EARTH OBSERVATION AND CRYOSPHERE SCIENCE: THE WAY FORWARD

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ABSTRACT

This paper summarises the main results and conclusions of the Earth Observation for Cryosphere Science Conference organised jointly by the European Space Agency (ESA), the Climate and Cryosphere project (CliC) of the World Climate Research Programme (WCRP) and the European Geosciences Union (EGU). The meeting, hosted at the ESRIN facilities of ESA, in November 2012, involved more than 200 scientists over 30 countries and addressed the latest advances and scientific developments in the use of Earth observation technology to observe, monitor and predict the different components and processes governing the cryosphere and reviewed the related applications. This paper summarises the main results of the discussions and provides guidance for future research and the development of activities in this fascinating scientific area.

1. INTRODUCTION

The Climate and Cryosphere project (CliC) established by the World Climate Research Programme (WCRP) defines the "cryosphere" as the term collectively describing elements of the Earth system containing water in its frozen state including sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, ice shelves, permafrost, and seasonally frozen ground. The cryosphere is an integral part of the global climate system with first-order linkages and feedback mechanisms generated through its influence on surface energy and water fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. The cryosphere plays an important role in global climate, climate system response to global change, and serves as a sensitive and informative indicator of change in the climate system.

Advances in Earth Observation (EO) satellites, coupled with recent extensive international collective efforts during the International Polar Year 2007-2008 (IPY) (Jezek K. and Drinkwater, 2010) have allowed improved observations of several key parameters governing major processes in the global cryosphere (Drinkwater et al., 2011). Current satellite missions such as CryoSat-2, GRACE, GOCE, Landsat Data Continuity Mission, SMOS, RADARSAT-1 and -2, TerraSAR-X, TanDEM-X, Terra and Aqua, Cosmo-SkyMed, combined with future missions such as Sentinel-1, -2 and -3, HyspIRI, GRACE-FO, DESDynI, and historical data from ERS, ENVISAT and ICESat, offer an exciting panorama for new scientific developments and discoveries in cryospheric science. The full exploitation of this capacity by the scientific community requires coordinated research efforts to develop robust EO-based products and facilitate their integration into suitable modelling systems aimed at better characterising cryospheric processes and the interaction between the cryosphere, atmosphere and the oceans.

In this context, the European Space Agency (ESA), CliC and the European Geosciences Union (EGU) organised the Earth Observation and Cryosphere Science Conference, (which took place on the 13th-16th November 2012 at ESRIN, the ESA premises in Italy), to advance our knowledge of the potential offered by EO technology to answer some of the major open questions in cryospheric science. The specific objectives of this topical conference were:

- To assess recent progress in the full range of cryosphere-relevant EO-based observations and techniques.
- To review the major scientific advances in cryospheric science, with special attention to understanding the different cryosphere-atmosphere-oceans interactions and their impact on climate change.
- To discuss the challenges and opportunities in cryospheric science offered by the new generation of EO satellites, as well as the major observational gaps for the coming decades.
- To consolidate a scientific roadmap outlining the main priorities and challenges for the cryosphere community in terms of novel observations, enhanced EO-based products and techniques and innovative scientific results.

This paper gathers the main conclusions and recommendations from the different discussion sessions held during the conference and it presents a basis for further activities in support of the cryosphere scientific community.

2. CRYOSPHERE IN THE WATER CYCLE

Three main topics were addressed in this session: (1) snow, (2) permafrost and (3) lake and river ice. In the following these three topics are discussed in separated sections.

2.1 Snow

As a major component of the water budget in many parts of the world, snow cover constitutes the dominating element of the cryosphere in terms of spatial extent and temporal variability.

From the launch of the first remote-sensing satellites, EO data demonstrated a great potential for investigating snow properties at regional and global scales. Significant advances have been achieved in recent years using a combination of multi-platform and multi-frequency sensors.

For example, a new analysis of snow cover observed using optical and microwave satellite data shows record lows in Eurasian snow cover for June each year since 2008. The same data showed a record of low snow cover extent in North America for three of the past five years. Finally, 2012 witnessed the lowest June snow extent since satellite observations began some 45 years ago. Critically, June snow cover extent is found to be diminishing much faster than expected from climate models, and the rate of annual decrease in area exceeds that of the summertime minimum in Arctic sea ice. These results, published in Derksen and Brown (2012) and Derksen et al. (2012) are based on snow chart data from the US National Oceanic and Atmospheric Administration (NOAA). They are consistent with indications of a decline in monthly-average snow mass published last year (Klehmet, et al., 2012) as part of ESA's GlobSnow project (Metsämäki, et al., 2012). GlobSnow, which also uses a combination of optical and microwave data (supported by weather station-based observations), has produced a long time-series of snow water equivalent (SWE) from 1979 to 2012 (in millimetres) (Takala et al., 2012), as well as a time-series of snow cover extent from 1995 to 2012. Results obtained indicate that the maximum snow mass at the end of winter is slowly reducing across the Northern Hemisphere, while spring snow is melting significantly earlier, particularly at high latitudes. The continuation of these studies and additional research are recommended for future years in order to enhance current methods for estimating SWE estimation and to monitor snow processes with a view of providing useful feedback to climate modellers.

Besides the GlobSnow project, investigations into SWE at global scale using active and passive multi-frequency microwave data, together with the development of electromagnetic models capable of interpreting this data, have provided significant improvements over the last decades. Moreover it is widely recognized that there is a need to establish a consolidated relationship between snow grain size measured in the field and the quantity (effective grain radius, correlation length, etc.) used in the models. In this context, the availability of measurements such as those proposed by CoReH_2O (Rott et al., 2000) may provide a significant improvement in this area of research.

These developments cannot be achieved without suitable complimentary in-situ data collection campaigns. For this reason there is a need to formulate guidelines and protocols for accurate and repeatable methods of measuring in-situ snow characteristics (e.g., following the work in Fierz et al., 2009). This may allow the creation of a common international platform for snow properties measured by in-situ data collection and their links with satellite observations.

The continued production of unified, consistent time series maps of snow/ice or land surface temperature is recommended to complement the time series of surface skin temperature and broadband albedo (e.g., from NOAA AVHRR that extends back to the early 1980s). As demonstrated by the ESA's STSE SnowRadiance project (Negi and Kokhanovsky, 2011; Kokhanovsky et al., 2011), ESA's Sentinel-3 will offer good prospects for developing a unified surface temperature product which (a) distinguishes between cloud/snow-ice surfaces and (b) applies different coefficients for land surface temperatures (where there is no snow or cloud), cloud top temperatures (where there is cloud) and snow/ice surface temperatures (for snow on land or ice sheets, or sea ice in the ocean).

Despite the fact that the energy available from melt comes primarily from the net solar radiation and depends on snow and ice albedo, the global community does not know enough on the spatial and temporal variation (especially in presence of dust, soot, or other pollutants) in snow albedo, all the way from surface albedo in glacier systems to the albedo of polar sea ice. For glaciers, though rather constant in time, albedo may range spatially from 0.9 to 0.1 with vast associated changes in melt rates and implications for exposure of glacier ice and glacier mass balance. Likewise, regional water cycles are acutely responsive to these changes in albedo and resultant fluxes of melt water to rivers. In the polar regions, snow albedo and the forcings of albedo remain largely untreated despite their critical role in modulating the melt and phase changes (that is, for example, their central role in the last decade's plunge in Arctic sea ice cover). For example, among the tens of variables measured in the NASA IceBridge project, albedo is not included.

In addition, light absorbing impurities such as black and brown carbon from industrial sources and mineral dust from natural and disturbed lowland surfaces can have first order impacts on snowmelt, in some regions far exceeding extant and projected atmopsheric warming. The NASA Jet Propulsion Laboratory has leveraged existing spaceborne sensors such as MODIS to give us access to global semi-quantitative retrievals of radiative forcing by dust and carbonaceous particles in snow and airborne imaging spectrometers for quantitative retrievals of radiative forcing (Painter et al., 2012). In addition to the capability to quantitatively retrieve radiative forcing, the imaging spectrometer also captures radiation across the spectrum allowing a more direct path to quantitative spectral albedo and broadband albedo.

Given the central nature of modulation of snow albedo in the cryosphere, and in turn its role in the global climate, it is strongly recommended that airborne imaging spectrometer programs are expanded and spaceborne imaging spectrometers with pointing capabilities be expedited to understand current radiative forcings and responses to regional increases in emissions (e.g. China's increase in coal-fire power plants) and mitigation efforts (e.g. the US Department of State call for reduction in short-lived pollutants). Additionally, missions such as the NASA Decadal Survey Hyperspectral Infrared Imager (HyspIRI) will provide temporally dense retrievals over polar sea ice and ice sheets, offering significantly enhanced knowledge of snow and ice spectral albedo with critical constraints for mesoscale and global climate and water cycle modelling.

Activities for integrating snow information derived from EO data in hydrological models are currently in progress and there is a lot of interest in this information from the scientific and user communities. This should be further encouraged.

Several presentations highlighted that future planned missions (e.g. Sentinel-1 and 2) will significantly contribute towards snow research, however these missions will not be able to solve all the problems (i.e. generation of daily global snow cover maps or the quantification of SWE at high resolution scale). Development of new dedicated missions are recommended, such as the proposed Earth Explorer CoReH_2O mission, which includes a multi-frequency SAR system, together with the development of multi-sensor approaches.

Several presentations underlined the need for new experimental activities using airborne and satellite data together with detailed ground snow measurements. This will lead to a better understanding of snow processes, thus enabling their effective integration into hydrological models. Validation and development of snow retrieval algorithms will also benefit from extended possibilities of data intercomparison.

2.2. Permafrost

Permafrost has been recognised as one of the Global Climate Observing System's (GCOS) Essential Climate Variables (ECV's). Field observations prove that the active layer and permafrost are already undergoing changes (Smith et al., 2010) with further influences on the hydrology, carbon budget, Arctic landscapes and biodiversity and the human infrastructure in the Arctic, Subarctic and mountain regions. The modelling and monitoring of permafrost is strongly hampered by sparse field data. In its strict sense, permafrost is a sub-surface thermal phenomenon that cannot be directly observed by remote sensing. However, there are a number of surface indicators and new developments (e.g., SMOS based retrievals of the evolution of seasonal freezing depth within the active layer; Rautiainen et al., 2012) that can be monitored by remote sensing means.

Local indicators include thermokarst lake dynamics, thermo-erosional events and surface elevation changes (frost heave and subsidence). These phenomena need to be observed on a local scale with high spatial and temporal resolution. High spatial resolution and free or low-priced EO data are required for this purpose. Specifically, the capacity to consistently monitor coastal and cliff erosion over large areas and subsidence associated with thaw settlement of the active layer and other hydrologic changes is urgently required.

Surface moisture, freeze/thaw, the soil water and ice content, snow cover and snow water equivalent are crucial parameters for thermal dynamics and are also critical to validate hydrological, ecological and climatic models. The freeze/thaw cycle together with the moisture and temperature regimes determine the fluxes of heat, water and greenhouse gases.

Regional to circumpolar monitoring requires the use of permafrost models and permafrost modules in climate models. Relevant satellite-observable parameters are geophysical surface products such as Land Surface Temperature (LST), Surface Soil Moisture (SSM), Frozen/non frozen ground, snow extent, SWE, and bio-physical vegetation parameters. If these geo-biophysical remote sensing products are also reliable for their scientific use in high-latitude landscape they can then be utilized to monitor permafrost landscape, to produce regional maps of current permafrost conditions and to develop and validate models. Therefore, the evaluation of all available and future geophysical and biophysical remote sensing products relevant for permafrost and carbon cycle research has high priority for the polar regions. Permafrost landscapes are a challenge for qualitative and quantitative remote sensing due to high heterogeneity, patterned ground, disturbances, abundance of small-sized water bodies, and sharp moisture gradients.

The ESA DUE Permafrost project (Soliman et al., 2012; Bartsch et al., 2012; Urban et al., 2009) established a permafrost-related monitoring system based on a first set of circumpolar and regional EO satellites: LST, SSM, frozen / un-frozen ground, terrain parameters, land cover, and surface waters. Climate and permafrost modellers as well as field investigators, including the International Permafrost Association (IPA), are associated users. The IPA supports the Global Terrestrial Network for Permafrost (GTN-P) responsible for the standardized collection, and dissemination of permafrost-related observations. The IPA and GTN-P also act as ad-hoc advisors to the science community and policy-makers and plan to work actively towards the integration of EO data.

Long-term multi-sensor monitoring sites for evaluation of remote sensing observations and products are needed (e.g., at locations of maximal coastal erosion, lake and hydrological changes and subsidence). However, it is recognised that the set-up of the field measurements needs to be applicable for a wide range of user communities: e.g., heterogeneous in-situ measurement grids are needed for evaluating models vs. homogeneous in-situ measurement grids that are needed for evaluating remote sensing observations.

Hands-on user workshops are needed with data, products and processing software to facilitate information flow from the EO community to the permafrost user community.

2.3. Lake and River Ice

Lake ice represents an important variable for numerical weather prediction and climate research and it governs the heat transfer between the lake and the atmosphere. This is of critical importance in several regions of the world where lakes cover a significant portion of the landscape, hence impacting weather and climate variability.

Knowledge of river ice is also critical, especially for hydrology and flood prevention systems in high latitudes. In particular, ice jams represent a significant risk for populations in many regions of the world.

Different automated approaches have been developed from scatterometer and passive microwave data (e.g., AMSR-E) to derive lake ice concentration, ice extent and ice phenology information. Whilst these data sets provide only coarse spatial resolution data (i.e. tens of kilometres or greater) they have the significant advantage of providing high temporal (daily) resolution repeat coverage and decadal records for the largest lakes in the Northern Hemisphere. By contrast, SAR data may provide higher spatial resolution (tens to hundreds of metres) for the interval dating back to the early 1990s, but existing automated approaches (mainly based on image segmentation algorithms) though promising, rely on labelling strategies which currently require the intervention of an interpreter/analyst.

Some operational products for lake and river ice do exist. For instance, the operational Canadian Ice Service (CIS) weekly product is suitable for weather forecasting requirements but not for climate monitoring. Additionally, the operational Interactive Multisensor Snow and Ice Mapping System (IMS) product (4 km), from the NOAA/NESDIS/OSDPD/SSD National Snow and Ice Data Center (Duguay et al., 2012), is suitable for climate monitoring but spatial resolution limits its use to the largest lakes. A MODIS 500 m optical snow product over lakes exists (Brown and Duguay, 2012) but is limited due to cloud cover and winter darkness. These products also have yet to be fully validated for lakes.

In the context of lakes and river ice, all-weather, year-round, daily multi-frequency/-polarization SAR data at 10-100 m spatial resolution would fulfil most requirements including the need to monitor lakes of all sizes – particularly throughout the winter months. Suitable techniques, including automatic but robust strategies for labelling need to be further developed and validated.

There is a recognised need to intensify the development of lake ice products for data assimilation into numerical weather prediction (NWP) models, including the timing of lake ice formation and disappearance, and ice thickness. Similar efforts are needed to make a critical assessment of lake ice models used as parameterization schemes in NWP and Regional Climate Models (RCMs) (e.g., ESA's STSE NorthHydrology project in Yang and Fernández-Prieto, 2009; World Weather Research Programme's Polar Prediction Project in URL PPP in the Reference Section).

Finally, there is a need to better identify river ice parameters (e.g., ice coverage, ice duration) required for investigating freshwater outflow into the Arctic Ocean. Questions remain about where this information must be obtained along the rivers (e.g., entire river or estuary alone), and what are the remote sensing requirements (sensors, geographical coverage, spatial and temporal resolutions) to effectively monitor these parameters.

A lake ice thickness retrieval algorithm has been developed from passive microwave data (AMSR-E), which provides the necessary high temporal (daily) resolution but the spatial resolution is too coarse for all but the largest lakes of the Northern Hemisphere. It also needs to be further evaluated on lakes other than Great Bear Lake and Great Slave Lake. Also in this case, multi-frequency SAR data remains to be evaluated to estimate ice thickness as variation of ice types present a challenge.

So far, no on-ice snow depth algorithm has been developed, though interferometric products demonstrate some promise in this regard. The potential of radar altimeter data (e.g. CryoSat-2 and follow-on missions) need to be examined whilst future dual frequency SAR satellites such as the proposed mission CoReH$_2$O, or combinations of SAR and passive microwave may be best suited for this purpose. There is an urgent need to create an exhaustive list of existing *in-situ* river ice observational sites for the validation of EO-based algorithms.

Results from recent analysis of the historical SAR data archives reveal that temporal variations of floating and grounded ice in shallow lakes represent an important proxy index of Northern Hemisphere climate change (see the results of ESA's STSE NorthHydrology project in Surdu et al., 2013). An approach to map grounded versus floating lake ice has been developed and successfully applied using C-band SAR data from ERS-1/-2 (VV-pol). It has also been shown to work with RADARSAT ScanSAR and ASAR Wide-Swath (HH-pol) data (Strip-Map mode represents a promising tool for this application). The continuity of same SAR configuration data sets is needed to secure long-term monitoring in lake-rich coastal regions of the Arctic. Meanwhile, Sentinel-1 and the recently approved RADARSAT Constellation Mission offer prospects to extend this important climate record.

Due to its climate relevance, lake ice phenology (freeze-up/break-up dates and ice cover duration) should be proposed for inclusion as part of the list of Global Climate Observing System (GCOS) Essential Climate Variables (ECVs) for lakes in the cryosphere context. Meanwhile, in order to further support validation efforts, there is the recognised need to establish lake *SuperSites* for algorithm development and validation and for long-term monitoring. Downscaling of future climate scenario calculations for estimation of regional to local climate change impacts are also in need of high spatial-temporal resolution lake ice data. The Sentinel series may provide a unique piece of information to cover this need in the near future.

3. ICE SHEETS

This session was opened by the presentation of the ESA-NASA Ice Sheet Mass Balance Intercomparison Exercise (IMBIE), which produced the first consistent assessment of ice losses from Antarctica and Greenland to date and reconciled apparent differences between published estimates (Shepherd et al, 2012). This study found that mass imbalance of the Antarctic and Greenland ice sheets has contributed 11.1 mm to global sea levels since 1992. This amounts to about 20% of all sea-level rise over the survey period. About two thirds of the ice loss was from Greenland and the remainder from Antarctica. In addition, the ice sheet contribution to sea level rise has increased over time and it is now 3 times what it was in 1990's.

Through IMBIE, 47 experts collaborated to use observations from 10 different satellite missions to reconcile the differences among numerous earlier ice-sheet studies and to produce the first consistent measurement of Polar ice sheet mass changes closing several years of scientific debate. A further achievement of IMBIE was to demonstrate that the three different geodetic EO techniques for mass balance estimation in principle agree.

An important shortcoming of satellite remote sensing for determining the mass balance of ice sheets are the data gaps in the time series of observations of critical parameters (e.g., elevation/volume and mass changes, ice flow velocities, albedo changes, ice sheet facies, etc.). This problem can be attenuated in some cases if different satellite missions are used in a synergistic manner. The IMBIE study supports the importance of ensuring that long-term data records are preserved since it was demonstrated that short-term records of mass balance are not reliable. Examples of these gaps include the seven-year gap between ICESat-1 and ICESat-2, the SAR data gap between Envisat ASAR and Sentinel-1 and ALOS PALSAR-1 and 2, the even larger gap in interferometrically viable datasets over ice surfaces, and the gap between GRACE and a GRACE-follow on mission. It is important to note that geographical data gaps also exist, for example at the Antarctic Peninsula (AP) and coastal southeast Greenland. In this context, space agencies must build on the success of past long-term, inter agency coordination, such as the IPY Polar Space Task Group (PSTG) (see URL PSTG in the Reference Section), by contributing to improve data acquisition strategies and underlying rationale for successive satellite missions in order to achieve continuity in fundamental climate data records.

In terms of the current data gaps, it is worth mentioning that the AP is likely to always be a problem for GRACE measurements as its area is too small, and the application of the Input-Output method (IOM) is also a challenge here due to the many small glaciers with thickness that are poorly known and steep climate gradients. Consequently, altimetry techniques (e.g., CryoSat SARIn) in synergy with high resolution DEMs (e.g., by single pass InSAR such as TanDEM-X) are likely the best option in this region.

A continuous working interaction with the scientific community is essential to ensure the key scientific goals are addressed. Planning longer operational lifetimes for EO satellite missions will also help achieve this goal as longer missions are more suitable for addressing change on decadal climate timescales. Satellite missions should be designed for lifetimes of 5 or more years (e.g. the 10-year operation of Envisat and MODIS on Terra and Aqua), avoiding short, (e.g., 3-year), lifetime missions.

In the future, the entire Greenland and Antarctic ice sheets need to be monitored for mass changes in response to surface mass balance and dynamic forcing at the ice sheet scale (the ESA's CCI project is currently supporting this effort over Greenland). In order to observe change in ice flow dynamics, ice sheet monitoring requires viable data to use interferometry and feature tracking techniques.

Velocities of outlet glaciers can be strategically sampled and selected glaciers should be monitored with high temporal resolution (e.g. for seasonal accelerations or slowdown). Nevertheless, the combination of ice-sheet scale monitoring of several key (ice sheet) parameters with more tactical or strategic monitoring of "hot spots or cold spots" requires interagency cooperation, and coordination of observations from a broad array of different satellites and sensors.

Gravity missions represent a significant development of our capabilities in respect to direct measurement of ice sheet scale changes since they provide comprehensive measurements of net large-scale mass changes in glacierised regions without the need to resolve individual glaciers and ice caps. However, significant work is still needed with respect to the contribution of glacial isostatic adjustment (GIA) to the resulting gravitational signal, and in order to further narrow down the range of residual uncertainty in absolute ice-sheet mass changes.

For regional-scale mass balance determinations, a gravity-based system with the highest spatial resolution achievable is needed. The GRACE mission has shown the very high value of this approach to tracking ice mass balance and hydrologic activity generally, but means to improve the resolution must be sought. This might be achieved by unique polar-elliptical orbits (for missions dedicated to polar ice alone) or by combining the gravity system with other sensors in the identical orbit (e.g. altimetry, InSAR, or stereo-image VIS-NIR).

Laser altimetry missions (ICESat-1 and ICESat-2) also contribute to measuring mass changes on glaciers and ice caps with high resolution. Like all altimetry measurements, corrections must be applied for firn densification processes to convert volume change to mass change. Meanwhile, detailed comparisons between laser and radar data will allow biases between the respective datasets to be calculated.

Radar altimeters today represent the primary long-term source of all-weather ice-sheet elevation information dating back to 1991. In this context, more emphasis needs to be placed on making validated CryoSat-2 Level-2 data products available to the community in a timely manner, such that the experience of the ice sheet altimeter community can be brought to bear on the scientific analyses. Adequate resources need to be allocated for implementation and revision of data-product algorithms and data reprocessing as lessons learnt from analysis of first-of-a-kind data (SARIn mode) are incorporated.

As an accompaniment to the continued use of radar-altimeter data there is a critical need to further develop reliable "backscatter corrections" for the variable (seasonal and inter-annual) penetration depth of radar altimetry (e.g., Envisat, CryoSat). This includes examination of the results from various retracking methods to determine the best approach. Studies of backscatter and penetration depth in Envisat radar altimetry data suggest that a strong relation between polarized signal and satellite direction relative to surface slope, and aligned surface structures. One suggestion is that this anisotropy may be minimized by investigating future technical solutions for acquiring circular-polarized transmission and linearly polarized signal reception, which should be evaluated for the future generation of radar altimeters.

Also important is the further development of repeat-track algorithms for the retrieval of elevation change. The CCI Ice Sheets round-robin exercise (www.esa-icesheets-cci.org) showed that repeat-track algorithms are able to measure change much closer to the ice sheet margin than crossover methods. The development of an "optimal" combination of cross-over and repeat-track measurements should be further explored.

Interferometric SAR (InSAR) is recognised as an optimal method (together with image correlation techniques) for precision ice-velocity mapping. Systematic mapping is needed with complete ice-sheet coverage at least twice a year with a minimum of 4 consecutive cycles each time to be able to monitor the impact of changes in surface mass balance on flow adjustment. It is important to note that three consecutive cycles are needed for grounding line mapping and one additional cycle is required to circumvent data gaps. Single-frequency datasets are considered adequate, although longer wavelengths are demonstrated to be more robust to minimise decorrelation effects. Fast-moving glaciers at the coast may require more rapid sampling to study (sub-annual) fluctuations.

In addition, InSAR represents a key technique to monitor grounding line retreat on the ice sheets (differential InSAR is used to remove the contribution of terrain elevation and ice flow in the coherent phase signal). In this context, suitable ice-sheet-scale coverage of Greenland and Antarctica is required, with combinations of image acquisitions from Sentinel-1 (and potentially other future SAR sensors such as RADARSAT Constellation Mission or ALOS2) in order to acquire SAR image pairs with a sufficiently short temporal and spatial baseline to maintain image coherence.

In particular, for Sentinel-1 a combination of Interferometric Wide Swath (IWS) and high resolution Strip-Map (SM) mode will be required for fast glaciers. The higher spatial resolution of Sentinel-1's SM mode is essential and needs to be frequent to capture all rapid changes. This need can be also potentially fulfilled by exploiting Sentinel-1 in conjunction with other satellite systems such as TanDEM-X, Cosmo-SkyMED and RADARSAT Constellation Mission (RCM).

Key regions, such as the West Antarctic Ice Sheet (WAIS) and Pine Island/Thwaites Glacier complexes present the greatest possibility for a substantial sea-level rise contribution in the medium term. Despite this fact, it is important to note that Greenland is likely to be the most important region for mass balance change in the coming century with regards to the current ice sheet component of sea-level rise.

In addition, even though the East Antarctic Ice Sheet (EAIS) is generally considered to be relatively stable dynamically, recent findings demonstrate a complex interaction of its outlet glaciers with the ocean, with direct relationships between impact of warming, basal melt rates and grounding line recession, and thus the potential destabilising impact of warming Antarctic deep water warrants continuous monitoring of these regions.

Obtaining a better understanding of the complex melting and basal hydrological processes below ice sheets, which affect ice-flow velocities, is needed to enhance our models for future predictions.

With respect to ice sheets in general, there is a need for novel techniques and services:

- With respect to mass balance estimates, there is a need of additional efforts in order to enhance the current limited knowledge of snow accumulation and the impact of firn processes.
- EO techniques to aid improved process modelling and surface mass balance studies are desirable (e.g. near surface stratigraphy). In fact, surface mass balance is really the largest remaining challenge for mass balance estimates from all EO techniques. It is not obvious whether this can be addressed only via EO (though there are some examples), but nevertheless it ought to be considered as an essential issue for the future.
- EO techniques and services for early detection of the following processes are highly desirable; grounding line retreat, accelerated glacier flow, ice shelf collapse, major calving, and others.

In addition, it is recognized the development of new products and services requires ancillary in-situ data (e.g. automatic weather stations, ice thickness, accumulation records, rock uplift, etc). Similarly, validation activities and independent measurements are still required to ensure the quality of the EO based products (e.g. radar altimeter backscatter corrections, etc) and to characterize the magnitude of the residual uncertainties.

4. ICE SHELVES

In the last years, EO has demonstrated a significant potential to improve our understanding of the role of ice shelves in maintenance of the stability of grounded ice. Satellite observations provide information for quantifying ice-shelf mass balance and its components, and ice shelf disintegration events (e.g. Larsen, Wilkins) which have demonstrably contributed to the destabilisation of inland ice, with resulting acceleration of the corresponding outlet glaciers.

Altimetry is essential to providing many of the required details. For ice shelves, CryoSat-2 is an excellent tool. A laser altimeter mission is currently lacking, but ICESat-2 is planned to be launched in 2016 (ICESat-1 ended in 2009). For surface mass balance of ice shelves, a precise satellite approach for reliable measurements of snow accumulation (Dierking et la, 2012) is still being sought and this would be a good objective for future missions.

High resolution repeat pass SAR and optical images (applying InSAR and/or image correlation techniques) are essential for monitoring the ice exported from grounded glaciers to ice shelves. SAR images offer the advantage of regular and frequent repeat observations, thus enabling detection of early changes and fluctuations of inflow to ice shelves in response to changing boundary conditions (e.g. surface mass balance, increased surface/basal melt, etc.). InSAR is also needed to map the grounding line position of ice shelves and how it fluctuates with time, with time scales ranging from the diurnal tidal cycle to decadal.

Looking at the future, improving predictions of the rates of glacier or ice stream acceleration when there are increases in basal melting or climate-driven loss of ice shelves, is a key outstanding scientific question. Additionally, monitoring the development of rifts, and mapping and tracking changes in the seasonal surface melting and melt ponding of ice shelves is important for forecasting their future stability or break up. Satellite-based altimetry (radar and laser) and ice velocity (via SAR and Vis-NIR image-based tracking) measurements contribute strongly to assessment of the first point; while measurements from active and passive satellite microwave sensors support the second.

Another important open issue for some of the Antarctic ice shelves is still the precise quantification of ice loss due to calving, in particular if the ice loss is dominated by regular and periodic calving events, as opposed to sporadic large-scale calving, or ice shelf collapse and disintegration as observed at the Larsen and Wilkins Ice Shelves. To solve this issue, regular repeat observations of ice shelf margins, shelf frontal height, and accurate modelling of firn density are needed.

In order to address these challenges and advance our knowledge of ice/ocean interactions and the role of ocean circulation for ice shelf melt rates, mass balance and stability, InSAR in combination with altimetry (dh/dt) and ice thickness is essential. These EO techniques must be augmented with in situ observations of the ocean, thermal and passive microwave observations of ocean surface temperature and surface salinity (respectively), and also with SAR observations of sea ice extent, ice type and coastal polynyas. In the case of tidewater glaciers, where ice-ocean interactions take place along the vertical face of the glacier, new techniques need to be developed to detect ice-ocean interactions.

For ice shelf calving, retreat and disintegration processes, high-resolution imaging (using both InSAR and Vis-NIR systems and high-precision altimetry) again represents a key observation requirement. Of particular interest are observations by repeat-pass SAR sensors (applying the InSAR technique) that enable mapping of vertical and horizontal deformation and quantification and monitoring of the onset and progression of fracturing. This enables the detection of possible precursors to ice-shelf disintegration, as witnessed on the Larsen Ice Shelf using ERS and the Wilkins Ice Shelf using Envisat, TerraSAR-X and Cosmo-SkyMED during IPY 2007-2009.

The coming Sentinel missions will extend current capacities to study and monitor ice-shelf processes. At the Sentinel for Science Workshop, held at ESRIN in March 2011, the scientific community stressed the great opportunity of the Sentinel-1, -2 and -3 missions for advancing cryosphere research, within which studies of ice shelves are a challenging part of this research theme. Of particular interest is the comprehensive coverage (spatial coverage, revisit capability, overall mission duration) of the Sentinel satellite series. For observations of ice sheets and ice shelves the SAR of Sentinel-1 and the altimeter and medium resolution optical imagers of Sentinel-3 have the potential for complete and frequent repeat coverage, complemented by high resolution multi-spectral optical images from Sentinel-2 for studies at regional scale (with the above mentioned limits in geographic coverage). For observation of surface motion and deformation on ice streams, and in grounding zones of ice shelves, the SAR experts stressed the large interest in using Sentinel-1 Strip-Map mode, although the use of this mode, instead of the Interferometric Wide Swath Mode, would render more problematic the regular coverage of large areas.

While much can be done from space, it is important to note that the space component inherently requires ground- and airborne-based sensors to fully understand processes and validate that measurements are accurate and un-biased. Good, extensive cal-val efforts exist as a part of any modern satellite mission, and frequent field expeditions are also planned and should be robustly supported by ESA and NASA in discussions of national budgets for logistical infrastructure. However, a key and growing gap in observations is the limited ground-based network of sensors for monitoring processes. In particular, a new effort should be initiated to build a strong network of advanced polar in-situ multi-sensor observation systems, including measurements of weather, GPS, accumulation, sub-ice and near-ice ocean properties and circulation, and surface energy balance.

5. GLACIERS AND ICE CAPS

Understanding glaciers and ice caps as integral parts of the climate system is a major scientific challenge where EO technology will play a key role. In this context, the collaboration and dialogue between the observation and modelling communities needs to be encouraged. Dedicated workshops would facilitate and foster that dialogue and also help to consolidate and elaborate the data requirements for modellers (e.g. requiring gridded fields with error assessment).

In recent years, significant progress has been made on the use of satellite data to monitor and to understand glaciers and ice caps. However, there is still a need for additional effort to fully understand and exploit all currently available EO data, especially new relevant missions such as CryoSat-2 and third party mission resources. In this context, it is recommended that ESA dedicates more resources to the exploitation phase of the ESA missions for science and development.

The Global Land Ice Measurements initiative from Space (GLIMS) initiative (Raup et al., 2007) has compiled digital glacier outlines and related metadata for the majority of the world's glaciers (e.g. Kargel et al., in press). However, the workload required to manually delineate debris-covered glaciers and the limited funding available for such activities precludes the production of a complete global dataset. For the fifth Assessment Report (AR5) of the IPCC a special effort was taken by the community to close the missing data gaps of the GLIMS database using cost-efficient methods (automated mapping from optical satellite data) and taking a locally reduced accuracy into account. The final dataset of glacier outlines was published as the Randolph Glacier Inventory (RGI) and is available from glims.org/RGI. A related technical document (Arendt et al., 2012) provides details to all datasets and its contributors. The recent development of the MODIS Permanent Ice (MODICE) annually-resolved product addresses what has been a missing element for the global cryosphere community, a single systematically derived base map of the Earth's glaciers and annual minimum snow cover. A first promising study on the potential of MODICE was published by Painter et al. (2012). It is important that this record continues with MODIS data and into VIIRS, Sentinel, and optical sensors beyond.

In terms of data availability and data needs, some important gaps exist such as the 7-year gap of ICESat-2 or the lost Landsat-5 for glacier mapping both have an important impact on our observation capacity. However, with the successful launch and deployment of the Landsat Data Continuity Mission, this data path has been restored. In this context, the effort of the IPY to collect DEM's over the cryosphere using SPOT SPIRIT (as part of the contribution to the GeoDyn IPY project), the availability of Pleiades data together with the continuity of ASTER are useful elements to fill the gap in elevation measurements. In addition, it is worth mentioning that NASA's Operation ICEBridge is monitoring key regions of interest to bridge the gap between ICESat1 and 2. It should be noted however that funding airborne campaigns such as ICEBridge to avoid data gaps in the long data time series is an expensive solution, which may not provide the required spatial coverage. On the other hand, such airborne campaigns also provide data that could not be acquired with spaceborne observations (e.g., ice thickness). In the long term, it may indeed be much more cost effective to plan for mission continuity of key EO datasets to ensure sufficient monitoring capacity in the future.

In respect to Sentinel-2, it was remarked that data would not be acquired on a global scale owing to the mission requirements specifying the GMES service need for coverage of all land areas between 56^o South latitude (tip of Cape Horn in South America) and 84^o North latitude (northern Greenland) including major islands (greater than 100 km^2 in size), EU islands and all other small islands located less than 20 km from the coastline. It was noted that this restriction currently affects the use of the Sentinel-2 mission for cryosphere (e.g. glacier/ice cap) applications (in particular south of 56^o S), and that scientific needs must be correctly accounted for, particularly in relation to seasonal imaging applications in high latitude regions beyond these geographic limits.

Glacier area and volume changes are well satisfied by existing EO techniques, but not with enough data. There is presently need for observation time allocated to glaciers and acquisitions need to be ensured.

For the future, satellite missions similar to TanDEM-X will be needed to provide high-resolution DEM's on intervals of approximately every 5 years. In this context, it is important to note that provision of free and open access for scientists to commercial DEM products such as the SPOT SPIRIT data has proven to be of great scientific value. Continuing to facilitate access to new DEM datasets (e.g., TanDEM-X) is equally important as it enables new scientific techniques to be applied, such as DEM differencing to determine surface elevation changes. It is recommended to promote joint Announcements of Opportunities (AO's) from different space agencies, facilitating the access to different data types such as TanDEM-X and Cosmo-SkyMed.

Also, looking into the future, exploration of dedicated mission concepts that address the current gaps in observations is required. For example, optical stereo measurements combining laser and passive optical are essential. Also, the development of a suitable sensor that tracks accumulation/snowfall over glaciers and ice caps as well as ice sheets is be needed but not currently available.

It is worth noting that EO data alone cannot solve all observation needs. Ground measurements are essential not only to validate them but also to understand the data and governing processes. In this context, a platform for the science community (e.g. UAVs) to bridge between field observations and satellite data, including small sensor development would be highly useful.

6. SEA ICE

CryoSat-2 has already demonstrated a great potential for sea ice applications (Laxon et al, 2013). Promising results based on level 1 data have been presented. The use of level 2 data needs some further correction and investigation.

Other new sensors such as SMOS have also demonstrated promising capabilities for sea ice studies (e.g., STSE SMOS Ice project). In particular, a novel methodology to retrieve thin sea ice thickness from SMOS has been presented (Kaleschke et al., 2012). Also, a preliminary validation with IceBridge data showed that the SMOS brightness temperature has the potential to deliver information about snow thickness on thick sea ice. This potential should be further investigated. MODIS data has also been used in this context as seen in poster presentations at the Frascati conference.

In terms of the potential offered by SAR systems for automatic operational (sea ice thickness) classification, further effort needs to be dedicated to develop and validate robust techniques for use by operational ice services. A major issue inhibiting Antarctic sea ice thickness retrieval is the unknown distribution of flooded and meteoric ice. This poses difficulties in the derivation and validation of the Antarctic sea ice thickness. Currently there exists no mature and validated Antarctic sea ice thickness product (at least we are far behind what is known for the Arctic). More information about ice type, flooding, and snow cover, potentially derived from multiple frequency SAR data, could help close the knowledge gap here.

There are promising developments in this direction (Moen et al., 2013), and the automatic methods for segmentation and later classification of sea ice can also be used for other purposes than operational issues; for example for monitoring and quantifying the sea ice in a region in connection with surface energy balance studies. Especially when it comes to large amounts of remote sensing images, and images with multipolarization data, limits are met concerning only manual classification.

Sea ice thickness distribution from remote sensing is either given along a line (Operation IceBridge data) or in a gridded fashion which requires averaging over larger areas (25 to 100 km squared) and longer time intervals (a month). These products lack information on the thickness distribution within each grid cell. A combination of altimeter sea ice thickness with a better classification of sea ice types and age based on SAR (similar to the RADARSAT Geophysical Processor System) could have the potential to improve our information about sea ice thickness distribution. This requires, however, a regular overpass (i.e., repeat cycle of less than 3 days).

Looking at the observation needs for the future, snow on sea ice is an essential parameter for understanding sea ice thermodynamics and remote sensing of the sea ice thickness using the freeboard method. In fact, space-borne remote sensing techniques for snow on sea ice are not yet mature. The possibility of retrieving snow parameters through a combination of near-simultaneous measurements by different satellite sensors is an exciting scientific prospect, however it will require a concerted data acquisition strategy and improved planning and ordering tools.

The validation concepts as well as the collection of reliable and extensive validation data for Arctic sea ice is a major issue. Collection of validation data will have to be planned even more intensively in order to bridge the different spatial and also temporal scales involved when observing sea ice as a moving target from space. It is important to make satellite data acquisition as flexible as possible to optimize the success of field campaigns. High resolution SAR and VIS/NIR can serve as an excellent tool to upscale results from a carefully planned in-situ measurement campaign to the scale provided (e.g. by scatterometers and passive microwave instruments). Ideally such campaigns cover multiple scales, like the SEDNA project (esearch.iarc.uaf.edu/SEDNA) and ESA CryoSat validation campaign (CryoVEx) (Gerland et al., 2013). As the multi-year ice fraction is declining, thin first-year ice becomes more important to the mass balance of the Arctic. An internationally coordinated freeze-up campaign is needed to collect more validation data over the vast areas of relatively thin Arctic sea ice. In this context, the exploitation of the knowledge gained during the IPY period in terms of best practices for in situ data collection is certainly an asset.

In the context of Sentinel-1 a number of issues are important for sea ice classification using Extended Wide-Swath (EWS) and IWS mode images (Dierking, 2010). Compensation of incidence angle for the effect of backscatter needs to be addressed along with mitigation of the noise level, i.e. intensity, variation between antenna beams and within a beam, particularly in cross-pol images. Acquisition of Sentinel-1 data in Strip-Map mode at ice sheet margins is beneficial for the ice sheet community as it provides a higher resolution dataset, however this presents a conflict and problem with mode switching close to the margins of the ice sheets to the broader swath imaging mode alternatives. The austral winter has been proposed as a potential time period for acquiring Antarctic Strip-Map mode data over the ice sheet margins, as in general tactical navigational aid during this time is of lower priority for the sea ice community. Despite this, two other important uses of the data for sea ice monitoring would be impacted, namely polynya monitoring along the coast and sea ice drift monitoring (Hollands et al., 2013) because experience shows that Strip Map mode doesn’t provide the necessary coverage. The sea ice community agrees that the coastal regions are important to have covered in EWS or IWS mode also during winter, but that a limited Strip-Map mode coverage for monitoring of the ice sheet margins could be accommodated without conflict with the sea ice requirements during the austral winter.

In recent years, much effort has been put into deriving sea ice drift from SAR. The development of an inexpensive buoy system to better assess the motion of the more and more seasonal sea ice cover would be highly desirable.

The integration of sea ice data into models needs further effort. A reasonable approach is data assimilation and the use of regional models for upscaling. A workshop lead by the International Ice Charting Working Group (IICWG) for such sea ice data assimilation will take place in Bremen in May 2013 and follow up workshops should be planned to continue these efforts.

Finally, it is worth noting that compilation of recommendations from the IGOS Cryosphere Theme Report (2007) are still valid, see http://igos-cryosphere.org/documents.html along with the ‘Sen4Sci’ report on the needs for Cryosphere products within the context of the Sentinel missions, http://wiki.services.eoportal.org/tiki-download_wiki_attachment.php?attId=1178.

7. FINAL REMARKS

The following final points summarize some cross-cutting issues that were mentioned in several sessions and represent general concluding recommendations shared by all the different thematic areas addressed in the conference:

Improve interdisciplinary collaboration and dialogue: This conference underlined the importance of an integrated approach to observe, characterize and study the cryosphere and its different components and processes. This requires stronger interdisciplinary collaboration and a continuous dialogue between the different communities (e.g., EO, modellers, climate, hydrology, oceanography, etc) involved in cryosphere and climate research.

Promote inter-comparison and assessment exercises: The large number of EO instruments and the related methods, techniques and products that have been developed in the last years addressing several components of the cryosphere requires a continued effort of cross-comparison, validation and consistency assessment (such as those promoted in the context of the Global Cryosphere Watch. For information see http://globalcryospherewatch.org/). In this context, promoting inter-comparison exercises (e.g., IMBIE, CCI round-robin exercises), which provide a clear understanding of the validity ranges, uncertainties, potential and limitations of algorithms and retrieved data products, represents a major need in all areas of EO cryosphere research. This is particularly important for those thematic areas where different sensors and methods are applied by the community to address the same problems (e.g., radar altimetry versus laser altimetry). Finding common grounds for addressing inconsistences, exploiting synergies and maximizing the potential for reconciled measurements represents a major challenge for the future.

Ensure in-situ data collection: In-situ data collection has been mentioned in all the sessions of the conference as a critical aspect to complement and validate EO data and is a major need for the future. Promoting, maintaining and expanding the significant efforts started during the IPY period represent an important need and a major challenge for the future. independent reference datasets at a suitable time and space scale are required to validate the satellite data under heterogeneous conditions, to establish instrument biases and residual uncertainties, or to enable cross-calibration between different instrument datasets. This sort of data comprise airborne instrument measurements and in-situ measurements at the appropriate scale

Maximize the exploitation of multi-mission multi-product synergies: The growing observational capacity offered by the increasing number of satellite systems creates an increasing need for dedicated research efforts aimed at exploring the potential for the synergistic exploitation of the different and complementary capacities offered by these new sensors. Multi-mission approaches that exploit synergies among different missions and data sets need to be further promoted. This is also of critical importance in order to guarantee the required data coverage over several regions of the world (e.g., Antarctica) where a single satellite system may be unable to meet all the requirements of the scientific community. This will require a closer cooperation between space agencies concerning the planning of satellite mission orbits, data acquisition timing and the ordering of data sets acquired by different satellite sensors. In this context, the work of the PSTG should be supported. Last, but not least, the development of dedicated open-source toolboxes facilitating the handling and processing of multi-mission data is recommended.

Exploiting data archives towards long-term data records: It is important to emphasize the need for internationally coordinated efforts for the development and preservation of long-term consistent data records from the cryosphere that may exploit the increasing archives of EO data.

Continuity of EO observations: last but not least, it is worth mentioning the importance stressed in all conference sessions about long-term data continuity. Ensuring data continuity of critical observations, avoiding short lifetimes for new missions and enhancing coordination between agencies to ensure the collection of suitable datasets providing sufficient coverage over all critical areas with the required datasets (e.g., suitable modes) is critical to guarantee the advance of scientific research in the coming years.

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