Atmospheric Research 182 (2016) 10–19

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

A modeling study of convection initiation prior to the merger of a sea-breeze front and a gust front

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ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form 21 June 2016
Accepted 5 July 2016
Available online 16 July 2016

Keywords:
Convection initiation
Modeling study
Sea-breeze front
Gust front
Merger

ABSTRACT

Convection initiation (CI) prior to the merger of a sea-breeze front (SBF) with a gust front (GF) in North China is investigated using a real-data Weather Research and Forecasting (WRF) simulation with a high resolution of 444.4 m. The overall evolution of the GF and SBF is well reproduced by the simulation. The GF was produced by the decaying convective storm over northern Beijing, while the SBF came from the Bohai Sea. Several convective cells were generated between the two fronts even though they were still about 25–30 km far away from each other. During the development of these cells, the low-level convergence and conditional instability averaged within the intermediate area between the two fronts were enhanced significantly, both of which favored the initiation of convection.

Vertical momentum budgets were conducted in the intermediate area as well as along the backward trajectories of parcels within a selected convective cell. The vertical acceleration was decomposed into dynamic and buoyant components, respectively. The diagnostic results showed that the dynamic acceleration dominated in the low level, while buoyant acceleration became evident only when the parcel reached a high altitude above 2 km. Therefore the dynamic forcing appeared to be more relevant to CI. The dynamic acceleration was further decomposed into four terms based on anelastic approximation. The positive dynamic acceleration was mainly caused by fluid extension associated with the low-level convergence, while fluid twisting in the vertical contributed negatively to the dynamic acceleration. The other two terms related to horizontal curvature and height variation of density were negligibly small.

1. Introduction

Convection initiation (CI) has been referred to as the process that air parcels reach their level of free convection (LFC), then achieve and maintain positive buoyancy over a significant upward displacement, and finally initiate a deep convective cloud (Markowski, 2007). Although much progress has been made in understanding storms, CI is still least understood and least well forecast (Lock and Houston, 2014). Clark et al. (2014) claimed that the greatest challenge in the forecast of convective storms was the prediction of the formation of new storm cells.

Lock and Houston (2014) investigated over 55,000 CI events over the central United States from 2005 to 2007. By computing a number of thermodynamic and kinematic parameters, they found four primary factors governing the behavior of CI, i.e., buoyancy, inhibition, dilution, and lift. While there was no threshold of any single parameter that was able to discriminate between initiation and noninitiation, lift appeared to be the most often factor that helped distinguish the thunderstorm initiation environment. Similarly, as mentioned in Markowski (2007), lift played a decisive role in the initiation of convection, including the lift by convergent boundaries (such as fronts, outflow boundaries, dry lines, sea breezes, and land breezes), circulations forced by differential heating (e.g. cloud-clear air boundaries, heating of sloped terrain), ascending of airflow over topography, and forced lifting by gravity waves.

Convergent boundary zones (CBZs) are characterized by a change in wind direction and/or speed, low-level convergence, and updrafts aloft (Karan and Knupp, 2009). Due to the convergence and associated lifting, CI or storm development often takes place when two or more CBZs merge, collide, or otherwise meet. For instance, 71% of 418 storms observed by Wilson and Schreiber (1986) were attributed to merging convergence zones. Similarly, 73% of the storms affecting the southeastern United States were the result of mergers (Purdom and Marcus, 1982). Furthermore, mergers of CBZs between sea breeze and prevailing monsoon were also found to lift atmospheric pollutants (e.g. Leon et al., 2001; Raman et al., 2002; Verma et al., 2006, 2016). Therefore, mergers of CBZs have drawn attention because of their high efficiency in CI, storm/cloud merger, generation of atmospheric bores (Kingsmill and Crook, 2003), and the spread of atmospheric pollutants.

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http://dx.doi.org/10.1016/j.atmosres.2016.07.003
0169-8095/

Sea breeze fronts (SBFs) and gust fronts (GFs) [i.e., outflow boundaries (OBs) of thunderstorms] are perhaps the most common CBZs that help initiate convection in the coastal area. Storm initiation and/or intensification have been studied extensively for GF merger (e.g. Droegemeier and Wilhelmson, 1985; Intrieri et al., 1990; Wilson and Mueller, 1993; Harrison et al., 2009), SBF merger (e.g. Pielke, 1974; Clarke, 1984; Xian and Pielke, 1991; Lee and Shun, 2003), as well as the merger of GF and SBF (Nicholls et al., 1991; Fankhauser et al., 1995; Kingsmill, 1995; Carbone et al., 2000; Kingsmill and Crook, 2003). Storms were also found to initiate prior to the merger of SBFs and/or GFs (e.g. Nicholls et al., 1991; Fankhauser et al., 1995), which was rarely studied however. In the simulation by Nicholls et al. (1991), deep convection initiated between the east and west coast SBFs on Florida peninsula when the two fronts came into proximity. Yet the authors did not conduct any targeted research on the genesis of convection between the two SBFs.

Fankhauser et al. (1995) investigated an OB-SBF merger and demonstrated that new convection can occur between the two fronts, several minutes prior to their merger. They stated that a well-defined convergence zone was formed in between due to the persistent quasi-stationary roll vortex. Nevertheless, it is not always the case. As will be shown in this study, CI does occur prior to the merger of two mesoscale fronts (an SBF and a GF) in North China, but with no well-defined convergence zone found between them. This kind of CI almost has no precursors to facilitate forecast, and has not yet been studied in detail. Actually, mergers of SBF with other mesoscale systems are very common in Bohai Bay area, North China. For example, Lu et al. (2012) showed that about 44% of the 50 SBF events in Bohai Bay during 2004–2009 underwent a merger process. This paper aimed to investigate the mechanisms of CI prior to the merger of the SBF and GF in the case studied in Abulikemu et al. (2015, hereafter A15), as the first attempt to investigate this kind of CI events.

The rest of this paper is organized as follows. Section 2 provides a brief overview of the severe convective weather associated with the merger process. Section 3 depicts the setup of numerical experiment and model verification. The mechanism of CI prior to the merger of the two fronts is addressed in Section 4, according to the analysis of vertical momentum budget. Finally, the paper is summarized in Section 5 with discussion.

2. Case overview

As reported in A15, during 0600 and 1200 UTC 14 July 2011, severe convective weather (including heavy rainfall, thunderstorm, high wind and hail) occurred in Tianjin and northern Hebei Province in North China due to the merger of a GF and an SBF (see Fig. 1b for the geographical location). This severe convective weather occurred in an area just ahead of the southern tip of the trough associated with a moderately intense cold low at 500 hPa (Fig. 1c). There were two pressure lows accompanied with two troughs at 850 hPa (see Fig. 2b in A15). The severe weather occurred between these two lows where there was relatively warm and moist air. According to the representative sounding derived from the Global Forecast System (GFS) analysis at 0600 UTC 14 July 2011 (i.e., 1400 local time), the near-surface atmosphere was notably heated by solar radiation, showing a well mixed boundary layer (Fig. 1d). The environment was featured by large convective available potential energy (CAPE) up to 2080 J kg^{-1} and negligible convective inhibition (CIN) of 7 J kg^{-1}. In contrast, the ambient vertical wind shear was fairly weak, which was not favorable for the development of intense convection (e.g. Rotunno et al., 1988).

The evolution of the GF, SBF, and the associated severe convective weather were shown in Fig. 2. The GF was produced by the decaying convective storm over northern Beijing, while the slow-moving SBF came from the Bohai Sea. (Note that the GF and the associated severe convective weather in Fig. 2a and b are located fairly close to the top of the plotted region, which is chosen to make a direct comparison with that of simulation shown in Fig. 3.) The 2-m height wind was southward/southeastward near behind the GF, while southeasterlies were predominant behind the SBF (Fig. 2a). The changes in the direction and/or speed of the wind field mark the location of the two fronts. At 0600 UTC, several weak convective cells occurred near behind the southwestern half of the GF, and weak clear-air radar reflectivity was found between and near the two fronts (Fig. 2a). By 0630 UTC, the two fronts get further close to each other, with a minimum distance of about 25–30 km. The weak convective cells behind the GF developed significantly. There were also two small isolated cells developed in the area between the two fronts (Fig. 2b). Both fronts kept moving toward each other, almost meeting at 0700 UTC (Fig. 2c). Meanwhile, several intense convective cells occurred between, and in the vicinity of the two fronts. It is worth noting that, there was no convergence zone observed in the area between the two fronts (see Fig. 4 below), quite different from the case studied in Fankhauser et al. (1995). By 0800 UTC (Fig. 2d), the two fronts had merged and the convective cells intensified markedly with upward development. Readers are referred to A15 for more details about this event (e.g., satellite images, surface temperature, pressure and wind observations).

3. Numerical experiment setup and model verification

A real-data simulation is performed using the Weather Research and Forecasting (WRF) model (v3.5) with the Advanced Research dynamics core (ARW; Skamarock et al., 2008). The model is configured with five-level domains that are two-way nested, with a horizontal grid spacing of 36 km, 12 km, 4 km, 1.33 km, and 444.4 m, respectively (Fig. 1). The temporal resolution of the innermost domain (d05) is 2 min. There are 45 vertical levels from surface to the 50-hPa model top. For all five domains, the model physics adopt the WRF Double Moment 6-class (WDM6) microphysics scheme (Lim and Hong, 2010), Dudhia short-wave radiation scheme (Dudhia, 1989), Rapid Radiative Transfer Model (RRTM) longwave radiation scheme (Mlawer et al., 1997), Unified Noah land surface model (Tewari et al., 2004), and the MM5 Similarity surface layer scheme (Paulson, 1970). The Kain-Fritsch scheme (Kain, 2004) is used in domains d01 and d02 for cumulus parameterization, while it is turned off in all other domains. The YSU planetary boundary layer scheme (Hong et al., 2006) is used in the outer four domains, with the large-eddy-simulation (LES) boundary layer scheme is applied in domain d05. The setup of outer four domains is the same as the simulation in A15 (except that 35 vertical levels were used in A15). They are initialized at 0000 UTC 14 July 2011, running for 18 h with the first 6 h in general for simulation spin-up. The initial and boundary conditions are created using the 6-hourly 0.5° × 0.5° Global Forecast System (GFS) analysis data. The innermost domain (d05) is activated at 0600 UTC 14 July 2011, integrating for 12 h with no spin-up. This is because domain d04 can well capture the merger process of the two fronts (see A15), thus providing accurate initial condition for d05.

In order to establish the credibility of the numerical simulation, the composite reflectivity (i.e., column maximum) and near-surface wind field (at 10 m height) in the simulation are compared with observations. The GF and SBF can be readily identified according to the change in the direction and/or speed of near-surface wind field. Before the merger of the two fronts (Fig. 3a), the GF and SBF developed about 2.5 h later than their observational counterparts, and they were displaced by about 100 km to the southwest. The northwestern convective system that generated the GF was stronger than observed, with the GF located more close to the parent system. The simulated SBF exhibited a farther inland penetration than its observational analog. Several isolated convective cells were generated between the two fronts while they were still about 25–30 km apart (Fig. 3b), in agreement with observation. When the two fronts almost merged (Fig. 3c), convective cells developed rapidly along their interface which finally organized into an intense convective system (Fig. 3d). During the merger process, there