



A review on factors influencing fog formation, classification, forecasting, detection and impacts

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Abstract

With the changing climate and environment, the nature of fog has also changed and because of its impact on humans and other systems, study of fog becomes essential. Hence, the study of its controlling factors such as the characteristics of condensation nuclei, microphysics, air–surface interaction, moisture, heat fluxes and synoptic conditions also become crucial, along with research in the field of prediction and detection. The current review expands for the period between 1976 to 2021, however, especially focused on the research articles published in the last two decades. It considers 250 research papers/research letters, 24 review papers, four book chapters/manuals, five news articles, 15 reports, six conference papers and five other online readings. This review is a compilation of the pros and cons of the techniques used to determine the factors influencing fog formation, its classification, tools and techniques available for its detection and forecast. Some recent advanced are also discussed in this review: role of soil properties on fogs, application of microwave communication links in the detection of fog, new class of smog, and how the cognitive abilities of humans are affected by fog. Recently India and China are facing an emergence and repetitions of fog haze/smog and thus their policies initiatives are also briefly discussed. It is concluded that the complexity in fog forecasting is high due to multiple factors playing a role at multiple levels. Most of the researchers have worked upon the role of humidity, temperature, wind, and boundary layer to predict fogs. However, the role of global wind circulations, soil properties, and anthropogenic heat requires further investigations. Literature shows that fog is being harnessed to address water insecurity in various countries, however, coastal areas of Angola, Namibia and South Africa, Kenya, Eastern Yemen, Oman, China, India, Sri Lanka, Mexico, along with the mountainous regions of Peru, Chile, and Ecuador, are some of the potential sites that can benefit from the installation of fog water harvesting systems.

Keywords Fog · Aerosols · Smog · Fog forecasting · Fog detection

1 Introduction

The atmosphere contains 0.001% of water (Gleick and Schneider 1996). Nearly all of the water contained in the atmosphere lies in its lower layer, the troposphere. Water present in the atmosphere is a critical component in determining the Earth's heat budget, thus being one of the major components responsible for driving climatic phenomena (Hay 2014). The ultimate visible manifestations of water in the atmosphere are clouds at various altitudes and fog near the surface of

both land and water. Owing to this being the only difference between fog and clouds, often, fog is referred to as a stratus cloud just above the ground. Lower visibility range < 1 km is the primary criteria when defining fog (WMO; IMD). Fog is formed when air approaches saturation by adding moisture (by evaporation or mixing two air parcels of contrasting temperatures) or by removing heat. Attributes such as synoptic conditions, climatology of the area, time of the year, thermal characteristic of air, stability of boundary layer, vertical and horizontal wind speed, dew point depression, terrain or topography, characteristics of the condensation nuclei are important when forecasting fog (https://www.weather.gov/source/zhu/ZHU_Training_Page/fog_stuff/forecasting_fog/FORECASTING_FOG.htm). So, the prediction of fog involves a vast range of physical processes starting from the microscopic level of aerosol to the synoptic scale. Gultepe et al. (2007) in their work have very vividly reviewed the

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past fog researches and the direction it is going to take in the future. There is a long and rich history of fog forecasting despite that, and accurate prediction is still tricky because of the sheer scale of physical and chemical processes involved (Koraćin and Dorman 2017).

Humans and related systems around the world where fog occurs are influenced by it either directly or indirectly. Naturally occurring fog, apart from reducing visibility, can influence the vegetation, air quality, radiation budget, which directly affects temperature and surface-air interaction. Several locations on the planet witness fog events, where some episodes are infrequent while others are widespread. Since fog events occur globally, various climate zones are impacted, including tropical, polar, temperate, and moist to dry zones. In cities where the concentration of haze particles is more due to increased levels of air pollution (Zheng et al. 2015), fog formed is relatively thicker due to the presence of an increased number of aerosols (Poku et al. 2019). The chemical, physical and composition of Fog Condensation Nuclei determine the direct and indirect impact on the health of humans, animals (directly affecting respiration and dermatological effects) and plants. As haze particles provide condensation surface for fog droplets to form in urban areas, current air quality scenarios prove how fog together with haze directly has a detrimental impact on humans (Polivka 2018; Cai and Wang 2017; Hutchings et al. 2010). Visibility obstruction during dense fog events are responsible for casualties, whether on roads, rails, aircrafts or water transport (Leung et al. 2020; Peng et al. 2018; Jenmani and Kumar, 2013; Abdel-Aty et al. 2011). Economic losses have also been reported, either due to loss of goods during crashes or due to delays, diversion and cancellation of the mode of transport (Kulkarni et al. 2019).

Apart from the negative impacts, fog also has some positive impacts. Biota of semi-arid, alpine and coastal regions are dependent on fog water for their survival and maintenance (Tognetti 2015; Zhang et al. 2015a; Baldocchi and Waller 2014). Tress and plant species in alpine and coastal areas fog water is responsible for not only fulfilling the water needs but also acts as a medium, vector and connector (Weathers et al. 2020). In desert ecosystems, both flora and fauna are dependent on fog (Mitchell et al. 2020; Qiao et al. 2020; Lehnert et al. 2018). Even humans have started accumulating fog water with the help of a “fog catcher” in places that do neither receive ample precipitation nor have groundwater but are usually shrouded in dense fog almost throughout the year (Ismail and Go 2021; Qadir et al. 2018). Domen et al. (2014) have presented a very good review on models incorporated for determining the potential of a particular site, designing and various applications of fog harvesting.

This review paper provides the readers with an overview of various aspects of fog. The work does not aim to provide the readers with a critical analysis of the topics

covered; instead, the paper's main objective is to present a comprehensive read covering both the scientific and social viewpoints. The previous review papers have reviewed the individual-specific topics and this article discusses all the fog-related topics briefly. Topics discussed in the present paper include factors influencing fog (global wind circulation, soil properties, climate change and anthropogenic activities); fog formation and classification; fog forecasting and detection (numerical modelling, satellite remote sensing, artificial intelligence, and microwave communication links)—their pros and cons; the impact of fog on—the quality of air (policies and measures to improve air quality), human health, transportation and economy, and ecology; and fog as a resource. Figure 1 shows the distribution of research papers/ research letters, review papers, book chapters/manuals, news articles, reports, conference papers and other online readings. In the article, there are many abbreviations used, so a list of abbreviations and their full forms are provided in Table 1.

2 Fog formation

Fog is formed from the combination of various influencing factors which can be microscopic (e.g. chemical and physical properties of CCN), mesoscale (e.g., topography and orography of the region) and synoptic (e.g. Winter teleconnections and PDO) nature. The presence of ample water vapor in the air is the most crucial factor in the occurrence and sustenance of fog. The microphysical properties of CCN, thermodynamic property of the atmosphere, boundary layer condition, all play a role in the formation of fog, its dissipation, and its occurrence frequency (Gultepe et al. 2007).

The formation of fog droplets requires aerosol, humidity, and cooling. Aerosols present in the atmosphere act as CCN; their size and chemical property influence its growth and its ability to form secondary aerosols (Moroni et al. 2016). The microphysical properties of fog are also regulated by aerosol; the activation of CCN is dependent more strongly

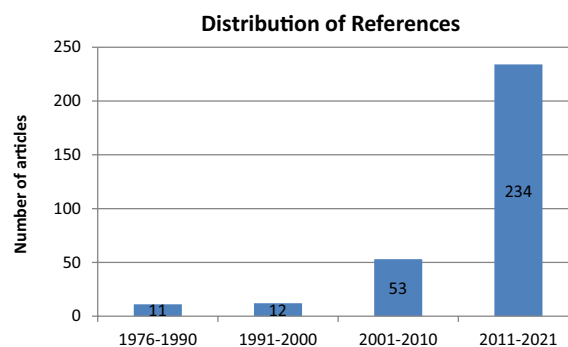


Fig. 1 Distribution of references used in the review article

Table 1 List of abbreviations used in the article

WMO	World Meteorological Organization
IMD	Indian Meteorological Department
NOAA	National Oceanic and Atmospheric Administration
NHP	North Pacific High
WNP	Western North Pacific
ENSO	El Niño-Southern Oscillation
AO	Arctic Oscillation
PDO	Pacific Decadal Oscillation
NWP ₁	North West Pacific
IGP	Indo-Gangetic Plain
PJ	Pacific-Japan teleconnections
MODIS	Moderate Resolution Imaging Spectroradiometer
UHI	Urban Heat Island
UDI	Urban Dry Island
LULC	Land Use Land Cover
AH	Anthropogenic Heat
WRF	Weather Research and Forecasting
CCN	Cloud Condensation Nuclei
MAMD	Maximum Attainable Mixed Depth
LWC	Liquid Water Content
ABL	Atmospheric Boundary Layer
ANFIS	Adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
AOD	Aerosol Optical Depth
APPCAP	Air Pollution Prevention and Control Action Plan
AVHRR	Advanced Very-High-Resolution Radiometer
AWS	Automated Weather Stations
BTD	Brightness Temperature Difference
CALIOPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAQM	Commission for Air Quality Management
CAT	Clear Air Turbulence
CNN	Convolution Neural Network
COBEL-ISBA	Couche Brouillard Eau Liquide—Interactions between Soil, Biosphere, and Atmosphere
COBEL-Noah	Couche Brouillard Eau Liquide—Interactions between Soil, Biosphere, and Atmosphere—National Centers for Environmental Prediction—Oregon State University—U.S. Air Force—National Weather Service Office of Hydrologic Development
CPC	Civil Procedure Code
CPCB	Central Pollution Control Board
DP	Deep Learning
DRF	Distributed Random Forest
EnKF	Ensemble Kalman Filter
EPCA	Environmental Pollution (Prevention and Control)
FIS	Fuzzy Inference System
FRAM	Fog Remote Sensing and Modelling
GBM	Gradient Boosting Machine
GHG	Green House Gases
GLM	Generalized Linear Model
GOES	Geostationary Operational Environmental satellite
GRAP	Graded Response Action Plan
HIRLAM-DMI	High-Resolution Limited-Area Model—Danish Meteorological Institute

Table 1 (continued)

HIRLAM-INM	High-Resolution Limited-Area Model—Instituto Nacional de Meteorología
IGI	Indira Gandhi International
IGP	Indo-Gangetic Plain
IHD	Ischemic Heart Disease
INSAT-3D	Indian National SATellite-3D
LANFEX	Local And Non-Local Fog Experiment
LPG	Liquified Petroleum Gas
LST	Land Surface Temperature
LSTM	Long Short Term Memory
MEP	Ministry of Environmental Protection
Méso-NH	Méso-Nonhydrostatic Mesoscale Model
MIR	Mid Infrared
ML	Microwave Links
MLP	Multilayer Perceptron
MMHg	Monomethyl Mercury
MoEFCC	Ministry of Environment, Forestry and Climate Change
MRD	Multirule Based Diagnostic
MRI	Magnetic Resonance Imaging
MSW	Municipal Solid Waste
MTSAT	Multifunctional Transport Satellites
NAAQS	National Ambient Air Quality Standards
NAMP	National Air Quality Monitoring Programme
NCAP	National Clean Air Programme
NCR	National Capital Region
NDMA	N-nitrosodimethylamine
NDRC	National Development and Reform Commission
NEMMP	National Electricity Mobility Mission Plan
NTPC	National Thermal Power Corporation
NWP	Numerical Weather Prediction
OCEMS	Online Continuous Emission Monitoring Systems
PAH	Polycyclic Aromatic Hydrocarbons
PAN	Peroxyacyl nitrates
PNG	Piped Natural Gas
RNN	Recurrent Neural Network
RSL	Received Signal Level
RUC	Rapid Update Cycle
SAFAR	System of Air Quality and Weather Forecasting and Research
SEVIRI	Spinning Enhanced Visible and Infrared Imager System
SOA	Secondary Organic Aerosol
SPCB	State Pollution Control Board
SST	Sea Surface Temperature
TIR	Thermal Infrared
UNEP	United Nations Environment Programme
USD	United States Dollars
VOCs	Volatile Organic Compounds
WRF-LES	Weather Research and Forecasting Large Eddy Simulation
WRF-PAFOG	Weather Research and Forecasting PArAmeterized Fog
XRT	Xtreme Randomized Tree

on particle size and its concentration than its chemistry (Stolaki et al. 2015). The saturation value needed for fog formation can be brought down by aerosol number concentration

(Mazoyer et al. 2019). According to Twomey (1967), the increase in aerosol concentration leads to an increase in the number of small-sized cloud droplets, causing the effective

droplet radius to decrease, increasing fog's optical thickness and hence the albedo (Fritz et al. 2021).

Latent heat released during the condensation process and high concentration of aerosol aggravates the Brownian collision, accelerating fog formation (Guo et al. 2015). Aerosol is a crucial component for fog droplets to form; in their absence, relative humidity far exceeding a hundred percent will be required to form fog droplets (Ahrens and Henson 2021). Aerosol in the atmosphere can have both natural and anthropogenic origin when they are introduced directly from the source, aerosol concentration they are termed as primary aerosols, while when they are formed from when they chemically or physically react with other aerosol or with other components of the atmosphere; they are termed as secondary aerosols. The life of an aerosol particle and conversion of aerosol to fog droplet is controlled by the processes of

- 1 Nucleation: process where ions, atoms, and molecules organize themselves in such a manner to form tiny crystals. The nucleation process is of two types, namely homogeneous nucleation, where water vapor condenses in the absence of any external nuclei, which requires unrealistic supersaturation levels, while the other type is heterogeneous nucleation which requires external nuclei for water vapor to condensation.
- 2 Coagulation: collision of aerosol particles as a consequence of their random movement forming relatively larger chain aggregates. The different types of coagulation processes are
 - Brownian coagulation is caused due to the thermal movement of agitating particles.
 - Turbulent coagulation induced by turbulent movement of particles.
 - Electrical coagulation is caused due to the opposite charges of two colliding particles.
- 3 Condensation: The condensation process is governed by the “Kelvin effect” or the “curvature effect” and the “Raoult's effect” or “solute effect”. Where one effect increases the saturation vapor pressure over the surface, increasing the evaporation rate, while the other has an opposite effect. The condensation may occur over a pre-existing tiny particle, in which case only the mass of the droplet increases (increase in liquid water content) and not the number. Through the process of homogeneous nucleation, a new particle can be formed, which may lead to an increase in the number of particles, however, for that to happen, the relative humidity needed will be too high, which is not practically possible for a droplet to remain suspended in the air at that level of relative humidity.

The size of CCN is also a determinant in its growth, a droplet will always try to maintain an equilibrium state

(equilibrium supersaturation of droplet = water vapor in the atmosphere), and to do that, the water molecules will either try to evaporate off the droplet surface or condense on the surface. If the equilibrium supersaturation < the amount of water vapor available in the atmosphere, condensation will occur, resulting in growth, whereas if equilibrium supersaturation > the amount of water vapor available in the atmosphere, evaporation will occur how droplet size matters are depicted by Koehler curve. Under the “curvature effect” and the “solute effect,” the droplets with more solute have lower critical supersaturation values, thus nucleating before much smaller droplets exhausting the amount of water vapor present in the atmosphere hindering the growth of smaller CCN (Saha 2008). As a result, small CCN does not get converted to raindrops but instead remains suspended as haze and does not form fog droplets.

There are two types of particles, namely hygroscopic and hydrophobic, classified based on their deliquescence property. This property of suspended particles determines whether the water vapor will condense on the surface of CCN at values of relative humidity > 100% or less (Tomasi et al. 2017). The chemical composition of fog particles is also dependent on this property of aerosols. The chemical composition of fog droplets is also dependent on this property, the hygroscopic particles will readily act as CCN through nucleation and the ones that are hydrophobic becomes a part of the droplet through scavenging via collision and coalescence. High concentrations of organic carbon are reported in polluted urban locations whereas the remote locations comparatively have less organic carbon content (Herckes et al. 2013).

In a very basic sense fog is formed when (A) the air temperatures drop to the dew point leading to the formation of radiation, advection and upslope fog and (B) when more water vapour is added to the air leading to the formation of frontal fog and stem fog (Ahrens and Henson 2021) The stages in the fog life cycle, begins with (a) the initial stage when the air is saturated, the temperatures are really low and there is the formation of a strong inversion layer, followed by (b) fog formation when the winds are calm, there is more temperature drop and the more aerosol particles activation paves way for the fog (c) to grow and expand where the degree of saturation is maintained either by continual cooling or by addition of more water vapour needing a little bit of mixing, followed lastly by d) the dissipation phase (Leipper 1994). It is necessary it is to get a clear picture of how fog is formed, it is equally important to understand how and when fog dissipates? or when does a shallow fog become thick? Attempts have been made in this direction, nocturnal fog evolution monitoring with the help of infrared imagery (Price and Stokkereit 2020); the role of turbulence (Price 2019; Maronga and Bosveld 2017). The term ‘Maximum attainable mixed depth’ (MAMD) was coined by Izett and

Wiel (2020). MAMD is the maximum depth of a fog layer beyond which it is more likely to dissipate, it is defined by the temperature and moisture profile and was only tested for radiation fog with not very dense fog. As stated in the study conducted by Boutle et al. (2018), the circumstances that facilitate the growth and maintenance of a well-mixed fog are (1) the duration of night and the time from the onset of first fog after sunset; (2) speed at which the fog layer deepens which driven by humidity profile; (3) increased concentration of activation aerosol during the early stages of fog life span and; (4) non-local effects of synoptic systems also play a significant role; another factor is turbulence (Ju et al. 2020) for radiation fog.

Dense fog inhibits shortwave solar radiation from reaching the ground, which could set a feedback loop in motion where the temperatures may further drop, conducive to fog formation (Vautard et al. 2009). In retrospect to the relation of fog with longwave radiation, emission of longwave radiation in the upward direction will form a positive feedback loop with condensation—longwave radiative cooling may occur, with higher LWC (Liquid Water Content), which will accelerate cooling in the upper part of fog layer followed by augmented relative humidity, fog layer expansion via condensation, and thus increasing LWC (Jia et al. 2019) whereas emission in the downward direction may hinder radiative cooling hence resisting the conditions conducive for fog formation (Guo et al. 2021). Another positive feedback is identified between turbulence and condensation where an increased rate of condensation will cause increased release of latent heat, which will invigorate turbulence and again increase condensation and LWC of fog (Jia et al. 2019; Guo et al. 2015). Here it can be argued that increased turbulence could cause dissipation of fog, and both arguments are correct. However, a threshold value exists for turbulent intensity below which condensation occurs and beyond which dissipation occurs. From the information mentioned earlier, it can be concluded that there is no definitive distinction between the causes and effects of each driving factor on different stages of the fog lifecycle.

3 Factors influencing fog formation

This article has discussed only those influencing factors that as a whole can influence the basic meteorological variables instead of just discussing the individual small components. These factors have been chosen observing the expansive research needed and ongoing in the last few decades.

3.1 Global wind circulation

Fog is influenced by large-scale circulations both directly and indirectly. In places like the Northern plains of India,

Western disturbances bring in moisture from the Mediterranean Sea, ample tropospheric humidity coupled with low temperatures, calm weather, and heavy aerosol leads to the production of dense fog (Ghude et al. 2017). Synoptic scale circulation plays a role in determining the intensity and magnitude of a fog event, especially marine fog. A study found that the formation of advection fog is attributed to. Synoptic-scale circulation (South Atlantic high and lower mean sea level pressure on land) circulation in Namib desert causes alteration in the moisture transport and intensified cooling of the marine boundary layer, helping in the formation of sustenance of advection fog (Andersen et al. 2020). Similarly, Koran Western peninsula experiences fog when there is the formation of a high-pressure zone in the Yellow sea, during night time the moisture-laden south-westerly winds flow towards the land where it meets offshore land breeze and Katabatic easterly winds, together with nocturnal cooling the air becomes saturated leading to the formation of advection fog near the coast (Choi and Speer 2006).

Regarding teleconnection patterns influence (North Atlantic Oscillation, Mediterranean Oscillation, and Western Mediterranean Oscillation) on fog water collection rate in the Iberian Peninsula. Corell et al. (2020) conducted a study, and the study revealed that Atlantic winds and the surface level anticyclonic conditions increase the number of foggy days, whereas the Mediterranean winds along with cyclonic conditions bring in higher quantities of moisture. In Kushiro, Japan on analysis of summer fog frequency showed a declining trend which was found to be associated with NHP (North Pacific High) shrinking and intensification of Okhtsk high during July and August shrinking of NPH (North Pacific High), leading to weak fog advection (Sugimoto et al. 2013).

El Nino and La Nina events significantly affect winter fog frequency in Eastern China. The generation of anticyclonic conditions in the WNP (Western North Pacific) during El Nino brings in moist winds towards land, promoting foggy weather, increasing fog frequency, whereas the opposite of this is experienced during the La Nina event. However, there is variability in the influence of El Nino, there is a clear increased frequency during Eastern Pacific El Nino, and the same is observed when Central Pacific El Nino is further eastward. In contrast, when the Central Pacific El Nino is more westward, the frequency decreases, making the location of the Central Pacific El Nino event more crucial (Hu et al. 2020). Eastern China experiences fog favorable conditions during the El Nino years caused due to increased temperature and humidity in the region brought by south-westerly winds. During La Nina, the opposite is observed. Individual effects of ENSO and AO are comparatively weaker than the combined effect. Under positive AO and El Nino, the frequency of foggy days during winter increases in North China. During later winter months, the impact of

AO is more prominent than El Niño and vice versa for the early winter months (Yu et al. 2021).

Impression of Boreal teleconnections, i.e., AO (Arctic Oscillation) and Eurasian circulation, was observed on the aloft anticyclonic conditions of radiation fog formation in the IGP by employing teleconnection indices. The sinking of air was observed for both positive and negative phases of AO, but odds for the fog to occur was more likely during the negative phase (high pressure over Arctic Circle), and its strength overshadows the effect of the positive phase Eurasian circulation. Whereas during the positive phase of AO, the Eurasian circulation negative phase is more responsible for aloft air subsidence (Hingmire et al. 2019). Northern China observes higher haze-fog during the negative phase of Eurasian teleconnections because of lowered 500 hPa geopotential height, the intensity of cold wave affecting northern China also declines, and during the positive phase, the exact opposite is observed (Li et al. 2019). In relation to Arctic Oscillation, the positive phase is found to increase the number of dense fog days in North China, decline on no if dense fog days in South China: an increased number of light fog days in eastern China. During the positive phase of AO, El Niño's influence. There is a decrease in polar pressure at 500 hPa and an increase in pressure in East Asia, leading to weakening of East Asia trough, causing the northeasterly jet stream to over northward, further restricting the cold westerly winds from moving south. Contrary to positive AO, the negative AO phase has the opposite effect, but variability is observed in corresponding wind patterns and foggy days (Liu et al. 2020a). Pacific-Japan teleconnections impact sea fog formation near the Kuril Islands; a case study performed by Long et al. (2016) found sea fog occurrence in July is supported by Pacific—Japan (PJ) teleconnections, years with higher PJ index showed the formation of stable stratification of the atmosphere by strengthening of anticyclonic conditions, but the opposite was observed when PJ index was lower.

3.2 Soil properties

Evaporation from moist soil surface adds water vapour to the atmosphere and when in harmony with other right meteorological conditions, facilitates the formation and maintenance of fog. However, a lack of studies directly explains the influence of soil property on the fog life cycle. Both soil temperature (Steenveld and Bode 2018) and moisture (Maronga and Bosveld 2017) are essential when fog simulation studies are conducted (Bartoková et al. 2015). The IGP region is shrouded in a layer of thick fog, and apart from the regional meteorology, an adequate amount of moisture provided to the atmosphere comes from the wet soil, which is a result of irrigation (Izhar et al. 2020; Ghude et al. 2017). In his research, Smith et al. (2021) found that the fog was

highly sensitive to the thermal conductivity of soil, causing the onset time of fog to shift by 5 h. Adhikari and Wang (2020) made the first attempt to study the influence of soil moisture on fog. The study was conducted at two sites of Namib Desert, one is a gravel plain, and the other is a sand dune. Water vapor was quantified from in-situ observation of soil moisture and temperature; and air temperature followed by a simulation run on HYDRUS-1D model. From the observation, it was inferred that soil moisture movement was responsive to soil and air temperatures. It was concluded from the simulation that the influx of water vapor to the surface comes from the vadose zone, and this water vapor may facilitate fog formation in fog-prone drylands.

The influence of soil properties on fog formation has not been analytically studied, neither in field studies nor as an important parameterization factor in prediction models. Smith et al. (2021) have studied the impact of both grass and bare soil on fog; nevertheless, they have also suggested that future research is needed on to what extent grass can act as an insulator between soil and atmosphere.

3.3 Climate change and anthropogenic activities

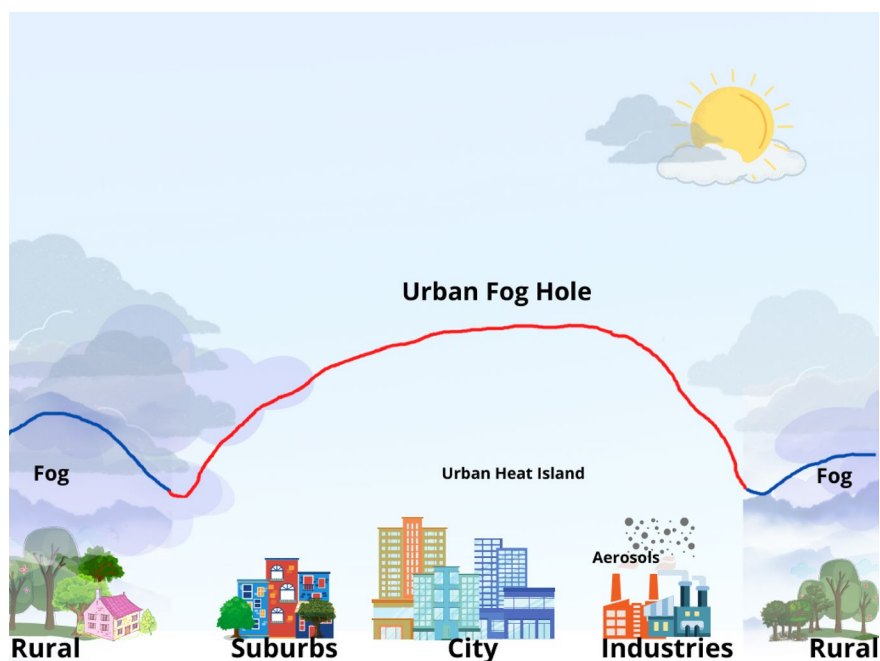
A single fog episode is governed by the interaction of various components of terrestrial, atmospheric, and hydrological systems; therefore, any alteration in those systems is likely to influence fog nature and life cycle (Torregrosa et al. 2014). One of the early studies (Bakun 1990) hypothesized that the coastal fog frequency along the California Coast might escalate due to the intensification of ocean upwelling triggered by Global Warming resulting from differential heating of land and ocean (Lebassi et al. 2009; Diffenbaugh et al. 2004; Snyder et al. 2003). Another study by Johnstone and Dawson (2010) showed evidence of reduced fog frequency for moderate fog in Eastern Pacific along California Coast, attributed to PDO (Pacific Decadal Oscillation) related temperature anomalies and ocean–atmosphere interaction. Recent past trend analysis studies carried out in various locations on the planet do not indicate a prominent increasing or decreasing trend. However, in places where fog variability shows a decreasing trend, there is debate whether the trends are due to changing climate or urbanization. A synergistic effect is seen as the most probable cause for these trends. Observational study of some significant locations in Taiwan established lower concentrations of PM₁₀ and low relative humidity due to rising urban temperatures to be the cause of improved visibility which was taken as a proxy for fog and haze episodes (Maurer et al. 2019). Fog climatology and trend analysis studies for various locations show a noticeable decline in the frequency of fog days for many locations of Asia, Europe, North America, and South America (Klemm and Lin 2015). LaDochy and Witiw (2012), in their study, observed a decrease in the number of dense fog events,

which may have been the result of cleaner air, increased urban warming, and warm phase of Pacific Decadal Oscillation (PDO) in California (LaDochy 2005). Eastern China has been reported to experience frequent winter fog events during the El Niño years due to anticyclonic conditions prevailing in the North West Pacific (NWP₁), in contrast the opposite of this happens during a La Niña event (Hu et al. 2020). Climatic models following historical and future emission scenarios have predicted reduced marine surface visibility and increased humidity in the arctic and subpolar North Atlantic region for the latter part of the century, indicating dense fog occurrence in the area (Danielson et al. 2020). Another regional climatic model has predicted the number of fog days to increase in the coastal areas of the Namib Desert and a decrease in the inland areas (Haensler et al. 2011).

Urbanization influences fog by altering local temperatures, manifesting as UHI; moisture content, wind speed; and aerosol loading (Bokwa et al. 2018). A prominent feature of almost all major cities and urban environments is exacerbated temperature that causes the relative humidity to decrease, making it unfavorable for fog formation. The most evident visual representation of urbanization's impact on fog is in the form of a fog hole seen in satellite imagery over cities. Urban Heat Island is a characteristic feature of cities and in the past few decades, the exacerbated heat emanating from some of the cities (India—Lahore, Amritsar, Jalandhar, Ludhiana, Patiala; North China Plain—Baoding, Tianjin, Dezhou; Po-Valley—Novara, Milan; and Central Valley California—Modesto, Merced) of the world and have been observed to distinctly punch holes in expanses of dense fog in satellite imageries (Gautam and Singh 2018). The

presence of fog holes over an urban setting was first observed in the California Central Valley by Lee (1987) and Munich, Germany by Sachweh and Koepke (1995, 1997). Figure 2 represents the fog hole. In the Indian Subcontinent, the fog holes, for the first time, were seen over a few cities of Northern Plain by Gautam and Singh (2018) in MODIS images of 30th June 2014, where the most prominent hole was seen over Delhi. Gautam and Singh (2018) hypothesized that the excessive heat emanating from the urban areas either does allow for the temperature to fall enough for the formation of fog or it causes the fog formed to dissipate a lot sooner. This might be the explanation for fog holes to form specifically over the urban areas. The impervious surface of town and cities and lack of vegetation are responsible for exaggerated nocturnal remittance of heat along with low evapotranspiration rates along with, both of which causes the temperature to rise (Lakra and Sharma 2019), decreasing the dew point depression bringing down the relative humidity (Baldocchi and Waller 2014), which again causes the condensation level to rise, thus increasing the cloud base height and reducing fog (Williams et al. 2015). UHI, UDI (Urban Dry Island) quell and delay low-level fog, but upper-level fog formation is promoted by vertical updraft (Yan et al. 2020). A study considering the impact of Land Use Land Cover (LULC) change and Anthropogenic Heat (AH) emission with the help of WRF models found these urban characteristics to weaken the inversion layer alongside hindering the ground level moisture from reaching dew point caused due to rise in nighttime temperature making it difficult for the fog to form in Shanghai, China (Gu et al. 2019). Urban locations are also places where the concentration of anthropogenic aerosols is

Fig. 2 Diagrammatic representation of Urban Fog Hole



relatively high, acting as another factor in controlling the nature of fog episodes. There are various arguments pertaining to the influence of urbanization on fog. Yin et al. (2015) argue that urban structural geometry is favorable for fog formation of small spatial scale, as it allows for restricted wind flow favorable for the formation of the stable boundary layer. Klemm and Lin (2016) state that increased evapotranspiration resulting from high temperature can initiate fog development. Aerosols are a crucial determinant in the dynamics of fog. In the recent past, the influx of aerosols in the atmosphere has increased many folds due to anthropogenic activities like—coal burning for the generation of electricity, from vehicles, industries and agricultural activities (Agarwal et al. 2017; Gilardoni and Fuzzi 2017). Urban dwellings, areas of rapid economic growth, and industries have turned into hotspots of aerosol loading. Very high concentration of fine aerosol particles that are radiatively significant and are suspended in the air for longer durations, along with conditions of high relative humidity and low wind speeds; support the formation of optically thick fog formation (Boutle et al. 2018). More number of fine aerosol particles leads to the formation of more fog droplets; however, the size of droplets does not increase much and weakens the sedimentation rate of droplets making the fog duration longer (Jia et al. 2019). The presence of a nocturnal inversion layer that assists in the formation of fog is also a contributing factor in locking air pollutants, restricting them from escaping and diluting in the free atmosphere. This process may form a positive feedback loop where with the increasing concentration of aerosols, the optical thickness of fog may also increase. Thermal inversion leads to suppression of updraught, making it ideal for air pollutants to get trapped and being an ideal condition for fog, and together, those two may lead to Smog. WRF/Chem simulation of a dense fog event in North China Plain found polluted air favoring fog events; aerosols intensify turbulence during the growth phase while suppressing it in the dissipation phase (Jia et al. 2019). In eastern-central China, aerosol loading was found to be responsible for altering the regional wind circulation, which generated favorable conditions of low wind speed and water vapor convergence leading to fog occurrence and maintenance (Niu et al. 2010a, b). Big old cities of Anhui Province, China, saw an increase in annual foggy days after the 1960s, but a decrease was seen after the mid-1980s was accounted to UHI, yet the newer cities saw an increase due to aerosol loading where the UHI effects were comparatively weak (Shi et al. 2008). In Europe, in the latter years of the industrial revolution, industries altered their functioning, air quality improvement policies were implemented, and coal mines were shut down, bringing down SO_2 concentrations in the atmosphere, which caused a decline in the number of fog days. Low visibility events due to dense fog and mist saw a declining trend (1976–2006) in Europe, attributing to low SO_2 emissions (Van Oldenborgh

et al. 2010). The Kraków region of Poland showed a decline in foggy days when the pollution levels (SO_2 aerosols) were low and increased when pollution levels were high in the cities (Bokwa et al. 2018). Prior research has observed a decline in the frequency of low-visibility events (fog, haze, and mist) in Europe, which was suggested to result from air quality improvement measures in the continent that caused reduced aerosol loading in the atmosphere (Vautard et al. 2009). Nevertheless, it has also been observed that high temperatures in cities result in moisture shortfall, which far outweighs the favorable effects of aerosol in initiating fog formation (Yan et al. 2020; Sachweh and Koepke 1995).

4 Fog classification

In a similar manner as any cloud, fog is formed in saturated air, and saturation is attained:

- (a) When cooling occurs by removal of heat (work done on the environment).

Radiation fog: As the name suggests, radiation fog is formed due to radiative cooling of the air just above the ground; when heat is lost, it drops the saturation vapor pressure changing the amount of water vapor present in the air. Hence fog initially forms in the layer of air that is directly in contact with the ground. Clear nights with high relative humidity are conducive to fog formation as during such conditions, cooling of the ground is more rapid, making it easier to attain dew point temperature. Calm air leads to the formation of shallow fog; for the fog to be vertically extensive, a light breeze is required to generate sufficient turbulence. Radiation fogs are more frequent during winter months as the nights are longer, providing more time for cooling to occur. Another factor that increases the likelihood of fog formation is the presence of an inversion layer. Surface heating and vigorous mixing lead to the dissipation of fog. This type of fog is sometimes also called valley fog because it is prevalent in valleys as the fog carrying air is heavier and denser, it settles at the bottom of the valley.

Advection fog: Fog formed when warm moist air mass moves over cold air mass (here, advection refers to the horizontal movement of air). When in contact, the warm air losses heat to the cold air, reaching the dew point, and the moist air condenses, forming fog. Advection fog is a common occurrence in coastal regions. Another type of advection fog is sea fog which is found where warm and cold currents meet. The critical determinants mentioned by Koračín (2017) and Fernando et al. (2021) while predicting coastal advection fog comprise precipitation; microphysical properties;

aerosols; turbulence; local circulation; advection and synoptic conditions; subsidence and inversion characteristics; radiative fluxes; topography; radiative fluxes; and air-sea interaction and ocean properties (coastal and open ocean upwelling).

- (b) When cooling occurs by adiabatic expansion.

Upslope fog: This type of fog is formed when a gradual upward movement of an air mass has high relative humidity along the slope of mountainous terrain. This upward movement causes adiabatic cooling of the air parcel, thus reaching the dew point.

- (c) When more water vapor is added to the air either by increased evaporation or by mixing or both.

Steam fog: This fog is the opposite of advection fog and is formed when cool air moves over the warm water surface. Evaporation from the warm water mass occurs, but the cool air above cannot hold the excess amount of water vapor, thus the excessive water vapor surpasses the saturation level leading to condensation and consecutively fog. When formed over the sea surface, it is also known as sea smoke.

Frontal fog: As the name indicates, frontal fog is formed at the frontal zones. When rain from warm air falls over the cold air at the frontal zone, it causes the raindrop to evaporate, and hence the air becomes saturated, resulting in fog. Due to this reason, they are often referred to as precipitation fog.

Fog can also occur as suspended ice crystals instead of water droplets, known as *ice fog*. At shallow temperatures, analogous to arctic temperatures, if any water vapor is released into the atmosphere, say from the burning of hydrocarbons, then in such conditions, the cold air is unable to hold any water vapour, thus causing them to form ice crystals.

From the description of various classes of fog, it is evident that the topography and location of a region is an essential factor in the occurrence of fog in that region.

When it comes to marine fog study, one of the limitations faced by the researchers is the absence of routine field observation of standard meteorological parameters and especially turbulence data over the ocean (Koraćin 2017).

5 Fog forecasting and detection

Monitoring and predicting fog today is no longer limited to in-situ observations with the advancement in technologies. Many newer tools and techniques are now incorporated for thorough research in studying fog and its related aspects. Statistical and dynamical forecasting are the two major pathways in prediction and forecasting fog. Traditional statistical methods were established on the different statistical analyses

such as classification, correlation, and regression. Newer statistical methods, with the evolution of computational abilities deep learning, machine learning neural network tools such as CNN (Convolution Neural Network), RNN (Recurrent Neural Network), and ANN (Artificial Neural Network) are also emerging as promising tools.

5.1 Numerical modelling

Since the advent of computer simulation in the 1950s, NWP (Numerical Weather Prediction) models have been used to predict future weather conditions using the current observational weather data through data assimilation. The most reliable and widely used prediction models are numerical models. A successful fog forecast using numerical models is dependent on the type of fog formed, as various processes drive various type of fog-like advection fog are dependent on dynamic processes whereas the radiative fog is mainly dependent on radiative processes, land–atmosphere interaction and turbulence (Bari et al. 2015). Models used for simulating fog take various processes of air–surface interaction, chemistry, aerosol movement, and environmental flow; dynamic processes of mixing, turbulence, subsidence; and thermodynamic processes and properties of radiation and moisture fluxes as well as microphysical properties of CCN all into account (Hůnová et al. 2018; Fernando et al. 2021). Another aspect of NWP is parameterization is how different atmospheric processes are indirectly included in the models meaning to say that the processes are not directly simulated; instead, their effects are taken into account. There are three basic models regarding spatial dimensions, namely 1D Model where their horizontal homogeneity of all the thermodynamic components and the fog is simulated based on the interplay between moisture wind and heat happening at the Earth's surface; 2D and 3D models considers both horizontal and vertical components (Niu et al. 2010a, b; Gultepe et al. 2007). The models are based on the laws of physics pertaining to radiative heat fluxes and moisture fluxes, their thermodynamic and chemical properties.

The previous studies reveal that the microphysical scheme for onset and identification of ABL height for dissipation of fog are amongst the most critical components for the forecast and the reduction of spin-up time (Steenveld et al. 2015; Lin et al. 2017). Prior studies have found 1-D models lacking in correctly predicting fog (Rémy and Bergot 2009; Bergot et al. 2007). For identification of the reasons responsible for the shortcoming, a few 1-D models were put to test by Bergot et al. (2007) taking two episodes of radiation fog, for the study COBEL-ISBA (Couche Brouillard Eau Liquide–Interactions between Soil, Biosphere, and Atmosphere); COBEL–Noah (Couche Brouillard Eau Liquide–Interactions between Soil, Biosphere, and Atmosphere—National Centers for

Environmental Prediction—Oregon State University—U.S. Air Force—National Weather Service Office of Hydrologic Development); HIRLAM-DMI (High-Resolution Limited-Area Model—Danish Meteorological Institute); HIRLAM-INM (High-Resolution Limited-Area Model—Instituto Nacional de Meteorología); Méso-NH (Nonhydrostatic Mesoscale Model); and tBM. The first conclusion was that the chief difference in prediction results of the above-mentioned models was regarding nocturnal cooling just above the ground preceding fog onset, especially considering light winds, higher vertical resolution and parameterization is needed for clearly defining the vertical gradients above the fog and the nocturnal boundary layer; second errors during fog dissipation occur due to lack of proper parameterization of gravitational settling and dew deposition.

Models with finer vertical resolution give output that is in harmony with ground observations (Boutle et al. 2016; Philip et al. 2016; Van der Velde et al. 2010), giving a better representation of cooling rates and evolution of LWC, whereas the coarse resolution model show delay in fog formation, presenting us with the evidence on how low-resolution models can cause alteration in thermodynamic processes. COBEL-ISBA model has been used to study the influence of a wind profile on its predicting capability (Bari 2019), and to improve its performance, the model was integrated with an ensemble Kalman filter (EnKF) (Rémy and Bergot 2009), both of which gave better-simulated results for near-surface level thermodynamics of short-range before onset and dissipation of fog.

The Weather Research and Forecasting (WRF) Model has turned into one of the extensively applied tool for predicting almost all short-range weather-related phenomena because of its regular advancement (Powers et al. 2017), and fog is no exception (Chaouch et al. 2017; Román-Cascón et al. 2016, 2012; Kim et al. 2019). To achieve improved forecasting capacity (for radiation fog event), Payra and Mohan (2014) applied a Multirule Based Diagnostic (MRD) method on the simulated output, and the results of the application were promising with 94% predictability for a foggy and non-foggy day. When comparing the performance of the basic WRF model with other extended versions such as WRF-LES (Large Eddy Simulation), the WRF-LES was found to better in near-surface parameter simulation and precise depiction of ABL height during fog evolution (Cui et al. 2019) similarly another extended model WRF-PAFOG (Parameterized Fog) also gave better results when data from the meteorological tower was employed (Kim et al. 2020b).

Bari et al. (2015) employed Meso-NH intending to understand mechanisms involved in a fog event at Casablanca, where the said event consisted of two different classes based on the topography and the physical processes involved in its formation, radiation fog which later on was observed over the coastal region due to advection of the initial radiation

fog. They concluded that improved SST (Sea Surface Temperature) accuracy gives improved results when predicting coastal fog. When using the single-moment microphysical scheme the model's performance is dependent on the proper microphysical parameterization.

In their study, Smith et al. (2021) analyzed the impact of soil temperature and soil moisture on the sensitivity of three NPW models. They found that soil thermal conductivity can cause the onset time of fog to change from 30 min up to 5 h; it also showed that even if the entire study area is covered with grass, it acts as a complete insulator prohibiting the influence of soil property from influencing the surface above. They also found that sub-km scale configuration performs better than km configured grids in terms of heat fluxes in complex orographic terrain.

LANFEX (Local And Non-Local Fog Experiment) was a commendable collaborative effort to better understand the entire life span of a radiation fog event combining field observations and modelling. A small system of valleys in the UK was taken up as study sites (Price et al. 2018). The project shed light on how fog behaved to its various components, to soil properties and performance of the model on a sub-km scale (Smith et al. 2021); the impact of local and non-local attributes on the fog, and microphysical properties (Ducongé et al. 2020); how boundary layer evolved during fog (Smith et al. 2018); application of infrared imaging devices for observing the entire dynamic processes involved (Price and Stokkereit 2020); initial formation and vertical growth in relation to the boundary layer, humidity, turbulence and dew (Price 2019); the influence of aerosol properties (Poku et al. 2019; Boutle et al. 2018). The ultimate motive of the work was to improve the predictions of NWP models, and the studies showed promising results. However, as the observational sites were in the valley-like terrain, places of almost pollution-free environment, the schemes and findings of the project may not apply to flat regions and cities.

For the most part, uncertainties in NWP models are concerning two areas—first, models' ability to predict the meteorological parameter, and second on the ability of models to link predictors to predictant (Miao et al. 2012). To date, accurate prediction of fog in NWP still poses a challenge because of the lack of a clear depiction of many interacting processes (Smith et al. 2021; Westerhuis et al. 2020). The accuracy of NWP over the ocean and in the case of ice fog is usually low compared to land due to limited observational data (Amani et al. 2020; Gulpepe et al. 2015). Many uncertainties in the fog microphysical aspect of the model arise because the characteristics, distribution, and evolution of CCN are not clearly available and thus cannot be adequately incorporated in the prediction models. Resolutions of mesoscale models are getting finer, but the parameterization gets compromised when resolution increases. Improved

techniques like large-eddy simulations can improve forecasting on a finer scale; still, they cannot accurately define initial conditions and boundary layer related to the evolution of synoptic conditions (Koračín 2017). The processes involved during each transition phase of fog life are complicated to be correctly incorporated into the forecasting models; this, in turn, increases the prospect of false alarms or biases. The current models present still are in need of more satisfactory vertical and horizontal resolution (Bergot and Koracin 2021). Queries such as identifying and understanding various mechanisms involved in fog formation and sustenance and interaction of micro-environments inside and outside the fog layer and how it affects fog life cycles can be explored with a varied range of tools and techniques available (Cuxart and Jiménez 2012). Practical sub-grid scale physics parameterization schemes along with accuracy in initial and boundary-layer conditions are needed. For advection fog simulation, apart from the Eulerian framework, Lagrangian pathway history and conversion of an air mass at the final location of fog formation is also essential (Koračín 2017). Various authors have applied an array of parameterization schemes for different locations (topography) mainly with the sole purpose of reducing uncertainties and increasing accuracy; however, it is essential to note that the suggested scheme could either predict with increased accuracy or it may not. Nevertheless, the best option is still to adapt schemes that give better results and are from those studies that have near similar components of fog as that of the place under consideration.

5.2 Satellite remote sensing

A majority of research involving the application of satellite data and imagery are used in detection (Weston and Temimi 2020; Ahmed et al. 2015; Chaurasia et al. 2011; Lee et al. 2011; Yoo et al. 2010), monitoring (Jiskoot et al. 2019; Wang et al. 2010), for developing fog climatology (Cermak et al. 2009; Bendix 2002) and as predictors in the machine learning algorithms for fog forecasting (Kim et al. 2020a, b). In locations where there is an absence of in-situ observations, or it is difficult to set up observation sites, the significance of satellite data plays a crucial role in forecasting. The majority of research on fog detection in satellite imagery makes use of infrared channels. The satellite senses the re-emitted solar energy as heat from the clouds and the atmospheric particles in the infrared channel. For nighttime fog detection, the band wavelengths whose range is around ~ 3.8 and ~ 11 μm are used owing to their emissivity properties (Bendix 2002). The Brightness Temperature Difference (BTD) thresholding method is widely used in detecting fog in satellite images. The concept behind this method is based on the fog droplet's interaction with the band's emissive and reflectance properties. The brightness

temperature corresponds to fog droplet size, its optical thickness, and its height (Bendix et al. 2005). For nighttime fog detection, the temperature retrieved from ~ 3.8 μm is slightly smaller than ~ 11 μm wavelength for fog droplets whereas the temperature at both the wavelengths is the same for larger-sized cloud droplets (Amani et al. 2020). The brightness temperature difference calculated between ~ 3.8 and ~ 11 μm is then compared to the threshold value and categorized into fog or cloud. The general consensus is, it is a clear sky if $\text{BTD} = 0$ $^{\circ}\text{C}$, it is a high cloud if $\text{BTD} < 0$ $^{\circ}\text{C}$, and it is fog if $\text{BTD} > 0$ $^{\circ}\text{C}$ (Eyre et al. 1984). Detection of fog during daytime using infrared bands poses a bit of difficulty as the brightness temperature of fog is annulled by its sunlight reflectance (Weston and Temimi 2020). So for fog detection during day the very high clouds (very low brightness temperature) showing pixels are eliminated using the thresholding method and the fog is discriminated from the low stratus clouds based on the calculation of geometrical thickness using the Visible and Near-Infrared bands. After the geometrical thickness is determined the elevation of the stratus/ fog from the ground is estimated using the DEM data to evaluate the height of the stratus/ fog from the ground, if the cloud base height is less than surface elevation the pixel is identified as fog (Cermak and Bendix 2011; Bendix et al. 2005). Geostationary satellites such as AVHRR (Advanced Very-High-Resolution Radiometer) (Baldocchi and Waller 2014; Wang et al. 2010; Choudhury et al. 2007), MODIS (Moderate Resolution Imaging Spectroradiometer) (Terra & Aqua, Wu and Li 2014; Chaurasia et al. 2011), CALIOPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) (Xiao et al. 2019; Wu et al. 2015) and polar-orbiting satellites such as GOES (Geostationary Operational Environmental satellite), SEVIRI (Spinning Enhanced Visible and Infrared Imager System) (Weston and Temimi 2020; Egli et al. 2018; Cermak et al. 2009), MTSAT (Multifunctional Transport Satellites) (Jun et al. 2012; Gao et al. 2009) and INSAT-3D (Indian National SATellite) (Banerjee and Padmakumari, 2020; Arun et al. 2018; Chaurasia and Jenamani 2017; Chaurasia and Gohil 2015). Comparatively, a more significant chunk of research literature in the past had utilized AVHRR data where BTD is calculated using channel 4 (thermal) and 3 (absorbing) (Bendix 2002); and MODIS data where TIR (Thermal Infrared) and MIR (Mid Infrared) is used for BTD retrieval (Chaurasia et al. 2011; Bendix et al. 2006).

There is no universal BTD value that may apply to all zones (Dey 2018; Amani et al. 2020), so for determining the applicability of the current threshold value (2.5 $^{\circ}\text{C}$ BTD) used by IMD (Indian Meteorological Department), a study was performed on few cities of IGP (Indo-Gangetic Plain) was put to test for retrieving nighttime fog, it was concluded that the threshold value of 1.5 $^{\circ}\text{C}$ was relatively more accurate in fog detection, but the accuracy declined with increase

in the droplet size $> 9 \mu\text{m}$ which may be due to aerosol presence in the study area (Ahmed et al. 2015). The threshold value of $1.5 \text{ }^\circ\text{C}$ is further supported by Dey (2018). As a guideline for implementing the same method for fog detection in INSAT-3D data, Chaurasia et al. (2011) evaluated the sensitivity of BTD value to fog properties (droplet size and thickness) during the night, employing a radiative transfer model. BTD value was found to be $> 1.5 \text{ }^\circ\text{C}$ corresponding to droplet size $> 9 \mu\text{m}$ or when optical thickness $< 3.5 \mu\text{m}$ or both. Both the two studies, as mentioned earlier, were carried out employing MODIS data. Instead of utilizing only the infrared bands or detection, visible bands can also improve accuracy (Jun et al. 2012). For detecting fog during the day in INSAT-3D data, Chaurasia and Gohil (2015) used the bi-spectral difference technique. However, by utilizing visible ($0.55\text{--}0.75 \mu\text{m}$) and thermal ($10.3\text{--}11.3 \mu\text{m}$) band instead of mid-infrared (MIR: $3.8\text{--}4.0 \mu\text{m}$) band and the methodology was satisfactory with few false alarms; however, the technique lacked in discriminating fog from other surfaces and also in detecting fog below clouds. Banerjee and Padmakumari (2020) also utilized INSAT-3D data to monitor fog's spatiotemporal variations and its evolution in three cities of IGP concerning AOD (Aerosol Optical Depth) and validated the retrieved satellite observation with ground observation data; the results were found to be in harmony when there were periods of moderate, dense and very dense fog (visibility = $0\text{--}500 \text{ m}$) whereas only occasionally fog was detected when there was a period of shallow fog (visibility $> 500 \text{ m}$). It was deduced that increased aerosol loading might have been one of the triggering factors in the initiation of fog formation.

Some recent studies have applied the integrated approach, combing the satellite data, models, and observational data for improved learning and insight into the varied components, interactions, and mechanisms involved in the different stages of the fog life cycle (Policarpo et al. 2017; Müller et al. 2010). “Fog Remote Sensing and Modelling (FRAM) project” was conducted by Gulpepe et al. (2009), combining the observations from three field sites, satellite data (Geostationary Operational Environmental Satellite (GOES) and Moderate Resolution Imaging Spectroradiometer (MODIS)) and model (Rapid Update Cycle (RUC) model) for classification of fog occurrence in marine and in-land setting taking into account its formation, evolution, and dissipation; it's microphysical parameterize for application in NWP models; enhancement of both application of remote sensing and model simulation; understanding and amelioration of instrument capabilities in detecting fog and its related environmental setting about microphysical properties; and for removal of uncertainties to a certain extent. Cuxart and Jiménez (2012) Integrated model (Meso-NH), observational data (from Automated Weather Stations (AWS) and WindRASS), and satellite data (MODIS LST data) approach

helped to grasp better the dynamic processes of radiation fog sustenance in a confined terrain for a long fog episode, where ground data (wind speed and direction, temperature, humidity, pressure, radiation, and rainfall) was provided by AWS; WindRASS provided direction, and vertical wind speed profile, and Atmospheric Boundary Layer's virtual temperature; and the blank pixels from the MODIS-LST product was used for validation and demarcation of fog's spatial extent but considering blank pixels has a drawback as it can also represent clouds decreasing the confidence level.

5.3 Artificial intelligence

Machine Learning is a part of artificial intelligence that deals with data analysis for analytical model building. The method is based on the idea that a system can make decisions and identify patterns from the data. There are various learning techniques through which a machine is trained to make predictions. So, basically saying that a machine acquires artificial intelligence via machine learning. They are suitable for now-casting because of their short computing time (Durán-Rosal et al. 2018; Dutta and Chaudhuri 2015).

Neural network (ANNs), as the name suggests, neural networks are computational models basic working structure is based on how the biological brain works. The several processing involved is performed by artificial neurons, generating output from previous datasets and predefined functions. Pasini and Potestà (1995) implemented ANN for the first time to forecast short-range visibility. Marzban et al. (2007) described how neural networks predict ceiling height and visibility at aerodrome forecasting stations in the northwest of the United States by post-processing the numerical model. Applicability of ANN was tested for predicting fog in the Canberra International Airport where the designing, training, testing, and validation using the historical observational data from the airport and recommended being used in other airports (Fabbian et al. 2007). A similar kind of practice was adopted for predicting visibility for nowcasting fog visibility at Kolkata airport; the study considered pollutants and meteorological data spanning eleven years where the predictors were decided with the help of decision tree algorithm and then used as input in ANN model using the MLP (Multilayer Perceptron) backpropagation learning method for visibility prediction (Dutta and Chaudhuri 2015), in Academia da Força Aérea (Colabone et al. 2015) in International Airport of MACEIÓ and Brazil (Costa et al. 2006). Another case study of Wamena Airport utilised a bunch of algorithms including Xtreme Randomized Tree (XRT), Generalized Linear Model (GLM), Gradient Boosting Machine (GBM), Deep Learning (DP, Distributed Random Forest (DRF), and stacked Ensemble comprising of all the model's aforementioned which gave the best result (Dewi and Harsa 2020).

Performance of various hybrid neural networks in predicting radiation fog events from the fog from the meteorological data collected from the Valladolid airport was compared, the Multiobjective Evolutionary training algorithms performed best, and the importance of each meteorological parameter considered was also presented in terms of prediction (Durán-Rosal et al. 2018). A method for short term fog forecasting applying the LSTM (Long Short Term Memory) was suggested by Miao et al. (2020) to train the model better; instead of using the observed meteorological data directly, the data was converted into a set of four datasets depending upon its duration, the algorithm was tested and was later compared with the output of other models where its performance was best, thus proving its effectiveness in short term prediction. Although the authors also pointed out that with a longer prediction time, the accuracy may decrease. In other words, the error percentage could increase with increased lead time (Goswami et al. 2020). Complex functions can be simulated easily in a more extensive network by increasing the number of nodes in the hidden layer of MLP (Fabbian et al. 2007). It overpowers basic statistical models because of its ability to handle complex non-linear interactions between input and objective variables (Durán-Rosal et al. 2018). However, for predicting onset and clearance times of fog, MLPs development is required.

Fuzzy logic is a reasoning method inspired by human decision-making abilities. Mitra et al. (2008) introduced a Fuzzy Inference System (FIS) based on fuzzy logic for fog prediction, 5–6 h before the onset, taking New Delhi as the study area; however, the results were slightly underpredicted. To improve prediction accuracy along with minimizing uncertainties in fog prediction at Perth Airport, input from the NWP model was used in fuzzy logic and, however, when compared with the Generalized Analogue Statistics Model and subjective method, the subjective method outperformed both, but the best results were observed from simply averaging the output of the three models, called the operational consensus forecast (Miao et al. 2012). Goswami et al. (2020) implemented output from Adaptive Neuro-Fuzzy Inference System (ANFIS) as predictor input in MLP neural network model for predicting visibility for one to twelve-hour lead time in Delhi airport; the errors in results were compared with other models—MLP, the Radial Basis Function neural network, the Generalized Regression neural network models and multiple linear regression, as well as with the results of other previous studies (Jenamani and Tyagi 2011; Fabbian et al. 2007; Wantuch 2001). Its ability to give understandable output from imprecise and vague inputs. Unlike other machine learning approaches, the output is not in binary form and instead is a range of values ranging between 0 and 1; for example, the machine learning usually gives output such as '0' if fog is absent or '1' if fog is present, whereas

fuzzy logic can give characteristic of fog as output say in terms of visibility such as 'low or medium or high'.

The decision tree is a supervised machine learning used in regression and classification and can have both a deterministic and probabilistic approach. A study for the Dubai region found that decision tree was more effective when predicting fog for the first six hours of initiating prediction and when output from coupled Weather Research and Forecasting (WRF) model and the PAFOG fog model was used as training data, the results were far more improved. However, the coupled system yielded good prediction results (Bartoková et al. 2015). Decision trees sometimes outperform neural networks because they have set rules similar to human understanding and thus can be evaluated. In contrast, in neural networks, only the output can be elucidated. The decision tree, though capable of dealing with the complex problem, may face the problem of overfitting. Dutta and Chaudhuri (2015) identified the pollutants and meteorological variables impacting visibility during fog events at Kolkata airport; in the study, NO₂ was identified as the one with maximum impact underlying the involvement of pollutants in fog formation. An automated fog detection algorithm was developed by employing in-situ and satellite data as training data into decision tree technique, considering Korean Islands as the study area, the false alarm rate was less during the initial guess, but when high clouds were removed from the imagery, the false alarm rate increases which could have been because of the presence of sea ice or stratus clouds or due to dust (Kim et al. 2020a, b).

The biggest issue with traditional statistical models and artificial intelligence techniques is the lack of methods to deal with missing data. Nevertheless, their fog nowcasting capability can be utilized as an independent tool and in alliance with other modelling tools (Koračín 2017). NWP models have proved their ability to predict weather on numerous occasions and, with time, have become more efficient, but they are computationally expensive in comparison to traditional statistical models.

5.4 Microwave communication links

Often detection of fog by remote sensing satellites becomes difficult due to high-level clouds that may conceal ground-level fog; in such settings, the employment of microwave telecommunication networks as a complementary technique to the existing tools and techniques. Incorporating communication signals for fog detection stems from the idea that the atmospheric conditions interfere with Received Signal Level (RSL), so why not monitor meteorological phenomena (Messer et al. 2006). The potential of microwave communications has been explored in the detection of near-surface moisture (David et al. 2011, 2009; Chwala et al. 2016;

Harel et al. 2015), monitoring air pollution (David and Gao 2016), rainfall (Lieberman et al. 2014; Overeem et al. 2013; Goldshtein et al. 2009; Leijnse et al. 2007). Employment of Microwave links (ML) for identifying fog is done by estimating LWC (David et al. 2013); the basic idea behind it is to calculate the attenuation in signals brought by fog. The range of 0.01–0.4 g m⁻³ LWC is identified to cause a reduction in the amplitude of microwave signals (Gultepe et al. 2006). There is a direct relation between visibility and LWC, i.e., higher LWC density is characteristic of dense fog, low visibility, and vice versa. Droplet concentration is another factor that influences visibility; hence, visibility can be estimated with the help of LWC and droplet number per cubic volume of air (Gultepe et al. 2006). This scheme creates a two-dimensional map for determining the LWC threshold value for each microwave link. So, naturally, only those links that intersect with fog help with its detection. Commercial communication signals have proved viable for monitoring temperature inversion and humidity by considering the attenuation caused by the atmospheric refractive index (David and Gao 2018). Prior research has demonstrated that the sensitivity of detecting fog increases if the frequency of signals is high and the links are tiny, which is the current demand in high population urban areas, making it suitable both for communication and detection purposes. Commercial microwave systems are installed in many locations with varying altitudes, resulting in expansive spatial coverage (David et al. 2015).

The drawbacks of this method are: (1) Locations, where the fog layer is below the ML pathways, detection of fog may not be possible (David et al. 2015). (2) Apart from fog, other atmospheric disturbances (water vapor and precipitation) that may be present along with it can cause signal interference and thus may lead to flawed measurements. Therefore other meteorological information is also required (David et al. 2013). (3) Uncertainties in measurement may also be due to wet antenna (David et al. 2013), MLs magnitude resolution, and white noise on top of other system issues. An integrated approach of incorporating meteorological, satellite, and microwave links to improve the accuracy of fog detection, such as for validating whether the fog seen in the satellite imagery is actually a fog or a stratus cloud, needs to be ventured (David et al. 2015).

6 Impacts of fog

6.1 Quality of air

Air in urban areas is usually loaded with pollutants that act as CCN and consequently, along with other favorable meteorological conditions, increase the probability of fog formation. What polluted air loaded with an aerosol can do to fog?

In the polluted atmosphere, the surface tension of CCN is affected, causing them to activate even at lower levels of relative humidity than cleaner air. The most infamous effect of the interaction of pollutants and fog is in the form of smog. Initially, the classical smog was simply defined as a mixture of smoke or soot with fog, coined by Dr. Harold Antoine Des Voeux after the smog episode of Glasgow, Scotland, in 1909. Later on, after the horrific smog event of London in 1952, where the culprit gas responsible was sulfur dioxide emitted from the excessive burning of coal, after that smog involving relatively high concentrations of SO₂ was also called “London Smog” (Allaby 2014), formed in winter months with high humidity. Another type of smog involves nitrogen oxide and ozone as main components formed in dry, sunny weather called “photochemical smog” because it is formed in sunlight and is also known as “Los Angeles smog” after the event in Los Angeles, or ground-level ozone. VOCs (Volatile Organic Compounds) are also responsible for the production of ozone (Osibanjo et al. 2021). Recently a new class of smog was identified in Poland, taking its namesake called “Polish Smog,” this was distinguished from the two smog as mentioned earlier classes in terms of crucial pollutants and the meteorological condition. They are also known as dusty smog because there high volumes of dust (PM_{2.5} and PM₁₀) and benzopyrene, where the high percentage of ammonium sulfate and ammonium nitrate was identified as the chemical present in the dust particles and formed in the anticyclonic conditions brought by the Easterly winds with temperatures below 0 °C (Wielgosiński and Czerwińska 2020).

There exists two broad class of aerosols—the ones that scatter the incoming solar radiation (scattering aerosol) and the ones that absorbs the incoming solar radiation (absorbing aerosols). The scattering aerosols are known to have a cooling effect on the atmosphere whereas the absorbing aerosols especially the black carbon emitted from anthropogenic sources have a warming effect. Aerosols play a vital role in the formation of fog droplets by acting as CCN. When absorbing aerosols are not acting as CCN they can still affect the fog by warming the air, reducing the relative humidity inhibiting fog formation in addition to causing fast dissipation of formed fog via enhanced evaporation of the fog droplets. This might be one of the reasons for declining fog frequency and for the formation of fog holes over urban areas along with the effects of UHI (Gautam and Singh 2018; Williams et al. 2015; LaDochy and Witiw 2012; LaDochy 2005; Sachweh and Koepke 1995, Sachweh and Koepke 1997) and of successful implementation of air quality improvement policies and measures (Vautard et al. 2009; LaDochy 2005). Increased air pollution can lead to the formation of fog as a direct effect while increasing air temperature as an indirect effect contributing to UHI, which again may give rise formation of Urban fog holes. So a clear effect of aerosol is debatable. Besides resulting in secondary

aerosol production, the interaction between fog and aerosol particles may affect the aerosol's chemical composition, size, and distribution; and vice versa; aerosol concentration in the atmosphere also regulates the optical thickness of fog (Poku et al. 2019). Haze caused by excessive concentration of particulate matter can cause Aerosol loading in the atmosphere is which is influenced by the presence of fog in mainly two ways:

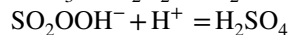
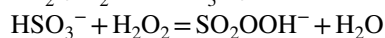
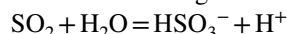
Scavenging: Same as cloud, fog acts as an agent for removing pollutants from the atmosphere. Mechanisms involved in scavenging are nucleation, coagulation, and uptake of gases depending on their concentration in fog droplets. The presence of fog can alter both the microphysical and chemical properties of the aerosol. Oxidation of aerosol particle increases the hydrophilic property of the aerosol whereas when scavenging take place through the process of coagulation and condensation the particle size increases (Herckes e al. 2013). Fog is proficient in scavenging acidic particles and gases and is formed upon neutralized CCN (Izhar et al. 2020). Hygroscopic chemical species are the first to get scavenged. Water-soluble chemical species attached to SO_4^{2-} , NO_3^- and NH_4^+ are washed down more readily (Rajput et al. 2018). As the development of fog progresses, LWC also rises, diluting the acid concentration in the droplets. Eventually, when fog evaporates, as a consequence, both relative humidity and pH drops (Tomasi et al. 2017). It has been reported that the $\text{PM}_{2.5}$ concentration was brought down by fog during the severe haze and fog episode; despite this effect, the dissipation of haze was delayed due to the presence of fog that occurred from November 27th to December 2nd, 2015 in Tianjin, China (Hao et al. 2017), PM_1 concentration is also found to be low during fog events (Rajput et al. 2018). Scavenging of newly added soot in a highly polluted zone is difficult as elemental carbon is both hydrophobic and small sized, thus scavenging of elemental carbon is not as effective in urban areas as it is for fog forming in remote locations (Herckes e al. 2013).

Addition of more aerosols: Primary aerosol, which is water-soluble, when comes in contact with fog, gets trapped in the fog droplet by aqueous processing. Once in the aqueous phase, the aerosol particles undergo an oxidation reaction and become secondary aerosol (Liu et al. 2020b). The SOA (Secondary Organic Aerosol) are less volatile organic compounds that are products of VOC (Volatile Organic Compound) that either gets attached to the existing particle whose surface area is more but the supersaturation of the gas is less or they form new particles (Herckes e al. 2013). After the fog evaporates, the newly formed secondary aerosol may contribute to aerosol loading. The size of secondary aerosol is larger than the primary, with the diameter ranging between 400 and 700 nm for inorganic aerosols ($(\text{NH}_4)_2\text{SO}_4$ & NH_4NO_3) and 400–600 nm for SOA (Secondary Organic Aerosol) (Gilardoni and Fuzzi 2017). Sulfate compounds in

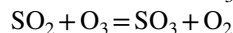
the atmosphere are not usually added to the atmosphere as a primary pollutant, but they are produced more as a secondary pollutant (Izhar et al. 2020; Sawlani et al. 2019). The basic Schematic reaction of primary aerosol converting into a secondary aerosol is given in Fig. 3.

Some examples: when $\text{A} = \text{SO}_2$.

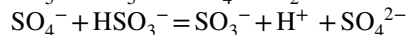
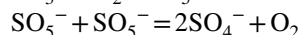
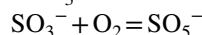
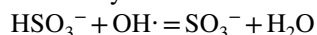
Case 1: when directly in contact with water leads to the formation of acid fog.



Case 2: when $\text{B} = \text{O}_3$



Case 3: by radical oxidation.



So, in a way, fog formation is acting as a sink by the process of scavenging and as a source by producing secondary aerosol particles, such as ammonium and calcium ion present fog, besides efficiently neutralising acidic aerosols (Sawlani et al. 2019), they lead to the production of new secondary aerosols (Nath and Yadav 2018). Apart from the generation of PAN, ozone and other secondary aerosols amid fog and haze episodes, metals often get bound to $\text{PM}_{2.5}$, increasing the probability of health risks due to inhalation of these airborne metals (Li et al. 2017). The lowered inversion boundary layer that is conducive for the occurrence of fog is also responsible for trapping air pollutants, showing a comparatively higher concentration of pollutants during foggy days, including gases, fine and ultrafine particulate matter (Gupta and Elumalai 2018; Özdemir et al. 2018; Sehgal et al. 2016; Zhang et al. 2015a, b) and consecutively providing more CCN, thus may form a positive feedback

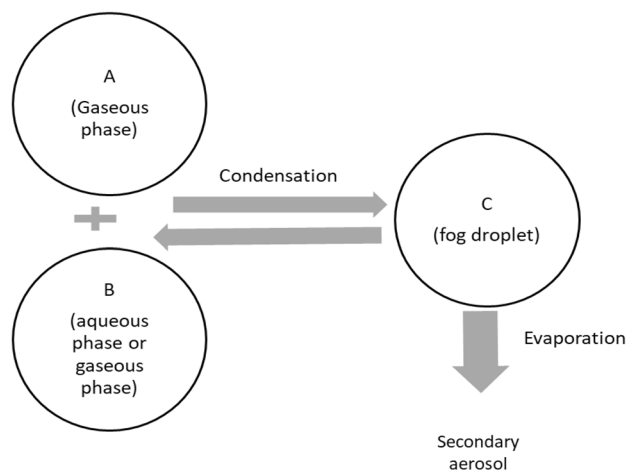


Fig. 3 Formation of secondary aerosol

loop. The frequency of stratosphere-troposphere Exchange, which acts as a regulator for tropospheric ozone budget, increases during the winter months in India (Ganguly and Tzani 2011), which may further exacerbate the probability of photochemical smog. These days, it is rare to find clean fog in cities; the fog in cities is usually found to coexist with haze and is loosely referred to as haze-fog (Guo et al. 2020; Fu and Chen 2017; Zhang et al. 2015b).

6.1.1 Policies and measures to improve air quality

Atmospheric conditions required for fog formation are also suitable for restricting the dispersal of air pollutants, and its ample supply in the locality provides for a more significant number of condensation surfaces for fog droplet formation. Thus, it becomes crucial to reduce air pollution levels. Only policies of China and India are discussed here because the air quality of its many cities is amongst the world's worst. Moreover, also because China has been able to improve its air quality relatively within a short period of time. Lessons on how to tackle the problem of air pollution? And where the measures are lacking? It can be taken from these two nations.

China's: China's enormously growing economy, industries, and urbanization are to be blamed for its current dire air quality (Hernandez 2015; Zheng et al. 2015; Chan and Yao 2008). The air pollution levels in many cities of China were too high in the past decades (Wang 2020; Zheng et al. 2016). However, China has shown remarkable progress in reducing its pollution. China's first law concerning air pollution, the Prevention and Control of Atmospheric Pollution, was enacted in 1987 and was amended in 1995, 2000, 2015, and more recently in 2016 (Fu and Chen 2017). The Law on the Prevention and Control of Atmospheric Pollution is the primary law that provides the framework of all matters concerning air quality and its related affairs. Other laws concerning air quality are- Environmental Impact Assessment Law (2003), Energy Conservation Law (2007), Law on Promoting Clean Production (2012), and Environment Protection Law (2015) (Hernandez 2015). Ambient Air Quality Standards, GB 3095-2012 has laid down limits for SO₂, NO₂, PM_{2.5}, PM₁₀, O₃, and CO in two types of areas, one comprises of natural reserves and scenic areas (Class I); and the other comprises of residential, rural, industrial and mixed-up areas (Class II) (<https://www.loc.gov/item/global-legalmonitor/2018-08-16/china-2020-air-pollution-action-plan-released/>). Initially, the five-year plans were based on a top-down model, where the standards set at the centre were gradually implemented at different stages of governance as per the hierarchical government structure, in combination with the account as the promotion of the people involved was dependent on the policy implementation (Wang 2020).

Before 2018, air pollution and control-related affairs were dealt with by the Ministry of Environmental Protection (MEP). The climate change, GHG emissions, and energy sector were the responsibility of the National Development and Reform Commission (NDRC). After April 2018 all the responsibilities of the MEP and NDRC were passed on to the Ministry of Ecology and Environment (Regulation of Air Pollution: China). Air Pollution Prevention and Control Action Plan (APPCAP), issued in 2013, was a five-year program aimed to improve the nation's overall air quality, specifically targeting the regions of Pearl River delta, Yangtze River delta, and Beijing-Tianjin-Hebei. The APPCAP consisted of ten tasks, covering: (1) emission reduction; (2) industrial structure optimisation; (3) acceleration of technological innovation; (4) clean energy supply (5) strict standards for industries; (6) environmental, economic policies; (7) Management and Regulation system; (8) Integrated Regional approach for environmental management; (9) Pollution Monitoring and warning system, and (10) Government, enterprise and societal roles and responsibilities (China Clean air Updates, State Council Air Pollution and Control Action Plan, 2013) called the "Atmospheric Pollution Prevention and Control of the Ten Measures of China" (Fu and Chen 2017). The World Bank provided financial aid under the Program for Results scheme to implement the plans and measures laid down in the APPCAP and the 13th five-year plan (2016–2020) for energy efficiency, renewable energy, and pollution control. With the financial help, waste energy from thermal power plants that was previously released into the atmosphere is now reused in keeping the homes warm in winters, due to which many coal burning boilers were shut down; similarly, the excess heat generated in other manufacturing industries is also redistributing its heat in the local homes alongside providing energy to other small scale industries (Helping China Fight Air Pollution 2018).

The government provided financial aid by introducing the Green Finance Centre (China: Fighting Air Pollution and Climate Change through Clean Energy Financing 2021) to adapt green technology in industries. To further reduce air pollution, the government reduced fossil fuel consumption and replaced non-renewable energy sources with renewable energy resources, greater involvement of social and market factors, and decentralization of policies (Wang 2020). Environment Protection tax was imposed on the industries that were directly releasing pollutants into the environment. The past two decades saw a surge in car purchases; aside from adding to the traffic problem, it also was adding to the already high emissions, so many local governments issued vehicle purchase restriction policies. The restriction policy was able to reduce PM₁₀ levels (He and Jiang 2021). Half of the buses running on the Beijing roads have been electric since 2016, and more than 200,000 e-vehicles in the nation's capital (He et al. 2019). APPCAP was succeeded

by the “Three-year Action plan to Win the Blue Sky Defense War” (2018–2020), whose focus was to bring down the levels of $PM_{2.5}$ at par with the goals set in the previous plan for the cities which were not able to reach their targets in the previous plan utilizing structural adjustments in industries, energy, transportation, and land (Jiang et al. 2021). Evidence of the improvement made in the air quality was observed in many areas (Cui et al. 2020; Yu et al. 2019; Huang et al. 2018; Chen et al. 2017). In a decade (2010–2019) China decreased its outdoor $PM_{2.5}$ levels by 30% by the emission curbing actions as a result of proper implementation of APPCAP and its successor measures (State of Global Air 2020). Though China has been able to significantly curtail the emissions of CO, SO_2 , PM_{10} , $PM_{2.5}$ but O_3 was observed to be increasing, actions are still needed to bring the emissions further down with greater effort to be made for bringing down the concentration of O_3 (Zhao et al. 2021; Yu et al. 2019). Outdoor $PM_{2.5}$ levels went down by 30% from

2010 to 2019 due to proper implementation of the policies. According to the Global Wind Report (2021) China is the World's leader in wind energy and hydropower generation capacity according to the 2020 Hydropower Status Report, showing its inclination towards renewable energy resources. Industrial and residential sectors switched from coal to gas, and an overall reduction in emissions was observed (State of Global Air 2020). The percentage of coal burning in total energy consumption dropped to less than 5% (A Review of 20 Years' air Pollution control in Beijing, 2019). In the light of the recent economic slowdown faced due to COVID-19, the new coal-burning capacity (Stanway 2021) instills fear of halting the progress made in curbing pollution. The effects of the various measure taken by the Chinese government is represented in Table 2.

India: The Northern Plains of India is one region where it observes very dense fog every year during the winter

Table 2 Effects of air pollution prevention and control action plan (APPCAP) and other emission control measures on the air quality, mortality, morbidity, and their economic benefits

Authors	Study area	Period	Conclusions
Zhao et al. (2021)	China	2015–2018	Annual mean concentration of CO, SO_2 , PM_{10} , $PM_{2.5}$ declined at a rate of 70, 3.8, 4.1, and $3.4 \mu g m^{-3}/year$. Though, O_3 increased by $3.4 \mu g m^{-3}/year$ and NO_2 did not show any prominent decline. The overall population exposure risk to $PM_{2.5}$ did decrease but 65% of the population is still at the risk of being exposed to levels higher than the standard limit of $35 \mu g m^{-3}/year$. During the 2015–2018 mortality attributed to increased O_3 was 70,024; 79,159; 105,150; and 104,404, respectively
Cui et al. (2020)	Jinan City, China	2013–2017	SO_2 and NO_x exhaust emission decreased notably. SO_2 reduced by 72.6%, $PM_{2.5}$ by 43.1% (which was quite high compared to the National Ambient Air Quality Standards Grade-I), and PM_{10} by 34.2%. In 2017 the city avoided 2317 premature deaths and 15,822 morbidity cases related to these air pollutants. In addition gaining economic benefit of 317.7 million USD
Maji et al. (2020)	Beijing, China	2014–2018	Reduced concentration of SO_2 , CO, NO_2 , PM_{10} , and $PM_{2.5}$ by 1.9, 80, 2.4, 8.1, and $7.4 \mu g m^{-3}/year$ was observed. Mortality rate was found to be lessened by 5.6% and 18.5% in 2018
Yu et al. (2019)	Guangzhou, China	2014–2016	Effects of Meteorology and emission control actions on air quality was estimated using WRF-MAQ (Weather Research & Forecasting—Community Multiscale Air Quality) model. The favorable meteorological conditions can bring the pollution levels down but when compared to joint emission control measures (of Guangzhou and neighboring cities) were found to be more effective and could possibly bring down pollutant concentrations of SO_2 by 48.4%, NO_2 by 17.7%, $PM_{2.5}$ by 14.6% and PM_{10} by 13.4%, and O_3 by 7.7%. Measures taken by Guangzhou alone reduced emissions for SO_2 (46.0%), NO_2 (15.2%), PM_{10} (9.1%), and $PM_{2.5}$ (9.4%) but O_3 concentration increased (2.4%)
Huang et al. (2018)	74 cities in China	2013–2017	Overall annual average of concentration of SO_2 , CO, PM_{10} , and $PM_{2.5}$ decreased by 54.1%, 28.2%, 27.8%, and 33.3%, respectively. NO_2 and O_3 concentration levels were around 9.7% and 20.4% which was not a significant change. In comparison to 2013, in 2017–42,240 deaths were avoided and 710,240 lesser years in life lost
Wang et al. (2017)	China	2013	Annual Average Standard of $35 \mu g m^{-3}/year$ for $PM_{2.5}$ was only achieved by 4.1% of the Chinese cities. Central-Eastern-China observed $100 \mu g m^{-3}$ and some regions crossed $150 \mu g m^{-3}$ of $PM_{2.5}$ concentration
Chen et al. (2017)	Beijing–Tianjin–Hebei Region, China	2013–2017	2014 $PM_{2.5}$ concentration data were simulated to predict the effects after the complete implementation of emission control measures. The study found that the $PM_{2.5}$ concentration might fall to 25% reaching $60 \mu g m^{-3}$ I Beijing. 3175 to 14,051 deaths attributed to $PM_{2.5}$ could be avoided. The combined economic benefit from reduced mortality was estimated by WTP (Willingness to Pay) was around 0.01–0.3% of 2012 GDP of Beijing, 0.01–0.2% of 2012 GDP of Tianjin and 0.03–0.8% of 2012 GDP of Hebei

months. Though topography and meteorological factors play an essential role in its formation, the contribution of air pollution cannot be ignored. Due to this reason, Delhi is the most polluted capital globally, according to the World Air Quality Report of 2020 by IQ Air (Swiss Organization). Therefore, EPCA (Environmental Pollution (Prevention and Control) Authority) was formed to manage all related environmental issues and for enforcement of GRAP (Graded Response Action Plan) formulated in 2016, whose work was to address severe air pollution emergencies in Delhi and National Capital Region. Recently, in 2020 the “Commission for Air Quality Management” (CAQM) was set up for Delhi and NCR dissolving the EPCA. This new body comprises national and state ministries, stakeholder representatives from the involved states, and people from scientific communities and civil societies (Clearing the Air: Highlights of city Actions in 2020 to Reduce Air Pollution 2020). For improving air quality, the government has taken many measures both at the national and local levels. At the national level Ministry of Environment, Forestry and Climate Change (MoEFCC) for monitoring India's policies related to the environment, forest, and climate change and CPCB (Central Pollution Control Board) is responsible for supervising all pollution-related matters and at the state level SPCB (State Pollution Control Board) takes on the same responsibility at the state level. National Ambient Air Quality Standards (NAAQS) given by CPCB have set standards for SO₂, NO₂, PM_{2.5}, PM₁₀, O₃, Pb, CO, NH₃, C₆H₆, BaP, As, and Ni emissions in industrial, residential, and rural areas; and in ecologically sensitive areas (https://cpcb.nic.in/uploads/National_Ambient_Air_Quality_Standards.pdf). Under the supervision of CPCB, NAMP (National Air Quality Monitoring Programme) oversees the trends and status of air pollutants—SO₂, NO_x and particulate matter (PM₁₀ and PM_{2.5}) and the standards are given by National Ambient Air Quality standards (enacted 1994, amended 2009). For continuous monitoring of air quality, there are 793 stations located nationwide as of July 2020 (Raw & Processed Data to Support Energy, Emission & Air Pollution Analysis in India). Another pilot project named SAFAR (System of Air Quality and Weather Forecasting and Research) provides near real-time data and a 1–3 day forecast of PM₁₀, PM_{2.5}, NO₂, CO, and O₃ for Delhi, Pune, Mumbai, and Ahmedabad (Beig et al. 2015, 2020). A report published by Sharma and Dikshit (2016) on the Air pollution of Delhi identified some sources (eateries still using coal; economically vulnerable population burning solid fuel for cooking and warming during winters; unmonitored burning of municipal solid waste; vehicles; industries; construction sites and road dust) responsible for poor air, and they suggested that tackling the problem by just managing one or two of the source alone and only during the winter months when the problem is visible will not be enough, the problem has to be treated as a

whole. In the report, they have advised some measures, the government and policymakers have taken up the recommendation to some extent. Like coal-fired tandors are banned (<https://timesofindia.indiatimes.com/city/delhi/delhi-corporations-act-against-500-eateries-withtandors/articleshow/71845177.cms>); and “Mandatory Implementation of Dust Mitigation Measures for All Construction and Demolition Activities” (Rule 106 & 107) were amended in the “The Environment (Protection) Amendment Rules, 2018 to manage dust from the construction and demolition sites. Stubble burning in North Western states of the nation is amongst the prime contributor of aerosol (Beig et al. 2020; Grover and Chaudhry 2019; Sawlani et al. 2019; Singh et al. 2018; Singh 2018), which gets accumulated in the National capital of Delhi where it mixes with fog forming dense smog. Crop residue burning is now banned under Section 144 of the Civil Procedure Code (CPC) (Bhuvaneshwari et al. 2019) in Rajasthan, Uttar Pradesh, Haryana, and Punjab. The national government recently instructed the NTPC (National Thermal Power Corporation) to incorporate crop residue in power plants (Bhuvaneshwari et al. 2019). Since 2015 CPCB has made it compulsory for all industries to install OCEMS (Online Continuous Emission Monitoring Systems) to monitor pollution release from high pollution potential industries. In 2019, intending to improve ambient air quality by 2024, the government launched the National Clean Air Programme, 2019 (NCAP) for 122 cities. Its aims were very much in compliance with the sectors (transport, industry, waste burning, residential, construction, and dust) specified by UNEP. Other measures include programs such as (1) Pradhan Mantri Ujjwala Yojana launched in May 2016 aimed provide LPG to rural areas: for urban areas to replace LPG with PNG and electricity (Patnaik et al. 2018); (2) for vehicle emission and fuel quality standards are to follow BS-VI from 2020; (3) Voluntary Vehicle Fleet Modernisation program and Vehicle Scrappage policy to be introduced in 2021 for removal of old and unfit vehicles from roads; and (4) NEMMP (National Electricity Mobility Mission Plan) 2020 to push the sale of electric and hybrid cars (National Clean Air Programme 2019). Though the program lacked the legal mandate and was majorly focused on cities, it caused the local governing bodies to increase their engagement in improving air quality (State of Global Air 2020). Waste management strategy in City Action Plans is supervised by Municipal Solid Waste (MSW) Management Rules, 2016, which includes converting waste into energy, recycling, and proper management of landfill sites to avoid open burning as a form of waste disposal. A significant number of the waste to energy conversion plants remained underutilized (Clearing the Air: A review of 10 city plans to fight Air pollution in India 2020). India's renewable energy capacity as of 30th November 2020 was 90.39 GW. To accelerate this progress, targeting increasing this capacity to 450 GW by 2030 and

the government is framing its policies to increase its renewable energy market (The Hindu Business Line 2020). This will greatly help in reducing our energy dependency on non-renewable resources. Though India has been able to reduce indoor pollution largely by shifting from traditional biomass burning to the use of clean fuel (State of Global Air 2020) but it has yet to show any significant decline in the outdoor emission rates. India has a far way to go for controlling its growing air pollution, there are very few achievements currently in this regard and they are mentioned in Table 3.

The economic slowdown because of COVID-19 had one remarkable positive effect on the air quality worldwide. The air pollution rates in many countries around the world were significantly lowered during the lockdowns that were happening in the last two years (Javed et al. 2021). However, as both air pollution and the coronavirus affects the respiratory system, the need for improving the air quality increases many folds.

All these plans and measures are made to mitigate air pollution directly or indirectly, and thus influencing smog.

6.2 Human health

Inhaling fog devoid of large percentages of chemical pollutants or particulate matter is nothing more than inhaling water droplets. However, since the industrial revolution, the concentration of air pollutants have increased so has its repercussions, as most of the suspended particulate matter and pollutants can directly act as cloud condensation nuclei (CCN) or can transform into chemical compounds or free radicals that can wreak havoc on our health (Allaby 2014). Those same air pollutants can have varied effects depending on the nature of air it is suspended in (wet and foggy or dry) (Park et al. 2015). Hence the previous pieces of literature provide us with information on indirect influence or the influence of associated variables on our well-being.

It has been reported that fog or misty nights have seen an increase in the number of emergency room visits for children who have asthma which is a direct indication of worsening health conditions in asthmatic children, still the study was unable to find whether it was the result of inhaling fog or the meteorological status (Kashiwabara et al. 2002). A study carried out by Avol et al. (1988) studied the short-term respiratory effects of sulfuric acid in fog on 44 adult volunteers (asthmatic and normal). By exposing the volunteers to light fog (having varied concentrations of sulfuric acid) in a controlled environment of a chamber. The results showed moderate development in respiratory symptoms and an increasing concentration of acid and even at the highest concentration of sulfuric acid, a minor influence on pulmonary function was observed. The conclusion was drawn that only modest respiratory systems and negligible pulmonary dysfunction are presumably to happen when inhaling sulfuric acid fog. Honma et al. (2000) investigated the response of asthma patients in foggy and non-foggy periods in context to effects of acid fog on inflammation and pulmonary functions; it was concluded from the study that the deterioration in the function of the respiratory system in asthma patients was caused due to inflammation induced by inhalation of naturally occurring acid fog, however, no such developments were observed in normal subjects. Another investigation done by Lavorini et al. (2001) found fog inhalation to induce cough in subjects with no asthma. It was able to evoke bronchoconstriction along with regular cough in subjects with asthma. *N-nitrosodimethylamine* (NDMA) of considerable concentration, found in radiation fog and clouds, was found to be a potentially carcinogenic compound (Hutchings et al. 2010).

Fog, when it morphs into smog, has detrimental impacts on human health. Since the first extensive episode of London Smog, the topic of smog and the role of aerosols and their effects on various other systems has been extensively

Table 3 Effects of the implemented air pollution control measures in India

Source	Area of interest	Conclusions
IEA (2021)	India	By 2040 SO ₂ , NO _x and PM _{2.5} concentrations can be brought down significantly if there is full implementation of control measures even when the captive power sectors operate on coal at the 2019 levels. If one third of the captive power is provided by the solar PV in 2040 NO _x and PM _{2.5} will see another half in reduction. However, if the emission control measures are not successfully implemented all the air pollutants level may double and SO ₂ emission may rise above 1.5 Mt by 2040. NO _x emissions related to transportation may peak in 2025 and then may decline by 60% in 2040, if strict fuel and vehicle standard along with will emission control measures are implemented
Pandey et al. (2021)	India	Death rate in India due to indoor pollution reduced by 64.2% in two decades (1990–2019), however, the deaths due to particulate matter rose by 115% and due to ozone rose by 139.2%. The associated loss was around 28.8 billion USD
Dholakia et al. (2013)	Delhi	Greenhouse Gases and Air Pollution Interactions and Synergies (GAINS) model was used to analyze the future effects of the air pollution curbing measures. The then policies will be able to decrease PM _{2.5} concentrations but still will not be able to attain the standards set by NAAQS (40 mg/m ³) by 2030

studied. Exposure to smog can have both immediate and long-term effects on the respiratory and cardiovascular systems, causing ischemic heart disease and cerebrovascular diseases (Polivka 2018; Cai and Wang 2017). Some studies show how the smog of 1952 affected the subjects who, during the episode, were still in their mother's womb or were in their first year after being born (Bharadwaj et al. 2016; Turner 2012; Barker 1990). Bharadwaj et al. (2016) first attempted to study the health consequences of exposure to smog, taking asthma as the targeted disease. It developed later in life in that part of the population in their early life stage. In the recent past, there have been instances when fog episodes were accompanied by haze holding suspended metals (Agarwal et al. 2017) such as Na, Mg, Al, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Sr, Mo, Cd, Ti, Ba, Pb and when their combined risks as a carcinogen were evaluated on children was 1.32×10^{-6} and on adults was 5.29×10^{-6} both of which were above the precautionary level of 10^{-6} (Li 2017). With the numerous amount of information available on the effects of ambient air pollutants (NO_2 , O_3 , PM_{10} , and $\text{PM}_{2.5}$) present in smog it is now a well established fact that increases the risk of developing cardiovascular diseases, ischemic heart disease (IHD) and various other respiratory issues (State of Global air 2019; Cai and Wang 2017; Park et al. 2015). The current pandemic situation can aggravate the health risks associated with smog, as both targets the respiratory system. The elderly and the people already suffering from any other type of cardiovascular or respiratory disease are at higher risk from smog, similarly the coronavirus disease is more fatal to them. The synergistic effect of COVID-19 and smog is explained in detail by Javed et al. (2021) in their review.

Much research was performed on the influence of air pollution on the pulmonary and cardiovascular systems. Research surrounding cognitive abilities and psychological effects started appearing over the past two decades. Children exposed to the heavily polluted air of Mexico city have higher chances of developing Neuroinflammation; this was concluded from their MRI (Magnetic Resonance Imaging) scan; another thing that was found was that these kids performance was comparatively poor to the children from cleaner air group in memory; cognition and intelligence test (Calderón-Garcidueñas et al. 2008). Inflammation in the brain interrupts the blood–brain barrier putting the children and new adults at a higher risk of developing diseases related to the central nervous system (such as Parkinson's and Alzheimer's disease), auditory language impairment, poor cognitive and memory (Calderón-Garcidueñas et al. 2012). Prenatal exposure to high concentrations of PAH, which is precursor gas for the development of photochemical smog (Polycyclic Aromatic Hydrocarbons), can impact a child's learning and understanding abilities in addition to the development of anxiety and depression (Genkinger

et al. 2015; Perera et al. 2012). Cognitive abilities in both older men and women have also been reported to compromise long-term exposure to particulate matter (Weuve et al. 2012; Power et al. 2011). In Barcelona, it was concluded by Vert et al. (2017) that adults are likely to develop depression when exposed for an extended time to particulate matter and nitrogen oxides. A thorough review linking air pollutants with brain function is provided by Power et al. (2016), and a short review is provided by Underwood (2017).

Tian et al. (2008) reported the influence of fog on malaria incidence in a rainforest area of China. The study was performed by Ecological time series analysis from the fog and malaria data. The positive impact of fog frequency on malaria incidences was observed after a gap of seven months, which may have resulted from additional water input for the breeding grounds of mosquitoes.

With the increasing air pollution across the globe, there is a vast sea of research dedicated to the influence of almost all air individual pollutant species but have mostly been restricted to lungs and heart diseases; there is a lack of research on the synergistic effect of various chemical species present in fog droplets, with regards to other diseases and its influence on other parts of the body. Proper pathogenesis on how a person already affected by a particular disease responds to inhalation of polluted fog for short and long exposure for various regions, as different locations can have different fog characteristics. In terms of neurological and psychological implications of smog, a large portion of the research is still concentrated in the developed nations; there is a dire need to conduct such research in developing nations as well where the cities are frequently inundated in smog, as the likes of Indian and Chinese cities.

6.3 Transportation and economy

Visibility reduction due to fog is a danger to any type of transportation activity, whether land, sea, or aviation (Croft 2003). Land transportation, including both roadways and railways, is prone to delays and disruption. Accidents on roads due to collisions are frequently observed in places under the influence of dense fog. Although accidents occur primarily due to collisions, some of them may be attributed to fire during a collision. Around the world, accidents related to fog result from restricted navigation ability caused due to restricted visibility and also because of the driver's inability to gauge the speed limits and the safe distance between the vehicles during such weather conditions. Fatal accidents due to poor visibility can also lead to a chain of collisions resulting in a piled-up condition (Whiffen et al. 2004). In India alone, reported road accidents due to fog in the year 2017 was 26,982 killing 11,090 and injuring 24,828; in 2018 the number increased to 28,029, killing 11,841 and injuring 25,265 (Road Accidents in India 2018), in 2019

the numbers further increased to 33,602 killing 13,405 and injuring 30,776. The road accidents in 2019 increased by 19.9%, and the reported fatalities increased by 13.2%, which was reported to be the highest in accidents caused due to poor weather conditions (Road Accidents in India 2019). Peng et al. (2018) analyzed the effect of reduced visibility on traffic flow parameters (speed, volume, and headway) on different vehicles (passenger cars and trucks) and vehicles running on different lanes implementing the statistical approach of t-test and ANOVA. Through the study, it was concluded that the headway variance could be a significant cause of accidents; effect on passenger cars is comparatively notable than trucks; different lanes experience different effects, and the effects on traffic parameters are more prominent in the inner lane and also when visibility < 300 m. It has been previously reported that fatal crashes in low visibility conditions due to fog or smoke are relatively more severe and may involve multiple vehicles for the Florida region (Abdel-Aty et al. 2011).

The cancellation, delays, and diversion of flights caused due to fog create inconvenience for the passengers, flight crew, and transportation management (The Economic Times 2019). The hassle of making alternate arrangements may sometimes add extra costs. Trade and commerce, businesses, import and export of goods and services are expansively dependent on transportation and are hindered, affecting the economy. Some studies reported that economic loss due to restrained transportation is comparable to tornadoes, hurricanes, and winter storms (Gultepe et al. 2007, 2009). Weather hazards, including mountain wave turbulence, clear air turbulence (CAT), microbursts, thunderstorm, poor visibility, and wind shear, are among the primary contributing reasons for aircraft and helicopter mishaps (Jenamani and Kumar 2013). Low visibility can hamper aircraft navigation safety in the course of takeoff, landing, and taxiing. It was reported that in Canada, one-half of all-weather-associated casualties at the airport was because of low visibility (Leung et al. 2020). Specifically, in the US, accidents during takeoff and crashes after takeoff are more frequent when visibility < 0.3 km (Wong et al. 2006). Pilots have expressed their concern regarding low visibility, stating that they could lose their spatial awareness and taxi to the wrong region (Obradovich et al. 1998). To avoid any chance of collision with fuel trucks, other aircraft, personnel, and other vehicles in the ramp area, pilots had to reduce their taxiing speed by one-half to one-third of the typical speed for fear of their inability to see in foggy weather (Andre 1995). As a precautionary measure, the distance separation between arriving and departing aircraft is more significant than usual, leading to delays and cancellation of flights. In addition, these foggy conditions often act as reasons that can lead to delays in emergency response, search and rescue endeavors (Joe et al. 2020; Croft 2003). Diverted, delayed, and cancelled

domestic and international flights in the Indira Gandhi International (IGI) Airport accounted for an approximate loss of 3.9 million USD (248 million Indian rupees) for 2011–2016, during the winter months when the dense fog conditions are prevalent (Kulkarni et al. 2019). A prior study conducted by Jenamani and Kumar, 2013 showed that the second-highest number (approximately 16%) of aircraft accidents between the period of 1992 to 2008 were attributed to low visibility; similar situations were observed in the US.

6.4 Ecology

The conditions of increased relative humidity, decreased evapotranspiration, more significant diffuse radiation, and trapped carbon dioxide in the inversion layer all prevail in foggy conditions, enhance photosynthesis, and augment plants' productivity and growth (Zhang et al. 2015a, b). Fog plays the role of both vector and medium in various ecosystems around the globe, inclusive of the coastal, desert, alpine, and inland ecosystems transporting and controlling input of crucial limiting resources such as light, moisture, and nutrients. Processes of decomposition, productivity, and water fluxes in a given ecosystem are affected by fog as it is a crucial component in mechanisms of crown wetting, elemental decomposition, light scattering, and absorption (Tognetti 2015; Weathers et al. 2020).

Fog is seen as a source of water in a local ecosystem, where the precipitation levels are incapable of fulfilling water requirements for both flora (Emery 2016; Jacobson et al. 2015) and fauna (Nørgaard and Dacke 2010; Parker and Lawrence 2001). The desert ecosystem is one such example where the vegetation is majorly dependent on fog for its moisture (Kalivodová et al. 2020; Lvončík et al. 2020; Riccardi et al. 2020; Lehnert et al. 2018) and nutrient (González et al. 2011) requirements. Hamilton and Seely (1976) performed the most remarkable research that paved the way for studying the dependency of desert species on fog water; Seely and Hamilton (1976), reporting the fog basking physiology of tenebrionid beetle (*Onymacris unguicularis*, *Lepidochora discoidalis*, *L. porti*, and *L. kahani*). A minimum of 48 animal species of the Namib Desert has been reported to consume fog water either in the liquid or vapor phase (Mitchell et al. 2020). Water-limited ecosystems have vegetation that has characteristic features making them adaptable to such harsh weather conditions here; the fog water is intercepted by the leaves (Riccardi et al. 2020; Borthagaray et al. 2010). Dwarf succulents species of *Canophytum* and *Lithops* are dependent on fog water for their survival in the desert. Guo et al. (2017) showed that there would be a reduced number of fog days in the future, habitat loss, and range contraction for the two species. The first attempt to study the influence of fog on vegetation implementing satellite data considering two sites of Namib Desert relieved a

positive impact on the vegetation in their study areas (Qiao et al. 2020). In the Atacama desert, Sotomayor and Drezner (2019) investigated the alteration in the microclimate caused by the dominant plant species in the fog desert. The extreme weather conditions are regulated by fog itself; any amelioration by the plants was also restricted on foggy days. Warren-Rhodes et al. (2013) conducted a study to observe the role of light, rain and fog on hypolithic communities of Namib Desert; in the study, it was found that the physical ecology of the community benefited from the presence of fog, the community was thriving, an adequate supply of water in the form of fog helped the microorganism to colonize readily on smaller sized rocks. Except for the Namib Desert, there is a lack of research in other desert systems exploring the dependency of desert animal species on fog (Mitchell et al. 2020). Coastal ecosystems dependent on fog for their sustenance will be affected mainly by any notable shift in fog; locations that experience dry summers, e.g., Mediterranean regions (Ferraguti et al. 2013; Pignatti et al. 2006), South Africa East Asia (Pignatti et al. 2006; Hukusima et al. 2005), Chile, Mexico (Pignatti et al. 2006) and California, are more likely to face habitat loss riparian, intertidal, and terrestrial species. Some researches on the implications of fog on the vegetation found in the California region have been investigated (Fischer et al. 2009; Ingraham and Matthews 1995). Winter chill provided by the foggy conditions of lowered minimum solar radiation lowered maximum and mean temperatures create an appropriate environment for fruit and nut productivity in California (Baldocchi and Waller 2014). During the summer drought, the plant species of the coastal prairie grassland utilized fog water rather than the remaining water from the last rainfall; the difference in utilization pattern was also observed for different species giving advantage to fog water using species over those which cannot (Corbin et al. 2005). In California, Santa Cruz regions, elevated levels of monomethyl mercury (MMHg) are found in fog water samples (Weiss-Penzias et al. 2012, Weiss-Penzias et al. 2016). This heavy metal is a neurotoxin and tends to bioaccumulate in the food web (Ortiz et al. 2015). Due to wet deposition of MMHg, higher mercury concentration was found in Puma (*Puma concolor*), where the concentration of Hg was more in adults than the younger ones. Hg entered the food chain via Lichens, where Puma consumed the mule deer, and Lichens were a significant portion of food for the deer species; this led to Hg's bioaccumulation with the progression of each level of the food chain (Weiss-Penzias et al. 2019).

Chances of forest fire may also increase due to reduced relative humidity and rise in temperatures since these conditions may prevail due to a decline in fog and cloud cover (Torregrosa et al. 2014). In forests, droplets of fog drip down from trees, leaves, and stems to the surface soil moisture (Li et al. 2018; Poca et al. 2018). Dependence of the Redwood

forest ecosystem on fog was investigated by Dawson (1998), in his study he found that though the fog input was normal, but the dependence on fog was more during the summer months, later studies concluded that fog promoting water conservation alongside reducing the probability of water scarcity (Johnstone and Dawson 2010). Low clouds provide an atmospheric mechanism for redwood water conservation by reducing transpiration rates during the dry summer season. The most likely effect of fog decline is heightened drought sensitivity for coastally restricted plants. Fog is a dominant climatic factor on the California coast, and long-term reductions likely have and may continue to impact the water and carbon economy of redwoods and other coastal endemic species. Interaction of nutrients that are brought to soil or plant by fog (González et al. 2011) is a less investigated topic; however, some studies have shown fog being a source of nitrogen for redwood trees (Templer et al. 2015), of phosphorus in the dry tropical forest of Mexico (Vandecar et al. 2015). Carbone et al. (2013) studied the response of the Bishop Pine ecosystem to low stratus clouds and fog drip on the microbial and plant activity, and it was found that the vegetation in areas having consistent cloud cover faced less water stress; increased basal growth; increased sap velocity and increased contribution in the carbon cycle by microbes. Baguskas et al. (2016) found that a single fog event of more significant magnitude was capable of counterbalancing the effects of seasonal drought on the California pine forest where the young sapling trees were more susceptible to changes in moisture content in the soil, the water status of Bishop pine saplings was more dependent on fog water than their mature counterparts. The presence of patches of rainforest found in the semi-arid climate of Chile is supported by the marine fog prevalent in the region; the windward side of the forest had maximum regeneration, whereas the leeward side had maximum mortality proving the significance of fog water in the region (del Val et al. 2006). There are many regions around the world, especially the tropical and subtropical regions where the presence of fog is a characteristic feature of the cloud forest, water loss due to transpiration in such forest type is primarily kept in check because of the wet and cold environment provided by fog (Regalado and Ritter 2021; Kalivodová et al. 2020; Goldsmith et al. 2013; Ritter et al. 2009) as well acting as a subsidiary water source (Berry et al. 2014). Mexican weeping pine species (Alvarado-Barrientos et al. 2014) of the montane forest also showed similar observations (Gotsch et al. 2014). A form of fog known as the acid fog has been observed to harm Beech (Nara et al. 2001), hindering physiological activity and growth of its seedlings (Shigihara et al. 2008), Red Spruce (Jagels et al. 2002, 1989). Red spruce on exposure to the acid fog of pH 4.2 initially showed an increase in wax production, but on long-term exposure, a decrease was observed; reduced de nova wax synthesis

rate; altered wax composition causing a decline in secondary alcohol production (pH 3.0 fog). Wettability and thickness of cuticular membrane of red spruce were affected (Percy et al. 1990, 1992). Another research conducted by Igawa et al. (2002) observed calcium and boron leaching happening in the shrinking fir forest present in the acid fog prevalent area; similar results were observed in simulated conditions making the trees calcium and boron deficient, which might have been a cause of declining forest cover.

Singh and Giri (2011), in their study, observed increased yield of wheat crop in relation to increased fog and mist duration in Amritsar, the cause behind this was reduced surface temperature, which was the resultant of radiative cooling caused by the restricted solar influx. Crop production in South West China benefits from fog since it cuts the high-intensity solar radiation during the morning hours, thus tempering the photodamage inflicted by chilling (Zhang et al. 2014).

7 Fog as a resource

Fog water has turned into an alternative and sustainable source of fresh water, especially in dry regions that experience frequent fog events. With rapidly changing climate, overconsumption, inadequate management, among other forces, has led to the scarcity of water around the globe and specifically in arid regions is more pronounced now. This scarcity directly impacts the availability of drinking water, agricultural production, and food availability. Regions like these greatly benefit from harvesting fog water. Coastal areas of Angola, Namibia and South Africa, Kenya, Eastern Yemen, Oman, China, Sri Lanka, Mexico, along with the mountainous regions of Peru, Chile, and Ecuador, are some of the potential sites that can benefit from the installation of fog water harvesting systems (Climate Technology Centre & Network). Southeast Asia also sees fog water as a promising water source to deal with the water scarcity in regions prone to fog events in the near future (Ismail and Go 2021). Harvesting fog water requires no ongoing energy supply making it ideal for isolated and rural communities, where water usage is relatively low (Domen et al. 2014). Fog water can also be seen as both complementary and supplementary to the existing water resource. Apart from being a green technology, providing water and ecosystem service, fog water harvesting projects have also impacted the economic aspect by providing livelihood and social aspects by promoting gender equality in the regions they are running (Qadir et al. 2018). Fog water is collected with the help of mesh nets standing perpendicular to the direction of fog-carrying winds. When the fog droplets come in contact with the net, they get trapped; as the droplet size increases by coalescence, it becomes heavier and drops down into a

receptacle, from where it is collected in tanks. In theory, collecting fog water is simple, but the attempt is futile if the actual feasible potential of the fog water collection rate is not predicted. So, at present, there are two models for depicting the potential of fog water collection in any given area using the mesh collector: *Impaction model*, fog is collected in the mesh by impaction, direct interception and Brownian diffusion of fog droplets even so the contribution by the latter two is almost negligible as the interception only happens for droplets that come within the range of one droplet radius from the mesh and Brownian diffusion is only possible for droplets with diameter $> 0.1 \mu\text{m}$. So, considering impactions the main process fog water collection can be determined by the following formula (Ritter et al. 2008):

$$q = 3.6 wA\eta V$$

q = rate of water collected (L h^{-1}), w = water content of the air (g m^{-3}), A = cross-sectional area of the mesh (m^2), η = fog collection efficiency due to fog (unitless), V = wind speed (m s^{-1}), 3.6 = conversion factor to express q in terms of L h^{-1} .

Efficiency model, this method is based on fog collector and the atmospheric conditions, developed by Imteaz et al. (2011). Fog water is calculated making use of the following formula (Imteaz et al. 2011):

$$Fw = fc \times (\text{FPI}) \times f(H) \times f(W) \times A$$

Fw = fog water yield (L), fc = fog collector efficiency based on the material of mesh (unitless), FPI = fog potential index (unitless), $f(H)$ = function of relative humidity (unitless), $f(W)$ = function of wind speed (unitless), A = area of fog collector mesh (m^2).

The potential of fog water collection is distinct to the site, depending on meteorological parameters and the design of the harvesting system. Meteorology cannot be controlled; therefore, it becomes more crucial for good design to maximize the collecting capabilities. The quality of collected water is affected by air quality and particles that get stuck on the collecting mesh. Fog has been known to dissolve bicarbonates, calcium, sodium chloride (Klemm et al. 2012), heavy metal such as mercury (Ritchie et al. 2006), nitrates, organic carbon, and other ions (Raja et al. 2008) depending upon the concentration of the dissolved chemical species may affect the quality of collected water accordingly.

Fog water is currently utilized for drinking and domestic purposes, but for irrigation purposes, reports indicating its usage are less; however, there is scope to be used for reforestation (Domen et al. 2014). The semi-arid region of southwest Morocco is a coastal region barely receiving rainfall with depleted aquifers; however, the site is covered with fog half the year and now uses this fog as a freshwater source (Dodson and Bargach 2015). Survival rates and health of

saplings are aided by water. Valencia region of Spain utilized fog water to restore forest after a wildfire, and the experiment was successfully reviving the pine forest. A similar practice was conducted near the desert regions of Peru by Ramírez et al. (2012) for irrigation of 2 years old *Myrcianthes ferreyrae* trees.

8 Conclusion

The review's objective was to provide an overview of various aspects of fog, including its controlling factors, its formation; its type; techniques for its detection and prediction; its implication on-air, humans, ecology, and transport. In many places, fog is generally viewed as a local phenomenon, and in many cases, it is. It expands up to hundreds of kilometers in many places, e.g., the Northern Plains of India. The factors that influence its formation, evolution, and dissipation are for sure controlled by local factors such as wind speed and temperature; characteristics of surface and air mass; physical and chemical properties of Condensation nuclei; stability of boundary layer; vertical and horizontal wind flow; cloud cover; relative humidity and terrain. However, large-scale wind circulation cannot be ignored, as they can very much control the local meteorological conditions that require more exploration for its incorporation in the prediction models. Efforts need to be made in the direction of the direct role of soil properties on fog. There are so many aspects of fog, and each forms a separate area of research. To understand various aspects of fog, research has been conducted widely and profoundly, but the researchers have repeatedly stated that fog forecasting is still lacking. There are many techniques through the fog that can be predicted or observed; apart from the NWP models, other techniques are rapidly developed, especially artificial intelligence. Identification of commonalities between various research studies provides insight into the fog life cycle. It thus helps in selection and development techniques for better prediction, which is possible with extensive research. Understanding the factors influencing and the physical processes involved in fog formation, evolution and dissipation help improve the prediction capabilities of the current techniques available and develop new algorithms in forecasting. Simulation of fog alongside improving the prediction also helps in understanding the involved mechanisms. Improved prediction and detection will significantly contribute to curtailing the accidents and economic losses related to fog. On the other hand, it will help identify locations where fog water can be economically collected.

Before and during the initial years of the past century, the fog was viewed as nothing more than an obstruction in visibility creating nuisance in transportation and, however, with the increased use of coal after the industrial revolution; the

term smog was coined and popularized, drawing attention on its direct detrimental impact on humans. Previously the microphysical properties were studied only from the angle of increasing the prediction capabilities of the prediction models; however, after the emergence of smog, concern was paid from the perspective of its health impacts. The urban atmosphere is saturated with various chemicals and CCN; their interactions among themselves and other metrological components need more comprehensive work on various regions as the behavior may vary with each location. Because of the complexity of atmospheric processes, the cause-and-effect relationship is not always consistent. Prior studies have shown that during the initial stages of haze fog events, the concentration of particulate matter increases, resulting from physical and chemical processes such as forming secondary particles and chain reactions all happening together. In addition to this, fog also has scavenging properties, so the particulate matter concentration drops after the fog event is over. These occurrences depict the importance of identifying and quantifying short-lived intermediate species formed during secondary aerosol generation. To garner such information, interdisciplinary techniques should be incorporated in the forecasting models to elucidate molecular-level processes. The characteristics, distribution, and evolution of CCN must be better understood to be adequately incorporated into the prediction models. Much exploration is required to understand fog concerning bioaerosols and their influence on human health (Gao et al. 2015). In the section of 'fog formation and classification,' as discussed, turbulence can have two contradictory effects on fog; therefore efforts are needed to determine threshold values of turbulent intensity, as there may be chances of this value range varying with other characteristics of different fog types.

It is predicted that the cities will become more concentrated throughout the twenty-first century (Kii 2021), this will impact the entire energy and infrastructure sector, but this can also lead to a rise in per capita pollution that can, in turn, influence the health of all those people unless the government and scientist effectively upgrade their strategies. One of the many lessons that the current global pandemic situation has taught us is that the government must be prepared enough to tackle the various problems before becoming uncontrollable.

Atmospheric conditions required for fog formation are also suitable for restricting the dispersal of air pollutants. Its ample supply in the locality provides a more significant number of condensation surfaces for fog droplet formation. India's air quality is worse during winters and requires effective policies to mitigate it. For regulating emissions from industries, policy suggestions were given by Harvard Kennedy School and University of Chicago researchers in "A Roadmap Towards Cleaning India's Air" (<https://epic.uchicago.in/wp-content/uploads/2018/>

08/POLICY-BRIEF-A-ROADMAP-TOWARDS-CLEANING-INDIAS-AIR-1-1.pdf). More recommendations for improving the air quality of India were given by Ganguly et al. (2020) and Bhuvaneshwari et al. (2019). Some of the strategies suggested in “Cleaning the Air: A review of 10 city plans to fight Air pollution in India” are (1) strengthening of regulatory frameworks, (2) strengthening of legal enforcement, and vehicle operation and access restrictions. The Supreme Court of India in 2018 has directed the Delhi government to come up with a real-time monitoring emission monitoring system on the road, incorporating remote sensing machines for easy detection of vehicles whose emissions are relatively high, to send notice to the vehicle owners regarding the same (<https://www.ndtv.com/delhi-news/supreme-court-directs-delhi-government-to-buy-remote-sensing-machines-to-detect-pollution-1850508>). As stated earlier, the problem of heavy aerosol loading from burning of crop residues can be managed by implementing the strategies devised by Dutta et al. (2020) including conservation of residue into biomass or briquettes; rotation of crops which is not limited to rice and wheat; practicing conservative farming; and use of crop residue directly for energy production in state-level thermal power plants; and conversion of residue into ethanol. The major cause of fog formation in the Indo-Gangetic Plains is the weather itself not much can be done in this regard, however, its conversion to smog can be controlled to some extent if the above-mentioned actions are taken and monitored properly. Though the measures suggest keeping Delhi in mind, pointers can be taken and used for other locations in the world.

Considering all aspects of fog, the information gathered from the prior research studies can be implemented to better evaluate and improve existing prediction and forecasting systems and framing policies.

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