Alpine Algorithms-Time Series of Innovative Remote Sensing Products for Alpine Areas: Snow Cover Leaf Area Index and Soil Moisture

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Abstract— **The derivation of bio-physical parameter time series from remote sensing data is of high importance for the monitoring and understanding of mountain ecosystems. However, their retrieval in mountain environments represents a challenging task due to the heterogeneous landscape and the topography. Already available global products may therefore present limitations in mountain areas. In this paper, innovative approaches for the derivation of snow cover, leaf area index (LAI), and soil moisture over the Alps are described, taking into account the peculiarity of the mountain areas. In order to account for the high heterogeneity, snow and leaf area index products rely on the use of 250 m spatial resolution MODIS data, in conjunction with elevation data and, in the case of soil moisture, radar data. Further, the correction of the topography on the remote sensing signal in implemented in all algorithms. Special conditions of mountain vegetation, such as snow in forests or the biophysical conditions of mountain grasslands, are also accounted for. The time series are used in conjunction in order to better understand key processes such as water and carbon cycles or vegetation phenology.**

Keywords—snow cover; leaf area index; soil moisture; MODIS; mountain ecosystems

I. Introduction

In July 2014, the Fair and Workshop on Mountain Observatories (http://mri.scnatweb.ch/en/events/fair-and-workshop-on-mountain-observatories) addressed a range of open issues regarding ecological processes in mountain environments, among them:

- *Go for the past for a better understanding of the future*: analysis of past trends enables the determination of low frequency changes (in terms of extreme events) and therefore the natural variability of the system.

- *Strong spatial heterogeneity in high mountain areas*: the task to extrapolate point data to an area was identified as an ongoing main issue. Therefore, a combination of in situ observations as "ground truth" and remote sensing techniques or reanalysis data for the second and third dimension was suggested.

- *What is changing and where*: a gap is found in the knowledge and understanding of ecosystem parameter and flux changes.

For addressing these issues, remote sensing data are a valuable source since they provide repetitive and spatially explicit information even for remote areas. For the above-mentioned monitoring of ecosystem processes, the knowledge on bio-physical parameters is of particular importance. However, the retrieval of bio-physical parameters from remote sensing data represents a challenging task especially in mountain environments. Already available products such as the MODIS snow cover (MOD/MYD10) and leaf area index (LAI) (MOD/MYD15) products are applicable worldwide but may present some limitations in mountain areas due to the heterogeneous landscape and the topography. In fact, the extreme topographic variability and the complexity of the landscape with patchy land-cover and ecosystem structures [1] make their retrieval more challenging and require specific algorithms to be developed. This paper presents innovative approaches to derive time series of bio-physical parameters, namely snow cover, LAI, and soil moisture, from medium resolution images. The exploited data are MODIS and ASAR time series. The approaches are specifically developed to take into account the peculiarity of the mountain areas in order to obtain more accurate remotely sensed products. Moreover, having long time series of tailored products for regions like the Alps allows better understanding of key processes such as water and carbon cycles or vegetation phenology.

II. Data Sets and Study Areas

The study area, which includes the whole Alpine Arc (43°-48° N / 5°-15°E), is represented in figure 1 where maps of grassland LAI and Snow Cover Duration (SCD) are illustrated. The remotely sensed images used to develop the new approaches are mainly of two types: i) MODIS Terra and Aqua surface reflectance time series from 2002 to 2015, and ii) ASAR wide swath (WS) time series from 2002 to 2012. Details on the input data for each product are listed in table 1.

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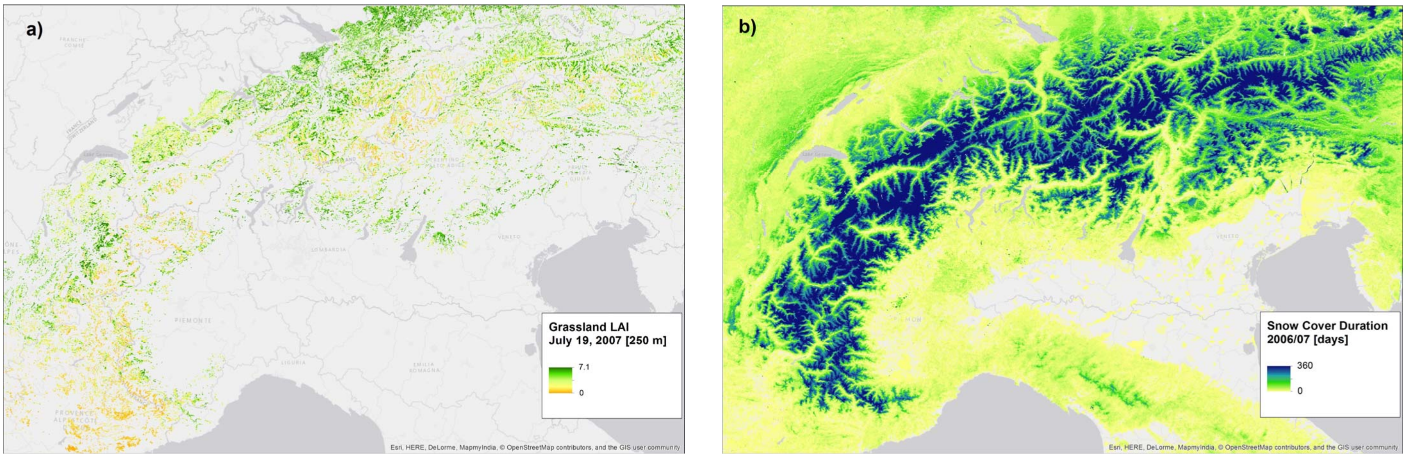

Figure 1: a) Grassland LAI for July 19, 2007, and b) SCD (in days) map for the winter season of 2006/2007 covering the Alpine Arc.

III. Methodology

A. *Snow Cover*

In contrast to the 500 m resolution MODIS snow products of NASA, the main goal was to maintain the resolution as high as possible to allow for a more accurate detection of snow covered areas (SCA). Therefore, the algorithm exploits only the 250 m resolution bands of MODIS as well as the Normalized Difference Vegetation Index (NDVI) for snow detection (band 1, 0.62–0.67 µm, band2 0.84–0.88 µm). Another relevant part of the algorithm is the development of a specific topographic correction for band 1. The detection of snow is mainly based on the decrease of NDVI in presence of snow. For the detection of snow in forest, on the other hand, a multi-temporal approach is applied where band 1 is compared to a reference image acquired during the summer period. Four different quality indices are calculated to verify the reliability of input data, snow classification, and viewing geometry. More details on the algorithm and the validation can be found in [2, 3].

B. *Grassland Leaf Area Index (LAI)*

LAI (Fig. 1a) is retrieved from MODIS Surface Reflectance (MOD/MYD09) satellite imagery with a procedure that has been specifically customized for mountain grasslands in the Alps. The main features of the proposed algorithm are: i) a higher spatial resolution (250 m) with respect to the corresponding standard MODIS product (1 km) and ii) the tuning of the model on the spectral characteristics of mountain grasslands. The algorithm relies on the Look-up table (LUT) based inversion of the radiative transfer model PROSAIL, which consists of the PROSPECT leaf optical model [4] coupled to the SAILH canopy reflectance model [5]. As input, daily red, near infrared, and oversampled blue reflectance data are used in conjunction with observation and geolocation statistics. The acquisition and illumination geometry information were corrected in order to take into account the extreme topography of the area. The daily data are merged in 4-day composites based on different quality criteria. More details on the algorithm and the related validation can be found in [6, 7].

C. *Soil Moisture*

The algorithm for soil moisture retrieval is based on an advanced machine learning regression approach, the Support Vector Regression (SVR) technique. The algorithm architecture is based on the solution proposed in [8]. Due to its flexibility, estimation accuracy and generalization capabilities, SVR is often adopted in the field of geo/bio-physical variable retrieval [9]. In this approach, ASAR WS, combined with ancillary data consisting of topographic information, land

Table 1: Overview on the remote sensing data sets used in the developed algorithms.

Product	Remote sensing data	Bands	Spatial resolution	Temporal resolution
Snow	MOD09GQ–MYD09GQ surface reflectance	1, 2	250 m	Daily
	MOD10A1-MYD10A1 cloud cover	-	500 m	Daily
LAI	MOD/MYD 09GQ/GA-LG2 surface reflectance, quality, and geometry information	1, 2, 3	250 m / 500 m / 1 km	4-day composite
	SRTM DEM	-	250 m	-
Soil moisture	ASAR	-		weekly
	MOD13Q1 NDVI	-	250 m	16-day composite
	SRTM DEM		250 m	-

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cover maps and MODIS NDVI for correcting for the presence of vegetation, is used as SVR input features. For the training of the algorithm, in situ measurements from 16 permanent monitoring stations are included as target values. To account for the discrepancy in spatial resolution between in situ point measurements and the remote sensing data, a scaling function is applied to the in situ measurements.

IV. RESULTS

A. Product validation

For the snow product, validation indicates good performance with accuracies ranging from 82% to 94% compared to 148 in situ snow depth measurements from ground stations in Central Europe, and around 93% compared to SCA derived from sixteen Landsat ETM+ images. The accuracy decreases with forest coverage and with very rugged terrain with northern exposition, while in open areas, the accuracy is the highest. More details on the algorithm validation can be found in [3].

LAI estimates were validated for both temporal consistency and accuracy using ground measurements time series collected at three permanent study sites in Tyrol. The results demonstrate the capability of the algorithm to follow the temporal and range dynamics of LAI in this challenging environment, showing an overall RMSE of 1.68 (m^2*m^{-2}). With respect to the MODIS standard product, the proposed algorithm shows the largest deviations in summer and a higher variability of LAI at the valley bottoms. For more details on the algorithm validation see [7].

For soil moisture, the algorithm performance was determined by selecting an independent test-set, which was excluded from the training phase. The algorithm is able to assess soil moisture with a relative RMSE of approximately 7%. Comparing the estimated soil moisture to the output of a model simulation, it was found that the temporal trends of both representations are in good agreement, separated only by a constant offset. Due to the continuous acquisition characteristics of remotely sensed data, it is possible to derive soil moisture with very high spatial detail, typically significantly superseding the possibilities of hydrologic modelling.

B. Derived parameters

To increase the understanding on ecosystem behavior and exploit the full time series, added-value parameters are derived from the bio-physical parameter time series. Some of them are shortly introduced below.

Snow cover duration (SCD, Fig. 1b), snow-cover start (SCS), and snow-cover melt (SCM) are derived from the daily SCA maps. For SCD, in every year from 2002 to 2014, starting from 1 October to 31 September of following year, the number of snow days is counted over each pixel of the map. For cloudy days it has been considered the classification of day before and after cloudy period and, if the classifications are different (snow before and no snow after or vice versa), it has been computed the average between two classes. Based on the 4-day composite LAI maps, the area under the curve (AUC) was calculated using a linear trapezoidal method. The AUC can serve as yearly ecosystem productivity measure as it is used e.g. for the identification of grassland usage intensities.

Additionally, 4-day 250 m NDVI time series were generated in the process of LAI estimation, from which phenological metrics such as the start (SOS), length (LOS), and end of season (EOS) are derived using the TIMESAT software [10]. For the temporal fitting, outliers are identified using a 0.5 deviation from the median. In a second step a double logistic function is applied to smooth the time series. Varying adaption strength to the upper envelope were identified for different land cover classes through manual fitting on 120 random sample pixels. The phenological metrics are then derived using an amplitude threshold procedure. The specific thresholds for the different land cover classes and the phenological parameters is thereby selected through the use of the yearly SCD information. Highest correlations of the snow cover metrics with the phenology metrics varied between land cover classes and ranges from amplitude thresholds of 0.3 to 0.5, with a tendency to higher values. The validation of these metrics is planned for summer 2015.

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