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Fog Research: A Review of Past Achievements and Future Perspectives

I. Gultepe,[1] R. Tardif,[2] S. C. Michaelides,[3] J. Cermak,[4] A. Bott,[5] J. Bendix,[4] M. D. Müller,[6] M. Pagowski,[7] B. Hansen,[1] G. Ellrod,[8] W. Jacobs,[9] G. Toth,[10] and S. G. Cober[1]

Abstract—The scientific community that includes meteorologists, physical scientists, engineers, medical doctors, biologists, and environmentalists has shown interest in a better understanding of fog for years because of its effects on, directly or indirectly, the daily life of human beings. The total economic losses associated with the impact of the presence of fog on aviation, marine and land transportation can be comparable to those of tornadoes or, in some cases, winter storms and hurricanes. The number of articles including the word "fog" in Journals of American Meteorological Society alone was found to be about 4700, indicating that there is substantial interest in this subject. In spite of this extensive body of work, our ability to accurately forecast/nowcast fog remains limited due to our incomplete understanding of the fog processes over various time and space scales. Fog processes involve droplet microphysics, aerosol chemistry, radiation, turbulence, large/small-scale dynamics, and surface conditions (e.g., partaining to the presence of ice, snow, liquid, plants, and various types of soil). This review paper summarizes past achievements related to the understanding of fog formation, development and decay, and in this respect, the analysis of observations and the development of forecasting models and remote sensing methods are discussed in detail. Finally, future perspectives for fog-related research are highlighted.

Key words: Fog review, fog observations, fog modeling, fog remote sensing, fog forecasting.

[1] Cloud Physics and Severe Weather Research Section, Meteorological Research Division, Environment Canada, Toronto, ON, Canada. E-mail: ismail.gultepe@ec.gc.ca; Stewart.cober@ec.gc.ca

[2] National Center for Atmospheric Research, Box 3000, Boulder, CO 80301, USA. E-mail: tardif@ucar.edu

[3] Meteorological Service, P.O. Box 43059, Larnaka Airport, CY 6650, Cyprus. E-mail: silas@ucy.ac.cy

[4] Laboratory for Climatology and Remote Sensing (LCRS), Department of Geography, Philipps-Universität Marburg, 35032 Marburg, Germany. E-mail: cermak@lcrs.de; bendix@lcrs.de

[5] Meteorologisches Institut Universität Bonn, Auf dem Hügel 20, D-53121 Bonn, Germany. E-mail: a.bott@uni-bonn.de

[6] Institute of Meteorology, Climatology and Remote Sensing, University of Basel, Basel, Switzerland. E-mail: mathias.mueller@unibas.ch

[7] Global Systems Division, NOAA Earth System Research Laboratory, Boulder, CO, USA. E-mail: Mariusz.Pagowski@noaa.gov

[8] NOAA/NESDIS (Retired), P.O. Box 240, Granby, CT 06035, USA. E-mail: gary.ellrod@gmail.com

[9] Deutscher Wetterdienst, Bildungs und Tagungszentrum, Am DFS-Campus 4, D-63225 Langen, Germany. E-mail: wilfried.jacobs@dwd.de

[10] Hydrology and Arctic Lab, Prairie and Northern Region, Environment Canada, Edmonton, AB, Canada. E-mail: garrym.toth@ec.gc.ca

1. *Introduction*

The effect of fog on human life was recognized in the early ages of mankind but its impact has significantly increased during recent decades due to increasing air, marine, and road traffic. In fact, the financial and human losses related to fog and low visibility became comparable to the losses from other weather events, e.g., tornadoes or, in some situations, even hurricanes. The purpose of this review is to summarize the earlier works on fog and to lay a basis for the articles presented in this special issue and outline perspectives for future fog research.

The earliest works on fog can be traced back to Aristotle's Meteorologica (284–322 B.C.). These were extensively referenced by NEUMANN (1989) in his study of early works on fog and weather. This paragraph is mainly based on his detailed work. In the English translation by H.D.P. Lee (1962, ARISTOTLE), a statement is given on the relationship between fog and good weather. Also, NEUMANN (1989) relates a poem by ARATUS (315–240 B.C.), which was referred to as Prognostication Through Weather Signs, in an English translation by G.R. Mair (ARATUS, 1921). The poem reads " *If a misty cloud be stretched along the base of a high hill, while the upper peaks shine clear, very bright will be the sky. Fair weather, too, shall thou have, when by sea-verge is seen a cloud low (fog) on the ground, never reaching a height, but penned there like a flat reef of rock''.* In this regard, Pliny the Elder (A.D. 23–79, PLINY, 1971), a Roman historian, admiral, scientist and author, states in his work of Natural History "……. *Mist (fog) coming down from the mountains or falling from the sky or settling in the valleys will promise fine weather.''* These works suggested that fog was recognized for use as a fair weather predictor.

The influence of fog was also felt on historical events. LINDGREN and NEUMANN (1980) describe one such event during the Crimean War, when the Russian empire faced the alliance of Britain, France, and Turkey. The allied forces landed in Crimea in September 1854. Intense fog developed early on the morning of the 5th, just when the Russian forces were launching their first major offensive. The allied forces could not realize what was occurring on the other side. It was stated that "…*for the vapors, fog, and drizzling mist* obscured the ground to such an extent as to render it impossible to see what was going on at a distance of a few yard.'' This suggests that fog was a major player in this historical event.

The formation of fog and its extent at the surface are not easy to predict. The fog formation does not always occur in calm windless conditions. In fact, the formation of fog associated with turbulent windy conditions was studied at the end of 18th century. SCOTT (1896) stated that fogs with strong winds occurred in the British Isles, and sometimes lasted a month. He also mentioned that the strong wind fogs were accompanied by rain which was frequently heavy. SCOTT (1894) showed that fog occurrence was correlated to strong winds (Beaufort scale of 6), and that there was no clear relationship between weather patterns (e.g., cyclonic or anticyclonic) and fog formation. Scott also stated that the total number of fog cases with strong wind was

estimated to be about 135 over 15 years. The role of aerosols in fog formation was recognized by MENSBRUGGHE (1892) who stated that "*aqueous vapor condenses in the air only in the presence of solid particles around which the invisible vapor becomes a liquid.*" The heavy London fog on 10–11 January, 1925 followed the great fog of December 1924 (BONANCINA, 1925). During this episode, two types of fog occurred: 1) unsaturated haze without condensation and 2) fog with liquid characteristics. These fog episodes paralyzed the entire city with very low visibility values. This discussion shows that fog formation and its relation to environmental conditions were known early on but detailed field and modeling works were limited.

The importance of fog and low ceiling in weather forecasting was studied by WILLETT (1928). In his detailed work, he emphasized the importance of condensation nuclei for fog formation. He listed that dust particles with some degree of surface curvature, particles having an electric charge or ions, and hygroscopic particles were facilitating agents to droplet formation. He also proposed a classification for fog and haze based on causes and favorable synoptic conditions. Overall, fogs were classified into two groups: 1) airmass fogs and 2) frontal fogs. Subsequently, he emphasized the importance of all meteorological parameters affecting fog formation. For each group, he then sub-classified them, e.g., advection type, radiation fog, and marine fog, etc. He also summarized the works done by others such as KÖPPEN (1916, 1917), TAYLOR (1917), and GEORGII (1920).

Numerous field studies with a focus on fog and other boundary layer clouds were performed over the last few decades. Among the regions where these experiments took place are the coastal regions off the California coast in the western United States. Review articles on issues of fog that focused on West Coast marine fog and stratocumulus were presented by LEIPPER (1994) and KLOESEL (1992). Among the noteworthy experiments was the CEWCOM project (1977) which consisted of a major set of experiments off the California coast conducted during the 1972–1982 time period under the US Navy Naval Air Systems Command. These series of meso- and micro-meteorological experiments involved a land and sea network of radiosonde observations, ships, aircraft, balloons, and kites. Studies based on observations were complemented by modeling studies. An investigation of low-level stratus/fog was performed by KORACIN et al. (2001) using a one-dimensional (1-D) model and observations with results suggesting that radiative cooling and large-scale subsidence was an important factor for fog formation. The interactions between radiative and turbulence processes studied in detail by OLIVER et al. (1977; 1978) suggested that radiative cooling at fog top was an important process in the fog life cycle. Similarly, it was shown by WELCH and WIELICKI (1986) that $\sim5C°$/hour cooling occurred during a simulation of warm fog layer in which the liquid water content (LWC) reached 0.3 g m^{-3}. These results were found to be comparable with observations. Radiation fog studies using detailed surface observations were lead by MEYER et al. (1986), ROACH et al. (1976), and CHOULARTON et al. (1981). These authors also focused on various aspects of fog formation and its evolution by using numerical models. FUZZI et al.

(1992) carried out the Po Valley Fog Experiment which was a joint effort by several European research groups from five countries. The physical and chemical behavior of the multiphase fog system was studied experimentally by following the temporal evolution of the relevant chemical species in the different phases (gas, droplet, interstitial aerosol) and the evolution of micrometeorological and microphysical conditions, from the pre-fog state, through the whole fog life cycle, to the post-fog period. FUZZI *et al.* (1998) also conducted a second field project called CHEMDROP (CHEMical composition of DROPlets) that took place in the Po Valley region. Their project focused mostly on fog microphysics and chemistry as in the previous field experiment. Ice fog studies (BOWLING *et al.*, 1968; GIRARD and BLANCHET, 2001; GOTAAS and BENSON, 1965) were limited due to the difficulties of measurement ice particles at sizes less than 100 μm (GULTEPE *et al.*, 2001). However, Gotaas and Benson results showed that 10°C/day cooling was due to ice fog occurrence on January 1962. More recently, GULTEPE *et al.* (2006a) and GULTEPE and MILBRANDT (2007) conducted a field project over Eastern Canada for marine fog studies and at a site in the Ontario region for winter warm fog studies with a focus on nowcasting/forecasting issues. These projects contributed to the better understanding of fog physics, and the development of parameterizations for numerical models and remote sensing studies.

In addition to fog formation, development and decay, the artificial dissipation of fog was also studied in the early 1970s. The main objective of these works was to study how fog can be eliminated from a specific area such as over an airport or a shipping port. Because the fog droplets are found in a narrow drop size range e.g., 4–10 μm, by somehow increasing droplet size, the dissipation of fog can occur through coalescence processes. The work by HOUGHTON and RADFORD (1938) was the first to use hygroscopic particle seeding to dissipate fog droplets. JIUSTO *et al.* (1968) studied the possibility of fog dissipation by giant hygroscopic nuclei seeding and stated that the use of carefully controlled sizes and amounts of hygroscopic (NaCl) nuclei can produce significant improvements in visibility. KORNFELD and SILVERMAN (1970) and WEINSTEIN and SILVERMAN (1973) also indicated similar results and stated that if the fog droplet size distribution is known, the seeding nuclei are to be chosen carefully for dissipating the fog. These works suggested that fog dissipation seems possible but its detailed microphysics should be known. Another method used helicopters to dissipate fog on the theoretical basis of turbulent mixing of dry air into the fog layer by the helicopter's downwash (PLANK *et al.*, 1971).

The increased fog water content as dripping water, opposite to the fog dissipating idea, was used as a resource for the ecosystem hydrology and water resources. The Standard Fog Collector (SFC) was developed by SCHEMENAUER AND CERECEDA (1994) which is a 1 m^2 frame with a double layer of 40% shade cloth mesh. It is set up perpendicular to the prevailing wind direction. The collected fog water is routed from the collection trough to a large-capacity tipping bucket gage with data logger to measure the amount and frequency of precipitation. The polypropylene nets similar

to the original SFC over the coastal cliffs and desert areas transform windborne fog and mists into water. Fog catchers use a simple idea in which a fine-mesh netting is placed against the wind that carries fog droplets, so that water would condense on the filaments. At the arid stretches of coastal Chile, Peru, Ecuador, and several other countries around the world, this method was utilized to obtain water from fog droplets. Trees also serve as natural fog catchers (AZEVEDO and MORGAN, 1974); a forest growing in an arid area can provide as much water as rain into the dry soil. They suggested that fog drifting inland is caught by plant leaves, the nutrients contained in the fog as nuclei and dissolved gases become available to the plants. Some nutrients may be absorbed directly by the leaf and the rest become available to the plants via the soil as water drips to the ground.

The number of articles that includes the word "fog" in the American Meteorological Society (AMS) published journals was found to be about 4700, suggesting that there is an abundance of works on this subject. In spite of this extensive body of work, concerns related to fog forecasting/nowcasting still remain because of fog's considerable time and space variability related to interactions among various processes.

Among the reasons behind the difficulties in accurately forecasting/nowcasting fog are the difficulties in detecting fog and representing the physical processes involved. Remote sensing of fog using satellites is very useful but more spectral channels compared to the ones available are needed to improve detection algorithms (ELLROD and GULTEPE, 2007). Lately, a Moderate Resolution Imaging Spectro-radiometer (MODIS) base algorithm (BENDIX et al., 2006) for fog detection has been developed and includes more channels in the near IR and better resolution (of about 100 m). Although various methods were developed for forecasting and nowcasting applications, the accuracy of these algorithms needs to be assessed further, especially over snow and ice surfaces. From the numerical modeling point of view, important issues are related to the horizontal (PAGOWSKI et al., 2004) and vertical (TARDIF, 2007) resolutions, and physical parameterizations (GULTEPE et al., 2007b). For instance, if the total droplet number concentration (N_d) is not obtained prognostically, it can be obtained diagnostically as a function of supersaturation or simply fixed (GULTEPE and ISAAC, 2004). It is a well known fact that visibility in fog is directly related to N_d. In the large-scale models, N_d is either not considered or is simply fixed. In most models, visibility is obtained from extinction versus LWC relationships (KUNKEL, 1984), in turn, LWC is obtained using either a simple LWC-T relationship (GULTEPE and ISAAC, 1997) or a prognostic equation (TEIXEIRA, 1999; BERGOT and GUÉDALIA, 1994; BOTT and TRAUTMANN, 2002; PAGOWSKI et al., 2004). Therefore, detailed three-dimensional cloud/fog models are needed to better understand issues related to fog, but they are not used extensively because of the computational cost involved in producing operational forecasts (MÜLLER et al., 2007; GULTEPE et al., 2006b). One-dimensional (1-D) models are cheaper to run and can prove to be useful in certain situations (BERGOT and GUÉDALIA, 1994; BERGOT

et al., 2005; BOTT, 1991). However, their applicability becomes limited in regions of complex and heterogeneous terrain (MÜLLER *et al.*, 2007). The applicability of the different modeling strategies for fog forecasting and various parameterizations requires extensive research.

In order to better evaluate forecasts of fog formation, development, and decay, field observations should be used for verification purposes. This can be done: 1) using carefully analyzed climatological surface data (TARDIF and RASMUSSEN, 2007), 2) *in situ* observations (GULTEPE *et al.*, 2006; GULTEPE *et al.*, 2007b), and 3) remote sensing data (CERMAK and BENDIX, 2006). Detailed studies by TARDIF and RASMUSSEN (2007), HANSEN *et al.* (2007), and HYVARINEN *et al.* (2007) suggest that the climatological data can help in developing better understanding of fog formation, forecasting methods, and organize better field programs (GULTEPE *et al.*, 2006b). In the following sections, fog definition and types, observations (including field and remote sensing observations), models, climatology and statistical methods, and concluding remarks together with discussions will be given in the context of prior achievements and future works.

2. Definition and Fog Classification

The international definition of fog consists of a collection of suspended water droplets or ice crystals near the Earth's surface that lead to a reduction of horizontal visibility below 1 km (5/8 of a statute mile) (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1995). If the visibility is greater than 1 km, then it is called mist (WMO, 1966). Prevailing visibility is the maximum visibility value common to sectors comprising one-half or more of the horizon circle (MANOBS, 2006). Water droplets and ice crystals, typically 5 to 50 μm in diameter (PRUPPACHER and KLETT, 1997), form as a result of supersaturation generated by cooling, moistening and/or mixing of near surface air parcels of contrasting temperatures. The presence of suspended droplets and/or crystals can render an object undistinguishable to a distant observer and thus causes poor visibility conditions. This occurs through a reduction in the brightness contrast between an object and its background by particle concentration and size-dependent scattering losses of the light propagating between the object and the observer (GAZZI *et al.*, 1997; 2001) and through the blurring effect of forward scattering of light due to the presence of the droplets/crystals (BISSONETTE, 1992).

Several approaches have been used in the classification of fog. It can be based on physical (freezing fog), thermodynamical (mixed phased fog) properties, dynamical processes (mixing and turbulence fog), chemical composition of particles (dry fog), physiographic character of the surface (valley fog), and meteorological features (frontal fog). An earlier work by PETTERSSEN (1956) suggested that fog can also be divided into three subsections: 1) Liquid fog (T > −10°C), 2) mixed phase fog

(−10°C > T > −30°C), and 3) ice fog (T < −30°C). These fog types can occur under the various scenarios listed above. One should recognize that the criteria used in this respect do not always occur in a clear-cut fashion as implied by the classification. For example, ice fog may occur at T = −20°C when excessive vapor is used by ice nuclei within a steady-state condition occurring with no mixing processes (GULTEPE et al., 2007b). Usually freezing fog occurs when T gradually decreases below 0°C.

As suggested by the discussion above, fog does occur in a wide variety of conditions. These conditions can be described using various fog types. WILLETT (1928) study, later modified by BYERS (1959), established a classification describing eleven types of fog, each defined by the main physical processes responsible for their formation as well as circumstances in which these processes occur.

The most studied and therefore well-described fog types are those associated with radiative cooling over land. These can be divided among: 1) radiation fog, 2) high-inversion fog, and 3) advection-radiation fog. Radiation fog usually forms near the surface under clear skies in stagnant air in association with an anticyclone. Numerous researchers have devoted efforts to understanding the relationship between the occurrence of this type of fog with the various mechanisms known to influence the evolution of the nocturnal boundary layer. The main mechanism is radiative cooling, but the opposing influences of upward soil heat flux, as well as warming effects and moisture losses through dew deposition from turbulent mixing in the stable boundary layer largely determine the likelihood and timing of radiation fog formation (TAYLOR, 1917; LALA et al., 1975; ROACH, 1976; ROACH et al., 1976; BROWN and ROACH, 1976; PILIÉ et al., 1975; FINDLATER, 1985; TURTON and BROWN, 1987; FITZJARRALD and LALA, 1989; BERGOT and GUÉDALIA, 1994; ROACH, 1995a; DUYNKERKE, 1999). Advection-radiation fog is a coastal phenomenon and results from the radiative cooling of moist air that has been advected over land from the ocean or from any large water body during the previous daylight hours (RYZNAR, 1977). So-called high-inversion fog usually forms in valleys within a deep moist layer capped by a strong inversion (HOLETS and SWANSON, 1981). The inversion results from prolonged radiative cooling and subsidence associated with a persistent anti-cyclone. This type of fog is common during winter in the Central Valley of California (UNDERWOOD et al., 2004).

Another relatively well-studied fog type is associated with the advection of a moist airmass with contrasting temperature properties with respect to the underlying surface and is therefore referred to as advection fog. BYERS (1959) makes the distinction between sea fog, land- and sea-breeze fog, and tropical-air fog even though all are associated with advection of moist warm air over a colder water surface. Sea fog typically occurs as a result of warm marine air advection over a region affected by a cold ocean current, and thus, it is common at sea in locations where boundaries with cold ocean currents can be found, such as the Grand Banks of Newfoundland and areas over the coastal northeastern United States, in the North Pacific, off the west coast of North America and over the British Isles (LEWIS et al.,

2004). The frequency of this type of fog is maximized when air with a high dew point initially flows over a sea-surface with a few degrees colder (TAYLOR, 1917; FINDLATER *et al.* 1989; KLEIN and HARTMANN, 1993; ROACH, 1995b; CROFT *et al.*, 1997; CHO *et al.*, 2000). In contrast to this, PILIÉ *et al.* (1979) reported cases where marine fog patches are associated with regions having a warmer ocean surface, where buoyant mixing of the moist near surface air results in saturation of the low-level air. Adding to the complexity, TELFORD and CHAI (1993) report on the dissipation of an existing fog layer over warmer water, with a sensitivity of the fog behavior on the temperature and moisture structure above the fog layer. Once fog has formed, its evolution is largely determined by the influences of radiative cooling at fog top, subsidence, drizzle and the evolution of surface heat and moisture turbulent fluxes as the air flows over sea-surface temperature gradients (FINDLATER *et al.*, 1989). Furthermore, it has been shown that the origin and history of air masses are important factors in the observed variability in the spatial distribution of fog/stratus in the coastal zone (LEWIS *et al.*, 2003). Land- and sea-breeze fogs are purely coastal phenomena and occur when warm moist air over land is transported offshore over the cool coastal ocean, leading to fog formation. This fog may subsequently move over land under the influence of a sea-breeze circulation that sets up during the following afternoon hours. Tropical-air fog is another advection fog type and is associated with long-range transport of tropical air pole-ward along the large-scale latitudinal ocean temperature gradient leading to gradual cooling of the air mass. Advection fog has also been observed over land in winter in the central United States as warm moist air flows over the cooler (sometimes snowy) surface (FRIEDLEIN, 2004).

Another type of fog associated with advection and mixing is the so-called steam fog. It tends to be observed in the Arctic and results from cold air with a low vapor pressure being advected over a relatively warm water surface. The difference in vapor pressure between the air and the water surface leads to evaporation, and mixing of water vapor into the cold air leads to supersaturation and fog (SAUNDERS, 1964; ØKLAND and GOTAAS, 1995; GULTEPE *et al.*, 2003).

Fog may also form as a result of a cloud base lowering all the way to the surface. Some influences have been cited by various authors, mainly dealing with conditions out over the open ocean. For instance, the presence of a sufficiently shallow cloudy marine boundary layer capped by a strong inversion and a sufficiently moist subcloud layer (dew point higher than the sea-surface temperature by a few degrees) have been cited by PEAK and TAG (1989) and TAG and PEAK (1996) as important factors. Furthermore, cloud base lowering has been shown to be tied to the diurnal cycle of stratiform boundary layer clouds related to the interaction of the cloud with radiation (DUYNKERKE and HIGNETT, 1993). The coupling of the cloud layer with the subcloud layer occurs as top-down turbulent mixing is generated by the destabilization induced by the radiative cooling at cloud top. Radiatively cooled air is transported downward by the turbulent eddies, cooling the subcloud layer and thus

leading to a lowering of cloud base (OLIVER et al., 1978; PILIÉ et al., 1979). It has been hypothesized that this process can be aided by the moistening of the subcloud layer by the evaporation of settling cloud droplets or drizzle drops (PILIÉ et al., 1979). Adding to this complex picture, KORAČIN et al. (2001) and LEWIS et al. (2003) have shown that stratus lowering can occur under the influence of persistent subsidence leading to a decrease in the depth of the marine boundary layer.

Fog forming together with precipitation, often referred to as frontal fog, is described as a common occurrence ahead of warm frontal boundaries (GEORGE, 1940a,b,c; BYERS, 1959; PETTERSSEN, 1969). Its presence has also been documented in regions of extra-tropical cyclones characterized by a transition in precipitation type (STEWART, 1992; STEWART et al., 1995) presumably due to the evaporation of melting or freezing precipitation hydrometeors (DONALDSON and STEWART, 1993). BYERS (1959) further divided the precipitation fog type into three subcategories: pre-frontal, post-frontal and frontal passage fogs. Pre-frontal fog is usually associated with an approaching warm front. The textbook explanation involves the evaporation of warm rain into the stable cold air near the surface, leading to saturation and fog formation. Post-frontal fog usually occurs behind a cold front and is much like pre-frontal fog as the main mechanism is the evaporation of falling precipitation, but is less likely to be widespread as the precipitation bands associated with cold fronts occur over a smaller spatial scale. Frontal passage fogs are said to be associated with the mixing of near saturated air from the warm and cold air masses. This further separation of precipitation-induced fog into subcategories merely describes the various scenarios under which fog is observed and does little in terms of providing a comprehensive description of the physical processes involved.

Finally, upslope fog is associated with the cooling of near-surface moist air resulting from an adiabatic expansion as it is forced to higher elevations, and thus lower pressure, by topography.

This discussion confirms that fog is influenced by numerous factors, spanning multiple spatial and temporal scales. This complexity is central to the persistent difficulty associated with providing accurate fog forecasts.

3. Observations and Models

3.1. Microphysics and Nucleation Processes

Fog formation typically occurs in aerosol-laden surface air under high relative humidity conditions, ranging from undersaturated to slightly supersaturated conditions (PRUPPACHER and KLETT, 1997). Fogs are typically composed of a mixture of micron-size haze (unactivated) particles and activated droplets reaching tens of microns in size (PINNICK et al., 1978; HUDSON, 1980; GERBER, 1981). Compared to convective cloud types where strong updrafts generate higher levels of

supersaturation, fog droplets are generally smaller than cloud droplets and the resulting LWC generally remain small. Most fogs have LWC ranging from 0.01 to 0.4 g m^{-3} (GULTEPE *et al.*, 2007b).

Significant variability has been observed in the droplet size distribution (DSD) in fog. For instance, KUNKEL (1982) reports various shapes in DSDs measured in advection fogs. Some DSDs were characterized by continuous decrease of droplet concentration with size which can simply be parameterized by a power law. Other DSDs were observed to be distinctly bi-modal (GULTEPE *et al.*, 2007b) while others exhibited hybrid characteristics, with the presence of a nearly constant droplet concentration for droplet size between 20 and 30 μm in diameter. Other studies have shown the development of mostly bi-modal DSDs in mature radiation fogs (PILIÉ *et al.*, 1975; ROACH *et al.*, 1976; PINNICK *et al.*, 1978; MEYER *et al.*, 1980; WENDISCH *et al.*, 1998). Processes shaping the microstructure of fog include activation and diffusion growth of droplets, droplet growth related to radiative cooling, as well as turbulent mixing and differential gravitational settling of drops of different size.

Intricate relationships exist between aerosols and fog characteristics since the activation and diffusion growth of droplets depends on the physico-chemical character of the ambient aerosols. For instance, fog is more likely to appear in an environment with large concentrations of aerosols characterized by a low activation supersaturation. Early efforts were performed by J. Aitken in 1880s (KNOTT, 1923). NEIRBURGER and WURTELE (1948) and ELDRIDGE (1966) studied aerosol characteristics and droplet nucleation related to various environmental conditions and they established a dependency between fog microstructure and the characteristics of condensation nuclei. This was later confirmed by HUDSON (1980), who found systematic differences in fog microstructure between polluted urban and cleaner maritime air masses. Fog which formed in polluted environments was characterized by DSDs for which the distinction between inactivated haze particles and activated droplets was not as straightforward as for other clouds types, whereas a clearer demarcation existed in the case of fogs forming in the cleaner maritime air. The complexity of the aerosol-fog microphysics interdependence is an important process in the understanding of fog processes. It has been shown that the occurrence of fog also has an impact on ambient aerosols (YUSKIEWICZ *et al.*, 1998) who summarized aerosol characteristics related to fog formation from measurements of particles in various size ranges (from 0.003 μm up to 47 μm) covering the ultra fine, Aitken, and accumulation modes as well as the activated fog droplets. A comparison of particle number concentrations during fog and clear air conditions suggested a 78% and 65% decrease in ultra fine and accumulation mode particles, respectively. This points out the important scavenging influence of fog.

A numerical study performed by BOTT (1991) provides further insight into the dependence of the fog's microstructure and life cycle on the properties of aerosols. He performed simulations using aerosol size distributions and properties typical of urban, rural and maritime environments and showed that aerosols have a direct

influence on the life cycle of a fog layer. In urban environments fog is characterized by the presence of absorbing aerosols and its formation is delayed by small aerosol number concentrations while higher number concentrations of aerosols yield the highest vertical extent of the fog layer and highest fog water contents. This is related to the radiative effects of absorbing particles, decreasing the incoming solar radiation at the surface and leading to an early initiation of the evening transition of the boundary layer and earlier formation of fog. The fog layer then is allowed to deepen over a longer time period and generate higher LWC under the influence of prolonged cooling at fog top.

In terms of DSD, the main difference between urban and other aerosol models has been found in droplet concentrations for the submicron-size droplets. The concentration of inactivated drops was found to be roughly an order of magnitude higher for the urban aerosols compared to the rural aerosols. Similar results were obtained for rural aerosols compared to maritime aerosols. Supersaturation within the fog was also found to be strongly dependent on aerosol properties. The higher the particle concentration, the lower supersaturation are. However, supersaturation levels have also been found to depend on dynamical processes, such as large supersaturations resulting from turbulent mixing processes (PILIÉ et al., 1975; GERBER, 1991).

Significant high frequency variability in fog droplet concentration and LWC has also been reported in the literature. Observations from GARCÍA-GARCÍA et al. (2002) suggest that fog layers are heterogeneous in nature. Small–scale variability in fog microstructure has been observed, with regions of decreased droplet concentration corresponding to broader DSDs. Rapid temporal variations in droplet concentrations, sometimes with amplitudes corresponding to two orders of magnitude (GERBER, 1981; 1991), and LWC from near zero up to 0.5 g m^{-3} have been observed (FUZZI et al., 1992). Some fluctuations are seemingly random while others are found to be quasi-periodic in nature. Random fluctuations are thought to be related to intermittent turbulent mixing events (PILIÉ et al., 1975; GERBER, 1991) while some evidence points to the fact that quasi-periodic oscillations are the result of the interaction between the radiatively induced droplet growth and subsequent depletion of LWC by the enhanced gravitational settling of the larger droplets (BOTT et al., 1990).

Lower frequency variations in the microphysical character of fog layers have also been tied to the various stages defining the life cycle of fog by some authors (PILIÉ et al., 1975; KUNKEL, 1982). Concurrent increases in droplet concentration, mean droplet size and LWC have been observed to occur gradually during the formation stage of fog. This is followed by the mature stage, generally characterized by nearly constant mean droplet concentration and LWC, and a gradually decreasing mean droplet size. JIUSTO (1981) suggested a relationship for visibility as a function of both droplet size and LWC, showing that LWC was directly related to droplet size. The dissipation stage typically occurs as the droplet concentration, mean droplet size, and LWC all decrease.

The variability in the fog microstructure translates into a considerable variability in the reduction of visibility (extinction) induced by the presence of droplets. Numerous efforts have aimed at defining relationships between the overall characteristics of fog and associated visibility reduction. Most have focused on power-law relationships between *LWC* of the fog and its associated extinction coefficient (β) (ELDRIDGE, 1971; TOMASI and TAMPIERI, 1976; KUNKEL, 1984) as

$$\beta = a(LWC)^b, \tag{1}$$

with coefficients determined empirically. Experimental results show considerable variability, with values falling in the range of $65 \leq a \leq 178$ and $0.63 \leq b \leq 0.96$. These values include results reported in GULTEPE *et al.* (2006a) obtained in warm stratiform boundary layer clouds. Some of the variability is related to the different instruments and experimental designs as well as variability in ambient conditions (ex. polluted vs. clean air masses). MEYER *et al.* (1980) took a different approach by establishing an empirical relationship between visibility and the product of total particle concentration and mean diameter. More recently, a relationship between visibility and the product of droplet number concentration (ND) and LWC was proposed by GULTEPE *et al.* (2006a) as

$$Vis_{fi} = \frac{1.002}{(LWC \cdot N_d)^{0.6473}}$$

This approach recognizes the presence of variability in droplet sizes and its role in influencing extinction (visibility) in fog.

In spite of a considerable body of work on fog microphysics, the overall role of interactions between the various processes shaping the microstructure of fog is still not fully understood and properly parameterized. For example, the effects of radiative fluxes on droplet growth are not considered in the growth equations in many fog models. The vertical structure in fog microphysics and its representation in fog models are still not well characterized and understood. In particular, the role of turbulent mixing remains a topic of discussion. Also, the occurrence of ice fog and associated physics still include many unknowns, e.g., ice particle concentration and nucleation, and saturation with respect to ice (MEYERS *et al.*, 1992). The difficulty in obtaining reliable measurements at the small sizes, as for other mixed-phase or ice clouds, contributes to our incomplete understanding. In particular, a multi-year dataset with consistent state-of-the-art instrumentation as shown in GULTEPE *et al.* (2006b) could prove invaluable in efforts to characterize, understand and parameterize the considerable variability in fog microstructure within the various environments.

3.2. Turbulent Fluxes and Surface Conditions

Fog is a boundary layer phenomenon; therefore, its formation and evolution are strongly influenced by surface conditions that are determined by the properties and

current state of the soil and canopy (vegetation or urban) for ground fogs, or by the state of the sea surface for marine fog. Effects of the underlying surface on fogs can be direct when the surface influences the profiles of wind, temperature, humidity, and local circulations through horizontal heterogeneities, or indirect through modification of radiative properties of the atmosphere by microphysical processes and varying aerosol spectra. In this section, only the direct effects of surface conditions on fogs are considered.

Surface cooling or warming is determined by an energy balance composed of incoming and outgoing radiation and heat fluxes in the atmosphere, canopy, and soil. Radiative balance at the surface is influenced by surface albedo and emissivity. The surface interacts with the atmosphere through momentum drag and sensible and latent heat fluxes. Especially in the case of radiation fog, complexities involved in the calculation of fluxes are substantial. Fog observations have a long history and provide a basis for the development and verification of numerical fog models. Detail numerical models can be used for forecasting and, most easily in the one-dimensional form, to investigate the importance of local processes affecting fog development. SIEBERT et al. (1992a;b;c) considered the effects of soil and vegetation on surface fluxes. In a detailed study with a one-dimensional soil-vegetation-atmosphere model and using a comprehensive parameterization of surface characteristics, they verified modeled surface fluxes against measurements and performed a series of sensitivity experiments. The experiments demonstrated the important role of vegetation coverage in damping the diurnal temperature amplitude, the significance of soil moisture content, and minimum stomatal resistance of plants in determining the Bowen ratio.

DUYNKERKE (1991) studied the effects of local factors on radiative fogs using a one-dimensional model of soil, vegetation and the atmosphere. He noted that large resistance of the canopy can lead to differences between vegetation and the upper soil temperatures (e.g., up to 10K for grass). This difference is significant for the deposition of dew or frost on the cool canopy (dewfall). Depending on the atmospheric conditions dew can lead to drying of the surface layer that can delay or prevent fog or, adversely, to further cooling of the air and formation of fog (LALA et al., 1975; BROWN and ROACH, 1976; DUYNKERKE, 1991; GUÉDALIA and BERGOT, 1994). Formation of dew on vegetation can also occur through distillation when an upward flux of moisture from warm and wet soil reaches the top of the canopy and is followed by condensation on the leaves. The presence of dew can lead to fogs when the surface warms up at sunrise (TARDIF and RASMUSSEN, 2007).

Intense turbulence, which leads to intense vertical mixing, usually has a detrimental effect on radiation fogs and its intensity (though in some cases the opposite can be true, see the discussion below on the role of turbulence in fogs). The most conducive conditions to radiative fog formation occur in stable boundary layers where turbulence is generated through wind shear. Surface roughness, a length scale representing the geometry of surface elements, is a primary factor for shear

generation. Thus fogs are generally less likely to occur over rough (e.g., urban) than over smooth (e.g., field) terrain but either way the air parcel needs to be saturated. Surface processes are rather easier to parameterize for marine fogs which are usually associated with advection of warm air over colder waters and vapor condensation in the cooled surface layer. A reverse process can also occur when cool and relatively dry air is brought over warm waters leading to evaporation from the surface and vapor condensation.

Turbulence and radiative processes can have an important role in fogs characteristics that can be both constructive to their formation, or destructive leading to their dissipation. Observations as well as modeling provide sometimes contradictory answers with regard to this problem (e.g., BROWN and ROACH, 1976; ROACH *et al.*, 1976; LALA *et al.*, 1982), depending on atmospheric conditions. For example, for radiative fogs, enhanced vertical mixing in strong turbulence can lead to droplet evaporation when they mix with the drier air above. On the other hand, fog can form after dew having evaporated from the surface is carried upward with turbulence, and then condenses in the air above. Destabilization of the atmosphere via radiative cooling of stratus tops can also lead to enhanced turbulence and downward mixing of cloud droplets leading to fog as mentioned in section 2.

As of now, modeling often does not provide a clear answer to the role of turbulence since results depend on the parameterization of turbulence and radiative processes, both burdened with significant uncertainty. Development and improvement of turbulence parameterizations in stable stratifications might lead to better understanding and forecasting of fogs. Complexity of turbulence and surface parameterizations plus the required high vertical and horizontal resolutions pose a major obstacle for successful and timely fog forecasts. For this reason, surface conditions and turbulence flux parameterizations will remain a significant research area for fog research and its modeling.

3.3. Remote Sensing Applications

The first goal in the investigation of radiative processes in natural fogs was to learn about the propagation and modification of electromagnetic radiation, and then develop and optimize optical systems to measure horizontal visibility. Pioneer work by GRANATH and HULBURT (1929), HOUGHTON (1931) and STRATTON and HOUGHTON (1931) dealt with absorption and transmission of light by/through fog in solar wavelengths. In the 1960s and 1970s, several studies addressed the relationship between fog properties and broad band extinction/horizontal visibility (e.g., DICKSON and VERN HALES, 1963; ELDRIDGE, 1971). The work was done to better understand the applicability of Koschmieder's law (KOSCHMIEDER, 1924) for various drop size distributions (DSD). To address the needs of the air traffic industry, slant visibility was investigated to find relations to horizontal visibility at ground level, required to estimate the visibility along the touch down path of aircraft through

fog/very low stratus (e.g., FOITZIK, 1947; STALENHOEF, 1974). STEWARD and ESSENWANGER (1982) presented a review paper on the relation between fog properties (DSD, LWC and geometrical thickness) and extinction of electromagnetic radiation at different wavelengths for several types of fog.

The relationship between fog properties and extinction/visibility was investigated for the specific wavelengths (e.g., BARBER and LARSON, 1985) with growing importance over the development of fog detection techniques based on multispectral satellite data. Based on the insights from earlier work, the radiative transfer models for a plane-parallel fog layer, including anisotropic scattering, were developed for the shortwave region (e.g., PAHOR and GROS, 1970), and also used for the infrared region (e.g., KORB and ZDUNKOWSKI, 1970). The state-of-the-art radiative transfer models were used as a part of numerical radiation fog forecasting systems (e.g., BOTT et al., 1990). HUNT (1973) presented an overview of radiative properties of the various cloud types. This publication has since become the basis of many fog-detection algorithms in satellite remote sensing.

Remote sensing of fog started with the development of fog detection techniques based on data obtained from the polar orbiting weather satellites. The detection of fog from satellite images at night was developed using observations from the Advanced Very High Resolution Radiometer (AVHRR) on board the NOAA satellite series. The potential of the delineation of fog/low stratus layers by the dual channel technique using the brightness temperature difference of the 10.8 μm and 3.7 μm bands was highlighted by the work of EYRE et al. (1984) and TURNER et al. (1986). HUNT (1973) as well as BENDIX and BACHMANN (1991) showed that this was mainly due to the reduced emissivity of clouds with small droplets in the 3.7 μm band. SAUNDERS and GRAY (1985) were able to show that clouds composed of small droplets (e.g., radiation fog) reveal a high reflectivity in the 3.7 μm spectral band. This method has since been widely used by numerous authors and on a wide range of platforms, including geostationary systems (TURNER et al., 1986; ALLAM, 1987; D'ENTREMONT and THOMASON, 1987; BENDIX and BACHMANN, 1991; DERRIEN et al., 1993; BENDIX, 1995a, 2002; ELLROD, 1995; LEE et al., 1997; REUDENBACH and BENDIX, 1998; PUTSAY et al., 2001; UNDERWOOD et al., 2004; ČERMAK and BENDIX; 2007a; GULTEPE et al., 2007a). These studies also suggested that accurate detection of clouds with small-droplets can be used for separation of low stratus from cloud-free regions, snow at the surface, and other cloud types.

The dual-channel technique also could be useful for fog/low stratus detection during daylight (KIDDER and WU, 1984). Because the 3.7 μm channel was not available for the first generation of geostationary systems (e.g., Meteosat MVIRI), in the past, special schemes including structural parameters (e.g., the spatial standard deviation) were used to detect fog/low stratus layers with a limited accuracy (e.g., GÜLS and BENDIX, 1996; KARLSSON, 1989). More recently, BENDIX et al. (2006) developed a radiative-transfer-based classification scheme for the MODIS (Moderate Resolution Imaging Spectroradiometer) instrument aboard the Terra and Aqua

satellites. In this approach, the authors derive albedo thresholds for modeled fog layers in a number of spectral channels using radiative transfer computations.

The general problems of daytime approaches using channels in the visible range are diurnal changes in illumination (solar elevation), and the separation of fog from other highly reflective surfaces (e.g., other clouds and ice surfaces). To compensate for these factors, ČERMAK and BENDIX (2007b) introduced a technique consisting of both spectral and spatial tests, allowing for a clear separation of fog/low stratus from other surfaces.

The retrieval of fog and low stratus properties is important for the characterization of the distinction between ground fog and elevated fog. Microphysical properties of fog can be retrieved based on radiative transfer parameterizations. Techniques along these lines have been presented by a number of authors (HEIDINGER and STEPHENS, 2000; MINNIS *et al.*, 1992; GULTEPE *et al.*, 2002; BENDIX, 1995a; NAUSS *et al.*, 2005a;b). In order to distinguish between ground fog and elevated low stratus layers, information on cloud base height is needed. This is obtained using cloud top height and cloud physical thickness as given in ČERMAK (2006). Cloud top height is computed using a cloud-entity-basis analysis, interpolating the marginal heights deduced from terrain and temperature lapse rates. For cloud thickness, a model of cloud liquid water distribution is fitted to liquid water path. A comparison of cloud base height and terrain height yields a decision on ground fog presence.

The dissipation of fog layers was modeled based on remote sensing data and a thermo-dynamical model developed for NOAA AVHRR by REUDENBACH and BENDIX (1998), and more recently, for Meteosat SEVIRI instrument by NAUSS *et al.* (2005a). Calculation of fog dissipation time from the satellite-based analysis techniques needs to be explored because of limited knowledge on the energy budget of a fog layer close to the Earth's surface.

The distinction of fog and low stratus at night remains a problem to be solved (BENDIX, 1995b). The daytime approach suggested by ČERMAK (2006) requires knowledge of cloud liquid water path as input for cloud base height computation. In order to adapt this method for nighttime application, a solid approach to retrieve fog microphysical properties (i.e., liquid water path) are needed. Such a technique based on optical sensors is not currently operational.

A number of approaches have been used to integrate the satellite data with SYNOP observations, model fields, and conventional surface observations (HERZEGH *et al.*, 2006). WRIGHT and THOMAS (1998) and GULTEPE *et al.* (2007) combined a forecast model output with satellite-based observations, and verified the results using surface observations. HUTCHISON *et al.* (2006), ELLROD (2002), and ELLROD and GULTEPE (2007) integrated the cloud base data from observations with satellite retrievals of cloud physical thickness to estimate low cloud base height. In general, satellite observations provide information for fog horizontal coverage and model-based data help to estimate variables such as the visibility, surface temperature and relative humidity, and fog physical thickness. In the future, increasing

accuracy of 3-D fog models can provide a better opportunity to integrate the satellite observations with other data sets.

Current and future active remote sensing instruments can provide great potential to further improve satellite retrievals of fog micro and macro physical properties. They can also be used for calibration of optical sensor algorithms. Among these instruments planned for future missions are satellite-based radars that will likely have the greatest potential by providing liquid water content profiles. Currently, a satellite based cloud radar on the NASA CloudSat satellite (STEPHENS et al., 2002) and an Earth-CARE instrument on the European-Japanese satellite (INGMANN et al., 2006) will likely lead to new methodologies for boundary layer cloud/fog studies.

3.4. Modeling and Forecasting

The formation, dispersion, and decay of fog are the result of complex interactions among microphysical, thermodynamical, and dynamical processes. DUYNKERKE (1991) identified the most important factors for fog formation as follows: Cooling of moist air by radiative flux divergence, mixing of heat and moisture, vegetation, horizontal and vertical wind, heat and moisture transport within soil, horizontal advection, and topographic effects; he also emphasized that atmospheric stability location, and season affect the contributions from each factor.

The presence of clouds increases the incoming longwave radiation at ground level and thus reduces the longwave radiative cooling at the surface, which has great influence on fog formation. Over a complex topography, cold air outflow and pooling, and advection over the heterogeneous landscape are also important in the forecasting of fog. Once the fog has formed, there are additional processes affecting the fog development such as longwave radiative cooling at the fog top, fog microphysics, shortwave radiation, and turbulent mixing. Owing to the complex interactions of various thermodynamic processes, in principle, an accurate 3-D model is needed for reliable fog forecasting.

The earlier work of ZDUNKOWSKI and NIELSEN (1969) included some of the listed processes above, however there was no parameterization for the sedimentation of liquid water. In addition to this, turbulence was treated by means of constant exchange coefficients. The latter were introduced by ZDUNKOWSKI and BARR (1972). A more sophisticated model was developed by BROWN and ROACH (1976), and later further refined by TURTON and BROWN (1987), including new formulations for turbulence exchange coefficients in the nocturnal boundary layer. A similar model was also used by MUSSON-GENON (1987) for the quantitative comparison between computed and observed fog characteristics. DUYNKERKE (1991) also developed a column fog model to study fog evolution and validated it using detailed measurements. A detailed cloud microphysical approach was introduced by BROWN (1980). BOTT et al. (1990) developed a fog model with a new two-dimensional treatment of spectral cloud microphysics. They also investigated in detail the interaction of fog

with the atmospheric radiation field. Later, BALLARD *et al.* (1991) used a 3-D numerical weather prediction model to simulate sea fog and they pointed out the importance of initial conditions and vertical resolution. GOLDING (1993) stated that the development of local nocturnal winds in complex terrain often determines the location and timing of fog formation. GUÉDALIA and BERGOT (1994) illustrated in their one-dimensional fog model the importance of advection terms and their role in fog formation and evolution. In addition to the above studies, SIEBERT *et al.* (1992a, b) and VON GLASOW and BOTT (1999) included the new modules into their fog models to simulate the influence of vegetation on the evolution of radiation fogs. In these later models, the evolution of the droplet size distribution and cloud condensation nuclei is explicitly calculated although even today such an approach is computationally very expensive. For a better understanding of the three-dimensional structure of radiation fog and its generation mechanisms, NAKANISHI (2000) applied a large-eddy simulation and found distinct flow regimes in the various stages of the fog layer's evolution. Based on these results, NAKANISHI and NIINO (2004, 2006) developed a second-order turbulence closure appropriate for fog modeling that was used for forecasting in a regional model. Other applications of 3-D models for fog forecasting include PAGOWSKI *et al.* (2004).

In addition to the one-dimensional models, single-column versions of existing 3-D models have been frequently used for the fog studies. (e.g., BRETHERTON *et al.*, 1999; DUYNKERKE *et al.*, 1999; TEIXEIRA, 1999). Recently, the 1-D models have been developed for research and operational purposes e.g., TEIXEIRA and MIRANDA (2001) who combined a set of established parameterizations with the finite-element methods for the vertical discretization. In fact, the microphysical and turbulence parameterizations for numerical weather prediction and climate models were first used as a part of the 1-D forecasting models.

The coupling of 1-D and 3-D models and their integration with observations lead to promising results for fog forecasting. BERGOT *et al.* (2005) clearly demonstrated the necessity of using surface measurements in 1-D models with a local assimilation scheme. CLARK and HOPWOOOD (2001) used a modified single column version of the UK Meteorological Office Unified Model which is driven by an operational 3-D forecasting model. Similarly, MÜLLER (2006) developed a 1-D variational assimilation scheme for surface observations and coupled two 1-D models with several operational 3-D models to produce an ensemble forecast. Currently, parameterized versions of detailed fog microphysics originating from 1-D models were incorporated into 3-D models and were able to improve visibility forecasts (MÜLLER, 2006; GULTEPE *et al.*, 2006b; GULTEPE and MILBRANDT, 2007).

Successful numerical modeling and forecasting of fog depends on the fog type that has to be predicted. Some fog events are largely driven by dynamic processes, such as advection fog and orographic fog (PEACE, 1969; WEICKMANN, 1979; MARKUS *et al.*, 1991; TJERNSTROM, 1993). The results of a study by PEACE (1969) suggested that orographic effects associated with the foothills of the Rocky Mountains tend to

broaden the frequency distribution of fog, and 20 days of heavy fog per year are located along the eastern slopes of the mountains. Obviously, the effective forecast of these fog events depends on the complexity of the underlying atmospheric models. For instance, the correct simulation of orographic fog may only be possible if the model is capable of accurately treating three-dimensional flow over a complex terrain surface, e.g., mountain-valley wind systems (TERRA et al., 2004; BANTA, 1990). Certainly, an adequate cloud model must also be part of the atmospheric model in which simple bulk microphysical cloud schemes (e.g., KESSLER, 1969) have been proven to be sufficient.

If the occurrence of fog is dominated by other than dynamical processes, e.g., atmospheric radiation, turbulence, and the direct interaction between the Earth's surface and the atmosphere, then the numerical fog forecast may become a very difficult task. For instance, owing to the large heterogeneities at the Earth's surface, the fluxes of mass and heat may be highly variable in space and in time, resulting in a corresponding patchy fog. Radiation fog over a heterogeneous Earth's surface is a typical example for a fog that is very difficult to predict (MASON, 1982; BOTT et al., 1990). In the following, the major uncertainties occurring in the numerical simulation of fog events are outlined.

a) Uncertainties for 1-D model simulations

In the simplest approach for the numerical simulation of fog, one-dimensional models of the atmospheric boundary layer are utilized. The basic assumption used in these models is the horizontal homogeneity of the thermodynamic variables. Thus, the evolution of fog is mainly driven by the atmospheric radiation field, turbulent mixing as well as the fluxes of moisture and heat at the Earth's surface. Other dynamic processes such as horizontal advection or large-scale subsidence are usually not considered. At first glance, one might think that in these simplified situations, where dynamical processes are considered to be less important for fog formation, the successful forecast of fog is relatively straightforward. However, the opposite is true. By comparing the numerical results of various one-dimensional models with observations (COST722 workshops), it turned out that, most of the time, the models failed to predict the fog event with reasonable agreement. There are many reasons for this deficiency and the most important are:

- The assumption of horizontal homogeneity is not valid. Certainly, disregarding horizontal gradients of thermodynamic variables in one-dimensional models results in large errors in the time evolution of fog parameters. Some authors (e.g., MUSSON-GENON, 1987; GUÉDALIA and BERGOT, 1994; TEXEIRA and MIRANDA, 2001) tried to avoid this deficiency by introducing the prognostic model equations with additional forcing terms describing horizontal advection processes. However, this treatment may be problematic since horizontal gradients in the one-dimensional models are not considered adequately; therefore, additional assumptions have to be introduced.

- Clouds are not correctly represented. Radiation fogs are characterized by a distinct cooling of the lowest atmospheric layers during the night, i.e., when the thermal emission of the ground is not balanced by the incoming solar radiation. However, the resulting radiative cooling strongly depends on the cloud cover and it increases with decreasing cloud cover. While permanent and complete cloudiness may be treated in the radiative transfer calculations with sufficient accuracy, cases with partial cloudiness cannot be adequately resolved.
- The fluxes of moisture and heat are not adequately treated in heterogeneous surface conditions. Of particular importance for the evolution of radiation fogs are the fluxes of moisture and heat at the Earth's surface. These fluxes strongly depend on the characteristics of the surface regarding vegetation, soil type, soil humidity, and soil temperature. Obviously, these soil characteristics are assumed to be horizontally homogeneous in the one-dimensional models. As a consequence of this, patterns of soil and vegetation cannot be represented adequately in the model. These heterogeneities may, however, be responsible for the patchy structure of fogs that is often observed.
- Atmospheric turbulence is not properly treated, particularly under strongly stable conditions. Although the numerical modeling of atmospheric turbulence has a long history, in many cases, the existing approaches fail to simulate turbulence sufficiently well. This holds, in particular, for situations with strong atmospheric stability, such as the temperature inversion evolving in the lowest atmospheric layers before the onset of radiation fog.

b) Uncertainties for 3-D model simulations

Fog forecasts using operational weather prediction models usually are very difficult. Owing to the relatively coarse grid resolutions in the horizontal (larger than 5 km) as well as in the vertical (grid distances of typically more than 50 m in the lowest atmospheric layers), these models cannot resolve the surface patterns with the necessary detail. As a consequence of this, operational fog forecast is usually performed by means of some proxy data. However, it might be possible to obtain a deterministic 3-D fog model by modifying existing weather prediction models in an appropriate way (MÜLLER, 2006). In these models, the horizontal and the vertical grid resolutions near the ground have been distinctly reduced. Modified grid resolutions influence significantly the parameterizations of the model physics, such as the turbulence and heat and moisture fluxes at the surface that in turn affect the fog evolution.

A comparison of several 3-D fog models has been performed during COST722. In this comparison, three fog episodes have been investigated and the model results have been compared with observations. The preliminary results of this study demonstrated that 3-D fog simulations have to cope with several problems that include:

- The grid resolution of the model must be sufficiently less than a few meters. It is very important to use fine grid resolutions in the horizontal and the vertical

directions. Particularly, the vertical grid distances of the lowest atmospheric layers must be small enough so that the time evolution of the physical processes within atmospheric boundary-layer near the ground can be resolved accurately. For example, a necessary condition for the simulation of radiation fog sometimes requires the evolution of an inversion layer at 10 m height above the surface before the fog forms.

- Horizontal heterogeneities of soil and vegetation must be adequately accounted for. The patchy structure of fog, which is often observed, is largely driven by the heterogeneities of the Earth's surface. Thus, for a realistic fog simulation, it is important to resolve the geographic distribution of soil moisture and vegetation over the resolved model grid area.

- The simulated fog episodes are rather sensitive to the model initial conditions. Usually, numerical models need some spin-up time before the numerical results may be used with confidence. The model intercomparison study during COST722 has shown that sometimes the fog formation strongly depends on the time of model initialization. For example, initializing a fog model at 00 UTC may yield completely different results compared to initializing it at 12 UTC. Also, initializing the models after the fog occurrence likely results in substantial uncertainties related to fog simulations.

- The verification of model results using observations cannot easily be done because numerical output represents a grid area with a spatial scale. On the other hand, observations represent a single point data. This especially, happens along the fog boundaries in the horizontal and vertical scales.

Based on the above-mentioned issues, the use of numerical weather prediction models for fog forecasting/nowcasting is still an issue and needs continued research. Furthermore, 3-D forecasting models for fog prediction should be developed for better forecasting of the various fog types.

3.5. *Statistical Forecasting Models*

Statistics have been traditionally used in Meteorology as a standard tool in tackling a variety of problems. The statistical approach in this discipline has been reviewed repeatedly (PANOFSKY and BRIER, 1958; WILKS, 1995). In this respect, efforts towards forecasting the occurrence of fog and low cloud base by using statistical or empirical techniques date back well before the widespread use of modern computer technologies, advanced statistically-based advanced computational methodologies and related software packages. A brief survey of the statistical models used in forecasting visibility is made in this section.

At first, the concept of statistical forecasting refers to the *traditional* methodologies of data fitting. In ceiling and visibility forecasting, examples with such traditional methodologies are those using a linear regression (e.g., VISLOCKY and FRITSCH, 1997) and a logistic regression (e.g., HILLIKER and FRITSCH, 1999).

However, new data driven methodologies are now available which can handle the inherent uncertainty in the analysis. The concept of statistical modeling is now-a-days more generic, in the sense that it encompasses a wider range of procedures for treating uncertainty and which have been devised as a result of modern computational methodologies. It is within this context that the term *statistical forecasting* is used in this section and some newer methodologies are reviewed briefly.

Artificial Neural Networks (ANN) are computational methodologies capable of establishing associations between the independent variables (i.e., the predictors) and the dependent variable (i.e., predictand), through the experimentation of a multitude of situations (i.e., learning data set). Information on the relationship between the predictors and the predictand is placed in a net of interacting nodes. Although ANN have been extensively used in atmospheric science (for a review see HSIEH and TANG, 1998; GARDNER and DORLING, 1998; MICHAELIDES *et al.*, 2006), their application in ceiling and visibility forecasting is rather limited. It is only very recently that a rather restricted number of researchers have adopted the use of ANN in the area of statistical ceiling and visibility forecasting (PASINI *et al.*, 2001; COSTA *et al.*, 2006; BREMNES and MICHAELIDES, 2007). A natural question arising is whether ANN have any advantages over the traditional statistical tools mentioned above. MARZBAN *et al.* (2006) compared neural network with linear and logistic regression in forecasting ceiling and low visibilities, and they concluded that the ANN approach yields superior forecast quality.

Fuzzy logic is a methodology to treat uncertainty in systems whose variables are rather qualitative, imprecise or ambiguous. Over the past few years, this methodology has been increasingly adopted as a favorable technique in a variety of environmental issues but has found limited applications in weather prediction. The appropriateness of fog occurrence for treatment with fuzzy logic has been tested with promising results (SUJITJORN *et al.*, 1994; MURTHA, 1995). More recently, PETTY *et al.* (2000) describe a fuzzy logic system for the analysis and prediction of cloud ceiling and visibility. Also HANSEN (2000) reports on the use of such a forecasting system to forecast ceiling and visibility and concludes that the fuzzy system outperforms persistence-based forecasts.

In a decision-making process, a *Decision Tree* is defined as a graphical representation of all the alternatives and the paths by which they may be reached. Decision trees are quite popular tools in many domains and can be powerful prediction tools (see ALMUALLIM *et al.*, 2001). In contrast to neural networks, decision trees represent sets of comprehensible rules. Despite the potential attractiveness of decision trees for weather prediction, there are few examples of applying them; COLQUHOUN (1987) lists a few such applications to meteorological issues. The complexity of the phenomena discussed in this paper makes the determination of "rules" a very difficult task. It is probably for this reason that examples of the application of decision trees in forecasting ceiling and visibility are also limited. WANTUCH (2001) presents one such successful attempt.

In terms of expressing the uncertainty which is inherent in any kind of statistical forecasting, two types of forecasting models can be generally identified as *deterministic* and *probabilistic*. *Deterministic* forecasts are statements indicating that the predictand takes some specific values without any notion on the uncertainty involved in forecasting it. In contrast, probabilistic forecasts with use of an uncertainty level are more informative, thus providing the best possible guidance for weather forecasters and other decision makers (LEYTON and FRITSCH, 2003; BREMNES and MICHAELIDES, 2007).

a) Selection of predictand and predictors

With regard to fog forecasting, it is natural to consider visibility (measured by expert observers or by appropriate instrumentation e.g., transmissometers) as the predictand. This is the most widely used predictand in low visibility/fog forecasting. Nevertheless, two early such methods used for forecasting fog formation (SAUNDERS, 1950; CRADDOCK and PRITCHARD, 1951) were designed to predict the fog-point temperature (i.e., the temperature at which radiation fog is formed by nocturnal cooling).

In the appropriateness of the statistical model to build for fog analysis, the second challenge is the selection of the appropriate informative predictors i.e., predictors which are considered to be strongly related to the predictand. In practice, there are numerous potential predictors to choose from, normally far more than would be suitable in any particular model. Although it is possible to employ all the available parameters as predictors in a statistical approach, the resultant prognostic relationship is generally less efficient. As a general *subjective* rule, concerning the choice of the predictors, it is advantageous to retain the lowest number of physically reasonable predictors, thus rendering the prognostic relationship more stable. However, the choice can be based on purely *objective* criteria. A forward stepwise screening algorithm is usually used to select the best predictor variables. In this method, potential predictors are added one at a time to the model. A predictor is retained when, combined with the predictors already selected, it contributes significantly to an additional reduction of variance; otherwise a potential predictor is considered as redundant (VISLOCKY and FRITSCH, 1995, 1997). Nevertheless, other approaches can be adopted too. ROBASKY and WILSON (2006) have recently summarized such objective steps which may be adopted in order to reach a set of predictors. These include the search for synergies within the set of potential predictors; the determination of the forecast models with the best performance by eliminating the least important predictors by a nulling process which is accomplished iteratively.

b) Statistical models versus learning and application data

Depending on a type of data used in developing and/or implementing the prognostic relationships, three approaches are recognized.

In the *Classical method*, both the building and application of the prognostic relationships use exclusively available observational data (VISLOCKY and FRITSCH, 1997). In such a forecast system the future visibility conditions are predicted through a time-lagged statistical relationship built and implemented with data derived from surface or upper level meteorological observations.

The *Perfect Prog method* is described by KLEIN *et al.* (1959). With this approach, in the development of the prognostic relationship, the predictand is related to recorded values of the predictors. In applying the Perfect Prog forecast system, however, the predictors' values are derived exclusively from a Numerical Weather Prediction (NWP) model output (assuming that the predictions are perfect, hence the name of the method).

The third approach is referred to as the *Model Output Statistics (MOS) method* and is described by GLAHN and LOWRY (1972). In this method, both in developing and implementing the statistically established forecast system, predictors are derived from the NWP model output, observations, and climatic data. BOCCHIERI *et al.* (1974) applied linear regression to both observations and output from atmospheric models as predictors in an automated system for predicting ceiling and visibility.

Bearing in mind the above description of the three methods, MOS can be considered as a procedure for optimizing the statistical forecast system's performance by post-processing NWP model output and observations. In the MOS procedure, observations (ceiling and visibility) are correlated to NWP model forecasts (e.g., predicted fields of humidity, precipitable water, vertical velocity, etc), climatic variables and observed parameters. Typically, the predictors based on observations are the most important components in short-range MOS forecasting systems (WMO, 1991). When the latest surface observation is also used as a predictor in the MOS scheme, this appears to have a strong impact on the forecasts.

3.6. Climatology of Fog

The main purposes of studying fog climatology are to better understand the nature of fog and to apply this understanding to better predict its occurrence. Surface observations at airports and climatological stations are a rich source of data for fog climatology. Long records of such observations exist for many sites in the world. Such observations are made following directions given in MANOBS (2006).

Various approaches have been used to devise fog climatologies. One of the most common approaches is the use of the mean annual number of days of fog over a geographic area (e.g., MURACA *et al.* 2001; PEACE 1969). Such analyses are useful for summary views and for visualizing locations that are relatively more prone to fog. When such analyses are stratified according to season, marked differences may be seen (HARDWICK, 1973) and this can provide insights into the seasonal dependence (or lack thereof) of specific fog regimes (TARDIF and RASMUSSEN, 2007). A problem in considering only mean annual or monthly number of days with fog is that such

analyses tend to exaggerate the actual amount of fog, because during any given number of days with fog, fog itself is typically only present for a fraction of the time. For example, PHILLIPS (1990) reported that in Halifax, Nova Scotia, there is on average 15 days with fog in June and 18 days in July. Such reports may give the impression that Halifax is foggier than it actually is: "half the time." However, when the average frequency of fog is analyzed in terms of hours as in Figure 1, then, the true frequency is less than "half the time."

Other approaches have also been employed, such as the use of *fog events* as a basis for the identification of important climatological parameters (MEYER and LALA 1990; TARDIF and RASMUSSEN, 2007). This approach seems more intuitive since factors influencing fog formation and its subsequent evolution are not constrained by the arbitrary change from one day to the next at midnight. By focusing on conditions leading to events at one or more locations, these authors were able to ascertain the importance of certain factors involved with fog formation. The occurrence of inland radiation fog during the fall season is driven by the radiative cooling potential (length of the night) and the availability of moisture. Radiation fog has also been shown to occur in spring in coastal plains under the influence of advection inland of moist marine air during the previous afternoon. Advection fog tends to occur in the spring and summer months (as shown in Fig. 1) as this is the time of year where the occurrence of warm air flowing over the cold ocean is maximized.
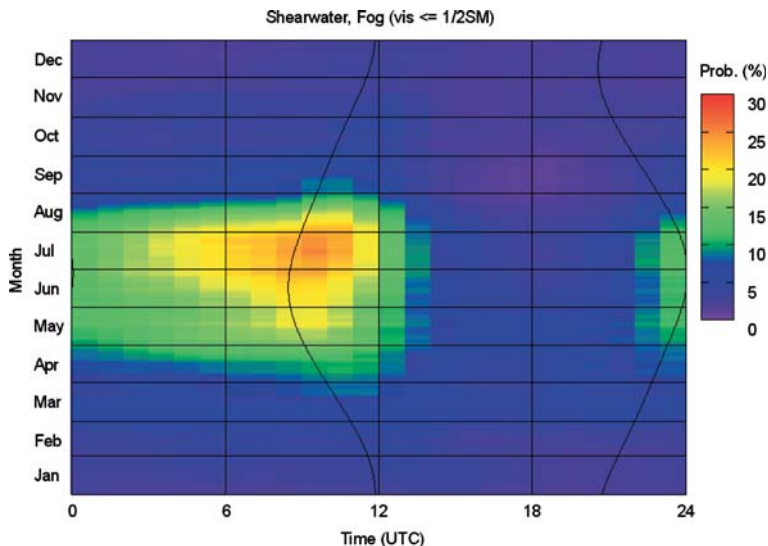

Figure 1
Seasonal-diurnal frequency of fog (visibility ≤ ½ statute mile) at Halifax, Nova Scotia (44°40′N, 63°30′W). Statistics based on complete hourly records from 1971 to 2005 inclusive. Curved gridlines correspond to time of sunrise (left) and time of sunset (right) (HANSEN *et al.*, 2007).

Apart from surface-based observations, data from polar-orbiting satellites have been successfully used by BENDIX (1994, 2002) for fog mapping and to derive the climatology of fog physical parameters for Germany and adjacent areas. Significant spatial variability was observed in microphysical properties between continental radiation fog and the coastal sea fog.

The study of interannual trends in frequency can also yield significant insights into the complex nature of fog. However, great care must be taken in extracting meaningful information from climatological time series. For instance, HANESIAK and WANG (2005) describe procedures for mitigating the effects of "artificial step changes" in long-term climatologies. Such changes are often plainly visible in time series plots of obscuration frequency, appearing as sharp discontinuities in trends and moving averages. Such changes can often be attributed to changes in instrumentation or changes in instrumented site. HANESIAK and WANG (2005), using the logistic regression technique, reported long-term trends in fog conditions in the Canadian Arctic, specifically, decreasing in the east and increasing in the southwest. FORTHUN *et al.* (2006), using simple linear regression, reported finding a variation of trends in the southeast U.S. (decreasing, flat, increasing); however, decreasing trends predominate. LADOCHY (2005) also found decreasing trends in the Los Angeles area on the West Coast of the United States and attributed them to the urbanization of the area and its associated urban heat island. Similar findings have also been reported by WITIW and BAARS (2003) for various cities in South and North America and the United Kingdom, while some cities in the United States and Asia are characterized by increasing trends. Some evidence points to increasing air pollution as a possible reason for fog increase. In many instances, decadal trends at individual sites are often quite distinct, which implies that knowledge of such trends should always be factored into any fog climatology-based forecast application.

The information extracted from fog climatologies can serve as a basis for the development of forecast decision support and guidance tools. For example, MARTIN (1972), using data from 15 airports in the U.S., comprising in excess of 340 years worth of hourly observations, showed how large amounts of climatological data can be condensed into a small amount of relevant conditional climatology information which is useful for short-term forecasting at airports. Frequencies of ceilings in various important flight categories were graphed as a field bounded by two axes: Time of year (month) and time of day (hour UTC). When the data for specific airports were thus graphed, seasonal and diurnal site-specific features in the climatology were revealed. Such seasonal-diurnal (SD) graphs were further refined to display probabilities of various ceilings given additional conditions, such as, probability of persistence of a category of ceiling at 2 hours, and probability of a ceiling category when the wind direction is from a given sector. This work was advanced for its time, however its applicability was limited mainly by two factors: 1) Low computing power meant that analyses for individual airports took a long time and had to be completed manually, and 2) forecasters still had to manually search

through numerous charts to locate specific information applicable to any current forecast situation.

In recent years, increases in computer power and improvements in data analysis methods and in graphic user interfaces have made possible a greatly increased applicability of SD analyses and graphs. FISK (2004) showed how production of such graphs could be semi-automated and how such graphs adapt well to presentation on the internet. TARDIF and RASMUSSEN (2007) use carefully prepared SD graphs to study the nature of various types of fog (types such as precipitation, radiation, advection, and cloud-base-lowering), particularly with respect to characteristic times of formation and times of dissipation of each type of fog.

Future efforts should concentrate on various aspects related to the improvement of how climatologies are put together. In particular, three complicating issues in the analysis of fog climatology from airport observations are: First, how to account for any changes in observational practices (i.e., climate data homogenization); second, how to account for any long-term changes in fog frequency (non-stationarity); and third, what to make of semi-subjective observations of simultaneous fog and precipitation (e.g., in an isolated observation of "1/2SM FG -RASN", it is difficult to know exactly how fog, rain and snow interacted to reduce the visibility to ½ statute mile). The analysis of long-term data from specialized instruments deployed at various sites characterized by distinct fog regimes would provide valuable information about such issues.

4. Discussion and Future Research

This review paper demonstrated that there have been numerous studies related to various aspects of fog. Persisting and emerging challenges, listed below, require further state-of-the-art observations and numerical modeling studies. Fog forms, develops, and dissipates as a result of complex interactions among various local microphysical, dynamical, radiative and chemical processes, boundary layer conditions, and large-scale meteorological processes, e.g., frontal systems. As a result, its definition and classification remain unclear, as evidenced by the numerous different names and classification methodologies used.

Extensive measurements of fog under various conditions are needed to better parameterize its physics, and develop accurate forecasting systems and retrieval techniques using remote sensing data. Further studies using combinations of 3-D and 1-D numerical models, remote sensing methods based on a greater number of channels on satellites (e.g., MODIS), along with the careful statistical analysis of climatological data, could further enhance our understanding of issues related to the improvement of fog nowcasting, and the changing character of fog under global warming conditions. The increased resolution and sampling rates from operational satellites such as GOES-R and METEOSAT could further improve the nowcasting of fog.

To cover the wide spectrum of processes involved in shaping the complexity of fog formation and evolution, a carefully designed high-resolution 3-D fog model is needed. The use of such a model becomes more feasible with the ever-increasing computing power made available with the new computing systems constantly being developed. However, in some situations, the less expensive 1-D models still represent a viable alternative, particularly in the context of frequently updated very short-term ensemble site-specific forecasts issued from initial conditions determined from local observations. Given the inherent uncertainty in initial conditions and inaccuracies of physical parameterizations, fog forecasting with ensembles would also provide a range of possible outcomes and thus improve fog prediction. In this respect, new research on data assimilation techniques and use of novel data sources providing better initial conditions could lead to more accurate forecasts.

Basic research is still needed with respect to the role of turbulence and interactions between the atmosphere and an underlying complex surface, particularly during the stable regime in the nocturnal boundary layer. Data from recent or upcoming field experiments, combined with results from a wide range of models (Direct Numerical Simulation, Large Eddy Simulation, high-resolution 1-D boundary layer and 3-D mesoscale models) are required. Also, fog formation in the turbulent high wind conditions should be investigated, along with fog forming large-scale systems, e.g., frontal systems.

Although there are efforts focusing on ice fog, freezing fog, and mixed-phase fog, their physical understanding is still in question because of limited measurements of particle sizes less than 100 μm and unknown nucleation processes of ice crystals in fog. In fact, ice fog and freezing fog in the northern latitudes can be one of the major hazardous conditions for transportation that include aviation, marine, and land transportation (THUMAN and ROBINSON, 1954; CHARLTON and PARK, 1984). Figure 2 is obtained using surface observations from seven northern Canadian stations. This figure shows that fog occurrence is likely related to rain, snow, or mixed phase precipitation conditions although this figure does not show joint probability distributions. Warm fog and drizzle occur at T > −10°C and ice fog conditions occur at T < −30°C. This suggests that field observations should focus on the above T range where models should be able to accurately forecast fog related parameters, e.g., LWC, ice water content (IWC), and visibility values. This figure here also suggests that heterogeneous nucleation at T > −40°C is likely the source of fog particle formations (GULTEPE and ISAAC, 1999; GULTEPE *et al.*, 2001) but ice fog microphysical properties need to be explored for its effect on aviation and transportation.

Statistical and climatological methods should be developed to support the design of future airport locations and next-generation aviation weather applications. Based on carefully crafted climatologies, better field programs can be developed for our further understanding of physical parameterizations for specific applications. For instance, current parameterizations are applied for all types of fog but averaging
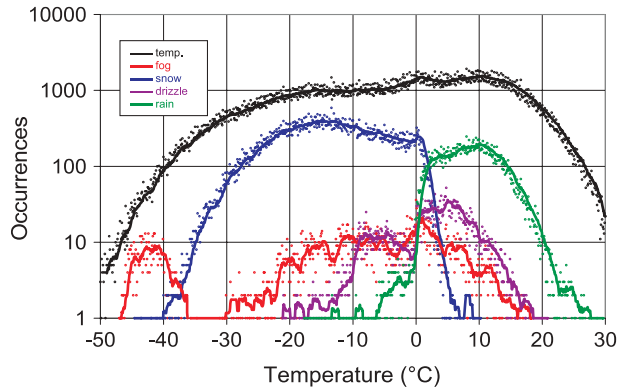
Figure 2

Occurrence of fog, drizzle, snow, rain, and temperature for seven northern Canadian airports. Points represent the number of occurrences in 0.1°C bins. Lines represent the 11-point moving averages.

scales are generally not considered (RÄISÄNEN *et al.*, 2003; GULTEPE and ISAAC, 1999). In fact, the amount (coverage and density) of fog over some scale is a strong function of the averaging scale itself GULTEPE and ISAAC (2007). Therefore the development of scale-dependent parameterizations is an important issue to consider.

Future efforts related to the issues summarized above would be extremely helpful to our better understanding of fog related processes and fog nowcasting/forecasting issues. It is our hope that the papers presented in this special issue serve as the basis for new research challenges and findings on the subject of fog.

Acknowledgments

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