Full Coupling Between the Atmosphere, Surface and Subsurface for Integrated Hydrologic Simulation

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Key Points:

- Coupling of HydroGeoSphere (HGS) to Weather Research and Forecasting (WRF).
- Demonstration of the coupled HGS-WRF model with the California Basin.
- Comparison of the coupled HGS-WRF model to standalone WRF.

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Abstract

An ever increasing community of earth system modelers are incorporating new physical processes into numerical models. This trend is facilitated by advancements in computational resources, improvements in simulation skill, and the desire to build numerical simulators that represent the water cycle with greater fidelity. In this quest to develop a state-of-the-art water cycle model, we coupled HydroGeoSphere (HGS), a 3D control-volume finite element surface and variably-saturated subsurface flow model that includes evapotranspiration processes, to the Weather Research and Forecasting (WRF) Model, a 3D finite difference nonhydrostatic mesoscale atmospheric model. The two-way coupled model, referred to as HGS-WRF, exchanges the actual evapotranspiration fluxes and soil saturations calculated by HGS to WRF; conversely, the potential evapotranspiration and precipitation fluxes from WRF are passed to HGS. The flexible HGS-WRF coupling method allows for unique meshes used by each model, while maintaining mass and energy conservation between the domains. Furthermore, the HGS-WRF coupling implements a sub-time stepping algorithm to minimize computational expense. As a demonstration of HGS-WRF's capabilities, we applied it to the California Basin and found a strong connection between the depth to the groundwater table and the latent heat fluxes across the land surface.

1 Introduction

Numerical modelers typically subdivide the terrestrial environment into multiple domains, the atmosphere, land surface, and subsurface, and commonly simulate each one independently. The most prevalent approach is to first run the atmospheric model, and then apply its output to a hydrologic simulation. Although sequential modeling may be seen as an acceptable practice, current climate models do not rigorously handle the near surface water balance, especially in the groundwater domain, which may produce a large simulation bias once forecasts exit their calibration envelope.

Current climate models coupled to land surface models (LSMs) are often utilized to predict the risks to water resources [**?**]. Typically, LSMs are one-dimensional vertical columns that include shallow vertical vadose zone flow, biogeophysics, heat transport, and snow processes [**?**]. However, LSMs lack physics-based lateral surface/subsurface water flow, groundwater storage dynamics, and the critical feedbacks between surface and subsurface hydrology [**??**].

To overcome these limitations, land-surface modelers have replaced their simple one-dimensional hydrologic models with more advanced water balance approaches, although these more advanced models still contain shortcomings [**???**]. For example, the Weather Research and Forecasting (WRF) Model, a 3-D mesoscale nonhydrostatic atmospheric model, has been coupled to several groundwater flow models, including Noah Disturbed, a 2-D areal Boussinesq groundwater flow model [**??**], which fails when groundwater tables are steep (e.g. near pumping wells or around mountainous topography). In a separate study, WRF was coupled to ParFlow, a 3-D finite difference surface/subsurface flow model [**?**]. Additionally, ParFlow was coupled to the COSMO (Consortium for Small-scale Modeling) atmospheric model via the OASIS (Ocean-Atmosphere-Sea-Ice-Soil) coupling package [**???**]. However, ParFlow relies on the Noah LSM or CLM for representing the evapotranspiration process, which limits root-zones to the near-surface.

Coupled hydrologic atmospheric simulations have been applied to a large host of problems. WRF-Hydro [**?**] simulated a three year period over the Crati River Basin in Southern Italy, and found that the fully coupled simulation outperformed the uncoupled precipitation patterns [**?**]. WRF-HMS, an LSM with a lateral 2-D Boussinesq groundwater flow model [**?**], was applied to Poyang Lake basin (160,000 km^2) and observed a 5% change in spatial precipitation patterns for coupled vs. uncoupled models [**?**]. WRF-ParFlow modeled the San Joaquin watershed and correlated a connection between the depth of water table with an increased planetary boundary height [**?**].

A framework fully coupling the atmosphere, surface, and subsurface should have more skill than previous serial methods because the hydrologic model would replace the climate model's shallow earth assumption, producing a dynamically linked atmosphere, surface and subsurface system. For this reason, we coupled an advanced hydrologic model, HydroGeoSphere, to a mesoscale meteorological model, the Weather Research and Forecasting Model (WRF Model Version 3.7.1, August 14, 2015) [**??**].

2 Numerical Models

2.1 HydroGeoSphere Terrestrial Model

HydroGeoSphere (HGS) is a fully-integrated, globally implicit, finite difference or control-volume finite element, surface and variably-saturated subsurface flow model with evapotranspiration processes, solved by a Newton-Raphson parallelized solver and an adaptive time-stepping scheme [**?????**]. HGS has been implemented over a large range of scales including small-scale test catchments [**????**], regional flow systems [**???**], large drainage networks [**???**], and continental scale basins [**?**]. Furthermore, HGS was adapted to include heat transport processes [**??**] and was used as an LSM coupled to an atmospheric boundary layer model [**?**].

HGS implements the non-linear three-dimensional variably-saturated Richards' equation for subsurface flow:

$$S_w S_s \frac{\partial \psi}{\partial t} + \theta_s \frac{\partial S_w}{\partial t} = \nabla \cdot (\mathbf{K} \cdot k_r \nabla(\psi + z)) + \sum \Gamma_{ex} + Q \tag{1}$$

where Γ_{ex} [T^{-1}] is the internal fluid exchanges between domains (surface, subsurface, fractures, macropores, pumping wells, and tile drains) and Q [T^{-1}] is the external fluid exchanges (e.g. evapotranspiration, snow melt). The parameters S_s [L^{-1}], z [L], θ_s [-], and $\mathbf{K}$ are the specific storage [LT^{-1}], elevation, saturated water content, and hydraulic conductivity, respectively. The pressure head, ψ [L], and relative permeability, k_r [-], are functions on the water saturation, S_w [-], which is approximated by lookup tables or by numerical parameterizations (e.g., **?**, **?**).

The two-dimensional surface domain is draped over the subsurface flow regime, and the two domains are directly linked by applying either the common node or dual-node techniques. The common node method enforces the exact same head values for each shared node, while the dual-node approach estimates a flux between the two domains. Overland flow in the surface domain is based on the diffusion-wave equation:

$$\frac{\partial(d_o + z)}{\partial t} = \nabla \cdot (\mathbf{K_O} \cdot \nabla(d_o + z)) - d_o\Gamma + Q \tag{2}$$

which assumes mild slopes, depth-integrated velocities, and neglects inertial effects. The surface hydraulic conductivity $\mathbf{K_O}$ [LT^{-1}] is approximated as a function of depth, d_o [L], by the Manning, Chezy, or Darcy-Weisbach equations.

HGS implements a process-based framework to calculate evapotranspiration (ET) based on the soil saturation, potential evapotranspiration (PET), soil type and vegetation parameters. ET processes are an implicit component of HGS' flow simulation and are simultaneously solved within the flow solution. Actual evapotranspiration, AET [LT^{-1}], in HGS is comprised of three components (canopy evaporation E_{can} [LT^{-1}], transpiration T_p [LT^{-1}], and bare soil (or open water) evaporation E_s [LT^{-1}]):

$$AET = E_{can} + T_p + E_s \tag{3}$$

where each component is always positive and the sum of the components can never exceed the PET [LT^{-1}]. The transpiration and evaporation functions are implemented as:

$$T_p = f_1(LAI)f_2(S)RDF[PET - E_{can}] \tag{4}$$

$$E_s = \alpha^*(PET - E_{can} - T_p)EDF \tag{5}$$

where LAI [-] is the leaf area index, S [-] is the soil moisture content, RDF is the root density function, EDF is the energy density function, and f_1 [-], f_2 [-], and α^* [-] are fitting functions. The reader is referred to the HydroGeoSphere user manual of the processes represented in HGS as well as the numerical solution procedures employed [**?**].

2.2 Weather Research and Forecasting Atmospheric Model

The Weather Research and Forecasting (WRF) Model is a non-hydrostatic mesoscale finite difference atmospheric model. The WRF modeling suite hosts two separate dynamical cores (for the purpose of this study we used only the Advanced Research WRF (ARW) core), data assimilation, advanced physics-based parameterization, numerous radiative schemes, and multiple land surface models. The WRF model implements the terrain following flux-based Euler equations solved by the third-order Runge-Kutta temporal discretization with a second-order split-time acoustic wave. A detailed description of WRF's development can be found in the NCAR Technical Note, *A Description of the Advanced Research WRF Version*

3 [**?**].

The Noah LSM [**?**] is one of the most popular land surface schemes in the WRF model. It simplifies the near surface as a shallow 2 m thick series of one-dimensional columns that incorporate vadose zone hydrology and heat transport. The subsurface domain is modeled with four vertical layers that range between 10 to 100 cm thick. The benefits of using the Noah LSM coupled to WRF are that it includes vadose zone hydrology, subsurface heat transport, plant physics, and it is computationally efficient and easy to use. However, the Noah LSM fails to include three-dimensional subsurface flow, surface water flow, and saturated groundwater flow.

3 Coupling Method

3.1 Spatial Coupling

Atmospheric and hydrologic models are inherently different because of their drastically contrasting fluid properties, physical equations, time-scales, geometrical arrangement, and grid sizes. Hydrologic models require high spatial resolution meshes to capture the local topographic and hydrogeologic properties, with discretizations ranging from centimeters (vertical resolution in the near-surface) to kilometers (horizontal resolution in large-scale regional systems). In contrast, mesoscale atmospheric models cover a greater surface area and implement significantly coarser meshes that are between several kilometers to tens of kilometers.

HydroGeoSphere, a temporally implicit model, implements three types of meshing algorithms: finite difference hexahedra (8-point elements), finite element triangular prism (6-point elements), or finite element tetrahedra (4-point elements). However WRF, a temporally explicit model, only employs a regular finite difference hexahedral elemental mesh. Linking HGS to WRF required the development of a custom coupling framework that independently correlates the communication of information between the two model's unique meshes.

The HGS-WRF coupling framework allows for independent model meshing and projection characteristics by comparing the geographic coordinates (i.e., latitude and longitude) between the two domains. Our coupling method, shown in Figure 1, handles overlapping grid cells by computing the spatially-weighted area-based arithmetic mean, which maintains energy and mass conservation. The coupled model scheme internally projects each element to its geographic coordinate and then passes the data to the receiving model. This data is then reprojected and interpolated to the model's mesh. For instance, the HGS model may implement an Albers projection with a horizontal discretization of 4 km, while the WRF simulation will use the Lambert conformal projection with a 10 km discretization.

Figure 1. Model linking framework between the HGS and WRF models. This example illustrates the passage of data (soil saturation and evapotranspiration fluxes) from HGS to WRF. Each color (green, red, blue, and orange) represents an HGS element that intersects the WRF element of interest.

Initially, the WRF model internally calculates the potential evapotranspiration (PET) and precipitation (I) rates and passes them to HGS:

$$PET_{hgs_j} = \frac{\sum_i^n A_i \cdot PET_{wrf_i}}{\sum_i^n A_i} \tag{6}$$

$$I_{hgs_j} = \frac{\sum_i^n A_i \cdot I_{wrf_i}}{\sum_i^n A_i} \tag{7}$$

where A is the overlapping elemental or cell area, and the subscripts wrf_i and hgs_j are the indices for the Weather Research and Forecasting and HydroGeoSphere models, respectively. After calculating the fluxes from WRF to HGS, our modeling framework passes HGS' actual evapotranspiration and soil saturation back to the WRF model:

$$S_{wrf_i} = \frac{\sum_j^n A_j \cdot S_{hgs_j}}{\sum_j^n A_j} \tag{8}$$

$$AET_{wrf_i} = \frac{\sum_j^n A_j \cdot AET_{hgs_j}}{\sum_j^n A_j} \tag{9}$$

where S is the soil water saturation and AET is the actual evapotranspiration. The current numerical implementation of HGS-WRF is for finite difference meshes, as shown in Figure 1. However, since HGS can also use unstructured element meshes (e.g. prisms or tetrahedra), Equations 6-9 can be readily adapted for the finite element method.

Hydrogeologic models typically use basin-divide lateral boundaries, which eliminates interflow from upstream catchments. The only water fluxes left are flows out of the basin and exchanges between the atmosphere via precipitation and evapotranspiration. Atmospheric models, on the other hand, implement rectangular domains that overlap multiple basins, water bodies, and political boundaries. Combining the two models together, required a domain splitting algorithm that allows for separate boundaries for each individual model. The smaller HGS domain is a subset of the larger WRF simulation. Inside of the WRF model, the HGS portion overrides the internal LSM with HGS' soil saturation and evapotranspiration calculations. However, outside of the HGS portion, the WRF model uses its own land surface scheme (Noah LSM).

Furthermore, to aid with the linkage between models, HGS implements the same near-surface layering used in the Noah LSM. In both models the first, second, third, and fourth layers are 10, 30, 60, and 100 cm thick, respectively. The fourth layer in the Noah model is the last layer, while the HGS model further discretizes the subsurface deeper than these four upper layers. As described earlier, HGS passes its soil saturation values to Noah and overwrites the values per layer.

3.2 Temporal Coupling

Integrated hydrology traditionally involves time scales ranging from hourly (surface water) to millennial processes (groundwater flow). In contrast, atmospheric physics have much faster time scales and require small time steps (seconds to minutes) to capture acoustic waves, radiative energy, and convective flow; for example, WRF recommends 6 second global time steps per kilometer of horizontal resolution (e.g. a WRF simulation with a grid spacing of 10 km would use a 60 second time step). Combining atmospheric and hydrologic models together creates a major discrepancy in time scales that need to be resolved.

The simplest temporal coupling method is to run both models at the same time step and directly exchange boundary information between the models at every time step. However, running both models at the same time step results in wasted computational resources, because the hydrologic model's moisture balance does not rapidly change over the course of seconds. For this reason, we implemented a sub-time stepping routine such that the atmospheric model can run at a much smaller time step, while the hydrologic model runs a coarser temporal resolution. This assumption is acceptable because WRF's radiative energy balance routine does not run every time step; the recommended WRF radiative time step is 10 times the global time step. This means that the potential evapotranspiration, a component of the radiative energy balance, is only updated during the larger time steps.

Our explicit temporal method, shown in Figure 2, remains first-order accurate which requires small time steps to resolve the diurnal PET forcing. HGS passes saturation and actual evapotranspiration fluxes to WRF. Meanwhile WRF transfers its potential evapotranspiration and precipitation fluxes to HGS.

3.3 Parallelization

Both the HGS and WRF models are extremely complex software packages that are implemented with advanced numerical solvers. HydroGeoSphere implements a shared memory OpenMP approach, and is optimized for multi-core workstations [**?**]. The HGS parallelization efforts were focused on optimizing the matrix construction and sparse-matrix solver, while minimizing error between serial and parallel solutions (difference in head between solutions is less than 10^{-3} m). In contrast, WRF has multiple parallel choices including OpenMP, MPI (a distributed memory algorithm better suited for multi-processor cluster computing), and a hybrid OpenMP + MPI option (for shared and distributed memory computing systems).

Figure 2. HGS-WRF coupling schematic. HGS passes the saturation and actual evapotranspiration to WRF. WRF passes the precipitation and potential evapotranspiration fluxes to HGS.

Ensuring parallelization in HGS-WRF is not a luxury, but rather a requirement to efficiently solve complex problems. Our method, which passes data between the two models, implements a quasi-parallel scheme. Each model is running as a standalone parallel process that alternate compute cycles. Initially, the WRF model will compute the PET and precipitation fluxes and pass them to HGS. Once WRF outputs these fluxes, the WRF simulation is placed on pause until HGS computes the AET and saturation values. After HGS outputs its values to WRF, the HGS simulation is placed on pause. This cycle continues until the end of the numerical simulation. Currently the parallelization is written for both models to only run OpenMP (i.e. on Linux workstations and IBM Power Systems), but several simple additions to the parallelization routine could allow the HGS-WRF model to be extended to a hybrid scheme, where HGS uses OpenMP and WRF implements OpenMP + MPI. These hybrid simulation approaches with optimal model communications will drastically improve the computational runtimes [**?**].

4 Model Demonstration

To illustrate the capabilities of HGS-WRF, we developed a prototype California Basin Model that covers the entire state of California. The hydrogeological California Basin Model is 14 layers thick with 400,000 nodes at a 4 km resolution (see Figure 5 for the extents of the WRF and HGS-WRF domains). The HGS-WRF model was built using the HYDRO1K digital elevation model [**?**], STATSGO2 soil database [**?**], and the **?** sediment thickness map. The model extends to 6,000 m below sea level, and the consolidated rock unit starts below the unconsolidated sediments calculated from **?**. A 3D contiguous database of the subsurface stratigraphy was unavailable, and the deeper rocks were simply assumed to be homogeneous. For illustrative purposes, the consolidated rocks saturated-zone properties K_x, K_z, S_s, and θ_s were set to $2.5 \cdot 10^{-6}$ m/s, $2.5 \cdot 10^{-7}$ m/s, $1.0 \cdot 10^{-6}$ 1/m, and 0.05, respectively. The WRF model was discretized to a 12 km horizontal resolution with 42 vertical layers (2.8 million nodes), and we implemented the ERA-Interim six-hour global reanalysis data, for the lateral boundary conditions [**?**].

Initially, the stand-alone HGS California Basin Model was spun up to current day conditions (with local water use [**?**]), then the coupled HGS-WRF model was executed. The coupled model ran for 10 days (January 1st to January 10th, 2011), and was computed on a 6-core Intel i7-3960X workstation with 32 GB of memory running the Ubuntu OS. WRF implemented a fixed 50 second time step, while HGS used an adaptive time step set with a maximum of 300 seconds. The data was exchanged between the two models every 300 seconds. The 10 day model demonstration took three days to compute and the results for the first day are shown in Figure 3. The plots include surface water in log-meter depth, precipitation, evapotranspiration, and change in soil saturation over three time intervals. Naturally, the ET undergoes a diurnal cycle due to the sun rising and setting during the day. As the ET increases, it removes water from the land surface and shallow subsurface, into the atmospheric domain, thus increasing the atmospheric humidity. Once water is removed from the surface and subsurface, the ET rates decline because it takes more energy to move deeper subsurface water into the atmosphere.

Conversely, as more water enters the atmosphere, the PET values decline due to a build up of humidity and a decrease in atmospheric temperature. Once the atmospheric humidity exceeds saturation, the water leaves the atmosphere and re-enters the surface and subsurface domains as precipitation. During heavy precipitation events, water quickly moves over the surface, collects into larger rivers, and discharges into the Pacific Ocean. Additionally, groundwater discharge replenishes the ET water loss and can continue supplying surface water flows and ET during low precipitation conditions.

The domain mass balance, shown in Figure 4, illustrates the inherent diurnal cycle of the system. During the day, evapotranspiration rates peak to a maximum value of 12,000 m^3/s, while at night the ET fluxes approach zero. Over the first two days, the large precipitation event in Northern California drastically increases river discharge to over 1,700 m^3/s. For the next eight days, the river fluxes follow the diurnal evapotranspiration pattern, due to an increase in groundwater discharge at night from the decrease in ET.

Figure 3. HGS-WRF simulation for the first day. The hours are listed in UTC time.

Figure 4. HGS-WRF mass balance showing actual evapotranspiration (AET), precipitation, and river outflow.

4.1 Comparison to Standalone WRF

The primary difference between the coupled HGS-WRF and the WRF model are the inclusion of two-dimensional surface water and deep three-dimensional groundwater flow, which influence the distribution of latent heat fluxes. A spatial comparison of the latent heat fluxes between HGS-WRF and standalone WRF for January 2011, is shown in Figure 5. Over the majority of the domain, both models use the Noah LSM and the latent heat fluxes between the HGS-WRF and WRF simulations are very similar. However, within the California Basin, where HGS-WRF implements the HydroGeoSphere model, there is a drastic difference in evapotranspiration. In the northern regions, the HGS-WRF model produces significantly more evapotranspiration than WRF, while in the southern portion of California, WRF yields more ET than HGS-WRF.

The main cause for this contrast is the influence of groundwater, shown in Figure 6, where each individual dot in the figure indicates a single node from HydroGeoSphere's surface layer. The shallower the groundwater table the more negative the divergence in latent heat fluxes between the two models, such that HGS-WRF produces more ET than WRF. Conversely for deeper groundwater tables, WRF produces more latent heat flux bias than the HGS-WRF model. Furthermore, a spatial trend in the pattern is apparent, where the northern regions, shown by green and red dots, cluster towards the bottom left portion (shallow groundwater table with negative LE difference). The southern regions in the blues and purples are grouped towards the right and middle section of the figure (deeper groundwater tables with positive LE difference). The influence of watertable depth on latent heat fluxes across the land surface has been previously noted by **??**.

Figure 5. Comparison between the latent heat fluxes between WRF and HGS-WRF models. The entire WRF model coverage area is shown above, whereas the HGS domain is restricted to the California Basin. Red regions indicate zones that the standalone WRF model produced more latent heat. The blue regions are regions that HGS-WRF produced more latent heat. Simulation comparison is averaged over January 2011.

Figure 6. Depth to groundwater versus latent heat flux comparison between WRF and HGS-WRF models. Each colored dot represent one HGS node with corresponding latitude. The depth to groundwater table is from the simulated HGS model results.

5 Discussion

There have been several studies that have successfully coupled groundwater flow to atmospheric models, and each of these previous coupling methods has had limitations. Currently, all coupled models require that the groundwater flow component be included over the entire land surface domain of the atmospheric model. The required atmospheric domain is much larger than the domain of interest in the hydrologic model, due to the necessity of having the atmospheric boundaries much farther away than the hydrologic domain (to eliminate influence of the model boundary). In some cases, as with the 2-D Noah Distributed groundwater model [**?**], including the coupled groundwater flow simulation over the entire atmospheric domain is acceptable because the addition of the saturated and linearized groundwater flow equation is such a small component of the simulation. Nonetheless, more comprehensive 3-D surface/subsurface models such as ParFlow still require the surface/subsurface domains to cover the complete atmospheric domain, which may cost additional computational resources and requires significantly more effort to construct the large-scale basin model [**?**].

The next main limitation that other coupling methods have is their reliance on a constrained land surface model for calculating actual evapotranspiration. Existing methods export the near surface soil moisture values (typically the first 2 meters) to the atmospheric model, then the atmospheric model's land surface routine internally calculates the evapotranspiration. However, root zones often extend past the shallow 2 m subsurface, and well-draining sandy-soils with shallow water tables may have dry near-surface conditions limiting actual evapotranspiration, in zones where high ET legitimately occurs.

The simplest method to couple atmospheric and hydrologic models is to directly overlay the meshing so that each model's node overlaps. In this method, no mass/energy interpolation is required between domains, thus simplifying continuity conditions. However, this assumption forces the atmospheric model to run at the same grid spacing as the hydrologic model. Depending on the system, either the atmospheric model will require an excessively tight model mesh (extra computational expense) or the hydrologic model will be overly coarse (not properly resolving the physical problem). In our coupling method, we implemented a custom domain-splitting framework such that each model utilizes it's own separate model mesh. This allows the hydrologic and atmospheric models to use separate projection methods, different mesh resolutions, and independent numerical methods (i.e. finite difference or finite element). An additional benefit of using independent model meshes is that our method can take existing HGS and WRF models that have been calibrated and tuned, and then they can be quickly coupled by running the HGS-WRF code. Integrated basin-scale modeling is an extremely time intensive process, which can require months to develop a well-tuned model.

The ten-day simulation of the California Basin successfully demonstrates the strong atmospheric, surface and subsurface connections within the HGS-WRF model. The diurnal signal is apparent in both the evapotranspiration and river outflow signal indicating the connections between the domains. Furthermore, the comparison of the coupled HGS-WRF model to the standalone WRF simulation indicates a strong correlation between depth to groundwater table and latent heat fluxes. A detailed explantation of the California Basin Model will be provided in a subsequent paper, which will include the details of spin-up process, an extended 200 day HGS-WRF simulation, and a comprehensive description of the setup of the HGS portion of the California Basin.

5.1 Future Work

Deep subsurface heat transport was not included in the current version of the HGS-WRF coupling, although HGS has the capability to simulate heat transport over the land surface and subsurface. The water balance was the primary focus for the first version of HGS-WRF, and it was desired to minimize the number of independent variables in the coupling scheme to reduce computational demand. In future releases, it is planned to incorporate heat transport coupling as an option in the HGS-WRF model. From experience with the HGS-ABL (atmospheric boundary layer) model, the depth of the subsurface may play a critical role for temperature regulation, especially during prolonged drought conditions [**?**].

The current HGS-WRF model also does not include snow accumulation and melting, and sediment freeze-thaw processes would be the next logical advancement to the coupled model. Currently, HGS-WRF treats all water as liquid precipitation, which may artificially increase stream flow during the winter months and decrease streamflow during the summer. HydroGeoSphere already incorporates snowmelt and soil freeze-thaw, and the WRF simulation would provide the solid-phase precipitation to simulate winter processes.

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