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Colorado Water Conservation Board

TASK REPORT

Using Snow Covered Area to Improve Snow Modeling and Water Supply Forecasts

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Prepared by

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1.0 INTRODUCTION

The Colorado Water Conservation Board (CWCB) provided funding to Riverside Technology, inc (Riverside) to assemble historical datasets of snow-covered area (SCA) for forecast locations in Colorado. SCA data have the potential to improve snow modeling, for example through data assimilation and model state updating (Rodell and Houser, 2004; Andreadis and Lettenmaier, 2006; Clark et al., 2006), and to improve water supply forecasts (McGuire et al., 2006). The potential benefits will vary by forecast location. The highest potential for benefit exists in basins with variable snow cover that produce significant snowmelt runoff after bare ground has begun to show (Clark et al., 2006). SCA data have the potential to improve both short-term deterministic forecasts as well as long-term probabilistic forecasts (Clark et al., 2006; McGuire et al., 2006).

Riverside compiled two historical SCA datasets. The first dataset was derived from the Snow Data Assimilation System (SNODAS) developed by the National Operational Hydrologic Remote Sensing Center (NOHRSC). SNODAS is a modeling and data assimilation system that simulates snowpack characteristics for the conterminous U.S. at a 1-km spatial resolution and a 1-hr temporal resolution (Barrett, 2003). The SNODAS dataset is advantageous in that the snowpack estimates are temporally and spatially continuous. However, the consistency of the SNODAS dataset varies over time due to improvements in the system as well adjustments that are made periodically to the model states during normal operations (NOHRSC, personal communication, July 20, 2011). Riverside processed the SNODAS dataset from September 30, 2003 (the earliest date available) to June 30, 2011.

The second historical SCA dataset was developed using fractional snow cover grids from the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Snow Cover Daily L3 Global 500 m Version 5 MOD10A1 dataset (Hall et al., 2011). The MOD10A1 dataset is available globally at a 500-m spatial resolution and a 1-day temporal resolution. The MOD10A1 dataset is advantageous in that it is based on remotely sensed observations. However, the dataset is impacted by cloud cover, vegetation, and misclassification errors. Riverside processed the MOD10A1 dataset from February 24, 2000 (the earliest date available) to June 30, 2011.

In addition to providing the historical SCA grids in ArcGIS format, Riverside also processed the grids to produce time series of areal averages over elevation zones, local drainage areas, and total drainage areas. The SNOW-17 snow accumulation and ablation model run by the National Weather Service (NWS) typically employs elevation zones as the modeling units. The statistical water supply forecast models utilized by the NWS and the Natural Resources Conservation Service (NRCS) are developed for the local and total drainage areas above a forecast location.

The historical SCA grids and time series were provided to the Colorado Water Conservation Board (as the funding agency) and to the NWS and the NRCS (as the federal agencies with forecasting responsibility). Within the NWS, four River Forecast Centers (RFCs) have responsibility for issuing streamflow forecasts in Colorado:

- Arkansas-Red Basin River Forecast Center (ABRFC) – Arkansas River Basin
- Colorado Basin River Forecast Center (CBRFC) – Yampa, Colorado, Gunnison, and San Juan River Basins
- Missouri Basin River Forecast Center (MBRFC) – North Platte and South Platte River Basins
- West Gulf River Forecast Center (WGRFC) – Rio Grande River Basin

The NRCS and the NWS RFCs are responsible for acquiring the SNODAS and MODIS SCA data in real-time as needed to expand the SCA data archive and to support forecast operations. The historical SCA datasets are intended to be used by these organizations for developing relationships with the SNOW-17 model states, enhancing water supply statistical models, and evaluating historical forecast improvements to inform future operations.

2.0 HISTORICAL SCA DATASETS

2.1 GIS Data

Riverside prepared shapefiles of elevation zones, local basins, and total basins that were used for areal processing of the historical SCA grids (***Figure 1***). The RFCs provided initial shapefiles for the elevation zones and local basins in their jurisdiction. Riverside edited the shapefiles as required to dissolve gaps between polygons and to remove overlapping polygons.

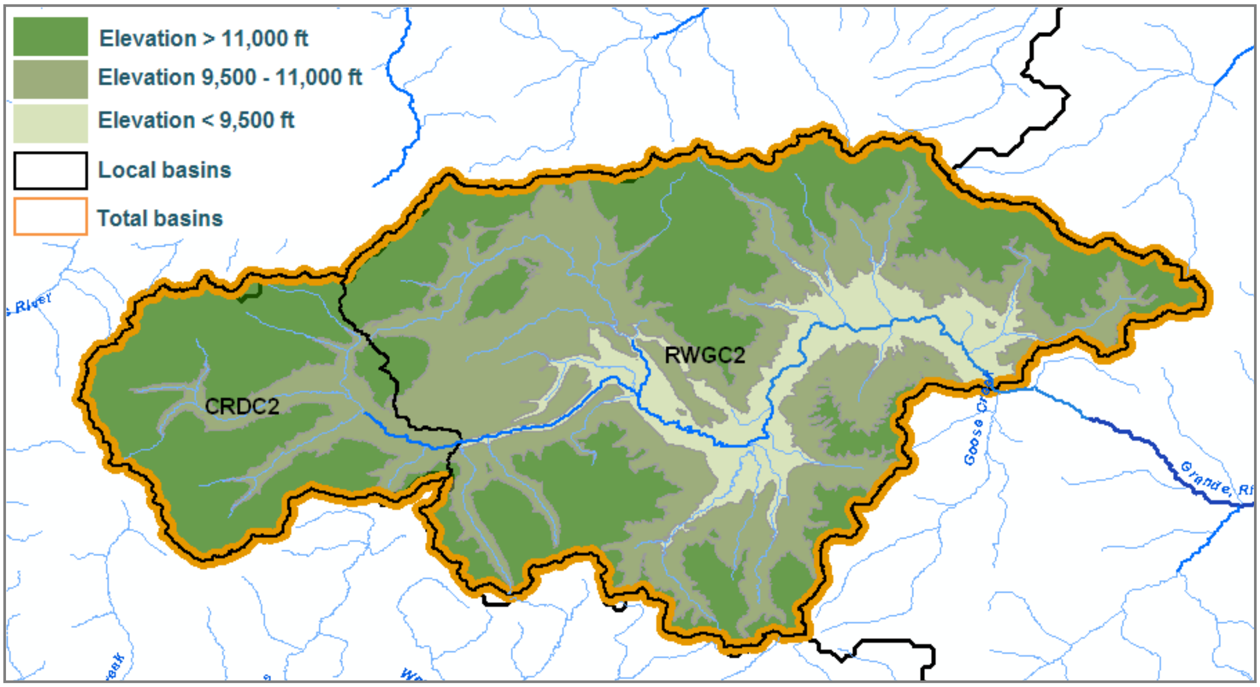

Figure 1. Example Elevation Zones, Local Basins, and Total Basins

Because the NRCS has sole responsibility for some forecast locations, the shapefiles provided by the RFCs did not contain all forecast locations within the State of Colorado. Riverside utilized information provided by the NRCS to identify seven locations that were added to the RFC shapefiles to provide a complete inventory of forecast locations. Five of the seven locations were located within the CBRFC jurisdiction; the remaining two locations were contained within the MBRFC jurisdiction (***Table 1***). The ***Subdivided RFC Basin*** column in ***Table 1*** indicates the polygon in the RFC shapefile that was subdivided to include the additional NRCS forecast location.

Table 1. Additional NRCS Forecast Locations

RFC	Forecast Group	Forecast Location Name	USGS Identifier	Riverside Identifier	Subdivided RFC Basin
CBRFC	UC	Slate River nr Crested Butte	09111500	SLATE_RTI	ALEC2
		Tomichi Creek at Sargents	09115500	TMCC2_RTI	TOMC2
		Gurley Reservoir Inlet	n/a	GURLY_RTI	SNMC2
		Cone Reservoir Inlet	n/a	CONE_RTI	SMUC2
		Lilylands Reservoir Inlet	n/a	LILY_RTI	SMUC2
MBRFC	SOPLATS	Bear Creek above Evergreen	06710385	EVER_RTI	MRRC2
		Big Thompson R at Canyon Mouth	06738000	BIGT_RTI	LSLC2

Once the local area basin delineations were finalized, the hydrologic connectivity among the basins was established using the RFC forecast system files (i.e., fs5files). Shapefiles were developed to represent the intersection between the local drainage areas and the forecast locations to indicate which local areas contribute to the drainage of each forecast location.

The elevation zone, local basin, and total basin shapefiles were used for data processing to generate time series of areal average SCA. All GIS layers were provided to the CWCB, NRCS, and NWS RFCs to facilitate future SCA data processing.

2.2 MODIS SCA

2.2.1 Background

The MOD10A1 dataset is generated by the National Air and Space Administration (NASA) and is archived by the National Snow and Ice Data Center (Hall et al., 2011). The grids are provided in compressed Hierarchical Data Format-Earth Observing System (HDF-EOS) format in an equal-area sinusoidal projection. Each HDF-EOS archive contains three data grids: binary snow cover, snow albedo, and fractional snow cover. The fractional snow cover product was extracted and processed to develop the historical SCA dataset. ***Table 2*** provides a summary of the raster values in the MOD10A1 fractional snow cover product.

Table 2. MOD10A1 Fractional Snow Cover Values (NSIDC, 2011a)

Raster Value	Description
0-100	Fractional snow cover (percent)
200	Missing data
201	No decision
211	Night (darkness, terminator, or polar night)
225	Snow-free land
237	Inland water
239	Open water
250	Cloud obscured
254	Detector saturated
255	Fill

2.2.2 Data Processing

To process the MOD10A1 fractional snow cover grids, Riverside employed the following procedure:

1. The MOD10A1 data grids were downloaded from the NASA file transfer protocol (FTP) site: ftp://n4ftl01u.ecs.nasa.gov/SAN/MOST/MOD10A1.005/

    a. Sub-directories contain the MOD10A1 data files for each day (i.e., YYYY.MM.DD). For example, for March 4, 2000, the uniform resource locator (URL) is: ftp://n4ftl01u.ecs.nasa.gov/SAN/MOST/MOD10A1.005/2000.03.04/.

    b. Four data tiles are required to obtain complete coverage over Colorado (***Figure 2***). The naming convention for the HDF-EOS data archives indicates a data tile, as specified by a horizontal tile number and a vertical tile number. For example, the MOD10A1.A2000064.**h09v04**.005.2007164045716.hdf data archive contains data for the tile with a horizontal spatial index of nine and a vertical spatial index of four (NSIDC, 2011b). The four tiles with coverage over Colorado have the following spatial indices:
    - Horizontal 9, Vertical 4
    - Horizontal 9, Vertical 5

- Horizontal 10, Vertical 4
- Horizontal 10, Vertical 5

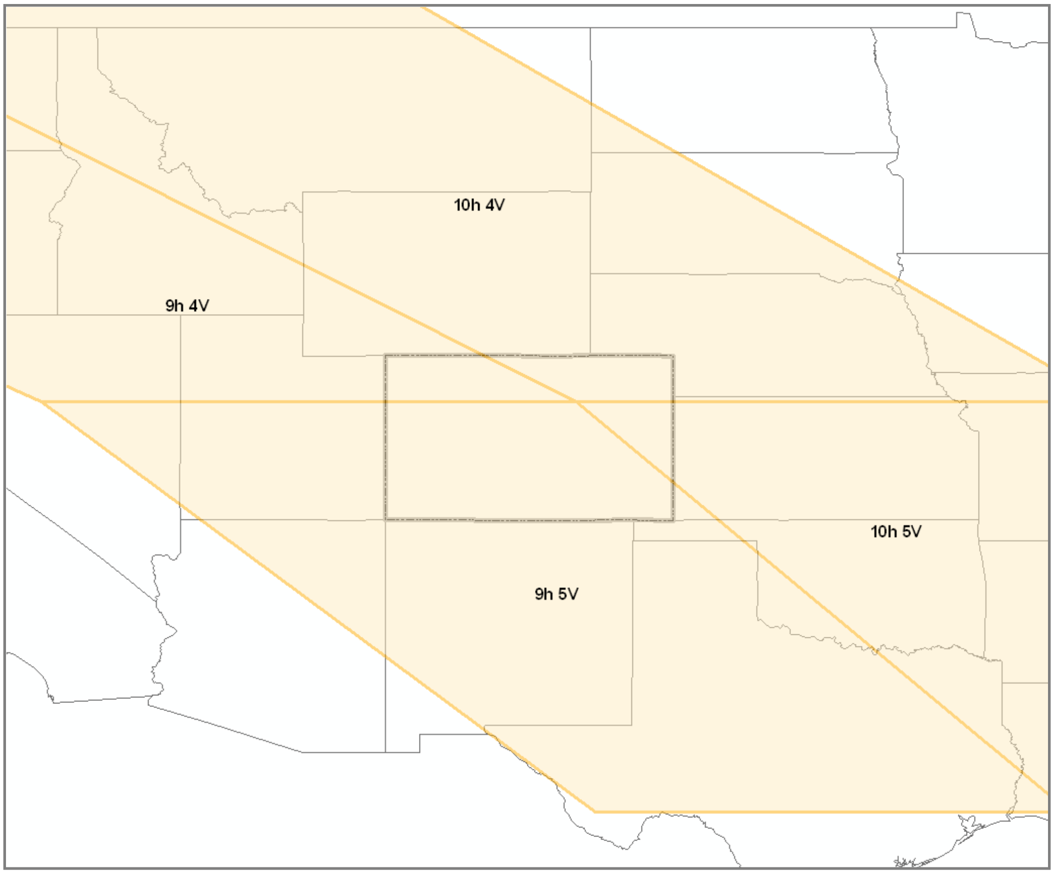

Figure 2. MODIS Data Tiles

2. The fractional snow cover grids were extracted from the HDF-EOS data archives for each day and data tile using the ArcGIS *Extract Subdataset* tool (Esri, 2011a). The extracted datasets have an equal-area sinusoidal projection.

3. The four tiles were merged for each day using the ArcGIS *Mosaic to New Raster* tool (Esri, 2011b).

4. The mosaics were re-projected to the Albers WGS84 projection using the ArcGIS *Project Raster* tool (Esri, 2011c). The original cell size of 463 m was retained when re-projecting the grids to ensure the data values were not affected. ***Figure 3*** shows an example MOD10A1 fractional snow cover grid that has been mosaicked and re-projected.

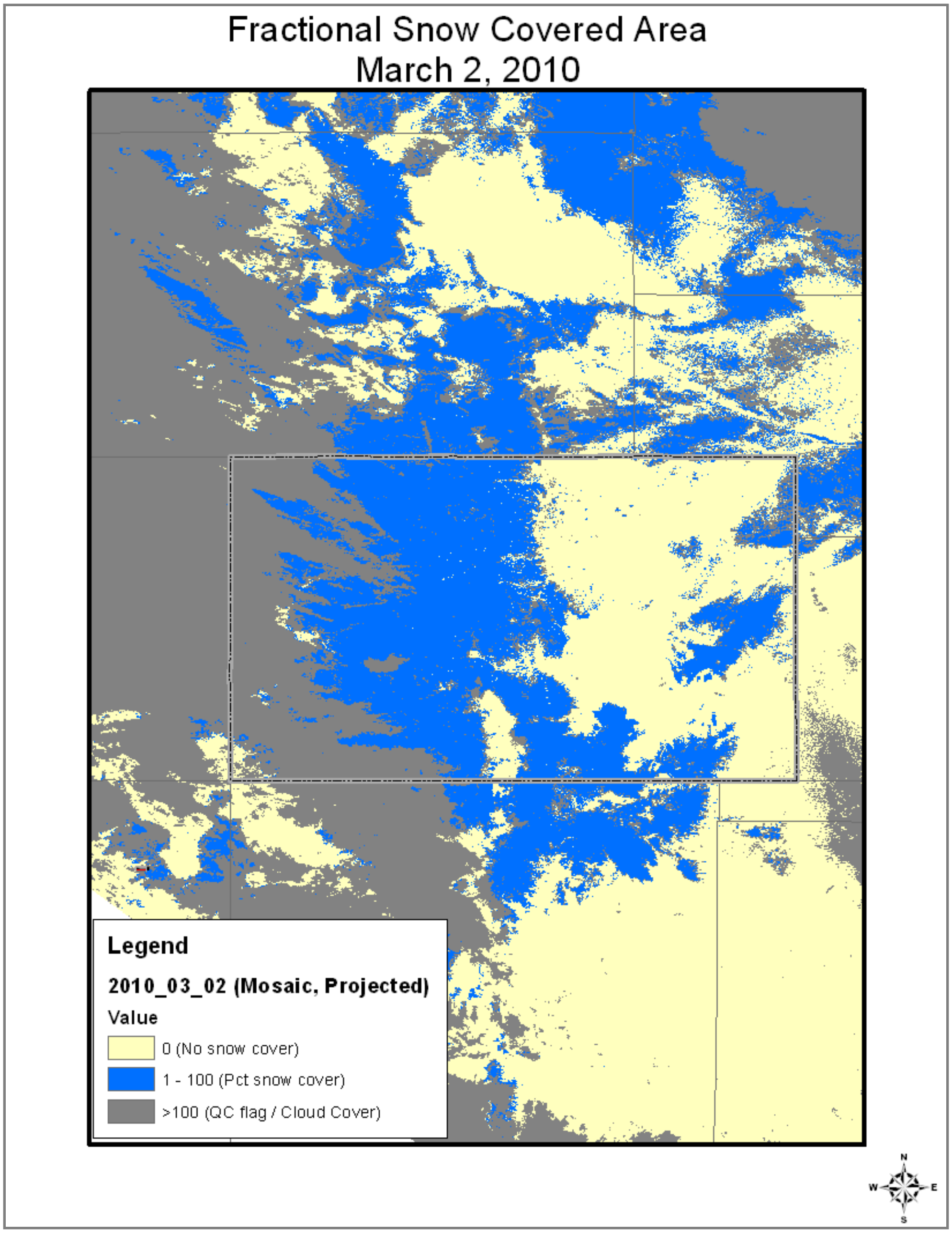

Figure 3. Example MOD10A1 Fractional Snow Cover Grid (March 2, 2010)

5. The fractional snow cover grids were reclassified to create two gridded datasets:

    - The final fractional snow cover (FSC) grid, where indeterminate values have been set to null.

    - A quality control (QC) grid that contains 100% values for cells with indeterminate values in the original MOD10A1 fractional snow cover product.

a. ***Table 3*** presents the reclassification scheme that was used to produce the FSC and QC grids. Code 250 (cloud obscured) is the most prominent indeterminate value that occurs in Colorado.

Table 3. MOD10A1 Reclassification Matrix

MODIS Grid Value	MODIS Grid Description	FSC Grid Value	QC Grid Value
0-100	Fractional snow cover	0-100	0
200	Missing data	No Data	100
201	No decision	No Data	100
211	Night	No Data	100
225	Snow-free land	0	0
237	Inland water	0	0
239	Open water	0	0
250	Cloud obscured	No Data	100
254	Detector saturated	No Data	100
255	Fill	No Data	100

b. ***Figure 4*** presents an example of reclassifying the MOD10A1 fractional snow cover grid into the final FSC grid and the QC grid.

MODIS FSC Grid		Final FSC Grid		Final QC Grid	
25	75	25	75	0	0
225	250	0	No Data	0	100

Figure 4. Example of Reclassifying the MOD10A1 FSC Grid into the Final FSC and QC Grids

6. Zonal statistics were computed in ArcGIS using the elevation zone shapefiles to obtain areal averages of the FSC and QC values. The areal average QC value represents the percentage of the elevation zone that has indeterminate snow cover. Higher QC values indicate higher uncertainty in the corresponding FSC values.

a. ***Figure 5*** shows an example overlay of the elevation zones on a FSC grid.

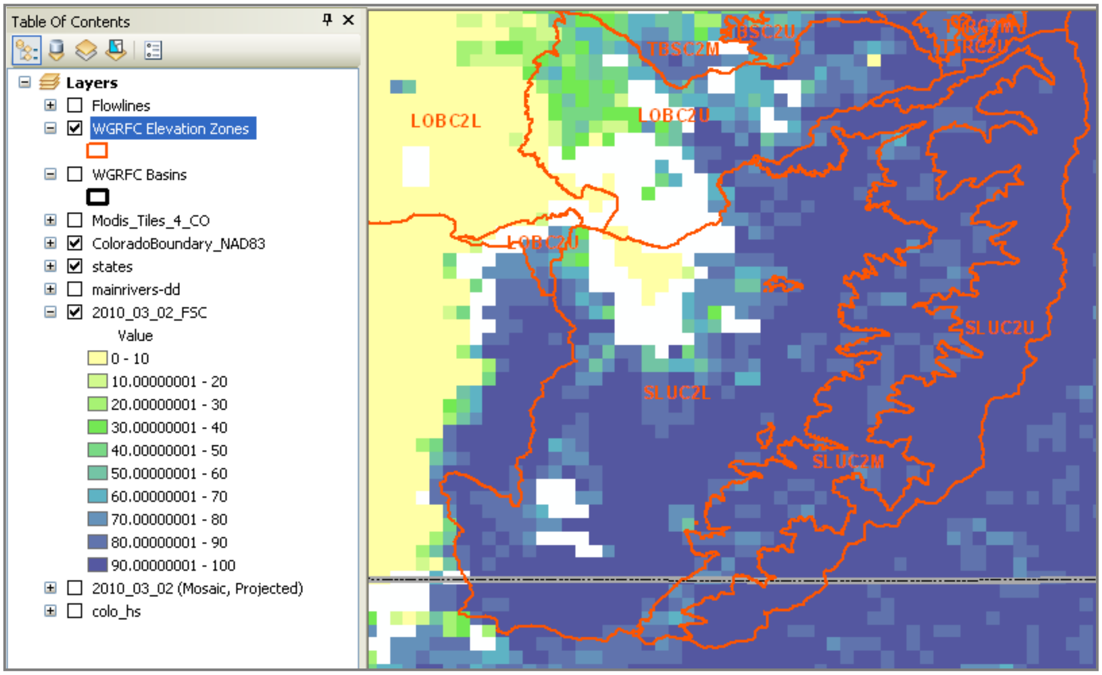

Figure 5. Example Overlay of Elevation Zones and a MOD10A1 FSC Grid (March 2, 2010)

b. ***Figure 6*** shows an example overlay of the elevation zones on a QC grid.

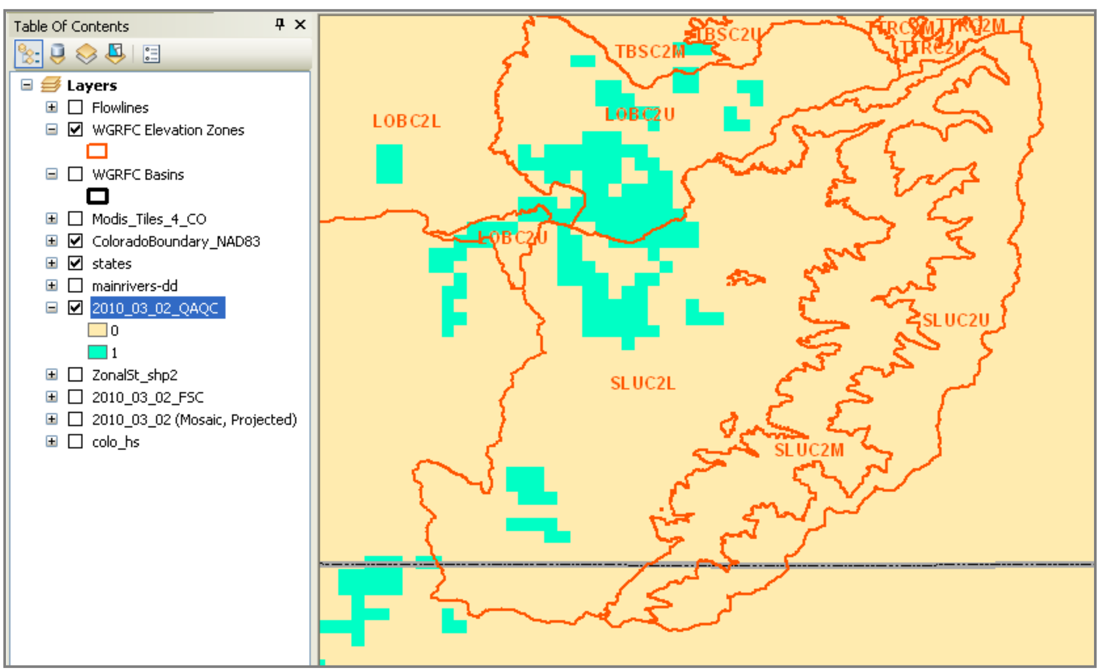

Figure 6. Example Overlay of Elevation Zones and a MOD10A1 QC Grid (March 2, 2010)

c. The output from the zonal statistics processing is daily time series of areal averages of FSC and QC by elevation zone (***Table 4***).

Table 4. Example Areal Averages of MOD10A1 FSC and QC by Elevation Zone (%)

Date	SLUC2L		SLUC2M		SLUC2U	
	FSC	QC	FSC	QC	FSC	QC
2010-03-02	89.2	10.2	92.4	0.0	98.9	0.0

i. The zonal statistics procedure ignores cells with null values. The areal average is computed over the portion of the polygon with valid cell values.
ii. The areal average FSC value may be null if all cells in an elevation zone had indeterminate values.
iii. The areal average QC value will be zero if all cells in an elevation zone had valid fractional snow cover values.

7. Zonal statistics were computed in ArcGIS using the local basin shapefiles to obtain areal averages of the FSC and QC values.

a. ***Figure 7*** shows an example overlay of the local basins on a FSC grid.

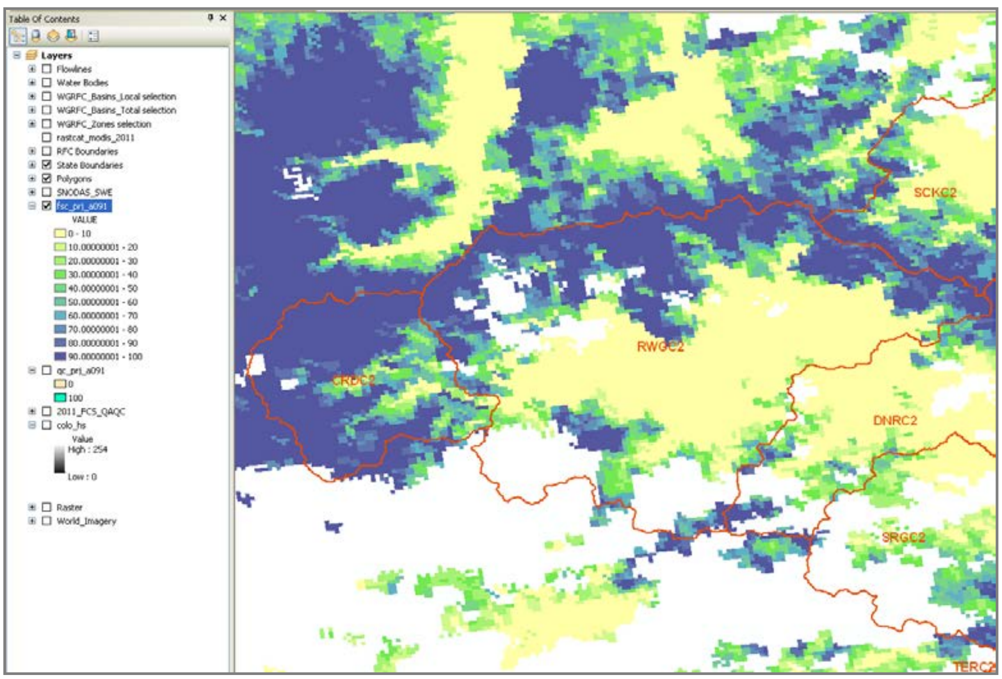

Figure 7. Example Overlay of Local Basins and a MOD10A1 FSC Grid (April 1, 2011)

b. ***Figure 8*** shows an example overlay of the local basins on a QC grid.

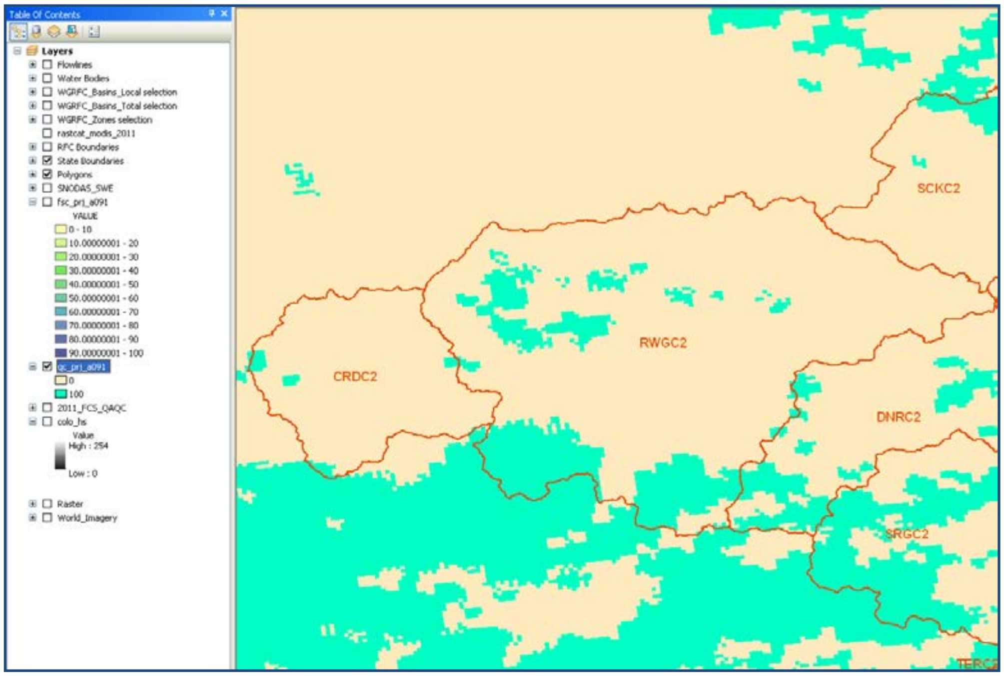

Figure 8. Example Overlay of Local Basins and a MOD10A1 QC Grid (April 1, 2011)

c. The output from the zonal statistics processing is daily time series of areal averages of FSC and QC by local basin (***Table 5***).

Table 5. Example Areal Averages of MOD10A1 FSC and QC by Local Basin (%)

	CRDC2		RWGC2	
Date	**FSC**	**QC**	**FSC**	**QC**
2011-04-01	81.5	3.0	42.6	16.7

i. The areal average values were computed for all local basins contained within the four MODIS tiles, even if the basins are located outside of Colorado.

8. Areal average values of FSC and QC were computed for the total basins by area weighting the results from the local basins. The output is daily time series of areal averages of FSC and QC by total basin (***Table 6***).

Table 6. Example Areal Averages of MOD10A1 FSC and QC by Total Basin (%)

	CRDC2		RWGC2	
Date	**FSC**	**QC**	**FSC**	**QC**
2011-04-01	81.5	3.0	51.8	13.8

a. For headwater basins, the areal average values for the local basins and the total basins are the same (e.g., CRDC2 in ***Table 5*** and ***Table 6***).

b. The areal average values for total basins were computed only for basins contained within Colorado.

9. The time series were imported from ArcGIS into file geo-databases in Microsoft Access. For MBRFC and CBRFC, separate versions of the geo-databases were created for the NRCS and the RFCs. The NRCS version includes results for the forecast locations listed in ***Table 1***, while the RFC version does not.

10. Exceedance probabilities were computed by month for the local basins to better understand the impact of indeterminate values. ***Figure 9*** presents an exceedance probability plot for CRDC2, a high elevation headwater basin. The figure shows that there is a 50% probability that at least 54% of the basin is covered by clouds during the months of March, April, and May, when snowmelt is likely to occur. Lower elevation basins tend to be less affected by cloud cover during the winter months than higher elevation basins.

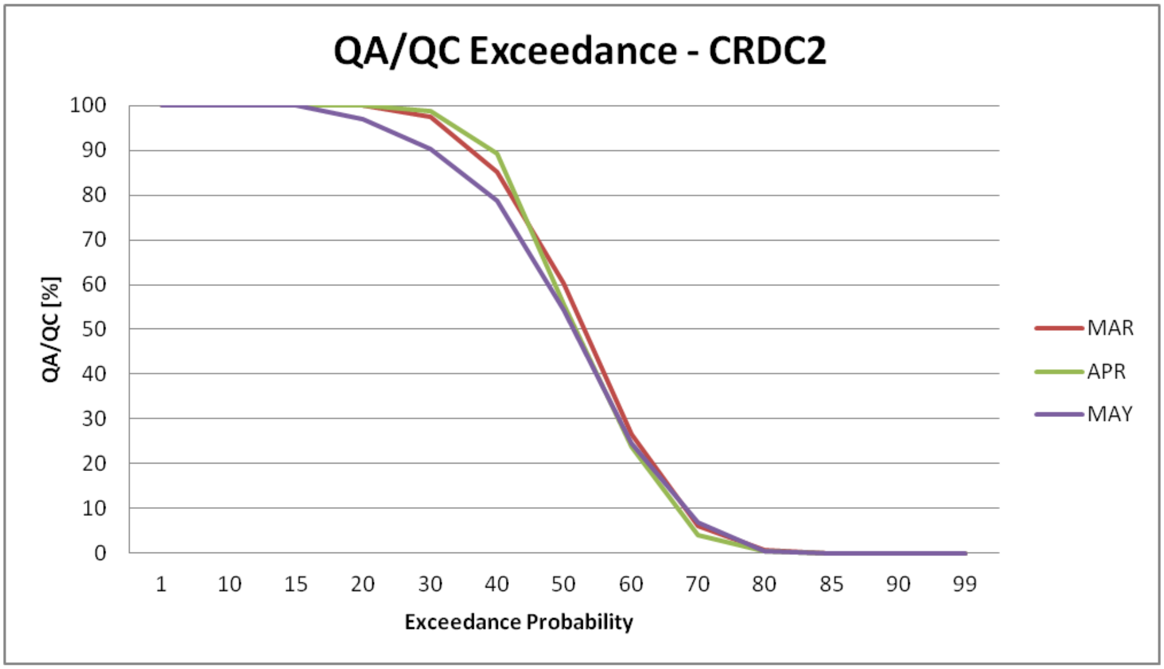

Figure 9. Example Exceedance Probability for MOD10A1 QC Values for CRDC2

2.2.3 Quality Control

The MODIS grids were reviewed to identify missing and problematic grids. The grid issues were categorized into four cases:

1. There is significant cloud cover, so the areal average FSC value may not be trustworthy. These data remain in the final time series and grids so that users can apply individual thresholds based on cloud cover.
2. The MODIS tiles show unusual or unnatural patterns such as bands of no data or zero values. These data remain in the final time series and grids.
3. The MODIS tiles are available but show no snow cover across all of the tiles in the middle of the snow season. These grids were deleted from the grid set, and the days were flagged in the QC time series with a value of 888.
4. One or all of the MODIS tiles are missing from the NASA FTP server. In the time series, these days are indicated by null FSC and QC values.

Appendix A contains a list of the dates with grid issues, along with the type of issue that occurred.

The time series of areal averages were quality controlled using multiple techniques:

- Hand calculations to check the GIS processing for selected basins and dates.
- Visual checks to ensure the time series values were in agreement with the FSC and QC grids for selected basins and dates.
- Plots of the FSC and QC time series to identify anomalous results.

2.2.4 Deliverables

The deliverables associated with the MOD10A1-derived historical SCA dataset included:

- **Grid Deliverables.** The FSC and QC grids were delivered as raster catalogs for the period February 24, 2000 – June 30, 2011. The grid deliverables included:
  - **MODIS_SCA_Grids.mxd:** An ArcGIS 10 map document that was created to visualize the MOD10A1 grids using animations.
  - **YYYY_mosaic:** Directories that contain geo-databases with the FSC and QC grids for each year.
  - **MODIS Grid Issues.docx:** A Word document that summarizes missing and problematic grids.
- **Script Deliverables.** Four scripts were delivered to facilitate future MODIS data processing. These scripts assume that the user has downloaded MODIS data to a local directory. The scripts were developed using ArcGIS 10, and will not work using earlier ArcGIS versions. The script deliverables were provided as a compressed archive (**MODIS_Tools.zip**) that included an ArcGIS toolbox, python scripts, and GIS data:
  - **Tools\Doc\(0) MODIS Data Download Procedure.docx:** This document includes instructions for downloading MOD10A1 data, including a limited description of the MODIS file naming convention.
  - **MODIS_SCA_Tools.tbx:** An ArcGIS 10 toolbox was created to contain the four data processing scripts. Documentation for the four scripts is included in the **Tools\Doc** directory.
    - **(1) Batch Process SCA products (From Raw HDF into ArcGIS GRID):** This script processes the raw MODIS data in HDF-EOS format into ArcGIS grid format. The script extracts, mosaics, projects, and reclassifies the MOD10A1 fractional snow cover grid into one FSC grid and one QC grid.
    - **(2) Convert Raster Workspace to Ascii folder:** This script converts all raster files in one directory to ASCII files that can be imported easily into the NWS Community Hydrologic Prediction System (CHPS).
    - **(2a) Convert Raster Catalog to Ascii folder:** This script converts all raster files in a file geo-database to ASCII files that can be imported easily into CHPS.
    - **(3) Process MODIS SCA Data:** This script can be used to compute areal averages of FSC and QC over elevation zones, local basins, and total basins.
  - **Tools\Data:** This directory includes GIS data of elevation zones, local basins, and total basins for each RFC.
- **Time Series Deliverables.** File geo-databases in Microsoft Access 2003 format were delivered that contain areal average time series of FSC and QC.
  - The databases contain one table for each combination of data type (i.e., FSC, QC), polygon type (i.e., elevation zone, local basin, total basin), and forecast group (varies by

NWS RFC). For example, the database for WGRFC, which has only one forecast group (URIO), includes 6 tables:

    - Zone_URIO_fsc
    - Zone_URIO_qc
    - Local_URIO_fsc
    - Local_URIO_qc
    - Total_URIO_fsc
    - Total_URIO_qc

  - If zone and total basin tables are missing for a forecast group, this indicates the forecast group is outside of Colorado and was not processed.
  - If differences exist between the RFC and NRCS forecast locations, two database versions were created:
    - XXrfc.mdb is intended for the NRCS.
    - XXrfc_RFC.mdb is intended for the NWS RFC.
  - The time series were also provided in comma-separated value (CSV) format for CBRFC.

- **XXrfc_QC_exceedance.xlsm:** A Microsoft Excel 2007 workbook that contains the exceedance probabilities of the QC time series (i.e., indeterminate values) for each local area basin in Colorado.

2.3 SNODAS

2.3.1 Background

The NOHRSC developed SNODAS to generate estimates of snowpack states and fluxes on a 1-hr temporal scale and a 1-km spatial scale for the United States (Barrett, 2003). Two major components within SNODAS are a spatially distributed snow model that simulates snowpack characteristics and a data assimilation algorithm that adjusts snowpack characteristics based on observations from the NRCS Snowpack Telemetry (SNOTEL) network, snow courses, satellites, and radars. SNODAS is forced by downscaled outputs from the Rapid Update Cycle (RUC) numerical weather prediction model. Outputs from SNODAS include snow depth, snow water equivalent (SWE), snowmelt, snowpack temperature, blowing snow sublimation, and snow surface sublimation and condensation.

The gridded outputs from SNODAS are provided as compressed archives that include a binary data file and a header file. Riverside receives the SNODAS products in real-time courtesy of a data feed established by the NOHRSC. The SNODAS products are also archived at the National Snow and Ice Data Center (NOHRSC, 2011a). Riverside retrieved additional grids from the NSIDC for the rare times that the data transfer feed failed or SNODAS failed to operate.

2.3.2 Data Processing

To generate a historical SCA dataset based on SNODAS, Riverside employed the following procedure:

1. The SNODAS SWE grids were assembled from Riverside's real-time data feed and the NSIDC FTP site.

a. The SNODAS SWE files have a naming convention of us_ssmv1**1034**tS__T0001TTNATS**YYYYMMDDHHH**P001.tar.gz, where:

   i. The 1034 code denotes the SWE product.

   ii. The YYYYMMDDHH string represents the year, month, day, and hour associated with the data file in Coordinated Universal Time (UTC).

b. The SWE grids associated with the 05:00 hour were selected to represent the daily values.

c. The SWE grids cover the conterminous U.S.

2. The SWE data archives were extracted to retrieve the binary data file (*.dat) and the header file (*.hdr). The *.dat extensions were changed to *.bil extensions for ArcGIS processing (Barrett, 2003).

3. The grids were clipped to the western U.S. to reduce data processing times.

4. The open water codes (i.e., 55537) were replaced with No Data values using the ArcGIS *Set Null* tool (Esri, 2011d).

5. The units of millimeters were converted to units of inches using the ArcGIS *Divide* tool (Esri, 2011e).

6. The grids were projected from geographic projection to Albers WGS84 using the ArcGIS *Project Raster* tool (Esri, 2011c).

7. The SWE grids were converted to binary snow cover (i.e., 0% or 100%) according to:

   a. If SWE ≤ 0.1”, then FSC = 0%.
   b. If SWE > 0.1”, then FSC = 100%.

Figure 10 presents an example binary snow cover grid derived from the SNODAS SWE product.

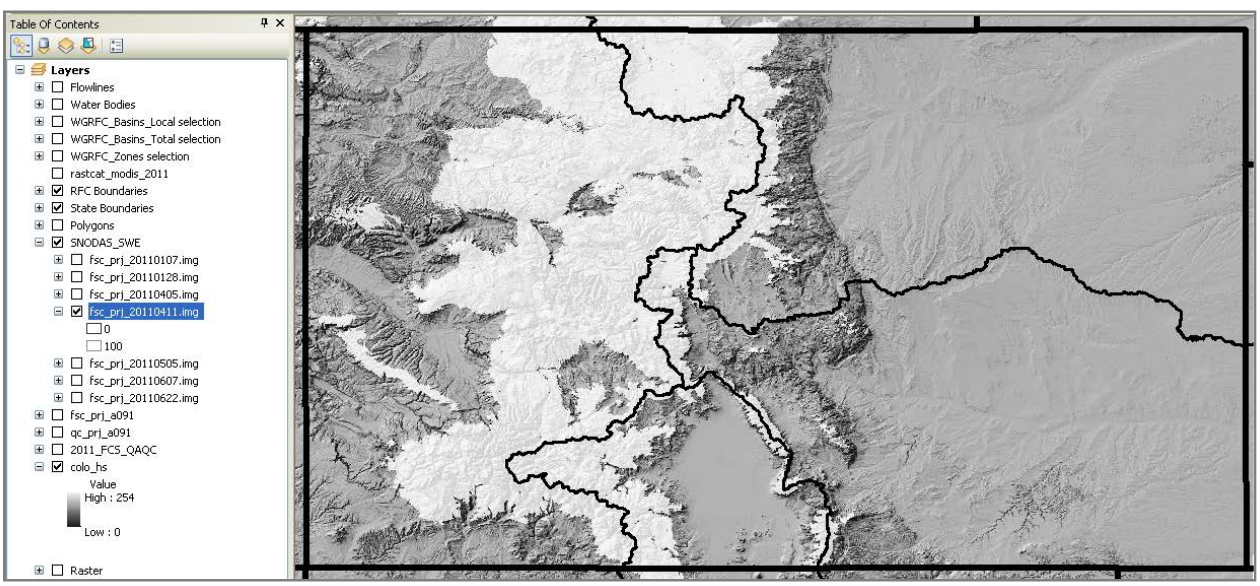

Figure 10. Example SNODAS-Derived Binary Snow Cover Grid (April 11, 2011)

8. Zonal statistics were computed in ArcGIS using the elevation zone shapefiles to obtain areal averages of FSC.

    a. ***Figure 11*** shows an example overlay of the elevation zones on a FSC grid.

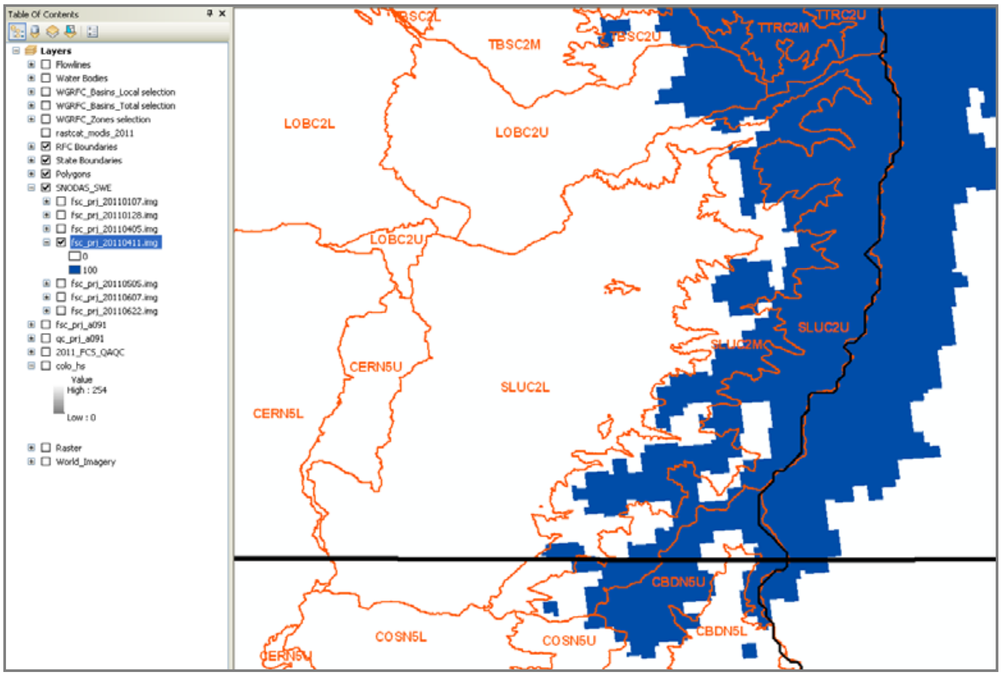

Figure 11. Example Overlay of Elevation Zones and a SNODAS FSC Grid (April 11, 2011)

    b. The output from the zonal statistics processing is daily time series of areal averages of FSC by elevation zone (***Table 4***).

Table 7. Example Areal Averages of SNODAS FSC by Elevation Zone (%)

Date	SLUC2L FSC	SLUC2M FSC	SLUC2U FSC
2011-04-11	0.1	48.1	85.6

    c. The SNODAS products are spatially and temporally continuous. The only null values that influence the GIS processing are the open water cells.

9. Zonal statistics were computed in ArcGIS using the local basin shapefiles to obtain areal averages of FSC.

a. ***Figure 12*** shows an example overlay of the local basins on a FSC grid.

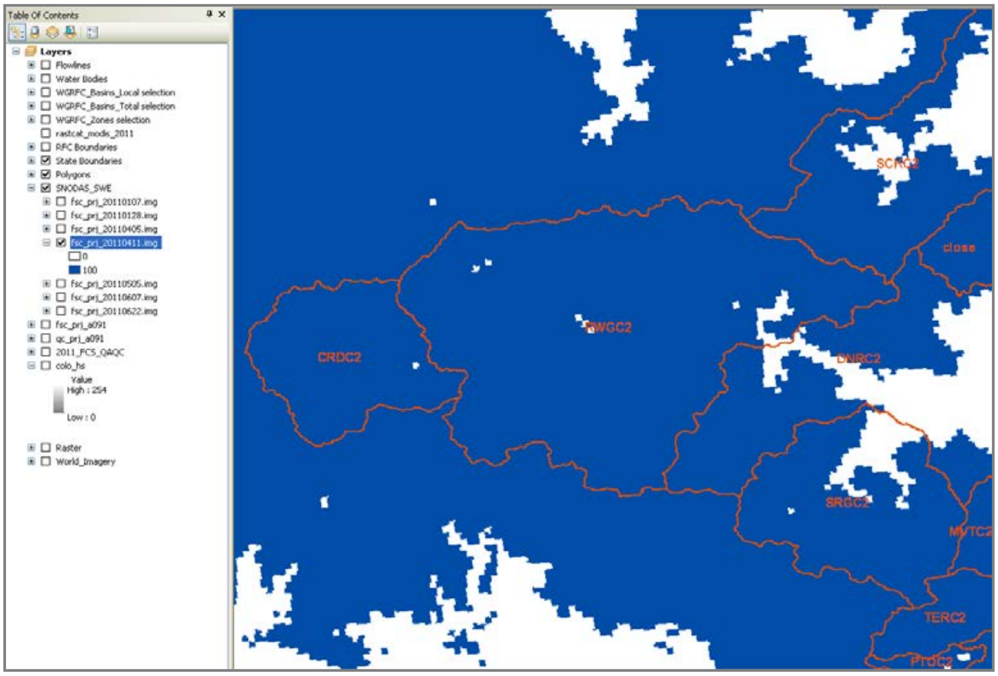

Figure 12. Example Overlay of Local Basins and a SNODAS FSC Grid (April 11, 2011)

b. The output from the zonal statistics processing is daily time series of areal averages of FSC by local basin (***Table 8***).

Table 8. Example Areal Averages of SNODAS FSC by Local Basin (%)

Date	CRDC2 FSC	RWGC2 FSC
2011-04-11	100.0	98.9

11. Areal average values of FSC were computed for the total basins by area weighting the results from the local basins. The output is daily time series of areal averages of FSC by total basin (***Table 9***).

Table 9. Example Areal Averages of SNODAS FSC by Total Basin (%)

Date	CRDC2 FSC	RWGC2 FSC
2011-04-01	100.0	99.1

12. The time series were imported from ArcGIS into file geo-databases in Microsoft Access. For MBRFC and CBRFC, separate versions of the geo-databases were created for the NRCS and the RFCs. The NRCS version includes results for the forecast locations listed in ***Table 1***, while the RFC version does not.

2.3.3 Quality Control

The SNODAS dataset was reviewed to identify missing grids. Only eight grids are missing over the period September 30, 2003 – June 30, 2011:

- 10/30/2003
- 02/25/2004
- 08/31/2004
- 09/27/2004
- 06/25/2005
- 09/08/2006
- 10/01/2006
- 03/26/2007

The time series of areal averages were quality controlled using multiple techniques:

- Hand calculations to check the GIS processing for selected basins and dates.
- Visual checks to confirm the time series values were in agreement with the FSC grids for selected basins and dates.
- Plots of the FSC time series to identify anomalous results.

2.3.4 Deliverables

The deliverables associated with the SNODAS-derived historical SCA dataset included:

- **Grid Deliverables.** The SNODAS-derived FSC grids were delivered as raster catalogs for the period September 30, 2003 – June 30, 2011. The grid deliverables included:
    - **SNODAS_SCA_Grids.mxd:** An ArcGIS 10 map document created to visualize the SNODAS-derived SCA grids using an animation.
    - **SNODAS\YYYY_SNODAS.gdb:** Geo-databases that contain the SNODAS-derived SCA grids for each year.
- **Time Series Deliverables:** File geo-databases in Microsoft Access 2003 format were delivered that contain areal average time series of FSC.
    - The databases contain one table for each combination of polygon type (i.e., elevation zone, local basin, total basin) and forecast group (varies by NWS RFC). For example, the database for WGRFC, which has only one forecast group (URIO), includes 3 tables:
        - Zone_URIO
        - Local_URIO
        - Total_URIO
    - If a total basin or zone table is missing for a forecast group, this indicates the forecast group is outside of Colorado and was not processed.
    - If differences exist between the RFC and NRCS forecast locations, two database versions were created:
        - XXrfc.mdb is intended for the NRCS.
        - XXrfc_RFC.mdb is intended for the RFC.
    - The time series were also provided in CSV format for CBRFC.

3.0 HISTORICAL SCA DATA COMPARISONS

Riverside performed limited investigations to compare historical snow cover estimates from SNODAS, MOD10A1, and the SNOW-17 model. Although these estimates of snow cover are developed using disparate methods and are expected to differ, it is uncertain how significantly the estimates may vary, and whether they show consistent patterns throughout a snow season.

Appendix B contains a comparison between the gridded SNODAS and MOD10A1 SCA for selected dates in 2011. In January, the two estimates are similar, though SNODAS tends to show higher SCA in areas with steep topographic relief, while MODIS tends to show higher SCA for flatter, lower elevation areas in eastern Colorado. In April, SNODAS simulates a much larger SCA than the MOD10A1 estimates, though the effect diminishes towards the end of the month into early May. Throughout June, SNODAS continues to estimate higher SCA is most areas, though MODIS estimates higher SCA on the west slope of the Rockies in the central portion of the state. This comparison confirms that the SCA estimates differ between MOD10A1 and SNODAS, sometimes significantly, and that the differences vary by date and location.

Figure 13 presents a time series plot of the SNODAS SCA, MOD10A1 SCA, and SNOW-17 areal extent of snow cover (AESC) state for the PTOC2U elevation zone. PTOC2 is a high elevation basin in the Rio Grande River Basin within the WGRFC jurisdiction. The basin is small, heavily forested, with relatively deep and uniform snowpack throughout the winter.

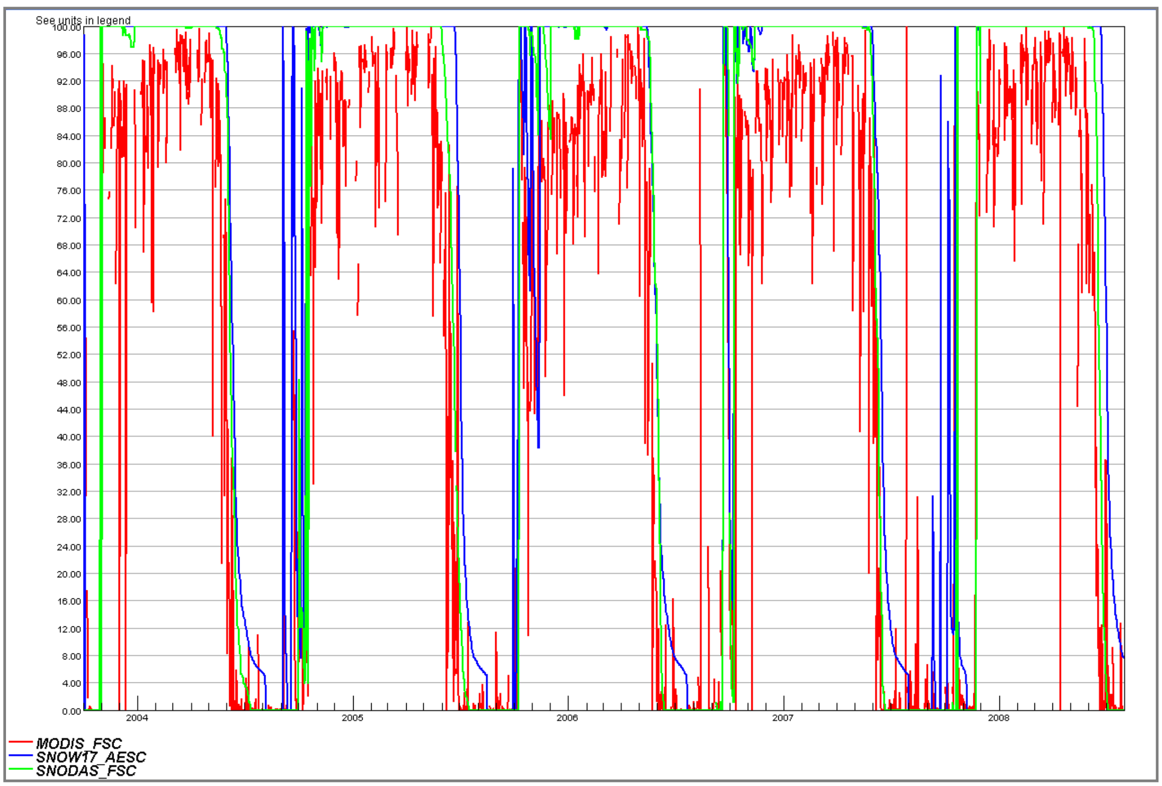

Figure 13. Comparison of MOD10A1 FSC (red), SNODAS FSC (green), and the SNOW-17 AESC model state (blue) for the PTOC2U elevation zone

Figure 13 indicates distinct differences between the MOD10A1 SCA and the SNOW-17 AESC:

- Related to the maximum SCA that PTOC2U experiences each year:
  - The SNOW-17 AESC consistently reaches 100%, whereas the MOD10A1 SCA rarely exceeds 95%.

- o The SNOW-17 AESC tends to remain at 100% throughout the winter, while the MOD10A1 SCA is variable.
- o The SNOW-17 AESC frequently spikes to 100% in the fall, while the MOD10A1 SCA is much lower. This may be an artifact of the assumptions made by the SNOW-17 model in constructing the areal depletion curve (NWS, 2006).

- For the rate of snowmelt, the MOD10A1 dataset indicates more rapid snowmelt than the SNOW-17 model, as indicated by the diverging SWE ablation curves, particularly for SCA below 30%.

Figure 14 presents an example relationship between MODIS FSC and SNOW-17 AESC for the month of May, after removing FSC values with QC values greater than 50%. The MODIS FSC and SNOW-17 AESC estimates are correlated, although the relationship is nonlinear and variable.

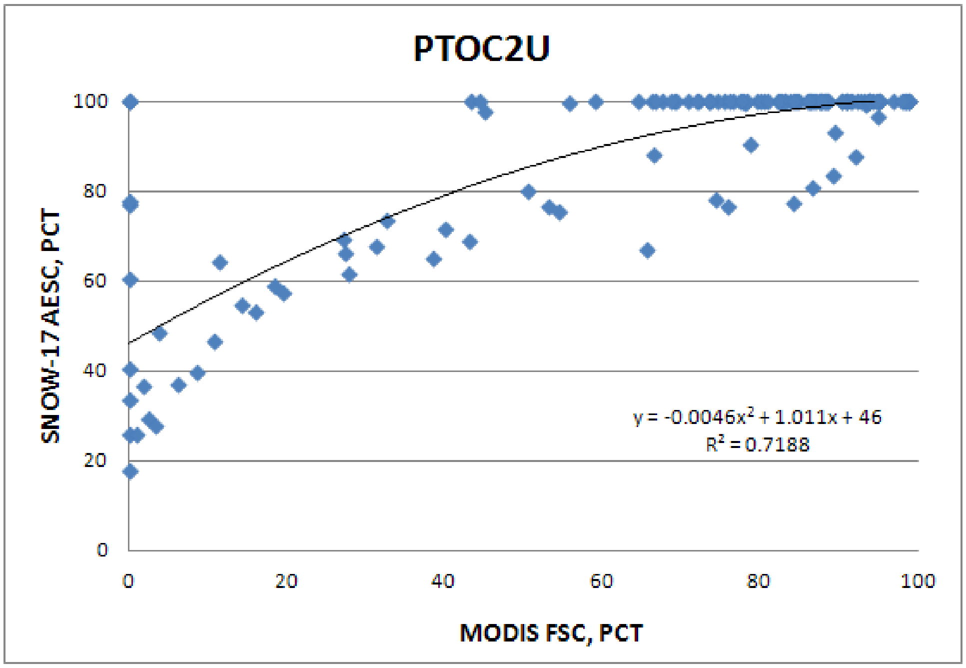

Figure 14. SNOW-17 AESC vs. MODIS FSC for PTOC2U for May (QC < 50%)

The maximum SCA estimated by SNODAS in PTOC2U is often 100% throughout the winter, similar to the SNOW-17 AESC values (***Figure 13***). However, the SNODAS dataset indicates more rapid snowmelt than the SNOW-17 model, consistent with the MOD10A1 dataset.

Figure 15 shows a promising linear relationship between SNODAS SCA and SNOW-17 AESC for the month of May. Other months are characterized by significantly more scatter between the datasets.

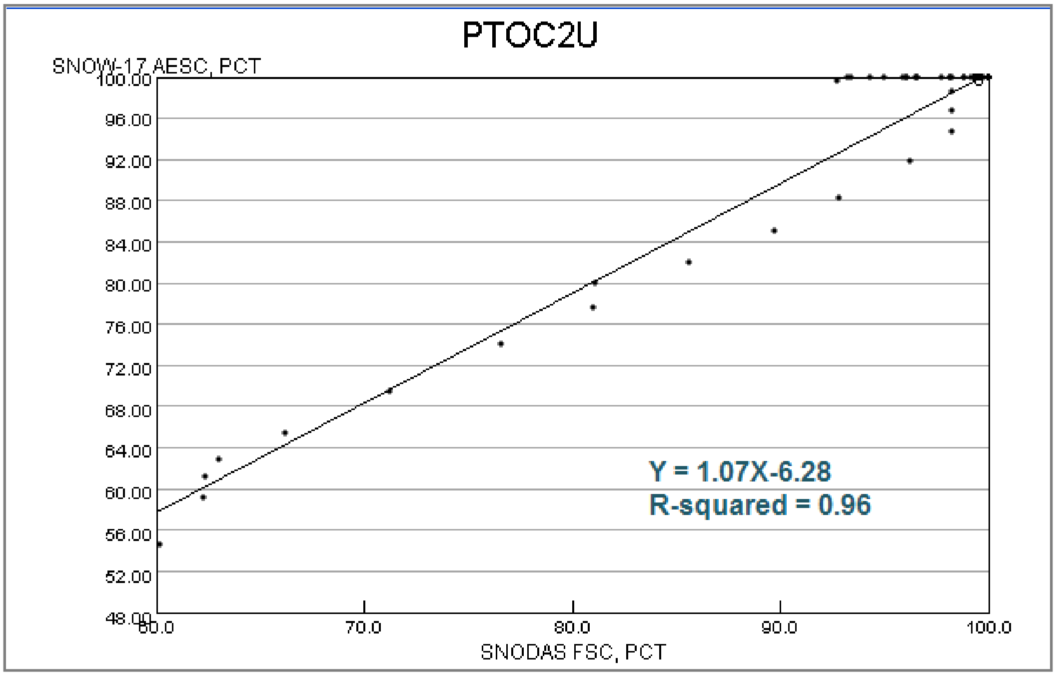

Figure 15. SNOW-17 AESC vs. SNODAS FSC for PTOC2U for May

Figure 16 presents a time series plot of the SNODAS SCA, MOD10A1 SCA, and SNOW-17 AESC for the SAOC2U elevation zone. SAOC2 is a lower elevation basin in the Rio Grande River Basin within the WGRFC jurisdiction. This basin exhibits more variable SCA and earlier snowmelt than the PTOC2 basin.

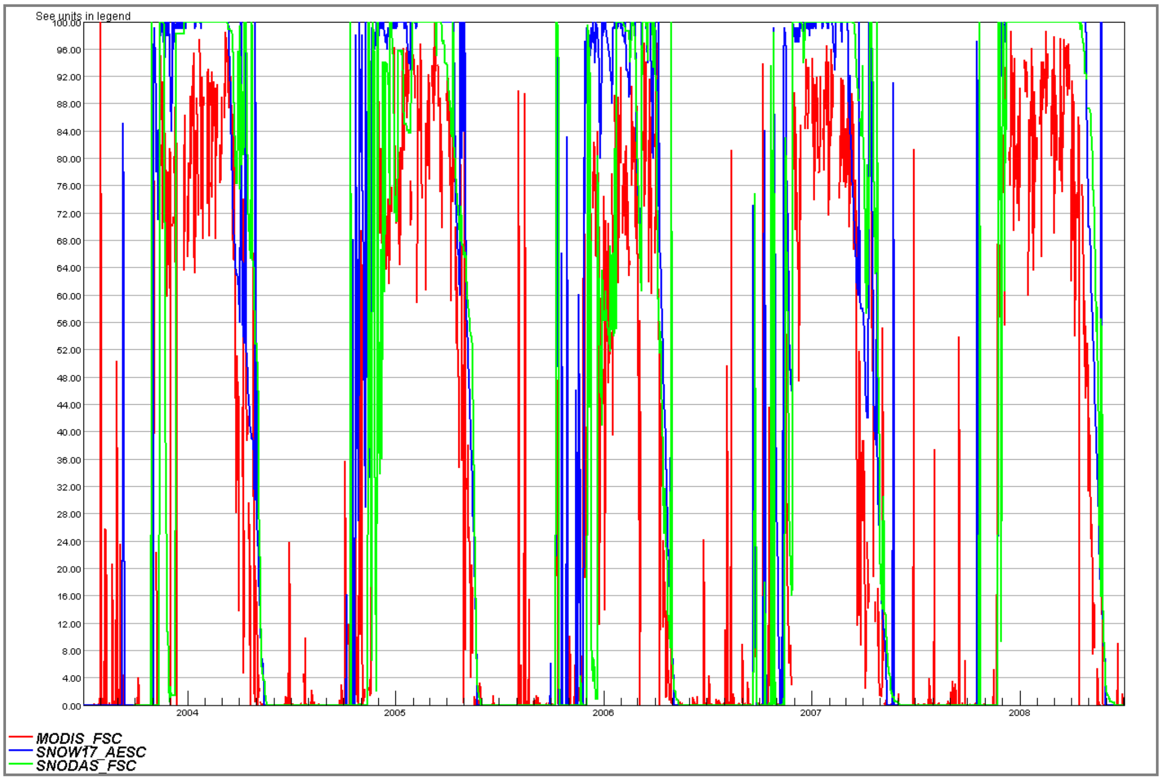

Figure 16. Comparison of MOD10A1 FSC (red), SNODAS FSC (green), and the SNOW-17 AESC model state (blue) for the SAOC2U elevation zone

Figure 16 indicates that the differences in maximum SCA among the three datasets are similar to those observed for the PTOC2U elevation zone. Both the SNOW-17 model and SNODAS simulate SCA near 100% throughout the winter, while the MOD10A1 SCA estimate is consistently lower, typically in the 80-90% range. The rate of snowmelt is more consistent among the three datasets than observed for the PTOC2U elevation zone.

Figure 17 presents an example relationship between MODIS FSC and SNOW-17 AESC for the month of May, after removing FSC values with QC values greater than 50%. The two estimates are highly correlated. The SNOW-17 AESC values are significantly higher than the MODIS FSC values in the month of May.

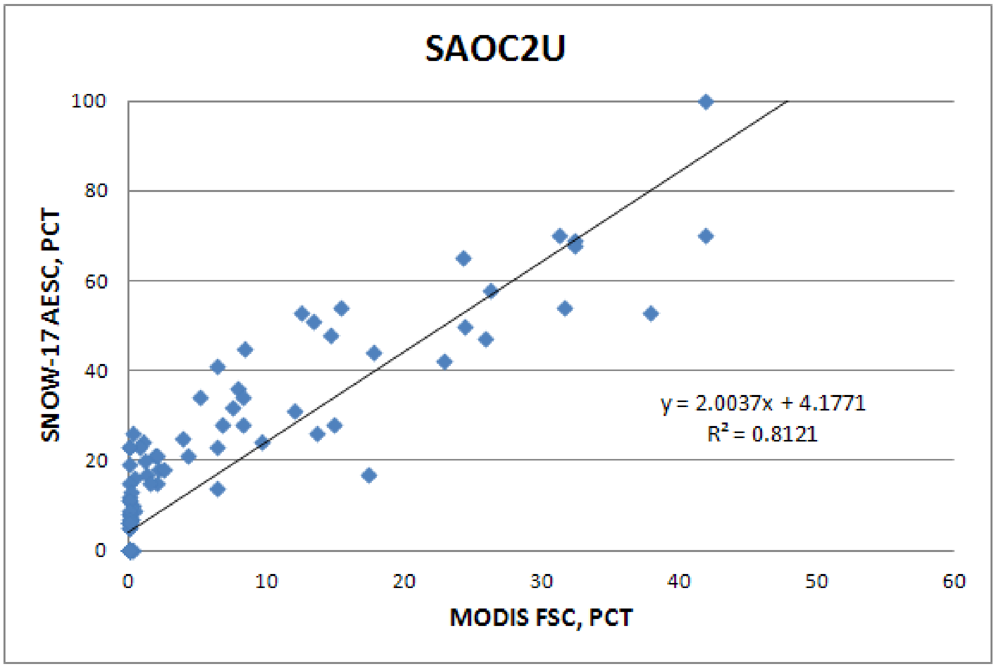

Figure 17. SNOW-17 AESC vs. MODIS FSC for SAOC2U for May (QC < 50%)

Figure 18 shows a scatter plot between SNOW-17 AESC and SNODAS FSC for the month of May. Although the relationship is more variable than that observed for PTOC2U, and may be nonlinear, there is a strong relationship between the two datasets. The relationship is more variable for other months.

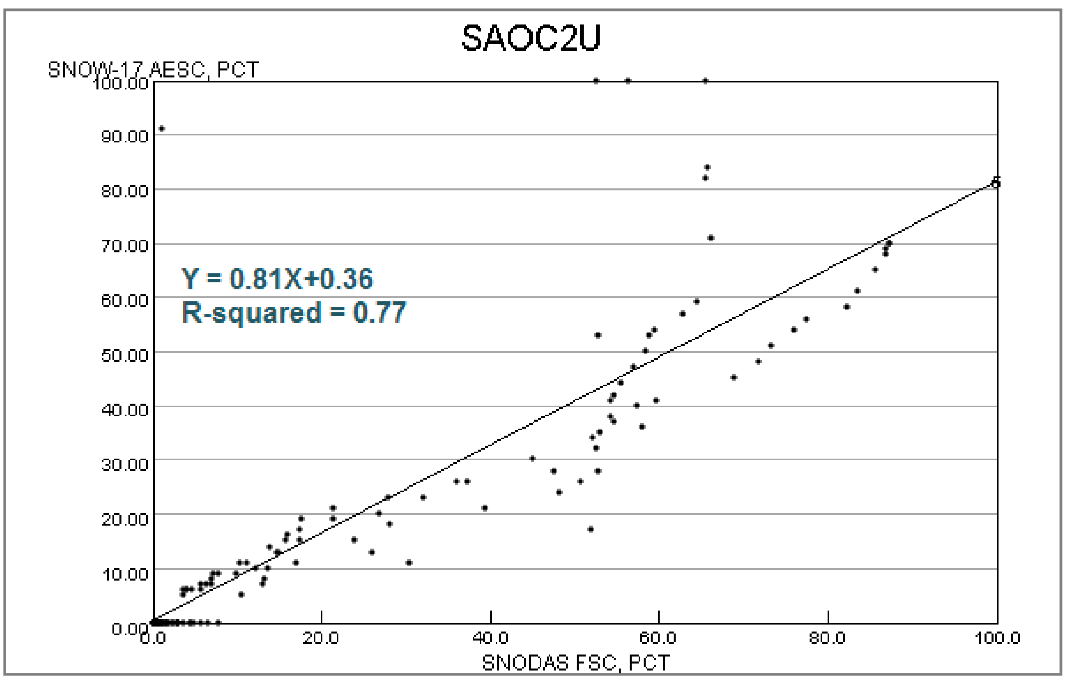

Figure 18. SNOW-17 AESC vs. SNODAS FSC for SAOC2U for May

These preliminary comparisons of historical SCA among datasets indicate there is a potential to develop historical relationships for data assimilation and model state updating. However, additional effort is required to develop these relationships for different basins and times of year, as the relationships are expected to change throughout the year, in addition to having differing amounts of variability.

4.0 SNOW MODEL DATA ASSIMILATION

Historical SCA data can be assimilated into a snow model to update model states in multiple ways. The historical SCA values can be used directly (i.e., direct insertion) or a relationship can be developed between the historical SCA values and the model states. The initial results shown in ***Section 3.0*** indicate that the latter option is more appropriate. Techniques such as subjective weights, Kalman filtering, and variational assimilation can be used to combine the observed and simulated values to obtain updated model states.

4.1 Prior Work

Under previous work for CWCB, Riverside developed and tested a methodology for updating snow model states in the NWS Research Distributed Hydrologic Model (RDHM; Riverside, 2009). Riverside calibrated the distributed SNOW-17 and SAC-SMA models to unregulated flows for the period 1980-2005 in three headwaters and one local area in the Upper Colorado River Basin. Riverside tested various procedures for updating the snow model states over an “operational” (i.e., hindcast) period that included WY 2006-2008. The CBRFC provided temperature and precipitation grids and unregulated flow time series for the full period of 1980-2008. Riverside quantified the impact of snow updating on simulated flow volumes over the April-July water supply period.

After testing several updating schemes, Riverside concluded that monthly updating using SNOTEL and snow course observations significantly reduced seasonal water supply errors. In addition to using snow observations, Riverside incorporated volume and spatial distribution information from SNODAS into the updating procedure. Because SNODAS began in October 2003, the information from SNODAS was incorporated directly into the snow updating procedure without the benefit of establishing a historical relationship with the RDHM model states, although the need for developing historical relationships may be less important for the distributed SNOW-17 model than the lumped model.

Figure 19 presents example results for the Blue River at Dillon Reservoir (DIRC2). In January-April 2006, the inclusion of snow distribution information from SNODAS resulted in modest reductions in the seasonal volume error (approximately 10-40 ac-ft) compared to the NRCS SWE updating alone. In January-April of 2007 and 2008, the addition of snow distribution information from SNODAS worsens the seasonal volume error. The most notable outcome is a consistent improvement (80-200 ac-ft) in June of each year. It appears that SNODAS contains better information regarding the spatial distribution of snow in the DIRC2 basin for June in these three years than the RDHM simulates.

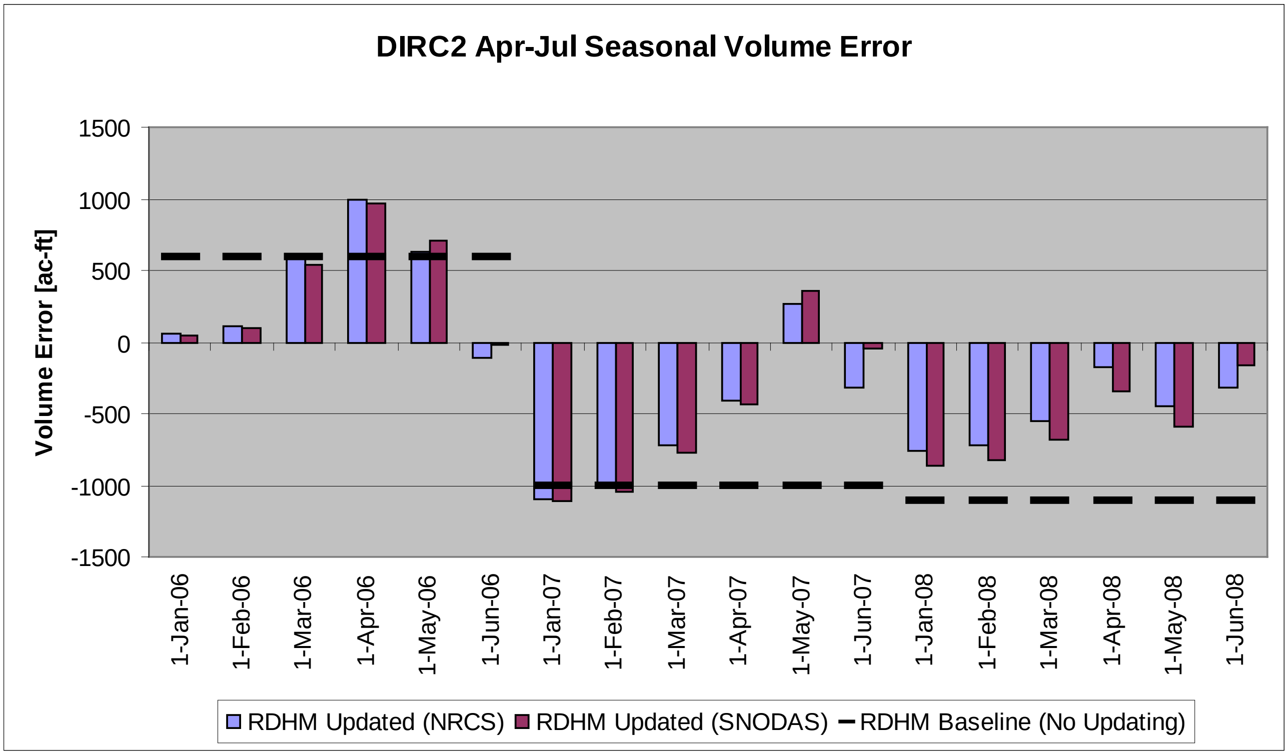

Figure 19. Seasonal Volume Errors for DIRC2 for NRCS+SNODAS, NRCS, and No Updating Scenarios (Riverside, 2009)

These preliminary investigations indicate that historical SCA data have the potential to improve water supply forecasts. However, additional effort is required to investigate and quantify this potential for different basins and times of year.

4.2 Issues

In developing a methodology for assimilating historical SCA into a snow model, the following issues must be considered:

- ***The appropriate period for data assimilation.*** Multiple references report little effect on streamflow simulations and water supply forecasts in the Pacific Northwest using the Variable Infiltration Capacity (VIC) model due to updates during the snow accumulation period prior to March 1 (Andreadis and Lettenmaier 2005), and detrimental effects occurring in mid-May (McGuire et al., 2006).
- ***The uncertainty associated with the SCA values.*** Both modeled (i.e., SNODAS, SNOW-17) and observed (i.e., MOD10A1) SCA values have uncertainty due to model formulation errors, measurement errors, and estimation errors. Additionally, the reliability of the MOD10A1 SCA estimates is reduced as cloud cover increases. A threshold for acceptable cloud cover should be

tested prior to using the MOD10A1 data. Thresholds that range from 20-50% have been reported (McGuire et al., 2006; Andreadis and Lettenmaier 2005), but are likely to vary by location and date.

- ***The covariance between model states.*** SWE and SCA are correlated variables, indicating that it may not be appropriate to update the model states independently using observations. Data assimilation techniques such as Kalman filtering account for the covariance among model states.
- ***The frequency of data assimilation.*** SCA is an autocorrelated variable, indicating that increasingly frequent data assimilations will offer diminishing benefits. Operationally, an update frequency of monthly or bimonthly is likely to suffice in improving the forecasts.
- ***The size of the grid cell compared to the model unit.*** The size of the MODIS and SNODAS grid cells can be relatively large, particularly compared to elevation zones that are small and spatially discontinuous. This may result in a higher uncertainty associated with the areal average SCA values due to a small number of cells being assigned to a polygon and sensitivity from the assumptions made about cell assignment.
- ***The need for different update procedures during the snow accumulation and the snowmelt periods.*** During the snow accumulation period, updating model states typically addresses errors in the real-time precipitation inputs that affect the accumulated snowpack. Once snowmelt begins, the updating procedure may capture errors in real-time precipitation estimation as well as errors in the snowmelt that affect the soil moisture states.
- ***The need to add snow when observations indicate snow cover where the model has none.*** This issue typically arises in areas of shallow snowpack between areas that rarely have snow and areas that consistently have snow (McGuire et al., 2006). In this circumstance, an assumption must be made regarding the amount of snow to add. A nominal value (e.g., 5 mm) is typically used (Rodell and Houser, 2004). Over time, this assumption can affect the water balance if air temperatures are above freezing, and the model melts the added snow in a short amount of time, necessitating further snow additions.

5.0 RECOMMENDATIONS FOR FUTURE WORK

The primary objective of this project was to assemble long-term historical archives of SCA data using MOD10A1 and SNODAS. Much work remains to evaluate the datasets and to demonstrate the potential for improving snow modeling, streamflow simulations, and water supply forecasts. Future activities include:

- Continuing to investigate the potential utility of the SNODAS and MOD10A1 datasets.
  - Initial investigations should focus on basins with variable snow cover, that have limited low elevation snow data, and that generate a high proportion of snowmelt runoff after bare ground appears. It may also be advantageous to select pilot basins that are relatively unaffected by regulation.
  - Investigations should evaluate improvements in seasonal water supply volumes and peak flow forecasts from the hydrologic models run operationally by the RFCs.
  - Investigations to improve the seasonal water supply volumes from the statistical forecast models could initially focus on correlating forecast errors with SCA. SCA could be incorporated into the regression model as a predictor variable, or could be used to categorize years to refine the regression models.
  - Investigations should compare the historical SCA datasets with simulated SCA from a distributed hydrologic model such as the RDHM.
- Investigating the potential to generate a longer historical record for the SNODAS and MOD10A1 datasets, for example:
  - Using snow cover information from a distributed snow model such as RDHM.
  - Using AESC information from the SNOW-17 model.
  - Relating SCA to other meteorological variables such as accumulated precipitation.
- Developing historical data archives and evaluating potential utility from additional SCA data sources:
  - **Snow Estimation and Updating System (SEUS):** The NOHRSC produced gridded SWE estimates for the period 1995-2003 based on linearly interpolated SNOTEL, snow course, and gamma flight line observations (NOHRSC, 2011b). Due to the linear interpolation, Riverside anticipates that these grids may be less accurate than recent data sources, but may be beneficial for extending the SCA record back in time.
  - **MODIS Aqua Snow Cover Daily L3 Global 500 m Version 5 (MYD10A1):** The MYD10A1 dataset is similar to the MOD10A1 dataset processed under the current project, except the data are produced from MODIS sensors on the Aqua satellite, rather than the Terra satellite. The MYD10A1 data are available for the period July 4, 2002-present (Hall et al., 2007). Utilizing the MOD10A1 and MYD10A1 datasets in conjunction may reduce the impact of cloud cover, since the satellites pass over a given location at different times of the day.
  - **MODIS Snow-Covered Area and Grain Size (MODSCAG):** The MODSCAG procedure aims to improve upon the MOD10A1 fractional snow estimates by using a physically based algorithm to estimate fractional snow cover and grain size. The MODSCAG procedure utilizes MODIS reflectance data but accounts for temporal and spatial variations in surface reflectances, whereas the MOD10A1 algorithm assumes pure snow reflectance (Painter et al., 2009). These data are not yet available operationally, though the CBRFC is working to obtain the MODSCAG data for their jurisdiction.

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- Paul McKee – West Gulf River Forecast Center
- Tom Perkins – Natural Resources Conservation Service
- Kevin Werner – Colorado Basin River Forecast Center
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Appendix A: MODIS Grid Issues

The MODIS grids were reviewed to identify missing and problematic grids. The issues were categorized into four cases:

- Case 1: There is a lot of cloud cover, so the mean areal fraction snow cover value may not be trustworthy (most common case). These data remain in the final time series and grids so that users can apply individual thresholds based on cloud cover. Case 1 issues are not listed in this appendix.
- Case 2: The MODIS tiles show unusual or unnatural patterns such as bands of no data or zero values (not very common). These data remain in the final time series (and grids), but the dates are noted below.
- Case 3: The MODIS tiles are available but show zero snow covered area across all of the tiles in the middle of the snow season (rare). These grids were deleted from the grid set, and the days were flagged in the QC time series with a value of 888. These dates are also noted below.
- Case 4: One or all of the MODIS tiles are missing from the NASA FTP server (rare). On some days, 1-4 of the MODIS tiles are missing from the NASA FTP server (4 being the number of tiles required for complete coverage over CO). In the time series, these days show up as FSC = null and QC = null. These days are also listed below with notes about which tiles are missing for each day.

Date	Issue	Action
2000-02-28	All tiles zero	Case 3
2000-03-01	All zero in northwest tiles, just impacting the very northwest MBRFC basins	Case 2
2000-03-02	All tiles missing	Case 4
2000-03-08	Missing 2/4 tiles: 95, 104 (all values zero except a strip of cloud cover in bottom right corner)	Case 3
2000-03-15	All tiles missing	Case 4
2000-03-16	All tiles missing	Case 4
2000-03-19	All zero in northwest tiles, just impacting the very northwest MBRFC and CBRFC basins	Case 2
2000-03-21	Missing 1/4 tiles: 94 (All zero in western tiles, impacts northern CBRFC and some MBRFC basins)	Case 2
2000-03-22	Missing 1/4 tiles: 94 (All zero in western tiles, impacts northern CBRFC and some MBRFC basins)	Case 3
2000-03-24	Band of no data running east-west	Case 2
2000-04-25	All tiles missing	Case 4
2000-04-26	All tiles missing	Case 4
2000-04-27	All tiles missing	Case 4
2000-04-28	All tiles missing	Case 4
2000-05-08	Southeast tiles appear as zero, impacts most of ABRFC and the eastern MBRFC basins	Case 2
2000-05-13	Southeast tiles appear as zero, impacts most of ABRFC and the eastern MBRFC basins	Case 2
2000-05-23	Center portion appears as zero, suspicious lines, impacts all basins	Case 2
2000-06-14	Band of zero values	Case 2
2000-06-16	Band of zero values	Case 2

Date	Issue	Action
2000-06-21	Stripe of no data, could be ok	Case 2
2000-06-27	All tiles missing	Case 4
2000-07-02	Band of zero values	Case 2
2000-07-29	Band of zero values	Case 2
2000-08-02	Band of zero values	Case 2
2000-08-06	All tiles missing	Case 4
2000-08-07	All tiles missing	Case 4
2000-08-08	All tiles missing	Case 4
2000-08-09	All tiles missing	Case 4
2000-08-10	All tiles missing	Case 4
2000-08-11	All tiles missing	Case 4
2000-08-12	All tiles missing	Case 4
2000-08-13	All tiles missing	Case 4
2000-08-14	All tiles missing	Case 4
2000-08-15	All tiles missing	Case 4
2000-08-16	All tiles missing	Case 4
2000-08-17	All tiles missing	Case 4
2000-08-18	Unnatural patterns of clouds	Case 2
2000-09-22	Line of no data through some ABRFC basins	Case 2
2000-10-01	Line through some ABRFC basins	Case 2
2000-10-04	Line through CBRFC basins	Case 2
2000-10-17	Zero line	Case 2
2000-10-21	Zero line	Case 2
2000-10-22	Zero line	Case 2
2000-10-26	All tiles missing	Case 4
2000-11-01	Zero tiles	Case 3
2000-11-05	Zero line	Case 2
2000-11-14	Zero tiles, impacts Western MBRFC and CBRFC basins	Case 2
2000-11-17	Missing tiles except for Northwest corner	Case 2
2000-12-13	Zero line	Case 2
2001-01-04	Zero tiles	Case 3
2001-01-13	Zero tiles	Case 3
2001-01-16	Zero line	Case 2
2001-02-10	Zero line	Case 2
2001-02-18	Zero line	Case 2
2001-04-02	Zero line	Case 2
2001-04-18	Zero line	Case 2
2001-04-24	No data line	Case 2
2001-05-21	Zero tiles	Case 3
2001-05-23	Zero tiles	Case 3
2001-06-15	All tiles missing	Case 4
2001-06-16	All tiles missing	Case 4

Date	Issue	Action
2001-06-17	All tiles missing	Case 4
2001-06-18	All tiles missing	Case 4
2001-06-19	All tiles missing	Case 4
2001-06-20	All tiles missing	Case 4
2001-06-21	All tiles missing	Case 4
2001-06-22	All tiles missing	Case 4
2001-06-23	All tiles missing	Case 4
2001-06-24	All tiles missing	Case 4
2001-06-25	All tiles missing	Case 4
2001-06-26	All tiles missing	Case 4
2001-06-27	All tiles missing	Case 4
2001-06-28	All tiles missing	Case 4
2001-06-29	All tiles missing	Case 4
2001-06-30	All tiles missing	Case 4
2001-07-01	All tiles missing	Case 4
2001-07-02	All tiles missing	Case 4
2001-09-07	Some zero tiles	Case 2
2001-11-05	Zero tiles	Case 3
2001-11-15	Some zero tiles	Case 2
2001-12-25	Vertical bands of zero values	Case 3
2001-12-26	Vertical bands of zero values	Case 3
2001-12-27	Vertical bands of zero values	Case 3
2001-12-28	Vertical bands of zero values	Case 3
2001-12-29	Vertical bands of zero values	Case 3
2001-12-30	Vertical bands of zero values	Case 3
2001-12-31	Vertical bands of zero values	Case 3
2002-01-23	Zero tiles for ABRFC, WGRFC, southern basins of MBRFC, and most of CBRFC	Case 2
2002-02-03	Band of no data around area of snow cover	Case 2
2002-02-06	Zeros for eastern portions of MBRFC and ABRFC	Case 2
2002-03-19	All tiles missing	Case 4
2002-03-20	All tiles missing	Case 4
2002-03-21	All tiles missing	Case 4
2002-03-22	All tiles missing	Case 4
2002-03-23	All tiles missing	Case 4
2002-03-24	All tiles missing	Case 4
2002-03-25	All tiles missing	Case 4
2002-03-26	All tiles missing	Case 4
2002-03-27	All tiles missing	Case 4
2002-03-28	All tiles missing	Case 4
2002-04-14	All tiles missing	Case 4
2002-04-15	All tiles missing	Case 4

Date	Issue	Action
2002-05-18	Zero line	Case 2
2002-06-19	Zero tiles	Case 2
2002-08-07	Zero tiles	Case 2
2002-10-10	Zero lines	Case 2
2002-12-05	Missing 2/4 tiles: 94, 104 (remaining are zeros)	Case 3
2002-12-06	Missing 2/4 tiles: 94, 104 (remaining are zeros)	Case 3
2002-12-11	Missing 2/4 tiles: 94, 104 (remaining are zeros)	Case 3
2002-12-25	Zero line through some CBRFC, WGRFC, and ABRFC basins	Case 2
2003-01-06	Zero tiles	Case 3
2003-01-15	Missing 2/4 tiles: 94, 104 (remaining are zeros)	Case 3
2003-01-16	Missing 2/4 tiles: 94, 104 (remaining are zeros)	Case 3
2003-02-01	All tiles missing	Case 4
2003-04-30	Some zero tiles	Case 2
2003-07-31	Some zero tiles	Case 2
2003-08-16	Some zero tiles	Case 2
2003-10-14	Line of no data in CBRFC and ABRFC	Case 2
2003-10-31	Mostly zero tiles	Case 3
2003-12-02	Some zero tiles, impacts eastern MBRFC and most of ABRFC	Case 2
2003-12-13	Some zero tiles, impacts western MBRFC, all of CBRFC and WGRFC, and some ABRFC	Case 2
2003-12-16	All tiles missing	Case 4
2003-12-17	All tiles missing	Case 4
2003-12-18	All tiles missing	Case 4
2003-12-19	All tiles missing	Case 4
2003-12-20	All tiles missing	Case 4
2003-12-21	All tiles missing	Case 4
2003-12-22	All tiles missing	Case 4
2003-12-23	All tiles missing	Case 4
2003-12-24	Missing 3/4 tiles: 95, 104, 105	Case 4
2004-02-18	All tiles missing	Case 4
2004-04-06	Some zero tiles	Case 2
2004-06-24	Some zero tiles	Case 2
2004-11-13	No data line	Case 2
2004-11-23	Some zero tiles	Case 2
2004-12-24	All tiles missing	Case 4
2005-02-28	Zero line	Case 2
2005-05-20	No data line	Case 2
2005-05-29	Zero line	Case 2
2005-06-09	Some zero tiles	Case 2
2005-09-15	Some zero tiles	Case 2
2005-09-23	Missing 3/4 tiles: 95, 104, 105	Case 4
2005-12-13	Some zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2

Date	Issue	Action
2006-05-24	Some zero tiles	Case 2
2006-07-07	Zero line	Case 2
2006-08-22	Missing 3/4 tiles: 94, 95, 104	Case 4
2006-08-23	Missing 3/4 tiles: 95, 104, 105	Case 4
2006-10-12	Some zero tiles	Case 2
2006-11-08	Some zero tiles, impacts most of ABRFC and MBRFC	Case 2
2006-11-14	Some zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2
2006-12-06	Some zero tiles, impacts northern CBRFC, most of ABRFC and southeastern basins of MBRFC	Case 2
2007-06-07	Some zero tiles	Case 2
2007-10-21	Zero line through western MBRFC basins	Case 2
2007-11-08	Some zero tiles	Case 2
2007-11-15	Some zero tiles	Case 2
2007-12-13	All tiles missing	Case 4
2008-04-15	Zero tiles over most all of the basins	Case 3
2008-04-16	All tiles missing	Case 4
2008-09-08	All tiles missing	Case 4
2008-10-24	Zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2
2008-11-06	Zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2
2008-12-20	All tiles missing	Case 4
2008-12-21	All tiles missing	Case 4
2008-12-22	All tiles missing	Case 4
2008-12-30	Zero line through MBRFC basins	Case 2
2009-04-26	Zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2
2009-05-10	All tiles missing	Case 4
2009-05-11	All tiles missing	Case 4
2009-05-12	All tiles missing	Case 4
2009-05-13	All tiles missing	Case 4
2009-05-14	All tiles missing	Case 4
2009-05-15	Zero tiles, impacts CBRFC, WGRFC, and ABRFC	Case 2
2009-06-12	Zero tiles, impacts western MBRFC, maybe some CBRFC	Case 2
2009-08-12	Some zero tiles	Case 2
2009-08-26	Missing 3/4 tiles: 95, 104, 105	Case 4
2009-09-07	All tiles missing	Case 4
2009-10-13	Zero tiles, impacts all 4 RFCs	Case 2
2010-01-04	Zero tiles, impacts all 4 RFCs	Case 2
2010-02-24	Zero tiles, impacts eastern MBRFC and ABRFC basins	Case 2
2010-03-05	Zero line through some CBRFC and MBRFC basins	Case 2
2010-06-01	Zero tiles, impacts all 4 RFCs	Case 2
2010-10-28	Zero tiles, impacts all 4 RFCs	Case 2
2011-01-19	Zero tiles, impacts all 4 RFCs	Case 2
2011-01-24	Vertical bands of 100% snow cover, impacts all RFCs	Case 3

Appendix B: Comparison of MODIS and SNODAS SCA

Notes

For SNODAS SCA and MOD10A1 SCA:

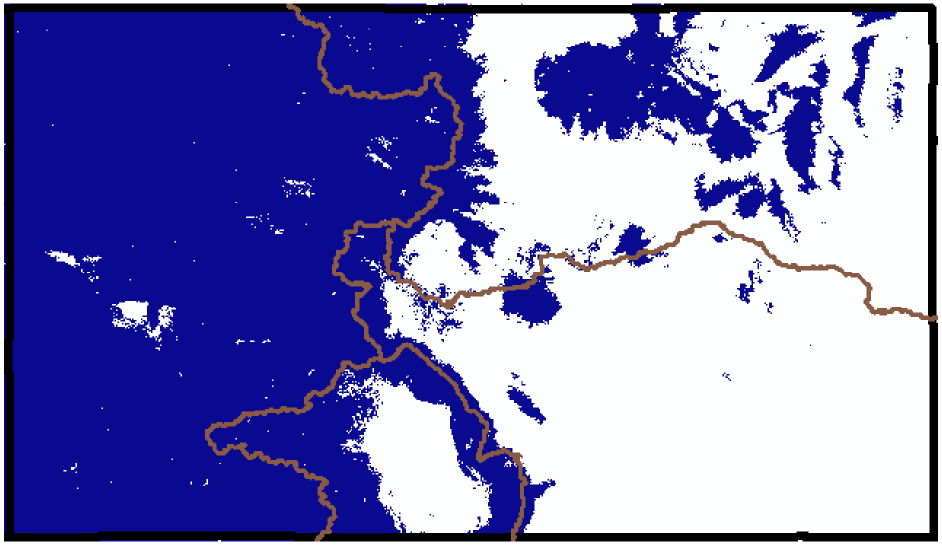
- Blue indicates snow-covered area.
- White indicates no snow.
- Yellow indicates indeterminate values.

For the change analysis:

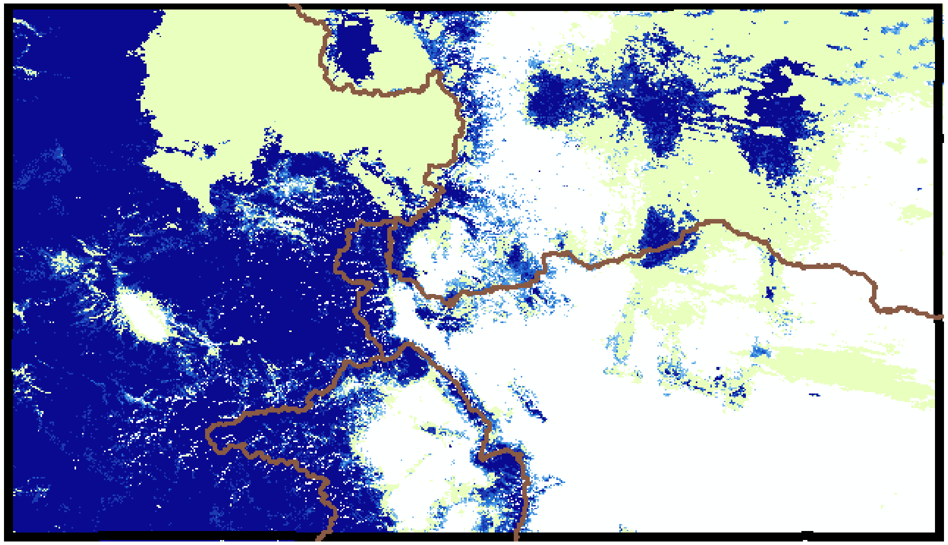
Change Analysis Legend Explanation	MODIS - Snow	MODIS - No Snow	MODIS - Indeterminate
SNODAS - Snow	Snow (MODIS and SNODAS)	Snow Only (SNODAS)	MODIS Clouds
SNODAS - No Snow	Snow Only (MODIS)	No Snow (MODIS & SNODAS)	MODIS Clouds

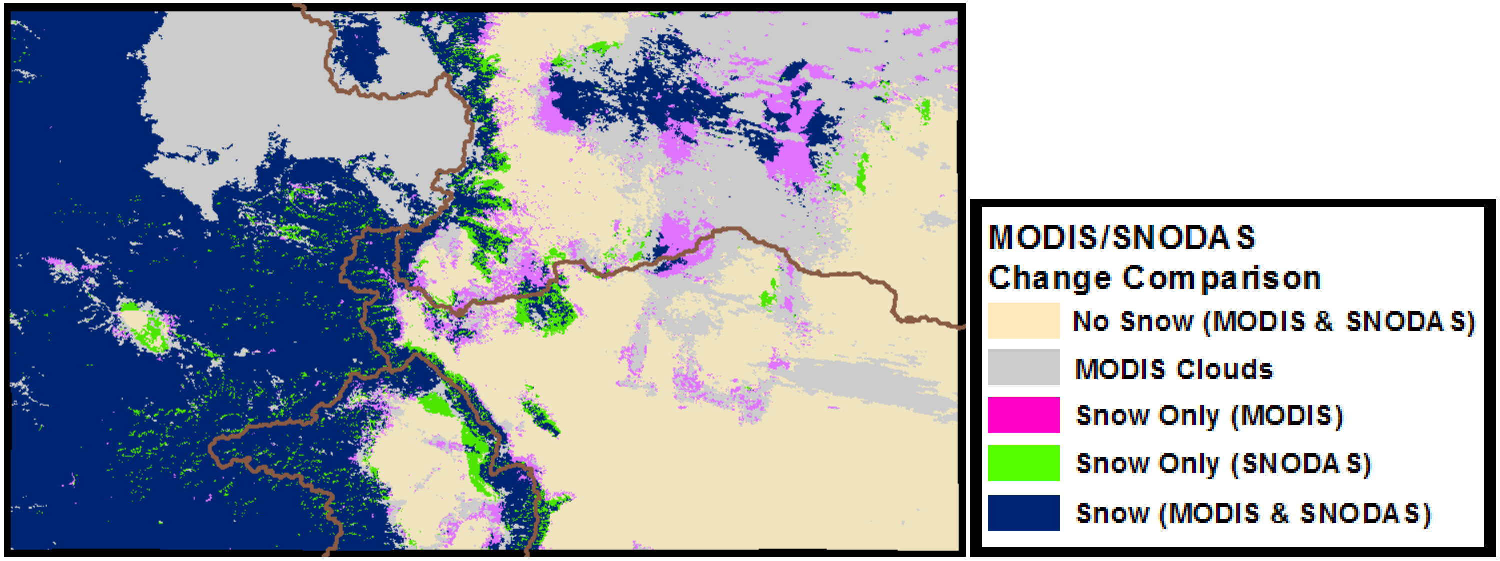
January 7, 2011

SNODAS SCA



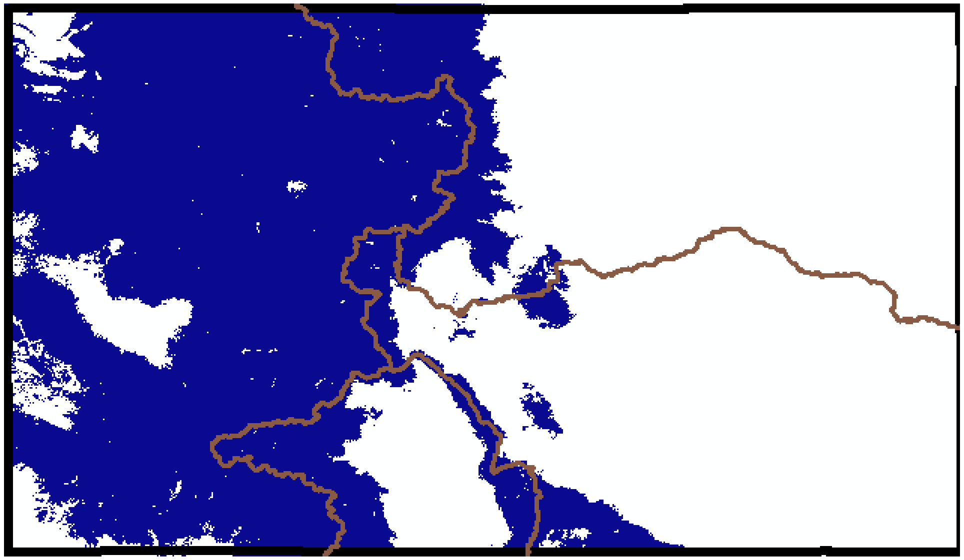
MOD10A1 SCA



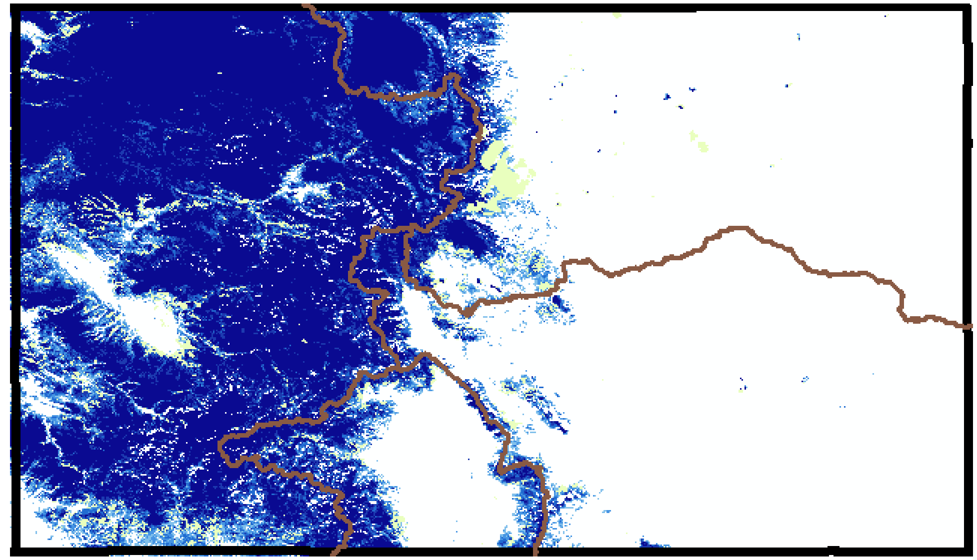


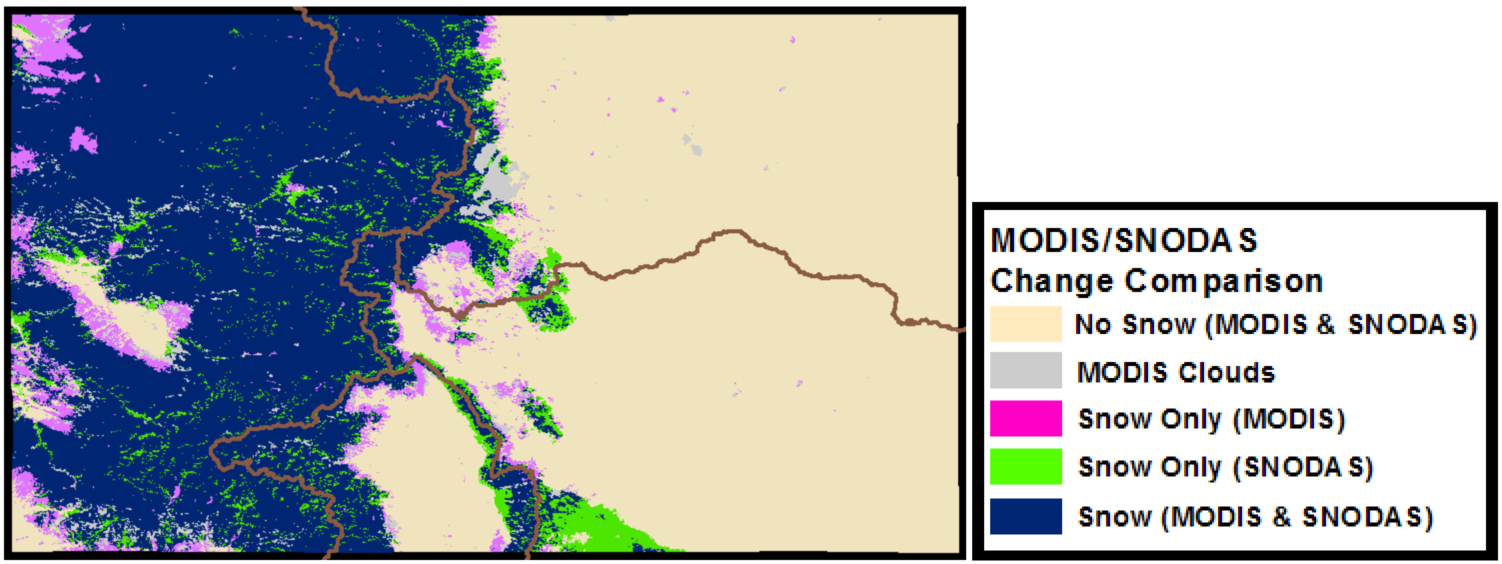
January 28, 2011

SNODAS SCA



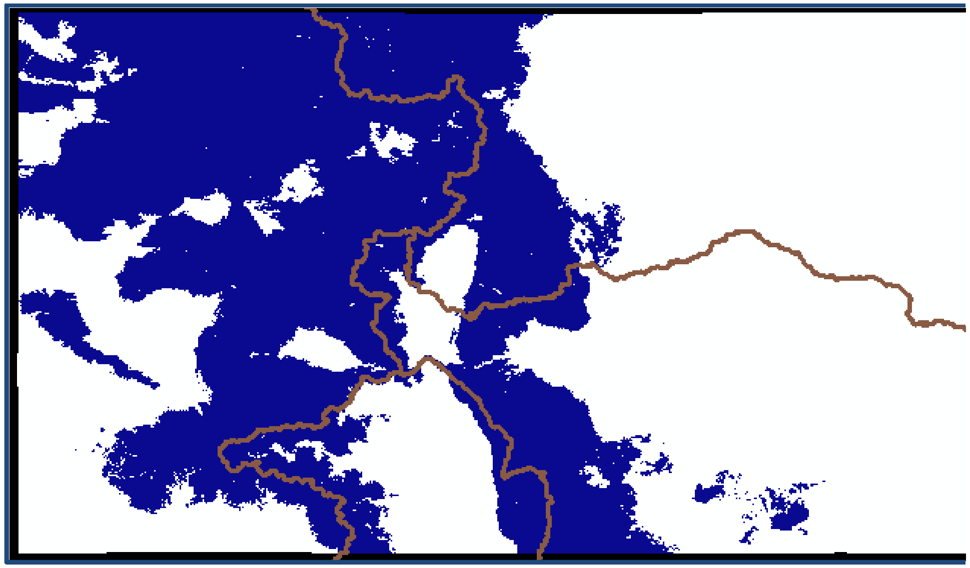
MOD10A1 SCA



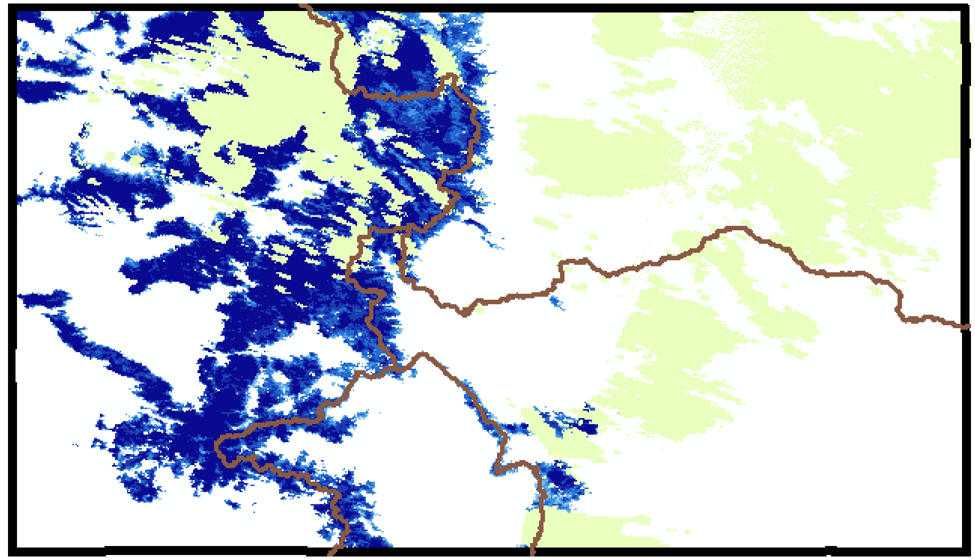


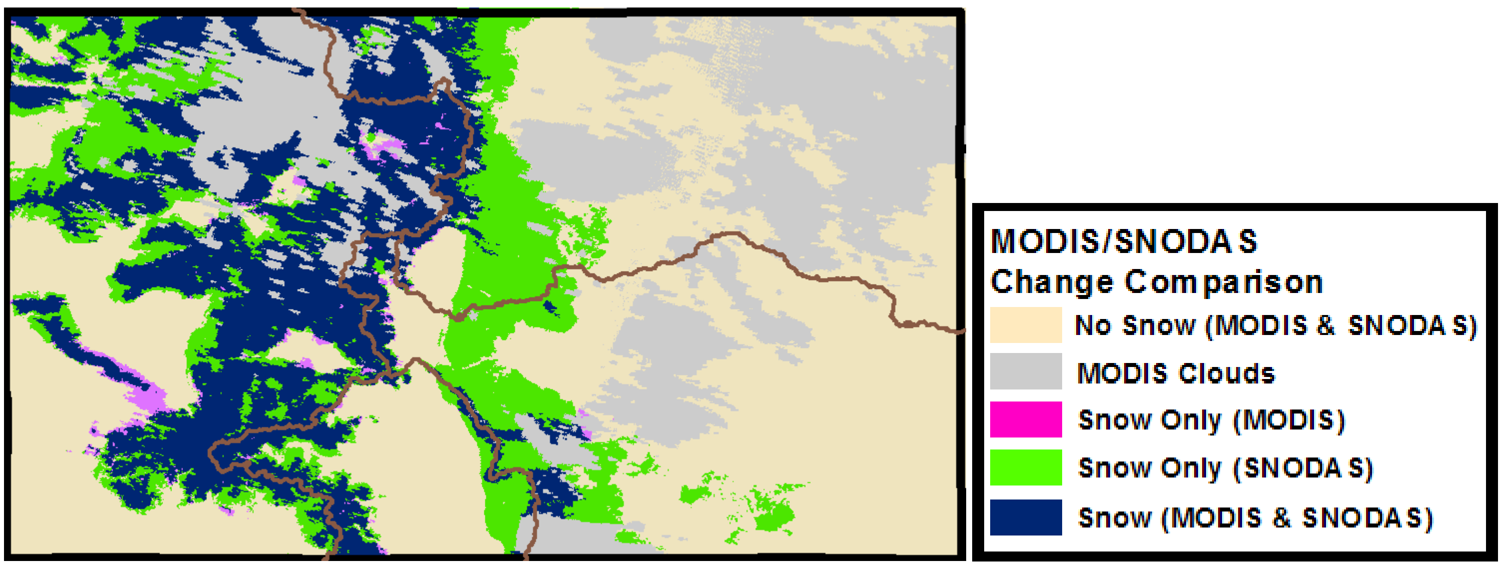
April 5, 2011

SNODAS SCA



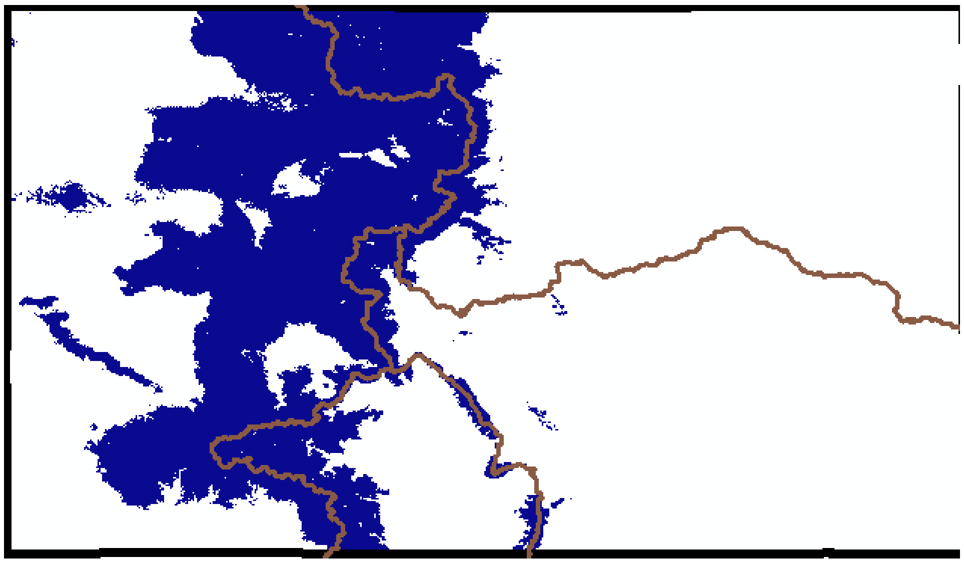
MOD10A1 SCA



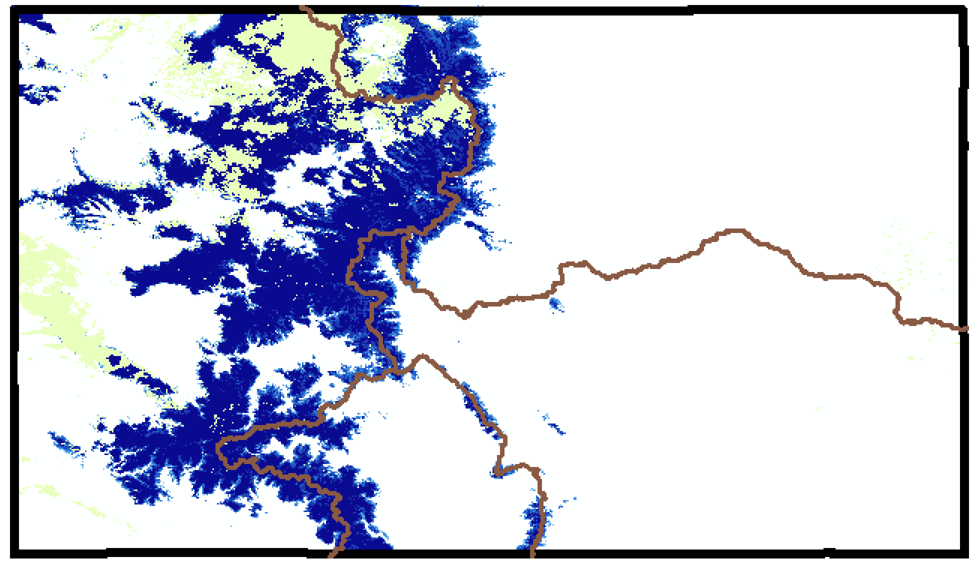


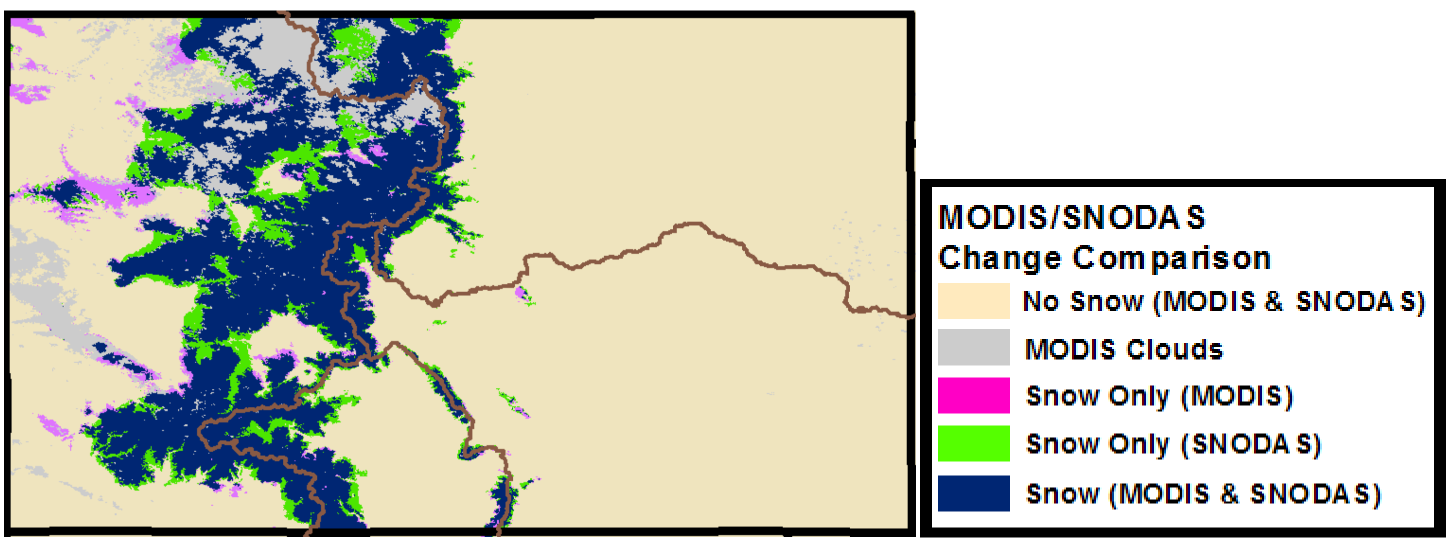
April 11, 2011

SNODAS SCA



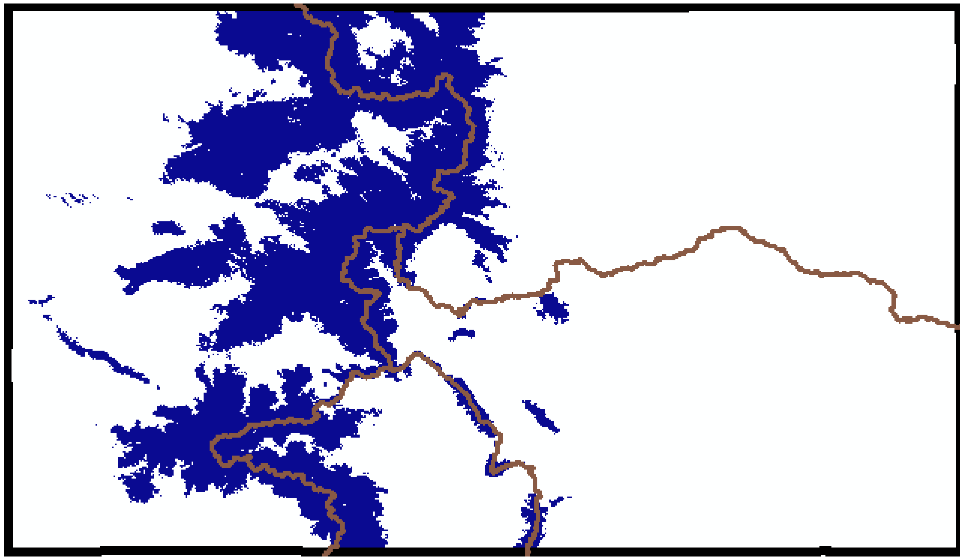
MOD10A1 SCA



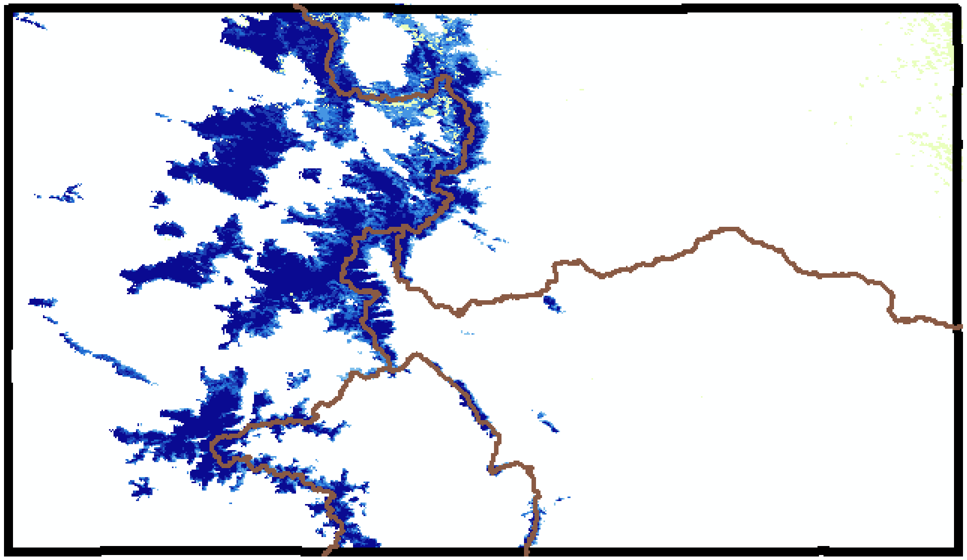


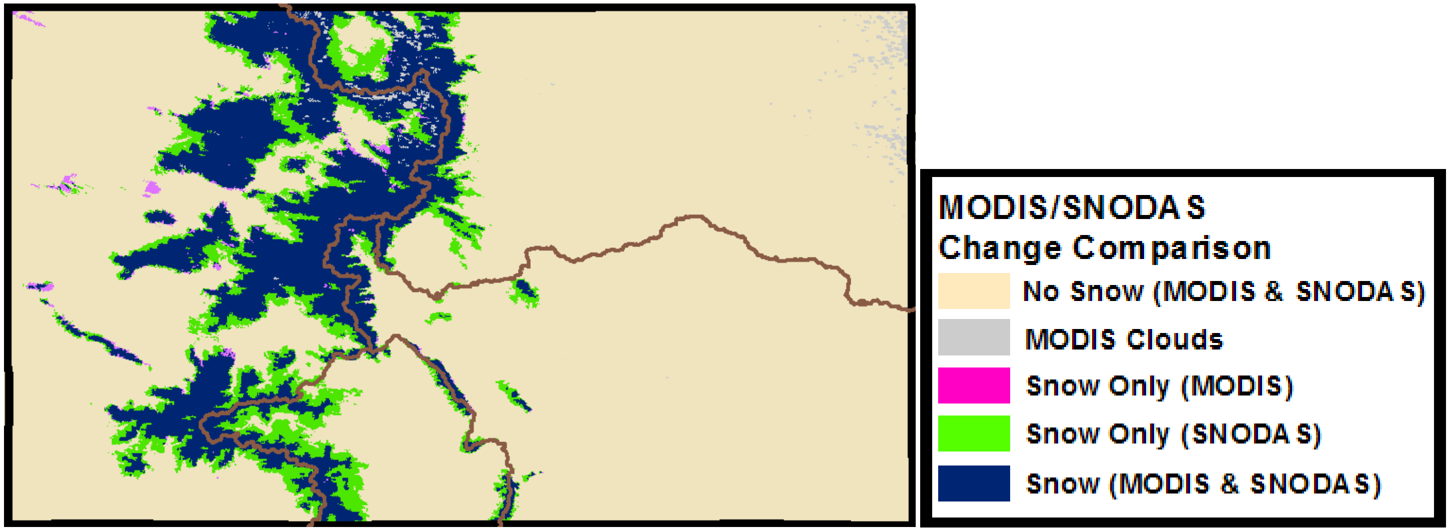
May 5, 2011

SNODAS SCA



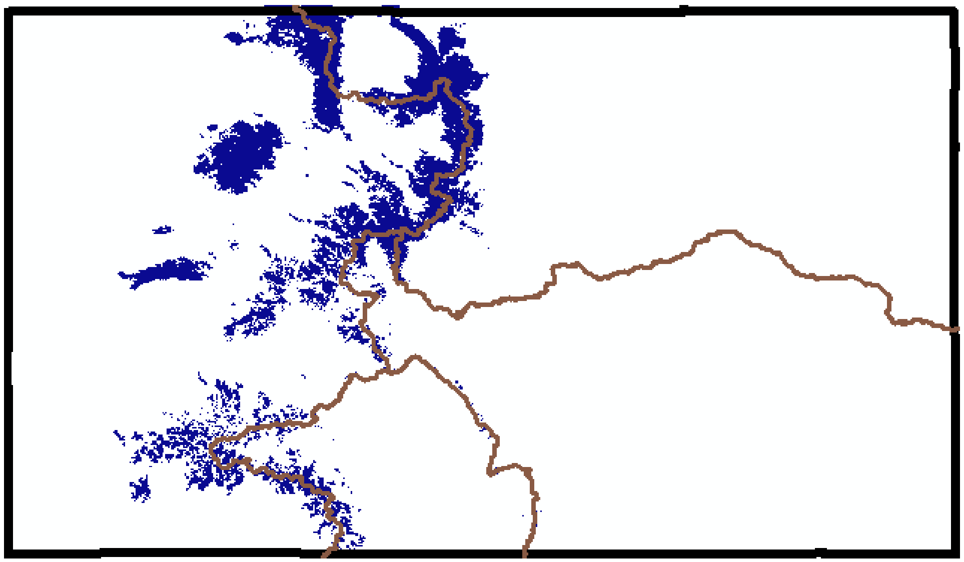
MOD10A1 SCA



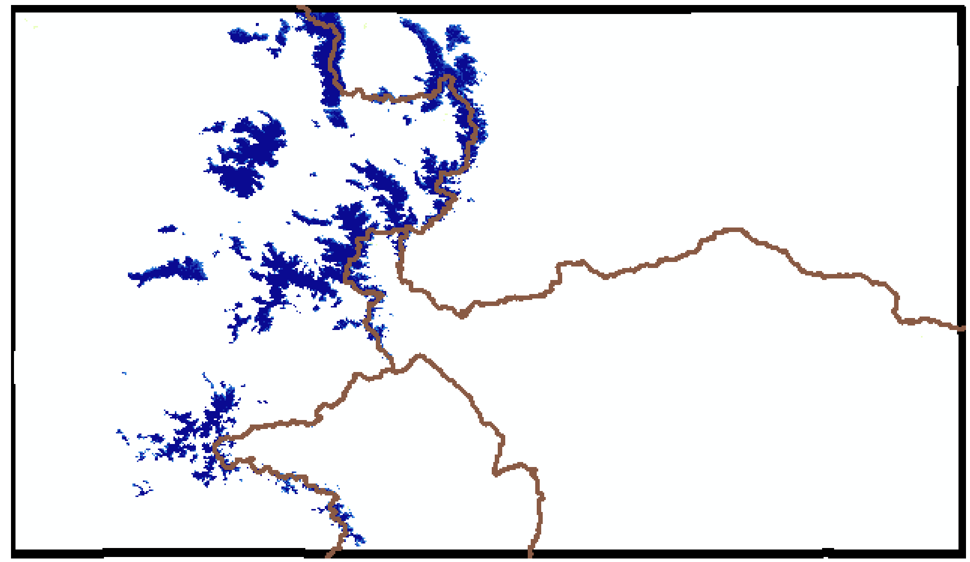


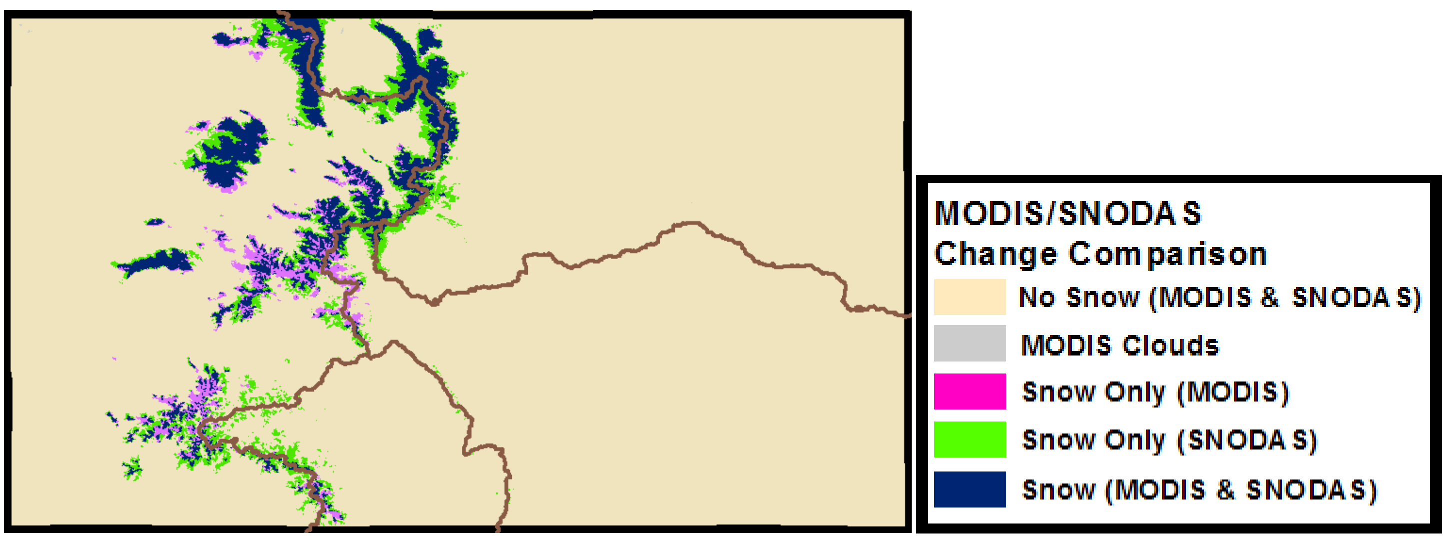
June 7, 2011

SNODAS SCA



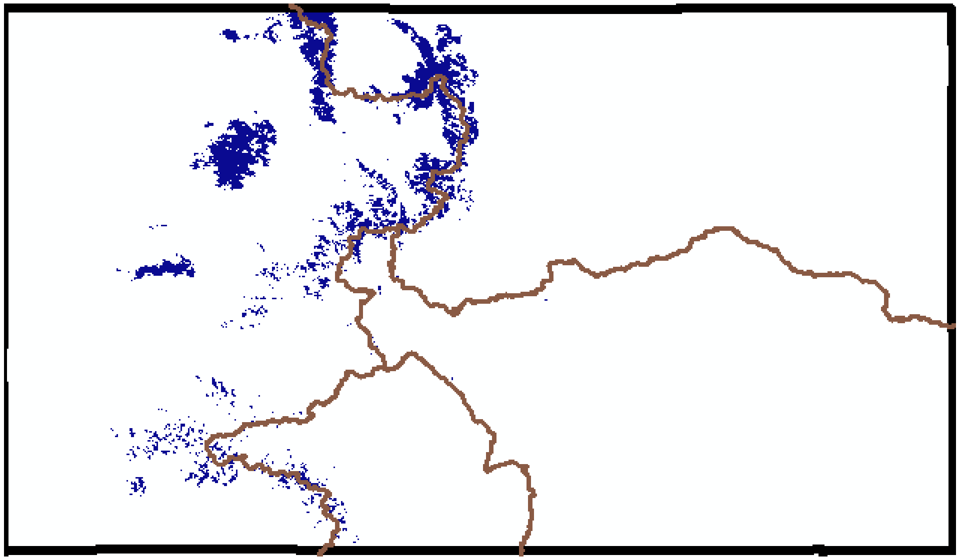
MOD10A1 SCA





June 22, 2011

SNODAS SCA



MOD10A1 SCA