Sodar studies of foggy atmospheric boundary layer characteristics over Delhi

Neha Gera[1], N.C.Gupta[1] , V. Mohanan[2] , B.S. Gera[2]

Abstract— Sodar observations of Atmospheric Boundary Layer (ABL) pertaining to foggy days of a decade long period winter periods (2001-2010) over Delhi have been used to study characteristic features of ABL response during Fog with reference to air pollution meteorological aspects. It has been seen that thermal structure characteristics of relevance in air pollution such as inversion/mixing height, fumigation, low level elevated inversion under go significant deviation of concern for air quality risk and management strategies planning. Depending upon fog density (light, medium or high density), period of breaking inversion (fumigation) may stretch from normal within couple of hours after sunrise to late afternoon hours during dense fog. During conditions of prolonged fumigation, breaking inversion stays as an elevated capping layer over weak thermal convection below. Such low level elevated inversions may persist during whole day, even continue to exist nighttime and may persist for 3-4 days at a stretch. These conditions are alarming air pollution meteorological hazards and their occurrence characteristics have been studied. Besides, some new typical observational characteristics such as nocturnal inversion lift, Gaussian curve type bell shaped evolution of ABL height trajectory and the two tier inversion structure are discussed as new highlights of Foggy ABL thermal structures. The results form useful inputs in real time dispersion modeling for environment impact assessment and now casting / short range fore casting of air quality and fog prediction modeling.

Index Terms—Air pollution Meteorology, Atmospheric Boundary layer, Fog, Inversion, Mixing height, Stability, SODAR.

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1 INTRODUCTION

Sodar is an acoustic remote sensing technique for real time monitoring of atmospheric boundary layer (ABL) thermal structures of concern in air pollution meteorology (Coulter and Kallistratova, 1999). Occurrence characteristics of the meteorological processes associated with ABL thermal structures such as inversion and thermally convective mixing height, stability, transitional phases of stable/ unstable atmosphere etc. play significant role in determining atmospheric carrying capacity of pollutants load. Therefore, knowledge of such city specific air pollution meteorological aspects is the back bone of planning strategies for city air quality management.

The characteristics of said air pollution meteorological aspects are governed by earth-atmosphere energy exchange budget and as such exhibit site/city specific characteristic diurnal/ seasonal variations according to its geographical location, topographical features, local and prone to synoptic climatologically conditions (Gera and Saxena, 1996).

In this context, winter is considered as the critical period of the year when the atmospheric carrying capacity gets reduced to its minimum and at times the environmental hazard for air pollution may develop. Occurrence of fog, during winter, further aggravates the situation due to smog formation that drastically reduces the visibility that halts /slow downs all modes of transportation. The slow dragging of vehicular motion adds to road side air pollution. In this context, real time modeling of environment impact assessment coupled with prevailing characteristics of air pollution meteorological aspects is vital for now casting and short range fore casting of air quality/ fog clearance etc. and action calls plan of dynamic capital region, Delhi, India. In particular, the analysis highlights the occurrence characteristics of the ground based/ elevated inversions strategies for rapid traffic transit control mechanism, industrial operational hours for air quality management in the true sense. Besides, a statistical study of the characteristics of city air pollution meteorology is important to evaluate city carrying capacity and accordingly check industrial expansion or setting up new industries.

The potential use of sodar information in prediction model of air quality and fog clearance has been reported several times (Walls, 2008). In particular, the sodar potential to map fog dynamics was earlier demonstrated clearly during the occurrence of synoptic fog storm associated with passage of Western Disturbance (Gera et al., 1990; Singal, 1997) in northern belt of India. However, in view of the expected criticalities of fog induced winter anomalies in normal characteristics of air pollution meteorological aspects, present studies are aimed to examine the same. Besides, typical characteristics of the new insight of Foggy ABL thermal are discussed.

- *Neha Gera is currently pursuing Ph.D in university school of environment management, GGSIPU, India, Delhi, PH-9958878884. E-mail: nehagera@gmail.com*
- *N.C Gupta is Associate Professor in USEM,GGSIPU, India,E-mail: ncgupta1@gmail.com*
- *V.Mohanan & B.S. Gera- scientist at National Physical Laboratory, Delhi*

In this context, an indigenously developed mono-static SODAR (Singal & Gera, 1982) at the National Physical Laboratory premises has been operating for the last several years. The observational data pertaining to foggy days of the decade long winter periods during the years (2001-2010) has been analyzed to unfold air pollution meteorological aspects of the national, thermally convective mixing, periods of fumigation, atmospheric stability, transitional phases of stable/ unstable atmosphere etc. Since inversion trap pollutants while thermal convection favors dispersal and vertical migration of pollutants, timings of inversion formation and onset of free thermal convection are also studied to know life span of good ventilation during winter.

2 SODAR-TECHNOLOGY CONSIDERATIONS

Sodar- Sound detection and ranging, is an acoustic remote sensing technique (McAllister, 1968, Little, 1969: Cliford and Kaimal et al., 1994: Giannini, et al., 1997) that essentially function like an active radar, lidar, sonar etc and probes the atmospheric height up to 1 Km. The operational principle banks upon acoustic wave scattering properties due to the presence of in-homogeneities in temperature, wind and humidity in the air. Since occurrence of fog in the lower atmosphere presents real time picture sodar tracers of in-homogeneities in temperature and moisture in air, sodar can be effectively used to study characteristics of foggy ABL. In particular, the SODAR can provide real time variations in vertical depth of the fog layer which is important input in modeling prediction of fog clearance. (Reudenbach and Bendix, 1998)

While in operation, sodar transmits highly directional high power short bursts of sound energy (10 – 20 Watt) of fixed audio frequency (between 1 – 6 K Hz) with duration of about 100 ms repetition rate of 6 seconds for 1 km probing range. The back scattered acoustic signals from atmospheric fluctuations, of eddy sizes 0.1 – 1 m within the inertial sub-range of turbulence, are received either by the same antenna (monostatic or back-scattering operational mode) or by another antenna (bi-static or forward scattering operational mode) placed at a little distance from the transmitting antenna. The signals are processed to produce pictorial view of the turbulent regions occurring in real space and time above the antenna.

2.1 Data Distribution

SODAR data pertaining to 184 observational foggy days pertaining to winter (November-January) periods spread over decade long span of 10 years (2001 - 2010) has been analyzed. The relative annual data distribution in terms observational days and hours is shown in Fig.1.It is seen that relatively the extensive fog occurred during the years 2002-03 and 2009-10 with swings of ups and downs during alternate years. The maximum fog occurrence percentage was during the winter period of 2009. The data has been, further, analyzed according occurrence of fog density being light, medium and dense according to its impact on visibility. Fog is considered light for visibility > 500m, medium density for 50m < visibility < 500m and dense fog visibility < 50m.

Based on fog classification, fog density was light for 88 days, medium for 57 days and it was dense fog for 39 days. Further, hourly analysis shows that of the total observational hours (4284 hours) fog density was light for 21% of the time, medium for 32% of the time and dense fog for 47% of the time. The analysis shows that there was occurrence of poor visibility for 79% of the time pertaining to days of medium and high density fog. Besides, it was noted that the fog mostly occurred during the nocturnal period at around midnight and persisted through early morning hours of the day overlapping over the period of fumigation during the morning hours.

3 CHARACTERISTICS OF FOGGY ABL THERMAL STRUCTURES

3.1 Fumigation

Under normal fair weather conditions ABL exhibits a well defined diurnal cycle, say, beginning with on set of a stable inversion layer, shortly after sun set, which grows in height with continued radiational cooling of the ground with passage of time. The inversion, which traps the pollutants, is mapped as ground based horizontal layer with more or less flat top. Inversion starts breaking (eroding) from below shortly after sun rise. The phenomenon appears as a rising layer, on sodar records, due to vertically directed thermal buoyant forces due solar heating of ground. This phase of breaking inversion is known as fumigation in air pollution meteorological terms and is considered a critical period from air quality point of view. During this period pollutants trapped over night within inversion literally start falling downwards towards the ground due to breaking of inversion from below as upper part of inversion is still stable. Therefore, fresh emission coupled with these downward fumigating pollutants from rising inversion increases the ground level pollutin concentration to its maximum. With continued increased solar heating, the breaking inversion gets weaken and finally disappear at one time and thereafter free thermal convection (marked on sodar as vertical air cells with broad base and tarpapered columns) takes over marking change over of stable to unstable ABL. Thermal convection migrates pollutants upwards through vertical mixing and dilutes pollution. It subsides around sunset and the cycle is repeated again.

In view of said characteristics of diurnal cycle of ABL stability, knowledge about life span of fumigation and its dissipation time (complete inversion break up) is important as it favors more of ground level pollution and demands strategies to check for avoiding/ minimizing on fresh emissions till onset of free convection.

In pursuit of the same, we have studied dissipation time of breaking inversion with reference to fog during winter conditions over Delhi. In this context, it may be mentioned that inversion break up time is a function of over night inversion strength (temperature gradient) and the solar heating of ground. Thus, fumigation life, beginning with sun rise, is the time required for the inversion to dissipate due to solar heating of the ground. Thus, its depends on the prevailing local/ synoptic meteorological condition, cloud cover, fog, aerosol optical depth, topographical features etc which directly or indirectly affect earth –air hear exchange energy budget. Under normal fair weather, fumigation (inversion break) is over within couple of hours during winter but it can continue to late afternoon hours or continue the day whole under adverse foggy weather conditions.

The typical example of the SODAR echograms (Figure 2) clearly illustrates comparatively different fumigation periods during a foggy and non foggy winter days. Thermal plume activity is seen to form under the eroding fog layer.

3.2 Persistence of Low Level Elevated Inversion

Prolonged fumigation associated with strong inversion coupled with poor solar heating of ground, during dense fog, often results in the persistence of a low level elevated inversion as shown above in Figure 2c. In fact, the poor ground heating results in weak thermals buoyancy which is insufficient to lift the ground inversion to higher heights and break through it on foggy. Under such conditions the eroding inversion stays as an elevated inversion level over and above the weak thermal convective activity at ground. Depending upon prevailing fog density, it may dissipate in afternoon hours or may continue to persist even during the night hours as an independent identity, besides development of nocturnal ground inversion or at times may merge with the nocturnal boundary layer as shown in Figure 4.

It is seen that the inversion layer remains lifted from evening onwards throughout the night within a height range of 500 meters. Besides, echograms depict lifting of inversion even during the nighttime (Fig.4b). Moreover, the ground level under the canopy of such elevated layers shows convective thermal plume type structure within a height range of 200 meters while rest of the space under the canopy does not show any structure.

In view of the said observation, it is presumed that probably, the continually persisting top elevated layer is associated with the advection of fog layer or cold front which may have its origin either in the hills due to heavy snowfall or other some other synoptic meteorological phenomena. While the formation of plume-like structure below may be due advection of surface winds from a nearby heat island zone. The no echo zone indicates that this zone is void of turbulence i.e., it is an adiabatic zone.

Further, the advection of heat from the heat island zone of the city further supports the observation of the ground based thermal plume structure (during night) under the canopy and lifting of the layer at night. However, all these conjectures need further planned studies with supporting mesoscale meteorological observations of wind and temperature profiles around sodar location during an occurrence of a fog event. Such data was not available to be examined for the present studies.

Further, the occurrence height of these persisting elevated layers, during the day, is of important consideration from the air quality point of view. Such elevated layers limits vertical mixing height of pollutants to its own occurrence height of about 200m as compared to normal weather day time mixing height of more than 1 km. This results in increased concentration of pollution level. Moreover, with continued persistence of such condition over successive days may lead to accumulation of excessive pollutant within lower levels of ABL and it may act as an environmental hazards of air pollution episode, particularly, under accidental release of toxic pollutants. Therefore, online information about such environmental situations is vital for real time environmental impact assessment, now casting, short range fore casting of air quality and strategies planning of emergency preparedness and disaster management, particularly under synoptic dense fog conditions.

3.3 Gaussian Bell-Shaped Curve Trajectory of Foggy ABL

Under highly dense fog conditions, it is seen that the morning eroding foggy inversion layer rises nearly exponentially to a height range of around one kilometer by the noon hour in accordance with unobstructed solar heating of ground. It descends, with same slope, towards the ground in the afternoon marking a Gaussian bell shaped curve trajectory of sodar echogram (Figure 5). Within the bell-shaped structure the intense thermal turbulence is indicated by high rise convective thermal plumes.

The observation indicates a unique case of strong foggy inversion layer with fairly good thermal heating below but that is not sufficient to either to completely break the inversion or lift it to heights beyond sodar probing range of 1 km. It may be mentioned that, even during normal fair weather conditions, the persistence o rising inversion layer overriding at the top of thermal convective boundary layer, during the day, is said to be a characteristic feature of the atmospheric boundary layer and it defines the height of the first inversion layer. However, it is not mapped by sodar for two fold reasons. Firstly, this height is normally more than the sodar probing range of 1km as such it can only been seen as rising layer going beyond range and descending part of layer in the late afternoon hours. The top being out of range, full trajectory is normally not traced on sodar records (Figure 4b). However, even such observation is not very frequent. Secondly, inversion in not strong enough to withstand piercing buoyant thermals from below and rising inversions continues to get weaker and weaker with the growth of convective boundary layer. It results, at one stage, in dominance of thermally buoyant turbulence over the weakening turbulence within rising inversion. Consequently, relatively stronger acoustic scattered sodar signals override the weaker sodar signals due to turbulence within the inversion. As such sodar signatures inversion disappears from the echograms and only thermal plumes are recorded. Time at which inversion disappears is normally taken as transition time of stable to unstable ABL. The experience show that, in general, rising inversion dissipates within reaching heights of about 500m (e.g. see Figure 2a). Even during normal cold winter, breaking rising inversion layer stays longer in the ABL but its height is seen to remains within range of 500m. More over, observations high lighting experimental evidence of complete physical description of mapping ABL height trajectory are hardly available to the best of our knowledge.

In this context, the present observation described is a rare case that has proven sodar potential to track complete diurnal evolution trajectory of inversion height. This information is very useful for model validation of ABL mixing height. Further, it also indicates that convective thermal boundary layer height can be perceived on the SODAR echograms under typical dense fog conditions. Under such situations, the height of ground level thermal plumes gives a direct measure of the mixing depth during daytime.

Besides, we have examined the impact of height of foggy inversion layer height on the visibility (Figure. 6). It is seen that the visibility also increases parallel in a bell-shaped manner. The data pertains to the foggy days when bell shaped ABL trajectory was recorded by sodar. The maximum of visibility is to correlate with periods of maximum height of ABL. The subject can be further developed, in conjunction with fog models, to forecast visibility on foggy days. The data for these plots was collected from India Meteorology Department.

4 FIGURES

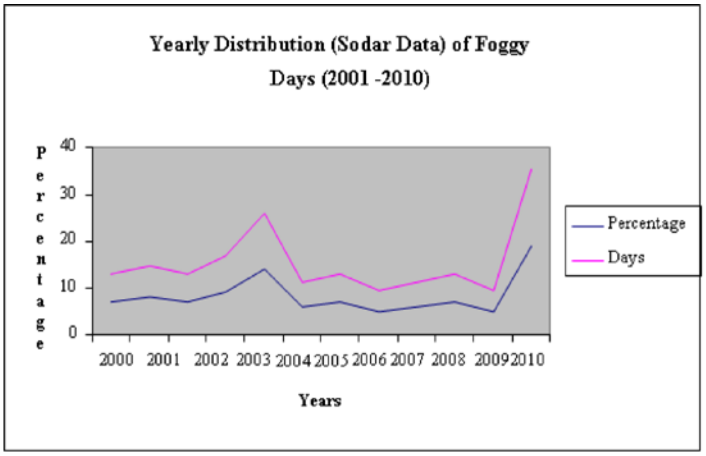
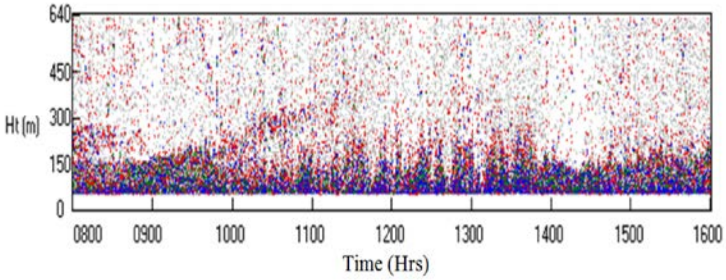
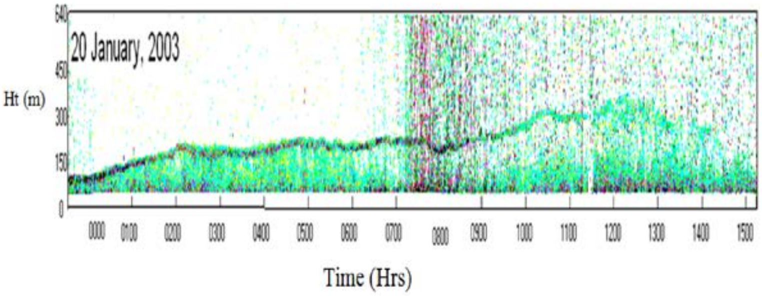


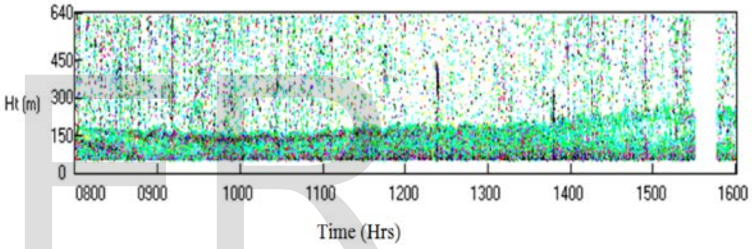
Figure 1: Yearly Distribution of Sodar Observations of Foggy Days during winter periods (November-January) over a span of 10 years (2001–2010)



(A) Dissipation Before Noon (No-Fog) 5 -2006



(B) Dissipation in the Afternoon (medium fog)



(C) Persistence in the Late Afternoon (Dense Fog) 16-1-2003

Figure 2: SODAR echograms showing comparative fumigation periods on foggy and non foggy days

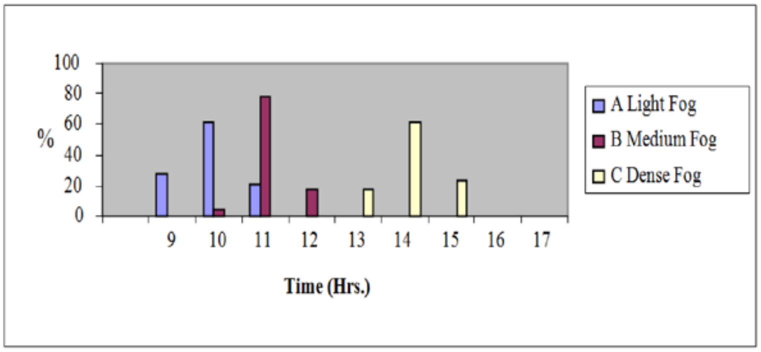
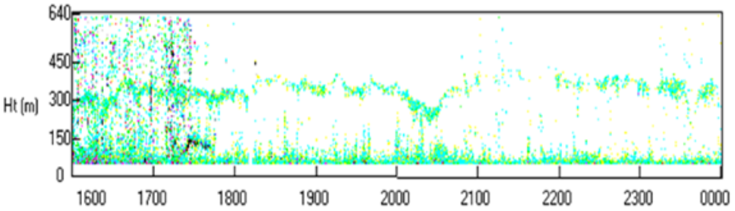
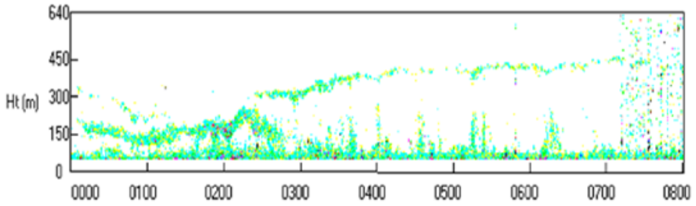


Figure 3: Dissipation times of eroding inversion during different (Light, Medium and Dense) fog conditions over Delhi (2001-2010)



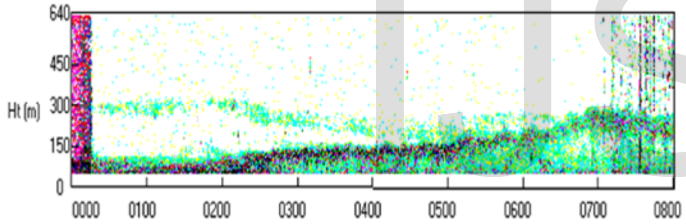
3-1-2003

(A) Elevated layer continuing from the afternoon to late night hours



9-1-2003

(B) Elevated layer continuing from midnight to morning Hours



13-1-2003

(C) Elevated layer continuing merging with the nocturnal ground Inversion

Figure 4: SODAR Echograms Elevated Layers during Fog conditions

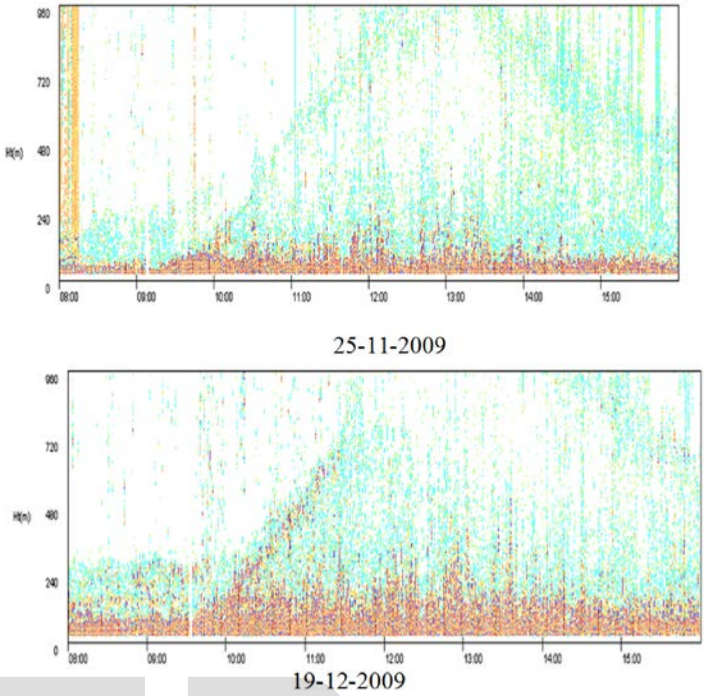


Figure 5: SODAR Echograms of Gaussian Bell-Shaped Foggy ABL thermal structure

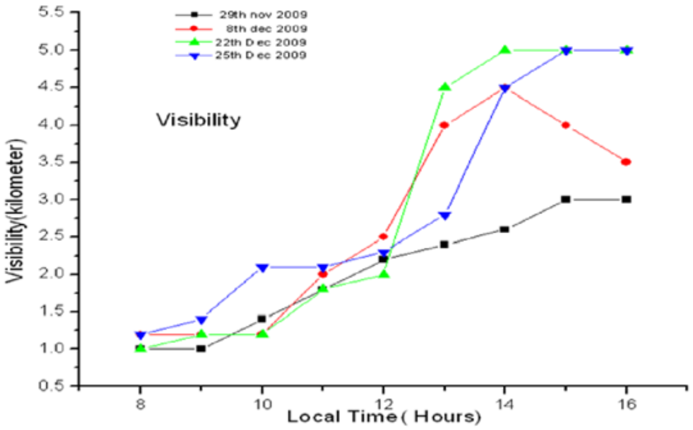


Figure 6: Visibility Plots on Some Days during the Winter Period (Courtesy of India Meteorological Department, New Delhi).

5 CONCLUSION

The present study has provided first SODAR observational evidence in support of meteorological considerations of first level inversion. Sodar could map complete physical description of a Gaussian bell shaped diurnal evolution characteristics of foggy ABL height during winter fog over Delhi. The height of ABL has a positive correlation with visibility. The information is useful for validation of ABL models and improving model performance of fog clearance. Besides, fumigation period during dense fog is seen to prolong till late afternoon hours and breaking inversion layer may continue to persist as an elevated inversion during the whole day. Such situations are environmental hazards for air pollution and need to be coupled with real lime dispersion modeling for EIA and strategies of air quality management. Conclusively sodar has great potential to deliver useful information about foggy ABL characteristics and share the same with other technologies in the interest of R&D and practical application for air quality management.

It will be prudent here to mention that in general the lifting of the long duration persisting fog layer due to solar heating is very slow throughout the day with the fog layer remaining close to the ground for most of the day time exhibiting poor visibility conditions. The usual daytime bell-shaped structure is absent i.e., the fog layer does not lower down or touch the ground level even in the late afternoon. This type of surface based fog layer structure sometimes persists for a few days at a stretch. This behavior of the fog layer is an indication of the continuity of the fog storm over a longer duration.

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