1.2 Fog regimes: a review[1]

One often thinks of specific regimes or types when fog is mentioned. The scenarios that most commonly come to mind when considering fog are associated with calm clear nights over land or fog observed at sea over cold waters. It is not surprising that these scenarios are the ones discussed the most in the literature. But the fact is that fog presents itself under various scenarios, including some associated with large-scale mid-latitude cyclonic disturbances. The various scenarios are often described through a classification according to fog types. As such, Willett (1928) established a classification, later modified by Byers (1959), 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. In terms of physical mechanisms, Jiusto (1981) lists fourteen factors thought to be influential in the formation and evolution of a fog layer. The local scale factors mainly involve moisture availability, radiative balance of the clear and cloudy air, turbulent mixing, heat and moisture transfer in the soil medium and microphysical processes. Other factors such as temperature and moisture horizontal advections and vertical motion associated with large scale and/or mesoscale circulations should also be added to the list. Due to the numerous factors involved, it is not surprising that fog forms under a wide range of scenarios.

As alluded to earlier, the most studied and therefore best-described fog type is

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[1] This section appears, with modifications, in the journal article: Gultepe, I., R. Tardif, S. C. Michaelides, J. Cermak, A. Bott, J. Bendix, M. D. Müller, M. Pagowski, B. K. Hansen, G. P. Ellrod, W. Jacobs, G. Toth, and S. Cober, 2007: Fog research: A review of past achievements and future perspectives. *Pure Appl. Geophys, 164.*

associated with radiative cooling over land. It can be sub-divided among *radiation* (*ground) fog*, *high-inversion fog* and *advection-radiation fog*. Ground fog usually forms near the surface under clear skies in stagnant air in association with an anti-cyclone. Under this scenario, fog formation has been shown to be sensitive to the coupled dynamical and thermodynamical structure of the evolving nocturnal boundary layer over land. 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 radiational 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 when warm marine air is advected over a region affected by a cold ocean current and thus 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 a few degrees colder at a speed of a few meters per second (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) report 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, studies have 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) as well as to the fog/stratus microphysical characteristics (Goodman, 1977). 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 be advected 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 poleward 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 as it results from cold air with a low vapor pressure being transported over a 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).

Fog may also form as a result of a cloud base lowering all the way to the surface (*cloud base lowering fog*). 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). Although, later work has suggested that radiatively driven well-mixed stratocumulus cannot persist in the presence of heavy drizzle (Stevens et al, 1998). This may indicate a sensitivity of the cloud base height evolution to the intensity of drizzle. 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, decreasing the depth of the marine boundary layer. Despite this body of work, a comprehensive understanding of the processes associated with cloud base lowering leading to reduced visibility conditions at the surface in complex coastal areas, where interactions with contrasting land surface properties may have an influence (Doran et al., 2002), still hasn't been achieved.

Another fog type lacking a comprehensive understanding and description is fog forming in precipitation. *Precipitation fog*, often referred to as *frontal fog,* is described as a common occurrence ahead of warm frontal boundaries (George, 1940; 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 and Stewart et al., 1995) presumably due to the evaporation of melting or freezing precipitation hydrometeors (Donaldson and Stewart, 1993). Byers (1959) further divides the precipitation-induced fog type into three sub-categories: *prefrontal*, *postfrontal* and *frontal passage* fogs. Prefrontal 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. Postfrontal fog usually occurs behind a cold front and is much like prefrontal 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 use of sub-categories 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 provides evidence that fog formation and subsequent evolution is determined by a plethora of mechanisms and interactions that span several time and space scales and all are still not fully understood. This fact is central to the difficulty of establishing a comprehensive understanding of fog in all of its forms, and thus to the difficulty of accurately predicting the various occurrences of fog.