CLIMATE-SCALE MAPS OF COLD-SEASON PRECIPITATION IN THE MOUNTAINOUS AREAS OF COLORADO FOR OPERATIONAL FORECASTING APPLICATIONS

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ABSTRACT: The PRISM precipitation model (v2013Aug) published by the PRISM Climate Group provides a gridded (4km spatial resolution) estimate of monthly precipitation (mm) over the conterminous United States derived from climate-elevation regressions which are weighted by topographic factors (such as elevation, aspect and terrain shadowing) and nearby weather station data. We have enhanced the PRISM gridded dataset by incorporating point precipitation values from the Colorado Avalanche Information Center's (CAIC) historical database. The data covers the water-year months of November through April, and was collected by ski area operators in Colorado and by the CAIC for highway avalanche forecasting operations. The result is a gridded dataset of long-term (1981-2010), cold-season precipitation for the Colorado mountains. The dataset includes mean precipitation values for both annual and winter months; variability: % of mean, standard deviation, and identifies outlier events. We used these data to produce a mapset that will help benefit daily weather and avalanche forecasting operations as well as increase our capability to characterize the snow and avalanche climate areas of Colorado.

KEYWORDS: forecasting, precipitation, mapping, snow climate, GIS.

1. INTRODUCTION

The Colorado Avalanche Information Center (CAIC) is responsible for backcountry and highway avalanche forecasting for the state of Colorado. While weather data is an integral component of avalanche forecasting on an hourly to daily time scale, longer-term climate data also informs operational forecasting.

Point data from weather stations provides insight for specific locations, but in rugged mountainous terrain there are large areas without weather station installations. Forecasting for data sparse areas is a challenge, and often relies on a forecaster's subjective sense of what might be happening in the terrain between weather stations. Interpolating and mapping climate data over forecasting regions aides the CAIC forecasting operations in several ways:

- Determining trends and changes in climate patterns over time
- Enables analysis of snow climates throughout Colorado, which informs how forecasting region boundaries are determined
- Informs spatial and temporal weather patterns

Here we describe a process for mapping precipitation for all mountainous areas in Colorado by enhancing an existing interpolated dataset with additional historical point data. This process can be repeated for most mountainous areas in the United States, and other forecasting operations may find the resulting information useful for operational forecasting.

2. SUMMARY OF METHODOLOGY

Development of the 1980-2010 Cold Season Precipitation in the Mountainous Areas of Colorado (v1.0) dataset required two types of data inputs:

- Baseline Precipitation gridded dataset (PRISM Climate Group (PRISMCG), 2013)
- Point snowfall data from ski area operations and Colorado Avalanche Information Center Weather Stations (CAICWx, 2013).

We utilized geospatial analysis tools to union PRISMCG precipitation (mm of water) values with CAICWx (inches of snow) values. The resulting output datasets were catalogued by month (No-

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vember 1980 – April 2010) and identifies existing PRISMCG precipitation with new CAICWx attributes for each 4 sq km grid cell. An applied conversion of all output dataset attributes to millimeters of water enables detailed mapping of monthly and seasonal snowfall statistics.

2.1 Input: PRISM Precipitation

The Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly et al., 2008) model details monthly precipitation (mm) attributes attached to an associated 4 sq km grid cell (Fig. 1), derived from climate-elevation regressions which are weighted by topographic factors (such as elevation, aspect and terrain shadowing) and

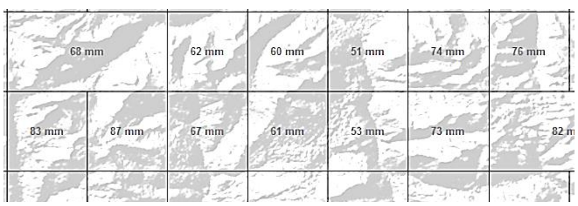

Fig. 1: example of 4km grid cells over San Juan County, CO. Units represent precipitable water value for October 1980.

nearby weather station data, including the following weather station networks in Colorado outlined in Tbl.1 below:

Tbl. 1: PRISM Input Weather Station Networks

Network Name	*Organization of Record*
AGRIMET	US Bureau of Reclamation
COCORAHS	Community Collaborative Rain, Hail, and Snow Network
COOP	Cooperative Network
HDSC	NOAA Hydrometeorological Design Studies Center
HYD	National Weather Service (NWS)
SNOTEL	Natural Resources Conservation Service (NRCS)
WRCC	Western Regional Climate Center

The specific baseline dataset chosen for the analysis is *AN81m* (PRISMCG, 2013) which details monthly total precipitation (rain and melted snow). The dataset was acquired in April 2014 for the months of November 1980 to April 2010 in a gridded x,y,z format and converted to shapefile vector (polygon) to enable the addition of future attributes associated with each grid cell.

The *AN81m* dataset summary (Tbl. 2) follows:

Tbl. 2: AN81 Precipitation Dataset Summary

Dataset Element	*Value*
Resolution	4 sq km
Time Series	Monthly
Interpolation Method	CAI (81 - 2010)
Version	2013, August
Predictor Grid	1981-2010 monthly climatologies
Sources	All stations included, regardless of observation time
Focus	Best estimate
Networks	AGRIMET, COCORAHS, COOP, HDSC, HYD, SNOTEL, WRCC
Units	ppt (mm); all values are floating point, rain + melted snow

2.2 Point Snowfall Feature Class – Monthly Snow Totals - CAICWx Dataset

Monthly Snowfall (inches) totals are tallied between the years of 1980-81 and 2009-2010 at 15 ski area locations in Colorado:

- Arapahoe Basin
- Aspen Mountain
- Aspen Highlands
- Beaver Creek
- Breckenridge
- Copper Mountain
- Crested Butte
- Keystone
- Loveland Ski Area
- Monarch
- Purgatory / DMR
- Steamboat
- Vail
- Winter Park
- Wolf Creek

Snowfall totals are stored in MS Excel .xls database and we converted the data into a shapefile .shp format. Each point contained attributes for ski area name, year, month, and snowfall total (in) for the associated month. We assigned each data point a geographical coordinate (x,y) feature associated with the data point's real-world location.

Monthly Snowfall (inches) totals are tallied between the years of 1980-81 and 2009-2010 at 9 CAIC weather stations in Colorado:

- Bear Lake, RMNP
- Berthoud Pass
- Gothic
- Loveland Pass East
- Coalbank Pass
- Molas Pass
- Monument
- Red Mountain Pass
- Wolf Creek Pass

CAICWx snowfall totals are stored in spreadsheet format and we converted the data into a shapefile .shp format for geospatial analysis. Each point contained attributes for CAIC name, year, month, snowfall total (in) for the associated month. We assigned each data point a geographical coordinate (x,y) feature associated with the data point's real-world location.

2.3 Incomplete Snowfall Data

CAICWx monthly snowfall totals contain incomplete (No-data) monthly snowfall records due to non-functioning sensors or other reasons. We determined No-data records to be '0' values, since '0' is stored as a monthly value for known years of sensor failures, known years of ski area non-operation, and known years that were before the sensor or station was implemented. Thus, we disregarded all '0' values in the monthly snowfall feature classes for CAICWx in the *Union of Attributes* spatial analysis.

2.4 Conversion of Units (mm)

We added a new field to each input as a designated container for the final mappable statistic – Millimeters (mm) of Precipitable Water. PRISMCG datasets already contained values in mm of precipitable water, however the CAICWx dataset contained values in inches of snow.

Using an assigned 10:1 ratio (inches of snow:inches of water), we applied the following calculation to each CAICWx value, then added as a new attribute to the existing dataset:

$$(x/10) * y = mm \qquad (1)$$

Where: x = snowfall total; y = 25.4 (millimeters per inch conversion)

2.5 Spatial Analysis: Union of Attributes

We applied geospatial union techniques to overlay the CAICWx feature datasets with PRISMCG feature dataset for each winter month between November 1980 – April 2010, and exported to a new monthly output feature class. Rules for the union analysis are as follows:

- For those 4 sq km PRISMCG features where a CAICWx feature intersects, an attribute matching the CAICWx value will be added, along with the CAICWx data point name.
- If a CAICWx data point location does not occur within a PRISMCG 4 sq km feature, no new attribute values are stored.

2.6 Hierarchy of Precipitation Values

After we completed the *union of spatial attributes* analysis, we applied an attribute hierarchy to determine the final updated precipitation value (mm of water), since there were several 4 sq km features in each monthly output where both PRISMCG attributes and CAICWx attributes are stored. We created a new field 'MMPRECIP' to store the final precipitation value for all 4 sq km features across the State of Colorado. We applied the attribute hierarchy to calculate the precipitation values within 'MMPRECIP' according to the following rules:

- Features where no CAICWx attributes are stored will maintain the source/original PRISMCG attribute
- Features where CAICWx attributes are stored will be recorded with the CAICWx attributes; Unless:
    - The CAICWx attribute is '0' (No-Data or Incomplete data as defined above)

3. SPATIAL OUTPUT – FINAL PRECIPITATION

3.1 4 sq km Monthly Precipitation Dataset

Monthly polygon vectors feature class outputs for each winter month between October 1980 and April 2010. Within each feature class, attributes from the original PRISMCG value are stored for all 4 sq km features across Colorado, along with the CAICWx values per the hierarchy described in section 2.6. The final precipitation value, 'MMPRECIP', contains the updated precipitation (mm water) for each 4 sq km feature. These monthly feature classes will be the source of additional future analysis and mapping based on the 'MMPRECIP' attribute.

3.2 <u>4 sq km Cold-Season Precipitation Dataset</u>

We combined monthly feature classes (November, December, January, February, March, April) for each winter season 1980-81 to 2009-2010 using an *Addition* overlay to create a Cold-Season Precipitation output. The *Addition* overlay adds each monthly 'MMPRECIP' value together and creates a new Cold-Season Precipitation total 'MMPPTOT' attribute (mm water) for each year. These resulting seasonal feature classes contain the final precipitation value 'MMPPTOT' for the entire season over each 4 sqkm feature across Colorado.

4. RESULTS

We compiled the resulting datasets in section 3.1 and 3.2 into visual graphics detailing spatial distribution of Cold-Season precipitation (mm) across the Colorado mountains over a 30-year period (1980-2010). The map graphics outline precipitation trends over the 30-year period, including:

- Mean precipitation
- variability from Mean
- Outliers

The poster presentation provides a sample of these precipitation trends and a statewide view of Cold-Season Mean precipitation in Colorado for the period of 1980-2010.

An example *Section 3.2* output map graphic follows in Fig. 2, where the total snowfall (inches) for the 2009-2010 Cold-Season months is quantified for the mountainous areas of northern and central Colorado.

CONCLUSION

These datasets and corresponding trend graphics will help benefit daily weather and avalanche forecasting operations as well as increase our capability to characterize the snow and avalanche climate areas of Colorado.

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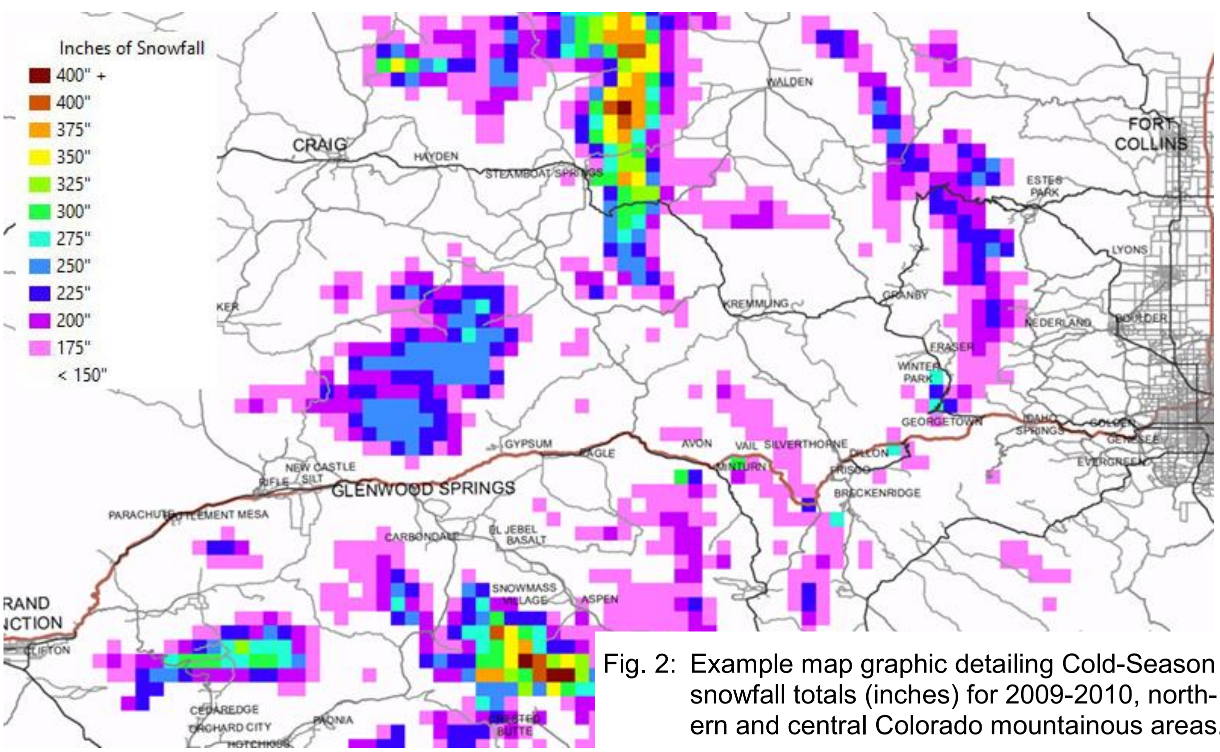

Fig. 2: Example map graphic detailing Cold-Season snowfall totals (inches) for 2009-2010, northern and central Colorado mountainous areas.