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Improved snow cover remote sensing for snowmelt runoff forecasting

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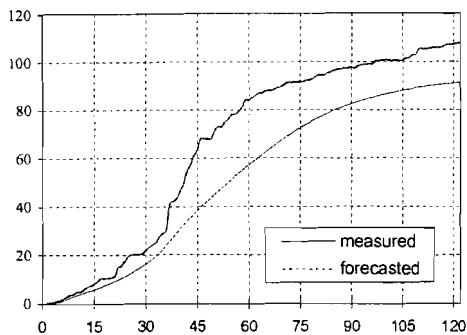
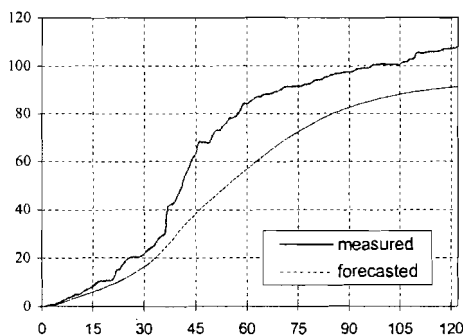
Abstract A system based on satellite remote sensing has been developed for snow cover monitoring of a number of basins in the Spanish Pyrenees. The snow covered area is used as an input for snowmelt runoff forecasts on 42 basins using the Snowmelt Runoff Model (SRM). The forecast snowmelt volume accumulated from May to September is sent to the hydropower companies for water resources management. A sub-pixel analysis is carried out to map the snow cover with Advanced Very High Resolution Radiometer (AVHRR) data on board the National Oceanic and Atmospheric Administration (NOAA) satellites. Two mapping methods are compared: a linear combination of visible and near infrared channels, and a snow classification based on the normalized difference snow index (NDSI) and the normalized difference vegetation index (NDVI).

Key words AVHRR; Spanish Pyrenees; remote sensing; snow mapping; snowmelt runoff; streamflow forecasting; sub-pixel analysis; water resources

INTRODUCTION

The Hydrology Laboratory (HL) at the Beltsville Agricultural Research Center of the US Department of Agriculture is analysing snow cover data and making forecasts of snowmelt discharge on 42 basins in the Spanish Pyrenees. The snow cover maps are obtained from NOAA-AVHRR (National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer) data. The Remote Sensing Laboratory at the University of Valladolid, Spain, receives the NOAA-14 images and performs a data calibration of AVHRR channels 1 and 2, and a geometric correction based on orbit parameters. Results are sent to the HL where another geometric correction is performed based on ground control points. Snow maps are obtained by a linear combination of channels 1 and 2.

Algorithms were developed at the HL to improve the snow mapping of small areas, combining several snow maps of consecutive days. Artificial patterns of snow were created and a series of training images was obtained from these patches simulating snow maps derived from AVHRR. Correlation coefficients between the snow patch and the algorithm output are improved if compared to those obtained between the snow patch and a single image. The linear combination method has been applied to Landsat TM scenes in order to compare its results with those obtained by the SNOMAP algorithm (Hall *et al.*, 1995), developed to be used with the MODIS (Moderate Resolution Spectroradiometer) instrument.

NR1 1999. Pont de Suert, 572.9 km²NR1 1999. Pont de Suert, 572.9 km²Fig. 1 Measured and forecast snowmelt volume (Hm³), 1999.

Conventional Depletion Curves (CDC) are obtained from the snow maps (Martinez *et al.*, 1998), representing the daily snow cover for each elevation zone of the basin. These curves together with temperature and precipitation are the three input variables used to run the SRM model in the forecasting mode. As an example, Fig. 1 shows the forecast vs measured accumulated snowmelt volume for two basins in the central Pyrenees. Table 1 shows a summary of results for six basins in the Pyrenees.

Table 1 Comparison between 1999 forecast and measured snowmelt volumes.

Basin name	Area (km ²)	Measured volume (Hm ³)	Forecast volume (Hm ³)	Difference (%)
NR1: Pont de Suert	572.9	107.8	91.4	+16.5
GA1: Garona en P. de Rei	557.5	144.3	122.7	+16.2
GA2: Garona en Bossost	449.2	98.1	88.5	+10.3
NR9: Embalse de Baserca	75.3	20.4	26.3	-25.3
NR8: Embalse de Cavallers	26.4	14.2	12.1	+15.9
NR10: Embalse de Llauset	8.3	2.8	3.0	-6.9

THE LINEAR COMBINATION APPROACH

This method uses visible and a near infrared albedoes. As in the Linear Mixture Models (LMM), the spectral proportion of each cover type is equal to its cover proportion (Quaidrari *et al.*, 1996). Each pixel of the snow map (I_m) has a digital value proportional to its snow cover percent, given by the linear combination:

$$I_m = a_1 C_1 + a_2 C_2 \quad (1)$$

where C_1 and C_2 are albedoes of channels 1 and 2, respectively. The combination coefficients a_1 and a_2 are derived by the following equation:

$$a_1 \begin{pmatrix} S_1 \\ G_1 \end{pmatrix} + a_2 \begin{pmatrix} S_2 \\ G_2 \end{pmatrix} = \begin{pmatrix} 255 \\ 0 \end{pmatrix} \quad (2)$$

where S_1 and S_2 are the snow threshold for channel 1 and channel 2, respectively, and G_1 and G_2 are the ground threshold for channel 1 and channel 2, respectively. The snow threshold is defined as the minimum digital value of a pixel fully covered with snow. It can be obtained from snow classification and using a snow histogram of frequencies, either graphically or numerically. The ground threshold is defined as the maximum digital value of bare ground. It can also be obtained from a ground classification on a monthly or a weekly basis.

Equation (2) imposes a maximum value (255) for pixels fully covered with snow and a minimum value (0) for bare ground pixels. The mixed pixels of snow and ground shall have a grey level proportional to their snow cover percent, given by:

$$a_1 = 255 \left(\frac{G_2}{S_1 G_2 - S_2 G_1} \right)$$

$$a_2 = 255 \left(\frac{G_1}{S_1 G_2 - S_2 G_1} \right) \quad (3)$$

$$Im = C_1 a_1 + C_2 a_2 = 255 \left(\frac{C_1 G_2 - C_2 G_1}{S_1 G_2 - S_2 G_1} \right)$$

Improvements of these snow cover maps are being developed using different versions of the snow patch provided by consecutive satellite images. Algorithms were tested on simulated snow patches, and correlation coefficients improve from 0.951 (for the snow pattern vs a single image) to 0.987 (for the snow pattern vs the algorithm applied to three images). To test this method in a real case, three NOAA images were chosen during the middle of February 1998. Figure 2 shows snow mapping analysis for a single image compared with the algorithm's output for three images.

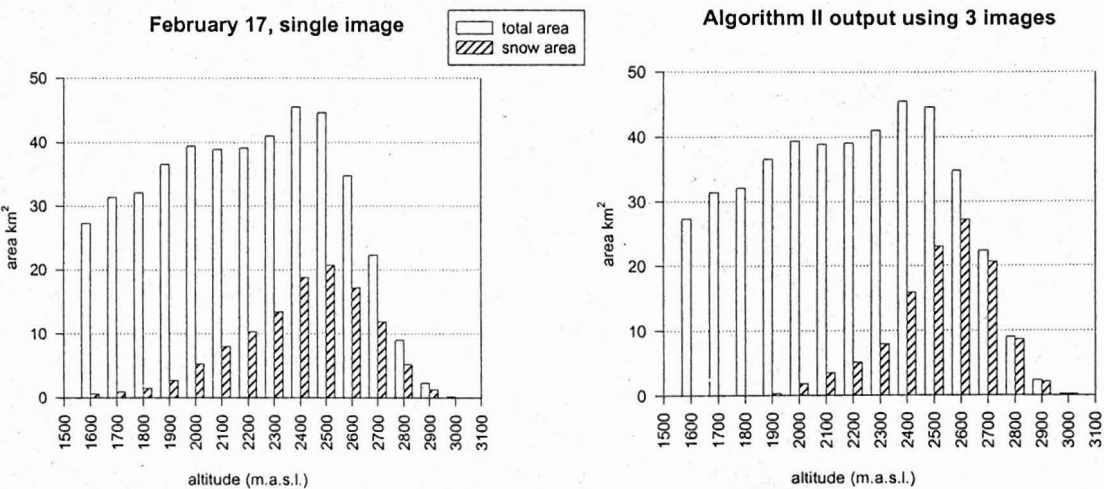


Fig. 2 Hypsometric representation of snow cover vs total area for Valira basin, Spain.

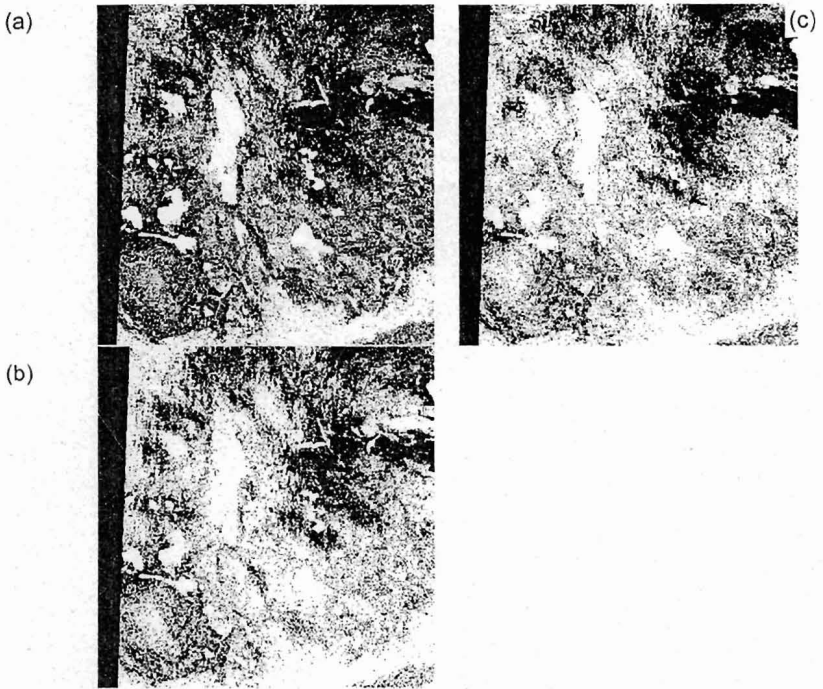


Fig. 3 (a) Snow map obtained by linear combination of Landsat TM channels 2 and 5; (b) two category snow map obtained from Fig. 3(a); and (c) snow map obtained from the SNOMAP algorithm.

THE NDSI-NDVI APPROACH

The SNOMAP algorithm was developed by the NASA Hydrological Sciences Branch for global snow cover mapping using MODIS data. The output (Fig. 3(c)) is a two category snow map in which pixels are either snow covered or snow free. It discriminates snow covered forests (Klein *et al.*, 1998) from snow-free forests based on NDSI and NDVI values. Several Landsat TM scenes were used to test the SNOMAP algorithm. The TM-NDSI index is calculated with channels 2 and 5, using the equation:

$$\text{NDSI} = \frac{\text{TM channel 2} - \text{TM channel 5}}{\text{TM channel 2} + \text{TM channel 5}} \quad (4)$$

The MODIS version of the SNOMAP algorithm will use channel 4 as the visible channel, instead of TM channel 2, and channel 6 as mid-infrared, instead of TM channel 5. Snow is discriminated from water by means of TM channel 4 (near infrared); pixels with an albedo lower than 11% in this channel are not considered snow pixels. For this condition, MODIS channel 2 (0.841–0.876 μm , near infrared) will substitute for TM channel 4. Also, a minimum pixel reflectance of 10% in TM channel 2 (MODIS channel 4) is required to be considered as snow pixels. The accuracy of this approach is estimated to be 91–95%, being slightly lower in forested

areas and higher in tundra type areas (Hall *et al.*, 1998). A fractional snow cover enhancement to the algorithm is also under development in the Hydrological Sciences Branch of NASA (Barton *et al.*, 2000).

COMPARISON OF BOTH APPROACHES

Both methods have been applied independently to Landsat TM scenes of southern Saskatchewan, Canada, 6 February 1994, and Glacier National Park, Montana, USA, 14 March 1991. The output images of the linear combination (Fig. 3(a)) were converted into two category snow maps. To obtain the correlation coefficient ρ , a square grid was defined on each image and the average was obtained for each cell of the grid. The ρ value was obtained between these average values of both methods. In the Saskatchewan scene, when the minimum snow cover percent is set to 33% (Fig. 3(b)), then ρ reaches a maximum of 0.91.

CONCLUSION AND DISCUSSION

Accuracy of snow maps strongly influences the snowmelt forecast through the SRM model. For instance, the snowmelt volume forecast in Embalse de Llauset basin, (Fig. 1 and Table 1) fails in late summer. This is probably due to an inaccuracy of the CDC curves extrapolated from May snow maps. The NDSI-NDVI criteria used in the SNOMAP algorithm have proved to be more accurate in forested areas than the linear combination due to: (a) the normalization of the spectral response of the target associated with NDSI and NDVI indexes, and (b) the use of a minimum visible albedo for snow, to avoid confusing forest pixels (having low visible albedo) with snow pixels (which have high visible albedo).

REFERENCES

- Barton, J. S., Hall, D. K. & Riggs, G. A. (2000) Remote sensing of fractional snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data. In: *Proc. Fifty-seventh Eastern Snow Conf.* (Syracuse, New York, May 2000). Eastern Snow Conference, USA (in press).
- Hall, D. K., Foster, J. L., Salomonson, V. V., Klein, A. G. & Chien, J. Y. L. (1998) Error analysis for global snow cover mapping in the Earth Observing System (EOS) era. In: *Proc. IGARSS'98* (Seattle, Washington, USA, July 1998). IEEE, Piscataway, New Jersey, USA.
- Hall, D. K., Riggs, G. A. & Salomonson, V. V. (1995) Development of methods for mapping global snow cover using moderate resolution imaging spectroradiometer (MODIS) data. *Remote Sens. Environ.* **54**, 127–140.
- Klein, A. G., Hall, D. K. & Riggs, G. A. (1998) Improving cover mapping in forests through the use of a canopy reflectance model. *Hydrol. Processes* **12**, 1723–1744.
- Martinez, J., Rango, A. & Roberts, R. (1998) Snowmelt Runoff Model (SRM) User's Manual. *Geographica Bernensia P35*. Department of Geography, University of Bern, Switzerland.
- Quaidrari, H., Begue A., Imbernon, J. & D'Herbes, J. M. (1996) Extraction of the pure spectral response of the landscape components in NOAA-AVHRR mixed pixels—application to the HAPEX-Sahel Degree Square. *J. Remote Sens.* **17**, 2259–2280.