gmdd-7-C2642–C2644,-2014, Development of the GEOS-5 Atmospheric General Circulation Model: Evolution from MERRA to MERRA2.

## Response to Reviewers

### Reviewer 1

We thank the reviewer for the comments about the clarity of presentation, and have addressed the mislabeling of figures in the revised manuscript.

# Specific Comments:

Section 3.2 would benefit from a bit more discussion of how the new source of nonorographic drag in the tropics was arrived as no reference is provided. How does it relate to other models schemes of tropical non-orographic drag? e.g. Manzini et al, 1997: Impact of the Doppler spread parameterization on the simulation of the middle atmosphere circulation using the MA/ECHAM4 general circulation model. J. Geophys. Res. or Scaife et al 2002: Impact of a spectral Gravity wave parameterization on the startosphere in the Met Office Unified Model. J Atmos Sci.

The new source is meant to better account for gravity waves excited by tropical convection, as described in Richter et al (2010). The other models mentioned by the reviewer include alternative techniques for modeling non-orographic sources of similar origin.

We have added an elaboration of the motivation for adding the new source of nonorographic gravity wave drag.

Section 4. This section might benefit from mentioning that lack of convergence in moist processes with increasing resolution is a common problem in atmospheric models. e.g. older studies Williamson 2008: Convergence of aqua-planet simulations with increasing resolution in the community atmospheric model, Version 3. Tellus. Pope & Stratton 2002: The processes governing horizontal resolution sensitivity in a climate model. Clim Dyn. Although the figures are slightly confusing it is still possible to understand the points being made in this section.

These additional citations for earlier studies that showed that there is a lack of convergence in moist processes with increasing horizontal resolution have been added.

**Technical Corrections:** 

*p*7584 line 15 refers to Fig 9. Panels (a) and (b) look identical and don't show the difference referred in the text. I assume one of the panels is wrong.

Indeed, panels a) and b) are both from Experiment 5 (MERRA-AGCM). Panel b) has been replaced and now shows the result from Experiment 4.

p7588 line 1 says that Panels 16(a) to (c) show resolutions 1., 0.5 and 0.25 but the figure says 2, 1 and 0.5, which is correct? (Figure 17 has the same resolutions as Fig 16.)

The figure shows 2, 1 and 0.5 degree resolutions as stated in the figure caption. The text describing figures 16 and 17 has been corrected.

*p*7588 line 19 references Tokioka (1988) but this does not appear in the references at the end.

The proper reference has been added

*Figure 7 - If colour key correct, then caption wrong as 1 degree is purple, 2 degree is blue.* 

The color key is correct, and the figure caption has been corrected to properly reflect the color coding.

Figure 12 - what is the grey shading on panels (c) & (f)?

The grey shading is to depict land surfaces. A statement was added to the caption to this effect.

Figure 18 - key has 2.5 degrees but figure caption has 2 degrees, which is correct?

The black line is the valid curve for the 2x2.5 degree resolution (2 deg lat, 2.5 deg lon). The figure caption has been modified to be consistent with the legend.

Figure 19 - Panels (b) and (c) both claim to be 0.5 degrees but look different. The units claim they are kg/m2/s but the colour bar has values of \_100 should it be g/m2/s?

The units are kg/m2/day. The figure caption now reflects the correct units and also now correctly refers to panel c) as the figure for the 0.25 degree resolution.

Figure 20 - Again panels (b) and (c) both claim to be 0.5 degrees but are different.

The caption was corrected to refer to panel c) as the result from the 0.25 degree simulation.

References:

Richter, J. H., F. Sassi, and R. R. Garcia, 2010: Toward a physically based gravity wave source parameterization in a general circulation model. *J. Atmos. Sci.*, **67**, 136--156.

Tokioka, T., K. Yamazaki, A. Kitoh, and T. Ose (1988), The equatorial 30–60 day oscillation and the Arakawa-Schubert penetrative cumulus parameterization, *J. Meteorol. Soc. Jpn.*, **66**, 883–901

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# Response to Reviewers

# Reviewer 2

In this manuscript the authors disentangle the development from one version of an atmospheric model to the next. This is something that is not often done, but the resulting information is useful for both users of the model and derived products, as well as for developers of other models that can find inspiration in their work. To be complete, I would add some tabulated global means of fluxes, precipitation, cloud cover/liquid/ice, etc. for the various runs.

We thank the reviewer for the recognition that the sort of "disentangling" of model development is rarely done but quite useful.

My main problem with reading the manuscript is that the authors take their new model as a starting point, and then back-track towards the old model. This is confusing because as the reader you naturally think forwards and not backwards, i.e. the effect of improving ocean surface roughness is this and that. Another general issue is the figures which need improvement. I provide several suggestions below.

We recognize that it would have been interesting and perhaps even more intuitive for some readers if we had written the manuscript presenting the experimental results from the "oldest model" to the "newest". We believe, however, that the sequencing through the results of the experiments as presented is valid as well, as the main point is to identify the differences between any set of two experimental results and attribute them to a specific change in the model physics. In addition, the task of re-ordering the presentation of experiments entails a fundamental rewrite of all of the results sections of the manuscript and a regeneration of almost all the figures. We will therefore retain the ordering of the manuscript.

The figures that needed improvement were modified, and the captions were corrected.

### Comments:

Section 3.3 got fairly confusing, partly because of the back-tracking issue, partly because the authors seem to define heat-flux positive upwards (which is fairly uncommon). If anything the Louis-scheme is among the more diffusive, which is also seen by the fact that the model hardly visits the very stable regime. Thereby sentences such as "indicating less sensible heating when using the Louis scheme", if not incorrect, become fairly difficult to comprehend.

Some additional text has been added to this section to make more clear which turbulence models are used in experiments 2 and 3. The Louis (1979) scheme was used in the MERRA AGCM for the surface layer turbulent fluxes only, and was replaced in the

MERRA2 AGCM with the Helfand and Schubert (1995) similarity theory based scheme for surface layer turbulent fluxes. The change in parameterizations, therefore, being evaluated in this section, is due only to the change in the algorithm for the surface layer turbulence (the bottom model level only, the constant flux layer). In addition, the fundamental differences between the two schemes are the choice of stable layer similarity functions and the implementation of the laminar viscous sublayer. This has now been elaborated in the text. The turbulent diffusion above the surface layer is modeled in ALL versions of GEOS-5 with a combination of the Lock scheme and the Louis and Geleyn (1982) scheme.

The sign convention for turbulent surface fluxes (positive upward) is the convention for atmospheric budgets and modeling and so was chosen for this study. Modeling studies (Donner et al., 2011; Pope et al., 2000; Neale et al., 2013 for example) and observational studies (Shie et al., 2009) also use this sign convention.

Our results indicate that of the two surface layer schemes discussed here, the sensible heat flux simulated when using the Helfand Monin-Obukhov scheme is generally higher, as shown in figure 6.

Section 3.5 is also difficult to comprehend for the uninitiated. I would suggest to add a better description of the parameterization, and to use a different figure to display the effects. The annual cycle of the zero-wind contour is not something that the most readers will be familiar looking at.

The time series of the zero-wind contour of the zonal wind, either at 60S or averaged from 50S to 70S, is used in many studies to examine the timing of the breakup of the southern hemisphere stratospheric jet. Some studies that present the timing of the jet breakup in this manner are Eyring et al. (2006) and Garfinkel et al (2013).

It may be worthwhile to contrast the strategy to limit convection at higher resolutions with alternative strategies to enhance the parameterized convection to avoid explicit convection (e.g. Bechtold et al. 2008, QJRMS, their equation 3).

Some discussion of other strategies to change the parameterized convection with resolution has been added to section 4. This includes the Bechtold et al. (2008) approach as well as the approach of Arakawa and Wu (2012).

The figures are all plotted using the rainbow colour scale, which is an unfortunate choice for a number of reasons elaborated here: http://www.climate-labbook. ac.uk/2014/end-of-the-rainbow/.

The objection to the rainbow color scale by the reviewer and by the authors of the climate lab book is noted. We do not find the shaded plots in this manuscript to be misleading, however, due to our use of the chosen color scale, as was suggested in the online article referenced by the reviewer.

Beware that acronyms must be defined.

The manuscript was re-read with this in mind. We believe that all acronyms are now defined (the acronym 'GEOS' was not defined in the original manuscript).

7576, 11 The term "nature run" is unspecific and not used later.

The term was removed.

7577, 27 I would avoid using hyphens, here and in most other places.

This line of text in the introduction does not contain hyphens. A hyphen was found on line 3 of this page (1-2 degree) and was removed. The hyphens in the following paragraphs used a line continuation markers, they were inserted by the GMDD typesetting.

7580, 17 'changes at a time'

The correct syntax, we believe, is "....one parameterization change at a time...". Later in the sentence we refer to "...small groups of parameterizations at a time...."

7584, 20, In my book a higher critical RH should give you less cloud fraction. If the model behaves differently then this is worth an explanation.

A higher RH crit results in two potentially competing effects. The requirement that the atmosphere must have a higher relative humidity before condensation can take place could indeed result in reduced cloud cover. The higher RH crit, however, also leaves behind an atmosphere with a higher relative humidity, which would be associated with increased cloud cover. One of these two effects may dominate, or they may cancel and the result would be no change in cloud cover. The results shown here demonstrate that the latter of these two effects is dominant in the GEOS-5 AGCM. It is not clear to the authors, however, precisely why the atmospheric relative humidity increases beyond the change in RH crit. We speculate that it may be related to the sequencing of the macro-and micro-physical processes in the moist parameterization combined with the enhanced rates of rain and condensate re-evaporation, leaving behind an atmosphere which is no longer in equilibrium with the specific RH crit (wetter in our case). These issues are typical of AGCM moist parameterizations, as can be seen in the complex sequencing described in Gettelman et al. (2015). Some text was added to the manuscript to explain this interplay.

7586, 13 What is SD?

SD was replaced with "standard deviation"

7588, 3 It is 'ERA-Interim' here and elsewhere.

This was corrected here and elsewhere

7589, 4 'severely'

### Corrected

Table 2, What is Fortuna AGCM?

References to Fortuna AGCM have been removed from the captions for Tables 1 and 2.

Figure 1. It is odd that the data shown in panel a (up to 0.001) is not visible in the lower left part of panel b).

The original Figure 1b was from an experiment with the upper limit in place but without the change in the lower wind regime. Figure 1a was removed altogether, and a single scatter diagram is shown spanning the entire range of wind speeds, reflecting the change in the middle range and at high wind speeds.

Figure 2. Panels b and e show the same thing.

The figure was changed to show only one copy of the "observed" panel.

Figure 9, panels a and b are the same.

Panel b) was replaced, and now shows the results from experiment 4.

Figures 11-14 are too small to be readable in print.

The size of figures 11 and 14 was increased.

Figure 15, caption does not reflect the displayed quantity.

The caption was changed to reflect the display of the zero wind contour.

Figures 16-17, panels b, e and h can be deleted.

The two figures were combined, removing the rows of "model" and "observation" panels from both and showing only the differences between the model and verification at each resolution for each version of the model.

References:

A. Arakawa and C.-M. Wu, 2013: A Unified Representation of Deep Moist Convection in Numerical Modeling of the Atmosphere. Part I. J. Atmos. Sci., **70**, 1977–1992. doi: http://dx.doi.org/10.1175/JAS-D-12-0330.1

Garfinkel, C., L. Oman, E. Barnes, D. Waugh, M. Hurwitz and A. Molod: Connections between the Spring Breakup of the Southern Hemisphere Polar Vortex, Stationary Waves, and Air–Sea Roughness. *J. Atmos. Sci.*, **70**, 2137-2151. doi:10.1175/JAS-D-12-0242.1

Gettelman, A., H. Morrison, S. Santos, P. Bogenschutz, and P. M. Caldwell, 2015: Advanced Two-Moment Bulk Microphysics for Global Models. Part II: Global Model Solutions and Aerosol–Cloud Interactions. *J. Climate*, **28**, 1288–1307. doi:http://dx.doi.org/10.1175/JCLI-D-14-00103.1

V. Eyring and co-authors, 2006: Assessment of temperature, trace species, and ozone in chemistry-climate model simulations of the recent past. *J. Geophys. Res.*, **111**, D22308, doi:10.1029/2006JD007327.

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# Development of the GEOS-5 Atmospheric General Circulation Model: Evolution from MERRA to MERRA2.

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#### Abstract.

The Modern-Era Retrospective Analysis for Research and Applications-2 (MERRA2) version of the <u>Goddard Earth Observing System - 5 (GEOS-5)</u> Atmospheric General Circulation Model (AGCM) is currently in use in the NASA Global Modeling and Assimilation Office (GMAO) at

- 5 a wide range of resolutions for a variety of applications. Details of the changes in parameterizations subsequent to the version in the original MERRA reanalysis are presented here. Results of a series of atmosphere-only sensitivity studies are shown to demonstrate changes in simulated climate associated with specific changes in physical parameterizations, and the impact of the newly implemented resolution-aware behavior on simulations at different resolutions is demonstrated. The
- 10 GEOS-5 AGCM presented here is the model used as part of the GMAO's MERRA2 reanalysis, the global mesoscale "nature run" global mesoscale simulations at 10 km resolution through 1.5 km resolution, the real-time numerical weather prediction system, and for atmosphere-only, coupled ocean-atmosphere and coupled atmosphere-chemistry simulations.

The seasonal mean climate of the MERRA2 version of the GEOS-5 AGCM represents a substantial improvement over the simulated climate of the MERRA version at all resolutions and for all applications. Fundamental improvements in simulated climate are associated with the increased re-evaporation of frozen precipitation and cloud condensate, resulting in a wetter atmosphere. Improvements in simulated climate are also shown to be attributable to changes in the background gravity wave drag, and to upgrades in the relationship between the ocean surface stress and the

20 ocean roughness. The series of "resolution aware" parameters related to the moist physics were shown to result in improvements at higher resolutions, and result in AGCM simulations that exhibit

seamless behavior across different resolutions and applications.

#### 1 Introduction

The various activities of NASA's Global Modeling and Assimilation Office (GMAO) neccesitate
 necessitate a model that can function seamlessly across many different resolutions and applications. These applications include real-time atmospheric analyses and forecasts at a resolution of 0.25°, long term reanalyses at 0.5°, coupled atmosphere-ocean and coupled atmosphere-chemistry simulations at 1-2°1° or 2°, and global mesoscale simulations at 7km and higher. The Modern-Era Retrospective Analysis for Research and Applications-2 (MERRA2) version of the Goddard Earth

- 30 Observing System 5 (GEOS-5AGCM-) Atmospheric General Circulation Model (AGCM) is part of an ongoing development of a new generation AGCM at GMAO. The focus of the development of the MERRA version of the GEOS-5 AGCM was on the behavior of the components of the hydrological cycle in reanalysis mode, while the focus of the development of the MERRA2 AGCM was on a model that functions seamlessly in numerical weather prediction, reanalysis, climate and global
- 35 mesoscale modes. To this end, some of the physical parameterizations were replaced, some parameters governing the behavior of other physical parameterizations were changed, and resolution-aware parameters were implemented in the moist process parameterizations.

Many studies exist that describe major improvements in new versions of AGCMs and show the improvements in simulations as compared to reanalyses and other observations (ie., Neale et al.,

- 40 2013, Donner, et al., 2011, Pope et al., 2000). The present study adds to that type of analysis by carefully documenting the connection between individual changes in the physical parameterizations of the AGCM and improvements in the climate simulation at coarse resolution. A series of sensitivity experiments were conceived and analyzed to explore, step by step, each important change in parameterizations between the MERRA and MERRA2 AGCMs, and to demonstrate the impact
- 45 on the simulated climate. The present study also describes and analyzes the improvements in high resolution simulations due to some changes in parameterizations specifically targeted for those resolutions.

The details of the changes in the AGCM physical parameterizations are described in the next section, the step by step experiments to isolate the impacts of these changes are described in section

50 3, and the impacts of the "resolution aware" aspects of the AGCM are described in section 4. The study is summarized in section 5.

#### 2 Description of the MERRA2 version of the GEOS-5 AGCM

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The generation of the GEOS-5 Atmospheric General Circulation Model (GCM) that was used as part of NASA's Modern-Era Retrospective Analysis for Research and Applications (MERRA) is described in Rienecker, et al. (2008), and most of the subsequent development of the physical

2

parameterizations for the current, MERRA2 version is described in Molod et al. (2012). In addition to the changes in the physical parameterizations, the development of the MERRA2 AGCM also included two fundamental elements that will not be addressed in the present study. The horizontal discretization of the MERRA2 AGCM is computed on the cubed sphere grid of Putman and Lin

- 60 (2007), although it still retains the option to use the latitude/longitude discretization. The cubed sphere grid allows for the relative uniformity of grid spacing at all latitudes, and avoids the grid spacing singularities found in the latitude/longitude grid. In addition, the MERRA2 AGCM has been modified to account for the change in total mass due to the change in total water content computed in the moist and turbulence processes. The total mass of each layer is adjusted to include these
- 65 changes in total water content, and the associated adjustment is then made to the specific masses of all constituents, including water substances. The benefit for the AGCM mean simulated climate is small, but results in the conservation of dry mass during the simulation. The algorithm for this adjustment and the benefits for AGCM simulations and data assimilation experiments are described in detail in Takacs et al. (2014).
- 70 A brief summary of the model's physical parameterizations relevant to the present study is provided here. The GEOS-5 AGCM physics includes parameterization schemes for atmospheric convection, large scale precipitation and cloud cover, longwave and shortwave radiation, turbulence, gravity wave drag, a land surface model, a thermodynamic sea ice model, and a simple glacier model.
- 75 Convection is parameterized using the Relaxed Arakawa-Schubert (RAS) scheme of Moorthi and Suarez (1992) and includes a scheme for the generation and re-evaporation of falling rain (Bacmeister et al., 2006). A "stochastic Tokioka trigger" function (Bacmeister and Stephens, 2011) governs the upper-lower limits on the allowable entrainment by sampling from a probability distribution function with specified parameters. The prognostic cloud cover and cloud water and ice scheme is from
- 80 Bacmeister et al. (2006). The scheme includes large scale condensation governed by the probability distribution function described in Molod (2012), evaporation, autoconversion and accretion of cloud water and ice, sedimentation of cloud ice and re-evaporation of falling precipitation.

The turbulence parameterization that acts above the surface layer is based on the non-local scheme of Lock (2000) scheme, acting together with the Richardson-number based scheme of Louis and

- 85 Geleyn (1982). The original Lock scheme was extended in GEOS-5 to include moist heating and entrainment in the unstable surface parcel calculations. The Monin-Obukhov similarity theory based parameterization of surface layer turbulence is the Monin-Obukhov similarity theory based scheme described in Helfand and Schubert (1995), and includes the effects of a viscous sublayer for heat and moisture transport over all surfaces except land. The ocean roughness is determined by a polynomial
- 90 which is a blend of the algorithms of Large and Pond (1981) and Kondo (1975), modified in the midrange wind regime based on recent observations in the southern ocean according to Garfinkel et al. (2011) and in the high wind regime according to Molod et al. (2013).

The longwave radiative processes are described by Chou and Suarez (1994), and the shortwave radiative processes are from Chou and Suarez (1999). The gravity wave parameterization computes

- 95 the momentum and heat deposition into the grid-scale flow due to orographic (McFarlane, 1987) and nonorographic (after Garcia and Boville, 1994) gravity wave breaking. The Land Surface Model from Koster et. al (2000) is a catchment-based scheme that treats subgrid scale heterogeneity in surface moisture statistically. Glacial thermodynamic process are parameterized using an adaptation of the Stieglitz et al. (2001) snow model to glacial ice (Cullather et al., 2014), and the catchment
- 100 and glacier models are each coupled to the multi-layer snow model of Stieglitz et al. (2001). Sea ice albedos in the northern hemisphere are from the monthly mean observations of Duynkerke and de Roode (2001).

#### 3 Evolution of Low Resolution Simulated Climate from MERRA AGCM to MERRA2 AGCM

- The mean climate characteristics of a single 30-year MERRA2 AGCM simulation on the latitude/longitude grid at a horizontal resolution of 0.5° x 0.5° were evaluated by comparison with reanalysis and with different satellite and *in situ* based observational estimates (Molod et al., 2012). They found substantial improvements in some key aspects of the mean circulation in the MERRA2 version of the GEOS-5 AGCM, and also reported on existing discrepancies between the modeled and observed climates. Here we present the results of a series of experiments designed to attribute each
- 110 fundamental improvement in AGCM simulated climate to a specific change in parameterization. The experiments to be described in this section were all conducted on the latitude/longitude grid at 2.° x 2.5° horizontal resolution, on a vertical hybrid eta-pressure coordinate grid with 72 levels, spaced to increase the resolution near the surface and near the tropopause, with an upper lid at 0.01 mb. The simulations were all forced with observed sea surface temperatures (Reynolds, 2002), and
- 115 ran for 30 years each. The sequence of experiments was designed to start with the MERRA2 AGCM as the control and backtrack, one parameterization change at a time or small groups of parameterization changes as a time, to a model that replicates the MERRA AGCM simulated climate. The parameterization changes are listed in table 1, and the full sequence of the control and 7 sensitivity experiments to be described in this section is listed in Table 2.

#### 120 3.1 Ocean Surface Winds

The parameterization of the surface layer turbulence in the MERRA2 AGCM includes a substantial modification of the functional relationship between ocean surface roughness and wind stress, shown in Figure 1. The relationship for the moderate range surface wind speeds from the MERRA AGCM (green) and in the MERRA2 AGCM (black) is shown in figure 1a, where the increased roughness

125 based on the implementation of Garfinkel et al. (2011)is apparent, and shows the increased roughness in that range relative to the MERRA AGCM (green). The first experiment in the series, experiment 1, reverts back to the formulation for the relationship between ocean surface roughness and stress used in the MERRA AGCM. The effect for simulations at  $2.^{\circ} \times 2.5^{\circ}$  resolution is expected be an increase in the experiment 1 simulated surface wind speeds in the mid-range of wind speeds, that

- 130 is, in the 5 m  $s^{-1}$  to 25 m  $s^{-1}$  range. Figure 1b shows the The relationship between wind speed and roughness for a larger range of wind speeds the higher wind speeds in the MERRA2 AGCM is after Molod et al. (2013), where the and the figure shows reduction of roughness at speeds greater than approximately 30 m  $s^{-1}$  is apparant. This change is expected to result in a net increase of wind speeds in higher wind regimes as was shown in Molod et al. (2013) for simulations at 0.25 ° resolu-
- 135 tion, but this impact is not apparent at the resolution of the experiments described here because the simulated wind speeds generally do not reach 30 m  $s^{-1}$ .

Surface wind speeds from the MERRA2 AGCM control and experiment 1 are shown in figure 2. The change in the simulated surface winds is most apparent in the southern hemisphere, where the Goddard Satellite-based Surface Turbulent Fluxes (GSSTF, Shie et al., 2009) surface winds, seen in

140 figure 2b, show values near 8 m s<sup>-1</sup>, experiment 1 (2d) shows surface winds near 12 m s<sup>-1</sup> and the MERRA2 AGCM control (2a) shows surface winds near 10 m s<sup>-1</sup>. The difference from the GSSTF estimate (shown in 2c and 2f) shows a reduction in the difference from up to 4 m s<sup>-1</sup> in experiment 1 (figure 2e) to a difference of up to 2 m s<sup>-1</sup> in the MERRA2 AGCM control (figure 2c), pointing out the improvement in AGCM simulated climate due to the change in roughess roughness formulation.

#### 145 3.2 Quasi-biennial Oscillation

The nonorographic gravity wave source in the MERRA (and MERRA2) AGCMs is specified as a function of latitude, and the source level is 400 mb, after Garcia and Boville (1994). The gravity wave source spectrum is specified *a priori*, and includes wave components with phase velocities in the range of -40 to 40 m s<sup>-1</sup>, at intervals of 10 m s<sup>-1</sup>. The latitudinal profile of background nonoro-

- 150 graphic drag in the MERRA2 AGCM was modified to include a specified source related to tropical precipitation in addition to the local maxima related to storm track precipitation. The background use of this structure is based on the physical argument that the major sources for nonorographic gravity waves are convective and frontal systems. The MERRA2 AGCM profile was designed to mimic the behavior of more complex models of nonorographic gravity wave sources such as the
- 155 state-dependant model of Richter et al. (2010), or the spectral wave source models of Manzini et al. (1997) and Scaife et al. (2002).

The latitudinal dependance of the background nonorographic drag profiles used in the MERRA2 and the MERRA AGCMs are shown in figure 3. Experiment 2 of the series examines the impact of the change in the gravity wave drag parameterization of background drag in the tropics, and

160 returns to the MERRA AGCM background drag. Experiment 2 is therefore expected to exhibit a stratospheric wind with no quasi-biennial oscillation (QBO) variability. The tropical (latitude range 10S to 10N) zonal average of the zonal wind as a function of height and time is shown in figure 4. The patterns of large easterly and westerly winds that slant downwards in pressure as time proceeds indicate the downward propagation of the variations due to the QBO. The QBO pattern is seen in

165 figure 4a and 4c, which are the results from experiment 1 from and MERRA reanalysis (Rienecker, et al., 2011), respectively. Figure 4b, however, that shows the results of experiment 2 that uses the old background drag formulation (from figure 3), shows no QBO pattern of variability.

#### 3.3 Stable Surface Layer Fluxes

The parameterization of the surface layer surface layer turbulence in the MERRA2 AGCM uses 170 the scheme of Helfand and Schubert (1995) based on Monin-Obhukov (MO) similarity theory. The scheme replaced the Louis (1979) scheme that was used in the surface layer only (the bottom model level) in the MERRA AGCM. The implementation of the MO scheme included the use of a different set of fundamental differences between the Louis (1979) description of surface layer turbulence and the scheme of Helfand and Schubert (1995) are the stable layer stability functions , and a different

- 175 and the formulation for the viscous sublayer (the laminar layer that can act to impede the flux of heat and moisture). The viscous sublayer in the Louis scheme is present over unvegetated land surfaces and over the oceans. The Helfand scheme removes the viscous sublayer over all land surfaces, including bare soil. The stable surface layer stability functions in the Helfand scheme result in are such that there is an increased turbulent heat exchange (of both signs) under stable conditions.
- 180 Figure 5 shows a scatter diagram of the sensible heat flux as a function of surface bulk Richardson number under conditions where the monthly mean air temperature exceeds the monthly mean skin temperature. The black points are from the simulation with the Helfand surface layer, and the red are from the simulation using the <u>surface layer from the</u> Louis scheme. The larger values of sensible heat flux in the Helfand simulation are apparent, and even more apparent when the monthly mean
- 185 sensible heat flux is downward.

Experiment 3 was designed to examine the impact of the change in the surface layer parameterization by reverting back from the Helfand and Schubert scheme to the Louis scheme. The turbulence parameterization above the surface layer, which is the combination of Lock (2000) and Louis and Geleyn (1982) is the same in experiments 2 and 3. Figure 6 shows the sensible heat flux from exper-

- 190 iments 2 and 3 along with the difference between them. The differences shown here are attributable to the removal of the viscous sublayer over land in the Helfand and Schubert scheme and to the change in the stable layer stability functions. Figure 6c shows that over most land surfaces the difference in sensible heat flux is negative, indicating less sensible heat flux when using the Louis scheme. This sign of the difference is consistent with the expectation that the removal of the
- 195 viscous sublayer over land surfaces in the Helfand scheme , that would remove some lessens the resistance to turbulent exchangethat is present over unvegetated land surfaces in the Louis scheme due to the viscous sublayer. Figure 6c also shows regions where the sensible heat flux is greater in the Louis scheme than in the Helfand scheme. These are regions where the surface layer is stable,

and where the sensible heat itself is largely downward (that is, the air temperature is greater than the

200 skin temperature). The change in stability functions between the Louis and Helfand scheme, that allows more turbulent exchange in the Helfand scheme, is consistent with the sign of the difference in sensible heat flux in regions where the heat flux is downward.

#### 3.4 Atmospheric Moisture, Clouds and Stationary Wave Pattern

#### 3.4.1 Critical Relative Humidity

- 205 The algorithm for large scale condensation, as described in Bacmeister et al. (2006), assumes that the probability distribution function (PDF) of total water is "top-hat" shaped. The width of the PDF can be shown to be associated with a "critical relative humidity" ( $RH_{crit}$ ) that governs cloud macrophysical and microphysical processes such as condensation and evaporation (Molod, 2012). The relationship between  $RH_{crit}$  and PDF width is such that a wider PDF corresponds to a lower
- 210  $RH_{crit}$ . The MERRA2 AGCM  $RH_{crit}$  (Molod, 2012) represents a change in both the magnitude and vertical structure from the  $RH_{crit}$  in the MERRA AGCM. Typical  $RH_{crit}$  profiles from the MERRA and MERRA2 AGCMs are shown in figure 7, and indicate generally lower values in the MERRA2 AGCM formulation except in the boundary layer, where turbulent mixing is sufficient to homogenize the total water distribution and so result in narrower PDF.
- Experiment 5 was designed to examine the impact of the change in  $RH_{crit}$ . Removing this change, which for much of the atmosphere means a larger  $RH_{crit}$ , should result in a simulation that is generally wetter because the atmosphere is being adjusted back to a higher relative humidity (RH). The zonal mean relative humidity from experiments 4 and 5, along with the difference between them, is shown in figure 8. The experiment 5 minus experiment 4 difference shows a clear increase
- 220 in relative humidity in the MERRA AGCM-like experiment due to the increase in  $RH_{crit}$ . Relative to available observational verification, the MERRA2 AGCM shows a general wet bias (Molod et al., 2012), which means that the experiment 4 relative humidity field is closer to the observed than experiment 5's RH field.

In addition to having a substantial impact on atmospheric moisture, the change in  $RH_{crit}$  also had an impact on the distribution of cloud cover. The higher  $RH_{crit}$  simulation (the  $RH_{crit}$  above the boundary layer of the MERRA AGCM-like experiment ) could either may be expected to have less cloud cover because result in two potentially competing effects. The requirement that the atmosphere must contain more moisture before new cloud water will be condensed, or could be expected to have more cloud coverdue to the feedback of a generally moister atmosphere. have a higher relative

230 humidity before condensation can take place could result in reduced cloud cover. The higher  $RH_{crit}$ , however, also leaves behind an atmosphere with a higher relative humidity (as seen in figure 8), which would be associated with increased cloud cover. One of these two effects may dominate, or they may cancel and the result would be no change in cloud cover. Figure 9 shows the zonal mean cloud cover from experiments 4 and 5, and an observational

- 235 estimate of zonal mean cloud cover from AIRS. The MERRA AGCM-like experiment, experiment 5 (figure 9a), shows increased cloud cover in the 300-600 mb range relative to the MERRA2 AGCM-like experiment, in particular at high latitudes in both hemispheres. In this regard, the MERRA2 AGCM-like experiment result more closely resembles the AIRS cloud cover estimate (figure 9c). This result confirms the hypothesis that
- 240 The results shown here demonstrate that influence of the wetter atmosphere due to the higher  $RH_{crit}$  results in an atmosphere that is wetter in is the dominant of the two competing effects in the mean and has more cloud. GEOS-5 AGCM. It is not clear, however, precisely why the atmospheric relative humidity increases beyond the change in  $RH_{crit}$ . It may be speculated that it is related to the sequencing of the macro- and micro-physical processes in the moist parameterization combined
- 245 with the enhanced rates of rain and condensate re-evaporation (see section 3.4.2), leaving behind an atmosphere which is no longer in equilibrium with the specific  $RH_{crit}$  (wetter in our case). These sequencing issues are typical of AGCM moist parameterizations, as can be seen, for example, in the complex sequencing described in Gettelman et al. (2015).
- The MERRA-like AGCM result (experiment 5) also shows smaller cloud cover near the boundary layer at almost all latitudes. At high latitudes, the MERRA2 AGCM-like boundary layer cloud more closely resembles the AIRS estimate, in the tropics the MERRA2 AGCM-like boundary layer cloud is larger than AIRS, while the MERRA AGCM-like boundary layer cloud is smaller. The change in boundary layer cloud between the MERRA AGCM-like experiment and the MERRA2 AGCM-like experiment is not consistent with the free atmosphere response to the  $RH_{crit}$  change because the
- 255 presence of boundary layer turbulence makes  $RH_{crit}$  less of a determining factor for model mean relative humidity there.

#### 3.4.2 Re-evaporation of Precipitation and Condensate

The MERRA2 AGCM scheme for the re-evaporation of precipitation and suspended cloud water and ice contains a series of new parameter settings that result in a substantial increase over the MERRA
model in the re-evaporation of snow and ice. The impact of the changes in parameter settings on the water vapor source due to re-evaporation for the December-January-February average is shown in figure 10. The largest increase in the MERRA2 AGCM is aloft, near 500 mb, where the increase is up to 0.7 g kg<sup>-1</sup> day<sup>-1</sup>.

Experiment 6 examines the impact of the change in re-evaporation of snow and ice in the MERRA2
AGCM, that is perhaps the most crucial parameterization change. The removal of this change is expected to result in a drier atmosphere, in particular aloft. Because of the importance of this change in parameterization, this simulation is expected to resemble in large part the climatology of the AGCM used as part of MERRA. Figure 11 shows the direct impact of the change from the MERRA2 AGCM to the MERRA AGCM re-evaporation, and, as expected, shows the drying related to the reduced re-

- 270 evaporation in the MERRA AGCM-like experiment. Figures 11a-c show the change in total precipitable water, and the difference (MERRA AGCM formulation minus MERRA2 AGCM formulation, shown in 11c) is always negative everywhere. The vertical distribution of the moisture is shown with the specific humidity in figures 11d-f, where the difference plot (11f) also shows an almost global reduction in atmospheric water vapor.
- 275 The resulting mean circulation in boreal winter underwent a substantial change associated with this drying, and represents the most substantial impact on the simulated climate of all the elements of the MERRA AGCM to MERRA2 AGCM transition. Figure 12 shows the <u>subtantial substantial</u> impact that changing the moisture levels had on the 30-year averaged December-January-February total precipitation. Given the Global Precipitation Climatology Project (GPCP, Huffman et al., 1995)
- 280 climatology as a reference, the MERRA2 AGCM-like experiment (experiment 5, figure 12d) exhibits an Intertropical Convergence Zone (ITCZ) structure that is properly placed in longitude, a South Pacific Convergence Zone (SPCZ) that properly slants from the western Pacific to the southeast, and more accurately simulated storm track maxima. The precipitation field represents improvements in all these areas related relative to the MERRA AGCM-like simulation (experiment 6) shown in figure
- 285 12a. The change in the tropical precipitation field related to the additional drying in experiment 6 also resulted in substantial changes in the Pacific teleconnection patterns, specifically the Pacific-North-America (PNA) pattern in boreal winter. The eddy height field is an indicator of the strength of the PNA, and is shown in figure 13 in relation to the eddy height from MERRA reanalysis. The MERRA2 AGCM-like simulated PNA pattern (figure 12d) has a stronger and more properly oriented
- 290 ridge near the west coast of North America relative to the PNA as simulated by the MERRA AGCMlike experiment (figure 12a). This change has implications for the poleward propagation of heat and momentum. The standard deviation of the difference from MERRA reanalysis estimates is also substantially reduced in experiment 5 (16.8 m) relative to experiment 6 (20.3 m). The direct impact of the change in re-evaporation was also evident in the boreal summer climatology. Figure 14 shows
- 295 this both in the total precipitable water fields and in the specific humidity fields, that exhibit where the differences between experiments 5 and 6 that are of the order of the differences seen in boreal winter. The impact on the mean summertime circulation, however, was minimal.

#### 3.5 Breakup of the Southern Hemisphere Stratospheric Jet

The changes to the gravity wave drag parameterization included the modification of the "inter-300 mittency factor", used to reduce the strength of the gravity wave drag based on expected departure from linear theory. The value of the intermittency factor was increased in the MERRA2 AGCM for orographic waves as a function of latitude, changing from a MERRA AGCM global value of 0.125 to values reaching 0.3125 south of approximately 40°S. This behavior is based on observational evidence of strong gravity waves from isolated small mountains in the Antarctic

305 peninsula (Alexander and Teitelbaum 2007) and the South Georgia islands (Alexander et al. 2009).

Experiment 7 is the last experiment in the series, incorporating the effects of all the fundamental changes between the MERRA and MERRA2 versions of the GEOS-5 AGCM. The removal of the intermittency change is expected to decrease the orographically induced drag in the southern hemisphere, thereby depositing less momentum aloft and increasing the strength of the westerlies. The

- 310 zero-wind contour of the zonal wind averaged from 50S to 70S in the southern hemisphere can be used as an indicator of the level and timing of the stratospheric jet breakup. Figure 15 shows the zero-wind contour of the averaged zonal wind from experiment 7, experiment 6, and MERRA. At the 2 degree horizontal resolution of the simulations described here, the zero wind line is higher in altitude and delayed in time relative to MERRA in both simulations, reflecting a delayed strato-
- 315 spheric jet breakup. The decreased intermittency factor in experiment 7, however, delays the jet breakup even more, showing the improvement in the MERRA2 AGCM-like simulation relative to the MERRA AGCM-like simulation. At higher spatial resolution (not shown) the increase of intermittency factor in the MERRA2 AGCM is effective in producing a reasonable evolution of the polar vortex breakdown in the southern Hemisphere.

#### 320 4 High resolution simulations and resolution aware behavior in the MERRA2 AGCM

The modifications to the MERRA2 AGCM physical parameterizations described above resulted in improvements in simulated climate at all the resolutions relevant to GMAO. Additional developments were implemented in the MERRA2 AGCM that were particularly applicable to higher resolution (0.25° or higher) simulations. These included the changes in ocean surface roughness at

high wind speeds (mentioned in section 3.1 and examined in detail in Molod et al., 2013) and the implementation of "resolution aware" parameters.

The implementation of the "resolution aware" behavior of the moist processes in the MERRA2 version of the GEOS-5 AGCM was designed in part to improve the behavior of the high resolution simulations and to ensure more uniformity of model mean state across resolutions and applications.

- Figure 16 shows an example of the undesireable behavior in the MERRA version of the AGCM that the "resolution aware" parameters were meant to address. Panels 16a-c show the difference between MERRA AGCM and ERA-Interim specific humidity at 1.°, 0.5° and 0.25° resolution, and panels 16g-i show 2.°, 1.° and 0.5° resolution, indicating the increase of the bias error in atmospheric moisture content relative to EC-Interim ERA-Interim reanalysis (Dee et al., 2011) as the resolution
- 335 increases.

Studies with many AGCMs used for climate and weather applications have reported large changes in the model solution as the horizontal resolution increases. For example, Williamson (2008) showed sensitivity of aqua-planet simulations to both resolution and time step, Roecker et al. (2006) reported on lack of convergence toward a single solution as the horizontal and vertical resolution changed

340 even though the higher resolution simulations showed improvements relative to the coarse resolution

result, and Bacmeister et al. (2014) showed a spurious precipitation pattern when the AGCM resolution was increased to 0.25 degrees.

In order to mitigate this change in the change (increasing error) in the GEOS-5 AGCM simulated climate with increasing resolution, the MERRA2 AGCM moist physics was modified to include two

345 governing parameters that are specified *a priori* as a function of horizontal resolution. These are the critical relative humidity used for large scale condensation, and a parameter which governs the minimum allowable entrainment used for the "stochastic Tokioka trigger" of the convective parameterization.

The dependance dependence of  $RH_{crit}$  on horizontal resolution is based on the Molod (2012) analysis of a global mesoscale simulation, and is such that the  $RH_{crit}$  above the planetary boundary layer increases with finer resolution, as was is seen in the progression from the 2° resolution curve up to the 0.25° 0.125° curve in figure 7. This progression is consistent with an intuitive expectation that the variability of total water within an AGCM grid cell decreases as the grid cell becomes smaller. The implementation of the horizontal resolution dependance dependence of  $RH_{crit}$  (as described in section 2) in the MERRA2 AGCM resulted in an atmospheric moisture field that is more consistent

across different resolutions, as seen in figure **??16d-f**.

The MERRA2 version of the GEOS-5 AGCM also includes a horizontal resolution dependent dependent and stochastic Tokioka (1988) type trigger (described in Bacmeister and Stephens, 2011) as part of the RAS convective parameterization. The cloud model in RAS computes the effect of in-

- 360 dividual entraining cloud plumes, and the trigger acts to effectively eliminate any cloud plume with too small an entrainment during ascent. Bacmeister and Stephens (2011) examined the observed relationship between the neutral <u>bouyancy buoyancy</u> level of a particular sounding and the observed condensate (a proxy for the convective detrainment level), and found that this observational relationship can be approximated by sampling the minimum entrainment from a power law PDF. The
- 365 parameters of the PDF are specified *a priori* in the MERRA2 AGCM, and vary with resolution. The stochasticity is designed to only occasionally permit the least entraining and therefore the deepest detraining cloud plumes. Lim et al., (2014) reported on a series of sensitivity studies to examine the impact of different choices of the PDF governing parameter on the simulation of strong tropical storms in the GEOS-5 AGCM.
- 370 The resolution dependence The resolution dependence of the stochastic Tokioka trigger is such that it more severly severely limits the parameterized convective mass flux at high spatial resolution, where we expect the larger scale convective updrafts to be resolved explicitly, and has little impact at low resolution. The This approach enables a relatively smooth transition from a fully parameterized cumulus convection at coarse resolution to a fully resolved cumulus convection at extremely high
- 375 resolution. The *ad hoc* specified change with resolution of the PDF parameters is shown in figure 17, presently specified in an *ad hoc* manner.

The basic approach implemented in the MERRA2 AGCM to limit the impact of the parameterized

convection at higher resolution is consistent with the approach of Arakawa and Wu (2013). They remove the assumption that the fraction of the grid box covered by convection is small, and model

- 380 the total convective transport in terms of a parameterized contribution and a contribution from eddy transport. The relative importance of these two contributions changes with resolution and in this way they generalize the cumulus parameterization so that it converges to an explicit simulation of convection at high resolution. Another approach to implementing resolution aware behavior in an AGCM's cumulus parameterization is that of Bechtold et al. (2008), implemented in the Integrated
- 385 Forecast System Model Cycle 40r1 of the European Center for Medium Range Weather Forecasting (documentation available at http://old.ecmwf.int/research/ifsdocs/). They compute a cumulus time scale that is sampled from a PDF whose parameters change with resolution, such that at high resolution the probability of finding a short time scale is increased. The net result is that the relative contribution of convective and resolved precipitation is relatively unchanged across resolutions, but
- 390 this scheme does not converge to allow a total dependance on explicitly resolved convection at the highest resolutions.

Figure 18 shows a sequence of the resulting-June averaged convective mass fluxes from MERRA2 AGCM simulations with different horizontal resolutions. The decrease of parameterized mass flux with resolution reflects the increasingly restrictive trigger, selected from the PDFs with increasingly

- 395 higher mimimum minimum entrainment values shown in figure 17. The effect of this repressed RAS mass flux on the simulated climate is reflected in the total change in moisture due to moist processes, shown in figure 19. The cloud model in RAS includes a grid scale subsidence to compensate for the updraft mass flux that results in a drying of the sub-cloud layer. Figure 19 shows the decrease of the low level drying with increased horizontal resolution. The benefits of the reduced low level
- 400 drying and the related maintenance of the cumulus available potential energy during tropical storm development in the GEOS-5 AGCM simulations at high resolution was demonstrated in the study of Lim et al. (2014).

#### 5 Conclusions

Synthesis and Discussion

- 405 The version of the GEOS-5 AGCM used in the Goddard Modeling and Assimilation Office (GMAO) MERRA2 reanalysis was developed for use across many different resolutions and applications. A unique series of AGCM simulations were performed with the GEOS-5 AGCM to detail the impact of each change in parameterization between the MERRA version and the current MERRA2 version. The series of sensitivity experiments began with the current AGCM version and regressed,
- 410 one step of development at a time, to the MERRA AGCM.

The most substantial positive impact on the simulated AGCM climate was shown to be attributable to the increase of the re-evaporation of frozen cloud water and precipitation in the MERRA2 AGCM.

The resulting atmosphere had a higher moisture content, and many aspects of the boreal winter climate were substantially improved relative to reanalysis. The moisture and cloud cover amounts

415 were shown to be further improved by the implementation of an AIRS-based PDF of total water.

The development of the MERRA2 AGCM also included the implementation of a set of parameters governing moist processes that contain an *a priori* change in behavior with horizontal resolution. The parameters are ones which govern the minimum minimum allowable entrainment into a convective updraft, and govern the atmospheric relative humidity needed for the onset of condensation. Results of a limited set of experiments were shown to demonstrate the benefits of this "resolution aware"

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behavior at higher resolution.

This study was focused on the results of atmosphere only simulations, but the resulting model has also performed well in coupled atmosphere ocean, coupled atmosphere chemistry, data assimilation, numerical weather prediction and global mesoscale applications.

#### 425 6 Code Availability

The GEOS-5 source code is available under the NASA Open Source Agreement at http://opensource.gsfc.nasa.gov/projects/GEOS-5/.

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#### References

- 450 Bacmeister Alexander, M. J., and H. Teitelbaum, 2007: Observation and analysis of a large amplitude mountain wave event over the Antarctic peninsula. J. Geophys. Res., 112, JD21103, doi:10.1029/2006JD008368.
  - Alexander, M. J., S. D. Eckermann, D. Broutmann, and J. Ma, 2009: Momentum flux estimates for South Georgia Island mountain waves in the stratosphere observed via satellite. Geophys. Res. Lett., 36, L12816, doi:10.1029/2009GL038587.
- 455 A. Arakawa and C.-M. Wu, 2013: A Unified Representation of Deep Moist Convection in Numerical Modeling of the Atmosphere. Part I. J. Atmos. Sci., 70, 1977–1992. doi: http://dx.doi.org/10.1175/JAS-D-12-0330.1
  - Bacmeister, Julio T., Michael F. Wehner, Richard B. Neale, Andrew Gettelman, Cecile Hannay, Peter H.
     Lauritzen, Julie M. Caron, and John E. Truesdale, 2014: Exploratory high-resolution climate simulations
     using the Community Atmosphere Model (CAM). J. Climate, 27, 3073-3099.
- 460 <u>Bacmeister, J.</u> T., Stephens, G.: Spatial statistics of likely convective clouds in CloudSat data. J. Geophys. Res., 116, D04104, doi:10.1029/2010JD014444, 2011.
  - Bacmeister, J. T., Suarez, M. J. and Robertson, F. R. : Rain reevaporation, boundary layer–convection interactions, and Pacific rainfall patterns in a AGCM. J.Atmos. Sci., 63, 3383–3403, 2006.
- Bechtold, P., M. Köhler, T. Jung, F. Doblas-Reyes, M. Leutbecher, M. J. Rodwell, F. Vitart, and G. Balsamo,
   2008: Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time scales. Quart. Journ. Royal MEteorol. Soc., 134, 1337-1351. DOI: 10.1002/qj.289
  - Chou, M. -D., and Suarez, M. J.: An efficient thermal infrared radiation parameterization for use in general circulation models. NASA Tech. Memorandum 104606-Vol 3, NASA, Goddard Space Flight Center, Greenbelt, MD, 1994.
- 470 Chou, M. -D., and Suarez, M. J.: A Solar Radiation Parameterization for Atmospheric Studies. NASA Tech. Memorandum 104606-Vol 15, NASA, Goddard Space Flight Center, Greenbelt, MD, 1999.
  - Cullather, R. L., Nowicki, S. M. J., Zhao B., and Suarez, M.J.: Evaluation of the surface representation of the Greenland ice sheet in a general circulation model. J. Climate, 27, 4835-4856. doi: 10.1175/JCLI-D-13-00635.1, 2014.
- 475 Dee, DP, and co-authors: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Q. J. R. Meteorol. Soc. 137, 553–597, 2011.
  - Donner, L., and co-authors: The Dynamical Core, Physical Parameterizations, and Basic Simulation Characteristics of the Atmospheric Component AM3 of the GFDL Global Coupled Model CM3 J. Climate, 24, 3484. doi:10.1175/2011JCLI3955.1, 2011.
- 480 Duynkerke, P., and de Roode, S.: Surface energy balance and turbulence characteristics observed at the SHEBA Ice Camp during FIRE III. J. Geophys. Res., 106, 15313–15322, doi:10.1029/2000JD900537, 2001.
  - Helfand, H. M., and Schubert, S. D.: Climatology of the Simulated Great Plains Low-Level Jet and Its contribution to the Continental Moisture Budget of the United States. J. Climate, 8, 784-806, 1995.
- Huffman, G., Adler, R.F., Rudolf, B., Schneider, U. and Keehn, P.R.: Global precipitation estimates based
  on a technique for combining satellite-based estimates, rain gauge analysis, and NWP model precipitation information. J. Climate, 8, 1284-1295, 1995.
  - Garcia, R. R., and Boville, B. A.: Downward control of the mean meridional circulation and temperature distribution of the polar winter stratosphere. J. Atmos. Sci., 51, 2238–2245, 1994.

Garfinkel, C.I., Molod, A., Oman, L. D. and Song, I.-S.: Improvement of the GEOS-5 AGCM upon Updating

- the Air-Sea Roughness Parameterization. Geophys. Res. Lett., 38, L18702, doi:10.1029/2011GL048802, 2011.
  - Gettelman, A., H. Morrison, S. Santos, P. Bogenschutz, and P. M. Caldwell, 2015: Advanced Two-Moment Bulk Microphysics for Global Models. Part II: Global Model Solutions and Aerosol–Cloud Interactions. J. Climate, 28, 1288–1307. doi: http://dx.doi.org/10.1175/JCLI-D-14-00103.1
- Kondo, J.: Air-sea bulk transfer coefficients in diabatic conditions. Boundary Layer Meteor., 9, 91-112, 1975.
   Koster, R. D., Suarez, M.J., Ducharne, A., Stieglitz, M. and Kumar, P.: A catchment-based approach to modeling land surface processes in a GCM, Part 1, Model structure. J. Geophys. Res., 105, 24 809–24 822, 2000.
  - Large, W. G., and Pond, S.: Open ocean momentum flux measurements in moderate to strong winds. J. Phys. Oceanogr., 11, 324-336, 1981.

500

- Lim, Y.-K., Schubert, S. D., Reale, O., Lee, M.-I., Molod, A. and Suarez, M. J.: Sensitivity of Tropical Cyclones to Parameterized 2 Convection in the NASA GEOS5 Model. J. Climate, Sub Judice, 2014.
  - Lock, A. P., Brown, A. R., Bush, M. R., Martin, G. M. and Smith, R. N. B.: A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. Mon. Wea. Rev., 138, 3187–3199, 2000.
- 505 Louis, J. E.: A Parametric Model of Vertical Eddy Fluxes in the Atmosphere, Bound. Lay. Meteorol., 17, 187-202, 1979.
  - Louis, J. and Geleyn, J.: A short history of the PBL parameterization at ECMWF. Proc. ECMWF Workshop on Planetary Boundary Layer Parameterization, Reading, United Kingdom, ECMWF, 59–80, 1982.

McFarlane, Manzini, E., N. A. McFarlane, and C. McLandress, 1997: Impact of the Doppler spread

510 parameterization on the simulation of the middle atmosphere circulation using the MA/ECHAM4 general circulation model. J. Geophys. Res., 102(D22), 25751-25762, doi:10.1029/97JD01096.

McFarlane, N. A.: The effect of orographically excited gravity-wave drag on the circulation of the lower stratosphere and troposphere. J. Atmos. Sci., 44, 1775-1800, 1987.

Molod, A., Suarez, M. J. and Partyka, G.: The impact of limiting ocean roughness on GEOS-5 AGCM tropical
cyclone forecasts. Geophys. Res. Lett., 40, 411-415. DOI: 10.1029/2012GL053979, 2013.

- Molod, A.: Constraints on the Profiles of Total Water PDF in AGCMs from AIRS and a High-Resolution Model. J. Climate, 25, 8341–8352, 2012.
  - Molod, A., Takacs, L. L., Suarez, M. J., Bacmeister, J. T., Song, I.-S. and Eichmann, A.: The GEOS-5 Atmospheric General Circulation Model: Mean Climate and Development from MERRA to Fortuna. NASA Tech.
- 520 Memo. 104606, Volume 28, Tech. Rep. Series on Global Modeling and Data Assimilation, Max J. Suarez, ed, 117 pp., 2012.
  - Moorthi, S., and Suarez, M.J.: Relaxed Arakawa Schubert: A parameterization of moist convection for general circulation models. Mon. Wea. Rev., 120, 978-1002, 1992.
  - Neale, R. B., Richter, J., Park, S., Lauritzen, P. H., Vavrus, S. J., Rasch, P. J. and Zhang, M.: The Mean Climate
- 525 of the Community Atmosphere Model (CAM4) in Forced SST and Fully Coupled Experiments, Journal of Climate, 26, p. 5150-5168, doi: 10.1175/JCLI-D-12-00236.1, 2013.
  - Pope, V. D., Gallani, M. L., Rowntree, P. R. and Stratton, R. A.: The impact of new physical parametrizations in the Hadley Centre climate model - HadAM3. Climate Dynamics, 16, 123-146, doi:10.1007/s003820050009,

2000.

- 530 Richter, J. H., F. Sassi, and R. R. Garcia, 2010: Toward a physically based gravity wave source parameterization in a general circulation model. J. Atmos. Sci., 67, 136-156, doi: http://dx.doi.org/10.1175/2009JAS3112.1.
  - Rienecker, M. M., and co-authors: The GEOS-5 Data Assimilation System—Documentation of versions 5.0.1 and 5.1.0, and 5.2.0. NASA Tech. Rep. Series on Global Modeling and Data Assimilation, NASA/TM-2008-104606, Vol. 27, 92 pp., 2008.
- 535 Rienecker, M.M., and co-authors: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. J. Climate, 24, 3624-3648, 2011.
  - Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An improved in situ and satellite SST analysis for climate. J. Climate, 15, 1609–1625.
  - Roeckner, E., R. Brokopf, M. Esch, M. Giorgetta, S. Hagemann, L. Kornblueh, E. Manzini, U. Schlese, and U.
- 540 Schulzweida, 2006: Sensitivity of Simulated Climate to Horizontal and Vertical Resolution in the ECHAM5 Atmosphere Model. J. Climate, 19, 3771–3791. doi: http://dx.doi.org/10.1175/JCLI3824.1

Scaife, A. A., N. Butchart, C. D. Warner and R. Swinbank, 2002: Impact of a spectral gravity wave parameterization on the stratosphere in the Met Office Unified Model. J. Atmos. Sci., 59, 1473-1489, doi: http://dx.doi.org/10.1175/1520-0460(2002)059;1473:IOASGW;2.0.CO:2

- 545 Schmidt, G.A. and co-authors:Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. J. Climate 19, 153-192, 2006.
  - Shie, C.-L., Chiu, L. S., Adler, R., Nelkin, E., Lin, I.-I., Xie, P., Wang, F.-C., Chokngamwong, R., Olson, W., and Chu, D. A.: A Note on reviving the Goddard satellite-based surface turbulent fluxes (GSSTF) dataset. Adv. Atmos. Sci., 26(6), 1071-1080, 2009.
- 550 Stieglitz, M., Ducharne, A., Koster, R. D. and Suarez, M.J.: The Impact of Detailed Snow Physics on the Simulation of Snowcover and Subsurface Thermodynamics at Continental Scales. J. Hydromet., 2, 228-242, 2001.

Takacs, L., Suarez, M. J. and Todling, R.: Maintaining Atmospheric Mass Balance within Reanalysis. NASA Tech. Memo. 104606, Volume 34 Technical Report Series on Global Modeling and Data Assimilation, R.

- 555 Koster, ed., 2014.
  - Tokioka, T., K. Yamazaki, A. Kitoh, and T. Ose (1988), The equatorial 30–60 day oscillation and the Arakawa Schubert penetrative cumulus parameterization, J. Meteorol. Soc. Jpn., 66, 883–901
  - Williamson, David L., 2008: Convergence of aqua-planet simulations with increasing resolution in the Community Atmospheric Model, Version 3. Tellus A 60, 848-862, DOI: 10.1111/j.1600-0870.2008.00339.x

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Fig. 1. Scatter diagram of surface wind speed (m  $\sec^{-1}$ ) versus ocean roughness (mm) in the MERRA (green) and MERRA2 (black) AGCMs.



**Fig. 2.** 30-year average December-January-February surface wind speed (m sec<sup>-1</sup>) from: a) MERRA2 control, b) GSSTF, c) Control-GSSTF, d) Experiment 1, e) Experiment 1-GSSTF



**Fig. 3.** Background nonorographic drag from the MERRA (dashed line) and MERRA2 AGCM (solid line) simulations. The dashed line underlies the solid line outside of the tropics.



**Fig. 4.** Spatial average of zonal wind in  $m s^{-1}$  from 10S to 10N latitude as a function of pressure level in mb and time from a) MERRA2 AGCM control, b) Experiment 2 and c) MERRA reanalysis.



Fig. 5. Surface bulk Richardson number as a function of sensible heat flux in W  $m^{-2}$  in a single July from experiment 3 (red) and experiment 2 (black).



**Fig. 6.** June-July-August averaged sensible heat flux in  $W m^{-2}$  from a) Experiment 3 (Louis surface layer scheme), b) experiment 2 (Helfand scheme) and c) the difference, experiment 3 minus experiment 2.



**Fig. 7.** Critical relative humidity. Black from MERRA AGCM formulation, blue from MERRA2 AGCM formulation for  $2^{\circ}$  resolution, purple from MERRA2 AGCM formulation for  $1^{\circ}$  resolution, brown from MERRA2 AGCM formulation for  $1/2^{\circ}$  resolution, green from MERRA2 AGCM formulation for  $1/4^{\circ}$  resolution, orange from MERRA2 AGCM formulation for  $1/8^{\circ}$  resolution.



**Fig. 8.** December-January-February averaged relative humidity in percent from a) Experiment 5 (MERRA AGCM-like), b) experiment 4 (MERRA2 AGCM-like) and c) the difference, experiment 5 minus experiment 4.



**Fig. 9.** December-January-February averaged cloud fraction from a) Experiment 5 (MERRA AGCM-like), b) experiment 4 (MERRA2 AGCM-like) and c) AIRS retreivals



**Fig. 10.** The difference (MERRA2 AGCM-like minus MERRA AGCM-like) of zonal mean specific humidity source term due to all re-evaporation for December-January-February.



**Fig. 11.** a) December-January-February total precipitable water in mm from experiment 6 (MERRA AGCM-like), b) same as a) but from experiment 5, c) same as a) but the difference, experiment 6 minus experiment 5, d) December-January-February specific humidity in  $g kg^{-1}$  from experiment 6 (MERRA AGCM-like), e) same as d) but from experiment 5, f) same as d) but the difference, experiment 6 minus experiment 5.



**Fig. 12.** December-January-February total precipitation in  $mm day^{-1}$  from a) experiment 6 (MERRA AGCM-like), b) GPCP, c) the difference, experiment 6 minus GPCP, d) experiment 5 (MERRA2 AGCM-like), e) the difference, experiment 5 minus GPCP. The gray shading indicates land areas.



**Fig. 13.** December-January-February 300 mb Eddy Height Climatology in m from a) experiment 6 (MERRA AGCM-like), b) MERRA, c) the difference, experiment 6 minus MERRA, d) experiment 5 (MERRA2 AGCM-like), e) the difference, experiment 5 minus MERRA.



**Fig. 14.** a) June-July-August total precipitable water in mm from experiment 6 (MERRA AGCM-like), b) same as a) but from experiment 5, c) same as a) but the difference, experiment 6 minus experiment 5, d) June-July-August specific humidity in  $g kg^{-1}$  from experiment 6 (MERRA AGCM-like), e) same as d) but from experiment 5, f) same as d) but the difference, experiment 6 minus experiment 5.



Fig. 15. The annual cycle of the zero-contour of the 30-year averaged zonal mean zonal wind, averaged from 70S to 50S latitude in  $m \sec^{-2}$  from Experiment 7 in red (MERRA AGCM-like), experiment 6 in blue (MERRA2 AGCM-like) and MERRA in green



**Fig. 16.** December-January-February seasonal mean difference of specific humidity in  $g kg^{-1}$  for a) MERRA-like AGCM - ERA-Interim at 2 degree resolution, b) MERRA-like AGCM - ERA-Interim at 1 degree resolution, c) MERRA-like AGCM - ERA-Interim at 1/2 degree resolution, d) MERRA2-like AGCM - ERA-Interim at 2 degree resolution, e) MERRA2-like AGCM - ERA-Interim at 1 degree resolution, f) MERRA2-like AGCM - ERA-Interim at 1/2 degree Resolution, f) MERRA2-like AGCM - ERA-Interim at 1/2 degree Resolution, f) MERRA2-like AGCM - ERA-Interim at 1/2 degree Resolution AGCM - ERA-Interim at 1/2 degree RE



**Fig. 17.** The probability distribution function for the mimimum entrainment allowed by the cumulus parameterization for different AGCM horizontal resolutions. Black line is for 2x2.5 degree, blue for 1 degree, red for 1/2 degree and green for 1/4 degree.



**Fig. 18.** June-July-August seasonal mean cumulus mass flux in kg  $m^{-2} day^{-1}$  from MERRA2-like AGCM for a) 1 degree resolution, b) 1/2 degree resolution, c) 1/4 degree resolution, d) 10 km resolution.



**Fig. 19.** June-July-August seasonal mean change in moisture due to moist processes in  $g kg^{-1} day^{-1}$  from MERRA2-like AGCM for a) 1 degree resolution, b) 1/2 degree resolution, c) 1/4 degree resolution.

Table 1.	Changes in	GCM Algorithms	from	MERRA	to MERRA2
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Module	Algorithm Change	Comments	
Moist	Increased re-evaporation of precipitation	Fundamental change in model climate	
	Modified autoconversion	Fundamental change in model climate	
	Modified effective radius of cloud drops	Fundamental change cloud forcing	
	Anvil fractions cut in half	Fundamental change cloud forcing	
	Autoconvert 'warm fog'	Important change in coupled simulations	
	New critical RH with resolution dependance	Substantial change in simulated moisture	
	Cloud base set at PBL depth	Remove clouds detraining below PBL height	
	RAS time scale no longer depends on turbulence		
	Stochastic RAS with resolution dependance	Substantial impact at high resolution	
Turb	Remove restrictions on diffusion from Louis	Increase near surface diffusion	
	Reformulate turbulent length scale in Louis		
	Reduce Lock scheme when there is wind shear	Impact on marine PBL	
	Reduce cloud top entrainment for Lock plumes	Impact on marine PBL	
Surf	Implement Helfand and Schubert scheme		
	Remove viscous sublayer over land surfaces	Improve land temperatures	
	Change ocean roughness for middle wind regimes	Reduce wind bias in S. Ocean	
	Change ocean roughness high wind regimes	Increase tropical cyclone intensity	
Land Surf	Changed parameters for evapotranspiration	Impact on ratio of surface to canopy evaporation	
GW Drag	Changed profile of background drag	Substantial impact on QBO	
	Added intermittency of drag	Impact on timing of winter jet breakup	

**Table 2.** Experiments to attribute MERRA to MERRA2 AGCM simulation changes to changes in parameterizations.

Experiment	Description
Control	
Exp 1	Back off change in ocean roughness
Exp 2	Exp 1 + Back off gravity wave background drag and surface hydrology
Exp 3	Exp 2 + use old surface layer parameterization
Exp 4	Exp 3 + Back off increase of Richardson-number diffusion
Exp 5	Exp 4 + Back off decrease of critical RH aloft and decrease below
Exp 6	Exp 5 + Back off increase of all re-evaporation
Exp 7	Exp 6 + Back off gravity wave drag intermittency