The Performance of a Revised Simplified Arakawa–Schubert (SAS) Convection Scheme in the Medium-Range Forecasts of the Korean Integrated Model (KIM)

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ABSTRACT

The Korea Institute of Atmospheric Prediction Systems (KIAPS) has developed a new global numerical weather prediction model, named the Korean Integrated Model (KIM). This paper presents the cumulus parameterization scheme (CPS) used in KIM, which originates from the simplified Arakawa–Schubert (SAS) convection scheme in the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) and has undergone numerous modifications in an effort to improve the medium-range forecast skill for precipitation and large-scale fields. The modifications include the following: 1) the threshold of the trigger condition is updated to consider the dependency on the environmental relative humidity (RH) averaged over the subcloud layer in order to suppress the trigger of convection in dry low-level environments; 2) the entrainment rate is modified to increase the sensitivity to environmental humidity, so that enhanced entrainment under lower RH conditions leads to a greater decrease in the strength of the convection that develops in drier environments; 3) the autoconversion parameter from cloud condensate to convective precipitation is changed to have a temperature dependency above the freezing level; 4) the closure is modified to consider rapidly varying boundary layer forcing; 5) the effect of the convection-induced pressure gradient force in convective momentum transport is enhanced in the upper part of the convective updrafts; and 6) scale awareness that enables a mass-flux CPS to work seamlessly at various grid sizes across gray-zone resolutions is addressed. The evaluation of medium-range forecasts with the KIM CPS reveals higher forecast skill, especially over the tropics, in comparison with its original version.

1. Introduction

Cumulus convection significantly influences the large-scale atmospheric circulation through latent heat release, vertical transports of heat, moisture, and momentum, and interaction with radiation (Tiedtke 1988).

However, most global atmospheric models for weather forecasts and climate predictions have horizontal grid spacing greater than the horizontal scale of cumulus convection; consequently, the effect of subgrid-scale convection on the large-scale flow should be parameterized. Numerous studies have demonstrated that significantly improved weather forecasting and climate simulation can be achieved through the improvement of cumulus parameterization (e.g., Han and Pan 2011; Bechtold et al. 2014; Freitas et al. 2018).

The Korea Institute of Atmospheric Prediction Systems (KIAPS) launched a 9-yr project in 2011 to develop a next-generation numerical weather prediction

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system [Korean Integrated Model (KIM); [Hong et al. \(2018\)](#)], with the ultimate goal of replacing the Korea Meteorological Administration (KMA) operational Unified Model (UM) imported from the Met Office. To better represent the thermodynamic and dynamic effects of subgrid-scale moist convection on the large-scale environment, the cumulus parameterization scheme (CPS) in KIM, named the KSAS, has also been developed. The KSAS originates from the simplified Arakawa–Schubert (SAS) convection scheme in the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) ([Han and Pan 2011](#)), and numerous revisions to the representation of the subgrid-scale convective properties are made to improve the forecast skill of the numerical weather prediction model in predicting precipitation and large-scale fields.

The original SAS scheme was developed by [Grell \(1993\)](#) by simplifying the [Arakawa and Schubert \(1974\)](#) convection scheme to consider only a single cloud type at each grid point, rather than the entire spectrum of cloud types, and including the effects of the moist convective-scale downdraft. It employs a bulk mass-flux approach that parameterizes an ensemble of cumulus clouds with different properties as a single bulk entraining/detraining plume in terms of the cloud mass flux under the assumption that it is in quasi-equilibrium with the large-scale forcing. The SAS scheme became an operational CPS in the NCEP Medium-Range Forecast Model in 1993 ([Pan and Wu 1995](#)). Since then, many subsequent modifications have been made, for example, to make the cumulus convection stronger and deeper to suppress unrealistically excessive precipitation at the grid scale, the so-called gridpoint storms, in the NCEP GFS ([Han and Pan 2011](#)) and to produce less parameterized precipitation with a finer grid space using the Weather Research and Forecasting (WRF) Model ([Lim et al. 2014](#)). This version of the GFS SAS scheme (NSAS), which has been available in the WRF Model since version 3.6 released in April 2014, was implemented in KIM in July 2015.

A large number of issues have been raised in KIM, which relate to the CPS, including excessive light precipitation, less incoming solar radiation over the tropical oceans, earlier timing of the afternoon peak in precipitation over land, and negative wind speed bias in the tropical upper troposphere. These biases were alleviated through a moisture-based trigger threshold and enhanced entrainment in drier environments, revised autoconversion from cloud condensate to convective precipitation, closure considering boundary layer forcing, and revision of convective momentum transport, respectively. Also, scale-aware capability is introduced in the KIM CPS. Information about upgrades in KIM

including the KSAS is provided in appendix A1 of [Hong et al. \(2018\)](#). The impacts of each revision on model performance were extensively assessed before each model upgrade (e.g., [Han et al. 2016](#); [Kwon and Hong 2017](#); [Han and Hong 2018](#)). However, combined effects of all the revisions in the CPS have never been examined previously and, therefore, are of particular interest to this study.

In this study, the KIM version of the SAS scheme developed by the KIAPS (KSAS; [Han et al. 2016](#); [Kwon and Hong 2017](#); [Han and Hong 2018](#)) is introduced, and the impact of its updates on the medium-range forecast skill are investigated in comparison with its original version (NSAS; [Han and Pan 2011](#); [Lim et al. 2014](#)). A more detailed explanation of each modification, including the background of its adoption and how biases in the KIM are alleviated via the modification, are presented in [section 2](#). The experimental setup and the combined effects of all the modifications are described in [sections 3](#) and [4](#), respectively. A summary and conclusions are given in [section 5](#).

2. KIM cumulus parameterization (KSAS)

[Table 1](#) summarizes the comparison of the KSAS and NSAS. More details of each modification and its main effect are described in the following subsections.

a. Moisture-based trigger threshold

In the SAS scheme, a parcel lifted from the updraft-originating level must reach its level of free convection (LFC) within a critical depth for convection to occur. In the original scheme, the critical depth is determined in proportion to the large-scale vertical velocity at the cloud base to produce more convection in large-scale convergent regions ([Han and Pan 2011](#)). Meanwhile, in the KSAS scheme, the trigger threshold is modified to be proportional to the environmental relative humidity (RH) averaged over the subcloud layer from the updraft-originating level to the cloud base, considering the observations that the low-level humidity increases ahead of the development of deep convection (e.g., [Kemball-Cook and Weare 2001](#); [Kikuchi and Takayabu 2004](#)) and that the formation of deep cumulus convection is inhibited over the subtropical high due to the dryness of the lower free atmosphere despite the strongly unstable thermodynamic stratification ([Emori et al. 2001](#)). With this modification, the trigger of convection is suppressed in dry low-level environments, leading to the alleviation of the systematic bias of excessive light precipitation in KIM, as shown in [Fig. 1](#). This change also results in an increase in heavier rainfall and,

TABLE 1. Summary of comparison of the KSAS (Han et al. 2016; Kwon and Hong 2017; Han and Hong 2018) and NSAS (Han and Pan 2011; Lim et al. 2014). The + sign (in the KSAS fields for entrainment rate and closure) indicates additional parameters considered by KSAS in addition to that in NSAS.

	NSAS	KSAS
Threshold for trigger condition between updraft-originating level and LFC	Dependent on the large-scale vertical velocity at the cloud base (Han and Pan 2011)	Dependent on the environmental RH averaged over the subcloud layer
Entrainment rate	Dependent on environmental RH (Bechtold et al. 2008; Han and Pan 2011)	+ Increased sensitivity to environmental RH
Autoconversion parameter	Constant with height	Exponential decrease with decreasing temperature above the freezing level (Han et al. 2016)
Closure	Using a quasi-equilibrium assumption (Arakawa and Schubert 1974)	+ Boundary layer forcing is considered
Parameter for convection-induced PGF	Constant with height (Han and Pan 2011)	Larger negative values in the upper part of the convective updrafts
Scale awareness	Trigger and convective mass flux dependent on the horizontal resolution (Lim et al. 2014)	Trigger, convective mass flux, and detrained convective cloud water dependent on the convective updraft fraction (Kwon and Hong 2017; Han and Hong 2018)

therefore, a reduction in the bias of underestimation of heavy precipitation.

b. Enhanced entrainment under lower RH conditions

Based on several studies that highlight the important role of environmental moisture in controlling not only the occurrence but also the intensity of convection, the entrainment rate is also modified to increase the sensitivity to environmental humidity. In the SAS scheme, following Bechtold et al. (2008), in which the explicit dependency of the entrainment rate on RH is considered, the entrainment rate above the cloud base is given by the sum of the turbulent entrainment, which is inversely proportional to the cloud-base height, and the organized entrainment, which increases with decreasing RH of the environment (Han and Pan 2011). We increase the dependency of the entrainment rate on the

environmental RH by increasing the organized entrainment 10 fold, so that enhanced entrainment under lower RH conditions leads to a greater decrease in the strength of the convection that develops in drier environments. This modification also causes a decrease in light precipitation, which alleviates the systematic bias of overestimation of rainfall in the light precipitation categories (Fig. 2).

c. Revised autoconversion

Whereas the original autoconversion parameter, which determines the fraction of condensate converted to convective precipitation, is assumed to be constant as in most convective microphysics parameterizations, the revised parameter takes the form of an exponential function of temperature above the freezing level, so that less frozen precipitating condensate is produced with

FIG. 1. (left) Bias score and (right) equitable threat score (ETS) for daily precipitation forecasts over the tropics against the Climate Prediction Center (CPC) unified gauge-based precipitation analysis for the 3-day forecast period during July 2013 from the control forecast (black) and the forecast with the revised trigger threshold (gray).

FIG. 2. (left) Bias score and (right) ETS for daily precipitation forecasts over the tropics against the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) observation for the 3-day forecast period during 1–10 Jul 2013 from the control forecast (black) and the forecast with revised entrainment rate (gray).

height as in the results from a cloud-resolving simulation (Lim 2011). Han et al. (2016) statistically evaluated the performance of the revised parameter with medium-range forecast experiments and found that this modification significantly improves precipitation forecasts by alleviating the systematic bias of excessive rain observed in the simulation with the original autoconversion. It is also found that the reduced convective heating and drying resulting from suppressed convection and the cooling and moistening due to enhanced moisture detrainment at the top of clouds considerably alleviate the warm and dry bias above the lower troposphere over the East Asia region. Using Climate Forecast System (CFS) version 2, Ganai et al. (2019) recently showed that the revised autoconversion provides an improved fidelity in simulating the mean Indian summer monsoon features as well. In the latest version of KIM, the exponential decaying rate b of the autoconversion parameter for convective precipitation is modified from 0.07° to 0.04°C^{-1} . The reduction of b (i.e., an increase in the autoconversion parameter) increases convective precipitation, whereas it decreases not only subgrid-scale condensate but also grid-scale condensate by suppressing moisture detrainment. This increases the solar radiation reaching the surface in the main convective regions, particularly over the tropical oceans, alleviating the bias of underestimated downward shortwave radiation flux at the ocean surface, which has been known as the systematic bias in KIM (Hong et al. 2018), as shown in Fig. 3. Note that subgrid-scale condensate is considered in the calculation of the effective radii and the cloud water path in the KIM radiation process (Bae and Park 2018).

d. Closure considering boundary layer forcing

The updraft mass flux at the cloud base is determined using a quasi-equilibrium assumption that the destabilization

of an air column by the large-scale atmosphere is nearly balanced by the stabilization by the convection (Arakawa and Schubert 1974). In other words, the cloud-scale stabilization effect depends on the mass flux, which is deduced from the large-scale destabilization effect. In the original scheme, the convective stabilization is achieved by adjusting the cloud work function toward a climatology that is derived from observation. The closure of the KSAS is devised to adjust the cloud-scale cloud work function toward a boundary layer forcing. In the KSAS, the boundary layer forcing to be responsible for the large-scale destabilization effect $(dA/dt)_{\text{LS}}$ is represented by the change in the boundary layer height between the current and previous time steps Δh :

$$\left(\frac{dA}{dt}\right)_{\text{LS}} = \frac{A - A_{\text{BL}}}{\tau_c}, \quad (1)$$

$$A_{\text{BL}} = \max\left(g\Delta h \frac{\tau_{\text{BL}}}{\Delta t}, 0\right), \quad (2)$$

where A is the cloud work function, which is a measure of the integrated cloud buoyancy; τ_c is the convective adjustment time scale, which is set equal to the convective turnover time scale; g is the gravitational constant; Δt is the model time step; and the subscript BL stands for boundary layer. The boundary layer time scale τ_{BL} is assumed to be equal to τ_c over land, while it is defined as $z_b/\bar{U}_{\text{BL}}$ over water, where z_b is the cloud-base height, and $\bar{U}_{\text{BL}}$ is the horizontal wind speed averaged over the subcloud layer. The revised closure follows the concept of the boundary layer–CPS equilibrium (Bechtold et al. 2014), in which the boundary layer forcing is proportional to the virtual temperature tendency integrated over the subcloud layer. The boundary layer forcing in Eqs. (1) and (2) plays a role in

FIG. 3. (a) Bias of the downward shortwave radiation flux at the surface (W m^{-2}) against the Clouds and the Earth's Radiant Energy System (CERES) observations from the control forecast and the differences in the (b) downward shortwave radiation fluxes at the surface and (c) root-mean-square errors (RMSEs) between the forecast with the revised exponential decaying rate of the autoconversion parameter for convective precipitation and the control forecast at forecast day 3 during July 2017.

FIG. 4. Mean diurnal variation of precipitation rate (mm h^{-1}) during July 2013 averaged over the East Asian land area from the TMPA observation (black), control forecast (blue), and the forecast with the closure considering boundary layer forcing (red).

leaving more fuel for severe convection at a later time. It is well known that intense convection occurs in the late afternoon or early evening when the boundary layer collapses. The revised closure improves the diurnal variation of precipitation over land by decreasing the bias of the overestimated precipitation in the morning and early afternoon and delaying the afternoon peak that tends to occur earlier than the observed one in most models (Fig. 4).

e. Revised convective momentum transport

The parameterization of convective momentum transport considered in the SAS scheme is designed to represent the effect of the convection-induced pressure gradient force (PGF), which tends to compensate for the vertical advection effect due to the convection-induced subsidence (Wu and Yanai 1994). In the original scheme, it is parameterized to be proportional to the environmental subsidence term with a negative proportionality constant of -0.55 (Han and Pan 2011). However, the cloud-resolving simulation results of Zhang and Wu (2003) show that the proportionality constant ranges from -0.3 to -0.7 , and its value in the upper troposphere (-0.4 to -0.7) is smaller than that in the lower troposphere (-0.3 to -0.5) (see their Fig. 9). So the proportionality parameter f_1 is modified in our scheme to have larger negative values in the upper part of the convective updrafts, thus leading to reduced convective momentum mixing in the upper troposphere:

$$f_1 = a\{1 + \exp[b(z - z_t)/z_t]\}, \quad (3)$$

where z_t is the cloud-top height, and a and b are constants with values of -0.5 and 3 , respectively. By using

the revised proportionality parameter, less effective momentum mixing in the upper part of the convective updrafts decreases the positive tendency of zonal wind due to the convection in the tropical upper troposphere, which makes upper-level easterlies in the tropics stronger, resulting in the alleviation of the negative wind speed bias in the tropical upper troposphere (Fig. 5).

f. Scale-aware CPS

Several modifications are introduced to make the CPS valid at various resolutions across the gray zone (Kwon and Hong 2017). The scale dependencies of the threshold of the trigger condition, the magnitude of the updraft mass flux at the cloud base, and the amount of convective cloud water detrained into grid-scale condensate are considered by modifying them to be functions of the convective updraft fraction. As a result, the triggering and strength of convection are suppressed and the detraining of convective cloud water is enhanced when the model resolution becomes finer. Kwon and Hong (2017) performed a high-resolution experiment using the WRF Model with the scale-aware CPS and demonstrated its ability to reproduce a well-organized precipitation core for a heavy rainfall event over South Korea. Recently, the skill of the scale-aware CPS at gray-zone resolutions is statistically evaluated with a focus on the quantitative precipitation forecast (e.g., Han and Hong 2018). The skill for light precipitation is much better with the scale-aware CPS than that for the conventional setup without CPS; however, the systematic bias of underestimated heavy rain leads to a lower score for the heavy precipitation categories. To alleviate this problem, the threshold of the trigger condition was further modified to increase the sensitivity to the convective updraft fraction, so that the suppression of the triggering of convection at higher resolution less than 10 km becomes more significant (not shown). The original threshold for the trigger condition of pressure difference between the updraft-originating level and its LFC is in the range of 120RH–180RH hPa, which decreases linearly with increasing the convective updraft fraction, while the modified one varies in the range of 0–180RH hPa with which no subgrid-scale convection is triggered when the convective updraft fraction reaches one.

3. Model and experimental setup

The global atmospheric model used in this study is KIM (Hong et al. 2018), which solves the nonhydrostatic governing equations using the spectral-element method for horizontal discretization and the finite-difference method for vertical discretization on a cubed-sphere

FIG. 5. (a) Difference in 100-hPa wind speed (m s^{-1}) computed against the NCEP final analysis (FNL) data from the control forecast and the differences in (b) 100-hPa wind speed and (c) RMSEs between the forecast with the revised convective momentum transport and the control forecast at forecast day 3 for February 2013.

grid (Choi et al. 2014; Choi and Hong 2016). The KIM physics package includes radiation (Baek 2017), land surface (Koo et al. 2017, 2018), ocean surface (Lee and Hong 2019), vertical diffusion (Shin and Hong 2015; Lee et al. 2018), subgrid-scale orographic (Choi and Hong

2015) and nonorographic drag (Choi et al. 2018), microphysics (Bae et al. 2016; Kim and Hong 2018), cloudiness (Park et al. 2016), and deep (KSAS; Han et al. 2016; Kwon and Hong 2017; Han and Hong 2018) and shallow (Han and Pan 2011) convection schemes. The model has 91 vertical levels and a model top at 0.01 hPa (approximately 80 km). A detailed description of the model can be found in Hong et al. (2018).

To evaluate the performance of the KSAS described in section 2, the WRF version of the GFS SAS scheme (NSAS; Han and Pan 2011; Lim et al. 2014) is implemented in KIM, and its skill is compared with the KSAS. For statistical evaluation of the medium-range forecasts, 31 10-day forecast experiments starting at every 0000 UTC during July and January 2017, for boreal summer and winter, respectively, are performed at a horizontal resolution of approximately 25 km (NE180NP3). The initial atmospheric and surface boundary conditions are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) new reanalysis product, ERA5, and the NCEP GFS analysis, respectively.

4. Results and discussion

a. Large-scale features

Figure 6 shows the time evolution of the vertical profiles of the biases and root-mean-square errors (RMSEs) of temperature, geopotential height, specific humidity, and wind speed against the radiosonde data during the period of July 2017, averaged over the tropics (20°S–20°N), from the NSAS and KSAS experiments. The NSAS experiment exhibits a cold bias in the troposphere, especially near 200–500, 600–750, and 925 hPa (Fig. 6a), and, therefore, an overall negative bias in geopotential height, which increases with height (Fig. 6b). A wet bias appears above 750 hPa, whereas a dry bias is observed below the level, especially near 850 hPa and in the near-surface layer (Fig. 6c). There exists a negative wind speed bias in the stratosphere and upper troposphere above 200 hPa, while a positive wind speed bias appears below the level, centered near 250 hPa, and it becomes more significant with forecast time (Fig. 6d).

Contrary to the NSAS temperature bias, the KSAS experiment shows an overall warm bias in the troposphere (Fig. 6e). Despite the increase in the warm bias with forecast time, the RMSE is smaller than that of the NSAS experiment, especially in the upper levels of the troposphere. A cold bias around 925 hPa also weakens. The contribution of each physical process to the change in temperature is shown in Fig. 7a, which displays the

difference in the heating/cooling rate due to deep convective, microphysical, and radiative processes that are the dominant processes driving the temperature change and their sum between the KSAS and NSAS experiments. It appears that the increased tropospheric warming in the KSAS experiment is mainly attributable to decreased microphysical cooling in the lower troposphere and increased heating by microphysical processes in the upper troposphere. In the KSAS experiment, convective heating is increased below approximately 700 hPa but reduced above it compared with the NSAS experiment. Changes in temperature by convective processes are largely compensated by the cooling (warming) resulting from an increase (a decrease) in radiative cooling in the lower (upper) atmosphere. Although the combined impact of all the revisions is not just the sum of effects of individual modifications, the revised autoconversion parameter, which leads to the inefficient conversion of cloud condensate to convective precipitation at colder temperatures, appears to have the most dominant impact on the change in upper-level temperature. It appears that enhanced moisture detrainment with the revised autoconversion induces convective cooling and moistening in the upper troposphere (Figs. 7a,b). Meanwhile, the increased heating by microphysical processes at the upper levels (Fig. 7a) appears to be caused by the enhanced depositional heating resulting from the increase in the amount of grid-scale condensate detrained from cumulus convection. On the other hand, the reduction of the radiative cooling in Fig. 7a could be caused by the increase in the amount of condensed water that remains in the upper part of the convective updrafts (Fig. 7c), by trapping more outgoing longwave radiation. The warmer troposphere results in a general increase in the geopotential height compared with that of the NSAS experiment (Fig. 6f). The negative geopotential height bias in the lower atmosphere is smaller than that from the NSAS experiment at later forecast times. In the upper atmosphere, the bias is switched to a positive value and strengthens as the forecast time increases; however, the RMSE is significantly less than that of the NSAS experiment. A dry bias appears even above 750 hPa (Fig. 6g) due to both increased convective drying in the lower troposphere above the boundary layer and decreased moistening by microphysical processes (Fig. 7b). Meanwhile, the bias in the near-surface layer is markedly decreased owing to the stronger moistening probably induced by the enhanced evaporation of convective precipitation below the cloud base. The KSAS experiment substantially alleviates the pronounced negative and positive wind speed biases in the upper troposphere above 200 hPa and around 200–350 hPa, respectively, found

FIG. 6. Time–pressure cross sections of the biases (shaded) and RMSEs (contour) of (a),(e) temperature (K), (b),(f) geopotential height (m), (c),(g) specific humidity (g kg^{-1}), and (d),(h) wind speed (m s^{-1}) against the radiosonde data during the period of July 2017 averaged over the tropics (20°S – 20°N) from the (left) NSAS and (right) KSAS experiments.

FIG. 7. Vertical profiles of the difference in the tendency of (a) temperature (K day^{-1}) and (b) specific humidity ($\text{g kg}^{-1} \text{day}^{-1}$) due to deep convective (gray solid), microphysical (gray dashed), and radiative (gray dotted) processes and their sum (black solid) between the KSAS and NSAS experiments, and (c) the subgrid-scale condensate from the NSAS (blue) and KSAS (red) experiments averaged over the tropics for the 3–7-day forecast period.

in the NSAS experiment and consequently shows a lower RMSE, especially in the upper levels of the troposphere (Fig. 6h).

The performance of the medium-range forecasts over the tropics is measured by the RMSE for forecasts of the 850- and 250-hPa wind vector against the ERA5 analysis data, as shown in Fig. 8. The RMSEs for the tropical wind are all reduced in the KSAS experiment throughout the 10-day forecast period for July 2017, and the reduction in errors is more significant in the upper troposphere. Note that the same overall trend is observed in the verification against the radiosonde data (see Figs. 6d,h). During the period of January 2017, the skill for forecasts of the wind vector is better at 250 hPa and comparable at 850 hPa. A comparison of anomaly correlations and RMSEs for forecasts of the 500-hPa geopotential height in the Northern (20° – 90°N) and Southern (20° – 90°S) Hemispheres (Figs. 9 and 10) indicates that the synoptic-scale forecast skill of the medium-range forecasts with the KSAS is highly comparable to that with the NSAS for July 2017 but improved during the late forecast period for January 2017.

b. Precipitation

Figure 11 depicts the global distribution of the precipitation from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) observation and the NSAS and KSAS experiments, averaged over the 3–7-day forecast period during July 2017. Also shown are the bias of the NSAS experiment and the differences in precipitation and RMSE between the KSAS and NSAS experiments. The overall

distribution of the observed precipitation, the intense precipitation in the intertropical convergence zone (ITCZ) and along the extratropical storm tracks, is well reproduced in both the NSAS and KSAS experiments (Figs. 11a–c). However, the NSAS experiment generally underestimates the precipitation over the tropical Indian Ocean, Maritime Continent, central tropical Pacific Ocean, tropical South America, and storm track regions over the Atlantic Ocean (Fig. 11d). On the contrary, the precipitation over the western tropical Pacific Ocean, eastern equatorial Pacific Ocean, tropical Atlantic Ocean, and extratropical storm track regions of the Southern Hemisphere is generally overestimated, and the areal coverage for light precipitation over the ocean is excessive compared with the observation. The KSAS experiment displays enhanced precipitation in the regions where the NSAS experiment shows underestimation of the precipitation (Fig. 11e) due to larger increase of convective precipitation in those regions (not shown). On the other hand, in the regions where the precipitation is overestimated in the NSAS experiment, especially in the western tropical Pacific Ocean, the KSAS experiment tends to decrease precipitation due to a larger decrease in grid-scale precipitation (not shown). The superior performance of the KSAS experiment is confirmed in terms of the pattern correlation (Figs. 11b,c) and RMSE (Fig. 11f) against the TMPA observation, which increases from 0.874 to 0.905 and decreases from 3.37 to 3.13, respectively. Note that the bias of excessive precipitation along the storm tracks in the Southern Hemisphere and in the light precipitation areas over the ocean, which are largely

FIG. 8. RMSE (m s^{-1}) for forecasts of the (left) 850- and (right) 250-hPa wind vector over the tropics against the ERA5 analysis data for (top) July 2017 and (bottom) January 2017 from the NSAS (blue) and KSAS (red) experiments.

attributed to gridscale and shallow convective precipitations, respectively (not shown), remains relatively unchanged.

To statistically evaluate the precipitation forecast skill of the KSAS compared with the NSAS, standard verification measures of the bias score and equitable threat score (ETS), which are the most widely used to verify the skill of predicted precipitation, are calculated at different precipitation thresholds. Note that a bias score close to one and a higher ETS indicate better forecast performance. Figures 12a and 12b display the bias score and ETS, respectively, for daily precipitation forecasts over the tropics against the TMPA observation for

the 3–7-day forecast period during July 2017 from the NSAS and KSAS experiments. Both experiments have a tendency to overestimate the frequency of light precipitation events and underestimate the frequency of heavier precipitation events in the tropical region (Fig. 12a), which is a typically observed bias in numerical weather prediction and climate models. However, this bias is largely reduced in the KSAS experiment owing to the suppression of light rain and enhancement of rainfall in the heavier precipitation categories. The ETS is also higher in the KSAS experiment than in the NSAS experiment for all precipitation thresholds considered, which is more pronounced in the moderate to heavy

FIG. 9. (left) Anomaly correlation and (right) RMSE (m) for forecasts of the 500-hPa geopotential height in the (top) Northern (20° – 90° N) and (bottom) Southern (20° – 90° S) Hemispheres against the ERA5 analysis data during July 2017 from the NSAS (blue) and KSAS (red) experiments.

precipitation categories larger than 5 mm day^{-1} (Fig. 12b). A better bias score and higher ETS in the KSAS experiment obtained by alleviating the systematic bias of excessive light precipitation and lack of heavy precipitation are consistently found in the verification over the tropics during the period of January 2017, and also, against the Climate Prediction Center (CPC) unified gauge-based precipitation analysis (not shown).

The bias score and ETS of the predicted precipitation from the two experiments over Asia (25° – 65° N, 60° – 145° E) and South Korea ($33^{\circ}06'$ – $38^{\circ}45'$ N, $124^{\circ}53'$ – $131^{\circ}52'$ E), which are our regions of interest, are also compared in Figs. 12c–f. The NSAS experiment shows

the same systematic bias as seen in the tropics, that is, overestimated light precipitation but underestimated heavy precipitation, over South Korea against automatic weather station (AWS) rain gauge observations (Fig. 12e) and over the Asian region against the TMPA observation (not shown). Meanwhile, it tends to overestimate rainfall for all precipitation categories over the Asian land area against the CPC unified gauge-based precipitation analysis (Fig. 12c). Compared to the NSAS experiment, the KSAS experiment shows that excessive light precipitation is suppressed while heavy precipitation is enhanced, which is consistent with the verification in the tropics. This contributes to a general alleviation of precipitation bias,

FIG. 10. As in Fig. 9, but during January 2017.

especially against AWS and TMPA observations, but the bias score for the heavier precipitation categories against the CPC analysis increases. Figures 12d and 12f show that the KSAS experiment has a higher ETS than that from the NSAS experiment over Asia and South Korea. Better forecast skill for precipitation is also confirmed for January 2017 over the Asian region, including South Korea, except that the bias of overestimation of heavy precipitation observed in wintertime over South Korea against AWS rain gauge observation becomes much larger (not shown).

5. Summary and conclusions

An updated version of the SAS convection scheme developed by the KIAPS, named the KSAS, is introduced

in this study. The KSAS is a moist convection scheme utilized in a newly developed global numerical weather prediction model from the KIAPS, named the KIM. It uses a mass-flux concept based on the SAS convection scheme and has been extensively modified since it was first implemented in KIM in an effort to improve the medium-range forecast skill for precipitation and large-scale fields. The major modifications are as follows: considering the important role of environmental moisture in controlling the occurrence of convection and its intensity, the threshold of the trigger condition is determined as a function of RH of the environment in the subcloud layer and the sensitivity of the entrainment rate to environmental humidity is increased; the parameter that determines the amount of condensed water that ultimately falls

FIG. 11. Global distribution of the precipitation rate (mm day^{-1}) from the (a) TMPA observation and the (b) NSAS and (c) KSAS experiments, (d) the bias against the TMPA observation from the NSAS experiment, and the differences in (e) precipitation and (f) RMSE between the KSAS and NSAS experiments, averaged over the 3–7-day forecast period during July 2017. The pattern correlation (PC) is shown at the bottom of (b) and (c).

out as rain is modified to produce less frozen precipitating condensate with height (Han et al. 2016); the closure is modified to consider rapidly varying boundary layer forcing; the effect of the convection-induced PGF is enhanced in the upper part of the convective updrafts; and scale-aware features that make a mass-flux convection scheme valid across CPS gray-zone resolutions are added (Kwon and Hong 2017; Han and Hong 2018). The impacts of the updated moist convection parameterization on the medium-range forecasts are investigated by comparing the results with those of its original version. The cold bias and negative bias in geopotential height in the

tropical upper troposphere are considerably alleviated, mainly due to increased microphysical heating and decreased radiative cooling that surpass the effect of enhanced convective cooling. It appears that the revised precipitation conversion parameter plays a predominant role in changing upper-level temperature by increasing the amounts of condensed water that remains in the upper part of convective updrafts and detrained condensate from cumulus convection. The dry bias in the near-surface layer is also reduced owing to increased moistening probably resulting from enhanced evaporation of convective precipitation below the cloud

FIG. 12. (left) Bias score and (right) ETS for daily precipitation forecasts (a),(b) over the tropics against the TMPA observation, (c),(d) over Asia (25° – 65° N, 60° – 145° E) against the CPC unified gauge-based precipitation analysis, and (e),(f) over South Korea ($33^{\circ}06'$ – $38^{\circ}45'$ N, $124^{\circ}53'$ – $131^{\circ}52'$ E) against AWS rain gauge observations for the 3–7-day forecast period during July 2017 from the NSAS (black) and KSAS (gray) experiments.

base. Also, improvement in the tropospheric tropical winds is found in the validation against the radiosonde and ERA5 analysis data. In addition, the forecast skill for precipitation is found to be significantly improved in terms of the bias score and ETS not only over the tropics but also over the Asian region, including South Korea.

Since the revision by [Han and Pan \(2011\)](#), the NCEP GFS SAS scheme has also been further modified ([Han et al. 2017](#)). Some updates such as revised entrainment rate and autoconversion parameter are the same as those in the KSAS, but others are not. For example, scale awareness is also considered in the GFS SAS scheme but in a different way. The KSAS was implemented in the

WRF Model, version 4.0, released in June 2018, replacing the old NSAS scheme; therefore, it has been available with `cu_physics = 14`. The old NSAS scheme has been moved to `cu_physics = 96`. Although scale awareness is considered in the KSAS, further efforts to optimize the scheme at gray-zone resolutions less than 10 km are still needed, for example by improving the definition of the convective updraft fraction or by improving the scale dependency of the subgrid-scale cloud properties, because the KSAS is mainly evaluated using global atmospheric models at a horizontal resolution of 25 or 12 km.

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