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VARIABILITY OF ICE-ALBEDO IN THE ARCTIC (2010-2012)

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ABSTRACT – Studies of albedo in the Arctic are essential because of the rapidly changing ice and snow cover in the region and the associated impact on the Earth's heat and energy balance. This study examined the large-scale variability of the narrow band albedo (NBA) in the Arctic using the EOS/Aqua MODIS data from 2010 to 2015. Seasonal and interannual changes in the different components of the Arctic cryosphere, including the sea ice cover, Greenland ice sheet, and the snow-covered and permafrost regions of North America and Eurasia, have been quantified. The data show a seasonal pattern indicating high albedo during spring, progressively declining towards low values during the summer season. The NBA varies considerably across the four sectors: Eurasia, Sea Ice, North America, and Greenland. Results show that the NBA for Eurasia, Sea Ice, North America, and Greenland ranged from 0.08-0.81, 0.23-0.75, 0.07-0.73, and 0.78-0.95, respectively. Generally, the correlations of NBA and surface temperature over Eurasia, Sea Ice, North America, and Greenland were weak, ranging from 0.07-36 in 2012 and 0.17-0.47 in 2014. Also, correlation analysis showed that NBA has a moderately high connection with SIC ($r = 0.80$), SIE ($r = 0.80$), and SIA ($r = 0.61$) based on sample years (2012 and 2015). The spatial variation of the NBA is mainly due to the regional variation in the mixture of ice types and their snow cover. The observed variability in NBA was a combination of a gradual evolution due to seasonal transitions and abrupt shifts resulting from synoptic weather events. Moreover, several factors affect the NBA in the Arctic, such as snow metamorphism, changing SIC, SIE, and SIA.

Keywords: ice surface temperature, narrow band albedo, reflectance. sea ice concentration, sea ice area, sea ice extent

INTRODUCTION

Albedo is one of the basic elements of the Earth's radiation budget and significantly influences the global climate system (Vesa Laine, 2013). It is a vital and critical component of the atmospheric circulation system and the spatial distribution of heat around the globe. Generally, albedo is defined as the fraction of the incident downward solar irradiance that is reflected from the surface. In particular, it is the

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integral of the contribution from the entire visible spectrum, which for some is from 400 to 1,500 nm (Perovich et al. 1998), while for others, it is from 300 to 3,000 nm (Hanesiak et al. 2001). Variability of its value could translate into large fractional changes in absorbed solar radiation (ASR) and in the overall energy budget at the ice surface (Carroll and Fitch, 1981; Pirazzini, 2004).

In the Arctic, the study of albedo is especially important because of the rapidly changing sea ice cover (Comiso et al., 2008). The changes in the ice cover are likely associated with polar systems. This is influenced primarily by ice-albedo feedback caused by the strong contrast in the reflectivity of snow-covered surfaces, bare liquid, or vegetation-covered surfaces. In particular, the absorbed net shortwave radiation is usually small in the Arctic (Warren, 1982) because the snow-covered ice reflects between 80% and 90% of sunlight, while the dark ocean without ice cover reflects only 7% of the light (Hudson et al. 2013). As the sea ice cover decreases, less solar radiation is reflected away from the Earth's surface in a feedback effect causing the absorption of more heat and the consequent rapid melting of ice. Changes in the surface's albedo also provide helpful information about its changing character and may be associated with changing the amount of liquid water in the snow-covered surfaces or changing vegetation in the tundra.

It has been elucidated that a drop of as little as 0.01 in Earth's albedo would have a major warming influence on climate — roughly equal to the effect of doubling the amount of carbon dioxide in the atmosphere, which would cause Earth to retain an additional 3.4 watts of energy for every square meter of surface area. Similarly, scientists from the University of California, San Diego, have analyzed Arctic satellite data from 1979 to 2011 and have found that average Arctic albedo levels have decreased from 52 percent to 48 percent since 1979. The amount of heat generated by this decrease in albedo is equivalent to roughly 25 percent of the average global warming currently occurring due to increased carbon dioxide levels (Poppick, 2014).

Changes in albedo have been occurring in other parts of the Arctic as well. Significant greening trends in the Arctic Tundra have been observed as a result of general warming associated with declining sea ice cover (Bhatt et al., 2013). Loss of albedo in the Arctic will also accelerate warming across the permafrost, releasing methane, a much more potent greenhouse gas than CO2. Melting permafrost may also reduce its albedo, which is another positive feedback that will accelerate warming. Widespread melting on the Greenland Ice Sheet was also observed during the spring and summer seasons of 2012. (Hall et al., 2013). An estimated 97 percent of the ice surface was melting with an unusually high melt index (MI). MI is calculated by multiplying the number of days when melting occurred by the area that melted. Compared to the 1979–2012 average, the 2012 MI was +2.4, nearly twice the previous MI record set in 2010. On average, the Northern Hemisphere now absorbs about 100 PetaWatts more solar energy because of snow and ice cover changes. One hundred PetaWatts is seven-fold greater than all the energy humans use in a year (Flanner et al., 2011).

This study uses EOS/Aqua data to study the seasonal and interannual variability of surface albedo in the Arctic. Realistic estimates of broad-band albedo at adequate spatial scales are a prerequisite for a realistic estimation of the global energy balance and detecting changes in the radiation balance of the global climate system (Laine, 2004). As an initial effort, we focus on the variability of the narrow band albedo (NBA) to gain insight into the connection of the changing Arctic to the changing albedo of the region. In particular, the NBA was used to study relationships with surface temperature, sea ice cover, and the extent of sea ice.

TECHNIQUE

Processing of MODIS reflectance and infrared data

This study examined the large-scale variability (5km resolution) of the NBA in the Arctic using the EOS/Aqua MODIS data. The primary data used is surface reflectance (MYD09CMG) from 2012 to 2015, which was downloaded from the NASA GSFC DAAC. The data was produced by the Land Surface Reflectance Science Computing Facility (NASA GSFC Terrestrial Information Systems Laboratory). MODIS Surface Reflectance is a seven-band product computed from the MODIS Level 1B land bands 1, 2, 3, 4, 5, 6, and 7. The surface spectral reflectance for each band has been corrected to take into account atmospheric effects, including those from atmospheric gases, aerosols, and thin cirrus clouds. In particular, the top of the atmosphere reflectance has been converted to surface reflectance using a radiative transfer model that utilizes atmospheric input profiles of aerosol and water vapor from MODIS and ozone and atmospheric pressure from the National Centers for Environmental Prediction (NCEP). The surface reflectance product has also been used to generate several land products such as vegetation indices, BRDF, land cover, snow cover, thermal anomalies, and LAI/FPAR (http://modis-sr.ltdri.org).

A customized Interactive Data Language (IDL) program was developed to retrieve the reflectivity, Ice Surface Temperature (IST), Sea Ice Concentration (SIC), Sea Ice Extent (SIE), and Sea Ice Albedo (SIA) from the downloaded MODIS products. IDL is a programming language used for data analysis. IDL shares a common syntax with PV-Wave and originated from the same codebase, though the languages have subsequently diverged in detail (https://www.ittvis.com/idl/). There are also two free implementations, GNU Data Language (GDL) and Fawlty Language (FL). IDL is vectorized, numerical, and interactive and is commonly used for the interactive processing of large amounts of data (including image processing).

Data on daily, weekly, and monthly reflectivity values used in this study were averaged over Greenland, Sea Ice, Eurasia, and North America. Daily reflectivity (narrow band albedo) over the Arctic region was retrieved from band 1 of the global surface reflectance MODIS product (MYD09CMG). The maximum daily reflectivity was then extracted using a three-day moving window to filter out the maximum daily reflectance within the 3-day window. On the other hand, weekly reflectance was obtained by taking the average 7-day reflectance without the filter. This was to preserve the original reflectance data. The monthly reflectance projection was then likely obtained by summing up the daily reflectance over the month divided by the number of valid data within the month. Spatial and temporal data were analyzed.

In general, the MODIS-derived IST provides an excellent measurement of the actual temperature of the surface of the sea ice.

Sea ice cover

The sea ice cover has been considered a key component of the climate system and an indicator and driver of high-latitude climate change. As such, numerous methods have been developed to estimate sea ice concentration. In this study, we use passive microwave data derived using the Bootstrap Algorithm (Comiso and Nishio, 2008), which is one of the most widely used algorithms for sea ice. For optimum accuracy, EOS/Aqua AMSR-E and GCOM-W/AMSR-2 data were used with SSM/I data used to fill in the gap in coverage in 2011-2012. Passive microwave sensors provide day/night almost all-weather coverage and have been available at a resolution of 12.5 by 12.5 km from AMSR-E and AMSR-2 and 25 by 25 km from SSM/I.

RESULTS

The study area

The study area is the Arctic region, as shown in Figure 1. The Arctic is located at the northernmost part of the Earth. The Arctic consists of the Arctic Ocean and parts of Alaska (United States), Canada, Finland, Greenland (Denmark), Iceland, Norway, Russia, and Sweden. The Arctic region consists of a vast ocean with a seasonally varying ice cover, surrounded by treeless permafrost. The area can be defined as north of the Arctic Circle (66° 33'N), the approximate limit of the midnight sun, and the polar night. Alternatively, it can be defined as the region where the average temperature for the warmest month (July) is below 10 °C (50 °F); the northernmost tree line roughly follows the isotherm at the boundary of this region (https://www.feelingeurope.eu/Pages/arctic%20region.html).

This study focuses on four sectors, namely: Greenland, North America, Sea Ice, and Eurasia (Figure 1).

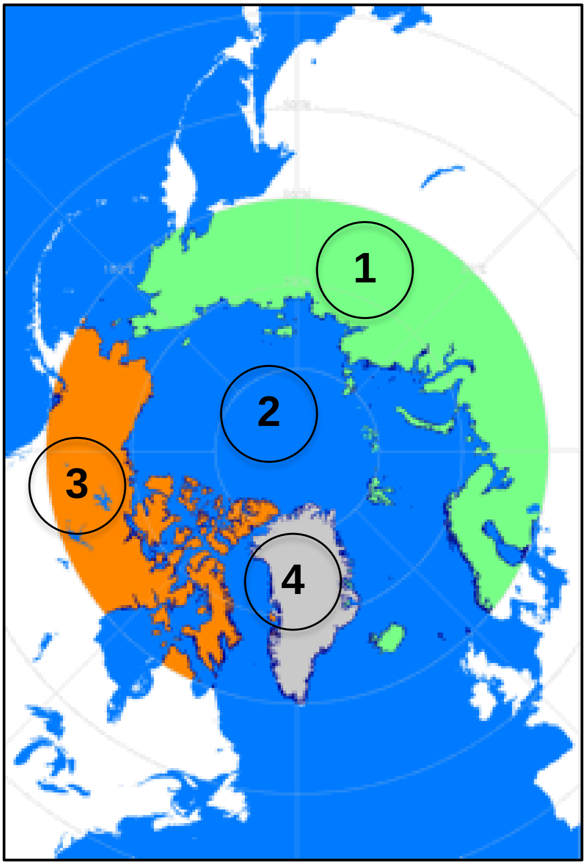

Figure 1. The study area: 1. Eurasia, 2. Sea Ice, 3. North America, and 4. Greenland.

Spatial distribution in spring and summer

Pixel-based maps have been prepared for the 2012 average spring (April and June) and summer (August and October) NBA of the study area (Figure 2) to illustrate the spatial distribution and provide a detailed image. Figure 2 shows distinctly different patterns of change in April, June, August, and October. The maps show the seasonal cyclic pattern wherein NBA is high during the onset of spring and progressively declined during the duration of the summer season. The NBA varies considerably across the four sectors: Eurasia, Sea Ice, North America, and Greenland. The observed changes in NBA were a combination of a gradual evolution due to seasonal transitions and abrupt shifts resulting from synoptic weather events. There were five distinct phases in the evolution of the NBA: dry snow, melting snow, pond formation, pond evolution, and freeze-up.

Looking at Greenland, the NBA could reach as high as 90-95% in April and could go down to as low as 78-84% in August. The average NBA in Greenland, which is almost homogenous in April, is much higher than in North America and Eurasia. The NBA regrows as the end of the summer approaches. Generally, the distribution of NBA may be closely related to seasonal IST and affected by altitude.

The seasonal distribution of the albedo values reflects that all main sea ice areas show an alternation of young and old, snow-covered and bare sea ice. Thus, the regional variation of the mean sea ice albedo is mainly due to the regional variation in the mixture of ice types and its snow cover.

Monthly and seasonal distribution across years

EOS-MODIS satellite data of snow albedo (MOD10A1 on Level 3) were used in the study to analyze the monthly and seasonal distribution of NBA of the Arctic from 2012 to 2015. The basic features of spatial changes of narrow band SIA, SIC, and IST were investigated.

Daily NBA in 2012 - 2015

Time series data of daily reflectance covering the months of spring, summer, and autumn (March – October) have been processed from advanced, very high-resolution MODIS data for the four sectors. These reflectance or albedo data are 3-day moving averages for the years 2012-2015 and were generated by time and area--averaging all the values from pixels identified as ice or snow for each sector (Figure 3). Results show that the albedo for Eurasia, Sea Ice, North America, and Greenland ranged from 0.08-0.81, 0.23-0.75, 0.07-0.73, and 0.78-0.95, respectively. Snow metamorphism is one of the main factors that affect NBA, particularly in the coastal regions, where the summer temperatures are relatively high. In the interior of the Arctic, snow metamorphism is slower due to the much lower temperatures (Pirazzini, 2004). The albedo decreases when snow ages due to the increase in snow grain size. After the new snowfall, the albedo is higher due to the small size of the snow grains. An albedo increase can also be due to snow drifting by the wind. The smallest grains of the suspended drifting snowfall last onto the surface, causing an albedo increase (Grenfell et al., 1994; Pirazzini, 2004).

On August 4-6, 2012, it was interesting to note that over Greenland, the NBA considerably dropped from 0.805 to 0.734. This decline may be attributed to the occurrence of a cyclone during this period that created melt ponds. These ponds, which form as snow and ice melt under the Arctic sun, can dramatically increase the amount of solar radiation the ice absorbs. This warms the surface and eventually affects the melting of sea ice. Pond-covered ice is seen as similar to open water. Open water reflects less of the shortwave radiation; hence there is more heat available to melt the surface of the ice. The albedo, however, immediately recovered from August 6-10, 2012.

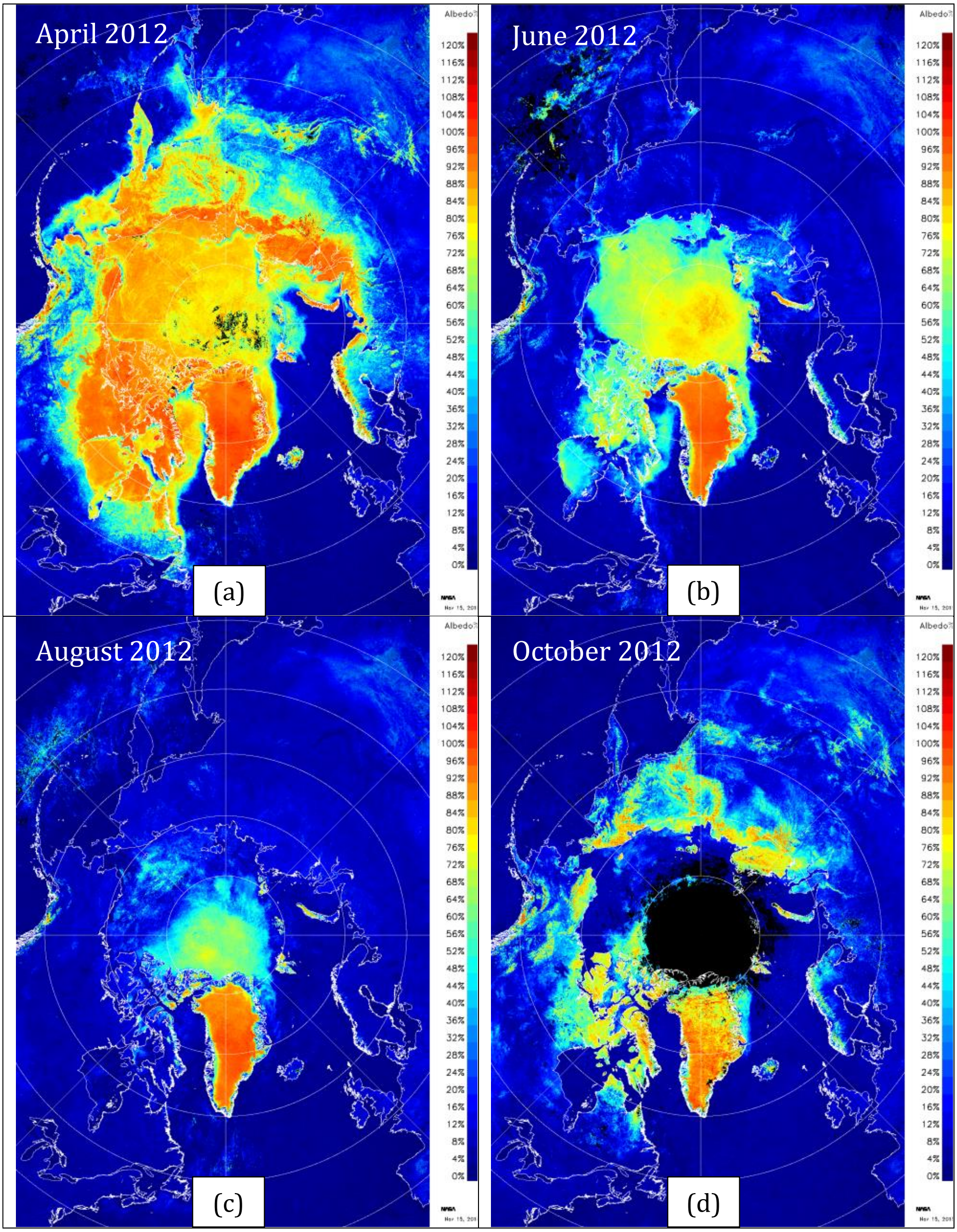

Figure 2. Spatial distribution of monthly albedo of the Arctic region in (a) April 2012, (b) June 2012, (c) August 2012, and (d) October 2012.

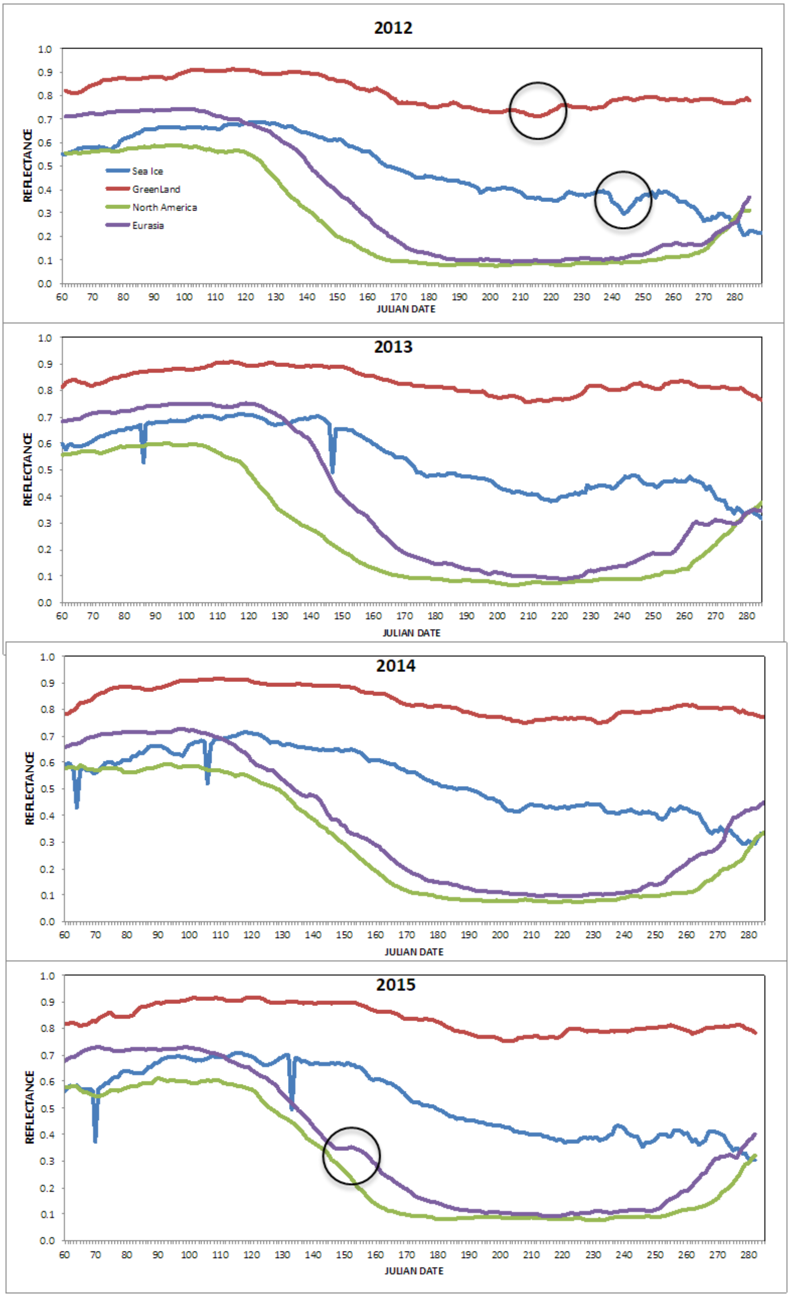

Figure 3. Comparison of seasonal narrow band albedo of Sea Ice, Greenland, Northern America, and Eurasia from 2012 to 2014 over the arctic region using 3-day moving average.

On the other hand, Figure 3 further revealed that the NBA of North America and Eurasia undergoes a dramatic steep drop from spring to summer and recovers slowly as it approaches the autumn season. Sea ice has a relatively smoother curve of NBA across seasons. Moreover, North America consistently has lower NBA values as compared to the other three sectors.

Furthermore, it was observed in Figure 3 that on 29 May – 4 June 2015, there was an unusual drop and spike (0.33-0.47) of NBA. The NBA values are generally consistent with the seasons.

The 7-day running average of NBA in Greenland as determined by elevation is shown in Figure 4. With the exception of 2012, the albedo for 2013-2014 relatively follows a normal seasonal pattern with respect to elevation. The distinct anomaly of Albedo in 2012 at an elevation of above 3000 m for the months of July-August (Figure 5) indicates some synoptic event. This supports our previous observation regarding the drop of NBA on August 4-6, 2012, from 0.805 to 0.734.

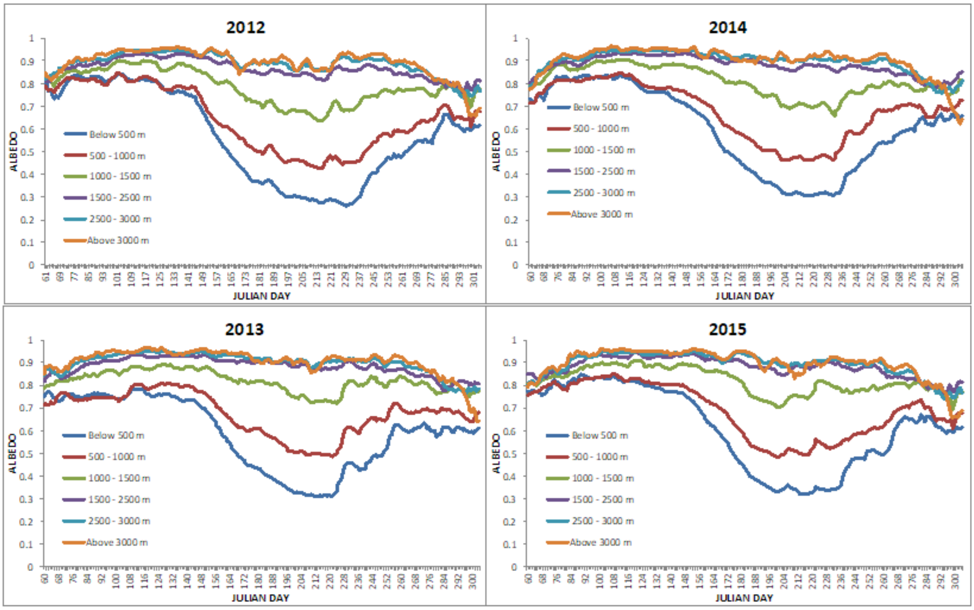

Figure 4. The 7-day running average of NBA in Greenland at a different elevation from 2012 to 2015.

Correlation analysis

Correlation between NBA and IST

Correlation analysis was conducted using the available data in 2012 and 2014 to determine the spatial and temporal correspondence between NBA and IST for the four sectors. Generally, the correlations of NBA and IST over Eurasia, Sea Ice, North America, and Greenland were weak as reflected by the low goodness of fit, ranging from 0.07-36 in 2012 and 0.17-0.47 in 2014 (Figure 6). This suggests that NBA was not sensitive to IST, implying that NBA is an integral result of more other factors. Weiss et al. (2012) explained that the ice thickness and snow cover strongly control the albedo and that the temperature is a

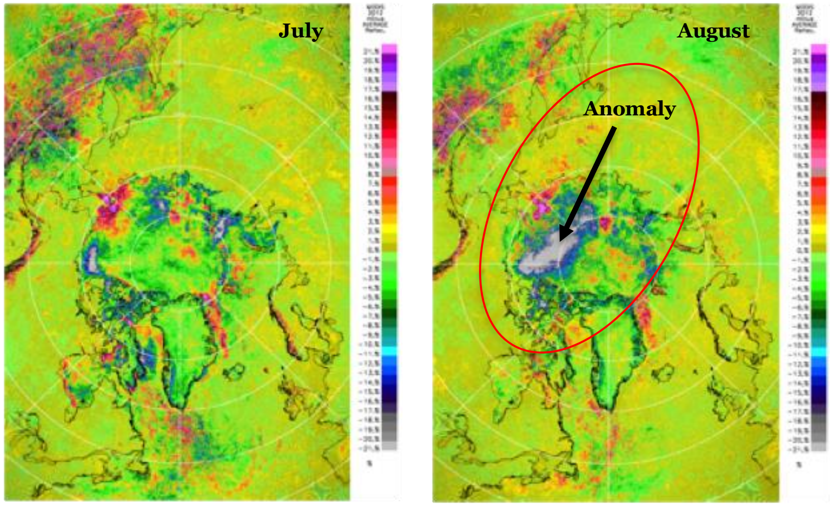

Figure 5. An anomaly of NBA in July and August 2012.

proxy for these parameters. Thicker ice with snow cover, like pack ice, has a lower surface temperature and has, in general, a higher albedo in comparison to very thin, dark nilas ice, which can be found in the polynya region and on just frozen leads. This thin ice, without snow cover, shows relatively warm temperatures near the freezing point and a low albedo. Perovich and Grenfell (1981) showed in laboratory experiments that when young sea ice like nilas becomes thicker, the albedo increases rapidly. The reason is that with the decrease in ice temperature, the amount of brine in the sea ice changes as well, which causes a change in its radiative properties. The temperature also acts as a proxy for the radiative properties of the snow cover and its evolution. The IST also influences snow metamorphosis. Colder and younger snow has generally smaller grains sizes than warmer and older snow. An increase in the average radius of the grain increases the length of a photon's travel path through the ice and decreases the number of opportunities for the photon to scatter out of the snowpack. This increases the probability of the photon being absorbed and reduces the surface albedo (Gardner and Sharp, 2010).

The lowest goodness of fit ($R^2 = 0.07$) was observed over Sea Ice, which might be due to the dilution effect of sea ice surface (SIS) on IST. The highest goodness of fit ($R^2 = 0.47$) occurred over North America, which might be attributed to some other physical factors. In a nutshell, the surface temperature is acting as a proxy for some of the physical factors, which influence the albedo of the ice-covered sea, but there are also factors that depend not directly on the temperature, such as changing cloud cover (Weiss et al., 2012). Previous experimental and theoretical model studies investigated how factors like solar zenith angle and cloud cover (Vashisth, 2005; Grenfell and Perovich, 1984), wavelength (Grenfell et al., 1994), salinity (Perovich and Grenfell, 1981), and snow cover (Brandt et al., 2005), among other factors, influence the radiative properties of sea ice. Vashisth (2005) showed that clouds have the effect of increasing the albedo of snow-covered surfaces by diffusing the incoming solar radiation and reducing the infrared radiation reaching the surface.

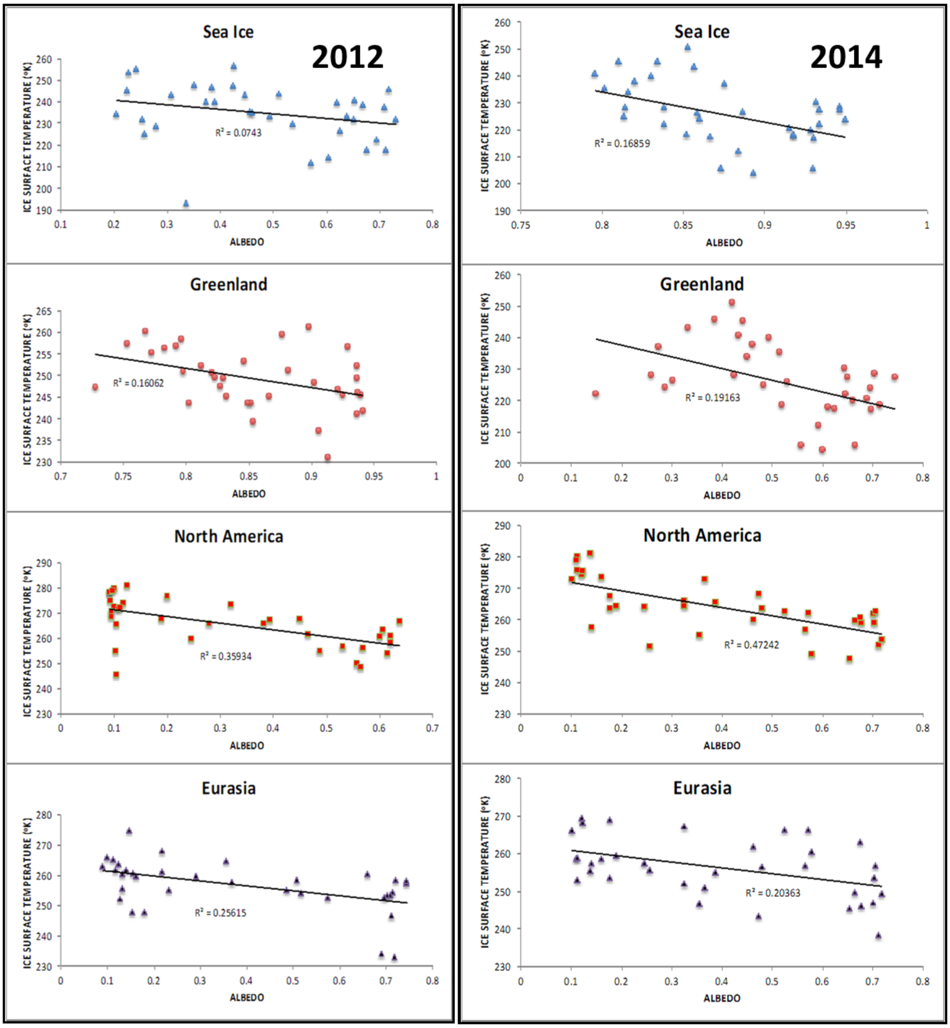

Figure 6. Correlation between sea ice albedo and ice surface temperature in 2012 AND 2014 over Sea Ice, Greenland, North America, and Eurasia.

Correlation of NBA with SIC, SIE, and SIA

A correlation analysis was performed to investigate the relation between the NBA and the three parameters (SIC, SIE, and SIA). Results showed that NBA has a moderately high connection with SIC, SIE, and SIA based on sample years (2012 and 2015), as reflected in Figure 7. In 2015, both SIE and SIA had a moderately high (r = 0.80) association with NBA. This implies that SIE and SIA have considerable influence on NBA. In contrast, a slightly lower correlation (r = 0.61) was observed between NBA and SIC.

Meanwhile, an unusually low correlation (r = 0.23) was obtained between NBA and SIC in 2012. Seemingly, the NBA does not follow the ice concentration pattern. This state might most likely have originated from several factors that are not within the scope of this study.

In regions of thin ice (low sea ice concentration), ice thinning or growth can be a significant cause of albedo change. However, in the Arctic, bare ice is usually rapidly covered by snow. Therefore, the albedo of the snow-covered sea ice depends primarily on the snow depth but also on the grain size and wetness.

Flooding by seawater and wave overwashing processes may also lower the albedo by removing the snow cover and wetting the snow. Other factors affecting albedo, such as snowfall, drift snow transport, and snow metamorphism, may be significant causes of albedo changes also in the sea ice regions.

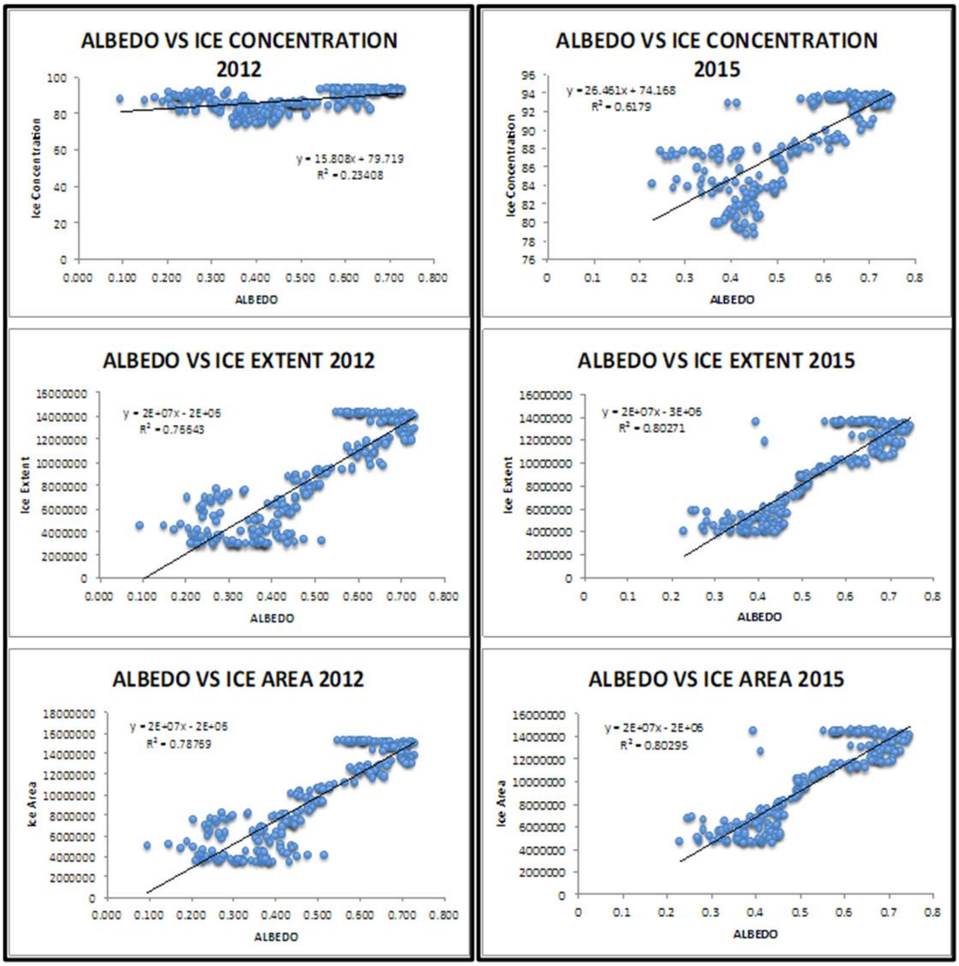

Figure 7. Correlation between NBA and three parameters (SIC, SIE, and SIA).

SUMMARY AND CONCLUSIONS

Satellite MODIS data provide the means to assess the spatial distribution of albedo in the Arctic for different seasons. It also allows for quantifying the seasonality of the surface albedo for the different components of the cryosphere and how they change from one year to another. This study makes use of the narrow-band albedo to characterize the recent changes in Arctic albedo. The NBA varies considerably across the four sectors: Eurasia, Sea Ice, North America, and Greenland. The spatial distribution of NBA is closely related to seasonal IST and is affected by altitude. As well, the regional variation of the mean sea ice albedo is mainly due to the regional variation in the mixture of ice types and its snow cover.

The NBA shows substantial temporal seasonal variability. The NBA is high during the end of winter or the start of summer, which progressively declines during summer. Regrowth of albedo starts during the onset of autumn. The observed changes in albedo were a combination of a gradual evolution due to seasonal transitions and abrupt shifts resulting from synoptic weather events. Moreover, several factors affect the NBA in the Arctic, such as snow metamorphism.

The correlation between NBA and IST over Eurasia, Sea Ice, North America, and Greenland clearly indicated that there was weak correspondence as reflected by the low goodness of fit, which ranged from 0.07-36 in 2012 and 0.17-0.47 in 2014. This suggests that NBA was not sensitive to IST, implying that NBA is an integral result of more other factors. Weiss et al. (2012) explained that the ice thickness and snow cover strongly control the albedo and that the temperature is a proxy for these parameters. Thicker ice with snow cover, like pack ice, has a lower surface temperature and has, in general, a higher albedo in comparison to very thin, dark nilas ice, which can be found in the polynya region and on just frozen leads.

On the other hand, results showed that NBA has a moderately high connection with SIC, SIE, and SIA based on sample years (2012 and 2015). In 2015, both SIE and SIA had a moderately high ($r = 0.80$) association with NBA. This implies that SIE and SIA have considerable influence on NBA. In contrast, a slightly lower correlation ($r = 0.61$) was observed between NBA and SIC.

In general, the NBA is greatly affected by the seasonal transition from spring to winter. The Arctic surface undergoes a profound transformation as it undergoes cyclic dropping and rising IST, i.e., snow-covered, ice formation on open waters, melt ponding. The corresponding changes in the optical properties of the ice surface increases or decreases the NBA. Moreover, the NBA has a considerable association with SIC, SIE, and SIA.

The global climate system is being influenced by the changes in the ice-albedo in the Arctic. Such detection of anomalies is important for evaluating heat and energy balance in the Earth's ground, atmosphere, and space. Global warming can be substantially abated if the human causes of such variability can be controlled. The data presented in this study can be a basis to strengthen global agreements in greenhouse gas emissions.

People and policymakers everywhere need to recognize the importance to all of us of what is being learned — and lost — in the Arctic (https://thehill.com/opinion/energy-environment/557548-climate-change-is-).

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STATEMENT OF AUTHORSHIP

The first author downloaded needed data processed the thematic maps and reviewed the paper. The corresponding author conducted the literature search, prepared the conceptual framework, identified thematic points, formulated recommendations, and undertook the writing up. The third and fourth author provided comments and suggestions, reviewed the paper.

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