USE OF SNOW DATA FROM REMOTE SENSING IN OPERATIONAL STREAMFLOW PREDICTION

Stacie Bender[1], Paul Miller[1], Brent Bernard[1], and John Lhotak[1]

ABSTRACT

The Colorado Basin River Forecast Center (CBRFC) issues operational forecasts of streamflow for the Colorado River Basin and eastern Great Basin. As part of a multi-year collaborative effort, CBRFC has partnered with the research-oriented Jet Propulsion Laboratory (JPL) under funding from NASA to incorporate remotely sensed snow data from NASA's MODIS instrument into operational hydrologic forecasting and modeling at CBRFC. Snowpack conditions indicated by MODIS inform CBRFC forecasters when determining causes of divergence between modeled and recently observed streamflow. The first two years of the collaborative partnership have yielded improved forecasts at select locations, in select cases, using information from remotely sensed snow data. CBRFC and JPL also retrospectively analyzed relationships between the MODIS-derived snow datasets and streamflow patterns for several watersheds within CBRFC region. The collaboration is expected to continue over the next several years as CBRFC and JPL work to further improve modeling of snowmelt and prediction of snowmelt-driven streamflow in operational hydrologic forecasting. (KEYWORDS: operational hydrology, remote sensing, streamflow forecasting, snowmelt forecasting, snow observations)

INTRODUCTION

Resource managers in the western United States depend on the timing and magnitude of snowmelt-driven runoff for water supply, irrigation, meeting environmental goals, and power generation. Flood potential is monitored by emergency managers, particularly in years with above average snow conditions. The Colorado Basin River Forecast Center (CBRFC) of the National Weather Service (NWS) issues operational forecasts of streamflow for watersheds within the Colorado River Basin (CRB) and eastern Great Basin (EGB), at multiple temporal scales. Runoff during the critical April through July period is predominantly driven by snowpack; therefore, the CBRFC and its stakeholders consider snowpack observations to be highly valuable. In the CBRFC's area of responsibility, observations of precipitation are generally provided by the Natural Resources Conservation Service's (NRCS) SNOwpack TELemetry (SNOTEL) network; however, the density of the gage network over the Colorado River Basin and eastern Great Basin is not ideal. As such, remote sensing estimates of snow may aid in filling data gaps where gage information is not available.

Observations of snow from satellite-borne instrumentation can inform forecasters of implications to snowmelt-driven runoff, particularly when combined with field reports and observations from automated, ground-based station networks. As part of a multi-year collaborative effort, CBRFC has partnered with the Jet Propulsion Laboratory (JPL) under funding from NASA to incorporate remotely sensed snow data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) into the operational CBRFC hydrologic forecasting and modeling processes.

In the first two years of collaboration, CBRFC and NASA/JPL increased forecaster awareness of snowpack conditions using information from remotely sensed data, which subsequently increased forecaster confidence in manual modifications to snowpack simulations. In select cases, indication of the presence or lack of snow by MODIS assisted CBRFC forecasters in determining the cause of divergence between modeled and gauged streamflow. Indication of albedo conditions at the snowpack's surface provided information to forecasters about the potential for accelerated snowmelt rates. CBRFC and JPL also retrospectively analyzed relationships between the MODIS-derived snow datasets and streamflow patterns for several watersheds within the CRB and the EGB. The collaboration is expected to continue over the next several years as CBRFC and JPL work to further improve modeling of snowmelt and prediction of snowmelt-driven streamflow in the CRB and EGB.

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OVERVIEW OF OPERATIONAL NWS HYDROLOGIC FORECASTING AND MODELING

The NWS CBRFC is one of thirteen NWS River Forecast Centers (RFCs). The RFCs are responsible for providing operational streamflow forecasts and guidance to many stakeholders, including NWS Weather Forecast Offices (which officially issue flood warnings) and resource management groups such as the Bureau of Reclamation, water conservation districts, environmental project managers, and recreationalists in the western United States. The hydrologic regimes within CBRFC's area of responsibility (Figure 1) range from snowmelt-dominated basins in Wyoming, Colorado, and Utah, to rainfall-dominated, flash-flood conditions in the lower CRB.

CBRFC Forecast Types

CBRFC primarily focuses on two types of streamflow prediction: (1) short-term deterministic forecasts of streamflow, including flood flows if conditions warrant, out one to two weeks, with lead times of hours to days, and (2) longer-term probabilistic projections of seasonal runoff volumes primarily driven by snowpack, with lead times of several months. These forecasts inform stakeholder and resource manager decision support paradigms. Other forecasts may be issued as requested.

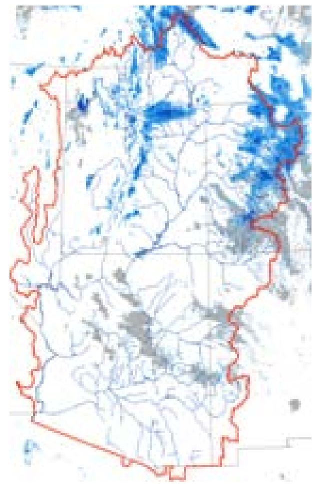

Figure 1. CBRFC area of responsibility (red outline) and gridded MODIS-derived snow cover data

Models Used Operationally at CBRFC

The snow model used by CBRFC is the SNOW17 accumulation and ablation model (Anderson, 1976, 2006). SNOW17 is a simple (relative to snow models with full representation snowpack physics and energy balance) conceptual model that requires only temperature and precipitation as input and represents the snowpack as a single layer. SNOW17 is a temperature-index model that computes snowmelt under non-rain conditions by multiplying the difference between the air temperature and a base temperature by a melt factor. Parameters used to define the melt factor are determined in the calibration process, along with additional model parameters. When snow is present in a modeled area and conditions warrant depletion of the snowpack, the melt water outflow volume from SNOW17 is subsequently passed to the soil moisture model.

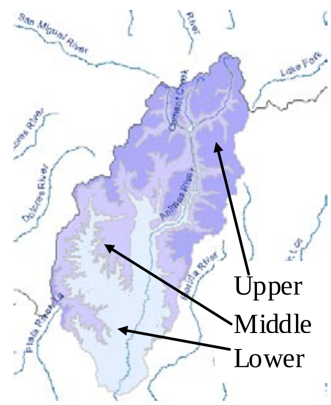

Figure 2. CBRFC-defined elevation zones (bands) for DRGC2 basin

The soil moisture model utilized is the conceptual Sac-SMA model (Burnash et al., 1973). Within Sac-SMA, the soil is represented in two layers to capture soil moisture processes near the surface as well as groundwater processes deeper within the soil column. Water may be stored within or exchanged between the two soil layers. Model parameters determined in the calibration process define the size of several soil moisture "tanks" for each layer and the rates of soil moisture transport between the two layers. If the volume of water input to the soil moisture model, either from snowmelt or rainfall, is greater than the available capacity to store water, or if the rate of water input exceeds defined transport rates, water will be available to the channel as runoff.

Both the SNOW17 and Sac-SMA models are run in a lumped framework for CBRFC operations over elevation bands, or elevation zones, within a watershed. Basins modeled by CBRFC are divided into up to three elevation zones, depending on the amount of relief within the basin. The zone boundaries are determined roughly based on general vegetation patterns and snowpack patterns. SNOW17 and Sac-SMA parameters are defined separately for each elevation zone. The elevation zones defined for the basin with the Animas River at Durango USGS stream gage (USGS ID 09361500, NWS ID DRGC2) are illustrated in Figure 2. The elevation boundaries for these zones are listed in Table 1, along with the area for each elevation zone.

Table 1. DRGC2 elevation zone boundaries, mean elevation, and area

Elevation Zone	Elevation Range (m)	Mean Elevation (m)	Area (km^2)
Upper	3353 to 4279	3645	605
Middle	2896 to 3352	3113	594
Lower	1986 to 2895	2553	619

Expanding the Snow Observations Dataset Used in Operational CBRFC Streamflow Prediction

Traditionally, the major sources of snowpack information used in operational hydrologic modeling and forecasting at CBRFC have been the point precipitation and snow water equivalent (SWE) observations from the NRCS SNOTEL network, along with information from the NWS's Cooperative Observer Program (COOP). The SWE observations from the SNOTEL network have been used to develop and run statistical models to forecast seasonal runoff volumes for water supply forecasting. The precipitation observations from the SNOTEL and COOP networks are used in the daily streamflow forecasting process at CBRFC as precipitation inputs.

While point information provided by the SNOTEL and COOP networks is invaluable to CBRFC, much of CBRFC's area of responsibility is located in remote areas, where the spatial density of the gage network may not be adequate to accurately represent snowpack conditions. Data from remote sensing can fill in gaps between stations (Figure 3). To gather a more complete picture of snowpack conditions, CBRFC began investigating ways to use snow data from remote sensing, specifically from the MODIS instrument managed by NASA. To accelerate the integration of MODIS-derived snow data into CBRFC operations, CBRFC partnered with JPL, a research-oriented remote sensing science agency, starting in 2012.

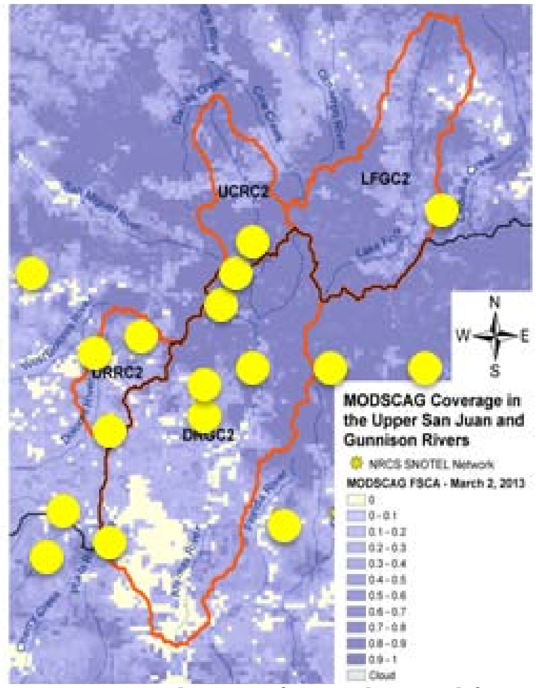

Figure 3. Spatial extent of remotely sensed fractional snow cover from MODIS (grid), with SNOTEL station locations in southwestern Colorado (yellow dots).

BRIDGING THE RESEARCH-TO-OPERATIONS GAP

RFCs have traditionally been end users of products and methods developed by academia and the hydrologic research arm of the NWS, the Office of Hydrologic Development (OHD). However, the role of RFCs in the NWS is changing, as some RFCs have become more actively involved in the research and development (R&D) process. To bridge the research to operations (R2O) gap, scientists and programmers from both research and operations groups must understand the unique characteristics of each other's environment and share information across traditional barriers (e.g., infrastructure, computing resources, and product delivery). The National Research Council (2012) heavily emphasizes the need for active collaboration among operational, research, and academic groups, despite barriers that have prevented such collaborations in the past. The success of collaborative partnerships between operational groups like CBRFC and research groups like JPL depends heavily upon cooperation among the people involved, particularly those who are building data processing systems and working with the data on a daily basis. Scientists and computer programmers in both the research and operations environments must be open-minded and willing to explore and understand the challenges faced by their counterparts if the R2O gap is to be bridged.

While collaborative partnerships like the one between CBRFC and JPL, as described in this paper, are extremely beneficial to both groups, roadblocks to full integration of research-oriented datasets into operational practice still exist. Currently, the primary roadblock is computing and network resources within the operational streamflow forecasting environment at NWS RFCs. As of 2014, the operational NWS hydrologic modeling system is run on a small cluster of Linux boxes; operational supercomputing resources are currently not available. Network bandwidth for data transfer is also limited at CBRFC, though upgrades are planned for summer 2014.

OVERVIEW OF SNOW DATASETS FROM REMOTE SENSING USED AT CBRFC

MODIS

NASA's MODIS instrument, which flies on the Terra and Aqua satellites, provides remote sensing data across several bands and portions of the electromagnetic spectrum (Figure 4). MODIS acquires information globally on a daily basis, at 500 m spatial resolution. Cloud cover is one impediment to MODIS-based datasets, as clouds obstruct the instrument's view of the earth's surface.

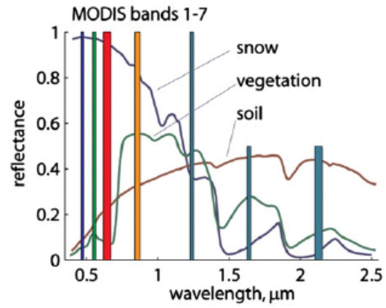

Figure 4. MODIS land bands, along with one sample spectrum each from vegetation, snow, and soil. (From Painter et al., 2009)

While other instruments such as those associated with the Landsat program provide data at a much higher spatial resolution than MODIS (30 m vs. 500 m), their temporal frequency of observation is much lower than that of MODIS (~2.5 weeks for Landsat instruments vs. daily acquisitions by MODIS). Currently, for operational purposes, MODIS-based datasets offer the best compromise of spatial and temporal resolution. MODIS's daily observation frequency increases the chance of obtaining at least partially cloud-free scenes and actual observations of the earth surface, including snow-covered portions.

CBRFC Data Processing of MODIS-based Snow Datasets

MODIS datasets are available as individual tiles (subsets) of the global dataset. Four tiles are necessary for complete coverage over the CBRFC area of responsibility (Figure 5). Data are available at a one-day lag. CBRFC pulls the newest tiles on a daily basis from a JPL server in the early morning hours, prior to the first daily run of the hydrologic model at CBRFC. Several different types of MODIS-based datasets are downloaded from JPL and processed by CBRFC: two snow cover products and two dust-related products (see MODSCAG and MODDRFS sections below). Once CBRFC has downloaded the four tiles for each dataset, the tiles are mosaicked into CBRFC-wide grids and archived. Further processing allows for graphical display of the MODIS-derived snow datasets to CBRFC forecasters. Geospatial processing tools such as the Geospatial Data Abstraction Library (GDAL), Geographic Resources Analysis Support System (GRASS), and the Community Hydrologic Prediction System (CHPS) allow for computation of spatially-averaged, scalar values from the gridded snow datasets, as well as percent of cloud cover, over the CBRFC elevation zones. The scalar values are more appropriate for consideration within CBRFC's lumped modeling framework.

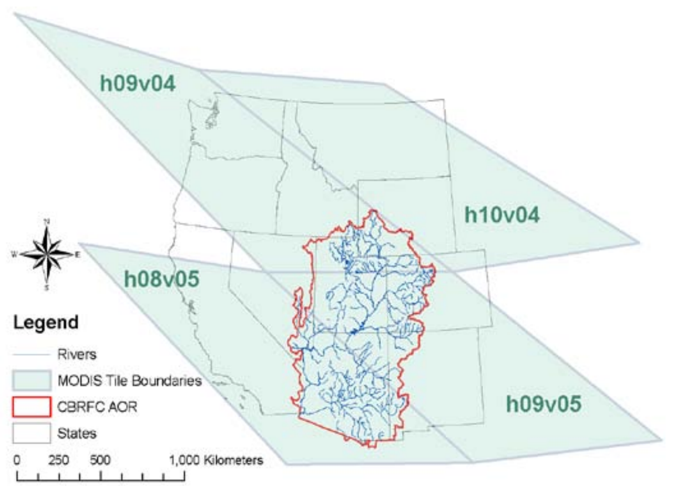

Figure 5. MODIS tiles comprising full coverage over the CBRFC area of responsibility (red outline).

MODSCAG Fractional Snow Cover

In the past several years, spectral mixture modeling has gained traction as a way to derive estimates of snow-covered area, even at the subpixel level. Spectral mixture analysis used by JPL assumes that the sensor (MODIS, in the snow remote sensing data used at CBRFC) observation is determined by a linear combination of contributions from individual endmembers such as rock, bare soil, vegetation and snow (Painter et al., 2009). Through spectral mixture analysis, the fraction of a pixel's area covered by snow (fSCA) can be estimated.

JPL generates MODIS-derived, gridded fSCA datasets via a spectral mixture model called MODIS Snow-Covered Area and Grain size (MODSCAG). CBRFC utilizes two versions of MODSCAG fSCA. The first is "viewable" fSCA, which is representative of what MODIS observes, in a remote sensing sense. The "viewable" fSCA reports what MODIS observes, and the product is influenced by the presence of vegetation. If snowpack exists under a coniferous canopy, and the trees are snow-free after a storm-free period, the "viewable" fSCA product will report a lower amount of fSCA than if the trees were snow-covered. Most of the snowpack beneath a snow-free coniferous canopy will not be observed by MODIS, particularly in areas of healthy conifers.

As an interim solution, JPL also provides a "canopy-adjusted" version of MODSCAG fSCA. In the "canopy-adjusted" fSCA product, an additional endmember from the spectral mixture analysis, the presence of green vegetation, is used to reset the fSCA value to a higher value if both green vegetation and snow are detected within the same pixel. The higher value of fSCA indicates that snow cover is indeed present under the canopy even though MODIS does not observe the below-canopy snowpack. Figure 6 shows samples of the two MODSCAG fSCA products, "viewable" and "canopy-adjusted".

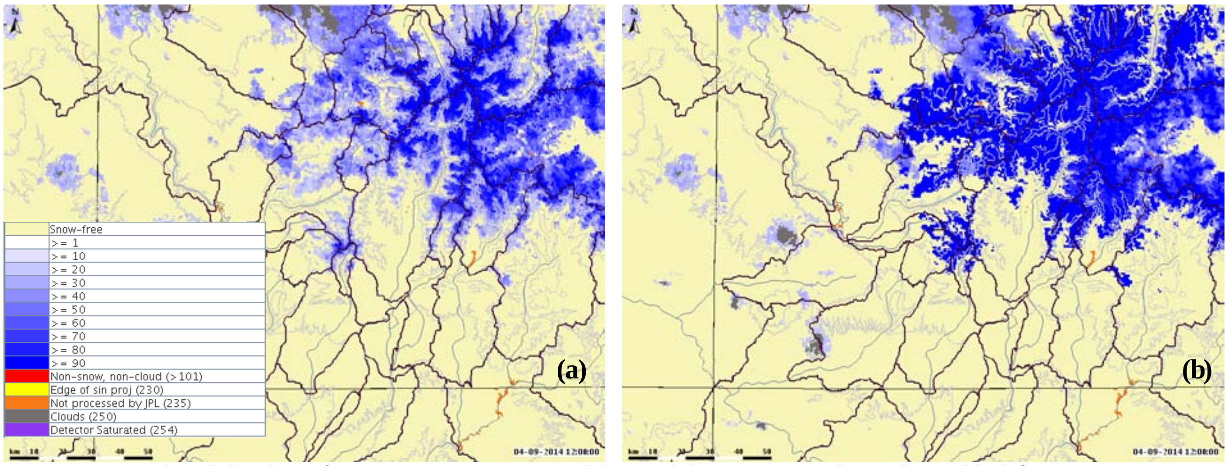

Figure 6. Graphical display of MODSCAG (a) "viewable" and (b) "canopy-adjusted" gridded fSCA over southwestern Colorado, April 9, 2014, as viewed by CBRFC forecasters within CHPS.

MODDRFS Dust-on-Snow and Albedo

The MODIS Dust Radiative Forcing in Snow (MODDRFS) algorithm outputs datasets that provide information about the albedo of the snowpack's surface. The albedo of the snowpack surface affects the amount of solar energy absorbed by the snowpack, which subsequently influences snowmelt rates. In particular, snowpack with an albedo reduced by the presence of dust or contaminants at the snowpack surface may experience accelerated snowmelt rates, especially on cloud-free, sunny days.

The MODDRFS dust radiative forcing values are computed by examining differences between reflectance observations and modeled spectra for clean snow (Figure 7). As the MODIS reflectance data indicate increasingly reduced albedo at the snowpack surface, the dust radiative forcing values increase in magnitude.

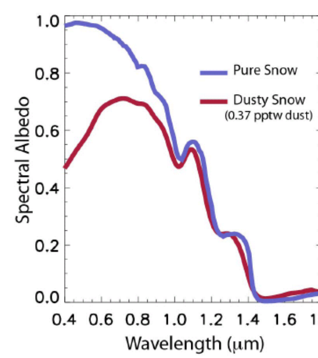

Figure 7. Spectral albedo of clean snow (modeled) and snow with dust (measured). (From Painter et al., 2012)

EXAMPLES OF JPL REMOTE SENSING SNOW DATA IN USE AT CBRFC

Overview of First Two Years of Collaboration

In 2012, the first year of official collaboration, CBRFC and JPL set up an ingest system to manage automated downloading, processing, and archival of JPL's remotely sensed snow data in-house at CBRFC. The ingest system was designed to be flexible, to easily allow for processing of additional JPL datasets with time, and to be portable to other NWS RFCs.

By the spring snowmelt season of 2013, CBRFC was routinely pulling remotely sensed snow data from JPL servers and processing the data with open source software. In 2013, CBRFC forecasters had regular access to graphical displays of the "viewable" fSCA from MODSCAG, as well as MODDRFS products of dust radiative forcing and percent difference of observed snowpack surface conditions from a clean snowpack surface. The graphical displays informed the forecasters as they made manual adjustments to the streamflow forecasts initially computed by the CBRFC hydrologic modeling system. JPL analyzed historical patterns in MODDRFS data and streamflow prediction errors over the 2000-2010 period (Bryant et al., 2013).

Over the winter of 2013 and into 2014, canopy-adjusted MODSCAG fSCA was added to the forecaster toolbox, bringing the number of daily remotely-sensed snow datasets available to CBRFC forecasters to four. Forecasters also began examining the MODDRFS data more closely in near real time. Specific examples of JPL's remotely sensed snow datasets being used in CBRFC operations are provided below.

MODSCAG Fractional Snow Cover

The JPL datasets of snow from remote sensing are valuable to CBRFC, particularly by informing the operational forecasters with a more complete picture of snowpack conditions. Starting in spring 2013, CBRFC forecasters used "viewable" fSCA from MODSCAG semi-quantitatively as a binary indicator of the presence or lack of snowpack. The MODSCAG fSCA product was especially useful when forecasters were investigating the cause of divergence between streamflow simulated by the model and recently observed streamflow. In these cases, CBRFC forecasters checked the MODSCAG fSCA data to see if a model error in simulated snow might be the reason why the streamflow simulation was departing from observed streamflow of the most recent few days. If the MODSCAG fSCA product indicated snow and the simulated snow water equivalent (SWE) was zero, the forecaster would manually increase the model SWE by a small amount. If the MODSCAG product indicated that the snowpack had completely melted and snow cover was zero, the forecaster would manually set the simulated SWE to zero. In general, manual SWE adjustments were conservative as forecasters cautiously incorporated snow information as inferred by MODSCAG into CBRFC operations, with increases or decreases of 25 to 75 mm of SWE.

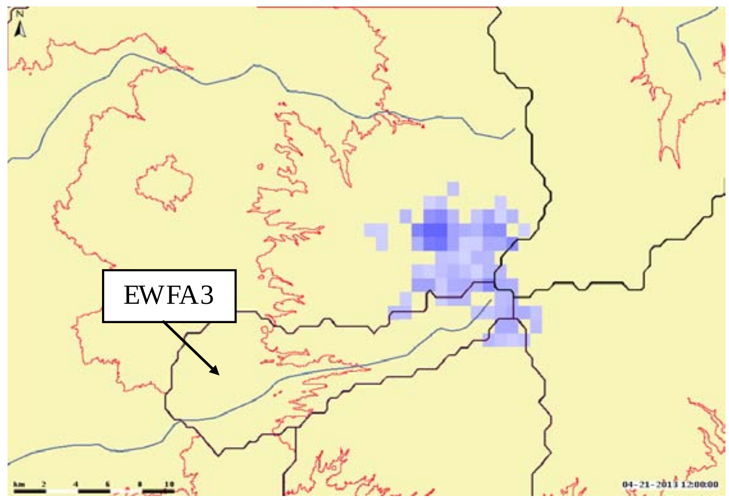

Figure 8. MODSCAG fSCA from April 21, 2013, showing snow in the far upper elevations of the EWFA3 basin.

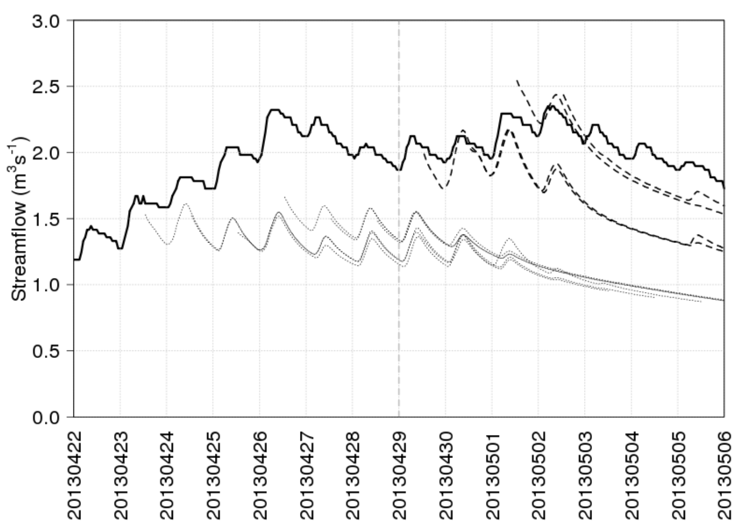

Figure 9. Observed streamflow (bold line), streamflow forecasts issued *before* SWE modification by CBRFC forecaster (dotted lines), and streamflow forecasts issued *after* SWE modification by CBRFC forecaster (dashed), for the East Fork of the White River near Fort Apache, AZ.

SWE adjustments were made in both northern and southern areas of CBRFC's area of responsibility. An example of a SWE adjustment in Arizona is shown in Figures 8 and 9. The basin is the East Fork of the White River, near Fort Apache, AZ (NWS ID: EWFA3, USGS ID: 09492400). Prior to a SWE adjustment by the CBRFC forecaster, the simulated streamflow was much lower than the observed streamflow (dotted lines in Figure 9). In this case, the forecaster reviewed the MODSCAG fSCA product (Figure 8) and noted that snow was still indicated in the upper elevations of the basin by the MODSCAG fSCA product. Because of the information provided by the MODSCAG fSCA product, the forecaster manually increased the amount of simulated SWE in the upper elevation zone, which resulted in higher simulated streamflow. Ultimately, the forecasts issued *after* the SWE adjustment were more accurate when compared to the observed streamflow (dashed lines in Figure 9).

MODDRFS Dust-on-Snow and Albedo

CBRFC recognizes that deposition of dust and other contaminants on the snowpack surface reduces the albedo of the snow surface, influencing the amount of solar radiation absorbed by the snowpack, snowpack melt rates, and timing of snowmelt-driven streamflow. The SNOW17 model used operationally at CBRFC uses air temperature as an index of radiation and the energy balance; SNOW17 does not explicitly account for abnormal albedo or dust-on-snow conditions. Despite the lack of a full representation of the energy balance within SNOW17, JPL researchers and CBRFC forecasters are still investigating ways by which the MODDRFS data can be used in operational CBRFC forecasts.

As part of the CBRFC-JPL collaboration, relationships between MODDRFS data and streamflow prediction errors for the years 2000-2010 were analyzed by JPL. The resulting analysis indicates that runoff prediction errors are significantly correlated to variability in dust radiative forcing during the melt period in regions of the CRB (Bryant et al., 2013). Figure 10 shows that, as dust conditions deviate from mean conditions in southwestern Colorado watersheds, the timing of melt and streamflow is impacted. The analysis results provide context to forecasters when they are working in real time. In particular, as the MODDRFS data indicate abnormally high dust conditions and reduced albedo at the snowpack surface, the forecasters know that abnormally early melt may potentially occur, depending on the amount of solar radiation reaching the snowpack, cloud cover, ripeness of the snowpack, and other factors.

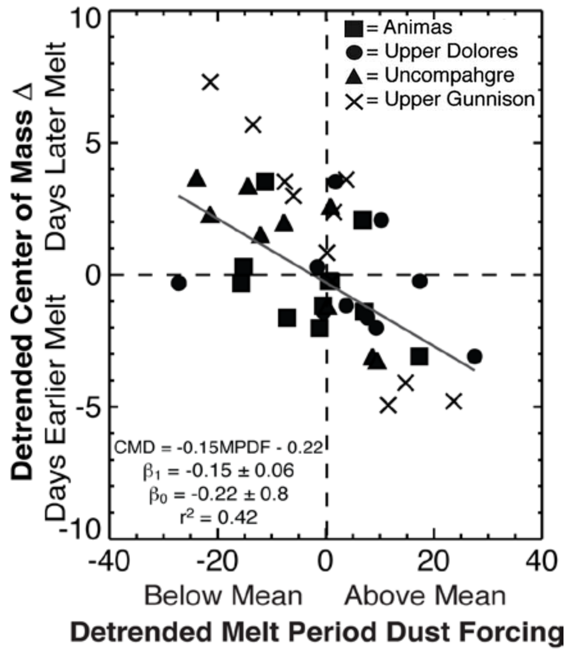

Figure 10. Least squares linear fit of melt period dust forcing and center of mass delta with their respective regression coefficient (β_0 and β_1) values (from Bryant et al., 2013)

When real-time conditions deviate from the typical conditions of the calibration period, the forecaster may manually adjust values related to the simulated snowpack if warranted. Since SNOW17 is a temperature-index snow model, air temperatures and their departures from normal are the primary consideration when CBRFC forecasters consider adjustments to simulated snowmelt rates. CBRFC forecasters currently consider MODDRFS data and their albedo information as a supplementary, supportive piece of snowpack information, to be used in a qualitative manner.

One example of a manual adjustment related to the snowmelt rate is a "melt factor correction" (MFC), which is a multiplier on the initial snowmelt volume computed by SNOW17. A MFC is used by a CBRFC forecaster to forcibly increase (MFC > 1.0) or decrease (MFC < 1.0) the snowmelt initially simulated by SNOW17. A manual adjustment to the simulated snowmelt may be needed when the energy input to the snowpack deviates from typical conditions (implied via air temperature as an index and, possibly, inferred from remote sensing snowpack albedo data as a secondary, supportive source of information).

In mid April 2014, air temperatures within and near the Animas River watershed alternated between below and above normal. Specifically, a period of above normal air temperatures occurred between April 9 and April 13, up to 8 C above normal (Figures 11 and 12). The above normal air temperatures were the first alert to CBRFC forecasters of the potential for an increase in solar radiation absorbed by the snowpack (indexed by air temperature within CBRFC's snow model) and accelerated melt rates.

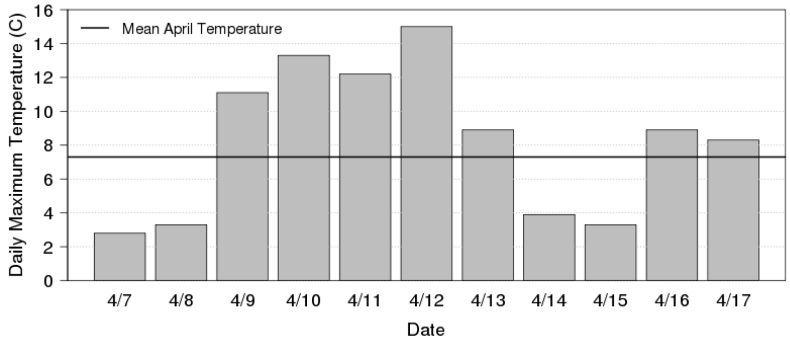

Figure 11. Daily maximum air temperature (gray) for Silverton, CO (NWS ID: SLVC2) in mid April 2014, with mean air temperature for the month of April (black)

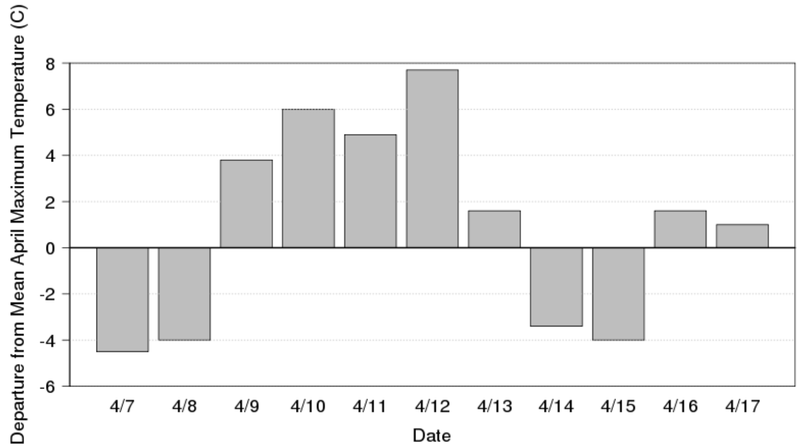

Figure 12. Departures of daily maximum air temperature from mean April maximum temperature (gray) for Silverton, CO (NWS ID: SLVC2) in mid April 2014

When air temperatures are above normal, MODDRFS data, along with field reports from the Colorado Dust-on-Snow (CODOS) Program (http://www.codos.org/), can provide supplementary, supporting information to forecasters about the potential for accelerated snowmelt rates. On April 4, 2014, an alert was posted by CODOS stating: "… dust layer D4 may emerge in the coming week, absorbing solar radiation and accelerating the warming of the underlying snow cover at higher elevations, or enhancing snowmelt rates at lower elevations where the snow cover was already isothermal." (CODOS, 2014). CBRFC forecasters also noted increasing dust radiative forcing in the MODDRFS products throughout the week of April 7, 2014, particularly in southwestern Colorado. A time series of MODDRFS images is shown in Figure 13, illustrating the increase in dust radiative forcing and accompanying reduction in albedo at the snowpack's surface for the Animas River at Durango, Colorado watershed. The combination of forecaster knowledge of (1) above normal air temperatures, (2) MODDRFS remote sensing data, and (3) CODOS field information resulted in a more complete picture of snowpack conditions and the potential for accelerated snowmelt rates.

In response to the above normal air temperatures as a representation of incoming solar radiation, MODDRFS remote sensing data, and the field reports from the CODOS program, forecasters applied a MFC greater than 1.0 on the snowmelt volume computed initially by SNOW17. The combination of the temperature, remote sensing, and field information gave forecasters confidence when they manually increased the snowmelt. Qualitatively, the remote sensing data and field reports served as supplementary support information for the forecasters' manual adjustment to the simulated snowmelt.

Streamflow forecasts issued for the Animas River *after* this correction was applied manually by the forecaster (dashed lines in Figure 14) better matched the streamflow that was ultimately observed than forecasts issued prior to the correction being applied (dotted lines in Figure 14). A snowstorm occurred on April 13, 2014, lowering air temperatures, increasing cloud cover, re-burying the exposed dust layer with fresh snow, and increasing the albedo of the snowpack's surface. Snowmelt rates slowed, and streamflow receded.

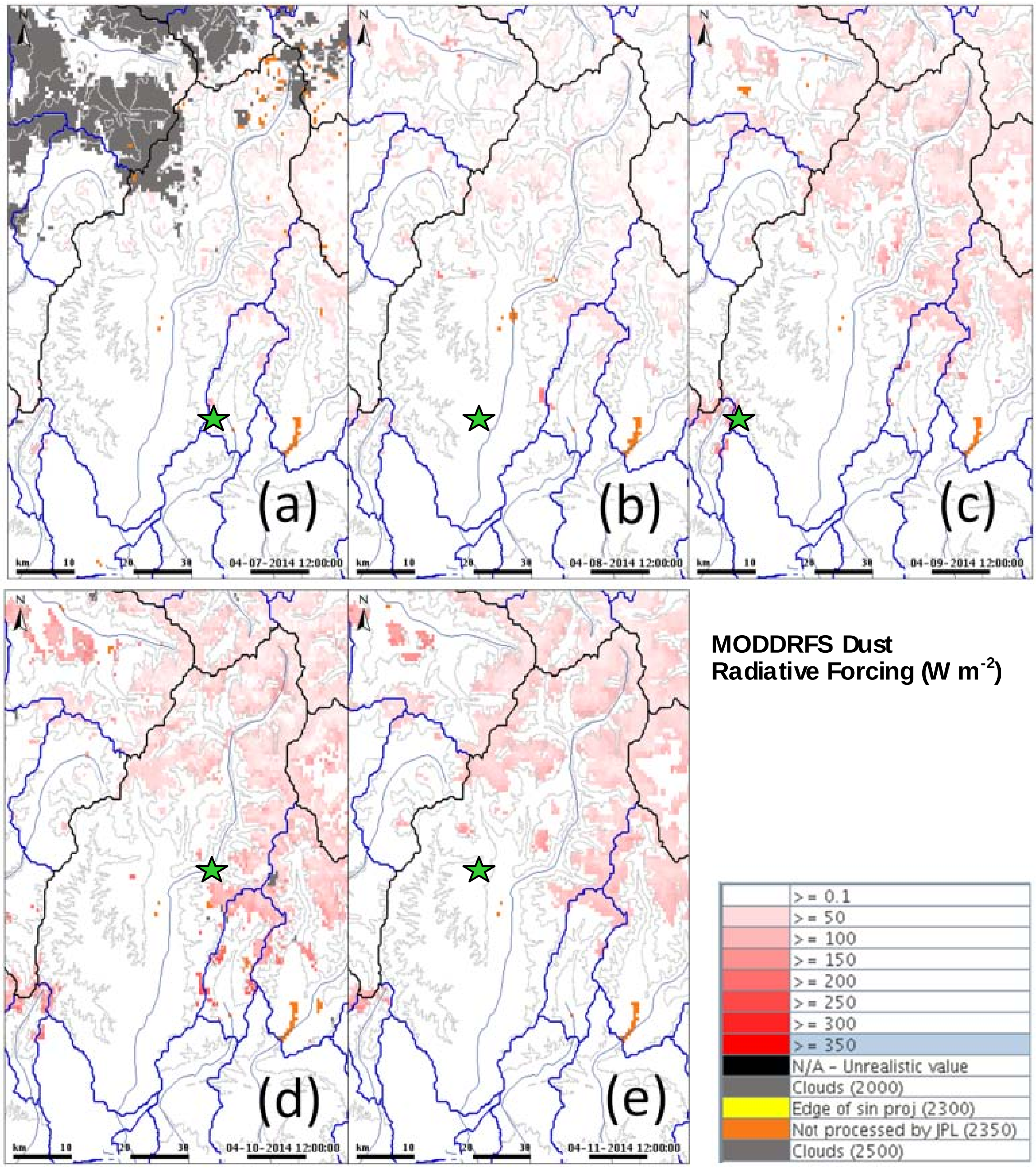

Figure 13. MODDRFS grids for (a) April 7, 2014 through (e) April 11, 2014, for southwestern Colorado, including the Animas River headwater basin near Durango, CO (indicated by the green star)

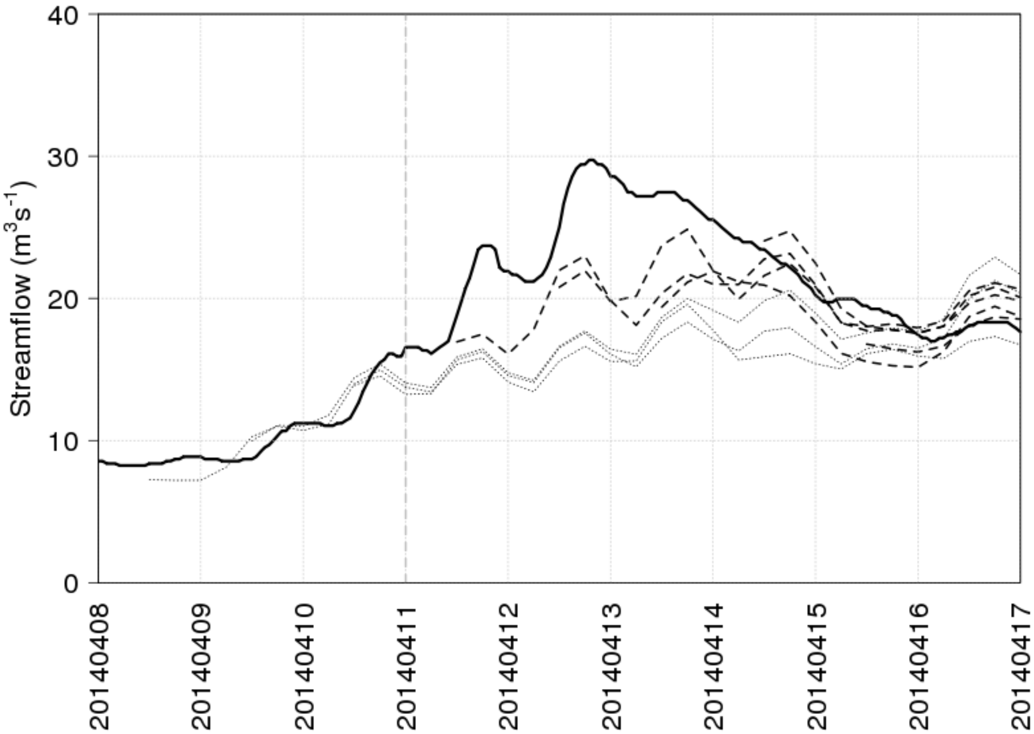

Figure 14. Observed streamflow (bold line), streamflow forecasts issued *before* MFC by CBRFC forecaster (dotted lines), and streamflow forecasts issued *after* MFC by CBRFC forecaster (dashed lines), for the Animas River at Durango, CO.

FUTURE WORK

The work completed in 2013 and 2014 by CBRFC and JPL with respect to the integration of snow information from remote sensing into CBRFC operations is a small part of overall plans for expanding forecaster knowledge of snowpack conditions, both in retrospect and in real time. While remotely sensed snow datasets have expanded the type and amount of snowpack information available to CBRFC forecasters, a robust, objective way of incorporating remotely-sensed snow data into operational streamflow forecasting has not yet been determined. Methods of quantitatively connecting snow remote sensing data with a specific range of values to be used in manual modifications by the CBRFC forecaster must be refined. Further analysis of historical patterns in MODIS-derived fractional snow cover (both viewable and canopy-adjusted), dust deposition, albedo information, and streamflow prediction errors is planned for summer and fall 2014.

Inclusion of snowpack information from remote sensing is only one piece of the overall snowmelt and snowmelt-driven streamflow forecasting challenge. Errors in snowmelt-driven streamflow forecasts arise from a multitude of sources, not just those related to snow data from remote sensing. Additional snow-related initiatives within CBRFC and collaborative projects between CBRFC and its research partners are already underway though not yet complete. Examples include testing of an energy balance snow model through a partnership with Utah State University, and studies of bark beetle impacts by Western Water Assessment. R20 efforts and collaborations between CBRFC and its external research partners are expected to extend into the next three to five years and beyond.

SUMMARY

The remote sensing snow data provided to CBRFC via the partnership with JPL and NASA has helped CBRFC forecasters make more informed decisions related to hydrologic model adjustments during the operational streamflow forecasting process. Forecaster awareness of abnormal conditions, as they occur in real time, is increased by making these datasets available to forecasters on a daily basis. More robust, numerical methods of incorporating the remote sensing data into the CBRFC forecasting process will be investigated as the collaborative CBRFC-JPL partnership continues over the next several years.

The success to-date of the partnership between CBRFC and JPL is due, in large part, to the dedicated scientists and programmers involved at all levels. This collaborative project shows that the R2O gap can be bridged, if people on both the research and operations sides are highly motivated.

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