A numerical study on steam devils in a moist convective mixed layer

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1. Introduction

When cold continental air breaks out over a relatively warm sea or lake in winter, a cumulus-topped moist convective mixed layer develops downstream. Microscale columnar vortices called steam devils are known to occur frequently near the water surface in the mixed layer, where they are made visible by steam fog. They can extend from the water surface to an overlying cumulus cloudbase. Although they are believed to be close cousins of dust devils which occur in a convective mixed layer during daytime over land, their characteristics have not been well understood because of difficulties in an observation over waters during cold outbreaks. This study aims at investigating the characteristics of steam devils by means of a large eddy simulation (LES).

2. Model and Experimental Settings

Advanced Research WRF (ARW) Version 3.1 (Skamarock et al., 2008) is used for the present study. The calculation domain is laterally doubly-periodic. The boundary condition at the top of the domain is free-slip. A bulk method is used to obtain sensible and latent heat fluxes and momentum flux near the water surface. A subgrid-scale turbulent mixing is modeled by Smagorinsky's scheme. Fourth and second order advection schemes are used in the horizontal and vertical directions, respectively. The initial basic atmosphere is stratified with temperature lapse rate of 4 K/km with the air temperature at the lowest level being ΔT colder than the fixed water surface temperature T_0, and has uniform relative humidity of 50% and a uniform general wind of 10 m/s. As time elapses, the atmosphere is heated by the relatively warm water surface, leading to a development of a moist convective mixed layer. Colioris force and radiation are not considered.

Results of two experiments with different settings are shown in the following section. The first experiment (Exp1) considers somewhat warmer environment than a typical one for cold air outbreaks (CAO) events: T_0=290 K, ΔT=10 K and Kessler-type warm-rain microphysics is used for a calculation domain of 12.8 km wide and 2.9 km deep with nearly 50 m resolution. The other experiment (Exp2) considers a typical CAO condition: T_0=275 K, ΔT=20 K and WSM6 cold-rain microphysics (Hon and Lim, 2006) is used for a calculation domain of 6.4 km wide and 2.9 km deep with nearly 25 m resolution.

3. Results and Discussion

Exp1 successfully reproduces vortices similar to steam devils, though steam fog visualizing the vortices is not reproduced. They have very similar features observed by Lyons and Pease (1972): Strong vortices are located in an updraft region around vertices of convective cells and extend toward non-precipitating cumuli above. These features are similar to those of dust devils except that the latter is not necessarily accompanied by cumuli. The structure of the subcloud layer (SCL) is much similar to a dry convective mixed layer except that the convection in the SCL extends into the conditionally unstable cloud layer, which is in good agreement with the results of previous simulation studies on moist convective mixed layers (Siebesma et al., 2003). A stable layer around the cloud base appears to prevent steam devils for penetrating into cumuli in the cloud layer.

Exp2 reproduces stronger steam devils than those in Exp1. This is not only due to the effects of improved resolution and larger temperature difference between the water surface and the air but also due to precipitation which is absent in Exp1. Once precipitation is initiated, cold downdrafts originated from precipitating cumuli spread over the surface and modify the convective pattern there. This leads to locally increase horizontal wind shear and convergence near the surface, both strengthening vortices in the updraft regions.

Two representative vortices in Exp2 are examined in detail: the first one develops during an initial development phase of new convective clouds at a convergence line where cold outflows from longitudinal convective clouds meet. This vortex experiences a transition from a one-cell vortex to a two-cell vortex. The second one is located at a vertex of cellular convection, and develops when a precipitation-induced cold outflow reaches the vertex while strengthening the convergence. This vortex and associated updraft are connected to the cloud base, and extend deeply into the convective cloud.

4. Summary and Conclusion

Steam devils which develop in moist convective boundary layers over relatively warm water during a cold air outbreak are reproduced by a large-eddy simulation model, and their characteristics, formation process and environment are studied. In a non-precipitating case, simulated vortices resembling steam devils are similar to dust devils and are associated with cellular convection in the subcloud layer. Some of the features of simulated steam devils exhibit a good agreement with observations. In a precipitating case, cold downdrafts from precipitating cumuli apparently cause stronger vortices by strengthening local horizontal wind shear and convergence near the surface.

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