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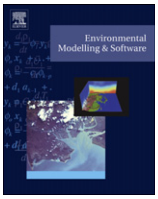

The NASA-Goddard Multi-scale Modeling Framework–Land Information System: Global land/atmosphere interaction with resolved convection☆

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ABSTRACT

The present generation of general circulation models (GCM) use parameterized cumulus schemes and run at hydrostatic grid resolutions. To improve the representation of cloud-scale moist processes and land–atmosphere interactions, a global, Multi-scale Modeling Framework (MMF) coupled to the Land Information System (LIS) has been developed at NASA-Goddard Space Flight Center. The MMF–LIS has three components, a finite-volume (fv) GCM (Goddard Earth Observing System Ver. 4, GEOS-4), a 2D cloud-resolving model (Goddard Cumulus Ensemble, GCE), and the LIS, representing the large-scale atmospheric circulation, cloud processes, and land surface processes, respectively. The non-hydrostatic GCE model replaces the single-column cumulus parameterization of fvGCM. The model grid is composed of an array of fvGCM gridcells each with a series of embedded GCE models. A horizontal coupling strategy, GCE ↔ fvGCM ↔ Coupler ↔ LIS, offered significant computational efficiency, with the scalability and I/O capabilities of LIS permitting land–atmosphere interactions at cloud-scale. Global simulations of 2007–2008 and comparisons to observations and reanalysis products were conducted. Using two different versions of the same land surface model but the same initial conditions, divergence in regional, synoptic-scale surface pressure patterns emerged within two weeks. The sensitivity of large-scale circulations to land surface model physics revealed significant functional value to using a scalable, multi-model land surface modeling system in global weather and climate prediction.

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1. Introduction

The land and atmosphere form a highly coupled system. Surface heat and momentum fluxes are linked to the surface net radiation flux, the vegetation state, and the profiles of temperature and water from below the surface up through the atmospheric boundary layer. The fluxes of heat, momentum, and moisture across the land/atmosphere interface are influenced by the heterogeneous character of the land surface layer and vary on spatial scales ranging from meters to thousands of kilometers. Linking the water and energy cycles is precipitation. Feedbacks between the heterogeneous land surface and the boundary layer affect the development of clouds and precipitation (review in Pielke, 2001). The vertical distribution of latent heat released through the formation of clouds and precipitation modulates the large-scale atmospheric dynamics of the low and mid-latitudes, affecting the distribution, intensity, and longevity of waves, jets, and fronts, and thus to future precipitation patterns. Coupling a general circulation model (GCM) to a land surface model (LSM) allows for two-way interaction of atmospheric moist processes with the land surface. By coupling a GCM to a multi-model Land Information System (LIS) rather than to a single LSM, significant additional physical and functional flexibility is achieved (Kumar et al., 2006; Peters-Lidard et al., 2007). This paper describes the NASA-Goddard finite-volume Multi-scale Modeling Framework–Land Information System (MMF–LIS), a global model framework capable of explicitly resolving cumulus convection and simulating cloud-scale land/atmosphere interactions. The MMF–LIS integrates an atmospheric GCM with a 2D cloud-resolving model (CRM) for explicit simulation of cumulus clouds and couples the LIS to the GCM. We describe the development and operation of the current Goddard MMF–LIS, focusing on the model coupling and its initial testing, particularly with respect to surface variables. This paper can be viewed as a third companion to two previous papers on LIS, the first

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description of LIS by Kumar et al. (2006) and the role of LIS in coupled mesoscale modeling by Kumar et al. (2008). The MMF–LIS enhances our ability to investigate the integrated impact of small-scale cloud microphysics and soil and vegetation states on regional to global-scale circulations, cloud patterns, and precipitation.

2. Background: global multi-scale modeling

The current generation of GCMs used in operational global weather and short-term climate forecasting by the National Centers for Environmental Prediction (NCEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and the NASA Global Modeling and Assimilation Office have fully interactive land/atmosphere coupling using single LSMs, respectively, Noah (Ek et al., 2003), Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land (H-TESSEL, Balsamo et al., 2009), and Catchment (Koster et al., 2000). Although the NCEP Global Forecast System (GFS) uses the NASA LIS for land data assimilation, only Noah is fully and directly coupled to the GFS atmospheric model component (Saha et al., 2010). These operational LSMs use tiles or catchment sub-divisions to improve the representation of the land surface heterogeneity within GCM gridcells. However, the surface fluxes generated are spatially averaged so that the atmospheric component can use a parameterized cumulus scheme to determine gridcell clouds and precipitation. Model comparison projects in the Global Energy and Water Cycle Experiment (GEWEX) have shown that simulations of various types of clouds and cloud systems from different geographic locations by cloud-resolving models (CRM) agree with observations better than those from cumulus parameterizations used by the current generation of GCMs (Moncrieff et al., 1997; Randall et al., 2003b). The lumping of land/atmospheric interactions and the use of cumulus parameterizations for cloud-scale moist processes are sources of significant uncertainty in predictions at larger scales (Zhang et al., 2005; Pauluis and Garner, 2006; Shutts and Palmer, 2007).

The grid size of GCMs is moving toward grids sufficiently fine to explicitly resolve many cloud systems, but the computational cost is enormous and, because of the importance of unresolved processes at still finer scales, convergence is by no means assured. A CRM can simulate clouds at meter- to kilometer-scale grid resolutions. Computational infrastructure typically limits the simulation of clouds and cloud systems by CRMs to a relatively small domain ($\leq 10^3$-km × 10^3-km) and short time periods (<1 month). Grabowski (2001) and Khairoutdinov and Randall (2001) first proposed the use of 2D cloud-resolving models as a *"super-parameterization"* to simulate cloud processes within GCM gridcells, replacing cumulus parameterizations. Arakawa (2004) describes this configuration as a *multi-scale modeling framework* (MMF). In the MMF, a non-hydrostatic 2D CRM takes the place of the single-column cumulus parameterization used in conventional GCMs (Randall et al., 2003a; Arakawa, 2004; Tao et al., 2009).

There are two teams developing MMFs, a newer effort by Goddard and a longer running effort by Colorado State University (CSU). The CSU MMF combines the Community Atmosphere Model 3.0 (CAM, Collins et al., 2006), the System for Atmospheric Modeling (SAM, Khairoutdinov and Randall, 2003), and the Community Land Model (CLM, Dai et al., 2003) to form the super-parameterized CAM (SP-CAM). The GCMs at the core of the Goddard and CSU MMFs share a common ancestor, the National Center for Atmospheric Research (NCAR) Community Climate Model Ver. 3 (CCM3), but underwent separate additional development by Goddard and NCAR researchers.

Taking on phenomena that have been identified as difficult for GCMs to reproduce well, CSU researchers have shown better results with SP-CAM in reproducing the diurnal cycle of convection (DeMott et al., 2007), orogenic propagating cloud systems (Pritchard et al., 2011), subtropical low cloud fields (Blossey et al., 2009), and precipitation anomalies associated with the Madden–Julian oscillation (Benedict and Randall, 2009) and El Niño–Southern Oscillation (ENSO, Khairoutdinov et al., 2008). Tao et al. (2009) compare the SP-CAM and an earlier version of the Goddard MMF. Both MMFs resulted in better representation of global energy and water cycles compared to GCMs with cumulus parameterizations but had their own set of biases from using 2D CRMs and prescribed sea surface temperatures. Researchers at Pacific Northwest National Laboratory (PNNL) added to SP-CAM an explicit-cloud parameterized-pollutant approach that links aerosol and chemical processes on the large-scale grid with statistics of cloud properties and processes resolved by the CRM (Wang et al., 2011a, 2011b). The PNNL MMF can be used to study aerosol effects on cloud microphysics (indirect effect) globally, a study topic typically confined to a CRM-sized domain.

In Tao et al. (2009), the differences between the CSU and Goddard MMFs were smaller than their differences with standard GCMs. These differences may become larger less from the diverging evolution of their parent GCMs than from the addition of additional model components. The emphasis here at Goddard on land/atmosphere interactions and hydrologic model development has produced an MMF in which "multi-scale" includes the land surface and a significant range of options are available to the user through LIS. Here, we describe the development and operation of the current Goddard MMF–LIS, focusing on the model coupling and its initial testing, particularly with respect to surface variables.

3. Components of MMF–LIS

Fig. 1 depicts the integration and coupling of the components of MMF–LIS. The three principal components are a finite-volume (fv) GCM (Goddard Earth Observing System Ver. 4, GEOS-4), a 2D CRM (Goddard Cumulus Ensemble, GCE), and the LIS, representing the large-scale atmospheric circulation, cloud processes, and land surface processes, respectively. All numerical analysis is written in FORTRAN90. The C language is used to expand object-oriented features already in FORTRAN90, providing a virtual object-oriented programming environment managing operations within and between components. The MMF–LIS components represent the work of several different teams of scientists and engineers at Goddard. The fvGCM was developed in the former NASA Data Assimilation Office. The successor to the Data Assimilation Office, the Global Modeling and Assimilation Office (GMAO), adopted the fvGCM as their first operational model. The CRM was developed in the Mesoscale Atmospheric Processes Laboratory, and the LIS was developed by the Hydrological Sciences Laboratory. Assisted by the Hydrological Sciences Laboratory, the Mesoscale Atmospheric Processes Laboratory performed the integration and coupling of the three MMF–LIS components.

3.1. The Goddard Earth Observing System Ver. 4 (GEOS-4)

The fvGCM of MMF–LIS, the GEOS-4, was constructed by combining the finite-volume dynamical core developed at Goddard (Lin, 2004) with the physics package of the NCAR CCM3, which represents a well-balanced set of processes with a long history of development and documentation (Kiehl et al., 1998). The unique features of the finite-volume dynamical core include an accurate conservative flux-form semi-Lagrangian transport algorithm with a monotonicity constraint on sub-grid distributions that is free of Gibbs oscillation (Lin and Rood, 1996, 1997), a terrain-following Lagrangian control-volume vertical coordinate (σ-coordinate),