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Review

Status of Korean Research Activity on Arctic Sea Ice Monitoring using KOMPSAT-series Satellite

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Abstract: Arctic warming is a global issue. The sea ice in the Arctic plays a crucial role in the climate system. We thought that a recent abnormality in many countries in the northern hemisphere could be related to the effects of shrinking sea ice in the Arctic. Many research groups monitor sea ice in the Arctic for climate research. Satellite remote sensing is an integral part of Arctic sea ice research due to the Arctic's large size, making it difficult to observe with general research equipment, and its extreme environment that is difficult for humans to access. Along with monitoring recent weather changes, Korea scientists are conducting polar remote sensing using a Korean satellite series to actively cope with environmental changes in the Arctic. The Korean satellite series is known as KOMPSAT (Korea Multi-Purpose Satellite, Korean name is Arirang) series, and it carries optical and imaging radar. Since the organization of the Satellite Remote Sensing and Cryosphere Information Center in Korea in 2016, Korean research on and monitoring of Arctic sea ice has accelerated rapidly. Moreover, a community of researchers studying Arctic sea ice by satellite remote sensing increased in Korea. In this article, we review advances in Korea's remote sensing research for the polar cryosphere over the last several years. In addition to satellite remote sensing, interdisciplinary studies are needed to resolve the current limitations on research on climate change.

Keywords: Arctic, sea Ice, cryosphere, remote sensing, KOMPSAT

1. Introduction

Arctic warming is a global issue. The sea ice in the Arctic plays an essential role in the climate system. We thought that a recent abnormality in many countries in the northern hemisphere could be related to the effects of shrinking sea ice in the Arctic (Bokhorst et al., 2016; Serreze and Barry, 2014; Serreze and Stroeve, 2015; Wu and Wang, 2018). The amount of water vapor evaporating from the sea is relatively higher than in the past due to the reduced amount of sea ice in the Arctic Ocean (Chang et al., 2019). Warmed air and increased water vapor are changing the cold airflow in the Arctic air, which weakens the temperature gradient of the atmosphere in the northern hemisphere (Kim et al., 2017). The most significant example is that jet stream has a wide radius of flow, which makes it more likely to drift farther south than usual (Ronalds et al., 2018). As a result, droughts and cold waves are occurring in the northern hemisphere, renewing the records of the past (Chu et al., 2017; Dong et al., 2018). Arctic sea ice has been pointed out as a cause of many kinds of weather changes that humanity is experiencing now (Knutti et al., 2015).

The European space agency (ESA) used satellites to estimate the loss of glaciers by region around the world (Plummer et al., 2017; Saunier et al., 2017; Zemp et al., 2015; Zemp et al., 2019). Observational statistics from 1961 to 2016 show that around 9,625 gigatons have decreased around the globe (Fig. 1). Notably, about 84% of them fell in the northern hemisphere. Greenland, which is believed to contribute

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significantly to sea-level rise along with the Antarctic ice sheet on land ice melting, reduced 1,237 gigatons, about 13% of total glacier decline (Zemp et al., 2019). As an extreme example, on July 13, 2019, about 2 billion tons of surface ice melted around the Qaanaaq in Greenland in a day, resulting in a dog pull a sled on water-covered ice (reported by Steffen M. Olsen at Danish meteorological institute). Thus, the cryosphere decline in the Arctic is occurring seriously and requires constant monitoring. For the unites states national aeronautics and space administration (NASA) and the ESA, the Arctic cryosphere is monitored using various types of satellites (Forsberg et al., 2018; Kaljord and Andersen, 2018; Tschudi et al., 2016; Zakharova et al., 2018). Canada, Germany, and Japan have also joined forces to continuously monitor the changes in the cryosphere that are taking place in the northern hemisphere. Satellite remote sensing is an integral part of the Arctic research conducted in each country (The White House, 2013). The Arctic is a large area that is difficult to observe with general research equipment and is an extreme environment where human access is difficult. Therefore, satellite remote sensing is the most appropriate and effective way to see the polar region.

Along with recent weather changes, Korean scientists are conducting polar remote sensing using satellite to cope with environmental changes in the Arctic actively. One example is that the Korea polar research institute (KOPRI) organized a the Satellite remote sensing and cryosphere information center in 2016 to monitor changes in the Arctic ice field using satellites. In particular, they are researching Arctic sea ice using Korean Arirang satellite (which is known as the name of KOMPSAT, Korea multi-purpose satellite) for the first time in Korea (Kim et al., 2018). KOMPSAT is a low orbit earth observation satellite. KOMPSAT-2 and -3 with optical and KOMPSAR-5 has imaging radar. Korea aerospace institute (KARI) developed and operating them.

In this paper, the author review advances in Korea's remote sensing research for the polar cryosphere over the last several years. In addition to satellite remote sensing, interdisciplinary studies are needed to resolve the current limitations on research on climate change.

2. Korea remote sensing activity in the Arctic

2.1. Satellite remote sensing and cryosphere information center

Since 2016, The satellite remote sensing and cryosphere information center in KOPRI starts to observe various changes in rapidly changing cryosphere and climate factors (Kim et al., 2018). They have studied changes in the cryosphere through remote sensing using

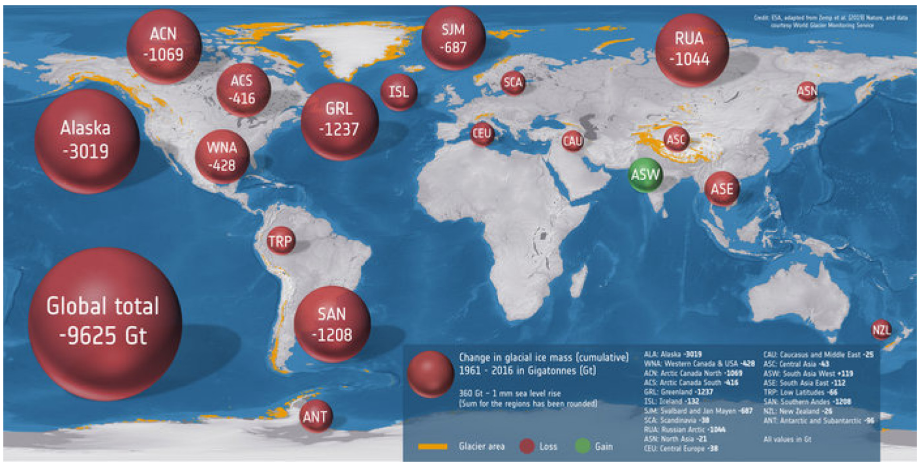

Fig. 1. Global glacier mass loss during 1961 to 2016 (figure from Zemp et al., 2019).

Fig. 2. A schematic illustration on the introduction of scientific research for sea ice at the Arctic Ocean using satellites. Courtesy by Korea polar research institute.

satellites and unmanned aerial vehicles (UAVs) (Fig. 2). Observation of changes in the extreme polar cryosphere is used to conduct joint studies with climate prediction model researchers to identify climate extremes on the Korean peninsula. Besides, the accumulated cryosphere information will be used as environment data for the coming era of the Arctic. For example, the use of sea ice information around the northern sea route. By visualizing the change of the cryosphere, which is the issue of warming as a cause of abnormal climate, using satellites, it contributes to interest in the polar region and interest in global climate change. Particularly in the polar region, joint research based on international cooperation is essential. Proactive polar remote sensing research is underway through the satellite remote sensing groups and memorandum of understanding (MoU) from various countries. They are currently conducting a joint investigation with the national snow and ice data center (NSIDC) in the United States (US), the international arctic research institute (IARC) and the Nansen environmental remote sensing center (NERSC) in Norway through MoU.

2.2. A system for data archive/manage

The changes in the polar cryosphere are the most direct result of the phenomena caused by warming. Most necessary is an acquisition of satellite data to monitoring changes in the cryosphere of vast and inaccessible. To this end, KOPRI has established a system for satellite data archiving and managing to systematically monitoring a cryosphere (Fig. 3). The most significant advantage of the system is to obtain the KOMPSAT data continually. KOMPSAT data, which are necessary for the monitoring of the Arctic and Antarctic cryosphere, are collected through close cooperation between the Korea aerospace research institute (KARI) and KOPRI. The system can automatically archive and efficiently manage a massive amount of satellite data from various countries, including the KOMPSAT. Besides, it can be easily accessible due to the system work through the web, which is in the internet environment.

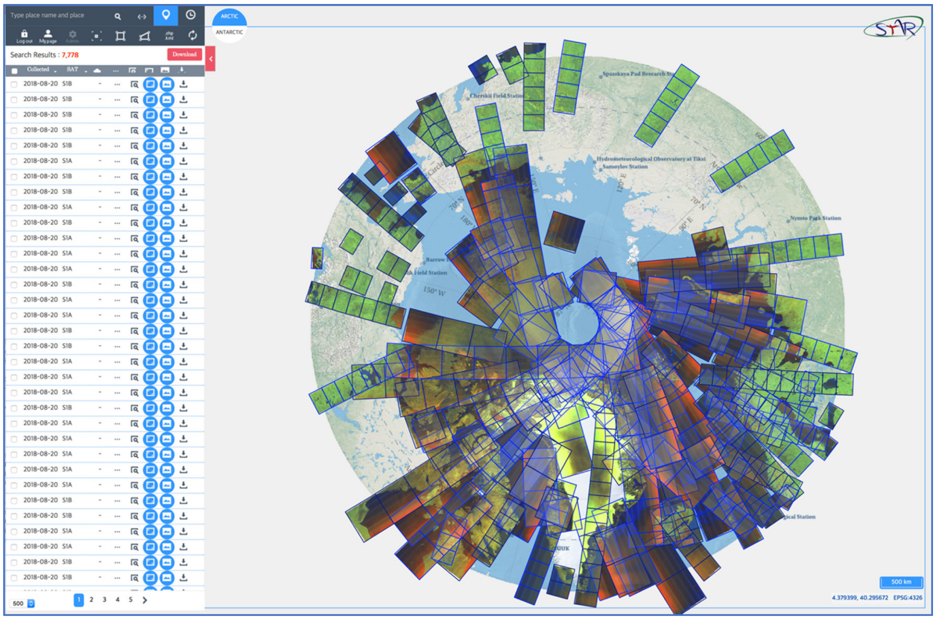

Fig. 3. Example of a web-based system, KOPRI satellite data archiving and managing system (figure from Kim et al., 2018).

2.3. Sea-ice remote sensing data processing

KOMPSAT-2, -3, -3A, -5 and other satellite data such as from NASA and ESA used to obtain precise and various sea ice information. Sea ice information is of great value in itself, and it also most importantly considered as an input parameter for studying changes in the cryosphere as a result of global warming. For this, sea ice thickness, sea ice surface roughness, sea ice extent, and sea ice surface temperature are necessary information for the numerical prediction model of climate. To get this information, the KOPRI remote sensing group analyzes the satellite data needed to characterize the sea ice characteristics and proceed with signal processing suitable for each satellite data, especially for KOMPSAT data. Besides, every year, the group conducts the Arctic sea ice fieldwork by using the Korean ice breaking-research vessel (IBRV), Araon, to investigate the physical properties of sea ice directly. They used the field data to improve the accuracy of satellite data processing. Moreover, they also uses the survey data to develop a new satellite algorithm to retrieve sea ice information.

2.4. International satellite observing network

Unlike Antarctica, the Arctic Ocean has an exclusive economic zone (EEZ) in coastal countries. Due to the area of the Arctic Ocean is about 14 million km^2, an international network is essential, like joint observation using satellites operated by each country. There are several programs already in progress, such as the European union's Copernicus program (http://www.copernicus.eu). However, there are still gaps in the aspect of regional coverage and satellite operation due to the width and varying Arctic Ocean. Therefore, it is necessary to fill the gap of an existing satellite network program. The KOPRI's Arctic satellite remote sensing program contributes to the research group as being carried out fulfill the gaps by using the Korean satellite, even though, Korean satellite, KOMPSAT, is not much applicated for the international. In the Arctic Ocean, the Korean Arctic research team surveyed the central Arctic Ocean to contribute to the intranational community by using IBRV Araon. This effort for contribution is a new study area between the Arctic research community. To

Fig. 4. Schematic features of near-polar orbit KOMPSAT series such as KOMPSAT-2, KOMPSAT-3, KOMPSAT-3A, and KOMPSAT-5 in order from left to right (http://www.si-imaging.com/ products).

this end, the group is working on mutual research cooperation with NSIDC and IARC in the US, NERSC in Norway, and the Hokkaido university-Arctic research center (HU-ARC) in Japan through MoU.

3. Sea-ice Satellite Remote Sensing in Korea

Of the last several years, the KOPRI's remote sensing program was the first and the only in Korea to concentrate on a satellite remote sensing research for Arctic sea ice (Kim et al., 2018). The satellite remote sensing and cryosphere information center in KOPRI has researched precise sea ice remote sensing using satellite and UAV. With satellite data from different countries, the KOMPSAT has used for research on Arctic sea ice remote sensing as the first time. This activity levels up Korean polar remote sensing, and it led to a leading role in international networks. Based on these activities on Arctic sea ice, the KOPRI is working as a representative research group of Korea to the International Arctic observation system (INTAROS, http://www.intaros.eu), which is a consortium in the European union and other countries have interest in the Arctic. In addition to, KOPRI and KARI will participate in the international Arctic drift expedition study, the multidisciplinary drifting observatory for the study arctic climate (MOSAiC, http://www.mosaic-expedition.org) from September 2019. In this section, the author will review a brief result of research conducted using KOMPSAT through the polar remote sensing program.

3.1. Applications of KOMPSAT-5 satellite

KOMPSAT-5 is South Korea's first satellite equipped with X-band synthetic aperture radar (SAR), which launched in August 2013 and operated at KARI, which has seven observation modes with different spatial resolutions. Also it has 28 days of the revisit period.

Han et al. (2017) conducts it as the first that the high-resolution KOMPST-5 apply to develop a sea-ice-mapping model based on the random forest. For this, KOMPSAT-5 data observed during summer in the Chukchi Sea from August to September 2015 (Fig. 5). Using 12 texture features from the KOMPSAT-5, authors provide input variables for the sea ice mapping model. The modeled sea ice map has 125 m in spatial resolution, which has excellently classified sea ice and open water with an accuracy of around 99%. Through the comparison with an ice chart, which provided by the Arctic and Antarctic research institute (AARI) of Russia, their sea ice concentration retrieved from the modeled sea ice map has the mean and median values of approximately 8.9% and 8.4%, respectively (Han et al., 2017).

Moreover, they conduct an accurate passive microwave sea ice concentration in the summer by using the Korea satellite, KOMPSAT. Even though a sea ice concentration derived from satellite PM sensors in polar regions since the 1970s, however, the accuracy of the passive microwave sea ice concentration is typically low and biased in summer. Hence there is necessary to evaluate the accuracy of the passive microwave sea ice concentration quantitatively and to

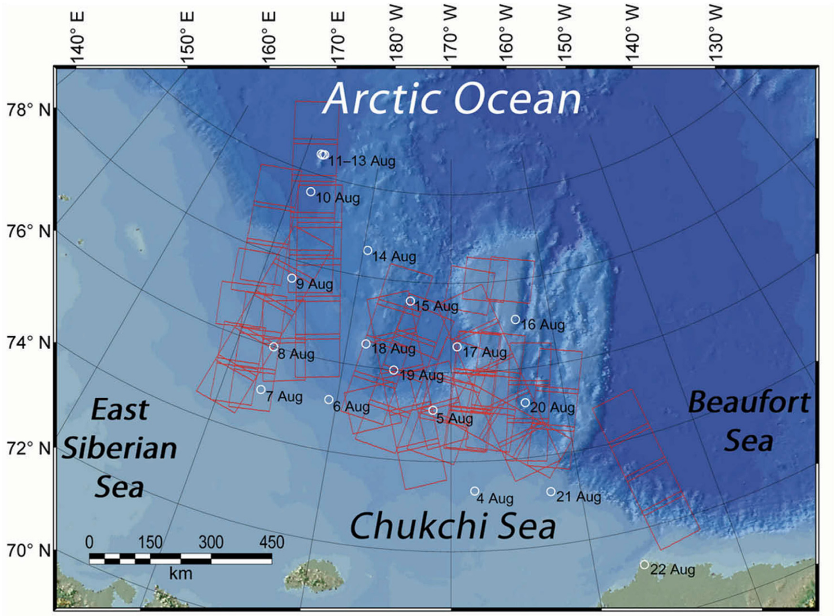

Fig. 5. Location of the KOMPSAT-5 samples (red boxes) in the Chukchi Sea of the Arctic Ocean (figure from Han et al., 2017).

account for its errors to provide more accurate information for climatic research. KOPRI evaluated the sea ice concentration data from a passive microwave using four representative sea ice algorithms, such as an algorithm of NASA team, the bootstrap algorithm, a hybrid algorithm of the ocean and sea Ice satellite application facility, and an algorithm from the Arctic radiation and turbulence interaction study sea Ice.

There is more critical research for the Arctic sea ice by using KOMPSAT. The authors extend their research on the Chukchi Sea in the summer using KOMPSAT-5. Classification of Ice and water was conducted more accurately by using a binary classification of texture features in the synthetic aperture radar images based on the random forest method. In their study, the estimated values of the sea ice concentration from KOMPSAT-5 showed different error trends than the commonly used sea ice concentration from passive microwave data, for example, sea ice concentrations from the NASA team algorithm, the bootstrap algorithm, the hybrid algorithm, and the algorithm from the Arctic radiation and turbulence interaction study sea ice. All four algorithms showed the overestimation of sea ice concentration in open drift ice zones. The NASA team algorithm showed largely underestimated sea ice concentration in marginal ice zones, while the bootstrap and the Arctic radiation and turbulence interaction study sea ice algorithms overestimated them considerably. All algorithms, except for the bootstrap algorithm, underestimated sea ice concentration in consolidated pack ice zones (Table 1). The authors found that the overestimation of some algorithm was influenced mainly by atmospheric water vapor content, while the underestimation of sea ice concentration was due to ice surface melting. They concluded that the differences in sea ice concentration from each algorithm were due to different sensitivities to atmospheric water vapor content in the regions (Han and Kim, 2018).

3.2. Applications of KOMPSAT-2 and -3 satellites

The KOMPSAT-2 and -3 equipped optical imaging sensors to acquire high-resolution images. The sensors on the satellite enable the acquisition of on panchromatic and four multispectral bands (Table 2). The KOMPSAT-2 and -3 have a spatial resolution of 1 and 0.7 m for panchromatic, respectively. Also they have 4 and 2.8 m for the multispectral band, respectively.

Table 1. Descriptive statistics of sea ice concentration (SIC) values from KOMPSAT-5 and sea ice algorithms for all SIC ranges, as well as for the open drift ice zone, marginal ice zone, and consolidated pack ice zone (table modified from Han and Kim, 2018)

SIC data		Mean (%)	Median (%)	CV	Min. (%)	Max. (%)
All SIC ranges	KOMPSAT-5	25.63	15.81	1.04	1.02	99.97
	NASA team	23.58	19.2	0.81	0.00	86.25
	Bootstrap	38.23	37.47	0.76	0.00	100.00
	OSISAF	27.45	20.66	0.89	0.00	100.00
	ASI	32.16	25.13	0.87	0.00	98.40
Open drift ice zone	KOMPSAT-5	6.18	5.20	0.65	1.02	14.92
	NASA team	10.77	11.00	0.77	0.00	42.00
	Bootstrap	16.31	13.00	0.88	0.00	56.14
	OSISAF	11.60	10.83	0.67	0.00	53.32
	ASI	10.54	6.43	1.17	0.00	69.97
Marginal ice zone	KOMPSAT-5	35.81	30.12	0.47	15.21	79.54
	NASA team	30.31	28.80	0.42	0.00	68.00
	Bootstrap	53.25	50.17	0.36	0.00	100.00
	OSISAF	35.18	31.17	0.53	1.53	97.81
	ASI	47.44	48.09	0.41	2.87	87.44
Consolidated pack ice zone	KOMPSAT-5	93.44	95.93	0.06	81.13	99.97
	NASA team	67.78	70.80	0.15	41.20	82.40
	Bootstrap	94.96	98.18	0.08	77.10	100.00
	OSISAF	85.85	87.31	0.17	46.89	100.00
	ASI	84.91	84.64	0.09	68.88	98.40

CV: coefficient of variation, OSOSAF: the ocean and sea Ice satellite application facility, ASI: the Arctic radiation and turbulence interaction study sea ice

Table 2. Specifications of the imaging sensors of KOMPSAT-2 and -3 and imaging sensors. PAN: panchromatic, MS: multispectral. (table modified from Hyun and Kim, 2017)

	KOMPSAT-2	KOMPSAT-3
Date of launch	Jul 28, 2006	May 17, 2012
Main payload	Multispectral Camera	Advanced Earth Imaging Sensor System
Orbit height	685 km	685 km
Spatial resolution	1.0 m PAN and 4.0 m MS	0.7 m PAN and 2.8 m MS
Spectral bands	500-900 nm PAN 450-520 nm MS1 (blue) 520-600 nm MS2 (green) 630-690 nm MS3 (red) 760-900 nm MS4 (NIR)	450-900 nm PAN 450-520 nm MS1 (blue) 520-600 nm MS2 (green) 630-690 nm MS3 (red) 760-900 nm MS4 (NIR)
Mean local time on ascending node	10:50 hours	13:30 hours
Data quantization	10 bit	14 bit
Swath width	15 km	16 km

KOMPSAT-2 and -3 provide high-resolution optical images, includes information on the precise and diverse surface morphology of sea ice. Time-series of optical images can provide accurate information on the deformation and movement of sea ice, result in the most productive research on sea ice formation. In polar regions, however, a long-time horizon and a cloudy atmosphere restrict the use of the high-

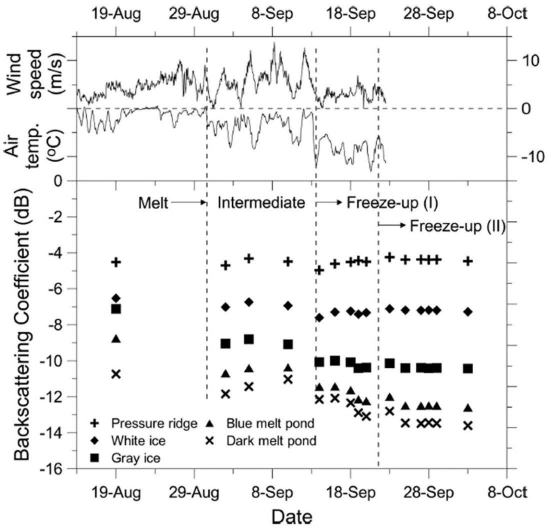

Fig. 6. Changes in the class mean backscattering coefficient of TerraSAR-X observations between Aug. to Oct. 2014 (Park et al. 2016).

resolution optical sensors in the Arctic.

Never the less these limitations in the Arctic, there was working to secure optical image sampling by KOMPSAT-2 and -3 within a collaboration between KOPRI and KARI during the annual survey of Arctic sea ice since several years. This chapter introduces the sea ice studies conducted using optical images.

The study of sea ice using KOMPSAT optical images conducted for the first time in 2014. Melt ponds formed on the sea ice surface affect the scattering characteristics of the synthetic aperture radar image (Rösel et al., 2012). However, it is not easy to detect melt ponds (Park et al., 2016). Park et al. (2016) studied the effect of melt ponds on KOMPSAT-3 images in the sea ice study using X-band HH-polarization synthetic aperture radar images (Park et al., 2016).

Melt ponds are considered as an essential parameter in sea ice dynamics due to accelerating the melting sea ice in the warmer season form their solar absorption radiation (Eicken et al., 2004; Park et al., 2016; Schröder et al., 2014). Park et al. (2016) conducted a high-resolution time-series analysis of the short-term variation of sea ice and melt ponds over the Beaufort Sea using space-borne multispectral and synthetic aperture radar images. The authors conduct an initial classification of the surface types by the KOMPSAT-3 optical image. In their study, using 15 TerraSAR-X synthetic aperture radar images covering 46 days in the 2014 Arctic summer, the authors perform a dense time-series analysis (Park et al., 2016). They classified the sea ice surface into six categories based on spectral characteristics. The authors found distinct patterns from temporal variation of the radar backscattering coefficient in each class. Moreover, it was closely related to surface changes. Thus, dynamic surface changes cause changes in the radar backscattering coefficient except over pressure ridges. The authors concluded that all ice classes show a two-step decrease in radar backscattering, whereas snow-covered ice surfaces shoed far fewer changes compared to bare ice surfaces. So surfaces around melt ponds have stronger negative declines than other classes. They also found that the changes in dark melt pond classes showed a complicated non-linear decrease, which differed from the stepwise reduction of blue melt ponds. The authors mentioned that their research would help to model of surface melting and freezing rates and to infer the variation over large areas using remote sensing data. (Fig. 6)

There was a study about sea ice motion and deformation using optical images of KOMPSATs as well. Before Hyun and Kim (2017)'s study, generally low-resolution passive microwave or mid-resolution radar remote sensing datasets of daily intervals used to study sea ice motion and deformation. Hyun and Kim (2017) conducted a feasibility study of sea ice motion and deformation measurements using high-resolution optical images of KOMPSATs. They measured the sea ice motion by using a maximum cross-correlation. They acquired multi-temporal high-resolution images on 14 through 15 August 2014 from multiple space-borne sensors onboard KOMPSATs with short acquisition time intervals (Fig. 7). The authors extracted the sea ice motion from the six image pairs of the spatial resolutions. They mentioned that the errors from both resolutions indicate more accurate measurements than from current sea ice motion datasets from passive

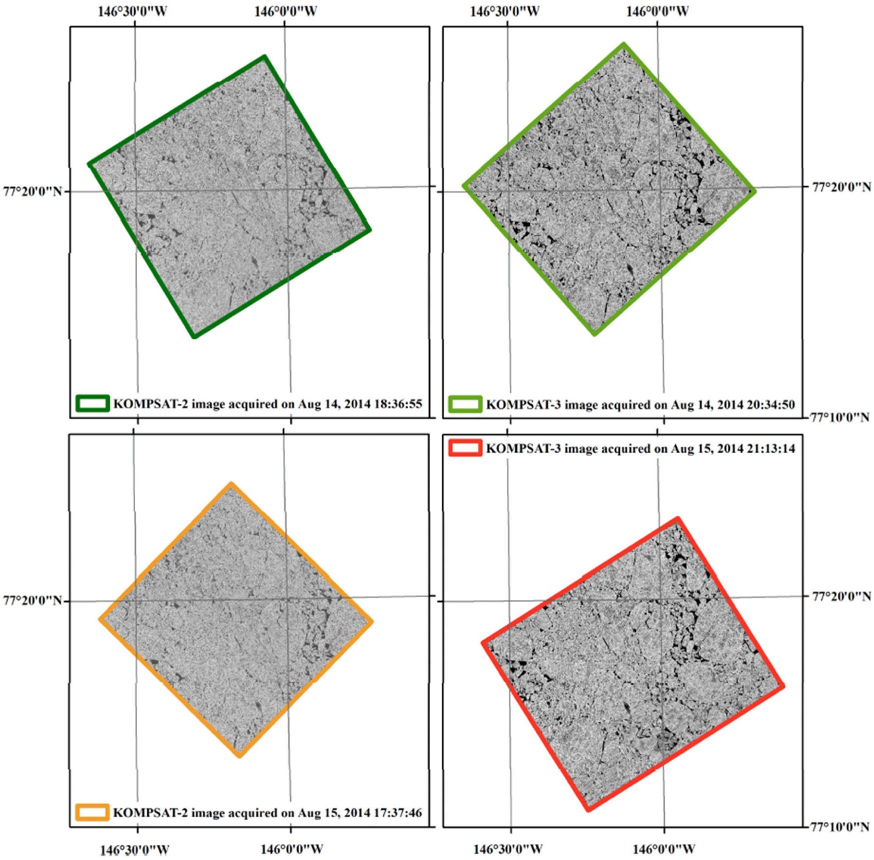

Fig. 7. Sea ice coverage captured during study the study period (Hyun and Kim, 2017).

microwave and radar data in ice and water mixed surface conditions. Moreover, they suggested the results of sea ice deformation caused by the interaction of individual ice floes, while free drift patterns of ice floes delineated from the 4 m spatial resolution images, the deformation was less revealing in the 15 m spatial resolution image pairs due to emphasized discretization uncertainty from coarser pixel sizes. Besides, they demonstrate that using multi-temporal high-resolution optical satellite images enabled precise image block matching in the melting season. Thus, their approach could be used for expanding sea ice motion and deformation datasets, with an advantage of many image acquisition capability in multiple areas employing many operational satellites.

4. Conclusion

With the frequent occurrence of extreme weather due to warming, many scientists are conducting many scenarios for future climate change due to the global cryosphere decline. The intergovernmental panel on climate change (IPCC) report has created a global warming scenario based on changes in atmospheric carbon dioxide since the industrial revolution. However, recent rapid changes are introducing more severe predictions than the IPCC's future forecasts. It concludes that accelerated warming weakens a resilient unless we do not dramatically reduce the amount of carbon dioxide in the atmosphere. At the same time, various efforts are underway to monitor the changes in the polar cryosphere by using different satellites, which can improve an understanding of the present change patterns, and will play a key role in developing a more precise climate prediction model.

In this paper, we briefly summarized the researches of Korean activities on the cryosphere using KOMPSAT, such as sea ice monitoring the Arctic. Based on these activities, Korea's KOMPSATs data will provide for international collaboration, such as MOSAiC, which is being jointly conducted by researchers all over the world. The cooperation between KARI and KOPRI, which belongs to different ministries, such as, the Ministry of Science and ICT and the Ministry of Oceans and Fisheries, respectively, to conduct joint research on climate change is Korea's active commitment to climate change. Sooner KOMPSAT-6 will launch, it will contribute to the international community for climate research.

The authors tried to share advances in Korea's remote sensing research for the polar cryosphere for the last several years as a review. Satellite remote sensing with an interdisciplinary study is essential to resolve the current limitation on research on climate change.

In this paper, Advances in Korea's remote sensing research for the polar cryosphere for the last several years was reviewed. Satellite remote sensing with interdisciplinary studies are needed to resolve the current limitation on research on climate change.

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References

Bokhorst, S., Pedersen, S.H., Brucker, L., Anisimov, O., Bjerke, J.W., Brown, R.D., Ehrich, D., Essery, R.L.H., Heilig, A., Ingvander, S., Johansson, C., Johansson, M., Jónsdóttir, I.S., Inga, N., Luojus, K., Macelloni, G., Mariash, H., McLennan, D., Rosqvist, G.N., Sato, A., Savela, H., Schneebeli, M., Sokolov, A., Sokratov, S.A., Terzago, S., Vikhamar-Schuler, D., Williamson, S., Qiu, Y., Callaghan, T.V., 2016. Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. Ambio 45, 516-537.

Chang, L., Gao, G., Li, Y., Zhang, Y., Zhang, C., Zhang, Y., Feng, G., 2019. Variations in Water Vapor From AIRS and MODIS in Response to Arctic Sea Ice Change in December 2002-November 2016. IEEE Transactions on Geoscience and Remote Sensing, 1-11.

Chu, G., Sun, Q., Zhu, Q., Shan, Y., Shang, W., Ling, Y., Su, Y., Xie, M., Wang, X., Liu, J., 2017. The role of the Asian winter monsoon in the rapid propagation of abrupt climate changes during the last deglaciation. Quaternary Science Reviews 177, 120-129.

Dong, L., Mitra, C., Greer, S., Burt, E., 2018. The Dynamical Linkage of Atmospheric Blocking to Drought, Heatwave and Urban Heat Island in Southeastern US: A Multi-Scale Case Study. Atmosphere 9, 33.

Forsberg, R., Sørensen, L., Simonsen, S., Barletta, V., Kusk, A., Nagler, T., Hetzenecker, M., Shepherd, A., Groh, A., Solgaard, A., Engdahl, M., 2018. 25 Year Time Series of Multiple-Satellite Ice Sheet Changes: the ESA Climate Change Initiative. 200.

Han, H., Kim, H.-c., 2018. Evaluation of summer passive microwave sea ice concentrations in the Chukchi Sea based on KOMPSAT-5 SAR and numerical weather prediction data. Remote Sensing of Environment 209, 343-362.

Kaljord, A.H., Andersen, S.I., 2018. Integration of Multi-Mission Satellite Data, Weather and Ice Information for Arctic Operations, OTC Arctic Technology Conference. Offshore Technology Conference, Houston, Texas, USA, p. 11.

Kim, B.-M., Hong, J.-Y., Jun, S.-Y., Zhang, X., Kwon, H., Kim, S.-J., Kim, J.-H., Kim, S.-W., Kim, H.-K., 2017. Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm. Scientific Reports 7, 40051.

Kim, H.-c., Han, H., Hyun, C.-U., Chi, J., Son, Y.-s., Lee, S., 2018. Research on Analytical Technique for Satellite Observstion of the Arctic Sea Ice. Korean Journal of Remote Sensing 34, 1283-1298.

Knutti, R., Rogelj, J., Sedláèek, J., Fischer, E.M., 2015. A scientific critique of the two-degree climate change target. Nature Geoscience 9, 13.

Park, J.-W., Kim, H.-C., Hong, S.-H., Kang, S.-H., Graber, H.C., Hwang, B., Lee, C.M., 2016. Radar backscattering changes in Arctic sea ice from late summer to early autumn observed by space-borne X-band HH-polarization SAR. Remote Sensing Letters 7, 551-560.

Plummer, S., Lecomte, P., Doherty, M., 2017. The ESA Climate Change Initiative (CCI): A European contribution to the generation of the Global Climate Observing System. Remote Sensing of Environment 203, 2-8.

Ronalds, B., Barnes, E., Hassanzadeh, P., 2018. A Barotropic Mechanism for the Response of Jet Stream Variability to Arctic Amplification and Sea Ice Loss. Journal of Climate 31, 7069-7085.

Saunier, S., Northrop, A., Lavender, S., Galli, L., Ferrara, R., Mica, S., Biasutti, R., Goryl, P., Gascon, F., Meloni, M., Desclee, B., Altena, B., 2017. European Space agency (ESA) Landsat MSS/TM/ETM+/OLI archive: 42 years of our history, 2017 9th International Workshop on the Analysis of Multitemporal Remote Sensing Images (MultiTemp), pp. 1-9.

Serreze, M.C., Barry, R.G., 2014. The Arctic Climate System, 2 ed. Cambridge University Press.

Serreze, M.C., Stroeve, J., 2015. Arctic sea ice trends, variability and implications for seasonal ice forecasting. 373.

The White House, 2013. National Strategy For The Arctic Region.

Tschudi, M.A., Stroeve, J.C., Stewart, J.S., 2016. Relating the Age of Arctic Sea Ice to its Thickness, as Measured during NASA's ICESat and IceBridge Campaigns. Remote Sensing 8, 457.

Wu, Z., Wang, X., 2018. Variability of Arctic Sea Ice (1979–2016). Water 11, 23.

Zakharova, E., Nielsen, K., Krylenko, I., Kouraev, A., 2018. Potential of the Radar Altimetry for Estimation of the River Input to the Arctic Ocean. 103. Abstract from 25 years of progress in radar altimetry symposium, Portugal.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N., Cáceres, B.E., Casassa, G., Cobos, G., Dávila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Ove Hagen, J., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015. Historically unprecedented global glacier decline in the early 21st century. Journal of Glaciology 61, 745-762.

Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., Thomson, L., Paul, F., Maussion, F., Kutuzov, S., Cogley, J.G., 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature 568, 382-386.

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