Upgrades to JMA's Operational NWP High-resolution Global Model

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1. Introduction

The Japan Meteorological Agency (JMA) applies results from its high-resolution Global Spectral Model (GSM: JMA 2019) to provide a variety of numerical weather prediction (NWP) products that play key roles in national and international weather services. Among these, tropical cyclone (TC) forecasting is of paramount importance in disaster mitigation and readiness. Against such a background, JMA has engaged in GSM forecasting improvement in recent years with focus on enhancement of various physical processes.

This report outlines four major related upgrades implemented since the start of high-resolution GSM operation on 21 November 2007 (Nakagawa 2009). These have enhanced the accuracy of forecasting of typhoon tracks, precipitation and other variables. The individual upgrades are referred to here using the notation "GSMYYMM" (YY: last two digits of the year; MM: month)

2. GSM updates

2.1 GSM1403

In March 2014, JMA began operation of an upgraded GSM with the number of vertical layers increased from 60 to 100 and the pressure of the top level increased from 0.1 to 0.01 hPa. The parameterization schemes (including the boundary layer, radiation and non-orographic gravity waves) were also revised for better representation of atmospheric characteristics (Yonehara et al. 2014). These changes improved the distribution of mean precipitation, large-scale wind divergence in the northwestern Pacific region, and representation of large-scale circulation, and slightly enhanced typhoon position prediction.

Surface exchange coefficients based on the Monin-Obukhov similarity theory (Beljaars and Holtslag 1991) were introduced for bulk exchange formulation of land surface fluxes, and vertical diffusive coefficients in the stable boundary layer were revised (Han and Pan 2011).

A new long-wave radiation scheme based on two-stream absorption approximation radiation transfer (Yabu 2013) was also introduced. In this approach, absorption relating to atmospheric molecules is calculated using k-distribution. Despite the increased number of vertical levels, the computational cost for radiation was reduced.

Non-orographic spectral gravity wave-forcing parameterization (Scinocca 2003) was also introduced to replace Rayleigh friction in the forecast model to improve the representation of long-term oscillation (such as the quasi-biennial type) in the tropical lower stratosphere.

2.2 GSM1603

In March 2016, JMA drastically revised various parameterization processes in the GSM (including deep convection, clouds, radiation, land models and sea surface) to improve the accuracy of typhoon and precipitation prediction (Yonehara et al. 2017). GSM1603 was one of the largest-ever upgrades to the high-resolution GSM, creating significant effects on tropical cyclone track forecasts.

In the convection scheme, the artificial energy correction used to compensate for the lack of melting process was eliminated. The previous approach was artificial and ad hoc, with heat and humidity tendencies estimated non-physically and with low accuracy, and was replaced with a melting process for convective rainfall. As this change resulted in excessive heat from melting and unrealistic convective rain distribution, the sub-cloud model of the convective scheme was improved with the introduction of Kessler-type auto-conversion to reduce upward transportation of water content. Below the cloud base, a new entraining plume model based on Jakob and Siebesma (2003) was also adopted, and artificial adjustment of detrained cloud ice was discontinued.

Clouds are prognostically determined in a fashion similar to that proposed by Smith (1990) with a top-hat-shaped probability distribution function whose width depends on deep-convection-scheme mass flux. This dependency was eliminated to reduce grid point storms occurring as a result of the convection sub-cloud model revision. The prediction equation for cloud ice descent, which included artificial non-physical terms (Kawai 2005), was also revised. Additionally, time discretization was improved to reduce dependence on the time integration interval. As these changes resulted in slower cloud ice descent, the representation of high cloud increased in the mid-to-high latitudes and elsewhere. Due to easing of high cloud amount deficiency, downward long-wave radiation error near the surface was reduced.

Surface exchange coefficients based on the Monin-Obukhov similarity theory (Beljaars and Holtslag 1991) were introduced for bulk exchange formulation of sea surface fluxes, and an improved sea ice model with more layers was adopted.

In the land model, overall specifications were comprehensively updated and refined schemes were introduced. Specifically, the force-restore method for soil temperature prediction was replaced with a multilayer soil heat and water flux model and separate layers for snow. A new snow model with up to four layers was also introduced, with consideration for thermal diffusion, increased density from snow compaction and reduction of albedo due to snow aging. The distribution of vegetation types was further updated.

A practical independent column approximation method for shortwave radiation cloud overlap in the cloudy area of the column was also adopted to replace random overlap (Nagasawa 2012). For a mixed state between spread anvil and narrow tower cloud (i.e., deep convection), cloud optical thickness was overestimated in shortwave radiation calculation with the previous random overlap approach. Parameterization methods for liquid water cloud optical properties in shortwave and longwave radiation were also improved (Dobbie et al. 1999; Lindner and Li 2000).

Figure 1 shows tropical cyclone track forecast errors for the northwestern Pacific region. As a result of these refinements, GSM1603 significantly reduced errors.

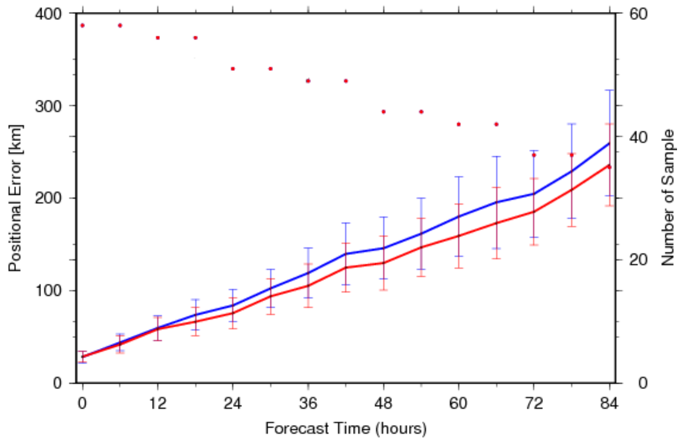

Figure 1. Tropical cyclone track forecast errors for the northwestern Pacific region with reference to JMA best-track data. The red and blue lines show track errors for the GSM1603 and GSM1403 models, respectively (left axis), with each point showing the number of samples (right axis). Error bars indicate the two-sided 95% confidence interval.

2.3 GSM1705

In May 2017, JMA refined various parameterized processes in the GSM, including cloud, convection, surface and radiation schemes, which collectively resulted in forecast improvement especially in the tropics (Yonehara et al. 2018).

Melting and re-evaporation processes were revised to address inadequate cooling caused by the artificial limiters applied to evaporation/condensation heating rates in order to ensure stable time integration. The new schemes consist of a rain evaporation scheme (Kessler 1969) with an implicit time discretization method and simple relaxation parameterization to account for melting of snow that falls across the freezing level.

The leaf area index (LAI), vegetation cover ratio and soil parameters were updated using more accurate reference sources. The soil moisture content climatology used to initialize the land model is now produced using atmospheric forcing datasets from the Global Soil Wetness Project Phase 3. LAI data were also updated based on more recent satellite observations (Myneni et al. 2002). These updates resulted in a reduction of the excessive sensible heat flux seen in the previous model.

Aerosol radiation treatment was refined for separate consideration of the radiative properties of five types of aerosols (sulfate, black carbon, organic carbon, sea salt and mineral dust) to improve representation of their radiative effects (Yabu et al. 2017). A deep cumulus diagnostic scheme was incorporated into the radiation scheme to reduce excessive biases seen in downward short-wave flux at the surface.

2.4 GSM2003

In March 2020, JMA upgraded its GSM to refine parameterized surface drag processes, land surface processes and surface albedo/stratocumulus over sea ice, which collectively resulted in forecast improvement over previous versions, especially in the Northern Hemisphere mid- and high latitudes (Yonehara et al. 2020).

The subgrid scale orography (SSO) scheme proposed by Lott and Miller (1997) replaced the previous scheme by Iwasaki et al. (1989), and represents low-level blocked flow drag produced by lateral flow around subgrid-scale orography. This flow generates gravity waves, which vertically transport and deposit momentum where waves break. A turbulent orographic form drag (TOFD) scheme (Beljaars et al. 2004) was also introduced.

The upgrade of land surface processes involves various changes, including consideration of snow coverage fractions (Roesch et al. 2001) and diagnostic schemes of soil thermal conductivity (Ek et al. 2003) to address surface biases. The former appropriately reduced the diagnosis fraction of snow coverage, and the latter relatively suppressed excessive diurnal amplitude of soil heat flux. These updates reduced the excessive sensible heat flux seen in previous land surface processes.

3. Summary

This report focuses on physical process improvement and outlines four major updates (GSM1403, GSM1604, GSM1705 and GSM2003) implemented since the start of high-resolution GSM operation with a horizontal resolution of 20 km on 21 November 2007. The updates enhanced the physics processes of the GSM and the accuracy of various forecasts, including those for typhoon position and precipitation. The changes also eliminated certain undesirable predictive properties, such as dry bias in the middle and lower troposphere, which would not have been possible with single-process improvement.

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