Impacts of new atmospheric physics in the updated GEOS FP system (Version 5.25)
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SUMMARY
In January 2020, GMAO (Global Modeling and Assimilation Office) upgraded the Goddard Earth Observing System (GEOS) Forward Processing (FP) system from version 5.22 to 5.25. This upgrade included major changes to the atmospheric component of GEOS. Of particular interest here is the inclusion of new convection parameterizations and changes in cloud and boundary layer turbulence parameters. These updates led to improved marine stratocumulus clouds and reduced errors in cloud radiative forcing. The precipitation intensity distribution is shifted, with reductions in the lightest (<1 mm d$^{-1}$) and heaviest (>10 mm d$^{-1}$) precipitation and increases in moderate rain rates. Forecast skill is substantially improved, with reductions in tropospheric root mean squared error for temperature, humidity, and wind fields, at all lead times out to five days.

BACKGROUND
The atmospheric model component of the GEOS-FP system uses a nominal horizontal grid spacing of 12 km and must rely on parameterizations to represent physical processes that operate on smaller scales. Among the most important parameterizations are those for moist convection and clouds, which impact the vertical transport of heat and moisture, momentum, precipitation, and the radiation budget. The version 5.25 upgrade of GEOS-FP features two new convection schemes: the Grell-Freitas parameterization of deep and congestus convection and the University of Washington shallow convection scheme. These replace the Relaxed Arakawa-Schubert (RAS) convection scheme, which was used in GEOS since its origin.
Introduction
The Goddard Earth Observing System forward processing (GEOS-FP) system underwent a major upgrade in January 2020, from version 5.22 to 5.25p3. This upgrade included a wholesale replacement of the convection parameterization and changes to a number of turbulence and cloud parameters, both of which had significant impacts on simulated atmospheric fields. This Research Brief highlights some of the changes GEOS-FP users can expect as a result of these cloud and convection updates. The GEOS-5.25 upgrade also included updates to the Catchment land-surface model (Koster et al., 2020) and a transition from the Chou-Suarez shortwave radiation parameterization to the RRTMG (rapid radiative transfer module for global climate model applications, Iacono et al., 2008) shortwave radiation code (Norris et al., 2020). We note that the initial upgrade to version 5.25p3 caused a large reduction in the convective mass flux diagnostic. A coding error was found and corrected in a subsequent upgrade to GEOS-5.25p5 in April 2020. The text below refers to both versions as 5.25, as the convective physics and model performance were essentially unchanged.

Changes in Parameterized Convection
The Relaxed Arakawa Schubert (RAS) convection parameterization, which has historically handled both deep and shallow convection in the GEOS atmosphere, was replaced with separate parameterizations focused on the three main tropical modes: deep, congestus and shallow (Johnson et al., 1999). In the updated GEOS-5.25, deep and congestus convection modes are represented with the Grell-Freitas parameterization (GF; Grell and Freitas, 2014; Freitas et al., 2018; 2020). The GF scheme is a mass flux scheme with a trimodal spectral size that contains a set of closures appropriate for each convection regime and includes convective scale downdrafts. It also employs the non-equilibrium closure of Bechtold et al. (2014), which improves the diurnal cycle of convection over land. GF applies an analytical function to represent the normalized mass flux, an effective method to set the vertical distribution of heat and mass. The GF scheme transports momentum, water, moist static energy, and tracers, and includes an in-line wet removal for tracers. For mass and energy, the spatial discretization of the tendency equation is conservative on machine precision.

In a major advance, the GF scheme uses a more sophisticated approach to horizontal resolution-dependence than used in RAS. As horizontal grid spacing is reduced, convection begins to be represented by resolved vertical motions, and parameterized
tendencies must be reduced to accommodate. In RAS, this adjustment was handled by gradually increasing the convective entrainment rate as grid spacing decreased. Although this successfully produced shallower and weaker parameterized convection at higher resolutions, the adjustment was ad hoc and without theoretical grounding. The GF parameterization employs the scale-aware approach of Arakawa et. al. (2011), which presents a self-consistent rederivation of the vertical eddy flux assuming that the parameterization must converge to an explicit simulation in the high-resolution limit. This approach is more consistently formulated and results in a smoother transition across resolutions than was achieved with RAS. The scaling of GF convection with horizontal resolution is illustrated in Figure 1 using a series of free-running experiments with a version of the atmospheric model nearly identical to that in GEOS-5.25. As grid-spacing is reduced from 25 km to 3 km, the mean total precipitation for August 2016 remains relatively constant (Figure 1, left panels), while the parameterized convective precipitation decreases (Figure 1, right panels).

Figure 1. The total (left) and parameterized (right) precipitation as a function of resolution, in experiments with the Grell-Freitas convection scheme. The parameterized precipitation decreases smoothly as grid spacing is reduced from 25 km (top) to 3 km (bottom), while the total precipitation remains nearly constant.
GEOS-5.25 is the first version of GEOS to include a dedicated shallow convection parameterization, the University of Washington shallow cumulus scheme (UWSC; Bretherton et al., 2004; Park and Bretherton, 2009). The UWSC was designed to better represent marine stratocumulus and trade cumulus clouds; this was a key target in its implementation in GEOS. The parameterization employs a single bulk updraft, assumed to originate at the planetary boundary layer (PBL) top, with mass flux at cloud base specified as a function of the relative magnitudes of convective inhibition and PBL turbulent kinetic energy (TKE). Here, TKE is estimated using diffusivity coefficients and PBL depth from the surface plume of the Lock et al. (2000) turbulence scheme. This decision limits shallow convection to convectively unstable PBL regimes with positive surface buoyancy flux.

UWSC determines entrainment and detrainment using a buoyancy-sorting approach. Above the cumulus base level, a height-dependent fraction of updraft air is mixed with an equal mass of environmental air, and a distribution of buoyancy is calculated assuming a linear mixture of the two. Mixtures with sufficient buoyancy and vertical velocity to reach the next model level are retained in the updraft, while the remaining mixtures are detrained. Air within the updraft is then homogenized, and the mixing process repeated at subsequent model levels. The updraft fraction subjected to mixing varies inversely with the cumulus height. The final updraft mass flux diagnostic for UWSC is linearly interpolated from the cloud base layer to zero at the surface.

Unlike GF scheme, and the UWSC as outlined in Park and Bretherton (2009), the GEOS implementation does not integrate precipitation to the surface internally. The scheme employs a simple internal microphysics, whereby any condensate exceeding an arbitrary threshold of 0.1 g kg$^{-1}$ is removed from the updraft, and the resulting condensate profile is then passed to the GEOS cloud microphysics to determine the precipitation, evaporation, and suspended cloud condensate. The UWSC provides a source of convective cloud fraction proportional to the mass of air detrained from the updraft. The scheme discretely conserves energy and moisture.

In GEOS-5.25, tracer tendencies due to transport and wet removal by convection are now calculated within the convection schemes, rather than in the GOCART aerosol transport module, using post hoc mass and precipitation fluxes diagnostics, a significant difference.
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from the 5.22 system. This provides a more internally consistent treatment of constituent transport.

Additional changes in atmospheric parameterizations in the 5.25 system include a reduction in cloud-top entrainment rate in the Lock et al. (2000) turbulence parameterization. This adjustment reduced the entrainment of warm, dry air into stratocumulus cloud layers, with the effect of increasing cloud amount. The update to GEOS-5.25 also removed several ad hoc adjustments made to cloud fields passed to the radiation scheme. These were previously used to reduce longstanding radiative biases in the model but were no longer necessary after the convection updates.

Impacts in GEOS-FP

Mass Flux
The updated convection in GEOS-5.25 results in an overall increase in convective mass flux, with a somewhat different spatial distribution relative to the previous system. The zonal mean convective mass flux for March 2020 for the 5.22 and 5.25p5 systems is shown in Figure 1. An increased mass flux is visible at most latitudes but particularly in the tropics, where both GF and UWSC are most active.

Figure 2. The March 2020 zonal-mean parameterized convective mass flux from the combined Grell-Freitas and University of Washington convection schemes in the 5.25p5 system (top), and the Relaxed Arakawa Schubert scheme in 5.22 (bottom).
Precipitation

Figure 3 shows a comparison of the monthly mean precipitation rate for May 2019 between the TRMM Multi-satellite Precipitation Analysis (TMPA, Huffman et al., 2007) and GEOS-5.22 and GEOS-5.24fpp (a parallel system very similar to the final 5.25 system, including all atmospheric physics changes described above). For both models, the monthly mean was obtained by combining the first 24 h forecast from each day of the month. The model versions well represent the global distribution of precipitation as retrieved by TMPA. A distinct difference is the precipitation rate intensity. While the 5.22 system shows more localized and intense rates, the 5.24fpp system has a smoother precipitation distribution, closely mirroring the TMPA data.

Figure 3. The monthly mean precipitation rate for May 2019: (A) as forecasted by GEOS-5.22, (B) from the TMPA dataset, and (C) as forecasted by GEOS-5.24fpp. The units are mm day$^{-1}$. 

Next, we explore the sub-daily rainfall estimates from TMPA and the GEOS FP systems to provide information about diurnal precipitation rates and check how the GF convection scheme impacts the GEOS FP forecasts. Figure 4 shows the precipitation rate from TMPA, and the GEOS-5.22 and 5.24fpp. TMPA shows two peaks: a nocturnal peak at ~3:00 AM and another in the afternoon at ~3:00 PM local time. Both FP systems also exhibit two peaks, but GEOS-5.24fpp shows better agreement with the TMPA afternoon peak. The 5.22 and 5.24fpp systems also somewhat overestimate the daily rainfall mean relative to TMPA by about 14 and 10 %, respectively. However, a more noticeable difference is the partition of rainfall produced by the convection parameterization and cloud microphysics. The 5.24fpp (5.22) system's parameterized precipitation produces 75% (34%) of the total observed precipitation.

![Figure 4. Diurnal cycle of precipitation from remote sensing-derived observation (TMPA) and NASA GEOS FP systems. The picture shows results for May 2019 spatial average over the Tropical region (20S-20N). The FP systems include the precipitation breakdown in terms of the GF parameterized and the grid-scale (resolved) parts.](image)

The new convection schemes also impact the intensity distribution of precipitation. In Figure 5, we compare precipitation intensities with version 6B of the 0.1-degree Integrated Multi-satellite Retrievals for GPM (IMERG; Huffman et al., 2019) product and the ERA-5 reanalysis (Hersbach et al., 2019). Here, all precipitation datasets were interpolated to a 0.25-degree horizontal grid and hourly time average for consistent comparison. Relative to GEOS-5.22, the updated model produces less drizzle, and has increased amounts of moderate rain rates (~10 mm day⁻¹), bringing both parameters closer to observations. By contrast, the most intense rainfall (>100 mm day⁻¹) occurs less often, shifting it away from observed rates. This may be a consequence of the increase in parameterized convection which generally produces smaller precipitation rates than the resolved convection (Figure 2). However, the new system is more consistent with the ERA-5 rainfall distribution (Figure 5).
Cloud Simulation

Like many atmospheric models, GEOS has long had difficulty simulating marine stratocumulus cloud, which is concentrated off the western coasts of North and South America, Africa, and Australia. In the GEOS systems, underestimates in stratocumulus cloud amount resulted in reduced albedo and excessive surface shortwave absorption, as exemplified by the top of atmosphere outgoing shortwave bias for August 2019, shown in Figure 3. Relative to CERES-EBAF version 4.1 (Loeb et al., 2018), the 5.22 system showed a bias exceeding $-40$ W m$^{-2}$ in stratocumulus regions. This bias was addressed with a combination of the additional convective mass flux from UWSC, and the reduction in cloud-top entrainment mixing in the Lock et al. (2000) turbulence parameterization.

The 5.25 system shows improved stratocumulus, with significant reductions in the local shortwave bias. The global mean shortwave bias becomes slightly positive, increasing from $-1.88$ to $1.43$ W m$^{-2}$, and the global RMSE drops from 13.88 to 11.72 W m$^{-2}$. Coastal stratus clouds are substantially improved in the new system but are still underestimated off the coasts of North and South America and Africa.
One of the most significant impacts of the new convection parameterizations is on the model forecast skill, that is, the agreement between forecast atmospheric fields and subsequent analyses incorporating observations. A Scorecard summarizing the change in forecast skill at various pressure levels, lead times, and regions is shown in Figure 7, using the 5.25 model run in parallel with 5.22 during Fall 2019. Anomaly correlations (COR) and root mean square errors (RMSE) are shown for geopotential height, specific humidity, temperature, and zonal (U) and meridional (V) wind components. Green colors indicate a reduction in error in the 5.25 system relative to 5.22, while red colors indicate an increase.

Statistically significant reductions in error are seen for all variables at all levels of the troposphere, with the possible exception of 850 mb temperature RMSE in the Southern Hemisphere. The stratosphere at 10mb shows some degradation, with larger RMSE seen in geopotential height and temperature forecasts.

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### f525land_fpp GEOS Scorecard

Comparison of scores for f522 tp (Control) and f525land_fpp (Experiment) experiments for the period of October 1, 2019 to December 31, 2019.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Northern Hemisphere</th>
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<td>RMS</td>
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<td>1 2 3 4 5</td>
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</tr>
<tr>
<td>Temperature</td>
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<tr>
<td>U-Wind</td>
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<td>70</td>
<td>100</td>
</tr>
<tr>
<td>V-Wind</td>
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<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

**Figure 7.** Scorecard summarizing changes in forecast skill metrics between the 5.22 and 5.25 systems. Green colors indicate reductions in root-mean-squared errors or increases in correlation coefficients, while red colors indicate degradation.
Summary

The January 2020 update to the GEOS-FP system introduced new convection parameterizations to the atmosphere model. The Relaxed Arakawa Schubert (RAS) parameterization, which previously represented a quasi-continuous spectrum of plumes, was replaced with the Grell-Freitas scale-aware convection parameterization (Freitas et al., 2018; 2020) and the University of Washington shallow cumulus scheme (Park and Bretherton, 2009). Impacts on the GEOS-FP system include an increase in parameterized convective mass flux; reduced errors in cloud fraction and top-of-atmosphere outgoing shortwave radiation, particularly in marine stratocumulus regions; and changes in the distribution of precipitation intensity. Forecast skill out to five-day lead times was increased on almost all metrics.

The updated model provides a strong foundation for continued development, using a more modern code base with greater community support, improved internal consistency, and overall better representation of physical processes. Development of the atmospheric physics continues, with a particular focus on updating the GEOS cloud microphysical and boundary layer turbulence parameterizations. The GF scheme is being expanded to include effects of cold-pools, a 2-moment convective cloud microphysics, an in-line lightning parameterization, and refined numerical aspects. Support for increased vertical resolution is also forthcoming.

References


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