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The turbulent structure and transport in fog layers observed over the Tianjin area

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ABSTRACT

This paper investigates the vertical structure and turbulence activities in fog events. Three fog cases that occurred in the winter of 2010 over Tianjin, China were selected, including two advection–radiation fog events and an advection fog event. Field observations collected at a 255-m tall meteorological tower in Tianjin were analyzed, including turbulence measurements using the eddy covariance systems installed at three levels, measurements of temperature, horizontal wind and humidity collected at 15 levels, surface radiation fluxes and horizontal visibility. The results suggest that the advection fog was more enduring and thicker than the advection–radiation fog. The fog events were characterized by low wind speed throughout the fog layer. A temperature inversion and low-level jet were observed above the advection–radiation fog layer. The surface net radiation reflected some differences among the fog events. The collapse of turbulence was a necessity for the formation fog, and moderate turbulence was favorable to the development and maintenance. The heat and water vapor fluxes in the advection–radiation fog were weaker than those in the advection fog, in which the stratification was slightly unstable. The relationships among the turbulent transport efficiencies of water vapor, temperature and momentum were examined. The results suggest the applicability of local similarity in the fog layer for the momentum transport efficiency.

1. Introduction

Fog is a weather phenomenon that occurs in the lower part of the atmospheric boundary layer (ABL). It reduces the atmospheric visibility and significantly affects human activities such as marine shipping, land transportation and aviation safety. The economic and human losses associated with fog events are comparable to those caused by tornadoes and even hurricanes and winter storms (Gultepe et al., 2007). Fog events have caused costly and even catastrophic events in China and occur more often in the southern and eastern areas of China than in the northern and western areas (Niu et al., 2010), especially in the autumn and winter seasons (Wang et al., 2005). The mean occurrence frequency of fog events observed at 16 different sites in the North China Plain (NCP) from 1983 to 2009 is 11.4 ± 6.9 days yr^{-1} (Quan et al., 2011). Tianjin city is located in the eastern portion of the NCP, with the Bohai Sea to the east. The climatology of fog events in Tianjin differs from that in other cities in China because of the local sea–land breeze and the large-scale eastern airflow that transports water vapor to this region (Liu et al., 2005; Wu et al., 2010a).

Previous observational and numerical fog studies have improved our knowledge of the characteristics and complicated physical mechanisms of fog episodes, from the synoptic, micrometeorological and microphysical perspectives (Akimoto and Kusaka, 2014; Dupont et al., 2012; Fuzzi et al., 1992; Gonser et al., 2011; Liu et al., 2010, 2012; Meyer et al., 1986; Niu et al., 2010; Price, 2011; Taylor, 1917). However, the accurate forecasting of fog is still challenging in operational aspects. Both fog and non-precipitating low stratus clouds are

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surprisingly resistant to forecasting with the numerical models (Tudor, 2010). The capabilities of numerical models to forecast fog are not yet satisfying and can be influenced by many factors, including the vertical resolutions of the models (Pagowski et al., 2004; Tardif, 2007), the initial conditions (Ballard et al., 1991; Bergot and Guedalia, 1994; Liang et al., 2009; Piccolo and Cullen, 2011; Yang et al., 2010), and the parameterizations of subgrid physical processes, especially the microphysics and turbulent mixing (Bott and Trautmann, 2002; Gultepe et al., 2007; Müller et al., 2010; Musson-Genon, 1987; van der Velde et al., 2010; Vellore et al., 2007). Therefore, it is of primary importance to develop a deeper understanding of the processes related to the formation and evolution of fog (Gultepe et al., 2009; Zhou et al., 2010).

Fog can be generally understood as a low stratus cloud located close to the ground (Stull, 1988) and is usually categorized according to the main physical mechanism involved in fog formation and maturity, such as the radiation flux divergence, advection, pre-front lifting, and orographic lifting, among others. The movement of the fog patch and changes in the fog droplet size distribution (DSD) can result in variations in the level of visibility within the fog layer (Okuda et al., 2010). Increases in wind speed (e.g., cold front passage), turbulence intensity and short-wave radiation may lead to the dissipation of fog or its transition into low stratus clouds. Complex physical processes, including radiation, turbulent transport, microphysics, mesoscale motion and synoptic forcing, interact synthetically during a fog event (Koračin et al., 2014). The evolution and structure of a fog layer are also related to the local terrain and ecological environment (Maier et al., 2013; Wu et al., 2007). Fog structures and fog evolution vary greatly with differences in local conditions (Liu et al., 2012).

Fog that mainly forms in relation to radiative cooling has been studied most (Dupont et al., 2012). The nocturnal long-wave radiative cooling of the underlying surface is often the trigger of ground fog. Extremely dense fogs occur only in radiation-related cases (Liu et al., 2012). The lifetime of a radiation fog event can be divided into several stages, consisting of development, maturity and dissipation (Maier et al., 2013). The turbulent kinetic energy, friction velocity, atmospheric stability, and fog DSD evolve differently during the various stages (Liu et al., 2010; Price, 2011; Terradellas et al., 2008). Within a radiation fog layer, temperature convergence is commonly observed, as well as weakly unstable stratification and increased turbulence (Price, 2011; Roach et al., 1976).

Long-wave radiation at the fog top is also a significant factor involved in fog dynamics. When fog becomes optically thick during its development process, the majority of the fog dynamics become dominated by the processes occurring at the top of the fog layer (Duynkerke, 1999). Oliver et al. (1978), using a second-order closure model, pointed out that the radiative cooling at the fog top is an important determinant of fog's life cycle. Radiative cooling can enhance turbulent mixing by destabilizing the cloud-topped boundary layer and promote the upward or downward development of initial fog or stratus layers. This process can lead to the vertical thickening of the fog layer or the formation of stratus fog (Koračin et al., 2005; Pagowski et al., 2004; Pilie et al., 1979; Pilié et al., 1975). In addition, large-scale subsidence is also expected to strengthen the inversion above the cloud top and force the stratus clouds to lower levels, which can also result in the formation of fog (Koračin et al., 2001).

The influence of turbulent transport on fog development has been emphasized in previous studies (Brown and Roach, 1976; Cuxart and Jiménez, 2011; Duynkerke, 1999; Gerber, 1981; Nakanishi, 2000). For radiation fog, Gerber (1981) observed rapid fluctuations in relative humidity (*RH*), with a mean period of 18 min, which was viewed as a quasi-periodic oscillation; the turbulent mixing of nearly saturated eddies was suspected to be the cause of fog droplet formation and the broadening of the DSD. In addition, according to a theoretical analysis based on a modified Monin–Obukhov Similarity Theory (MOST), surface-layer fog dynamics are highly dependent on the divergence of the turbulent fluxes of water vapor, heat and liquid water content, and the enhanced eddy diffusivity in the surface layer causes an increase in the height of the fog top (Kraus, 1993). The influence of turbulence on the collision and coalescence of droplets, as well as the entrainment of dryer air volumes into the cloud (heterogeneous mixing), was suspected to be the reason for rapidly occurring differences in *RH*, DSD and visibility (Gonser et al., 2011). However the quantitative effects of these mechanisms remain unclear.

Given the development of fast-response instruments, methods of the direct observation of turbulent fluxes and rapid variations in fog have been realized for observational experiments. Terradellas et al. (2008) employed the wavelet method to estimate the turbulent kinetic energy and sensible heat flux in a radiation fog, using measurements from sonic anemometers at 96.6 m and 5.6 m. Their results indicate that, before formation of fog the turbulence energy is much weaker near the ground than aloft; there is a strong inversion and an increase in specific humidity above the top of the fog layer. Based on the Eddy Covariance (EC) method, the characteristics of the turbulent fluxes during advection fogs and steam fogs over the Yellow Sea were compared (Heo et al., 2010), suggesting that weakening wind and collapsing turbulence may contribute to the onset of advection fog. In comparison, the increases in both the mean and turbulent kinetic energies were observed approximately 10 h before the onset of fog in the lower boundary layer (Zhang et al., 2005). The characteristics of the turbulence and energy transport in terrestrial advection fog events have been evaluated statistically, yielding various insights concerning the turbulent spectrum and the applicability of the MOST in foggy condition (Wu et al., 2010b, 2011). Zhou and Ferrier (2008) deduced a critical turbulence exchange coefficient, based on a theoretical analysis of the asymptotic solution of a liquid water content equation under steady-state conditions. The critical turbulence exchange coefficient denotes the maximum turbulence magnitude that a steady radiation fog layer can endure. This magnitude of this coefficient can be used to diagnose the persistence or dissipation of a steady fog layer (Zhou, 2011). However, quantifications of turbulence transport and its vertical structure are quite rare because of the lack of continuous and comprehensive field observations of the turbulent transport in fog. This hinders the validation of numerical modeling and improvement of related parameterizations.

In this paper, we focus on the vertical structure and turbulent mixing of three fog events that occurred during the winter of 2010, including two advection–radiation fog events and one stratus fog event, using the in-situ observations obtained at a 255-m meteorological tower located in Tianjin.