Atmospheric Research 182 (2016) 335–345

Contents lists available at ScienceDirect

Atmospheric Research

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

Response of rainfall to land surface properties under weak wind shear conditions

Yuya Baba

Application Laboratory, Japan Agency for Marine-Earth Science and Technology, 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 14 July 2016
Accepted 11 August 2016
Available online 16 August 2016

Keywords:
Rainfall
Land surface properties
Convective structure

ABSTRACT

Responses of rainfall trends to land surface properties (roughness length and sensible heat flux) under weak wind shear conditions were investigated by numerical simulation and idealized experiments. The results show that total amount, spatial pattern and intensity of rainfall were highly affected by the difference in sensible heat flux rather than the difference in roughness length. The initiation time for occurrence of rainfall became more delayed and the rainfall intensified as the given sensible heat flux decreased. A smaller sensible heat flux and a larger roughness length increased the convective available potential energy before the rainfall occurrence, resulting in stronger initial convection. The initiation processes affected the resulting convective structure, such that initial latent heat release occurred and remained downstream, leading to a widely spread convective structure above the cold pool. Spread and connected convection magnified the upright structure, thereby causing release of much more latent heat for ice water species and thus stronger rainfall intensity.

1. Introduction

Rainfall trends change according to land surface properties such as roughness length, sensible (and latent) heat flux when the topographical gradient is small, especially over in-land urban area. Observational studies have indicated that the existence of urban area influences rainfall trends (e.g., Jauregui and Romales, 1996; Bornstein and Lin, 2000; Shephered et al., 2002; Diem and Mote, 2005). Results of numerical studies also suggest that urbanization can cause rainfall to increase (e.g., Thielen et al., 2000; Baik et al., 2001; Rozoff et al., 2003; Han and Baik, 2008; Miao et al., 2011). However, some studies have shown the contrary, that is, urbanization does not cause an increase in rainfall, thus, there are still uncertainties regarding the effect of surface properties on rainfall patterns (Dabberdt et al., 2000; Kanae et al., 2004).

Variation of land surface properties affects rainfall trends through the surface fluxes, with their effects tending to vary with the conditions. Numerical simulations have revealed the sensitivity of rainfall to factors related to land surface properties. Thielen et al. (2000) noted that sensible heat flux (SHF) has a significant impact on rainfall change. Han and Baik (2008) investigated initiation of convection due to thermal forcing mimicking urban heat island effect, and simulated different response of rainfall to the different forcing. Miao et al. (2011) reported that rainfall increase mainly derives from SHF and latent heat flux rather than from momentum flux. These studies indicate that thermal forcing from the land surface is more important for generating convection than the momentum flux. However, an effect of nonlinear interaction between thermal and momentum fluxes on rainfall has been recognized (Rozoff et al., 2003), thus the effect of momentum flux (which derives from roughness of land surface) on rainfall cannot be negligible.

Another important factor affecting rainfall trends that is related to surface flux is the wind profile of atmospheric condition. Differences in wind shear are known to alter convective activity and structure, resulting in different rainfall trends (e.g., Weisman et al., 1988; Fovell and Ogura, 1989; Ferrier et al., 1996; Weisman and Rotunno, 2004). Findings of studies on the sensitivity of convection to wind shear indicate that wind profile can affect rainfall trends induced by land surface properties. In particular, weak wind shear or weak wind speed has been observed in events of strong rainfall intensity (e.g., Bornstein and Lin, 2000; Kim et al., 2012). Therefore, the mechanism of convection formation under such condition and the sensitivity to the land surface properties need further study to understand in-land heavy rainfall.

The purpose of this study is to examine the response of rainfall trends to land surface properties under weak wind shear conditions using numerical simulation and idealized experiments. The analysis

E-mail address: babay@jamstec.go.jp (Y. Baba).

http://dx.doi.org/10.1016/j.atmosres.2016.08.010
0169-8095/

focuses on detailed initiation and transition processes of convection in terms of rainfall intensity induced by land surface properties. For simplicity, orography is not considered; thus, the orographic effect on rainfall is not discussed in this paper. In order to simplify the effect of land surface properties including urban area on rainfall, the model uses prescribed roughness lengths and SHFs. In Section 2, details of numerical experiments are described. In Section 3, an overview of rainfall trends is presented, and the initiation of rainfall is investigated. The convective structure of subsequent convection and its transition process are then discussed. Section 4 gives a summary and provides the conclusions of the study.

2. Numerical experiments

In this study, the response of rainfall is investigated by using presumed land surface properties. The surface roughness length (SRL) condition is given by using a Gaussian function,

$$z_0(x) = z_m e^{-x^2/a^2} + z_o \quad (1)$$

where $z_0(x)$ is the SRL for momentum surface flux; it is a function of x, the horizontal coordinate, z_m is the maximum SRL, and a ($= 25$ km) is the half width of the region of increased roughness length. The value of a approximates urban width of 50 km (e.g., Rozoff et al., 2003; Miao et al., 2011). z_o ($= 1 \times 10^{-2}$ m) is the background roughness length. The sensible heat flux (SHF) condition is also described by a similar Gaussian function,

$$F = Q_H e^{-x^2/a^2}, \quad (2)$$

where Q_H is the constant SHF. Here, the latent heat flux is set to zero, since the effect is known to have less significance on rainfall change than SHF when the atmospheric condition is moist (Thielen et al., 2000). Some studies showed that the existence of urban results in decreasing latent heat flux and modifying location of rainfall (e.g., Rozoff et al., 2003; Miao et al., 2011), however, the effect is considered not to contribute to rainfall intensity directly and thus is omitted for simplicity.

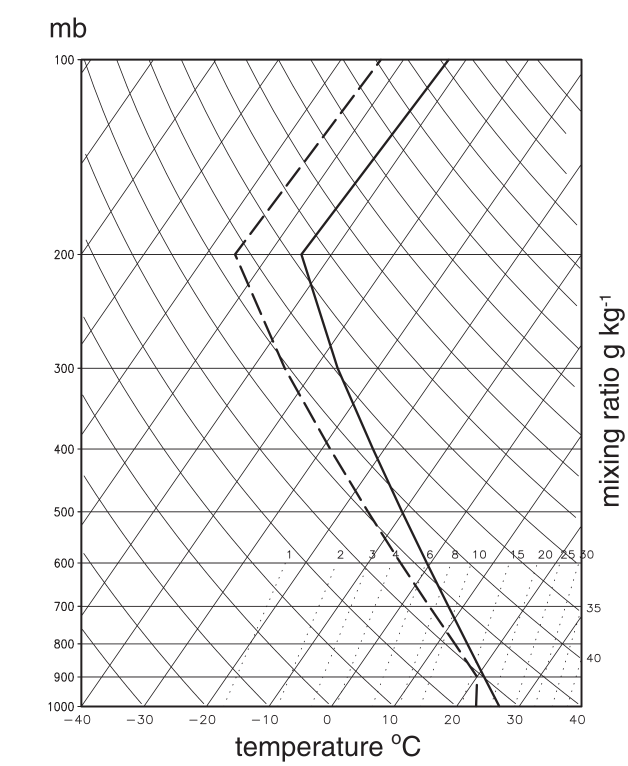

Fig. 1. Skew-T lop-P plot of the initial meteorological condition. Solid and dashed lines represent temperature and dew point temperature, respectively.

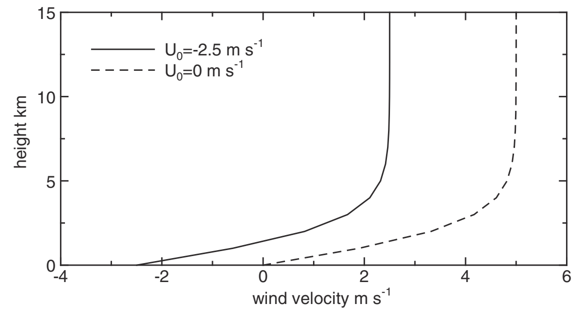

Fig. 2. Vertical profile of the initial wind velocity. Solid line: initial wind profile in the present study; dashed line: original wind profile.

The present experimental setup for the meteorological condition is based on a study by Weisman and Klemp (1982). The skew-T log-P plot of this condition is shown in Fig. 1. In their study, low-level maximum water vapor mixing ratio q_{v0} is limited to a certain value to represent boundary layer. This value is set to 18 g kg^{-1} in the present study in order to initiate convection within the duration of time integration (the resulting convective available potential energy (CAPE) is approximately 3000 J kg^{-1}). The horizontal westerly wind velocity U from the study of Weisman and Klemp (1982) is modified as follows:

$$U(z) = U_s \tanh\left(\frac{z}{z_s}\right) + U_0, \quad (3)$$

where U_s is the maximum wind velocity (set to 5 m s^{-1}), U_0 is the background wind velocity (set to -2.5 m s^{-1}), z is the vertical coordinate, and $z_s = 2.5$ km. The present wind profile is set to mimic the typical vertical wind profile of weak-shear-wind profile obtained from observation, the wind direction is skewed between 2.5 km height and the ground surface (e.g., Houston and Wilhelmson, 2011; Kim et al., 2012) (Fig. 2).

The values of parameters considered in the present study are summarized in Table 1. The SRL and SHF are varied to examine their effect on the rainfall trends. Values of z_m in Table 1 (ranged from 10 to 20 m) are adopted from the study of Nakayama et al. (2011), and values of Q_H (ranged from 100 to 400 W m^{-2}) are based on observational values (Grimmond and Oke, 2002).

An atmospheric model (Baba and Takahashi, 2014) is used with different numerical setup in the present study. For simplicity, a two-dimensional computational domain is utilized. The maximum domain height is 20 km with non-uniform vertical 46 layers and the horizontal size is 2000 km at 2 km grid spacing. Here, a resolution lower than that used by Baba and Takahashi (2014) is chosen because the domain size and time integration need to be expanded. The horizontal sponge region is set such that open boundary conditions are applied to the horizontal direction. Rayleigh damping is applied to the upper 15 km region in order to avoid reflection of gravity waves. The top boundary condition is slip condition, and the surface flux for momentum based on the model of Louis (1979),

Table 1
Summary of parameters for the condition of land surface properties. z_m: maximum surface roughness length; Q_H: maximum sensible heat flux.

Parameter (unit)	Values
z_m (m)	10, 20
Q_H (W m^{-2})	100, 200, 300, 400