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Editorial

Status of Earth Observation and Remote Sensing Applications in Svalbard

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1. Introduction

Remarkable developments in the fields of earth observation (EO) satellites and remote sensing (RS) technology over the past four decades have substantially contributed to spatial, spectral, and temporal sampling. This has enabled the subsequent retrieval of geographical information (GI) to better understand the current state of the Arctic. Massive data gaps exist in Svalbard, even if it is probably one of the most in situ data-rich regions in the Arctic. These gaps can be filled by installing new research infrastructure (RI), acquiring regular observations, generating new geospatial products using EO and RS, and integrating in situ data with EO-based information. The Svalbard Integrated Arctic Earth Observing System (SIOS) is an international consortium of 28 member institutions from 10 countries, tasked with developing an efficient observation system for long-term in situ and RS measurements in Svalbard and associated waters to address key Earth system science (ESS) questions. RIs, associated with or funded by SIOS, are scattered all over Svalbard to acquire long-term in situ observations. In situ measurements, collected as a part of the observing system, provide value for a variety of existing (e.g., Sentinel and Landsat series) and upcoming (e.g., CRISTAL, CIMR and ROSE-L) satellite missions. The function of these data in such situations are calibration and validation (Cal/Val) efforts and use in ESS modelling community. Such integration of in situ and satellite-based measurements is beneficial for Svalbard science community in addressing broader scientific questions in Arctic science. Our Special Issue (SI) was designed to provide a comprehensive platform for researchers to present regional and Svalbard-wide cross-disciplinary studies, conducted using EO and RS. The SI was focused on attracting ground/field-, underwater-, space-, and airborne platform-based RS studies of Svalbard.

The SI offered broad possibilities to potential authors and encouraged contributions in all areas of Svalbard science, including the following: (1) EO and RS studies pertaining to field studies/campaigns, ESS modelling, and long-term monitoring programs in terrestrial, marine, atmospheric, and cryospheric environments of Svalbard; (2) RS-based studies on cross-sphere interaction of cryosphere with ocean, terrestrial, and atmosphere; (3) The derivation of geophysical and biophysical parameters e.g., chlorophyll concentration, eddies information, snow cover dynamics, vegetation growth, sea ice drift and type, phytoplankton blooms using satellites; (4) Svalbard-wide GI retrieval including geospatial product generation and operationalization using optical (e.g., Sentinel and Landsat series), microwave (e.g., SAR) and Lidar (e.g., ICESat-1/2) applications in Svalbard; (5) Cal/Val activities for various satellite missions, e.g., Pandora (https://www.pandonia-global-network.org/, accessed on 12 January 2023) installation, validation of snow parameters derived using satellite, Cal/Val activities using ocean moorings; (6) Integration of RS, in situ, modelling and previously available GI to advance new knowledge about Svalbard; (7) Artificial intelligence (AI) including deep learning (DL), machine learning (ML), neural networks (NN) and cloud computing-based applications in Arctic areas; (8) RS applications in glaciology including snow cover and its properties, geodetic glacier mass balance, mapping glacier facies, deriving glacier surface elevation changes, etc.; (9) RS of terrestrial and marine cryosphere including snow/firn/ice, sea ice, snow on sea ice, icebergs, ground ice, avalanche studies, and permafrost subsidence studies; (10) RS of terrestrial vegetation, estimating vegetation growing season and primary productivity, mapping vegetation abundance and extent, and time series analysis of terrestrial vegetation; (11) Applications of very high resolution (VHR) satellite and airborne platforms in Arctic areas, including use of airborne imagery and hyperspectral data acquired by Dornier research aircraft, VHR satellites (e.g., WorldView, Planet) and uncrewed aerial vehicles (UAVs); (12) Applications of new technologies, such as robots, autonomous underwater vehicles (AUVs), drone-based mapping using surface from motion (SfM), and terrestrial laser scanners (TLS).

2. Challenges Related to Svalbard Studies and Possible Solutions from SIOS Remote Sensing Activities and Special Issue

2.1. Challenges Related to In Situ Data Collection and Integration with RS Data

The regular collection of in situ measurements by field scientists using field campaigns and ground-based RI is useful for space agencies, Arctic scientists and RS experts for validating geospatial products in Svalbard. Conversely, Arctic field scientists benefit from the geospatial products derived using RS data to widen the scope of their study beyond limited field observations. Therefore, a dedicated platform for facilitating communication between field scientists and RS experts in Svalbard is necessary to make the best use of in situ measurements and RS resources. Presently, SIOS facilitate such dialogue between field scientists and RS experts through its online conferences (https://sios-svalbard.org/RS_OnlineConference, accessed on 12 January 2023) and regular webinars (https://sios-svalbard.org/WebinarSeries, accessed on 12 January 2023). In future, we anticipate launching a dedicated platform or discussion forum on the SIOS website to facilitate discussion between field scientists and RS experts, hopefully widening the scope and usage of RS data in the Svalbard science community.

Even if Svalbard is one of the most in situ data-rich regions in the Arctic, there are gaps that are limiting modelling-based studies. For example, most of the in situ data in Svalbard are clustered in coastal regions and are very sparse in the interiors of Svalbard. More datasets are required from the more remote eastern part of Svalbard, as there are huge differences compared to western parts of Svalbard. Most of the field campaigns are focused on summer seasons, causing an imbalance in intra-seasonal measurements. Due to changing weather conditions and logistical constraints, conducting fieldwork matching with satellite overpasses remains a challenging exercise. Most of the observations are clustered around field bases such as Longyearbyen, Ny Ålesund and Hornsund, causing data gaps in other areas of Svalbard. Filling spatial and temporal gaps in terms of in situ measurements will facilitate further modelling-based studies in the future. Regular maintenance of ground-based RIs is one of the challenges facing researchers, specifically during wintertime and periods of travel restrictions, such as the pandemic. For example, repair and maintenance of several sensors may take months to reinstate the equipment because of logistics, causing gaps in measurements during unexpected failure and maintenance periods. The cost of logistics in Svalbard is one of the challenges for Svalbard researchers. However, generous field grants and access to RI by Svalbard Science Forum (https://www.forskningsradet.no/en/svalbard-science-forum/, accessed on 12 January 2023), SIOS access programme (https://sios-svalbard.org/AccessCall_2023, accessed on 12 January 2023), and INTERACT trans-national access (https://eu-interact.org/, accessed on 12 January 2023) have been useful for supporting field activities in Svalbard.

2.2. Technological Challenges and Innovation

Some of the practical solutions to overcome the challenges, outlined above, for conducting field-based measurements include (1) use of remote or autonomous platforms; (2) reduction in power consumption for remote stations using technological innovation; (3) technical solutions for communication with RIs/sensors in remote locations; (4) development of new measurement methods or infrastructure that can replace manual fieldwork that has a high environmental impact; (5) pilot efforts for community-based observation to support ESS monitoring; (6) cooperation with a manufacturer to further develop existing technology and protocols. To implement these solutions and overcome practical challenges in data collection, SIOS and SSF launched the call for proposals in 2021 (https://sios-svalbard.org/InnovationAward, accessed on 12 January 2023) to promote the development of an innovative technology, solution or method to advance observation capability or reduce the environmental footprint of research and monitoring in Svalbard. The funding awarded supports the development of new technologies, methodologies or means of using products and data within Svalbard science and infrastructure operations.

2.3. Challenges Related to Sunlight Dependent Optical Sensing

Varying resolutions of optical data are useful for many applications in Svalbard. However, traditional issues such as frequent cloud cover and light conditions over Svalbard, limit the usage of sunlight-dependent optical sensing. Time-lapse cameras, UAVs and aircraft-based data can be utilized to complement satellite-based observations; however, such observations can cover only limited areas in Svalbard in one field season. Besides, aircraft-based measurements are also weather-dependent, and low-lying clouds can seriously hamper the quality of the data. Multi-polarization, multi-frequency, and multi-temporal radar observations can be useful to fill data gaps during both cloudy days in summer and limited light conditions in winter. SAR guarantees ground-covering (cloud-free) images, both during summer and dark winter in Svalbard. The failure of Sentinel-1B in December 2021 has impacted the frequency of SAR observations in Svalbard, a situation which is expected to be improved with the launch of Sentinel 1C in 2023.

2.4. Challenges Related to VHR Observations in Svalbard

Very high resolution EO satellite data are mainly available through commercial providers, an arrangement which necessitates dedicated funding for research projects. Most VHR satellite observations are carried out on a request-by-request basis, rather than via continuous monitoring, causing large data gaps in Svalbard. This affects the studies involving temporal change detection, such as surface changes of glaciers, calving events, vegetation dynamics, and many more topics. To address this, SIOS has recently launched the project proposal call with Planet (https://sios-svalbard.org/SIOS_PlanetCall2023, accessed on 12 January 2023) to provide free access to high-resolution optical satellite data, acquired by Planet's satellite constellation (https://www.planet.com/, accessed on 12 January 2023), to stimulate geospatial product generation in Svalbard. Similar to the SIOS–Planet call, SIOS also looks forward to cooperating with other commercial satellite data providers to facilitate the usage of VHR data in Svalbard. SIOS also promotes the usage of UAVs and airborne campaigns using Dornier aircraft (https://sios-svalbard.org/AirborneRemoteSensing, accessed on 12 January 2023) to collect high-resolution data. Since 2020, SIOS has supported around 20 scientific projects by coordinating 50 flight hours to acquire airborne data using the Dornier aircraft and UAVs in Svalbard. Coordinated flight campaigns by SIOS have enabled the optimized usage of aircraft to reduce the environmental footprint of observations, facilitate international collaboration within the Svalbard science community, train the next generation of polar scientists using the collected data, and fill gaps in observations that occurred as a result of pandemic-related travel restrictions.

2.5. Challenges Related to Methods and Applications

Most of the studies published in this Special Issue focus on regional aspects of Svalbard. Methods, applications and data used in these studies should be scaled up to cover the entire archipelago in order to broaden the scope of the study. However, it remains a challenge to address scaling issues because of the variety of issues involved, including varying spatial/spectral/temporal resolutions of satellite and in situ data. Ideally, methods adapted to regional studies such as mapping vegetation or glaciers using VHR data should be scaled up for the entire archipelago using the available coarse resolution or medium resolution satellite data. However, only limited attempts have been demonstrated in this Special Issue. Several manuscripts have shown the potential of having their methods upscaled for Svalbard-wide studies. Such challenges can be circumvented by the colocation of RIs, filling in situ data gaps, improving coverage of in situ data, frequent satellite observations, and the integration of data. To some extent, these challenges can also be addressed using better data management and making data available with FAIR principles. The SIOS Data Management Service (https://sios-svalbard.org/Data, accessed on 12 January 2023) and observation facility catalogue (https://sios-svalbard.org/sios-ri-catalogue, accessed on 12 January 2023) provide effective platforms for making data available to the scientific community in Svalbard.

2.6. Challenges Related to Access Restrictions Such as the Pandemic

Situations such as the pandemic may recur, causing temporary gaps in field measurements due to travel restrictions. To address this, an overview of the maturity of EO technology and its ability to fill in situ gaps using space-borne observations is necessary. In this direction, SIOS started supporting researchers in filling gaps in data using RS observations during the pandemic through a dedicated service (https://sios-svalbard.org/PatchUpData, accessed on 12 January 2023). Besides, SIOS is currently setting the stage for developing citizen science-/community-based observation efforts to involve residents. These efforts will not only involve residents in scientific observation but also complement science studies and long-term monitoring in Svalbard. Such community-based observations will be useful, particularly in future pandemic situations.

3. Overview of Manuscripts Published in Special Issue

Twelve experts from five countries representing nine SIOS member institutions and SIOS-Knowledge Centre (SIOS-KC) have edited this SI. This SI attracted 24 manuscripts (more than 100 co-authors across the globe) over the span of two years (March 2020−June 2022) as an outcome of its broader scope. SIOS also hosted two online conferences on EO- and RS-based studies in Svalbard to attract scientific presentations and publications from the Svalbard science community. After careful review and subsequent revisions, the editorial expert group accepted 19 manuscripts in this volume. All the accepted papers in our SI have the potential to stimulate our knowledge about Svalbard. An accidental result of the unexpected timing of launching the SI at the beginning of the pandemic ultimately presented a stage for Arctic researchers to publish their RS-based studies, of particular value at a time when many researchers were constrained to their home offices. The present volume of the SI covers a wide range of applications of EO and RS in Svalbard, especially with regard to the usage of data, methods, infrastructure, and spheres of the ESS. The available topics included EO and RS applications in snow, glaciers, Arctic vegetation, ocean eddies, permafrost, glacier facies, aerosol, and lake phenology studies in Svalbard. These were investigated using a variety of methods and infrastructure, including interferometric synthetic aperture radar (InSAR), UAVs, TLS, photogrammetry and many more techniques. In brief, the SI consisted of various contributions focused on the usage of various remote sensing platforms and satellite sensors to develop applications in a wide span of environments (atmosphere, terrestrial, marine, and cryosphere) on Svalbard. The contributions are briefly described in the following sections.

3.1. Atmospheric Remote Sensing Applications

Anthropogenic climate change is leading to major changes in the Arctic environment. Arctic aerosol and its related feedback mechanisms are inseparably impacted, whereas the influence of the spatio–temporal variability of aerosols on the radiation budget of the Arctic has not yet been fully understood. To address this gap, Nakoudi et al. [1] exploited synergistic RS observations of a long-range aerosol transport episode in April 2018 using lidar and sun-photometer measurements over two parts of the European Arctic. The aim of the study was to investigate intra-Arctic aerosol alteration and assess its impact on the local radiative budget. The research showed that aged aerosol was transformed, even in neighbouring Arctic upper tropospheric levels, because of changes in the aerosol source regions (north Europe and north-east Asia) and the interaction of removal processes such as nucleation scavenging and dry deposition.

The near-surface warming rate in the Arctic has at least doubled (*Arctic amplification*) in comparison to elsewhere on our planet over the past decades [2] and is reported to be as much as four times the global average [3]. Clouds are an important modulator of the Arctic surface energy budget [4]. Cirrus formations are known to be the only cloud type to cause daytime cooling or heating at the top of the atmosphere. However, the present research into its geometrical and optical properties over the Arctic is inadequate. To address this gap, Nakoudi et al. [5] analyzed the long-term characteristics of cirrus clouds over Ny-Ålesund, Svalbard for the first time. The authors used lidar and radiosonde observations from 2011 to 2020, showing that cirrus layers were geometrically thicker in winter and spring. The authors suggest that for more Arctic cirrus studies in the American and Russian regions of the Arctic are necessary to evaluate potential intra-Arctic variations in cirrus properties.

3.2. Remote Sensing in Arctic Limnology

Arctic lakes are vulnerable to climate change. Ice phonological properties, such as timing and length of ice presence or absence on the surface of lakes, can be used as effective climate indicators. Tuttle et al. [6] compared ice phenology on the Linnévatnet lake surface using satellite-based data, photographs from automatic cameras, and constant observations of lake water temperature. Linnévatnet is one of the largest lakes on Svalbard. Moderate-resolution imaging spectroradiometer (MODIS)-derived surface reflectance data from 2003–2019 were utilized to identify the change in the mean surface reflectance of Linnévatnet. Besides, smoothing splines were used to determine the date of summer ice-off (“break-up end”—BUE). Subsequently, fall ice-on (“freeze-up end”—FUE) was determined using the mean time series (2014–2019) of Sentinel-1 microwave backscatter over the lake. In general, the ice timing dates determined from the satellite-based observations agreed with the in situ observations (RMSE values of $\approx$2–7 days for BUE and FUE). In brief, this regional study indicates that optical and SAR satellite-based measurements can be successfully used to observe changes in the lake ice in the High Arctic, and its results can be extended to study changes in lake ice in regional scales across the Arctic using different optical and SAR satellites and sensor-specific considerations.

3.3. Ocean Remote Sensing Applications

It is well documented that the Arctic coasts are affected by climate change, including the melting of glaciers and variations in precipitation and runoff. These changes are expected to impact productivity in fjordic estuaries. The study by Walch et al. [7] demonstrates the spatio-temporal variability of suspended particulate matter (SPM) in the Adventfjorden, Svalbard. The authors used in situ field measurements, taken in 2019 and 2020, along with Sentinel-2 imagery. This study highlighted the importance of RS in studying fluxes in light-attenuating particles, particularly in the coastal Arctic Ocean. This study also indicates that the Adventfjorden can serve as a representative study area for regions dominated by marine-terminating glaciers and largely glaciated catchments. The authors found that the fine-tuning of the ocean color RS algorithms using field-based measurements resulted in satisfactory estimates of spatiotemporal variability of SPM in the Adventfjorden.

Eddies that form at the ice edge and within marginal ice zones (MIZ) are common geophysical features of ice edge progression in polar oceans. Earlier studies indicate that MIZ eddies are widespread in polar ocean regions, such as the Fram Strait. These studies discuss the wide variety of methods for generating mechanisms eddies using available in situ, airborne, and satellite-borne data. Kozlov and Atadzhanova [8] used Envisat ASAR and Sentinel-1 to investigate the generation of eddies and their properties in the MIZ regions of the Fram Strait and around Svalbard in the winters of 2007 and 2018. The authors analyzed 2039 SAR images to identify 4619 eddy signatures. The authors found that the number of eddies detected in MIZ is similar for both years. Besides they found that the sub-mesoscale and small mesoscale eddies dominate, with cyclones identified twice as repeatedly as anticyclones. The range of Eddy diameters varied from 1 to 68 km, with mean values of 6 km for shallow and 12 km for deep water.

3.4. Remote Sensing for Permafrost Studies

The degradation of carbon-rich permafrost can contribute to global warming through the processing and emission of greenhouse gases (GHGs) that were confined to the frozen ground in the past. Changes in permafrost can also have instant impacts on infrastructure and ecosystems in the Arctic. Rouyet et al. [9] used Sentinel-1 SAR Interferometry (InSAR) to study the seasonal vertical displacement progression on Svalbard. Their study yielded Sentinel-1 InSAR data showing the spatial variability and timing of the seasonal thaw subsidence maxima in three regions of Svalbard. The study indicates the necessity for the development of regional InSAR products in Svalbard to study cyclic subsidence in permafrost areas. The authors examined the possibilities and shortcomings of using the timing of the maximal subsidence as an alternative for the end of the thawing season.

3.5. Glaciological Remote Sensing Applications

In order to understand the contribution of a surging glacier system to sea-level change it is necessary to study the evolution of ice dynamics, mass transfer within the glacier, surface elevation changes, glacial hydrology, and calving resulting in mass transfer from the glaciers to the ocean. A study by Herzfeld et al. [10] evaluated the capabilities of airborne ICESat-2 advanced topographic laser altimeter system (ATLAS) measurements in surface height estimations over crevassed glacial terrain of the surging Negribreen glacier in Svalbard. The authors collected airborne geophysical data in two field campaigns in the summers of 2018 and 2019. Their results of the validation indicated that ICESat-2 ATLAS data, processed with the density–dimension algorithm for ice surfaces (DDA-ice), facilitate surface–height estimations over crevassed terrain.

RS observations of dynamic glacial systems are effective tools for observing the overall changes that are constantly occurring in the cryosphere [11]. Glacier surface facies are among the especially important signatures of variations experienced by a glacial system. These surface facies are shaped by the natural ageing and redeposition of snow and its seasonal melting, and refreezing with dust and debris. Surface facies are easily recognized based on certain variations in surface reflectance values [11]. In a series of three papers, Jawak et al. [12–14] demonstrated the usage of VHR WorldView-2 and WorldView-3 satellites in mapping glacier surface facies on Svalbard and the Himalayas by standardizing image processing routines associated with pixel-based and object-based machine learning methods. These papers are expected to stimulate the operational mapping of glacier facies in the cryosphere using a variety of satellite sensors.

Almost 60% of Svalbard is glaciated and thus glaciers form most of the local ecosystem. Kavan et al. [15] studied tidewater glaciers on the south-east coast of Svalbard to deduce surface elevation changes and retreat rates using satellite images and historic maps. The authors used a 1970 digital elevation model (DEM) and an ArcticDEM mosaic generated from aerial images by the Norwegian Polar Institute. The authors showed that the tidewater glaciers under consideration have retreated at a substantial rate ranging between 10 and 150 m year^{-1}, with a mean retreat rate of 48 m year^{-1} between 1970 and 2019. The maximum retreat rate was revealed at Hambergbreen. The substantial retreat reported by this study revealed that four out of the eleven glaciers completely lost their physical link with the fjords/ocean, resulting in terrestrial glacier systems. Authors showed that the massive retreat of the glaciers has exposed many newly emerged coastlines that are presently being reshaped by coastal processes.

As stated previously, the Arctic is experiencing incessant and substantial variations in land relief, resulting from various geomorphological, glaciological, and hydrogeological processes. DEMs and precise high spatial resolution maps are of crucial importance to studying these changes. Błaszczyk et al. [16] assessed the accuracy of orthomosaics and high-resolution DEMs derived using photogrammetric methods on aerial images captured by Dornier aircraft in 2020 over Hornsund, Svalbard. The authors evaluated and combined the two methods based on terrestrial laser scanning and photogrammetry to produce a continuous and gap-free DEM for the diverse Arctic scientific community. This approach enabled authors to study geomorphological activity over a year, including alterations along the shoreline, the snow thickness in gullies, and the melting of ice cores in the periglacial zone. The study underlines the possibility of combining other RS methods to study the active processes in this region.

3.6. Arctic Studies Using UAVs

Uncrewed aerial vehicles (UAVs) are being progressively utilized as a tool to study rapidly changing arctic environments. Eischeid et al. [17] provided a comprehensive method for producing ground-cover maps using UAVs for effective ecological monitoring in a High Arctic tundra environment. Authors used random forest (RF) classifiers to map up to 15 different ground-cover classes, including two disturbance classes. These were goose grubbing and winter damage which were assessed based on lower NDVI values in comparison to their undisturbed counterparts. The authors showed that UAV image analysis can be an effective tool for studying rapid changes in vegetation at local scales in Arctic tundra ecosystems. The authors also advise ecologists to integrate UAV mapping into long-term ecosystem monitoring programs. The authors suggest stronger interdisciplinary cooperation between EO experts and ecologists to effectively blend the data, knowledge and information to further enhance the quality of ecological monitoring in the Arctic.

3.7. Arctic Vegetation Studies Using Remote Sensing

Variations in the timing of phenological phases in terms of the RS-based onset of vegetation growth are sensitive bio-indicators of climate change. To address this issue, Karlsen et al. [18] focused on the central part of Spitsbergen to study the onset of vegetation growth. The authors prepared, analyzed and presented a time series of daily NDVI products using cloud-free Sentinel-2. The NDVI 2016-2019 time series datasets were merged with ground-based phenocam observations for mapping the onset of growth. The Sentinel-2 NDVI-based mapping and analysis of the onset of growth revealed significant variations between the years. For example, except at higher altitudes, the onset of growth was more than 10 days earlier in 2018 in comparison with 2017. The data presented in this paper were not adequate to clarify these variations. Therefore, authors formulated a future study to examine the connection between early growing season temperature and the timing of snowmelt.

3.8. Snow Remote Sensing in Svalbard

The first day free of snow and the timing of snowmelt are considered reliable markers of the Arctic ecosystem's status in response to global warming. This is mainly because the last day of snow cover and snowmelt timing have a substantial impact on the phenological characteristics of vegetation in Svalbard. In an attempt to assess the seasonal changes in snow, Stendardi et al. [19] used a multi-sensor approach and analyzed the sensitivity of the SAR backscatter to vegetation growth and soil moisture. The authors showed that the C-band SAR data, combined with optical data, can be useful in monitoring the seasonal changes in the timing of snowmelt in Adventdalen. The results also verified that vegetation can be satisfactorily detected by the HV polarization channel. The late melting and resulting disappearance of snow impart a further challenge in the monitoring of vegetation and soil dynamics.

Changes in seasonal snow cover can be considered a sensitive marker of climate change. In response to the changing climate in Svalbard, seasonal snow cover is expected to undergo spatio-temporal changes owing to its sensitivity to temperature and precipitation changes. As vegetation is closely linked to snow cover, the timing of terrestrial productivity is expected to change. Vickers et al. [20] used MODIS Terra data for the period 2000–2019 to produce a 20-year snow cover fraction time series data for Svalbard to study changes in the timing of the first snow-free day (FSFD). The authors have investigated the impact of changes in sea ice concentration (SIC) on FSFD and the effect of FSFD on the phenological growing season. Their results showed obvious patterns of earlier FSFD in the southern and central parts of the archipelago. On the other hand, the northernmost regions exhibited minor changes toward later FSFD. Authors noticed that FSFD led to the onset of the phenological growing season, with an average variation of 12.4 days for the entire archipelago.

Snow models are complementary tools to EO- and RS-based observations for snow cover monitoring, and may be used to fill in spatio-temporal data gaps in field-based observations. In a study involving overlapping periods of data coverage, Vickers et al. [21] used three optical RS datasets and two snow models to study the similarities and inconsistencies in snow cover estimates over Nordenskiöld Land, Svalbard. A 20-year MODIS snow cover dataset was calibrated using Sentinel-2 data. Snow cover fraction estimates, derived using lower-resolution AVHRR and snow model datasets, were corrected using MODIS-based snow cover data. This study practically demonstrated the effectiveness of using current-day high-resolution datasets to improve the consistency of past low spatial resolution snow cover datasets.

3.9. Hyperspectral Remote Sensing in Svalbard

Field-based hyperspectral measurements of ice and snow cover are important for the calibration and validation activities of airborne and spaceborne hyperspectral imageries. However, such measurements are strongly affected by the limited accessibility of data services integrating spectral libraries with comprehensive descriptions of the observed surface cover. To fill this knowledge gap for snow and ice cover, Salvatori et al. [22] presented an updated version of the Snow/Ice Spectral Archive (SISpec 2.0). This version is integrated into a web portal (https://www.cnr.it/en/institutes-databases/database/1076/sispec-snow-ice-spectral-library-project, accessed on 12 January 2023), as exemplified by various functionalities such as accessibility and interoperability.

3.10. Remote Sensing in Response to the COVID-19 Pandemic

The coronavirus (SARS-CoV-2) disease 2019 (COVID-19) pandemic impacted research on Svalbard in a number of ways. In March 2020, Norway announced a nationwide lockdown, including stringent measures to protect the Svalbard community from the possible spread of the infection. Because of the lockdown, associated travel restrictions, and quarantine regulations announced by various countries, most of the field campaigns in Svalbard were cancelled by the first week of March 2020. Jawak et al. [23] highlighted the activities undertaken in response to the exceptional situation enforced by the global pandemic of COVID-19. This study provides a first crucial point of view on general response, potential wider impacts, consequences to other observing systems, and advice for future directions related to field-based research in Svalbard.

4. Vision and Direction for Future Remote Sensing Research in Svalbard

Nearly all polar-orbiting EO satellites pass over or at a marginal distance from Svalbard, enabling high satellite track coverage. Its strategic location has facilitated Svalbard to become the largest downlink site for polar-orbiting EO satellites. The high-latitude geographic location of Svalbard has had a tremendous impact on scientific and monitoring communities in three ways: (1) Regions of Svalbard and associated waters are frequently well covered by EO satellite data, (2) RI in Svalbard offers numerous possibilities for ground-based validation of satellite data for cross-disciplinary research in the Arctic, and (3) effective use of EO satellite data has no adverse impact on the environment. However, the growing volumes of in situ and RS data clearly show the need of using advanced methods in artificial intelligence to make the best use of the ground, airborne, underwater and space-borne research infrastructure in Svalbard. Future research projects should focus on aligning field campaigns and in situ data collection with upcoming satellite missions (e.g., NISAR, CRISTAL, CIMR and ROSE-L) to facilitate cal/val activities and the construction of a sustained EO-based observatory for Svalbard science.

Glacier surface types and zones can be mapped using SAR and optical sensors by applying either pixel- or object-oriented methods. In future, a fusion of various sensor (optical/SAR) data and methods to generate high-resolution spatio-temporal datasets should be considered. For summer seasons, high-resolution optical (multispectral and hyperspectral) data has shown great potential to map surface change. For winter seasons, frequent SAR studies are anticipated to complement optical sensor-based studies. A new generation of VHR optical sensors such as WorldView Legion, Planet, and Pléiades NEO with high temporal, spatial and spectral resolutions are expected to complement field data and medium-resolution optical data such as Landsat series, Sentinel series and MODIS.

Scaling issues across spatial/spectral/temporal scales in Svalbard studies will be essential going forward in stimulating knowledge acquisition from regional studies. This, in turn, will allow researchers to derive Svalbard-wide information using a variety of ground, airborne, underwater and space-borne sensors. Accordingly, training the new generation of cryosphere scientists and field scientists in EO and RS skills is essential. In this vein, SIOS hosts an annual RS training course (https://sios-svalbard.org/Training, accessed on 12 January 2023) on specific topics such as terrestrial/marine RS, hyperspectral RS, and artificial intelligence methods in EO.

Future studies on Svalbard may also consider filling gaps highlighted by several chapters in the State of Environmental Science in Svalbard (SESS) reports (https://sios-svalbard.org/SESSreport, accessed on 12 January 2023) and the recent SESS synthesis report (https://sios-svalbard.org/SESSRecommendationsSynthesis, accessed on 12 January 2023). Additional gaps in snow research in Svalbard have been highlighted in the snow agenda paper (https://sios-svalbard.org/SnowResearch, accessed on 12 January 2023). Future attempts are expected to fill these knowledge and data gaps using in situ and RS data. Several attempts have been already started such as the Snow Pilot project (https://sios-svalbard.org/SnowPilot2022, accessed on 12 January 2023). In situ observations will be enriched by the recently started Cryosphere Integrated Observatory Network on Svalbard (CRIOS) project (https://crios.pl/, accessed on 12 January 2023). Finally, cross-disciplinary studies across various spheres of Svalbard using in situ, space-borne, airborne and underwater platforms are expected to be conducted in future to address broad scientific questions in Earth system science.

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