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Structure and evolution of a squall line in northern China: A case study

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ABSTRACT

The dynamical, thermodynamical and microphysical structures of convective cells associated with a squall line that occurred on 23 June 2011 in northern China are investigated using observational data and the Regional Atmospheric Modeling System (RAMS). The results suggest that: 1) The squall line appears in the front of the upper-level trough with moderate vertical wind shear at the low levels. 2) The cold pool is formed mainly by rainfall in the initial developing stage. During both the developing and mature stages, the cold pool locates behind the leading edge of the storm. The convergence of the cold air diverged from the cold pool and the warm-moist air transported from the southeast environment is the major mechanism that maintains momentum for the squall line development. Meanwhile, the front-to-rear flow forms systematically in the squall line system. During the dissipation stage, the front-to-rear flow fades away and the air flow passes through the storm at the high level. The cold pool moves ahead of the storm and cuts off the supply of the warm-moist air to the updraft of the storm, leading to demise of the storm. 3) The location of the squall line leading edge is closed to the location where the wind speed and direction at 1 km altitude suddenly occurs to be changed. 4) The total warming effect during all the stages processes similar trends of change with height. During the developing stage, the total cooling effect mainly comes from evaporation of cloud water. During the mature and dissipation stages, the melting of hail dominates the total cooling effect in the lower layer. 5) In the developing stage, the growth of hail primarily comes from the processes accreting with raindrops and cloud droplets. During the mature and dissipation stages, the hail particles grow mainly through their accreting with raindrops. Correspondingly, during the initial developing stage, the rainwater comes mainly from cloud water by accreting process near the freezing level. During the mature and dissipation stages, however, the rainwater comes mainly from the melting of hail below the freezing level. The conceptual models of the distribution of the airflow field, cloud microphysical structure and precipitation during the various development stages are presented.

1. Introduction

Many studies have demonstrated that there are multiple impact factors related to the structure and maintenance of severe storm cells, including vertical wind shear (Ogura and Liou, 1980; Thorpe et al., 1982; Fovell and Dailey, 1995; Takemi, 2007, 2014), rear-to-front flow (Smull and Houze, 1987; Zhang et al., 1989; Tao et al., 1995; Grim et al., 2009), cold pool (Thorpe et al., 1982; Weisman and Davis, 1998; Bryan et al., 2006), and microphysical process (Forvell and Ogura, 1988; Flossmann, 1998; Yin et al., 2000a, 2002; Khain et al., 2001; Flossmann and Wobrock, 2010; Noppel et al., 2010; Yang et al., 2012).

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Vertical wind shear and cold pool play crucial roles in the maintenance of deep convections at the leading edge of fast-moving severe storms (Rotunno et al., 1988; Lafore and Moncrieff, 1989; Weisman, 1992; Takemi, 2007; Takemi, 2014). The ambient vertical wind shear that is perpendicular to the squall line is a key impact factor in the evolution of the squall line (Newton, 1950, 1966; Fujita, 1955; Ludlam, 1963). Typically, the front of the cold pool is the storm outflow boundary position. Studies show that if vertical wind shear exists in the low atmosphere, strong vertical upward motion can be triggered by the cold pool near the surface, thereby favoring the triggering of new cells in the front of the cold pool (Droegemeier and Wilhelmson, 1985, 1987). Furthermore, other studies indicate that vertical wind shear is favorable for the evolution of supercell storms. However, the vertical wind shear and cold pool are not beneficial to the development of the squall line that is formed by non-supercell storms. The interaction between cold pool and low-level vertical wind shear affects the lifting height and the magnitude of the vertical velocity at the forefront of the squall line, and is the most important factor for triggering new convective cells.

The rear inflow jet (RIJ) plays a key role in the development and maintenance of severe storms (Smull and Houze, 1987; Tao et al., 1995; Grim et al., 2009; Alcântara et al., 2011). The RIJ forms in response to midlevel horizontal pressure and buoyancy gradients. These gradients are generated by both the latent heating through microphysical process of the convective updraft and the cold pool related to the downdraft of the storms (Brown, 1979; Smull and Houze, 1987; Weisman, 1992; Haertel and Johnson, 2000). The rear-to-front flow impacts convective intensity by: 1) enhancing convective downdrafts that aid in strengthening of the surface cold pool (Forvell and Ogura, 1988; Weisman, 1992; Tao et al., 1995); and 2) transporting momentum from aloft to the surface of the cold pool, thereby assisting deeper lifting near the gust front (Weisman, 1992). In brief, the RIJ affects the convective intensity mainly through the cold pool.

The influence of the rear inflow on convective systems varies from case to case. Sometimes, the appearance of intense rear inflow coincides with a noticeable weakening of the active convective zone and a slow dissipation of the system as a whole (Smull and Houze, 1987; Rutledge and Hobbs, 1983); while on other occasions, the convective cells and overall system circulation remain strong for many hours after the development of the rear inflow (Smull and Houze, 1987; Chong et al., 1987; Houze et al., 1989). Many studies suggest the rear inflow as a sign of the maturity of convective systems (Fovell and Ogura, 1988; Weisman et al., 1988; Lafore and Moncrieff, 1989). The emergence of the rear inflow is often accompanied by strengthening of the cold pool (Rotunno et al., 1988). The cold pool plays an important role in the life cycle and dynamical process of severe storms (Thorpe et al., 1982; Weisman et al., 1988; Weisman, 1992; Bryan et al., 2006). As for upshear-tilting convective systems, the RIJ transports hail and rain particles that have dropped from the updraft back into the updraft again, which is favorable for enhancing the latent heat release and positive buoyancy.

Many studies have shown that there are very close relationships between the microphysical processes and the deep convections, especially through the effect of cold pool. Microphysical processes play a great role in the evolution of severe storms (Khain et al., 1999; Yin et al., 2000a; Levin et al., 2005; Yin et al., 2005; Morrison et al., 2009; Van Weverberg et al., 2012; Guo et al., 2015). Tao et al. (1995) demonstrated that the melting process of ice particles below the freezing level plays an important role in the dynamical structure of midlatitude continental squall systems. The melting process of ice particles strengthens the RIJ and forces the squall line to tilt upshear as a multicellular system. In simulations, the convective system is found to be much weaker in the absence of evaporative cooling by rain. For a given vertical shear of horizontal wind, cooling by evaporation in the convective region is found to be essential for maintaining a long-lived convective system, while the cooling effect of the melting of ice-phase particles plays only a secondary role. Recently, Adams-Selin et al. (2013) suggested faster melting rates accompany stronger rear inflow and more intense bow echoes. The melting process of ice-phase particles increases the negative buoyancy, enhances the convective downdrafts, and plays a great role in the thermodynamic characteristics of convective systems (Braun and Houze, 1994). The melting of snow and graupel particles is a major source of rain in the stratiform region of a squall line system (Houze et al., 1979; Tao et al., 1990). The evaporative cooling associated with precipitation can be a major energy sink in the stratiform region. Numerical modeling shows that when the cooling caused by evaporation is turned off, the magnitudes of the mesoscale downdraft and surface pressure perturbations are significantly reduced. Therefore, the cloud microphysical processes of severe storms can be altered by changing the loading and the latent heat release by hydrometeors. There is an intricate balance among the microphysics, which is responsible for the latent heating and the associated buoyancy, and the dynamics of the convective systems.

The phase transformation between hydrometeors can cause latent heating or cooling, thereby affecting the dynamic field, and thus feeding back into the formation of hydrometeors (Flossmann, 1998; Khain et al., 1999; Yin et al., 2000b; Khain et al., 2004; Levin et al., 2005; Yin et al., 2005; Flossmann and Wobrock, 2010; Chen et al., 2011; Adams-Selin et al., 2013; Guo et al., 2014). Seigel and van den Heever (2013) showed that a circulation centered at the freezing level supports midlevel convective updraft invigoration through increased latent heating rates. The circulation starts with hail particles that initiate within the convective updraft above the freezing level, and are then ejected upshear because of the front-to-rear flow of the storm. When the hail falls below the freezing level, the rear-to-front inflow advects the hail particles downshear and into the upshear flank of the midlevel convective updraft. Below the freezing level, some ice particles melt into raindrops. The addition of hail and rain to the updraft increases the latent heating on account of an increase of riming and vapor deposition onto hail and rain. The enhanced latent heating boosts buoyancy within the updraft, thereby increasing the precipitation and cold pool intensity. Hjelmfelt et al. (1989) suggested the phase change of the hydrometeors is important in producing the downdraft. The downdraft is initiated in cloud primarily as a result of precipitation loading by the graupel. Melting of graupel to form rain below the melting level is found to contribute to the development and acceleration of the downdraft. It can be found that the maximum cooling rate for melting occurs below the level of the maximum horizontal convergence into the downdraft. The relatively large cooling