Air and Space Natural Environment Modeling and Simulation Executive Agent

Terrain Domain Modeling in the Environmental Data Cube Support System (EDCSS)

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1. Concept Overview

The Environmental Data Cube Support System (EDCSS) is intended to provide the suite of capabilities required to meaningfully inject dynamic environment representations, and correlated effects, into Modeling and Simulation (M&S) applications. The focus domains for the EDCSS include the atmosphere, ocean, and space, as well as the dynamic aspects of the terrain representation resulting from coupling to the atmospheric representation. The EDCSS program is managed by the Air & Space Natural Environment Modeling and Simulation Executive Agent (ASNE MSEA) under the sponsorship of the Modeling & Simulation Coordination Office (MSCO), US Air Force and US Navy.

The EDCSS architecture is designed to make as many of its components as possible domain-neutral. The EDC Production Site provides a project-oriented customer front end for the specification of project requirements (e.g. products, region, and scenario) and the framework for production and delivery of completed support packages that include products from all domains. The EDC Production Site is backed by EDC Provider Sites, and it is here that domain specific modeling and product generation occurs. In the case of the terrain domain, the EDC Provider Site will encompass the execution of the Fast All-season Soil STrength (FASST) model to capture the dynamic response of the terrain representation to a selected atmospheric scenario, access to base terrain representation databases providing elevation, slope, aspect, soil type, etc. and the Standard Mobility (StndMob) model to translate the soil strength predictions into vehicle performance metrics. Additional models such as for terrain radiance can also be integrated. The EDC Products to be generated by this terrain domain provider site will include data, effects in the form of hypercubes, and graphic products to provide terrain-domain situational awareness.

The EDCSS Hypercube product is a domain-neutral storage mechanism to capture and deliver the results from multi-dimensional problem spaces. In the context of information technology, a Hypercube simply refers to a multidimensional storage array, the dimensions of which represent distinct categories of data used in analysis. The EDCSS Hypercube format consists of an XML descriptor file that defines its dimensions, ordinate values, and metadata about the model used to generate it, and an associated binary data file that contains the payload. In the case of vehicle mobility, a hypercube might store a vehicle performance metric such as “maximum speed” and the dimensions of the hypercube characterize the significant input parameters to the analysis such as vehicle type, vehicle pitch, ground conditions, etc.

2. Soil Properties Modeling

The FASST model, developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), is designed to provide a representation of the physical response of terrain hydrologic and thermal parameters to changing atmospheric conditions. FASST models each terrain spatial element independently (e.g., runoff from a terrain point does not affect its neighbors) based on a time-series of atmospheric parameters. The terrain representation is provided to FASST in terms of static properties (soil type, slope, aspect, elevation, etc.). A FASST hypercube can be developed that provides dynamic hydrologic and thermal parameters indexed to a specified range of terrain properties, the atmospheric model grid coordinates, and time. When the hypercube is generated, terrain properties to be modeled can be tailored to the geographic region of interest and/or special user requirements (e.g., specific soil or road types). When the hypercube is accessed, the user specifies the location, time, and terrain type of interest and the hypercube provides products modeled for the given terrain type and consistent with local atmospheric history. This enables use of FASST products derived from a lower-resolution atmospheric sceanrio (e.g., 1-40 km) that is consistent with static terrain properties defined on a high-resolution grid (e.g., 100 m) or on a terrain feature basis (e.g., road networks).

The hypercube generation process includes preparing atmospheric model products for FASST input and running FASST at each atmospheric model grid point and for each combination of the specified terrain properties. FASST is flexible regarding the atmospheric parameters required, deriving missing parameters in a pre-processor from whatever atmospheric fields are provided. However, to ensure consistency with other modeling done elsewhere in EDCSS, we opted to provide the full list of required atmospheric parameters directly to the FASST model, bypassing the pre-processor. This expanded parameter set includes 2-m air temperature and relative humidity, wind speed, atmospheric pressure, precipitation rate and type, and cloud cover, type, and base height for low, middle, and high cloud decks, solar direct and diffuse radiation, and down-welling atmospheric long-wave radiation.

For each unique weather grid cell, the FASST model is executed over the course of the scenario for each combination of specified soil type, terrain slope, terrain aspect, and vegetation type. For example, for a requested hypercube with five soil types, three slope angles, four aspect angles, and no vegetation, there would be 60 FASST model runs executed per atmospheric model grid point.

After completion of FASST model runs, a hypercube is created by extracting soil temperature and moisture data from the FASST output files, deriving secondary products, and storing them in the hypercube format. The FASST hypercubes generated to date contain input dimensions of Latitude, Longitude, Time of Day, Soil Type, Soil Slope, and Soil Aspect. The output options include soil moisture and strength at three depth layers, soil temperature at the surface, and MWIR/LWIR radiances. Additional input or output dimensions can be added at a later time to address vegetation or other concepts handled by FASST.

To validate the FASST hypercube generation process a one-month atmospheric scenario was developed for a region in Afghanistan. Figure 1 shows terrain properties for Afghanistan, and the white box indicates the study area (~2 deg square) for this test. Terrain slope and aspect were derived from the 3 arcsec (~90-m) SRTM topography database, down-sampled to 15 arcsec (~450 m). Soil types were defined by matching soil properties from the Global Soil Data Task 2000 (GSDT2000) database with the FASST USCS soil properties definitions. However, the GSDT2000 data are provided at 5 arc-min (~9 km) resolution. In order to simulate a higher-resolution soil type database that might be available in well-studied areas, we developed a simple soil type remapping system based on topographic height data. For each topographic grid point, a 3x3 neighborhood of 5 arc-min soil type grid points was searched for the one that minimized a weighted cost function of horizontal distance and terrain height. The soil type of the selected grid point was then assigned to the topographic grid point.

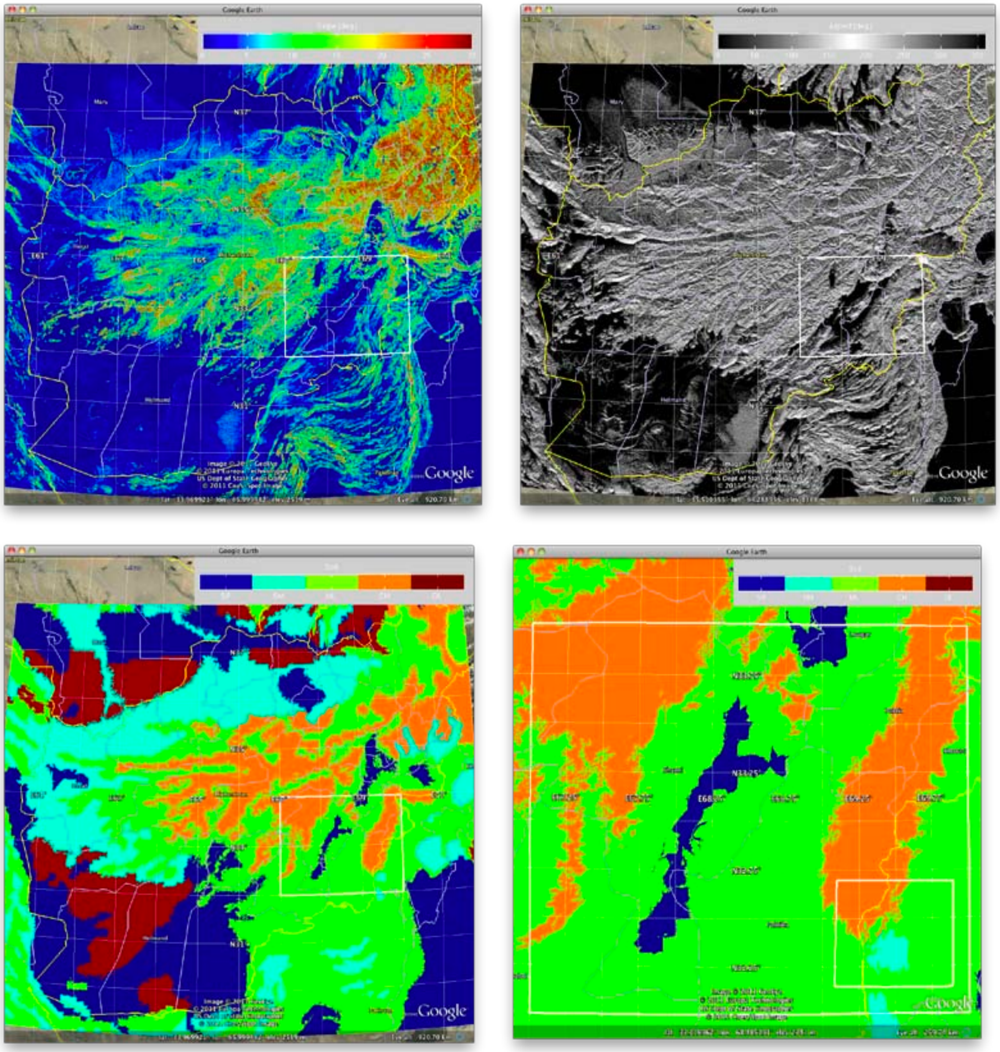

Figure 1: Top: Terrain slope (left) and aspect (right) at 15 arcsec. Bottom: FASST USCS soil types mapped to the same 15 arcsec grid; the image on the right shows expanded view of study area.

The EDCSS hypercube generation process was used to run the FASST model over the range of terrain types found within the region covered by the atmospheric model grid, including five soil types (SP, SM, ML, CH, OL), three slope angles (0, 15, 30 degrees), and four aspect angles (0, 90, 180, 270 degrees from North) with no vegetation.

Parameter time series (e.g., Figure 2 and Figure 3) help verify that the simulation products are consistent in time, among the various parameters, and across atmospheric model grid points. For example, clear sky conditions occur on most days in the simulation, which means that the radiation parameters usually follow regular daily cycles. Air temperature also follows a daily cycle on most days but it is less regular due to changing weather patterns. Consistency between the parameters can also be seen where there are rain events, which are accompanied by high cloud cover, reduced solar total and direct radiation, higher relative humidity, and periods of increasing soil moisture. Consistency and differences across grid points can be seen by comparing Figure 1 and Figure 2. Rain events occur around the same time at both points but total rain amounts and the resulting soil moisture changes are significantly different.

Soil type has the largest effect on soil moisture variation among the hypercube terrain types. The effects of terrain slope and aspect are seen most after longer dry periods during which south-facing slopes dry faster than north-facing. Soil freezing can also be seen to be a factor, particularly for the steepest north-facing slope (solid red line), which has lower (liquid) soil moisture at times due to freezing of some or part of water in the soil layer. Slope and aspect have a greater effect in warm months when drying rates on south-facing slopes are significantly higher.

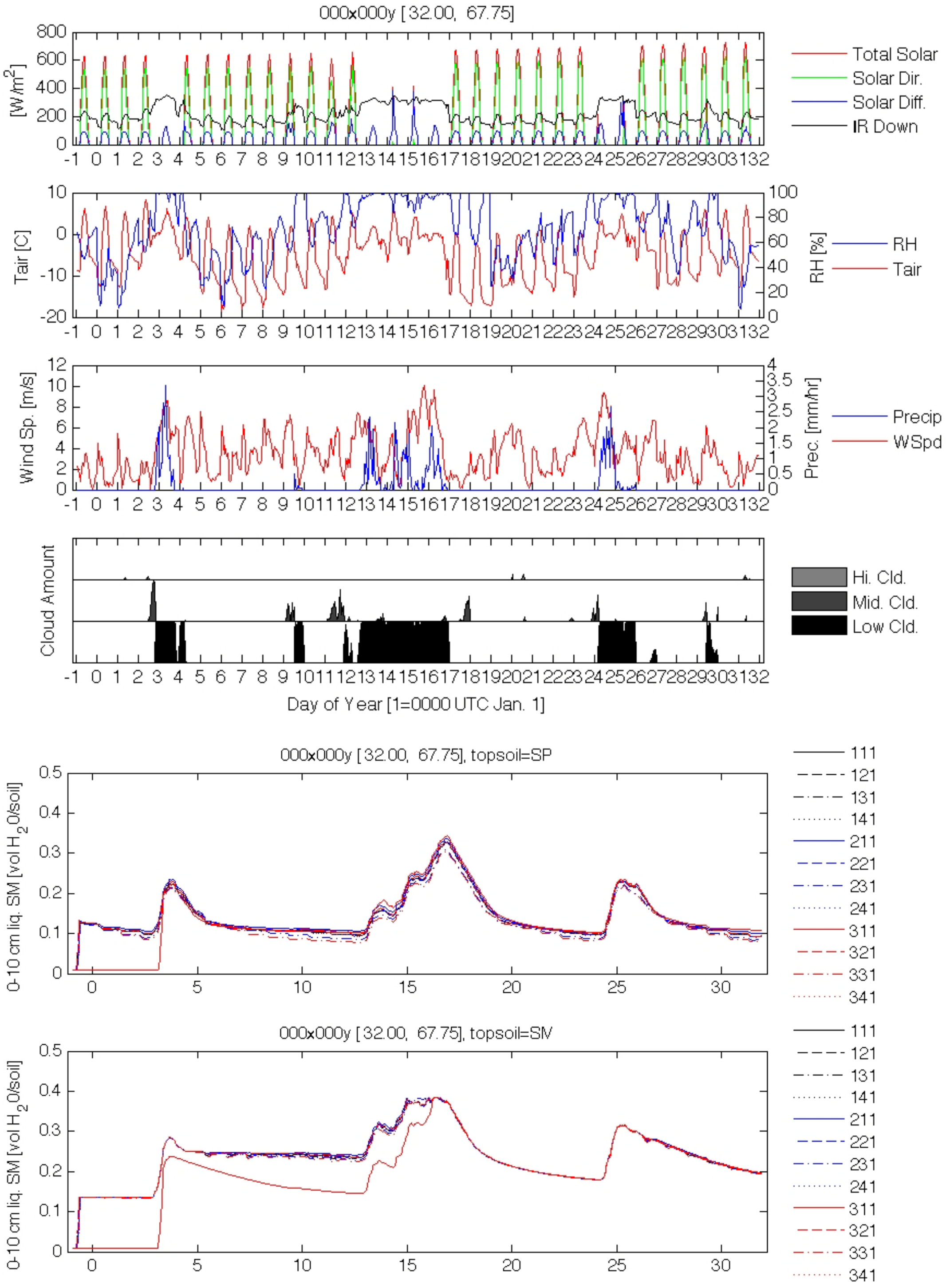

Figure 2: EDCSS atmospheric scenario (top set of plots) and FASST soil moisture products (bottom set) for a one-month model period. Hourly products for a single grid point (32N, 67.75E) are shown. Atmospheric products: total solar radiation, direct radiation, diffuse radiation, and downwelling longwave radiation, 2-m relative humidity, 2-m air temperature, precipitation, wind speed, and high, middle, and low cloud amounts. FASST soil moisture (unfrozen part only) is plotted for two soil types (ML, CH) and three terrain slope angles (0, 15, and 30 degrees, first index in plot legend) and four terrain aspect angles (0, 90, 180, 270 degrees from North, second index).

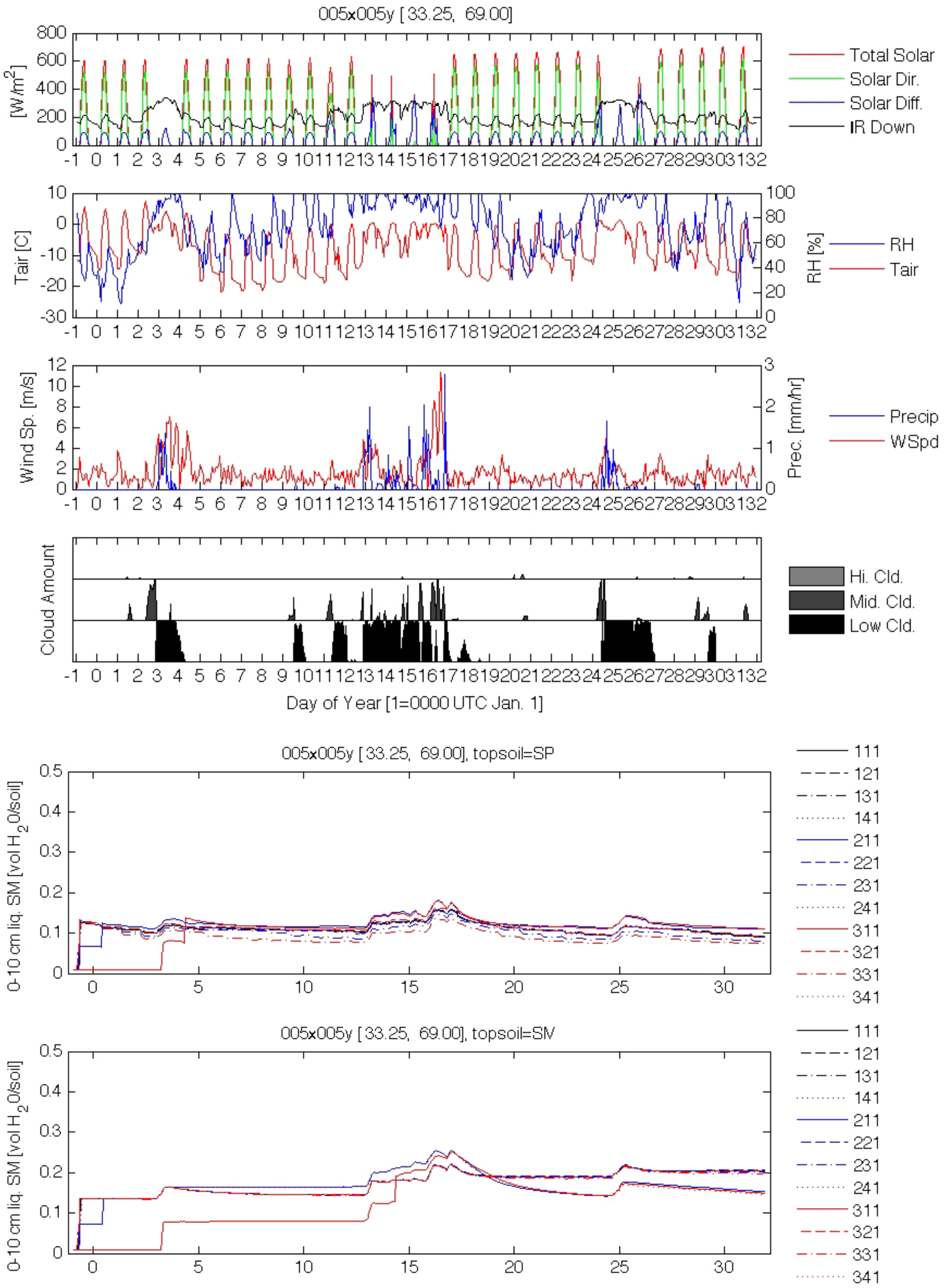

Figure 3: Same as Figure 2 but for grid point at (33.25N, 69E).

Figure 4 depicts soil moisture (0-5 cm depth) and strength (0-5 cm) extracted from the hypercube using the terrain properties shown in Figure 1. Products at 0600Z on January 12 and 18 are shown. Conditions on Jan. 12 were significantly drier than the 18th due to the nearly rainless stretch from Jan. 4 to 13 followed by rain from Jan. 13 to 17 (see Figures 2 and 3). As a result, the soil moisture on the 18th (top right of Figure 4) is generally higher than the 12th across the domain. An exception is the long vertical patch of sandy soil (SP) in the center of the domain which has drained more quickly than the other soil types. Soil strength is also significantly lower on the 18th across the domain, but again the soil type has an important effect: the patches of the clay (CH) soils on the right and upper left of the domain are stronger at the higher soil moisture values than the other soil types.

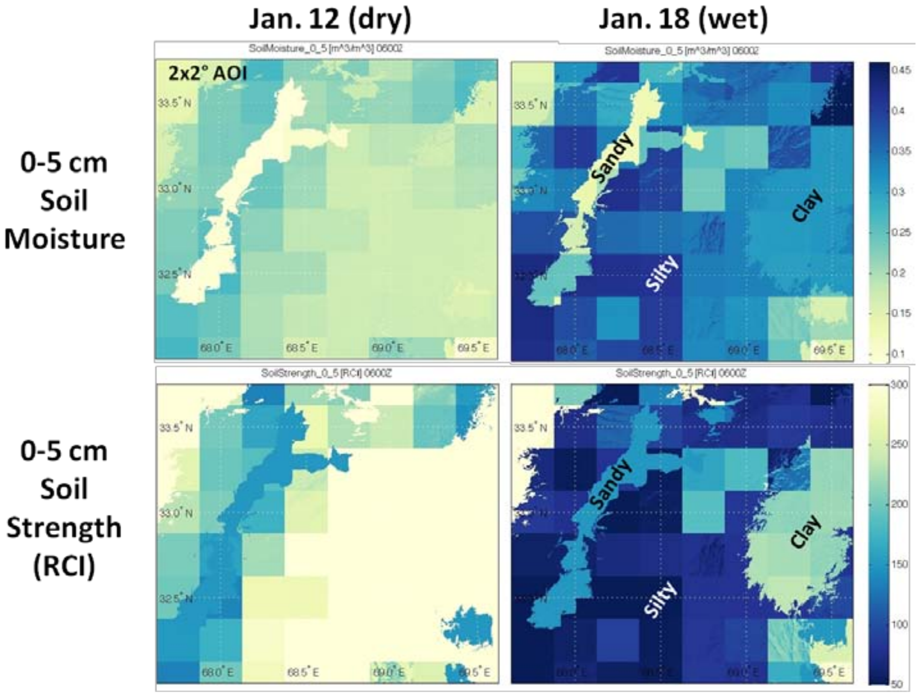

Figure 4: Hypercube soil moisture and strength at 0600Z on January 12 and 18 for the entire atmospheric model domain and terrain parameters shown in Figure 1.

Figure 5 illustrates the ability to use hypercube products at any terrain representation scale. The terrain properties in Figure 5 were derived at the full resolution version of the SRTM topography database (3 arcsec or about 90 m). At the higher resolution, it is possible to see the effects that topography can have on soil moisture, strength, and temperature contrast. For example, south-facing slopes dry more quickly than north-facing and this is reflected in parts of both the soil moisture (left) and soil strength (middle) maps. The north-south dryness contrast depends on many other factors as well (e.g., initial moisture amount, cloudiness), so not all areas show the same amount of topography-driven variation. The combined effects of soil moisture content and topography can be seen in the soil temperature maps (right). The higher soil moisture values on the 18th limit the rise in temperature on the south-facing slopes and therefore decrease the north-south contrasts.

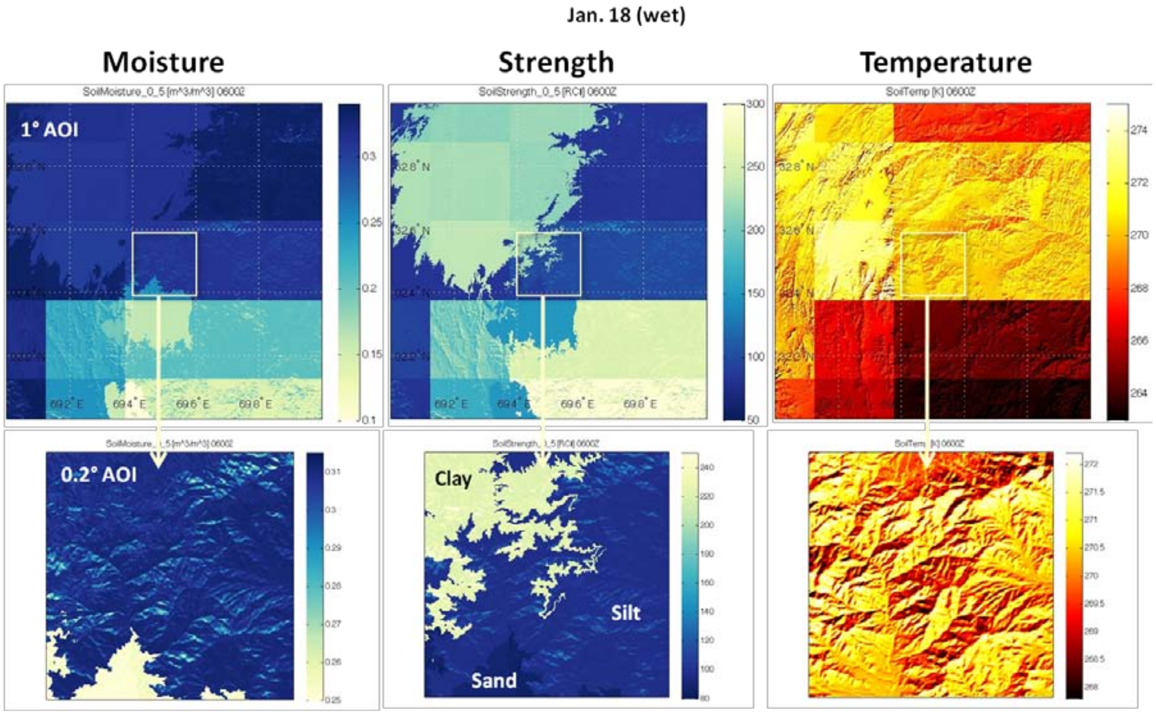

Figure 5: Hypercube soil moisture, strength, and temperature at 0600Z on January 18 produced using 90 m terrain source information.

3. Standard Mobility Modeling

The Army Engineering Research and Development Center (ERDC) has implemented the Standard Mobility (StndMob) model as a Java API layer that exposes multiple levels of fidelity to the underlying NATO Reference Mobility Model (NRMM), which is the standard Army model for vehicle mobility. By leveraging the well-defined interfaces offered by StndMob, we are able to implement a Hypercube generation process for vehicle mobility performance. Version 3.0 of StndMob was utilized for this effort, which encapsulates version II of the NRMM. The primary reference document used for this effort was the "Standard for Ground Vehicle Mobility" (ERDC/GSL TR-05-6, Feb 2005) and all technical specifications about StndMob stated here come from that document.

StndMob provides two API's (Level 1 and Level 2) with different input requirements and degrees of model output granularity. The StndMob Level 1 API provides a lower-fidelity modeling capability by characterizing terrain conditions in classes instead of discrete values. The primary environmental input for terrain conditions is a Climatic Zone parameter, of which there are 16 supported sub-climates. The Level 1 API uses the Climatic Zone parameter to set a number of StndMob input parameters including soil strength. Because for this effort the objective was to force the StndMob model with dynamic soil strength conditions as derived from an atmospheric model forcing of the FASST model, it was determined that the Level 1 API was insufficient for our purposes.

The StndMob Level 2 API provided a medium-fidelity modeling capability that exposes more of the terrain representation parameters individually. For this initial study, many of these parameters were left as defaults or assumed static values, but the Level 2 API allowed us to effectively develop a range of Mobility Hypercubes by defining the following dimensions:

Soil Type: Defined by the USCS Soil Type codes (e.g. SM, SP, etc.)
Soil Strength: Defined by a Cone Index at the 40 cm level
Vehicle Type: Defined by the StndMob Vehicle Bin Classes (Baylot and Gates, 2002)
Vehicle Pitch: Indicating the operating orientation of the vehicle
Throttle Setting: Indicating the throttle position of the vehicle

A number of the assumptions made about the remaining parameters in the Level 2 API are worth noting here. No attempt was made to handle vehicle plow settings, or to define any individual obstacles or debris in the vehicle's path. For these initial tests, frozen and/or snow-covered ground is not handled; this will be implemented once the modeling of these conditions is adequately validated from the FASST model process. For now the assumption is unfrozen ground with zero snow cover. Given the above assumptions, a reference Mobility Hypercube was defined with the following dimensions:

Soil Type: SM, SP, ML, CH
Soil Strength (Cone Index) = 50, 100, 150, 200, 250
Vehicle Type = 2, 5, 8, 10, 12
Vehicle Pitch = -30, -15, 0, 15, 30 deg
Throttle Setting (%) = 25, 75

The soil types defined above equate to:
SM: Silty sand
SP: Poorly-graded sand
ML: Silt (low plasticity)
CH: Clay (high plasticity)

The vehicle types defined above equate to:
2: Medium-Mobility Tracked
5: Medium-Mobility Wheeled
8: Medium-Mobility Wheeled w/ Trailer
10: Amphibious Combat Vehicle Tracked
12: Light ATV

The concept here is that the Mobility Hypercube soil strength input dimension will be obtained dynamically by consulting the FASST Hypercube discussed in Section 2 at specified inputs of Lat, Lon, and Time for weather conditions as well as soil type, slope, and aspect for local terrain type. In this way, using the two hypercubes combined, an end-user can obtain vehicle performance as a function of Lat, Lon, Time, Slope, Aspect, and Soil Type.

The above combination of input parameters results in 1000 independent executions of the StndMob Level 2 API. However, this is done independent of the weather scenario, and resulting FASST Hypercube, because the soil strength input is parameterized at sufficient resolution to capture the NRMM model response. Additional parameters for each dimension can be added (for instance all 12 vehicle classes, additional soil types, etc.) and new dimensions can be added later to capture frozen ground and/or snow cover.

The resulting parameter from StndMob is always a Maximum Speed that the vehicle is expected to be able to operate at in the prescribed conditions. This parameter can then be used as a limiter on a vehicle performance model in a simulation, or as the basis of support products to provide decision makers some insight into expected performance.

The EDCSS process for generating Mobility Hypercubes of the form above involves the configuration of an EDC Processor that is first configured to execute the StndMob model via a Java driver, and then can be configured by a SME through the definition of an extension that defines the desired hypercube dimensions and values for each. New dimensions must be implemented in the Java driver for the first time, but otherwise new hypercubes can be specified through only the XML extension and no coding required.

4. Conclusions

This initial research and development effort has proven that the EDCSS architecture is indeed extensible into the terrain domain and that a number of valuable terrain domain products can be readily defined and generated so as to be couple to a realistic atmospheric scenario. The FASST model was successfully wrapped within an EDC Processor and executed thousands of times in automated fashion to generate dynamic soil property hypercubes for a one month scenario. The StndMob model was also successfully wrapped within an EDC Processor and utilized to generate vehicle mobility hypercubes on demand. Both models were implemented such that representative terrain and vehicle performance responses to the atmospheric scenario can be modeled without the use of a specific terrain database during the generation process. The resulting hypercubes were then subsequently applied with specific terrain databases to yield dynamic soil property and vehicle performance products coupled to geo-specific regions and atmospheric scenarios. This technique offers great efficiency in both production and consumption, with the substantial additional benefit of allowing complete flexibility in the selection of terrain representation by the consumer.

The EDCSS hypercube generation processors implemented for this effort were implemented to allow flexibility and further tailoring in the future in response to customer requirements and/or terrain domain SME recommendations. Both the FASST and StndMob models have a considerable range of options for their configuration. Under this initial effort, only the most significant configuration parameters were implemented to be varied by the hypercube input specification; many more that were deemed less significant were simply set to reasonable default values. However, any and all input parameters to either model could be included in the hypercube generation process as a dimension that is allowed to vary. This range of configurations should be further explored with the help of terrain domain SME's based on the known sensitivity of the respective models to each input parameter.