Perspectives for a European Satellite-based Snow Monitoring Strategy

White Paper

A Community White Paper

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Process

This white paper has been circulated among the European satellite snow monitoring community including scientists, data providers, satellite agencies, and end-users. It does not reflect the interests of specific agencies but refers to all agencies and decision makers to optimize available financial resources and to best serve the user community. The White Paper has been discussed at several workshops between December 2012 and February 2014 including user consultation meetings. It offers an overview on the status and gaps of satellite-based snow monitoring from research to services. This White Paper should be understood as a work in progress, updated and complemented regularly by the snow community. So far, the current status of the White Paper marks a first consolidated overview of gaps, requirements and recommendations, elaborated within the ESA DUE GlobSnow-2 project, in collaboration with service providers and experts from various agencies, institutions, and projects.

Executive Summary

The aim of this White Paper is to set out recommendations to space agencies, international and national institutions and decision makers responsible for determinations regarding strategic and financial issues. This White Paper identifies future challenges, opportunities and needs regarding satellite-based snow services and product development within European and global frameworks over the next decade.

The White Paper gives a short overview on the current status of satellite-based snow services and products. It identifies gaps in the services and products with respect to user's needs. Requirements for future R&D and snow services are presented to meet these needs. It concludes with recommendations to move forward with a satellite-based snow monitoring strategy.

The White Paper refers to ongoing programmes and initiatives with the intention of improving coordination within and between communities monitoring, developing, disseminating and implementing satellite-based snow products. The summary of current user's needs, and gaps in needs regarding satellite-based snow services and products are based on user consultation workshops, review processes within the snow community, and literature.

The White Paper identified the following needs for progress towards a Satellite-based Snow Monitoring Strategy for the benefit of the users:

- Establish a cross-continental Group on Satellite Snow Monitoring Perspectives.
- Improve the user-interaction in all product phases from development to data dissemination for a better user acceptance of satellite-based snow products.
- Perform regular product inter-comparison, validation and product assessment exercises (e.g. WMO GCW endorsed ESA SnowPEX project), coordinated with the community.
- Communicate and provide quantified product uncertainties following common definitions and establish rules and procedures in consultation with the end-users.
- Promote the timely transfer from R&D products and services into future sustainable initiatives to guarantee continuity for the end-users.
- Promote successful demonstration projects and pilot-products through various channels to exploit the improved capabilities of new EO sensors in upcoming national and international space programmes.

The White Paper provides a high-level description and identifies what should be done to better meet user's needs with upcoming new satellite infrastructure and what roles funding agencies, users and the entire community could play.

Introduction

As a major component of the water budget in many parts of the world, snow cover constitutes an important element of the cryosphere in terms of spatial extent and temporal variability. Therefore, understanding of the water cycle over terrestrial regions requires accurate observations of the snow pack. The impact of climate change and variability on this resource, including feedbacks and amplifications, can only be assessed and predicted if the coupling between the dynamic processes of snow and ice with other main components of the Earth system is quantified and modelled.

Accurate and timely information on snow parameters such as snow extent, snow depth, and snow water equivalent is also important from a socio-economic point of view, including sectors such as agriculture, management of water resources, transportation, construction, tourism, and natural hazards. Satellite instruments have proven to be essential for delivering sustained, area-wide and consistent observations of snow cover, thereby complementing other observing systems (e.g. in-situ measurement networks).

This White Paper identifies future challenges, opportunities and needs regarding satellite-based snow services and product development within European and global frameworks over the next decade. The summary of current user's needs, and gaps in satellite-based snow services and products are based on user consultation workshops and the open review process of the document. The White Paper provides a high-level description of operational snow services and the state of development of satellite snow products and examines how well user's needs are currently met. The paper identifies what should be done to better meet user's needs with new upcoming satellite infrastructure, and the role funding agencies, users, and the entire community can play.

1 Current status of Satellite Snow Services

Satellite-based snow products are generated within a large diversity of frameworks and initiatives all over the globe, demonstrating the capabilities of satellite based snow information for various societal benefit areas as well as a variety of users.

European funded projects from EUMETSAT, ESA and within EC FP7, demonstrate the excellence of satellite snow information for the benefit of governmental, public, commercial and scientific users by providing snow products for various fields of applications. Focusing on hydrological and meteorological applications, the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management Snow Monitoring (H-SAF) operates on a sustained basis (funding secured until 2022). Within the H-SAF, snow cover is monitored in near-real time in an operational manner and snow products are generated (for large-scale hydrological applications and to support Numerical Weather Prediction (NWP)). Until the end of February 2017, the H-SAF is committed to a number of operational snow products (e.g. snow detection from SEVIRI, AVHRR and snow water equivalent from SSMIS).

A broader field of application is covered by the EC FP7 CryoLand GMES Service Snow and Land Ice, running until 2015. CryoLand develops, implements and validates a standardized monitoring service for snow, glacier and lake/river ice. The project develops downstream services in a value added chain with the Copernicus/GMES Land Monitoring Service and is

set up for a potential cryospheric component of the Copernicus/GMES Land Monitoring Service. The ESA DUE GlobSnow project, completed in 2014, focused on the generation of long-term Climate Data Records (CDR) of hemispheric and global snow information from ERS-2 ATSR and ENVISAT AATSR and Passive Microwave data of SMMR, SSM/I and SSMIS. Terminated in 2013, the ESA GSE POLAR VIEW Snow Services were established to improve information for decision making and planning, by the provision of accurate, real-time information on the snow cover primarily for hydrological applications. Within Polar View, a network of service providers delivered regional satellite snow mapping products for Central Europe and Alps, Baltic Region and Scandinavia.

A large number of diverse snow products are made available through other space agencies worldwide (i.e. NASA; JAXA) including operational and research data sets for a wide variety of uses and applications.

2 Current status of Satellite Snow Products

Today, a large number of satellite-based snow products exist, with varying characteristics regarding temporal and spatial resolution, the derived geophysical parameter (snow extent, snow water equivalent, melting snow area, surface wetness, etc.), the retrieval algorithm (e.g. snow cover fraction, binary snow extent), the product provider (commercial, research) for specific applications, and the end-users (near real-time, operational, science, decision-making). The corresponding products are generated within a large diversity of frameworks and initiatives.

Current European snow services provide snow cover products (fractional and binary maps) derived from polar- and geostationary platforms using passive sensor data (e.g. MODIS, (A)ATSR(2), AVHRR, SUOMI NPP VIIRS, SEVIRI). The snow cover products extend from a regional to hemispheric scale at a spatial resolution of 500m up to around 5km. These products are derived operationally and/or near real time at a daily, weekly to monthly temporal resolution.

Microwave imagers (e.g. SSM/I) and active synthetic aperture radars (SAR) are used to generate the extent of wet snow on a spatial resolution of 100 m (e.g. CryoLand) to 10 km (e.g. H-SAF). Regarding snow water equivalent (SWE) and snow depth products, passive-microwave radiometers such as AMSRE, SSM/I, SSMIS and AMSR2 on GCOM-W1, are applied to generate daily SWE/snow depth maps of 10-25 km pixel spacing on a continental to global scale. These coarse resolution SWE products are ideally applied to climatological and hydrology applications in regions of seasonal snow cover where the sizes of drainage basins are large and topography is not complex. For small scale river basins in complex topography (e.g. Alps), equivalent products are not presently generated due to the coarse resolution of passive-microwave measurements and/or the availability of SAR measurements with suitable characteristics for SWE retrieval.

3 Overview of the User's Needs

Over the last 10 years, advances in satellite-based snow monitoring capabilities were achieved through the implementation of various projects and programmes by addressing a broad spectrum of user needs. Accurate, timely, and user friendly information regarding snow cover is needed for a large variety of users.

For example, reliable information is needed on past and future variations in snow cover to assist policy and decision makers in their efforts to define impact and adaptation activities. Long-term comprehensive satellite data sets enable the generation of "Climate Data Records" (CDR), providing a significant contribution to the Global Climate Observing System (GCOS). Hydrologists depend on assessment of water resources for strategic as well as operational planning such as water management for hydro-power and agricultural production. Radiation is the driving force for all atmospheric processes, influenced i.a. by the snow cover and an important parameter needed for planning and monitoring of solar energy systems. Natural hazard assessments and risk managements count on timely and accurate products (snowmelt) for flood forecasting and avalanche warnings. Furthermore, in meteorological and climatological modelling, observational ground- and satellite-based datasets of snow parameters are required for developing, initializing and validating the corresponding models, improving regional weather forecasting and, e.g., warnings of severe storms.

4 Gaps in Satellite Snow Services with respect to User's Needs

Various projects and programmes are running simultaneously, focussing on diverse fields of applications (e.g. global climate records, regional products for hydrology, etc.) which provide data dissemination and access mostly for a limited period of time. End-users set up their processing chain (e.g. product assimilation) with a certain reservation due to the temporary nature of current services, developed and operated for a limited time as long as the (R&D) project and programmes are running (e.g. pilot-projects).

Different users demand different data formats and access possibilities (e.g. near-real time, re-processing), and data providers sometimes disseminate products to various users and communities (e.g. NWP, climate) requiring user-specific demands and tailored standards. Hence, data providers and services are facing great challenges in fulfilling user's recommendations.

On many occasions, data processing chains and services are updated at irregular but frequent intervals, with the intention of improving data streams and services for the users. However, such updates are partially undertaken with limited contribution from end-users and documentation and communication of the update is possibly followed with a delay due to lack of time. The user then faces a change in the data dissemination process without being involved actively at an early stage. Data discovery, selection, delivery and decoding of snow data is time consuming for the end-users, depending on the required scale and time period and particularly on the user data delivery system and interface.

The vague continuity of projects and programmes and its unsecure transfer to a possible operational service might not have a clear signal to the end-user to further strengthen its adaptation of data assimilation schemes and the use of the product. With this weak basis of data and service continuity, commercial applications and economic returns of investments for service providers and users is under-realized.

5 Gaps in Satellite Snow Products with respect to User's Needs

Satellite-based snow products are becoming increasingly important for short-term hydrological, meteorological and climatological modelling as well as for the generation of long-term "Climate Data Records".

Data assimilation methods for hydrological purposes are increasingly being developed, as well as probabilistic forecasting techniques. Due to consequent changes of hydrological models from lumped to distributed, demands for satellite products with continuous spatial coverage, are growing. Regarding snow cover, the main requested parameters are: snow extent, snow water equivalent, wet/dry snow conditions, and thawing/freezing conditions. The retrieval of these parameters is challenging when using operational near-real time satellite systems over all types of terrain (e.g. mountains) at an adequate spatial and temporal resolution. So far, there is no satellite system available today, which provides high-resolution SWE information – a product often requested by various users. Nevertheless 10-20 km resolution is accepted for large river catchment monitoring. Main problems concern SWE retrieval accuracy, retrieval of SWE at melting snow conditions, and conversion from snow depth to SWE. Snow extent products based on VIS/IR sensors suffer from problems due to cloudiness and low sun elevations. Snow extent products from combined VIS and MW data are necessary to mitigate challenges from cloud cover and polar darkness, but typically require the merging of measurements with different temporal and spatial resolutions.

Accurate representation of snow cover in meso-scale Numerical Weather Prediction (NWP) models is essential for calculations of surface exchange fluxes, and subsequent forecasts of atmospheric variables. So far, the near real-time assimilation of satellite-based snow information in the snow analysis of NWPs is not that common and mostly based on visible and near-infrared data. Despite the fact that the spatial resolution is important, the temporal resolution holds more value. The key variables in the NWP snow analysis are snow extent and snow water equivalent. Observations used in NWP snow analysis are mainly derived from snow depth data from synoptic surface weather stations (SYNOP). However, the main limitation of SYNOP lies in the fact that large regions and countries have extremely low SYNOP station counts and typical SYNOP data have low representativity on large spatial scales. For data assimilation in NWP and reanalysis systems, high quality and purely satellite-based products are required at a sustainable level.

In addition to its regional to local impact, snow is expected to influence remote large-scale atmospheric modes of variability. However, most general circulation models (GCMs) still suffer from recognized deficiencies in the simulation of snow, including its impact on Earth's radiative budget, mainly due to simplified snow schemes in the GCM land models.

Observational ground- and satellite-based datasets of snow parameters are required for developing, initializing and validating models in a hydrological, meteorological, or climatological context. Moreover, long-term comprehensive satellite data sets enable the generation of CDRs providing a significant contribution to the GCOS and the WMO Regional Climate Centres (RCCs). However, the generation of thematic data sets based on Fundamental Climate Data Records (FCDRs) requires comprehensive validation of satellite based snow parameters. There is a gap in long-term homogenous and consistent over time SE and SWE data sets for the globe needed by the climate community. This gap concerns mainly the SE for the early period of satellite missions (1980) until 1995 (at least), while for later periods products exist for the northern hemisphere (e.g. ESA DUE GlobSnow).

Especially in mountainous regions, the estimation of snow parameters plays a vital role (e.g. water resource management, transport, tourism). Within such complex topography, snow

distribution and snow properties (e.g. wetness) are temporally and spatially heterogeneous , requiring high temporal and spatial resolution of satellite-derived snow products for various applications (e.g. flood forecasting). SWE as a main variable for hydrological and NWP modelling as well as for GCM inter-comparisons, could not be estimated over alpine areas by passive-microwave and/or SAR instruments in the required temporal (daily) and spatial (< 100 m) accuracy. This is a major gap for a diverse user community engaged in mountainous regions worldwide (see also the White Paper *"Towards strategic acquisition planning for the mapping of wet snow using spaceborne SAR sensors*").

6 Requirements for future R&D to meet User's needs

Future Research and Development in the context of new satellite-based snow products faces a broad spectrum of user needs. With the Copernicus/GMES Sentinel Satellite series the satellite data availability in Europe will be further improved providing access to data in near real-time for research and commercial applications. With guaranteed access to SAR and optical satellite data in near real time, improved products and services will be provided to end-users. There is a high demand from various users for high-resolution maps of SWE in mountainous terrain (in the order of 100 m), complementing in-situ SWE measurements, which are operated in reduced numbers and unevenly distributed on a global scale.

New opportunities arise for algorithm development and improved product quality (e.g. cloud cover). With the increase of satellite data, new products such as merged satellite snow products might overcome persistent challenges (fusion of polar-orbiting and geostationary data). Such multi-data products increase the product complexity for end-users to fully understand and benefit from it. As a consequence, the complexity of these multi-source products and its advantages need to be fully evaluated, communicated and demonstrated to end-users by the developers and data providers.

The quantification of uncertainties in satellite snow products is needed to understand the significance of differences in products generated from various sensors and algorithms and to understand the differences presented from validation studies using a variety of data sources (e.g. *in-situ* and high-resolution remote sensing data). Large and unexplained differences between snow products are detrimental to product credibility. It is a user need to receive an accurate error estimate along with the product distribution. At best, error estimates and uncertainties could be delivered for specific regions and land covers (e.g. mountains, higher latitudes, forested regions) to fully understand product reliability for specific regions.

The generation of thematic data sets based on FCDRs for climatological purposes (e.g. GCOS) requires comprehensive validation of satellite based snow parameters. Therefore, the systematic observations of snow variables at the ground are crucial for the development and assessment of satellite-based products. Of fundamental importance is the access to long-term data archives.

7 Requirements for future Services to meet User's needs

The high socio-economic need for accurate and timely snow products, as well as the maturity of satellite systems and retrieval techniques, turn snow products into prime candidates for future operational services, (e.g. Copernicus/GMES Service). To guarantee a sustainable operational snow service, a long-term funding strategy and operationally available satellite data are essential. The latter will be realised by the upcoming Copernicus/GMES Sentinel

Satellite series. Beside the increase of data, the number of European users is steadily growing.

In the coming decade, new Earth Observation (EO) data will be provided through European and National missions at an unprecedented scale, resolution and precision. In contrast, on-going missions and programmes come to an end with no guarantee of continuity or transfer into future initiatives. With further developments in the direction of open data policy, the demand for data and products will further increase enabling new EO applications, leading to EO based information services being further expanded through the private sector.

The dissemination of snow products to the user community through operational services relies on stable processing chains and easy data access within a user accepted or defined timeline and format. End-user activities rely on a continuous operational service and product dissemination system which requires software development, maintenance and support. A continuous extension and improvement of the data processing has to be approved by the product developers, processing operators and the end-users, documented in up-to-date user guidelines.

8 The way forward: collaborative activities

An important step within the snow community is to improve the interaction between existing cross-continental satellite snow monitoring collaborations. A global engagement is essential in satellite-based snow monitoring to develop sound and sustainable activities and to link these efforts with international bodies (e.g. WMO), initiatives (e.g. EC Copernicus, WMO Global Cryosphere Watch) and also the private sector.

A platform and mechanism of coordination for certain community-wide studies (e.g. inter-comparison studies, user surveys) should be put in place while innovative partnership mechanisms should be explored. Existing initiatives (working groups, data providers and services) should be linked in an integrated way with the user community and agencies/politics, responsible for the allocation of funding. A joined and consistent perspective will further improve the confidence in products and services.

Recommendation #1: Establish a cross-continental Group on Satellite Snow Monitoring Perspectives including various stakeholders from developers to end-users to guarantee a regular exchange of information to efficiently coordinate cross-cutting issues (e.g. inter-comparison studies).

Different users have different requirements for EO snow products (differences in snow variables, spatial and temporal scale) and services (near real-time, data access, data format). It is of great importance that these highly relevant requirements are collected, synthesised, published and updated on a regular and standardised basis within the whole community. This information should be collected through workshops, questionnaires and surveys and compiled in a consistent way. Various projects and initiatives have highlighted the importance of demonstration products and pilot services for users. To guarantee efficient allocation of resources within the product development context, a continuous and regular user-interaction is needed in all product phases (development, validation, generation/operation, dissemination). This will help for a wider employment of EO snow products to develop and to further encourage users to verify the use of satellite-based snow products for their own field of application.

Recommendation #2: User recommendations, experiences and acceptance of EO snow information should be collected systematically and regularly for a target-oriented continuous development of snow products and services. Users should be provided with updated information about the product developments and services.

With the involvement of the user community, obstacles to the broader adoption of snow products by the users should be identified and removed. Users might raise concerns particularly when snow products are generated by merging satellite-based data with other data sources (e.g. modelled data). Such multi-data products increase the product complexity for the end-users to fully understand and benefit from them. As a consequence, the complexity of these multi-source products and their advantages need to be fully evaluated, communicated and demonstrated to the end-users by the developers and data providers.

Recommendation #3: Users need support to understand the capabilities and differences of each product (e.g. EO data, modelled data, assimilated analysis) and to successfully integrate satellite snow information into their own applications.

To facilitate the use of satellite snow products for various applications and to improve acceptance of the products, regular cross-algorithm studies and data quality assessments are essential. It is absolutely essential to provide product metadata to users including data-quality flags and error bars. Community-wide inter-comparison and validation studies would support the elaboration of product and parameter definitions. Within the WMO GCW programme, such efforts are being initiated and should be considered for these activities (e.g. SnowPEX). Furthermore neighbouring communities (e.g. modelling groups) using satellite-based snow products should be involved in inter-comparison studies and vice versa (e.g. WCRP CMIP5/6).

Recommendation #4: The satellite snow community should perform regular product inter-comparison, validation and product assessment exercises, to help improve user acceptance of satellite snow products. Incorporating further communities (e.g. NWP/GCM/reanalysis) is essential to better understand product performances and requirements. The product accuracies and errors need to be communicated explicitly to Users following established rules and procedures. Common definitions of snow variables should be adopted by the satellite snow community.

Community-wide inter-comparison and validation studies rely on high-quality validation data such as ground-based snow information. Countries are urged to define comprehensive and systematic in-situ networks for snow, based on existing ground-based long-term measurement series (e.g. National Basic Climatological Network for Snow NBCN-S in Switzerland). In the framework of the WMO GCW, specific working groups are involved in the improvement of operational data exchange and data rescue (e.g. GCW-CryoNet). Such efforts further help to identify historical in-situ snow depth and SWE records at specific sites and provide quality controlled and documented in-situ measurements.

Recommendation #5: Existing in-situ networks should be strengthened, maintained, and coordinated on a national, regional and global level (e.g. GCW Snow Watch). Common reference sites in varying regions with sustained, and standardized observing programmes for snow variables should be established (e.g. GCW CryoNet). Uncertainties in the record of the measurements need to be characterised in detail and the Climate Monitoring Principles of GCOS should be fully recognized.

Continuous efforts are needed to ensure that future sensor designs take into account the requirements of the snow user community. Therefore, the consistent promotion of successful demonstration products and pilot projects and the communication by the developers, service providers, and end-users through various channels and at various levels is essential. The user community has to be involved constantly when dissemination systems of data products are developed, maintained, and updated, to guarantee stable processing chains and easy data access on the long term.

Recommendation #6: The community (developers and users) needs to promote user requirements of EO snow products in relation to future sensor capabilities to ensure that the needs and the related benefits of the community are heard and understood by national/international decision bodies.

Several projects which were developed so far under a research and development context and successfully demonstrated product benefits to users, will terminate in the near future. End-users rely on the continuity of the development and data provision of satellite-based snow products (e.g. climate monitoring, NWP, reanalysis). Cooperation among agencies and with commercial providers should be considered to establish complementarities in the observations and selected modes of operations, allowing e.g. increased revisit (e.g. SENTINEL-1 mission and RADARSAT Constellation Mission).

Recommendation #7: The community (developers, data providers and users) shall promote the need for Invitations to Tenders (ITT) and open calls for R&D projects in order to develop algorithms and methods for snow parameter retrieval, exploiting the improved imaging capabilities of new EO sensors in the upcoming programmes of national and international funding agencies.

During the last decade of development and operation, based on the investment from institutions (e.g. EC) and agencies (e.g. ESA, EUMETSAT), satellite-based snow monitoring established a durable growing confidence in products and attestable benefits in different topics. With an ongoing consolidated support of satellite snow monitoring the return of investment, in sense of science, security and also economic benefits, needs to be strengthened.