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Research Paper

Impacts of air–sea exchange coefficients on snowfall events over the Korean Peninsula

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ABSTRACT

Snowfall over the Korean Peninsula is mainly associated with air mass transformation by the fluxes across the air–sea interface during cold-air outbreaks over the warm Yellow Sea. The heat and momentum exchange coefficients in the surface flux parameterization are key parameters of flux calculations across the air–sea interface. This study investigates the effects of the air–sea exchange coefficients on the simulations of snowfall events over the Korean Peninsula using the Weather Research and Forecasting (WRF) model. Two snowfall cases are selected for this study. One is a heavy snowfall event that took place on January 4, 2010, and the other is a light snowfall event that occurred on December 23–24, 2011.

Several sensitivity tests are carried out with increased and decreased heat and momentum exchange coefficients. The domain-averaged precipitation is increased (decreased) with increased (decreased) heat exchange coefficient because the increased (decreased) surface heat flux leads to more (less) moist conditions in the low level of the atmosphere. On the other hand, the domain-averaged precipitation is decreased (increased) with increased (decreased) momentum exchange coefficient because the increased (decreased) momentum coefficient causes reduction (increase) of wind speed and heat flux. The variation of precipitation in the heat exchange coefficient experiments is much larger than that in the momentum exchange coefficient experiments because the change of heat flux has a more direct impact on moisture flux and snowfall amount, while the change of momentum flux has a rather indirect impact via wind speed changes. The low-pressure system is intensified and moves toward North when the heat exchange coefficient is increased because warming and moistening of the lower atmosphere contributes to destabilize the air mass, resulting in the change of precipitation pattern over the Korean Peninsula in the heat exchange coefficient experiments.

1. Introduction

The atmosphere and the ocean are closely linked by the transfer of heat, moisture, and momentum from one to the other. All these transport processes modify the properties of the atmosphere by fluxes of momentum and heat across the air–sea interface. Therefore, surface fluxes are important ingredients of numerical weather prediction models in simulating the atmospheric phenomena related to air–sea interactions.

The surface fluxes are parameterized in numerical weather prediction models because they cannot be directly resolved. Most of the surface flux parameterizations use a bulk method based on the Monin–Obukhov similarity theory. In the bulk formulation, the heat and momentum exchange coefficients are one of the key parameters of flux calculations. Although many parameterizations of these exchange coefficients have been developed, the exchange coefficients over the ocean are still largely unknown, especially in strong wind conditions (e.g., Bell, 2010; Green and Zhang, 2013). There have been many sensitivity studies using numerical models to examine the effects of the exchange coefficients focusing on the intensity and structure of tropical cyclones (e.g., Bryan, 2012; Green and Zhang, 2013). For the heavy rain events in the Mediterranean Basin, some sensitivity studies regarding the air–sea interactions were performed (Lebeaupin et al., 2006, 2008, Berthou et al., 2015).

Beside the tropical cyclones and the torrential rain events, few studies have been conducted regarding the impacts of the air–sea interactions on other major weather events. Snowfalls are one of those atmospheric phenomena influenced by air–sea exchange coefficients when the properties of the air mass are changed by obtaining heat and moisture from the ocean. Cheong et al. (2006) classified snowfalls over the Korean Peninsula using synoptic weather charts, satellite images, and precipitation data into five

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categories; they reported that the air mass transformation during cold-air outbreaks over the warm Yellow Sea is the most frequent type of snowfall event. Despite the importance of the air–sea interactions on snowfall over the Korean Peninsula, there have not been many sensitivity studies conducted using a numerical model in order to quantify the impacts of air–sea interactions.

In this study, the effects of exchange coefficients on the simulation of snowfall events over the Korean Peninsula are investigated by air–sea exchange coefficient sensitivity experiments. Two snowfall cases are selected for the experiments, and the heat and momentum exchange coefficients are increased or decreased. We focus more upon the response of the atmosphere and the snowfall phenomena to the change of air–sea exchange coefficients to understand the physical processes, rather than finding better air–sea exchange coefficients. In Section 2, the settings for the sensitivity experiments of the exchange coefficients, case selection, and experimental setups are discussed. The simulation results for the snowfall events and the comparisons among the sensitivity experiments are presented in Section 3. The summary and discussion of this paper are provided in Section 4.

2. Methodology

2.1. Modification of air–sea exchange coefficients, C_H and C_D

The fluxes of momentum, τ, and sensible heat, SH, can be written as

$$\tau = -\rho C_D U^2 \text{ and} \tag{1}$$

$$SH = \rho c_p C_H U \Delta\theta, \tag{2}$$

respectively, where ρ is air density; U is wind speed at a reference height, z_1; c_p is the specific heat capacity; $\Delta\theta$ is temperature difference between the surface and a reference height ($\theta_{sfc}-\theta_{z_1}$); and C_D and C_H are bulk exchange coefficients for momentum and heat, respectively. The bulk exchange coefficients can be expressed as below by the Monin–Obukhov similarity theory

$$C_D = \frac{k}{ln\left(\frac{z_1}{z_0}\right)-\psi_m\left(\frac{z_1}{L}\right)} \times \frac{k}{ln\left(\frac{z_1}{z_0}\right)-\psi_m\left(\frac{z_1}{L}\right)} \text{ and} \tag{3}$$

$$C_H = \frac{k}{ln\left(\frac{z_1}{z_0}\right)-\psi_m\left(\frac{z_1}{L}\right)} \times \frac{k}{ln\left(\frac{z_1}{z_T}\right)-\psi_h\left(\frac{z_1}{L}\right)}, \tag{4}$$

where k is the von Kármán constant, and z_0 and z_T are momentum roughness length and thermal roughness length, respectively. The stability correction functions for momentum and heat are ψ_m and ψ_h, respectively, which become zero under neutral conditions, and L is the Obukhov length scale.

In this study, the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), version 3.6.1, is used for the sensitivity tests of air–sea exchange coefficients. For the surface layer parameterization, the revised MM5 surface layer scheme (option 1 in WRF version 3.6) (Jiménez et al., 2012) is used. The momentum roughness length z_0 is based upon Charnock (1955), and the thermal roughness length z_T is set equal to z_0 (isftcflx=0, default option). The exchange coefficients of sensible and latent heat, C_H and C_Q are set to identical as in most surface layer schemes. In order to examine the sensitivity of air–sea exchange coefficients, the heat and momentum exchange coefficients over the ocean are increased or decreased, and the simulation results are compared with those of the original exchange coefficients.

The sensitivity tests for the heat exchange coefficients are designed as follows. As seen in Eq. (4), the heat exchange coefficient is a function of momentum and thermal roughness lengths, and stability function. In order to see the sensitivity of heat exchange coefficient only, it is necessary that the change of heat exchange coefficient does not alter the momentum exchange coefficient. If user-specified heat exchange coefficient (explained below) with the original momentum roughness length is prescribed and the neutral condition is assumed, the thermal roughness length only becomes unknown in Eq. (4). Then, the thermal roughness length for various sensitivity tests can be obtained by solving Eq. (4). Once the thermal roughness length is determined, the heat exchange coefficient can be finally obtained with the stability function by removing the neutral assumption.

For the sensitivity tests of the heat exchange coefficient, C_H, a simple linear relationship between the lowest model level wind speed (U) and C_H over the ocean is obtained from the control run (CHctl) using a linear regression method (Eq. (5)).

$$\text{CHctl: } C_H = 4.\,0e^{-5} \times U + 0.\,0009. \tag{5}$$

Using this linear equation, C_H is increased (CHup) and decreased (CHdn) by changing the y-intercept of the equation for the ocean as in Eqs. (6) and (7).

$$\text{CHup: } C_H = 4.\,0e^{-5} \times U + 0.\,0018 \tag{6}$$

$$\text{CHdn: } C_H = 4.\,0e^{-5} \times U \tag{7}$$

The momentum exchange coefficient C_D is changed in a similar manner to that of C_H. A simple linear relationship between the lowest model level wind speed (U) and C_D over the ocean is obtained from the control run (CDctl) as below:

$$\text{CDctl: } C_D = 4.\,0e^{-5} \times U + 0.\,0008. \tag{8}$$

Because C_D and C_H profiles are the same in the control simulation, Eq. (8) has the same form of Eq. (5). Increased and decreased C_D (CDup and CDdn, respectively) equations are defined as follows:

$$\text{CDup: } C_D = 4.\,0e^{-5} \times U + 0.\,0016 \text{ and} \tag{9}$$

$$\text{CDdn: } C_D = 4.\,0e^{-5} \times U \tag{10}$$

The z_0 can be obtained using the Eqs. (3), (9) and (10) under neutral conditions since z_0 will be the only unknown when C_D is given and neutral conditions set. In order to investigate the sensitivity of momentum exchange coefficient, the heat exchange coefficient is as invariant as possible when C_D varies. Thus, one extra step is taken to take care of keeping constant C_H in the sensitivity tests, which is solving z_T in Eq. (4) by using predefined default C_H (Eq. (5)) and z_0 obtained from the previous steps under neutral conditions. The C_D and C_H profiles over the ocean for the sensitivity tests are shown in Fig. 1. For the heat exchange coefficient experiments (Fig. 1(a) and (b)), C_H shows large difference as designed, while C_D values are similar for CHctl, CHup, and CHdn experiments. For the drag exchange coefficient experiments (Fig. 1(c) and (d)), although we set the C_H unchanged for neutral conditions, C_H values are somewhat different from each other for CDctl, CDup, and CDdn experiments because of the stability correction functions. The stability correction functions tend to diverge when the wind speed is low, resulting in spread C_H values especially for low wind speed conditions.

2.2. Case selection and model configuration

Two snowfall events are selected in this study: a heavy snowfall event and a light snowfall event. The heavy snowfall occurred