SNOW COVER MAPPING USING MODIS IMAGES AND ITS POTENTIAL IN HYDROLOGICAL MODELING

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Abstract

Satellite MODIS snow cover images are appealing for hydrological applications because of their good spatial and temporal resolution and acceptable mapping accuracy. Their main limitation, however, is cloud obscuration. The main objective of this study is to evaluate a snow cover mapping approach that enables cloud reduction by combining MODIS data from two platforms, the Terra and Aqua satellites. The potential of the combined snow cover product for hydrological modeling is illustrated by two case studies. The first study focuses on the integration of snow cover data into the calibration of a conceptual hydrologic model. In this case, snow cover images are used jointly with runoff data in model calibration over 148 Austrian catchments. The second case study demonstrates the usefulness of combined MODIS images in constraining and validating a distributed energy-balance based snow model in the context of a detailed operational simulation of snow water equivalent in one of Vienna’s water supply regions. Both case studies demonstrate the value of MODIS snow cover images in hydrological modeling. Especially in alpine regions with sparse observations, the remotely sensed images provide a very valuable source of information which has strong potential for operational applications.

Keywords: MODIS snow cover, hydrological modeling.

1 INTRODUCTION

Satellite MODIS snow cover images are appealing for hydrological applications because of their good spatial and temporal resolution and acceptable mapping accuracy. Their main limitation, however, is cloud obscuration. The study of Parajka and Blöschl (2008) recently presented an evaluation of simple mapping methods that reduce cloud coverage by using information from neighboring non-cloud covered pixels in time or space and by combining MODIS data from one of the Terra and Aqua satellites. They found that the combination of Terra and Aqua MODIS images enables efficient cloud reduction and the resulting snow maps are still in good agreement with the ground snow observations.

The main objective of this study is to demonstrate a potential of MODIS data in hydrological modeling. The added value of MODIS snow cover images is illustrated in two case studies. The first example focuses on the potential of MODIS snow cover images for validation and calibration of a conceptual hydrologic model. In this case, snow cover images are used jointly with runoff data in model calibration over 148
Austrian catchments. The second case study describes the application of combined MODIS images in constraining and validating a distributed energy-balance based snow model. This example shows the application of satellite snow images within the context of a detailed operational simulation of snow water equivalent in one of Vienna’s water supply region.

2 MODIS SNOW COVER DATA

The snow cover maps used in this study have been acquired by the MODIS instrument mounted on the Terra and Aqua satellites of the NASA Earth Observation System. Both satellites use the same type of MODIS instrument, but the differences in their orbits result in different viewing and cloud cover conditions. The most noticeable difference is the local equatorial crossing time: approximately 10:30 a.m. in a descending node for the Terra and approximately 1:30 p.m. in an ascending node for the Aqua satellite. Both snow cover products are freely available through the Distributed Active Archive Center located at the National Snow and Ice Data Center (NSIDC, www.nsidc.org), which also publishes and updates technical documents presenting a detailed description of the snow mapping algorithm, data formats, spatial and temporal resolutions and references to numerous validation studies.

This study utilises the combined snow cover product proposed by Parajka and Blöschl (2008). This product is based on merging the original Terra and Aqua snow cover images observed on the same day, shifted by several hours. The pixels classified as clouds in the Aqua images are updated by the Terra pixel value of the same location if the Terra pixel is snow or land. An example of merging is presented in Figure 1. The top panel shows a snow cover map on 25th October 2003 acquired by the Aqua satellite; the middle panel shows the Terra image for the same day. The combined snow cover map presented in the bottom panel indicates a significant decrease in cloud coverage. On this day, the cloud coverage observed by Aqua and Terra was 61.4 % and 55.6% respectively. Their combination resulted in cloud coverage less than 47% over Austria.

The benefits and accuracy of the combined snow cover product is in detail evaluated in Parajka and Blöschl (2008). An extension to this evaluation is presented in Figure 2. Figure 2 presents spatial pattern of the mean cloud frequencies acquired by Aqua, Terra and their combination in the period 2003-2006. It is clear that the snow cover images from Terra have slightly lower cloud coverage than those from Aqua, but there is a remarkable decrease in cloud coverage when the two are combined. The combination of the two snow cover products decreases the cloud coverage mainly in the south of Austria and in the valleys of the main ridge of the Alps. This is likely due to less persistent cloud coverage compared to high alpine regions where clouds tend to be more continuous in time.
Figure 1. Example of merging the Terra and Aqua MODIS images. Snow cover maps are observed on 25th October 2003.
Figure 2. Mean cloud coverage of the Aqua, Terra and combined snow cover products in the period 2003-2006.
3 CASE STUDY 1: CALIBRATION OF A CONCEPTUAL HYDROLOGIC MODEL USING MODIS SNOW COVER DATA

The objective of this demonstration is to show the potential of snow cover data from the MODIS satellite sensors for calibrating a conceptual semi-distributed hydrological model. The methodology is based on an indirect comparison of snow water equivalent simulated by the hydrologic model (in detail described e.g. in Parajka et. al, 2007) and the snow cover data from the combined images. The hydrologic model was calibrated by minimizing a compound objective function which involves and weights two parts related to the runoff and the snow cover, respectively. The runoff part \( Z_Q \) consisted of a combination of two variants of the Nash-Sutcliffe Model efficiency:

\[
Z_Q = w_Q \cdot (1 - M_E) + (1 - w_Q) \cdot (1 - M_{E}^{\text{log}}).
\]

The weight \( w_Q \) was set to 0.5 and \( M_E \) and \( M_{E}^{\text{log}} \) were defined as:

\[
M_E = 1 - \frac{\sum_{i=1}^{n} (Q_{\text{obs},i} - Q_{\text{sim},i})^2}{\sum_{i=1}^{n} (Q_{\text{obs},i} - \overline{Q_{\text{obs}}})^2}.
\]

and

\[
M_{E}^{\text{log}} = 1 - \frac{\sum_{i=1}^{n} (\log(Q_{\text{obs},i}) - \log(Q_{\text{sim},i}))^2}{\sum_{i=1}^{n} (\log(Q_{\text{obs},i}) - \log(\overline{Q_{\text{obs}}}))^2},
\]

where \( Q_{\text{sim},i} \) is the simulated runoff on day \( i \), \( Q_{\text{obs},i} \) is the observed runoff, \( \overline{Q_{\text{obs}}} \) is the average of the observed runoff over the calibration (or verification) period of \( n \) days. The idea of equally weighted \( M_E \) and \( M_{E}^{\text{log}} \) is to emphasize both the high and low flows, respectively.

The snow model performance (snow cover part of the compound objective function) was represented by the sum of snow over- \( (S_{EO}^C) \) and underestimation \( (S_{EU}^C) \) errors. Both types of error measures are based on counting the number of days when the snow simulations of the hydrologic model do not correspond to the snow cover observations (e.g. the MODIS image indicates snow cover in a catchment, but the hydrologic model does not simulate the snow water equivalent there). A more detailed description of the definition and thresholds applied in the evaluation of snow model performance is given in Parajka and Blöschl (submitted to Journal of Hydrology).

The added value of the MODIS snow cover images in hydrologic model calibration was analysed over 148 catchments in Austria. For the evaluation, the runoff and snow cover data from the period 2002-2005 was applied. A detailed description of the available hydrologic dataset and catchment boundaries is presented in Parajka et al. (2006) and Parajka and Blöschl (submitted in Journal of Hydrology).

The runoff and snow model performance measures obtained by the calibration that utilizes runoff and the MODIS snow cover images (MULTI approach) are presented in
Figure 3. Figure 3 compares the spatial patterns of MULTI model efficiencies with the usual model calibration (SINGLE approach) that constrains the hydrologic model parameters by the measured runoff only. The comparison shows that the regional distribution of the runoff ME efficiency has very similar patterns for both calibration concepts. The most noticeable differences are the snow cover efficiencies (the SE\textsubscript{O} and SE\textsubscript{U} errors), where the MULTI approach resulted in significantly improved snow model performance in comparison to the traditional SINGLE approach. The comparison of the SE\textsubscript{O} and SE\textsubscript{U} obtained by the SINGLE approach shows that the SE\textsubscript{O} errors dominate in catchments located in the central alpine part of Austria, while in most of the northern prealpine catchments the SE\textsubscript{U} errors are larger.

Figure 3. Spatial patterns of the runoff ME and the snow over- (SE\textsubscript{O}) and underestimation (SE\textsubscript{U}) errors estimated by the two different calibration concepts: the traditional calibration using runoff only (SINGLE) and the multiple-objective approach (MULTI) based on runoff and MODIS snow cover data. The multiple-objective approach utilizes the combined MODIS snow cover product in model calibration. The spatial patterns represent the efficiencies in the calibration period 2003-2005.
The added value of the MODIS snow cover images is evaluated in more detail in Figures 4 and 5. Figures 4 and 5 show the improvement in runoff and snow model performance with respect to the number of climate stations available in each catchment. The improvement in model performance is defined as the difference between runoff efficiency or snow errors obtained by the SINGLE and MULTI calibration concepts in the calibration (Figure 4) and verification (Figure 5) periods. A negative improvement implies that the model performs poorer when calibrated to MODIS data. The results indicate that the number of climate stations in a catchment provide a good indicator of the added value. In small catchments with insufficient climate observations the MODIS data are particularly useful in hydrological modelling. In these catchments, MODIS data may significantly improve the snow model performance (Figure 4, right). Interestingly, the MODIS images tend to improve also the runoff model efficiency in the verification period (Figure 5). Clearly, if in a catchment only a few ground based observations exist, the remote sensing data become relatively more important.

Figure 4. Improvement in the runoff (ME) and snow model performance (SE) with respect to the number of climate stations in a catchment. The improvement in performance is defined as the difference between the model errors obtained by the single-objective and multiple-objective calibration in the calibration period 2003-2005.
Figure 5. Improvement in the runoff (ME) with respect to the number of climate stations in a catchment. The improvement in performance is defined as the difference between the model errors obtained by the single-objective and multiple-objective calibration in the verification period 1987-1997.

4 CASE STUDY 2: VALIDATION OF A DISTRIBUTED ENERGY BASED SNOW MODEL USING MODIS SNOW COVER DATA

The main objective of the second demonstration is to show the potential of MODIS data for tuning and validation of a distributed snow melt model in regions with sparse meteorological and hydrological observations. This example shows the study that has focused on the snow water equivalent estimation in the catchments of Rax, Schneeberg and Hochschwab. Existing snow cover in these areas is a significant source of the natural water storage, which is particularly important for the water supply system of the city of Vienna. A distributed snow melt model (Blöschl et al., 1991) was calibrated and validated against a range of different sources of snow observations, including MODIS images. Two types of comparisons were performed with MODIS data. The first comparison focused on the snow cover simulated by the model as compared to MODIS snow cover in terms of its spatial statistics (i.e. per cent snow cover). This type of comparison indicates potential biases of the snow model. The second test was against MODIS snow cover patterns that assess the spatial snow variability as well as the seasonal depletion of the snow cover. Examples of both evaluations are presented in Figure 6 and 7. Figure 6 shows the percent snow covered area (SCA) of the model simulation examined against the snow covered area as derived from MODIS. To minimise the effect of cloud cover, MODIS images of only those days have been used where cloud cover was less than 60% and the percent SCA was related to the remaining cloud free pixels. The comparison indicates that SCA is simulated very well, including the depletion periods. This suggests that, overall, the model has very little bias.
Figure 6. Snow covered area simulated by the distributed snow model (line) as compared to MODIS snow covered area (dots) for days with less than 60% cloud coverage. Schneeberg/Rax domain.

Figure 7 demonstrate the testing of the snow simulations against MODIS snow cover patterns at the 500 m grid scale. The strength of the MODIS data is that daily images are available and they cover the entire domain, so the large scale spatial variability can be tested in a spatially explicit way. In this example, a sequence of three consecutive days in the Rax/Schneeberg domain during the 2004 snow melt period is presented. It is clear that the simulated patterns very closely mimic the MODIS patterns during this sequence of melt days. Results in Figure 6 and 7 indicate that the joint application of both types of evaluations enables an efficient assessment of the quality of snow model simulations.
5 DISCUSSION AND CONCLUSIONS

This study has focused on the evaluation of the potential of MODIS snow cover images for the application in hydrological modeling. Evaluation of the runoff and snow model efficiencies over 148 Austrian catchments demonstrated that the integration of MODIS data into a multiple-objective calibration framework enables a robust estimation of hydrologic model parameters (model calibration). Application of snow cover information improved remarkably the snow model efficiency of the hydrologic model. The runoff performance obtained in the calibration period was similar or only slightly poorer than obtained by calibration to runoff alone, but the MODIS snow cover data slightly improved the runoff model performance in an independent verification period. The assessment of the added value of the MODIS data indicates that they are particularly useful for improving the snow model performance in catchments with no or only a few ground based observations. These results and more general analyses (performed in Parajka
and Blöschl, submitted) of snow simulations suggest that data availability is the major factor that controls the snow model performance. The magnitude of the improvement is also likely related to the quality of the MODIS data. It is clear that with more accurate satellite data the added value in hydrologic simulations would also increase.

Application of MODIS for tuning and validating a distributed snow melt model indicates that MODIS images are particularly useful for the assessment of overall model bias and also for detailed spatial evaluation of snow cover patterns. Case studies demonstrate that especially in alpine regions with sparse observations, the remotely sensed images provide a very valuable source of information which has strong potential for operational applications.

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