IMPROVING STREAMFLOW FORECASTS IN THE NOAA NATIONAL WATER MODEL USING OBSERVATIONAL CONSTRAINTS ON SNOWPACK ALBEDO AND SNOW-COVERED AREA FROM STC-MODSCAG

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EXTENDED ABSTRACT

The NOAA National Water Model (NWM) is a physically-based modeling system which simulates major hydrologic processes across the conterminous United States (US). Difficulties in accurately simulating snowpack states hinder the NWM's ability to provide high-quality streamflow forecasts, particularly in snow-dominated western US mountains. Errors in snowpack simulations propagate into streamflow time series as errors in both magnitude and timing of peak streamflow in snow-dominated basins.

We imposed observation-based constraints on simulated fractional snow-covered area (fSCA) and snowpack albedo in the NWM using remotely sensed data and investigated the impacts on simulated snow states and streamflow over the Upper Colorado River Basin. We identified a set of parameters that influence the relationship between snow depth and fSCA (the snow depletion curve) and seasonal snowpack evolution. For each parameter, we derived spatially-distributed values using 15 years of data from STC-MODSCAG (Spatially and Temporally Complete MODIS Snow-Covered Area and Grain Size), which provides daily estimates of fSCA, snowpack albedo, and other variables at ~500 m spatial resolution. When implemented into the NWM's snow model, the derived values tended to shift simulated streamflow peaks lower and earlier, often improving agreement with observed streamflow. Results from these experiments will help to improve streamflow forecasting for water management and inform NWM data assimilation strategies with model parameter uncertainties.

INTRODUCTION

Streamflow forecasting is central to water resource management strategies, particularly in regions prone to water scarcity such as the western United States. The accuracy of streamflow forecasts at lead times varying from hours to weeks affects flood risk assessments, irrigation management decisions, drought severity predictions, and numerous other management applications. The NOAA (National Oceanic and Atmospheric Administration) National Water Model (NWM) is a hydrologic modeling system intended to meet this streamflow forecasting need at high spatial (1 km) and temporal (hourly) resolution across the continental United States (https://water.noaa.gov/about/nwm). The NWM provides streamflow forecasts at multiple lead times ranging from 18 hours to 30 days for ~2.7 million stream reaches within this domain. As a physically-based modeling system, the NWM simulates the terrestrial water and energy balances, outputting spatially-distributed estimates of soil moisture, evapotranspiration, snow water equivalent (SWE), and other quantities in addition to streamflow forecasts.

As is the case for any method of streamflow prediction, NWM forecasts contain errors which are spatially and temporally variable. This error budget encompasses uncertainties in meteorological forcing data as well as errors related to model structure and parameterization in the NWM's numerous land surface model modules (e.g. snow, soil moisture, groundwater, etc.). Structural and parametric errors in the NWM's snow model (Noah-MP (Niu et al., 2011)) are particularly impactful on the quality of streamflow predictions in the western United States, where,

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on average, >50% of annual streamflow originates as snowpack (Li et al., 2017). Errors in NWM snow simulations affect the magnitude and timing of peak simulated streamflow—key metrics used in water management decision making throughout the western United States. Remotely sensed constraints on model snowpack have previously shown some promise in improving streamflow simulations (e.g. Berezowski et al., 2015), but require additional investigation.

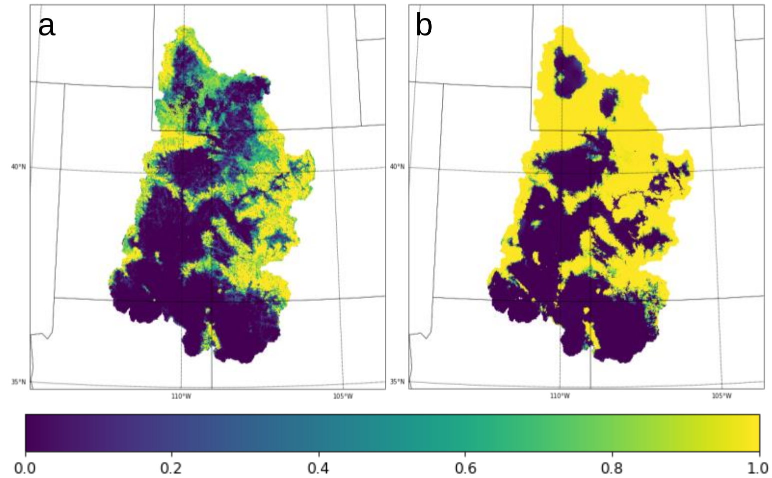

Figure 1. (a) Observed (STC-MODSCAG) and (b) simulated (NWM) fSCA over the Upper Colorado River Basin for April 1, 2010.

In this study, we investigated the extent to which simulated streamflow could be improved by applying observational constraints to parameters within Noah-MP. We chose two empirical model parameters that affect NWM fractional snow-covered area (fSCA) and snow albedo. We ran constrained simulations and quantified improvements in simulated streamflow by comparing to both observations and default, unconstrained simulations. Parameter value constraints were derived using fSCA and snow albedo from STC-MODSCAG (Spatially and Temporally Complete MODIS Snow-Covered Area and Grain Size)—a suite of remote-sensing-based data products generated from MODIS (Moderate Resolution Imaging Spectroradiometer) Terra observations (Rittger et al., 2020), available at the National Snow and Ice Data Center through Snow Today (https://nsidc.org/reports/snow-today). We present results from the Upper Colorado River Basin (UCRB).

METHODS

Observational Data Products

fSCA and snowpack albedo are produced at ~500 m spatial and daily temporal resolution across the western United States. fSCA is generated using the MODSCAG spectral unmixing algorithm (Painter et al., 2009). Snow grain size from MODSCAG is used to estimate the clean snow albedo and the impact from light-absorbing particles is estimated using the MODIS Dust and Radiative Forcing (MODDRFS (Painter et al., 2012)) algorithm. The fSCA and albedo products have additionally been recently updated with improved cloud discrimination and corrections to tree-canopy occultation of snowpack (Rittger et al., 2020), with MODIS view-angle accounted for in the canopy correction and spatial-temporal interpolation (Dozier et al., 2008). The remotely sensed snow albedo has been shown to outperform typical snow aging models, including the BATS (Biosphere-Atmosphere Transfer Scheme (Yang et al., 1997)) model used in the NWM (Bair et al., 2019). Both variables have been validated at the small basin and/or study plot scale, where they have exhibited low root mean square error and minimal bias in areas where forest canopy density is less than 75%. We regridded STC-MODSCAG fSCA and snowpack albedo to the 1 km NWM grid for ease of comparison.

Model Parameter Adjustments

NWM simulations of fSCA and snowpack albedo with default snow parameters differed in key ways from their STC-MODSCAG equivalents. NWM fSCA exhibited nearly binary behavior: NWM grid cells tended to be either 0% or 100% snow covered, lacking the intermediate fSCA values common in STC-MODSCAG (Figure 1). This behavior results from the model's snow depletion curve—an empirically derived relationship between snow depth and fSCA (Niu and Yang, 2007). The Noah-MP snow depletion curve relies on coarse resolution data from AVHRR (Advanced Very High-Resolution Radiometer) that uses a binary—rather than fractional—snow cover classification. Although disagreement between simulated and observed snowpack albedo was less pronounced compared to fSCA, discrepancies in the temporal variability of snowpack albedo indicated issues with the snowpack aging component in the model.

In order to use STC-MODSCAG fSCA and snowpack albedo values to constrain NWM simulated snow states and streamflow, we identified parameters that impact the maximum fSCA and snowpack aging rate in a given grid cell. For fSCA, we chose the parameter 'scamax', which directly imposes an upper bound on the model snow

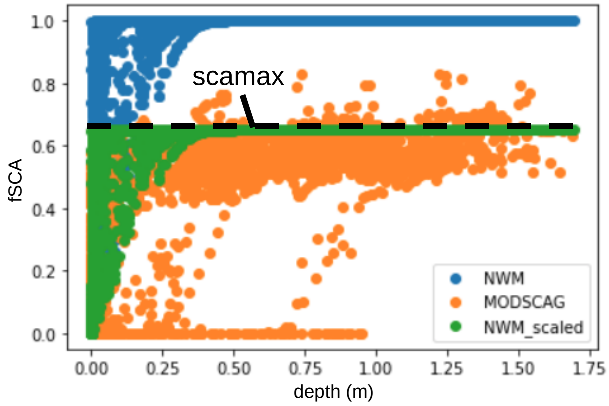

Figure 2. Observed (orange), simulated (blue), and re-scaled simulated (green) relationship between snow depth and fSCA for an individual grid cell. Each point represents a different day. Simulated points are re-scaled to match the approximate observed maximum (scamax).

depletion curve (Figure 2). In each grid cell within the model domain, we iteratively solved for the scamax value which most closely matched the 99th percentile value from 15 years of observational data (water years 2004-19). The result was an optimized map of scamax constrained by long-term STC-MODSCAG observations. We used this optimized scamax distribution in an updated NWM simulation over the UCRB over water years 2008-10.

The NWM contains two snowpack albedo model options: BATS (Yang et al., 1997) and CLASS (Canadian Land Surface Scheme) (Verseghy, 1991). We used BATS snowpack albedo as it exhibited better baseline agreement with STC-MODSCAG. The BATS model employs an exponential decay-style aging routine, where snowpack albedo declines from a pre-set new snow value as the snowpack ages. Models such as BATS assume knowledge of when and where snowfall occurs. In practice, remote sensing observations are necessary to constrain this distribution and timing of new snow. We chose to vary the BATS parameter ‘swemx’, which determines the amount of new SWE required to reset the model’s snowpack age to zero and broadband snowpack albedo to the new snow value (~0.84) (Figure 3). The swemx parameter impacts snow albedo less directly than scamax impacts fSCA. As such, deriving a spatially heterogeneous, optimized swemx distribution is significantly more complex, and remains in progress. Instead, we varied swemx in a spatially homogeneous manner across a small test basin—the Animas River Basin in southwest Colorado. We present results using the default value of swemx, as well as a high swemx endmember (swemx_max).

RESULTS AND DISCUSSION

We found that the scamax simulation agreed more closely with observations than the default simulation throughout the UCRB with respect to both fSCA and streamflow. The NWM default simulation exhibited pervasive high biases in fSCA, particularly at lower elevations (e.g. Figure 4a). These high biases were largely corrected by constraining the model with observational data (Figure 4). Impacts on snowpack albedo were relatively small. Impacts on SWE were also small, but shifted the onset of snowmelt slightly earlier in the season at low elevations (not shown).

Streamflow in the scamax simulation was also improved relative to the default simulation as measured by typical objective functions (e.g. bias, root mean square error, Nash-Sutcliffe Efficiency (NSE), etc.). In the default NWM simulation, streamflow peaks tended to be too large in magnitude and occur too late in the year. In the scamax simulation, streamflow peaks shifted lower and earlier, yielding modest overall improvements in error metrics. These modest improvements were observed at stream gauges distributed across the UCRB (Figure 5). The shift in streamflow peaks likely resulted from reduced SWE and earlier snowmelt timing, as described above.

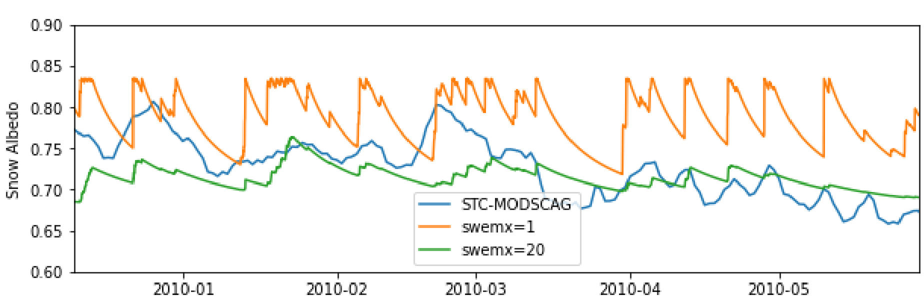

Figure 3. Comparison of STC-MODSCAG snow albedo (blue) against NWM snow albedo calculated with default (orange) and high (green) swemx values over a single grid cell.

The swemx simulations in the Animas River Basin yielded mixed results (Figure 6). Relative to the default simulation, the swemx_max simulation exhibited degraded performance with respect to snowpack albedo, but slightly improved performance with respect to both fSCA and streamflow. Specifically, the advent of snowmelt occurred earlier in the swemx_max simulation, in better agreement with STC-MODSCAG observations (not shown). As in the scamax simulation, the earlier melt in the swemx_max simulation incurred lower, earlier peaks in simulated streamflow compared to the default simulation (Figure 6). Given the observed spatial variability in snowpack albedo—both sun angle and terrain slope and aspect modify snowmelt—we expect that the spatially heterogeneous, optimized swemx distribution currently in development will yield further improvements to streamflow performance without degrading simulated snowpack albedo.

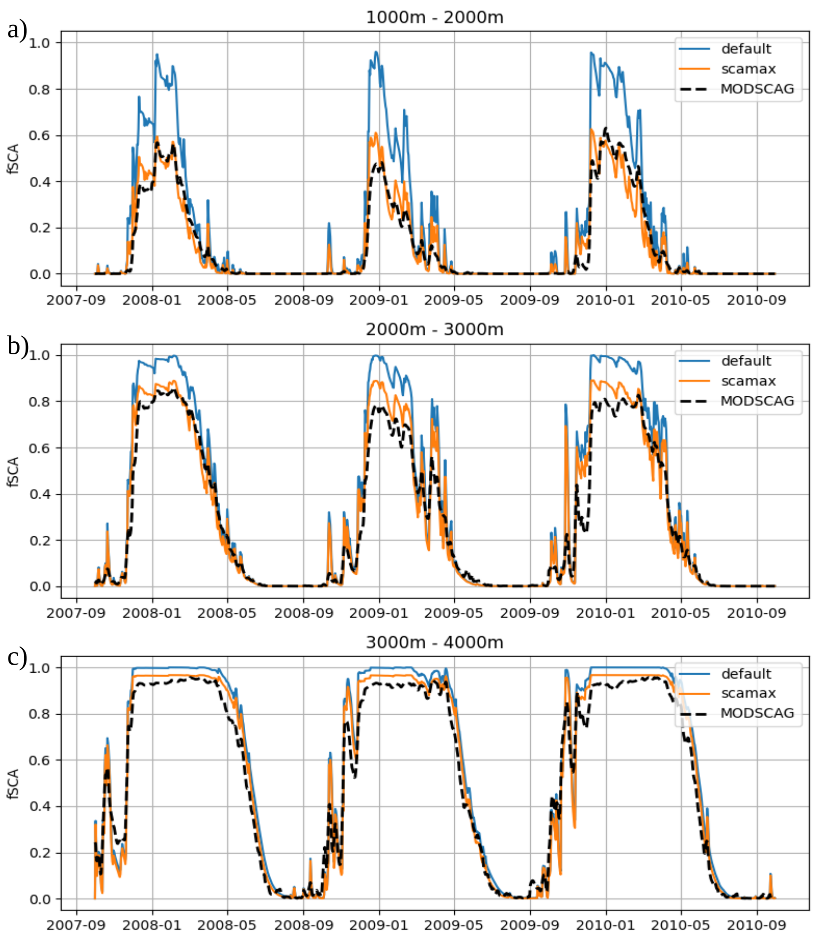

Figure 4. Time series of UCRB fSCA averaged across (a) low, (b) intermediate, and (c) high 1000 m elevation bands. High biases in the default simulation are largely absent in the scamax simulation.

Results from this study underscore the importance of high-quality, observation-based data products such as STC-MODSCAG. These data offer vital insights into model behavior, such as the propensity of Noah-MP to overestimate fSCA, particularly at low elevations (e.g. Figure 4a). Our finding that streamflow performance can be improved by forcing model fSCA to more closely resemble STC-MODSCAG fSCA is encouraging, and suggests that future efforts to assimilate STC-MODSCAG data into the NWM may offer further improvements. Future modeling work may also assimilate observations from the NOAA VIIRS (Visible Infrared Imaging Radiometer Suite) instruments, which have exhibited comparable snow mapping performance to MODIS (Rittger et al., 2021).

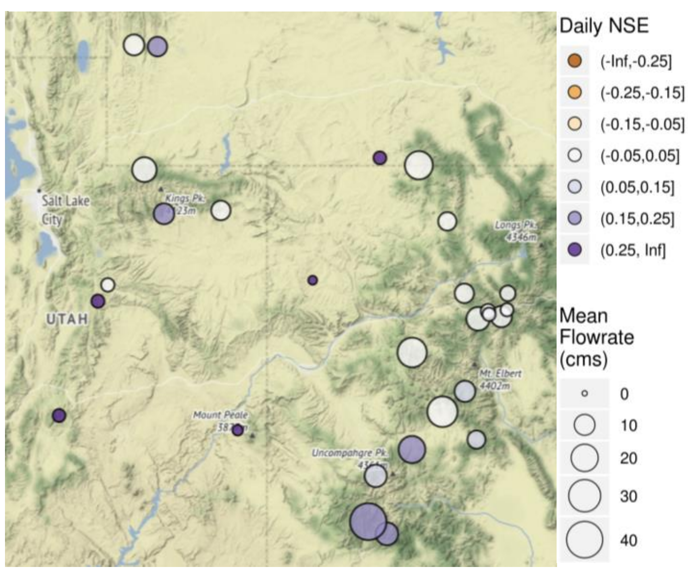

Figure 5. Change in Nash-Sutcliffe Efficiency of daily streamflow at UCRB stream gauges. Positive changes (purple) indicate improved performance in the scamax simulation relative to the default simulation.

Our results also signal a need to re-evaluate the interdependent components of Noah-MP. Given our finding that increasing swemx_max improved model fSCA and streamflow but degraded albedo, it is clear that the interactions between the individual Noah-MP snow modules fail to approximate real snowpack dynamics in some conditions. One future avenue to improve snow simulations in the NWM will be to re-derive or reformulate the empirical snow depletion curve relating snow depth to fSCA (Figure 2). A reformulation might address the tendency of the model to produce binary fSCA

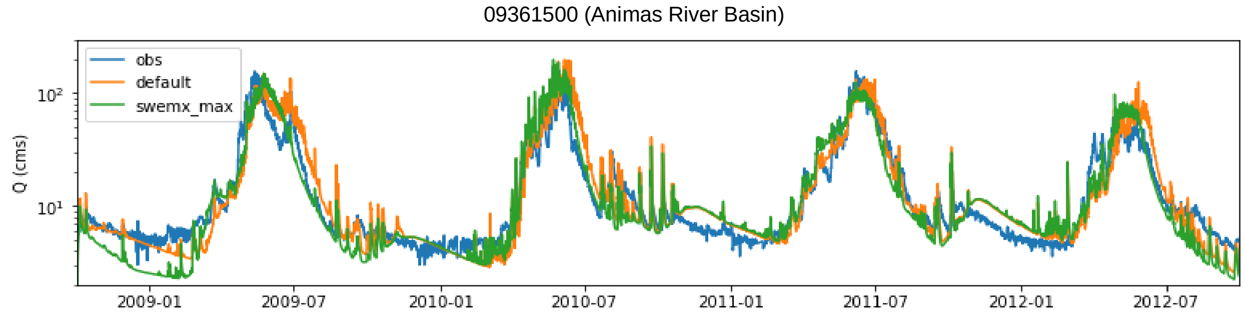

Figure 6. Comparison of observed (blue), default (orange), and swemx (green) streamflow at U.S. Geological Survey gauge 09361500. Changes in error metrics indicate improvement in the swemx simulation relative to the default simulation.

maps by leveraging high-resolution data from MODIS or VIIRS with fractional snow cover classification. The snowpack albedo models in the NWM likely require similar treatment, as both rely heavily on empirically-estimated parameters and relationships which may not hold over the range of snow conditions the NWM must simulate. Data products such as STC-MODSCAG offer a significant opportunity to improve upon the model structure and parameterizations currently in place in the NWM, and therefore to improve the predictive power of the model over the wide range of conditions observed across the model spatial domain (i.e. the conterminous United States). (KEYWORDS: National Water Model, streamflow, snowpack albedo, snow-covered area, MODSCAG)

REFERENCES

Bair, E. H., Rittger, K., Skiles, S. M. K., & Dozier, J. 2019. An examination of snow albedo estimates from MODIS and their impact on snow water equivalent reconstruction. Water Resources Research, 55, https://doi.org/10.1029/2019WR024810

Berezowski, T., Chormanski, J., & Batelaan, O. 2015. Sill of remote sensing snow products for distributed runoff prediction. Journal of Hydrology, 524, https://doi.org/10.1016/j.jhydrol.2015.03.025

Dozier, J., Painter, T.H., Rittger, K., & Frew, J. 2008. Time-space continuity of daily maps of fractional snow cover and albedo from MODIS, Advances in Water Resources, 31, https://doi.org/10.1016/j.advwatres.2008.08.011

Li, D., Wrzesien, M.L., Durand, M., Adam, J., & Lettenmaier, D.P. 2017. How much runoff originates as snow in the western United States, and how will that change in the future?, Geophysical Research Letters, 44, 6163– 6172, doi:10.1002/2017GL073551

Niu, G.-Y., et al. 2011. The community Noah land surface model with multiparameterization options (Noah-MP): Model description and evaluation with local-scale measurements, Journal of Geophysical Research, 116, D12109, doi:10.1029/2010JD015139.

Niu, G.-Y., and Yang, Z.-L. 2007. An observation-based formulation of snow cover fraction and its evaluation over large North American river basins, Journal of Geophysical Research, 112, D21101, doi:10.1029/2007JD008674.

Painter, T.H., Rittger, K., McKenzie, C., Slaughter, P., Davis, R.E., & Dozier, J. (2009). Retrieval of subpixel snow covered area, grain size, and albedo from MODIS, Remote Sensing of Environment, 113, https://doi.org/10.1016/j.rse.2009.01.001

Painter, T.H., Bryant, A.C., & Skiles, S.M. 2012. Radiative forcing by light absorbing impurities in snow from MODIS surface reflectance data, Geophysical Research Letters, 39, L17502, https://doi.org/10.1029/2012GL052457

Rittger, K., Raleigh, M. S., Dozier, J., Hill, A. F., Lutz, J. A., & Painter, T. H. 2020. Canopy adjustment and improved cloud detection for remotely sensed snow cover mapping. Water Resources Research, 55, e2019WR024914. https://doi.org/10.1029/2019WR024914

Rittger, K., Bormann, K.J., Bair, E.H., Dozier, J., & Painter, T.H. 2021. Evaluation of VIIRS and MODIS snow covered fraction in High Mountain Asia using Landsat 8, Frontiers in Remote Sensing, 2, https://doi.org/10.3389/frsen.2021.647154

Verseghy, D.L. 1991. Class—A Canadian land surface scheme for GCMS. I. Soil model. Royal Meteorological Society, 11. https://doi-org.cuucar.idm.oclc.org/10.1002/joc.3370110202

Yang, Z.-L., Dickinson, R.E., Robock, A., & Vinnikov, K.Y. 1997. Validation of the snow submodel of the Biosphere-Atmosphere Transfer Scheme with Russian snow cover and meteorological observational data, 10, https://doi.org/10.1175/1520-0442(1997)010<0353:VOTSSO>2.0.CO;2