
2. advection of warmer and drier air at the edges of the fog field;
3. penetration of the ground temperature inversion by the subsiding dry air from the high. pressure system

Other important observational results obtained from the GCE experiment are:

1. the individuation of a clear difference between the high of advected and radiation fog. In fact advected fog reached up to 80-200 m and can be defined as a boundary layer fog; on the contrary radiation fog was lower than 30 m and can be defined as a surface layer fog. The same phenomenon was also observed in the case of the Hudson Valley fog (Fitzgerald & Lala, 1989);
2. the ambivalent role of the wind turbulence was also confirmed: fog formation was accompanied by wind increases as well as decreases;
3. the radiative cooling of the surface and the adjacent layers could only result in a very shallow and non persistent fog; for the formation of high reaching and persistent fogs, additional processes (e.g. mixing and advection) are required;
4. the very strong fluctuations of wind, temperature and humidity and frequent irregularity of the fog top in the course of the fog events.

These evaluations show that fog events are very complex due to he influence of a very wide range of atmospheric phenomena.
So we can rearrange the classical classification given by Pettersen (1940), obtaining the scheme represented in Tab. 7.

Tab. 8 – routine observational data useful for the nowcasting of fog.
Tab. 8 *–Dati osservativi di routine utili per il nowcasting delle nebbie.*

Type of data (from observation or forecast)	Instruments	Information inferred
Stability of atmosphere	Soundings, instrumental and sensorial observations, analysis of low and mid - troposheric circulation structures	Possibility of vertical mixing of air mass
Meteorological variables near the ground (air temperature and humidity, solar and net radiation, wind velocity and direction, etc.)	Meteorological stations	Knowledge of thermal and hygrometric conditions of air mass; analysis of surface energy balance
Ground conditions (dryness, wetness, snow coverage, presence of hoarfrost, etc.);	Sensorial observations	assessment of surface energy balance
Ground temperature	Meteorological stations	assessment of surface energy balance
Cloud coverage	Sensorial observations	assessment of surface energy balance

Tab. 9 –example of a table for the nowcasting of fog (Taylor, 1917).
Tab. 9 *–esempio di tabella per il nowcasting delle nebbie(Taylor, 1917)*

T	Difference T-Tw at sunset above witch the fog doesn't form	Difference T-Tw measured two hours past sunset above witch the fog doesn't form	Difference T-Tw above witch the fog doesn't form for the following 4 hours
25	9	4	3
20	6	3.3	2.5
15	4	2.5	2
10	2.5	1.9	1.5
5	1.5	1.5	1
0	0.8	0.8	0.5

FOG FORECASTING

The forecast of fog formation (hour of beginning, probability of fog) and fog clearing up (hour of disappearance and probability of this) is very difficult because the fog is the product of a wide series of factors, covering a wide range of scales from micro to macroscale and often very difficult to gauge (e.g.: surface energy balance, type e quantity of condensation nuclei).
The consequence is that for the now-casting of fog is necessary an operational monitoring at local scale and microscale, considering the factors listed in the following table with the observational instruments.
Data listed in Tab. 8 are also the input of some semi-empirical or empirical equations for the estimate of daily thermal minimum (e.g.: equation of Brunt, equation of Swinbank) and for the estimate of surface energy balance (Oke, 1978; Stull, 1997).
An approach to the problem of fog forecasting is represented by the **local statistics of fog**. This method is based on the study of correlation between fog presence (measured with subjective methods or with visibilimeters) and meteorological records of temperature, humidity, cloud coverage, etc.
Time series of sufficient length (10 – 30 years) are useful for this analysis.
An example of this kind of approach is presented in Tab. 9 and was deduced from a nomogram obtained for the British plain by Taylor and cited by Fea (1988). Taylor correlated the initiation of fog with the difference between dry bulb and wet bulb air temperature (T-Tw). Tab. 9 can be used only with clear sky and very low wind.
Similar models can be defined and experimented for Po valley, considering the variables listed in Tab. 8.
The nowcasting of advection fogs is more complex because we must evaluate not only local data but also the characters of incoming air masses.
Short range (12-24 h) and medium range (2-7 days) forecast can be carried out by means of forecasted values of different meteorological data.

SOME ASPECTS OF RURAL AND URBAN CLIMATOLOGY OF FOG

Intensity, **frequency** and **persistence** of fog phenomena are quantitative elements fundamental to establish a fog climatology.
The climatological survey of fog in the Po valley has a very long history. For example Filippo Eredia (1916) wrote a paper titled "Le nebbie in Valpadana" (fogs in the Po valley) which discussed the mechanisms of formation, the synoptic determinants and reported the statistics for the period 1892 – 1914 for 23 stations of the Regio Ufficio Centrale di Meteorologia.
In the past, a lot of extreme fog events where observed at Milano Linate airport, which for a long time was the European airport with the higher yearly number of shut-down due to the fog. In particular Eichenberger (1973) wrote that at Milano Linate the mean yearly number of fog events with persistence > 24 hours was 4.5 and an extreme case of 422 hours - about 18 days of uninterrupted fog was also gauged.
In Tab. 10 is represented the mean monthly number of days with fog (visibility below 1000 m) at 7 a.m. for the Lombardia plain (from Palmieri).
From this table we can deduce that the risk of fog is high for September to April.
From the processing of the visibility data of Milano Linate was obtained the following empirical relations

(Tebaldi, 1989) that estimates the average frequency of days with visibility level less than a specified threshold:

- relation for 7 a.m.: $F_7 = 92*(VV_7)^{0.5}$
- relation for 1 p.m.: $F_{13} = 64*(VV_{13})^{0.5}$

where F_7 and F_{13} are the average frequency of days with visibility less than the thresholds VV_7 and VV_{13} (km).

As can be seen from values in Tab. 11, obtained from these two equations, on an average of 92 days per year the visibility at Linate airport is less than 1000 m (fog) at 7 a.m. and on 29 days there is an extremely thick fog (visibility less than 100 m).

This frequency is reduced by 30% during the daytime, and moreover the phenomenon becomes less frequent and persistent in the areas to the north of the Milano-Venezia railway line in the east, and the Milano – Torino line to the west of the urban area of Milano (Tebaldi, 1989).

Some statistics about fog events in the urban centre of Milano and at Linate are reported in Tab. 12.

This table shows a general reduction of the fog days as a result of a lot of phenomena acting form macro, meso and microscale.

At macroscale the change of frequency and persistence of different weather types can be considered a key factor in order to produce time variation in frequency and persistence of fog. In this context a primary role was surely played by the change of phase in Atlantic circulation (Werner *et al.*, 2001) with the prevalence of westerlies and the strong decrease in easterly weather types responsible of the advection of cold polar continental air. A microscale phenomenon with important implications or fog frequency is represented by the relevant changes in the land use observed in the last fourty years in the Po valley. In particular can be highlighted

- the increase of the dryness of the rural area due to the disappearance of the winter irrigated meadows (marcite) (Mariani & Sovrano, 2001).
- The progressive increase of the levels of anthropization of the territory with the progressive reduction of the sources of humidity in the boundary layer, necessary for fog onset (Mariani & Sovrano, 2005).

Furthermore Tab. 12 shows a more significant reduction of the number of fog events in the Milano Centre than at Linate airport. This phenomenon can be explained in the light of the change in the pollutants (quantity and quality) in the urban areas. For example in the last 30 years the urban area of Milano experienced a strong reduction of SO_2, a molecule known as extremely effective for the production of fogs.

Fog climatology in urban areas is strictly related with the substantial modification of temperature and relative humidity in the urban boundary layer (phenomena of Urban Heat Island – UHI and Urban Relative Humidity Island – URHI) (Oke, 1978). The spatial behaviour of fog and air temperature in the transition zone from rural to urban area is shown in Fig. 7, that highlight the presence of 3 different zones:

Tab 10 – number of days with fog (visibility below 1000 m) in Lombardia plain (from Palmieri, modified).

Tab 10 *– numero di giorni con nebbia (visibilità inferiore a 1000 m) nella pianura lombarda (da Palmieri, modificato).*

Month	Mean number of days with fog at 7 a.m. (*)	Risk (**)
GEN	10-16	4
FEB	4-10	3
MAR	2-6	2
APR	1-2	1
MAG	0-1	1
GIU	0	0
LUG	0	0
AGO	1	1
SET	2-5	2
OTT	8-13	3
NOV	8-14	4
DIC	12-20	4

(*) the range signify the spatial variability among the different areas of the plain.
(**) risk index: 4=very high, 3=high, 2=medium, 1=low, 0=null.

Tab 11 - Frequency of days with low visibility at Milano Linate (Tebaldi, 1989)

Tab 11 *- Frequenza di giorni con visibilità ridotta a Milano Linate (Tebaldi, 1989)*

Visibility (m)	At 7.0 a.m. Number of days	At 1.0 p.m. Number of days
<= 30	16	11
<= 50	21	14
<= 100	29	20
<= 200	41	29
<= 400	58	41
<= 1000	92	64
<= 2000	130	91
<= 4000	184	128

Tab. 12 – yearly mean number of fog days at Linate and in the centre of Milano (Belloni & Pelfini, 1991; Giuliacci *et al.,* 2001; Santomauro, 1970)

Tab. 12 – Numero medio annuo di giorni yearly mean number of fog days at Linate and in the centre of Milano (Belloni & Pelfini, 1991; Giuliacci et al.*, 2001; Santomauro, 1970)*

period	Linate	Milano – Centre	% of reduction
1960-1969	151	27.5 (*)	82%
1970-1979	136	15.9 (*)	88%
1991-2000	72.6	7.5 (**)	90%

(*) data form Brera observatory
(**) data gauged by the author during 1991-2000.

Tab. 13 – Main effects of fog on agro-ecosystems.
***Tab. 13** – Effetti principali della nebbia sull'agro-ecosistema*

Physical phenomenon	*Final effects in crops and natural vegetation*
Reduction of evapotranspiration	- reduction of water needs of crops - decrease of the uptake of nutrient from soil
Effects on radiation balance and energy balance (see table 14).	- decrease of daily warming and nocturnal cooling of vegetals - reduction of photosynthetic assimilation
Presence of saturated conditions with liquid water on plant surfaces	- enhanced risk of infections by fungi that need liquid water for infection (e.g.: *Peronosporaceae*) - deposition of chemical pollutants on vegetation

Tab. 14 - Fog effects on radiation and energy flows referred to a surface below a fog layer (all terms con be expressed in W m^{-2})
***Tab. 14** – Effetti della nebbia sui flussi di radiazione ed energia riferiti ad una superficie al di sotto di uno strato nebbioso (tutti i termini possono essere espressi in W m^{-2})*

	Term	symbol	fog effect on absolute values
Radiation balance	Global solar radiation	Rg	decrease (scattering effects with strong prevalence of diffuse radiation)
	Net long-wave radiation directed towards space	RLn	decrease
	Net radiation	Rn	decrease
Energy balance	Sensible heat	H	decrease
	Latent heat	LE	decrease
	Heat flow into the body	G	decrease

- rural zone (UHI=0, URHI=0, high fog presence);
- transition zone (strong increase of UHI and URHI – "cliff" in Fig. 6, strong decrease of fog);
- low fog zone (plateau of UHI and low fog presence)

The volume of the heated buildings in Milano (Fig. 7), can be considered as an index of the UHI effect and, by consequence, of the attenuation of the fog cases in the urban area. In the case of Milan area we can roughly locate the transition zone in the area between 1 and 3 millions of m3 km-2 of volume and we can adopt the isoline of 3 millions of m3 km-2 as the limit of the low fog zone.

AGROMETEOROLOGICAL ASPECTS OF FOG

The main consequences of fog on crops and natural vegetation are listed in Tab. 13. It can be seen that many physical effects are the direct consequence of changes in (i) energy balance of soil and plants and (ii) water balance of soil. Fog effects on the main terms of energy balance are qualitatively described in Tab. 14, which highlights that the decrease of the net radiation flow (Rn) gives a significant reduction in the values of the three flows (H, LE, G) triggered by it. An important consequence of this is that, during sunny anti-cyclonic weather, canopy meteorological variables below a fog layer (surface and air temperature, relative humidity, wind speed and so on) are substantially "buffered", with daily ranges significantly reduced in comparison with that observed in areas without fog; this has important effects on thermal and radiation limitations but, on the other hand, can prevent strong decreases of vegetal tissues temperature, reducing frosts hazard; this justify the systems of frost protection based on the production of artificial fog.

Other effects of fog are referred to water balance of crops and natural vegetation and are the result of (i) increase in water released to surfaces and (ii) reduction of evapotranspiration.

Water quantity released to soil and vegetation during foggy periods is usually insufficient for a significant contribution to water balance. For example in the Po plain the daily quantity of condensed water is normally below 0.2 mm and only exceptionally 0.2-0.4 mm are released (1-2 tips of a standard pluviometric bucket). On the contrary, fog can be an important alternative source of moisture for areas close to significant humidity sources like lakes or oceans. A specific example referred to the relic laurel ecosystems of the Canary Islands located at 500-1400 m.a.s.l. (Garajonay National Park) was described by Ritter *et al.* (2008). In this environment, which is located at the same latitude of the Sahara desert, trade winds from North leads to an almost permanent layer of clouds between 900 and 1500 m asl in windward areas; this foggy layer sustains an evergreen cloud forest characterised by the extensive presence of Erica arborea L., an evergreen shrub or small tree. Data of water deposition are referred to four micrometeorological stations placed at 1145, 1185, 1230 and 1270 m a.s.l. and are obtained by means of a specific model parameterised with data gauged by artificial catchers. The main result is that the average fog water collected by needles of Erica arborea was significant only at the highest monitoring site (one order of magnitude greater than at lower altitudes) amounting up to 496 mm year−1 during the two-year period. This can be crucial for this kind of ecosystem because fog water collection was distributed more evenly around the year in an environment where rainfall exhibited seasonal effects with a well defined dry season. Other effects of foggy conditions compared to fog-free periods in the above-mentioned area were:

- 42% reduction in global radiation
- 3–6°C mean temperature decrease

- substantial limitation in evapotranspiration.

Significant amounts of precipitation from fog are probably present in Alpine and Apennine areas exposed to humid air masses. For example measurements taken in locations within the Alps where fog occurs relatively rarely have revealed an additional precipitation from fog of 5–25% (Turner 1985). Figures for locations exposed to wind in the main areas where fog occurs will be far higher (Spreafico and Weingartner,, 2005).

Chemical effects of fog on vegetation are related to molecules of pollutants intercepted by fog drops, giving the phenomenon of smog (smoke + fog). When drops are intercepted by vegetal surfaces the pollutants are deposited, giving significant biological effects described for example by Lorenzini (1999).

Conclusions

This work has presented a description of the fog phenomenon in the light of the microphysics and the mechanisms of formation acting at different scales. The relevance in rural and urban contexts of North Italy was also discussed with particular reference to Milano area. The decrease of the frequency and persistence of fog in the last years was also presented and analyzed in the light of the determinants at macro end microscale.

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