EVALUATION OF SEASONAL WATER BUDGET COMPONENTS OVER THE MAJOR DRAINAGE BASINS OF NORTH AMERICA USING AN ENSEMBLE-BASED LAND SURFACE MODEL APPROACH

C. Vuyovich[1], S. Kumar[1], L. Mudryk[2], R. Kim[1,3], J. Lundquist[4], M. Durand[5], C. Derksen[2], A. Barros[6], P. Houser[7], E. Kim[1]

[1]Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA;
[2]Climate Research Division, Environment and Climate Change Canada, Toronto, Ontario, Canada;
[3]Universities Space Research Association (USRA), Columbia, MD, USA;
[4]Civil and Environmental Engineering, University of Washington, Seattle, WA, USA;
[5]School of Earth Sciences and Byrd Polar and Climate Research Center, The Ohio State University, Columbus, OH, USA;
[6]Civil and Environmental Engineering Dept., Pratt School of Engineering, Duke University, Durham, NC, USA;
[7]Dept. of Geography and Geoinformation Sciences, George Mason University, Fairfax, VA, USA

ABSTRACT

An ensemble of land surface models and forcing data was developed to assess variability in SWE estimation over North America. In this study, the ensemble output was used to assess how SWE uncertainty impacts streamflow estimation. The analysis was conducted by major basins of North America over the 2009-2017 time period.

***Index Terms*—** SWE, snow, uncertainty, streamflow

1. INTRODUCTION

On 30 to 50% of Earth's land area, runoff processes are dominated by snow in mountainous, temperate, boreal, and Arctic environments. Accurate real-time and long-term estimates of snow water equivalent (SWE) are required for hydrologic analyses, infrastructure design, water resource allocation, flood forecasting, and for quantifying trends in snow mass due to climate change [18]. Currently no single observational technique or modeling approach provides global snow data with the accuracy and resolution required to address water resource needs.

Methods to merge multiple observations through a physics-based modeling framework are a potential solution to meet those needs. Multiple sources of snow information, from models, remote sensing and in situ networks can be merged within the framework through data assimilation; however, well-characterized estimates of uncertainty for assimilated observations are required. One possible approach to estimating uncertainty is to evaluate the spread in existing products. Mudryk et al. [13] used this approach on a selection of reanalysis-derived and remotely sensed snow analyses to estimate SWE uncertainty.

In this study, we use an ensemble of land surface models and forcing data, developed to characterize SWE uncertainty across North America [7]. We evaluate this ensemble by major basins to determine how uncertainty in SWE estimation impacts snowmelt runoff, and how basin characteristics influence uncertainty in the snowmelt contribution to total water budget. In addition, we compare the results to GlobSnow v2.1 [17], which combines a physical snow model with assimilated passive microwave and in situ observations to provide global SWE estimates.

2. METHODS

Four different land surface models (LSMs) of varying complexity were run using the NASA Land Information System (LIS) [10, 15]: 1) Noah version 2.7.1 (Noah2.7.1), 2) Noah-Multi-Parameterization (Noah-MP), 3) Catchment version 2.5 (CLSMF), and 4) the Joint UK Land Environment Simulator (JULES). Three different forcing datasets were used to drive each of the LSMs: 1) Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2), 2) Global Data Assimilation System (GDAS), and 3) the European Centre for Medium-Range Weather Forecasts (ECMWF). The 12-member ensemble was run at a 5-km spatial resolution over the time period 2000 – 2017, with the first nine years were used as model spin-up and analysis conducted over the remaining years (2009-2017). Full details of the ensemble study are provided by Kim et al. (in prep). The Hydrological Modeling and

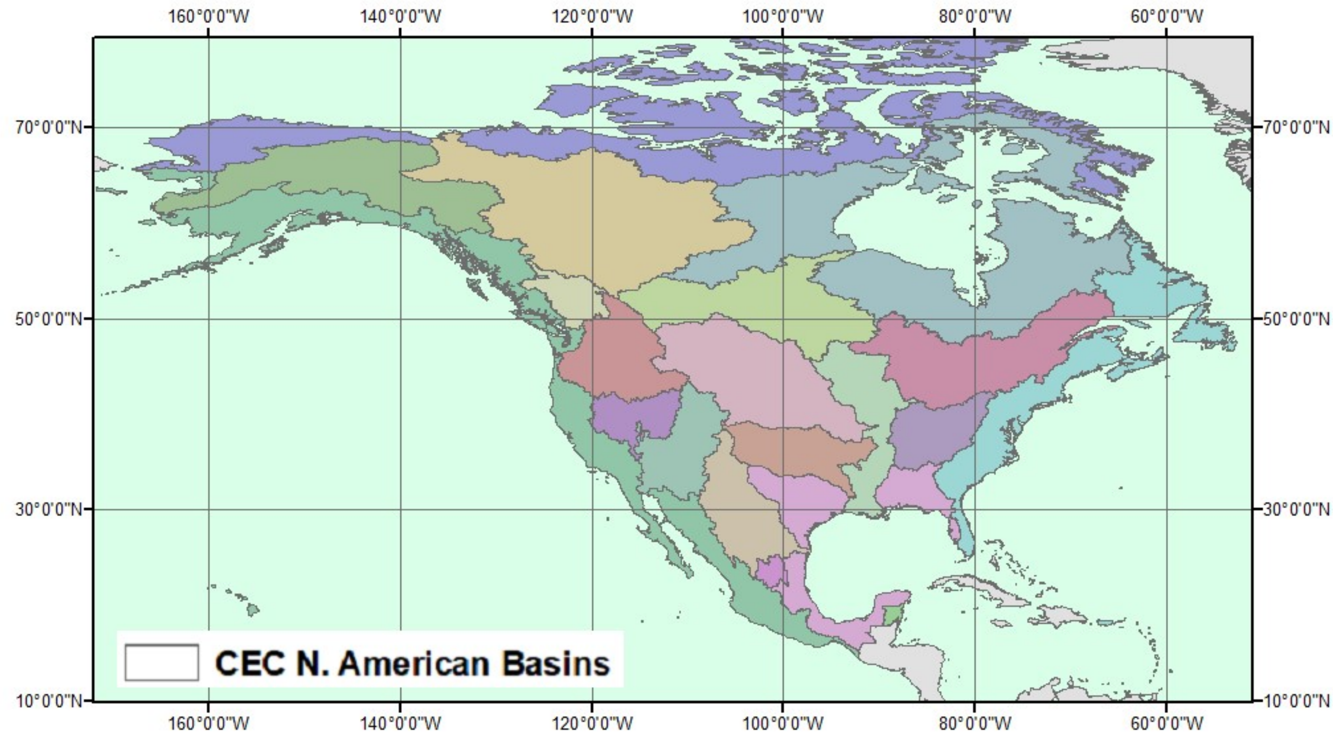


Figure 1. Snow Ensemble Uncertainty Project (SEUP) North American domain, showing major drainage basins

Analysis Platform (HyMAP) was employed as a routing model in order to derive estimates of streamflow.

2.1 Land Surface Models

The four LSMs selected are all well-established and currently used operationally at various modeling centers, and they include physically-based snow models, ranging in model maturity and complexity. They are therefore expected to represent a realistic variability in SWE estimates. Noah2.7.1 was developed through community efforts to simulate land surface temperature, snow depth, SWE, canopy water content, surface energy, water balance, soil temperature, and soil moisture [5, 8]. This study employs the Noah version 2.7.1 with a single snow layer, which simulates SWE as the residual of snowfall minus the sum of snowmelt and sublimation.

The Catchment model used in this study is based on the Fortuna 2.5 version [4, 9]. CLSMF includes a three-layer snowpack model incorporates snow physics including densification, snowmelt, refreeze, and snow insulating properties.

The Noah-MP LSM [14] is built upon Noah but includes up to three layers for snow, depending on snow depth. The revised snow scheme allows for snow compaction due to the weight of overlying layers and for melt metamorphism. Snow cover fraction is a function of snow depth, ground roughness length, and snow density.

JULES [1] combines a sophisticated land-atmosphere heat and water exchange model with vegetation dynamics. In the zero-layer model, used in this study, snow processes are incorporated in the top layer of the soil. Snow is given as a constant thermal conductivity and a constant density.

2.2 Forcing Data

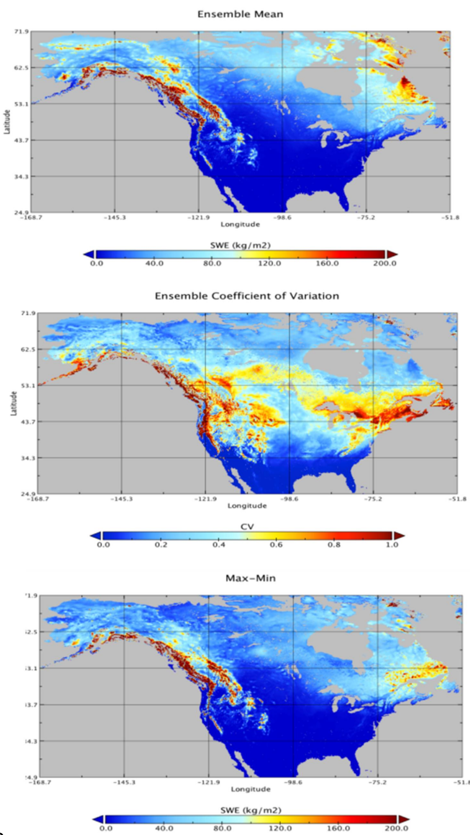
The forcing data sets were selected based on their availability during the study period, inclusion of all required forcing data and independence from each other. MERRA2 [6] is a global reanalysis product which assimilates spaced-based observations and represents their interactions with other physical processes in the climate system. MERRA2 has a native spatial resolution of 0.5^{o} latitude by 0.625^{o} longitude, and is available from January 1980.

GDAS is a global, operational atmospheric analysis system based on the operational Global Forecasting Systems (GFS) developed at the Environmental Modeling Center (EMC) of NOAA/NCEP [3]. The GDAS model grids have been upgraded from T170 (roughly 80 km) to T1534 (~13km; since January 2015) for the years 2000 to 2015.

The ECMWF data [12] is obtained from the operational, global analysis products, available on a TL511 triangular truncation, linear reduced gaussian grid (roughly 40 km) for four synoptic hours: 00, 06, 12, and 18 UTC.

2.3 Study area

The study area is North America, which consists of a 0.05^{o} latitude by 0.05^{o} longitude grid that extends from 24.875^{o}N to 71.875^{o}N and 168.625^{o}W to 51.875^{o}W (Figure 1). The glacier regions are excluded due to large uncertainties in the model simulations. Analysis of the water balance was



a.

b.

c.

Figure 2. SEUP results showing a. ensemble mean SWE, b. coefficient of variation and c. ensemble range

conducted over major continental basins using the North American Atlas – Basin Watersheds dataset [2].

2.3 Analysis

Several metrics were used to evaluate the contribution of forcing data and model differences to SWE uncertainty, including difference from ensemble mean and coefficient of variation. Regions with shallow or ephemeral snow were filtered out to limit the coefficient of variation analysis to areas with significant snow.

Uncertainty was assessed spatially by evaluating ensemble spread across regions with different snow classes, land covers and topography, and temporally throughout the snow accumulation and melt season. Additionally a water budget analysis was conducted to compare the contribution of snowmelt and other components from each ensemble member. This analysis was conducted for the entire North American domain as well as for each of the major basins.

Within each basin, the water budget was evaluated to determine the uncertainty in SWE propagates to snowmelt contribution. Variability in modeled runoff was assessed in basins with a single outlet point (non-coastal) using various metrics, including spring volumetric flow, peak spring flow and timing of spring peak. Runoff was computed using HyMAP, which is a global-scale routing scheme capable of simulating surface runoff and baseflow processes, flow routing in rivers and floodplains, and open water evaporation, and has been evaluated extensively, including over North America [11].

3. RESULTS

The largest total variability in SWE is seen in regions with the deepest snow, in particular along the northern Pacific coastline (Figure 2). The northern Rocky Mountains and in Eastern Canada along the Atlantic coast also show a large range of mean SWE between ensemble members. The relative variability (normalized by mean SWE) shows greater uncertainty across the middle of North America, roughly following regions of heavier vegetation.

These results indicate that variability between ensemble members is due more to model differences than to forcing data, with the greatest spread seen at the time of the peak SWE (Figure 3). This is in contrast to the findings of other studies, which found forcing data to drive SWE uncertainty [e.g. 16]. Noah-MP tends to provide the highest estimate of SWE, followed by JULES. CLSMF and Noah2.7.1 both tend to have the lowest SWE estimates.

The water budget analysis helps evaluate which components are contributing the greatest amount to differences between ensemble members (Figure 4). A computed residual represents sublimation and canopy interception which were not explicitly output. Larger mid-winter residual estimates in the CLSMF and Noah2.7.1 results are likely driving the lower SWE estimates in those models.

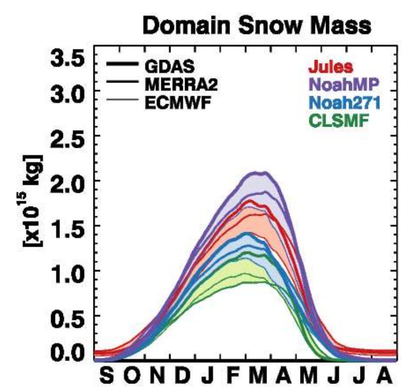


Figure 3. Total snow mass over North America showing greatest spread between models and less due to forcing data

4. CONCLUSIONS

In this study, a 12-member ensemble dataset made up of 4 different snow models and 3 different forcing data sets is evaluated to better understand how SWE uncertainty differs across major basins of North America and impacts streamflow estimation uncertainty. The results of this study show that over the entire North American domain, SWE

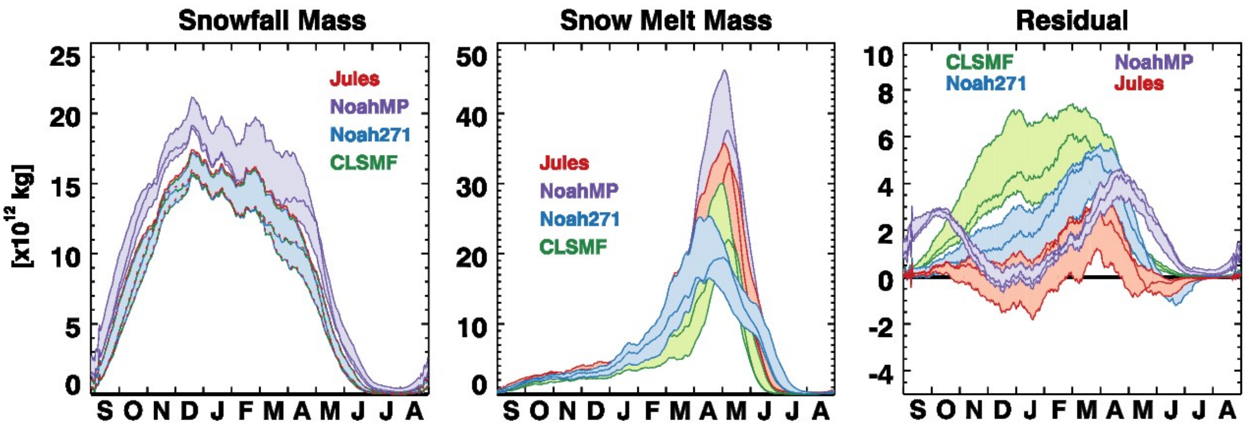


Figure 4. Water balance over North American domain, where residual represents differences in sublimation and canopy interception.

uncertainty is correlated with regions of greater snow depth and heavy vegetation. This is likely caused by how different models handle physical processes in these regions.

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