5th International Conference on Fog, Fog Collection and Dew
Münster, Germany, 25–30 July 2010
FOGDEW2010-138

Analysis of Paris- Fog using ground based aerosol and meteorological measurement

N. Boyouk (1), M. Haeffelin (2) J- C. Dupont (2) T. Elias(3)
(1) LMD - Ecole Polytechnique, France, (2)IPSL /SIRTA, Ecole Polytechnique, (3)IPSL/ CEA,France
(neda.boyouk@lmd. polytechnique.fr)

Abstract

Fog is important atmospheric phenomena interns of air quality. Low visibility as imperative fog factor may result due to high level of aerosol number concentration in affirmative meteorological condition and high relative humidity. This work analysis micro-physical and optical aerosol properties and meteorological condition of fog and quasi fog event to improve understanding of micro-physical process during fog occurrence and the influence of aerosol on fog formation.

Based on high decrease on visibility on foggy days(less than 1km) and quasi fog (between 1km and 2 km), we have compared the temporal evolution of aerosol parameters (mass and number concentration, extinction and absorption coefficient) for fog and near fog event. In addition, the analysis of temporal series of meteorological parameter (temperature, humidity, wind speed, wind direction) help us to better understand the micro-physical process which are the important reason for formation ,removal or modification of particle and increase of fine aerosol number concentration during fog event.

An increase in aerosol micro-physical or optical properties (mass, accumulation number, extinction coefficient) shows large variation in visibility. This variability is much higher in case of fog event compare to near fog. The chemical analysis used to find the influence of fog on aerosol type characteristic specially the aerosol acidity. The cation-to-anion ratio for explain how accumulation mode are acidity. There is a good correlation between the Pm2.5 and visibility during fog event with a correlation coefficient of R=0.84.

1. Introduction

Fog formation and low surface visibility are important to be predicted due to their influences on aviation, transport, navigation and traffic. Low visibility prediction is not easy due to complexity of formation processes which depends on physical and chemical properties of aerosol and meteorological elements. However using the ground based or remote sensing measurement and models, many studies (Baumer et al. 2008; Gultepe et al. 2009; Kokkola 2003; Nowak et al. 2008; Stolaki et al. 2009) have been acquired to understnd the microphysical and meteorological process and effect of pollution result in fog formation, but Operational forecasting of fog in Environmental centers and for numerical weather prediction is difficult due to complexity of fog and limited computing resources available for forecasting. It is necessary to present aerosol emission, related pollutant and land surface properties in fog situation for climate simulation models (Oldenborgh et al. 2010). Zhou et al (2010) have used multivariable diagnostic(lowest level liquid water content, cloud top, cloud base, wind speed, relative humidity) fog prediction method which works better than unique variable method. The application of this multivariable approach to a multi model mesoscale prediction system and performance of ensemble base forecast was statistically superior to single- value. They can found occurrence of fog but not intensity of fog.

Using satellite measurement can help us for fog prediction, The map of fog and low stratus distribution over Europe based on Satellite data have been presented by (Cermak et al. 2009). They have found general pattern of Meteosat second generation and 26 year ground base measurement of visual cloud observation are in good agreement.

Large scale atmospheric circulation influences micrometeorological conditions of formation of advection and radiation fog at ground level. Large scale circulation also indirectly could be a reason for enhancement of aerosols concentration, advection of pollutant, height of mixed layer and probabilities of precipitation in favorable meteorological conditions and high relative humidity(Oldenborgh et al. 2010). The radiation fogs are influenced by not only local pollution but also by long range transport. Radiation fog is formed when pollutant stagnates in the surface under the anticyclonic condition with calm wind and the pollutant can settle around fog droplet (Ogawa et al. 2004).

Gultepe et al (2009) have been shown that interaction of microphysical, dynamical, radiative process and surface conditions influence on life cycle of fog. The large variability on RH and visibility parameterization has been observed. Oldenborgh et al. (2010) have shown contribution of dynamic of atmosphere depends on topography and season is about 40%. The fog duration and intensity depends on meteorological, regional, geographical parameters. Wang et al (Wang et al. 2010) based on satellite data and meteorological parameters have found that distribution of radiation fog depends on types of surface underneath. Dunkerke (1998) have compared a deep and shallow fog observations (surface net radiation, soil heat flux, Liquid water content, temperature) by a one dimensional average model for parameterization of vegetation.

Fog frequency influenced by the airborne pollutant properties (particulate matter PMx, aerosols, sulfure-dioxide,….) in megacities. An analysis of trends in fog frequency by Shi et al (2008) shows that the impact of urbanization on fog is different at various stages of urban development. The number of annual fog days in most cities studied has increased since the 1960s but decreased after the mid 1980s in large, old cities. New cities, on the other hand, are characterized by still increasing fog frequency. During the last thirty years, average fog duration increased and visibility decreased at most urban stations. Based on observations over Europe 1976-2006 it has been found a decrease in number of fog and mist days which is spatially and temporally related in SO_2 emissions. The correlation is more at 5km visibility, for dense fog the correlation are significant (Oldenborgh et al. 2010). In foggy days Diurnal variation of SO_2 and NO_2 have inverse relation with visibility due to formation of secondary pollutant sulfate and lesser extent nitrate (Mohan; Paraya 2009). Kokkola et al (2003) reveal the oxidation of SO_2 to sulfate has significant effect on fog droplet gross when hygroscopic trace gases, for example HNO3 and NH3 are present. Wen et al (2010) have analyzed the influence of airborn pollutant and meteorological parameters on visibility in Taiwan. They have found high visibility is along with low level of PM10 less than 150 μgm^{-3} with clear atmosphere. They have found a method of prediction of airborne pollutant based on visibility.

The decrease of visibility is associated to increase in the aerosol number concentration of particle less than 300nm (Baumer et al. 2008). Increase in number concentration of nucleation and accumulation mode with decrease in nucleation mode radius and increase in accumulation radius shows hygroscopic and coagulation growth of particles (Das et al. 2008). Elias et al (2009) shows that the accumulation mode have been contributed to extinction in haze condition 100%, clear sky 50% and fog condition 20% ±10. During fog condition nucleation mode is decreasing by collision to droplet. The accumulation and droplet mode are significant on extinction.

Das et al. (2008) show the relationship between aerosol optical thickness and visibility during fog days. They have found that the aerosol optical thickness increase in fog days compare to the previous day.

In this study we have chose the period of Paris fog (Jan, Feb, March 2007) in that the aerosol properties have been measured during fog and quasi fog events. Based on definition from AMS (American-meteorological-society 2000)fog is Water droplets suspended in the atmosphere in the vicinity the earth's surface that reduce visibility below 1 km (10-min averaged visibility remains below 1 km during at least 30 minutes over a 50-min time window). Mist is suspension in the air consisting of an aggregate of microscopic water droplets orwet hygroscopic particles (of diameter not less than 0.5 mm or 0.02 in.), reducing the visibility at the earth's surface to not less than 1 km. (not used in this study because it lacks precise upper boundary in visibility) Near fog are the events in that 10-min averaged visibility ranges between 1 and 5 km during at least 30 minutes over a 50-min time window. In Quasi fog events, the 10-min averaged visibility ranges between 1 and 2 km during at least 30 minutes over a 50-min time window (Haeffelin et al. 2010).

Our objective is to better understand the microphysical and dynamical processes which have the most influence on life cycle of fog. We want to find a key parameter between microphysical and meteorological elements for fog prediction. In section 2, we present the instruments which have been used to measure the visibility and microphysical, optical and meteorological parameters (number and mass concentration of aerosol and droplet, aerosol optical thickness, backscattering coefficient, pollutant concentration; PM2.5 and PM10). In section 3, we will discuss the method which have been used to understand the process before formation of fog ; in haze regimes which occur as transition between the clear-sky and fog regimes, visibility is highly variable in this regime. Haze regime is defined as visibility smaller than 5000 m, down until fog occurrence(Elias et al. 2009). We retrieve visibility using aerosols optical thickness: AOT and backscattering coefficient for fog and quasi fog events when the atmosphere is convective and considering uncertainties in the retrieval and assumptions on the mixing of the boundary layer. In section 4, we present the meteorological condition during fog and quasi fog events. The section 5, first, present the analysis which have been acquired to find the key parameters between meteorological, microphysical properties of aerosol and pollutants (accumulation aerosols number and mass concentration, wind component and PM2.5) for formation of fog. Second the result of the retrieved visibility using aerosol optical thickness and ceilometer backscattering coefficient at lowest level is presented. In section6, the results are resumed.

2. Instrument

We have used the measurement acquired for the Paris - Fog experiment (Haeffelin et al. 2010) on the Sirta observatory (48.7°N, 2.2°E) during winter 2006 and 2007. Simultaneous measurements of dynamic, thermodynamic, radiative, microphysics of aerosols and fog properties have been monitored. During several intensive observational period (IOP) (Haeffelin et al. 2010) measurements have been acquired as manual-system . We have focused on period of Jan to march 2007. The instruments used in our study are presented in table1. A complete description of Paris -Fog and instrument can be found in Haeffelin et al (2010) and Elias et al (2009).
The degreanne visibilimeter working at height of 4m provide the ground- level visibility. For the measurement of scattering coefficient the nephelometer TSI 3563 have been used working at 450, 550, 700nm. The counting of aerosol particles has been measured by TSI smps in range of 0.01 to 0.50 µm diameter. Palas Welas 2000 particle spectrometer is sampling the particle number and size in range between 0.39-42 µm (aerosol and droplet).
A modified vaisala ceilometer ct 25k 905 nm was used to profile aerosol backscatter. The backscattered radiation caused by particles allows aerosol layers, haze, and cloud base to be identified. In rain and fog, the ceilometers is only used to measure cloud base.

Table 1 List of instruments deployed during ParisFog, parameters that can be retrieved from their measurements, instrument range (vertical range, spectral range, as relevant) and resolution, and type of operations (RT: routine operations).
T: temperature, RH: relative humidity, WS: wind speed, WD:Wind direction, AOT: aerosol optical thickness, Vis : visibility, βc: aerosol scattering coefficient , β, Back scatter by eilometers ND: droplet number, NA: aerosol number,D: Particle diameter, PM Particle mass concentration, AO: ambient outdoor

Instrument	Model	Temporal resolution	Parameter	Uncertainity measurement	Sampling.
Thermometer, humidity sensor		1 min	T, RH		AO, RT
Sonic anemometre		1s	WS, WD		AO
sunphotometer	Cimel 318 λ= 440, 670, 870, 1020 nm	15min	AOT, ω₀	AOT 5%	AO, RT
Visibilimetre	Degreanne (DF320&DF 320+) λ= 490- 750 nm	10s	Vis	10-25%	AO
Nephleomerer	TSI3563 λ= 450, 550, 700 nm	1 min	βc	10%	PM10 inlet
Particle counter	Welas-2000 D=0.39-42 µm	5 min	ND and NA	20%	AO
Particle counter	TSI- smps D=0.01-0.5 µm	10 min	NA	20%	PM10inlet
Particle counter	Grimm-5400	1min	NA	10%	PM10 inlet
Ceilometer	Vaisala CT25K λ= 905 nm	1 min	β		PM10 inlet, RT
TOEM			PM2.5		

There are two types of measurement stations in Ile-de France region air quality monitoring network (http://www.airparif.asso.fr), 41station of air quality monitoring which are situated far from the urban circulation and near to traffic. They are classified as traffic, urban, suburban and industrial. The mean inter station distance are 2km in the urban zone and 6 km in the suburban one. The concentrations of SO2, NO, NO2, PMX, CO, O3 have continuously been monitored and data are available on an hourly basis.
In the present study we are using PM2.5 and PM10 data collected by a Tapering Element Oscillation Microbalance TEOM (Patashnick; Rupprecht 1991) operated by the regional air quality network. Comparisons of TEOM to gravimetric measurements show that routine TEOMs can underestimate PM10 by up to 35% (Allen; Ress 1997; Van Dingenen et al. 2004). TOEM at SIRTA is not working continuously. We have used the measurement of VITRY-SUR-SEINE. The two stations are in different geographical But there is a good correlation between the PM2.5 measurement. The simple regression between data shows that PM2.5(Vitry) =0.98 PM2.5(SIRTA)+3.6 with correlation coefficient R^2=0.87 (Figure.1).

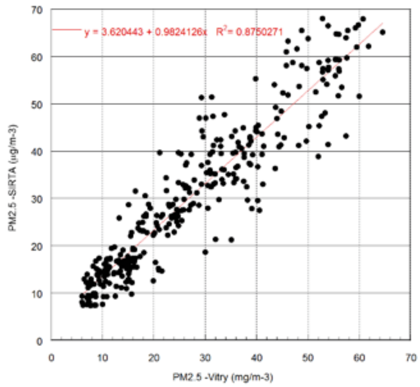

Figure 1 Relationship of PM2.5 at vitry- sur- sein and Sirta PM2.5 measurement

3. Methodology

You We have analyzed the processes taking place during fog formation versus non-formation in similar conditions (quasi-fog), in clean and polluted air masses. We know the droplet are formed in haze, causing fog outbreak then based on our main question in terms of aerosol properties difference between the pre-fog haze and near fog conditions, which are close to fog conditions we have used different method which will be described as following. The radiation fog are chosen as fog days.

First, We have analyzed the temporal variation of meteorological parameters and visibility to find out the difference which makes fog (visibility less than 1km) and quasi fog events when they have the similar situation. We have analyzed compared the hourly average of data during these events.

Second, We had analyzed the temporal variation of AOT and number concentration for the days when fog and quasi fog occur: implication of accumulation mode aerosols in visibility, AOT, relation mass-visibility. This is to check consistency of the data base as we showed in the paper for visibility and microphysics. With combination of remote sensing and ground based measurement we want to study the relationship of visibility and aerosol properties during fog and quasi fog events. We have retrieved the visibility using columnar aerosol optical thickness to find out how AOT and visibility are in good correlation. Using available hourly data of AOT of Aeronet, we have retrieved the visibility by a simple relationship between AOT($_{\lambda=440)}$ and visibility. The measured visibility is averaged every 10min and AOT depends on local situation and is available just in clear sky. In the Koschmeider equation formula then visual range can be expressed in term of extinction coefficient ($b_{ext)}$ with unity of km^{-1} (Seinfeld; Pandis 2006).

$$\text{Vis}= 3.912/b_{ext} \tag{1}$$

And aerosol optical thickness is defined by following equation in range of 0 to Z_l

$$\tau =\int b_{ext}\, dz \tag{2}$$

Combining Equation 1 and 2 we obtain the simple relationship between visibility and aerosol optical thickness as following

$$\text{Vis}= 3.912\, Z_l/_{\tau} \qquad [3]$$

We have assumed that the Z_l; is mixing layer height which can is calculated from the ceilometers measurement when the atmosphere is convective and considering uncertainties in the retrieval and assumptions on the mixing of the boundary layer.

We have then determined the altitude of the boundary layer by using a simple gradient method applied to the ceilometer profiles acquired during the day and night at a time resolution of 1 min. Under the basic assumption that the aerosol mass is well mixed in the boundary layer and that the relative humidity has a negligible impact on the extinction coefficient.

Using the first available level of the ceilometer signal, S(z) at the lowest available altitude can be used to infer the mass concentration close to the ground. We have estimated that the first level that can be used is at z = 15 m. Secondly using the first available level of the ceilometer signal, the error in estimating ground-level visibility is proportional to the error in the ceilometer backscattered signal in the first hundred meters. An additional source of error comes from the impact of the relative humidity on the aerosol optical properties. This impact can be modeled (Hänel 1976) when the aerosol type (hygroscopic factor) and the vertical profile of relative humidity are known (Raut; Chazette 2008). Since we have the relative humidity measured at the ground, we have only applied a correction factor for the ceilometer signal close to the ground following Raut and Chazette (2007) with an exponent factor of 0.55. $S^*(z_l)$ is the corrected signal:

$$S^*(z) = S(z) * (1 - RH)^{0.55} \tag{3}$$

Where RH is the relative humidity. The overall uncertainty is between 20 and 40% (Boyouk et al. 2009).

$$\text{Vis}=3.912 /(S^*(z_l) * \text{L}) \tag{4}$$

Where it is assumed in the first level the attenuation is negligible. L is a constant value of extinction to backscatter coefficient at 905 nm.

Fog and quasi fog event are classified based on observation of visibility and to make comparison between fog event and quasi fog event we have averaged data on different time scale of 10 minute, 30 minute, 1 hours. The microphysical properties of aerosol data as mass and number concentration of accumulation, ultrafine and fog droplet have been averaged every 30 minutes. meterological data, visibility and lowest level of backscatter of ceilometer and boundary layer height is averaged over 10 minutes. PM2.5, PM10 and other pollutant which have been used in our analysis were available on hourly average (http://www.airparif.asso.fr).

Table 2 Radiation fog and quasi fog event during Jan, Feb, March 2007 –Paris fog the time is corresponded to the time of the observation of lowest visibility

FOG	Date / Time	Fogtype	Lowest visibility m	synoptic
	27/01/2007 23:30	RAD	0.07	H
	18/2/2007 22:40	RAD	0.07	H
	4/3/2007 6:30	RAD	0.15	T
	13/03/2007 23:10	RAD	0.1	H
Quasi fog	Date/ Time	Weather – condition		
	1/6/07 2:10	PCP+LowC	1.92	L
	1/29/07 19:20	SKC	1.82	H
	2/1/07 2:10	LowC	1.31	H
	2/5/07 21:00	LowC	1.99	T
	2/7/07 3:30	LowC	0.85	T
	2/19/07 20:10	SKC	0.4	H
	3/2/07 18:00	PCP+LowC	1.86	H
	3/9/07 10:20	PCP+LowC	1.78	L
	3/11/07 3:50	SKC	1.41	H
	3/27/07 0:20	SKC	1.58	L
	3/27/07 23:00	SKC	1.6	T
	3/29/07 3:10	SKC	1.12	L

4. Synoptic condition and visibility

The formation, dissipation and evolution of fog are highly depended on meteorological condition. The near fog situation has also been influenced by synoptic condition. Table 2 shows the list of the fog and quasi fog event which have been analyzed in this study. Based on the time of observation of the lowest visibility we have averaged the data on fog and quasi fog event. We have compared fog and quasi fog events in different average scale to find the key elements. The 4 days of radiation fog and 12 days of quasi fog events have been analyzed. We have studied the meteorological situation as a permanent parameter in fog formation during Jan, Feb and March 2007 for fog and quasi-fog events. The monthly average of meteorological data and visibility has been shown on Table. 3.

The visibility (Vis) is ranged between 22 and 28 km during winter. There is 6 days with daily average of Vis less than 5k during the period. Two foggy days 27 Jan and 2 Feb and 3 days of quasi fog events are included. 28 days of whole period has the daily average of visibility more than 29 km. The average of lowest visibility at fog days is 270 m and for quasi fog event is 1450m. We have considerd the time of the day, the local meteorological influence like temperature, humidity and wind speed to better describe the daily evolution of the visibility and the important keys of fog formations.

The evolution of Relative Humidity (RH)during the 3 months Jan, Feb, March have been studied (are not shown here). Before 6 Jan there is no high variation of RH. But the morning of 6 and 7 Jan RH increase to 95% the morning and decreases in afternoon. The days before fog and foggy days (1, 5, 7 and 8 Feb) in the morning the values of RH are larger than 95 %. We have observed an important variation before 18 and 19 Feb (value between 50% and 90%) during fog and quasi fog events. Radiation fog, which generally occurs as ground fog, is caused by the radiation cooling of Earth's surface. The average of temperature for whole period is about 7°C. It is primarily a night time occurrence but it often begins to form in late afternoon and may not dissipate until well after sunrise. Radiation fog is common in high-pressure system where the wind speed is usually low (less than 2.5m/s) and clear skies are frequent. Table.3 shows that we have higher pressure on January compare to March and February. The dominant wind in the whole of period is blowing from south-west with the speed of 3m/s in Jan and Feb and 2.6 ms^{-1} on March.

Table 3 The monthly average of visibility and meteorology data during Jan, Feb and March 2007, and average of meteorological parameter and visibility at thetime of lowest visibility of fog and quasi fog event Average[min-max]

Date	VIS(km)	T(°C)	RH(%)	P(hPa)	WD(deg)	WS(m/s)
Jan	28 [0-99]	6.9 [-6-14]	86[25-99]	1002 [987-1017]	220	3.8[0.1-11.7]
Feb	22 [0.07-99]	7.4 [-1.2-17]	84[45-99]	992 [970-1017]	200	3.1[0.1-11.4]
March	23 [0.07-99]	7.1 [-1-19]	80[36-99]	998 [976-1022]	227	2.6[0.1-10.7]
Fog	0.27 [0.1-0.9]	4 [2-7]	96[92-99]	1006 [998-1017]	206[96-343]	1.4[0.4-2.4]
Quasi-fog	1.47 [0.4-1.99]	6 [1-11]	91[81-97]	999 [981-1017]	166[48-337]	1.8[0-4.8]

Mean while the table. 3 shows the10 minute average of visibility and meteorological parameters at the time of observation of lowest visibility for fog and quasi fog days. Stolaki et al (2009) have studied fog events which is mainly formed in winter in Greece. They observed that Formation of fog is around sunrise or 1 or 2 h before it in Thessaloniki. The mean duration is about 4h with density of 75%. In our study, Fog days happened normaly after sunset between 22 and 24 UTC except 4 March in that fog happened before sunrise. Lowest visibility in quasi fog event (12 days) have been observed between 0 to 3UTC, one case at 10 UTC and between18 and 23 UTC after sunset. We have higher temperature in quasi-fog days compare to fog events whereas the relative humidity is about 96 and 91 for fog and quasi fog days respectively.

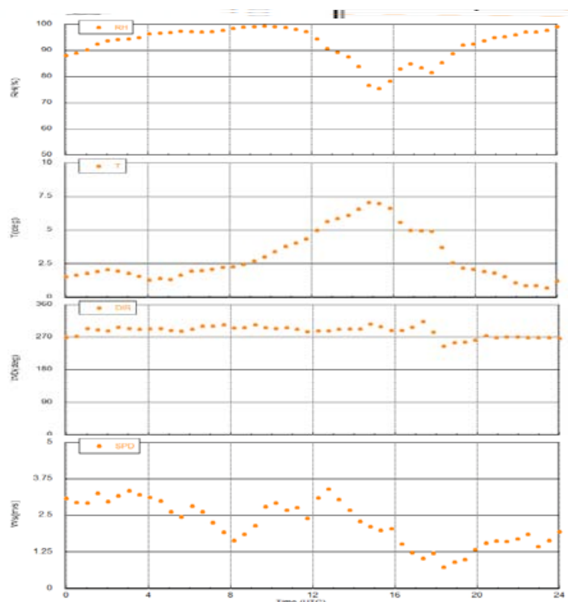

Figure 2 10 minute average of meteorological parameters of a fog condition on 27 January 2007; fog formation at 23:50 visibility, relative humidity, temperature, Wind direction speed and wind speed

In foggy days dominant wind is from south-west and for quasi fog event is south-east with the calm wind of about 1.5 m/s. Figure 2. shows the synoptic –meteorology and visibility of a fog study on winter of 2007 on 27 January. The fog has been formed at 23:50 UTC. All of the meteorological parameters have been compared by the variation of the visibility. The temporal variation of these parameters before formation of fog can help us to better understand the impact of meteorology on visibility. The visibility changes between 100 m and 15km. It can be observed that the highest value of relative humidity 99% is related to 100 m of visibility. The wind direction approximately is in NW section whole days and it changes to SW at 17UTC . The largest value of visibility is observed at 17 UTC and it changes to less than 5km (haze before fog) 2hours before formation of fog.

5. Result and discussion

Aerosol optical and microphysical (mass, number, aerosol optical thickness, extinction coefficient) properties have been analyzed during Paris –fog experiment 2007. Table.4 shows the microphysical and optical properties of aerosol which have been averaged based on the time of observation of lowest visibility. It can be observed that the AOT has the same average value for fog and quasi fog event at the time of lowest visibility. Fog event has higher AOT between 0.1 and 0.2. The available AOT data on quasi fog event is 50% and for radiation fog event 100%. The average mass concentration of ultrafine aerosol particle is higher for fog event. The PM2.5 and PM10 mass are higher in radiation fog compare to quasi fog event 65 and 83% respectively. Accumulation mode number during radiation fog days is ranged between 459 to 2973 cm-3 and their mass is ranges between 305 and 2271 µgcm-3. As the droplet are forming before the time of observation of lowest visibility then microphysical and meteorological parameters some hours before the fog formation are important to be analyzed. Table 5. shows the average of microphysical parameters 3h, 2h and 1h before observation of minimum visibility. The hourly average of the parameters has been presented after the observation of reduction of visibility 3h before formation of fog or observation of minimum visibility. 3h before observation of lowest visibility; first, the level of hourly average of visibility is decrease about 72% compare to one hour before fog formation. For quasi fog the visibility of

12 km decreases 3h before observation of lowest visibility to 10.9 km and to 9.9 km 1 h later which is about 20%.

Table 4 Average of aerosol microphysics characteristic at the time of lowest observed visibility, *UF : Ultra-Fine mode (r<0.5µm) , AC : Accumulation mode 0.4<r<2µm) , FD : Fog Dropplet (r>2µm)*

		Number of part. /m³						Mass of part. /m³	
Moyenne [Min-Max]	AOT	PM2.5 Fitry	PM10	UF	AC	FD	PM2.5 SIRTA	UF	AC
FOG	0.13 [0.1-0.2]	44 [20-66]	53 [15-81]	10553 [7280-16000]	1482 [459-2973]	76 [85-194]	34 [7-63]	4 [2-6]	1347 [305-2271]
QUASI-FOG	0.13 [0.01-0.2]	24 [9-55]	32 [12-63]	12798 [1580-28200]	103 [44-446]	2.9 [0.2-8.1]	32 [16-48]	2.7 [0.6-5.1]	144 [45-289]

Wind direction during fog days is in WS and it is approximately blowing from the same direction during 3h before formation of fog whereas in quasi fog days the wind changes from S to SW. we have higher wind speed 3h before observation of lowest visibility quasi fog days but the wind speed does not vary a lot.

Table 5 .Average of microphysical parameters before observation of minimum visibility. The hourly average of the parameters has been presented after the observation of reduction of visibility from 3h before formation of fog or observation of minimum visibility.Q-Fog are the quasi fog event.

	Vis (km)	DIR (deg)	SPD (m/s)	N1	N2	N3	M1	M2	M3
3h before Min Vis									
Q_FOG	12.0	177.4	1.9	8535.5	9515.6	142.4	30.1	2.2	91.9
FOG	8.1	208.1	1.2	5706.2	15446.3	119.5	27.7	3.3	94.1
2h before Min Vis									
Q_FOG	10.9	219.9	1.8	7333.4	11436.9	427.5		2.7	197.0
FOG	5.4	202.4	1.3	2464.8	14333.8	556.7	39.6	3.4	247.1
1h before Min Vis									
Q_FOG	9.9	221.0	1.8	7685.5	12558.8	692.1		2.9	690.2
FOG	2.2	222.1	1.4	1307.0	13562.5	1147.6	43.3	3.7	713.2

N1 (cm-3) aerosol number concentration measured by CPC, for diameter D < 3 um, N2 (cm-3) ultra fine aerosol number concentration measured by SMPS (D<0.5 um), N3 (cm-3) accumulation mode aerosolnumber concentration measured by WELAS-2000 (0.4<D<2 um), M1 (ug/m3) aerosol mass measured by TEOM, M2 (ug/m3) ultra fine aerosol mass measured by SMPS (D<0.5 um), M3 (ug/m3) accumulation mode aerosol mass measured by WELAS-2000 (0.4<D<2 um)

Number of aerosol measured by CPC is less than quasi fog days. Ultra fine particle number is decreasing about 25% in foggy days however their mass is approximately constant. The accumulation mass and number has approximately higher value of 89% and 86% 1h before formation of fog compare to 2h former. The variation in mass and number of accumulation mode in fog and quasi fog events has upward trends which is one of the most important keys in fog formation beside meteorological parameters.

5.1 Microphysiccal and optical properties of aerosol(Mass, number)

5.1.1 Particle mass concentration PM2.5, PM10 and other pollutants

The role of aerosol in fog formation not only depends on their optical properties and their size distribution of diurnal cycle of particle mass concentration on reduction of visibility and fog formation.

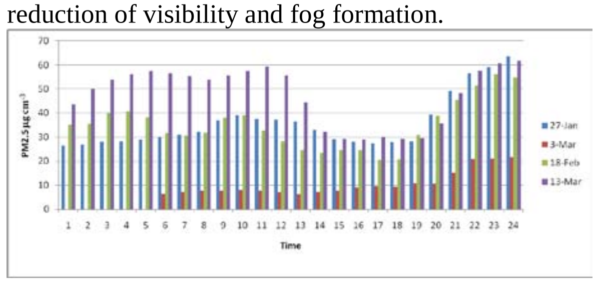

Figure 3 diurnal cycle of the PM2.5 mass concentration for foggy days, 27 Jan, 18Feb, 3 and 13 March

Figure3. shows the diurnal cycle of PM2.5 for foggy days. It can be observed that after sunset the level of PM2.5 have a high increase and is not just due to urban circulation. It can be also related to increase of humidity after sunset but the increase of humidity is not the single reason because the level of AOT in the foggy days has been high. As we are interested in the key parameters for formation of fog compare to quasi fog event that have approximately the same level of relative humidity, it seems the level of pollution can be one of the main parameter after the aerosol number concentration.

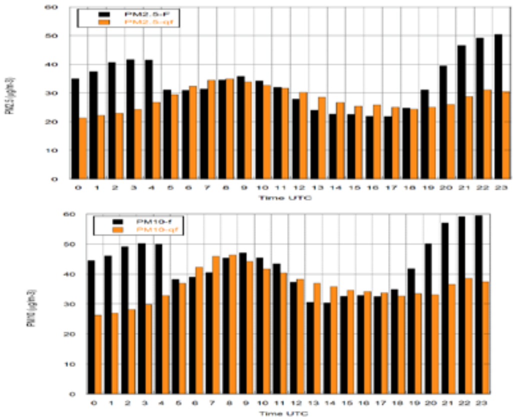

Figure 4 Diurnal cycle of PM2.5 and PM10 for fog and quasi fog

In figure 4 we have compared the diurnal cycle of PM2.5and PM10. The level of PM2.5 in fog days is 42% and higher compared to quasi fog event. The percentage changes from 20 to 98% after 17 UTC in the evening. No2 concentration varies between 40 to 20 % during 19 and 23 UTC. We have observed the same trend of diurnal cycle of PM2.5 and PM10 which start to have upward trend from 20 to 55 µg/m-3 and 33 to 60 respectively between 17 UTC and 23 UTC. Increase of PM2.5 and PM10 is related to decrease of boundary layer height during foggy days. The calculated boundary layer height shows the quasi fog days have higher boundary layer height compare to fog days about 25% between 17 UTC and 22 UTC is obvious reason of increasing of PM2.5 and PM10. Figure 5 shows the relationship between the hourly average of visibility and PM2.5 and PM10 between 17 UTC (time of highest observed visibility) and 23UTC. The good correlation coefficients of R2 of 0.79 and 0.73 have been observed respectively during fog events. Wen et al (2010) have found the visibility versus PM10 as exponential curves which enable the range of the range of visibility to be predicted from measured PM10 concentration. The removal and production of aerosols have been evaluated in fog. The fog top has important role in entrainment due to the mixing as a process which provides reactant to fog layer.

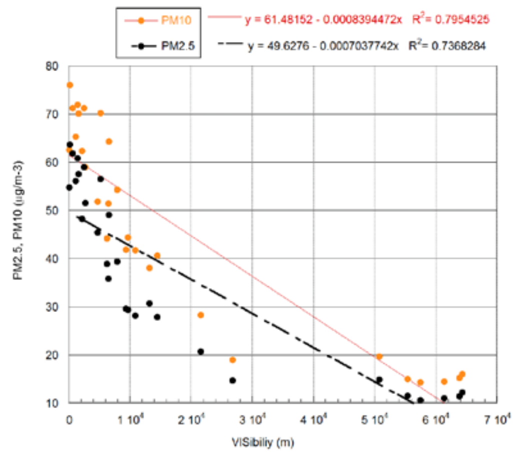

Figure 5 Relationship between the PM2.5 and PM10 and visibility between 17 UTC and 23 UTC on fog events

Fogwater concentration of nitrate and sulfate and ammonium can increase up to 30%. The fraction of scavenged aerosol by fog droplet is important for the fog effect on PM (Lillis et al. 1999). Dall'osto et al (2009) have shown the formation of the secondary aerosols during a fog event in London. They have found change in chemical properties in droplet mode. Particle which are rich on nitrate and organic carbon (200-300 nm) have been formed during fog events.
Nitrate and sulfate can be removed from the air by fog formation depends on the presence of gas phase and oxidants. The level of sulfate and nitrate differs on fog and quasi fog events.

5.1.2 Aerosol accumulation mode

To understand the influence of aerosol microphysical parameters on visibility we have compared the aerosols accumulation number and visibility for the time before a fog formation and near fog. It is clear that before fog formation we have abrupt reduction of visibility which is normally between 3 to 1 hours before fog formation. We have found the good correlation between augmentation of accumulation number and reduction of visibility for the interval of visibility on near fog (1km <Vis< 5km)(Table 4). Figure 6 shows the relationship between the visibility and accumulation number concentration during haze condition before fog formation in fog event and quasi fog event. We have chosen the visibility between 1km and 5km.

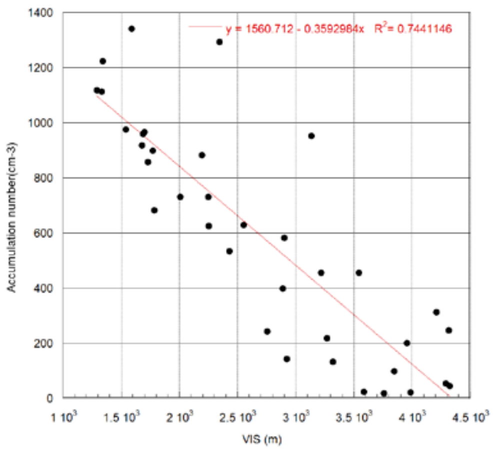

Figure 6 Correlation between accumulation number and visibility for the near fog definition range of visibility between 1 and 5 km

The simple regression coefficient of 0.86 shows the important roles of activated mode. Figure 6 shows the relationship between accumulation mass concentration and visibility. It can be observed that the correlation coefficient between visibility and mass R is decreased to 0.76. It can be conclude that aerosol activated number mode concentration are more related to visibility reduction.

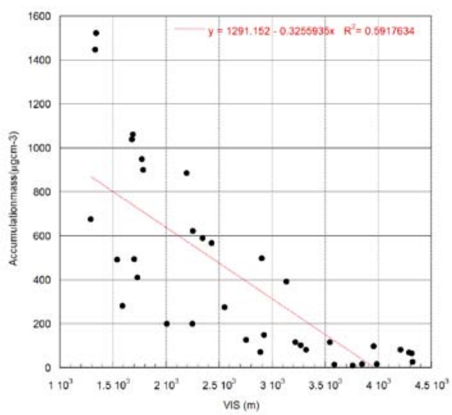

Figure 7 Correlation between accumulation mass and visibility for the near fog definition range of visibility between 1 and 5 km

5.1.1 Aerosol backscattering vertical profile and boundary layer

Figure 8 shows the structure of low level boundary layer on 27 Jan 2007 which was similar to profile of aerosol backscatter on 18 February (not shown) after 18 UTC until the formation of fog at 23:50 and 22:40 respectively. These cases have different vertical structure from 4 and 13 of mars. In all case before formation of fog the backscatter signal of ceilometers increased which is corresponded to aerosol concentration. On 27 Jan and 18 Feb we had the dense fog in that 30 minutes before the fog formation the layers gradually lowers at 22:40 and 23:50 the fog makes ground contact. As the surface visibility suddenly lower to a minimum which continues for the duration of the fog.

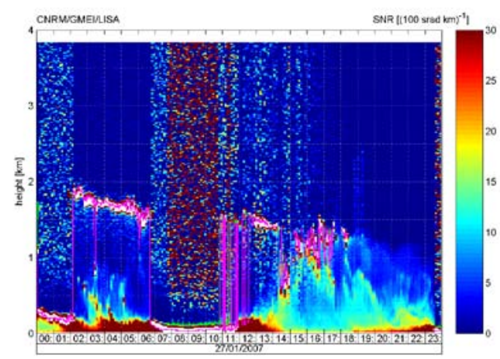

Figure 8 Ceilometer image of the radiation fog days 27 Jan

The Ceilometer plots shows the formation of fog and after some hours depends on dissipation process the fog lifts to an elevated layer for example on 19 Feb after 9 UTC (which have not been shown here) and it can be seen from the level of visibility. Surface level of relative humidity also showed a decrease in relative humidity. The ceilometers shows the presence of fog in all cases except 13 of March which have been observed a very thin layer of fog.
Hourly average of diurnal cycle of boundary layer height calculated using gradient method for fog and quasi fog events using backscatter signal of ceilometer. After sunrise the boundary layer height is increasing to have its maximum at 16 UTC late. We have observed the mixing in the boundary layer as a function of the day. We can define the period when the turbulence occurs by looking at the wind reinforcement and the temperature decrease and

relative humidity increase. The impact of the relative humidity on PM2.5 is observed for fog days and quasi fog days. We show that using additional information on the structure of the boundary layer detected by ceilometer, first we can understand better the variation of PM2.5 and PM10 in end of the day, secondly we can improve the correlation between aerosol optical thickness and ground-level visibility**.**

5.2 Retrieved visibility from Aeronet aerosol opticl thickness and backscatter signal of ceilometer

First, we compared the temporal evolution of AOT of foggy days and the day after and before. The AOT measured by aeronet are not available for all of the fog and quasi fog events. The AOT in foggy and the day after of fog between 17 and 20 February has been compared in that period 18 is the day with a dense fog and 19 is a quasi fog event. The day before the fog days has lower value of AOT_{440} of 0.098 and it change to 0.17 on 18 February. On 19 and 20 the value of AOT continuously is increasing because of long range transport. There is no available prove for the relative influence of regional transport on fog radiation. The value of AOT is about 73% higher in 18 Feb compared to 17 Feb. Secondly we have retrieved the Visibility using

the Koschemier method which is explained on the Section 3. It can be observed considering the constant value of Z=1km is not enough good for best estimation of visibility(Figure 10) because during the winter, the boundary layer height is most of the time less than 1km.We have used the boundary layer height which is obtained by backscatter signal of Ceilometer to find the best estimation of visibility.

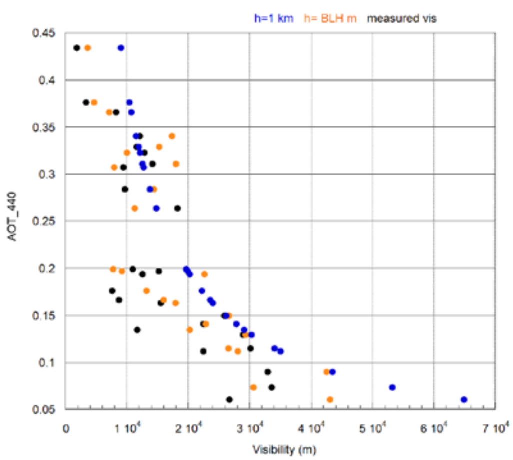

Figure 9. Retrieval of the visibility using AOT –Aeronet

The retrieved visibilities are in good agreement of calculated visibility. Figure shows the regression coefficient of R= 0.8(Figure 10).
The ceilometers –TSI is able to detect cloud layers and fog may be the base altitude could be obscure due to ground based fog. We have applied a relative humidity correction factor on the low level ceilometer signal. The regression coefficient is about R^2 =0.62(Figure 10).

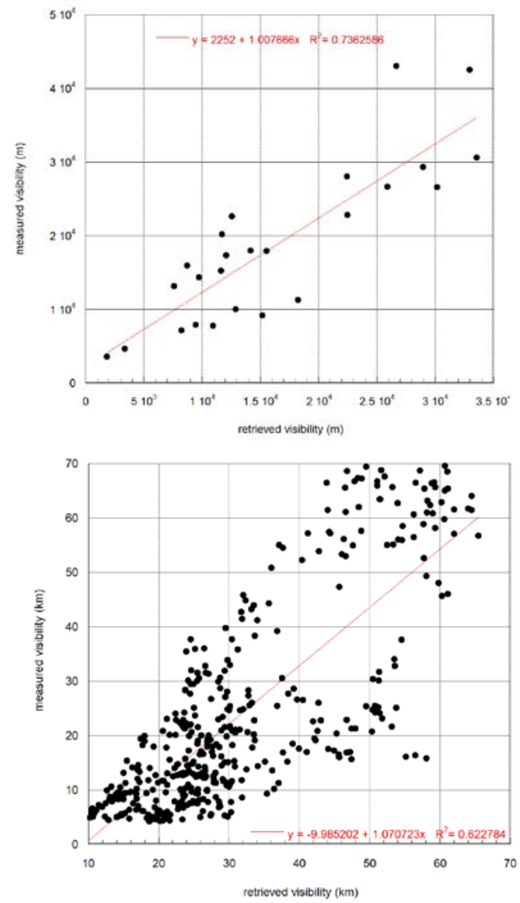

Figure 9 The regression equation between retrieved visibility a) using available aerosol optical thickness and measured visibility b)using backscatter ceilometers signal at first level and visibilty

Refrences

[1]. Alföldy, B., and Coauthors, 2007: Aerosol optical depth, aerosol compoistion and air pollution during summer and winter conditions in Budapest. *Science of the total environment*, 383, 141-163.

[2]. Allen, G., and R. Ress, 1997: Evaluation o the TEOM method for measurement of ambiant particulate mass in urban areas. *J. Air Waste Manage. Assoc.*, 47, 682-689.

[3]. American-meteorological-society, 2000: Online Glossary of Meteorology, 2nd Ed ition. *Accessed in 2009 at* http://amsglossary.allenpress.com.

[4]. Baumer, D., B. Vogel, S. Versick, R. Rinke, O. Mohler, and M. Schinaiter, 2008: Relationship of visibility, aerosol optical thickness and aerosol size distribution in an ageing air mass over South-West Germany. *Atmospheric Environment* 42, 989–998.

[5]. Boyouk, N., J.-F. Léon, H. Delbarre, T. Podvin, and C. Deroo, 2009: Impact of the mixing boundary layer on the relationship between PM2.5 and aerosol optical thickness. *Atmos. Environ.*, in press.

[6]. Cermak, J., R. M. Eastman, J. Bendixc, and S. Warren, 2009: European climatology of fogand low stratus based on geostationary satellite observations. *Q. J. R. Meteorol. Soc*, 135, 2125–2130.

[7]. Dall'Osto, M., R. M. Harrison, H. Coe, and P. Williams, 2009: Real-time secondary aerosolformation during a fog event in London. *Atmos. Chem. Phys.*, 9, 2459-2469.

[8]. Das, S. K., A. Jayaraman, and A. Misra, 2008: Fog-induced variations in aerosol optical and physical propertiesover the Indo-Gangetic Basin and impact to aerosol radiative forcing. *Ann. Geophys.*, 26, 1345–1354.

[9]. Duynkerke, 1998: Turbulence, Radiation and fog in Dutch Stable boundary layer *Boundary-Layer Meteorology*, 90, 447-477.

[10]. Elias, T., and Coauthors, 2009: Particulate contribution to extinction of visible radiation: Pollution, haze, and fog. *Atmos. Res.*, 92, 443-454.

[11]. Gultepe, I., and Coauthors, 2009: The fog remote sensing and modeling field project. *AMS*.

[12]. Haeffelin, M., and Coauthors, 2009: ParisFog, shedding new light on fog physical processes. *American Meteorological Society*.

[13]. ——, 2010: ParisFog, shedding new light on fog physical processes. *American Meteorological Society*.

[14]. Hänel, G., 1976: The properties of atmospheric aerosol particles as functions of the relativehumidity at thermodynamic equilibrium with surrounding moist air. *Adv. in Geophys.*, 19, 73-188.

[15]. Kokkola, H., et al., 2003: On the formation of radiation fogs under heavily polluted conditions. *Atmos. Chem. Phys.*, 3, 581- 589.

[16]. Lillis, D., N. C. Celia, CollettJr. b, and L. W. R. a. S. N. Pandis, 1999: Production and removal of aerosolnext term in a polluted previous termfognext term layer: model evaluation and previous termfognext term effect on PM *Atmospheric Environment*, 33, 4797-4816.

[17]. Mohan, M., and S. Paraya, 2009: Influence of aerosol spectrum and air pollutants on fog formation in urban environment of megacity Delhi, India. *Environ Monit Assess*, 151, 265-277.

[18]. Nowak, D., D. Ruffieux, J. Agnew, and L. Vuilleumier, 2008: Detection of fog and low cloud boundaries with ground-based remote sensing system. *J.of.Atmos. and Ocean. Tech*, 25, 1357-1368.

[19]. Ogawa, N., K. Youshimura, R. Kikuchi, T. Adzuhata, T. Ozeki, and M. Kajikawa, 2004: Effect of long- range

transport of Air Mass on the Ionic Component in radiation fog in northen Japan. *Analy. Sci*, 20.

[20]. Oldenborgh, G. J., P. Yiou, and R. Vautard, 2010: On the roles of circulation and aerosols in the decline of mist and dense fog in Europe over the last 30 years. *Atmos. Chem. Phys.*, 10, 4597- 4609.

[21]. Patashnick, H., and E. G. Rupprecht, 1991: Continuous PM10 measurements using the tapered element oscillating microbalance. *J. Air Waste Manage. Assoc.*, 41, 1079-1083.

[22]. Raut, J. C., and P. Chazette, 2008: Vertical profiles of urban aerosol complex refractive index in the frame of ESQUIF airborne measurements. *Atmos. Chem. Phys.*, 8, 901-919.

[23]. Seinfeld, J. H., and S. N. Pandis, 2006: *Atmospheric chemistry and physics: from air pollution to climate change, second edition.* J. Wiley & Sons, 1203 pp.

[24]. Shi, C., M. Roth, H. Zhang, and Z. Li, 2008: Impacts of urbanization on long-term fog variation in Anhui Province, China. *Atmospheric Environment 42 (2008) 8484–8492*, 42, 8484 -8492.

[25]. Stolaki, S. N., S. A. Kazadzi, D. V. Foris, and T. Karacostas, S., 2009: Fog characteristic at the air port of Thessaloniki, Greece. *Natural hazards and earth system sciences*, 9, 1541-1549.

[26]. Van Dingenen, R., F. Raes, and et al., 2004: A European aerosol phenomology - 1: physical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. *Atmos. Environ.*, 38, 2561-2577.

[27]. Wang, J., S. M. Li, and x. L. Liu, 2010: An analysis of the fog distribution in Beijing for the 2001–2005 period using NOAA and FY data. *Atmos. Res.*, 96, 575-589.

[28]. Wen, C. C., and H.-H. Yeh, 2010: Comparative influences of airborne pollutants and meteorological parameters on atmospheric visibility and turbidity. *Atmo. Res*, 96, 496-509.

[29]. Zhou, B., and J. Du, 2010: Fog prediction from a multi model mesoscale ensemble prediction system. *weather and forecasting*, 25, 303-322.