Local Strong Sandstorms

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The local strong sandstorms (LSS), similar to haboobs in Sahara and the North America, often occur suddenly, in tens of minutes during the late afternoon, and before dusk in deserts in China, causing a significant impact on the local atmospheric environment. The Sudan haboob or American haboob often appears in the wet season, followed by thunderstorm events. In contrast, the LSS in China appears most frequently in relatively dry season. The lack of observational data in weather conditions before their formation, during their development and after their disappearance have hindered our understanding of the evolution mechanism of LSS/haboobs.

local strong sandstorms haboobs squall cold-air pool convection

1. Introduction

Sandstorms are severe weather events that can often be observed in the arid, semi-arid and adjacent regions. The frequency in the occurrence of sandstorms depends on the natural climatic variability and anthropogenic activities [1]. The sandstorms can be divided into regional sandstorms and local sandstorms according to their sizes. Regional sandstorms are caused by the synoptic-scale weather (such as the passage of cold front), ranging from hundreds to thousands of kilometers. Whereas, on the contrary, local strong sandstorms (LSS) are caused by meso- and small-scale local strong convections, usually ranging from tens to hundreds of kilometers [2]. High intensities of regional sandstorms or local sandstorms have been recorded, which were measured at all observation stations.

Regional sandstorms in China frequently occur in spring and have attracted significant interest from researchers [3][4][5][6][7]. For example, based on the meteorological data from 2001 to 2015, Yuan [5] analyzed the space-time distribution characteristics, weather system types and dynamic causes of sandstorms in some arid areas in China in the 21st century. He concluded that regional sandstorms mainly occur in spring and winter. Sandstorms in spring accounted for 97.6% of the total large-scale sandstorms in a year. Basha et al. [8] analyzed the spatial and temporal evolution of dust storms based on hourly observations at four stations in the United Arab Emirates during 1983–2014, and found most dust storms that lasted for about 5–11 h occurred in March and April.

In summer and autumn in China, there are frequently other dust events that occur in the desert. These mostly appear in the form of a LSS [9] or small dust devils [10][11][12]. In particular, the local strong sandstorms in northwestern China bear a striking resemblance to haboobs, which are dust phenomena found in the Sahara and North America. Haboobs can last for more than six hours with peak intensities of 0.5~1 h [13] often occur in northern and southern margins of the Sahara [14]. “An American haboob” [15] was introduced to describe dust storms that occurred over the arid southwestern United States, which are similar to Sudanese haboobs. Haboob phenomena have also been observed in the Middle East [16][17][18]. The sinking of cold air mass that push warm air near the ground to upraise was proposed to be the main cause of these events [19].

LSS or haboobs, generally associated with a strong wind, are complicated weather processes. A dust wall, usually up to hundreds of meters long, can form at the front of LSS/haboobs, and the propagating front is lobe-shaped. Airborne dust can strongly affect human life through respiratory and eye irritations, and pathogenic transmissions, and can cause damage to agriculture [20]. The occurrences of LSS and haboob are both attributed to severe convection weather processes, dry convection or moist convection. Sudan haboobs and American haboobs mainly occur in wet season with subsequent thunderstorm events, but heavy rain precipitation rarely occurs with LSS in China. This is because of the difference in relative humidity of squall line, which would be formed when cold air surges. LSS are always followed by the occurrence of a dry squall. The interaction of dust radiation heating near the ground with a mesoscale anticyclone air mass (cold-air pool) in the upper layer is the key process that lead to LSS. Haboobs are followed by the occurrence of a wet squall. The release of latent heat due to the condensation of water vapor, involving moist convection and cold downdraughts, is the main driving force that causes the occurrence of a haboob.

The basic features of LSS/haboobs can be drawn from conventional observation data and sometimes from mesoscale simulations. However, the lack of observational data on weather conditions prior to their formation, during their life span and after their demise have hindered our understanding of the evolution mechanisms of LSS/haboobs [21][22]. More research on the evolution of LSS or haboobs should be conducted based on a different scale simulation that combine the mesoscale meteorology simulation with micrometeorological methods, and with the computational fluid dynamics (CFD) method [9].

There are similar evolutions between LSS and haboob in the squall line of convection mechanisms and front shape in the mature stage, although they appear in different parts of the world with different meteorological conditions.

2. Triggering of LSS and Haboobs

LSS/haboobs are caused by meso- and small-scale weather phenomena, such as local strong convection, usually ranging from tens to hundreds of kilometers. The interplay of dust radiation heating and local atmospheric instability in the growth process of the squall line are responsible for triggering LSS/haboobs [23][24]. In fact, Africa or American haboobs often appear in the wet season, but LSS in China mostly appear in the dry season. Therefore, there are differences in the triggering conditions between the haboob and LSS, which are closely related to the relative humidity of the formed squall line in the invasion of the cold air. The generation of a LSS is mainly driven by the thermal convection, while the haboob is driven by the moisture convection and the thermal convection.

The difference in the surface albedo could result in an uneven distribution of air temperatures on the earth. Desert and wilderness areas have high surface albedos, such as 0.35 in desert and 0.25 in wilderness areas, so that the height of the near-surface mixing layer are usually larger in deserts than in other areas. The ascending rise of warmed air causes a convergence of the surrounding air, producing a local thermal circulation. Due to the stable atmospheric stratification, the local rising of air is usually presented in a well-organized convective cell structure [25][26]. For open convective cells, the air sinks at the center of the convective cell and then rises in the surrounds of the center [27][28]. Hexagonal clouds are often formed in up-draught areas of open convective cells [29].

Once a mesoscale cold air enters into the upper layer of the mixing layer, the downdraught of the cold air would induce the ground convective cells into an unstable movement. The cellular convection would then transformed into a strong convection of massive helical cells. The movement of swirling convective cells is similar to a tornado or a dust devil. In order to maintain the stability of these swirling convective cells, the ascending velocity at the leading edge of the swirling convective cells increase significantly, and lead to an unstable vertical airflow of convective cells, and consequently, a large-scale instability of a near-surface mixing layer [10]. The fall of the cold air tends to concentrate on the gust front as the cold front advances, forming a density current head, as shown in Figure 1 [30].

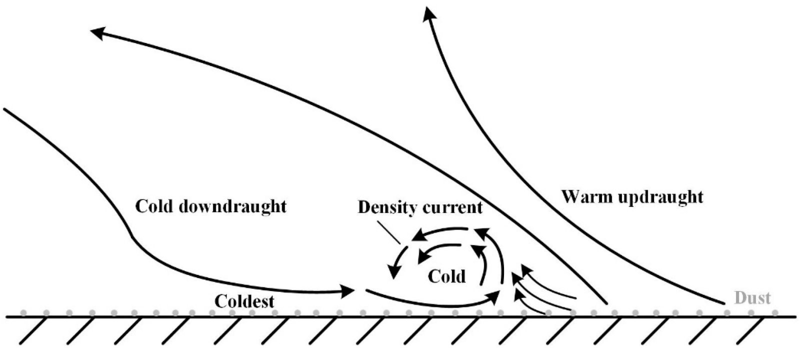

Figure 1. Schematic diagram of the front lobe of a dust storm. A downdraught of the cold air that spreads out along the ground and moves forward to form a density current pick up loose dust and sand from the surface. The dense cold air pushes up warmer air, which it meets, thereby reinforcing the warm up-draught (Modified from Idso, S.B. 1976, pp. 108–114).

Figure 2 depicts the morphological characteristics of the front edge of a LSS that occurred on 5 May 1993 in the northwestern China [31]. Similar to the entrainment mechanism of particles in the dust devils [29], the uprising dust particles from the ground were projected by the swirling air flow in the azimuthal area of swirling convective cells, forming a nose-like front, as illustrated in Figure 2a [31]. At the same time, particles in different sizes can be stratified under the helical up-draught of swirling convective cells [32]. The stratified dust particles exhibit the shallow and uneven layers of a LSS, as shown in Figure 2b. Fine particles are shown to concentrate in the upper layer (zones G and H in Figure 2b), medium size particles concentrated in the lower level (zones A and B), and coarse particles circulated near the ground. Due to different properties of light reflection and absorption according to particle sizes, the sand wall appeared in layers in different colors at the leading edge of a LSS, with the upper yellow layer of fine particles, the middle red layer of medium size particles and the lower grey-black layer of coarse particles occured near the ground [31]. In fact, the observation of LSS on 5 May 1993 showed that the dense sand wall was about 0.3 km high, while the dust layer was higher, about 0.7 km. Moreover, prior to the occurrence of a LSS, the warm air in the near-surface layer would became very unstable, and during the development stage, the sand inside the sand wall began tumbling. The weather process with a severe convection, produced the characteristics of a squall line [23][24].

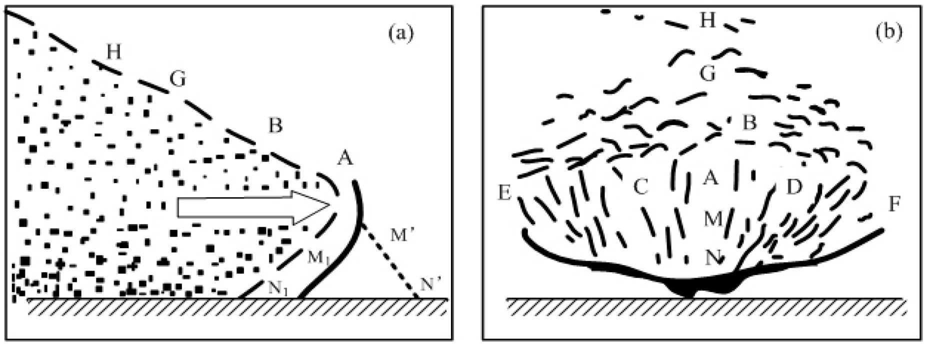

Figure 2. The front features of a LSS event. (**a**) Side view diagram. Due to the ground friction and other retardation, the wedged front of the cold air is not directly grounded like a dashed line AM'N', but is shaped like a nose (line BAMN) that folds backwards. A is the nose tip. (**b**) Main view diagram. The front view is the CD portion of the nose tip of the cold air, which is just a small segment of the curved cold air pushing forward. To the left and right sides to E and F, up to G and H, down to M and N, the dense sand edge and its inner rolling gradually become blurred. The uneven layers, deep or shallow, are caused by separated process of different sized dust particles (The Figure was reproduced from Lu, Q. and Yang, Y.L. 2001, p. 158).

The above analyses agree with the observations of a LSS. LSS is a motion of massive swirling convective cells, caused by the interaction of convective cells in the near-surface mixing layer with the upper cold air pool [33][34]. The triggering of a LSS is not only the full development of convective cells in the mixing layer, but also the transitioning of a mesoscale anticyclone with a certain vorticity (helicity) in the upper mixing layer. In particular, the horizontal movement of the anticyclone or the cold pool should be within a certain range to induce the transition of the simple honeycomb convective cell structure to the massive swirling convective cell structure. This produces larger and longer-lived downdraughts, which subsequently leads to cold air spreading over much larger areas. The cold airflows in LSS and haboobs have very similar structures as they both clearly display similar lobes, clefts, billows and nose structures.

3. Summary and Perspective

LSS and haboobs usually occur in the sand source areas or their marginal areas. Their basic features and characters could be drawn from conventional observation data and sometimes by mesoscale simulations. LSS and haboobs can occur throughout the year, but LSS are more common in dry season and haboobs are more common in the wet season. LSS and haboobs occur suddenly and locally in the afternoon or evening, in short duration. They can also cause a significant impact on the local atmospheric environment quality. The basic meteorological conditions include the convective cell flow in the near-surface mixing layer in desert regions or close to deserts. The transitioning of a mesoscale anticyclone or a cold air pool can occur over the desert. The squall line and the sand-blown process are distinctive characteristics of LSS and haboobs. The occurrence and evolution of thermal convection and convective cells in the desert area favor the occurrence of LSS and haboobs.

Much progress in model simulation has been made, such as the mesoscale convection-permitting simulations (3.75 km grid-spacing) of haboobs in the USA, the CFD simulations for microscale behaviors. The CFD simulation includes the LES simulation of haboobs induced by a cold-air pool and the RANS simulation of LSS induced by a cold-air pool. The CFD simulation for LSS showed that, after a large dust storm has fully developed, there are often many subsequent sub-vortices (secondary vortices) in its convection field. The distribution of wind velocity in these vortices is consistent with the “nose-like” shape of LSS. The subsequent sub-vortices can result in a quick dissipation of energy of LSS, which decay and retard the occurrence of the LSS. The simulation results are consistent with observations of the LSS, indicating the critical role of the invasion of the cold air pool in the upper layer and the formation of convective cell structure in the mixing layer. The following aspects need to be addressed in further studies, in order to deepen our understanding of the triggering mechanism and evolution of LSS and haboobs.

- Observations of meteorological factors in desert and marginal/periphery areas with high-resolution time-series are necessary to obtain the basic information relating to the evolution of LSS or haboobs.

- The development of mesoscale anticyclone or cold pool as the vorticity to trigger LSS or haboobs should be carefully investigated. The intensity and size of a cold pool vorticity usually determines whether convective cells in the mixing layer can develop into LSS or haboobs.

- Small scale, high-resolution CFD numerical simulations should be further developed to investigate the interaction of the upper cold pool with the deep mixing layer for the evolution of haboobs or LSS that cause an up-draught of the air. The simulation of wind-blown gas-solid two-phase flows further supplement our understanding of the uplifting of sand particles by LSS or haboobs and rapid energy dissipation.

- Appropriate numerical simulation analysis method is necessary to determine the dynamic evolution of the downdraught of a cold pool acting with convective cells in the mixing layers. This provides useful information to analyze the transformation of simple thermal convective cells to massive swirling convective cells. The numerical simulation analysis also provides the statistical diagnosis of parameters in the low-pressure zone for the formation of swirling convective structure and the uplifting of sand.

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