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Enhancements to, and forthcoming developments in the Interactive Multisensor Snow and Ice Mapping System (IMS)†

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Abstract:

The National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service (NOAA/NESDIS) Interactive Multisensor Snow and Ice Mapping System (IMS) has undergone substantial changes since its inception in 1997. These changes include the data sources used to generate the product, methodology of product creation, and even changes in the output. Among the most notable of the past upgrades to the IMS are a 4-km resolution grid output, ingest of an automated snow detection algorithm, expansion to a global extent, and a static Digital Elevation Model for mapping based on elevation. Further developments to this dynamic system will continue as NOAA strives to improve snow parameterization for weather forecast modeling. Several future short-term enhancements will be evaluated for possible transition to operations before the Northern Hemisphere winter of 2006–2007. Current and historical data will be adopted to a geographic information systems (GIS) format before 2007, as well. Longer-term enhancements are also planned to account for new snow data sources, mapping methodologies and user requirements. These modifications are being made with care to preserve the integrity of the long-standing satellite-derived snow record that is vital to global change detection. Published in 2007 by John Wiley & Sons, Ltd.

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INTRODUCTION

The interactive multisensor snow and ice mapping system (IMS) has been the main operational snow and ice charting tool of the National Oceanic and Atmospheric Administration's National Environmental Satellite Data and Information Service (NOAA/NESDIS) for almost a decade. This product was primarily created to improve the quality and timeliness of Northern Hemisphere snow and ice maps for National Centers for Environmental Prediction (NCEP) numerical forecasting (Ramsay, 1998). Prior to the IMS's operational inception in 1997, snow and ice charts were constructed manually once a week. The IMS is produced daily using geographic information systems (GIS) technology. This system had substantial impacts on production speed, product spatial accuracy, and time between observations. A comparison and validation review of the product transition from manual/weekly to IMS daily charts was conducted between 1997 and 1999. Preliminary examination of the data between these periods suggests the IMS output to be superior to the weekly manual snow and ice charts (Ramsay, 2000). In June 1999, the manual charting of snow and ice extent was supplanted operationally with the daily IMS. Since the charts are now constructed digitally, their distribution has increased, with hundreds of known users viewing data each month from the NESDIS site and an unknown number of users obtaining the IMS data from other sources.

While there are potentially many uses, the primary function of the product is to provide cryospheric input for environmental modeling. There are two operational government customers for this product, the NCEP/Environmental Modeling Center (EMC) and the NCEP/Climate Prediction Center (CPC). These customers help support and influence the direction of the product. The feedback from the NCEP modeling agencies and preliminary NOAA Program Observational Requirements have led to advancements in the product and point toward its continued improvement. The EMC applies the models for each 3 h modeling run for North America and temporally coarser models for the entire planet. Snow plays an important role in model input and can lead to substantial error in forecast results based on incorrect representations of snow distribution, age, depth, snow water equivalent (SWE), and snow density (Mitchell *et al.*, 1993; Sheffield *et al.*, 2003). The importance of correctly initialized sea ice conditions is also vital to Numerical Weather Prediction.

Along with serving as an initial state of the surface cryosphere for the Northern Hemisphere for weather prediction, NOAA's snow maps serve as a 40-year environmental monitoring record for hemispheric snow cover. This is considered the longest continuous satellite-derived

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record of any environmental variable (Robinson *et al.*, 1993). It is vital for climate change detection and a key element in NOAA's Mission Goals to 'understand climate variability and change to enhance society's ability to plan and respond' (USDOC/NOAA, 2005). Given the importance of this record, changes in the record should be considered with great care to preserve the integrity of the product for climate monitoring. Consultation within the snow and ice climate monitoring community has been sought before the integration of changes to safeguard the IMS's environmental monitoring role.

The IMS was designed to allow meteorologists to chart snow cover interactively on a daily basis using a variety of data sources within a common geographic system. Since first outlined by Ramsay (1998), there has been additional information learned over time about the production methodology, and there have been noticeable changes in the input data sources, production techniques, and output format. This paper will cover changes in the input, production techniques, and output files since 1997, including statistics regarding the production methodology. The paper will also discuss the future enhancements and pending developments to the product in both the short and long term. The conclusion will summarize the present state of and future changes in the product and what this means to the user community.

IMS PRODUCT EVOLUTION

System architecture enhancements

A limiting factor of the original IMS system architecture was the inability of analysts to map snow while looping imagery. This adversely affected mapping in the areas covered by geostationary satellites where imagery animation distinguishes snow and ice from fog and clouds. This limitation was changed in February 2004 to allow IMS analysts the freedom to loop imagery while drawing, erasing, or using any of the other IMS features. With this enhancement and other features such as image enhancement, product overlays and terrain mapping, the analysts can deduct snow and ice without relying on looking at a nearby system with looping imagery.

Another feature modified within the system architecture in February 2004 was enhancing how the geographic area assignments of imagery were made within the system. Previously, the system applied fixed zones for each satellite used in the analysis. These fixed geographic zones often only covered the best viewed regions. These regions also had set screen boundaries, which did not allow analysts to recenter. This made it difficult for analysis of areas that straddled fixed zones. An analyst would need to change fixed zones to view neighboring areas. The current IMS allows analysts to pan globally and select different datasets/satellite data independent of regions. This greatly enhanced the flexibility of the IMS to optimize the snow mapping display.

Improved resolution

One of the largest changes in the product since the creation of the IMS has been the improvement in output resolution introduced in February 2004. This increased resolution was made to improve model input for the EMC, providing greater detail of snow and ice cover. These improvements were possible due to advancements in computer speed and imagery resolution that enabled production of a higher resolution Northern Hemisphere product at approximately 4 km resolution (6144×6144 grid). Changes were made to all ancillary data layers such as coastlines, elevation, and vegetation cover to support the improved resolution. Impacts of this change are still under evaluation but positive feedback has been noted from National Weather Service (NWS) field stations in regard to snow season temperature predictions. This is in part due to the improvements in snow distribution mapping, as well as resolving of many water bodies not present in lower resolution products. When not correctly mapped there can be significant forecast errors where sea or lake ice cover affects heat and moisture fluxes to the atmosphere (Grumbine, 2005). Figure 1(a) and (b) demonstrate the difference in resolutions over northern North America. This easily demonstrates the noticeable differences in the inclusion of interior lakes and more detailed coastlines. Snow on mountainous terrain is also better represented using the 4 km versus lower resolution products. The 4 km product is also upscaled to the original previous IMS spatial resolution of approximately 24 km resolution (1024×1024 grid). This is to maintain the satellite snow cover historical dataset. As previously mentioned, the IMS record is an important climate monitoring element and careful consideration must be taken to preserve the integrity of this snow cover record. Validation and monitoring of the IMS product at the 24 km resolution is carried out under a joint effort by NESDIS and Rutgers University (Robinson, 2003).

Added input data sources

The IMS was designed to allow meteorologists to chart snow cover interactively on a daily basis using a variety of data sources within a common geographic system. The original input satellite data sources were outlined as NOAA polar orbiters (POES), NOAA geostationary (GOES) data, Japanese geostationary meteorological satellites (GMS), European geostationary meteorological satellites (METEOSAT), US Department of Defense (DOD) polar orbiters, and Defense meteorological satellite program (DMSP). Indirect satellite sources also include a weekly National Ice Center (NIC) chart and the US Air Force (USAF) daily snow depth and ice cover product (Ramsay, 1998). Several additional input products have been added to the IMS over the past decade. A few of these enhancements were outlined as prospects before, but have since become operational input options (Ramsay, 2000). These products include the Advanced Very High Resolution Radiometer (AVHRR) channel 3A, added in February 2001, the moderate resolution imaging

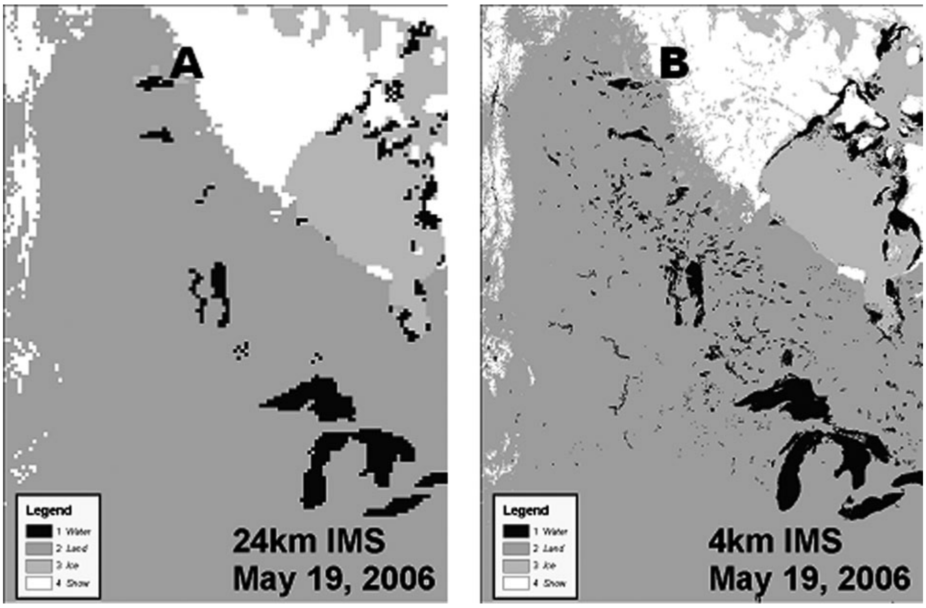

Figure 1. The 24 km IMS product (A on the left) as remapped from the 4 km IMS (B on the right) for 19 May 2006. The 24 km represents the same land/sea mask used in previous 24 km products prior to February 2004. Note the differences in representations for mountainous snow, inland lakes, and sea ice leads

spectroradiometer (MODIS) channel 1 added in February 2004, and an experimental automated snow mapping system over North America added in February 2004. Other product enhancements and their impacts are outlined in the following paragraphs.

Meteosat 5 for INDOEX. The original primary geostationary coverage left large portions of Siberia, central Asia, the Himalayas, and the Tibetan Plateau unobserved by looping imagery. This is an important and difficult area for snow charting. Snow cover in this vast area has been identified as a significant influence on the Asian Monsoon (Hahn and Shukla, 1976; Huaqiang *et al*., 2004), global circulation (Bamzai and Marx, 2000; Clark and Serreze, 2000; Gong *et al*., 2003), and regional river discharge (Yang *et al*., 2003; Shaman *et al*., 2005). While nongeostationary satellite data sources such as polar orbiting imagery and microwave measurements provide mapping snow input, they are not the preferred data source by our analysts. Microwave retrievals over the area are often erroneous in the winter due to atmospheric signal distortion, high elevation bare ground low temperatures, and/or soil grain scattering (Basist *et al*., 1996; Armstrong and Brodzik, 2001). Polar orbiters have limited over-pass times, thus providing only a limited number of observations per day. This amplifies the common problem of misidentified snow/ice and clouds in an already hazy area known for its difficulty in visual identification from satellites (Clark and Serreze, 2000).

The placement of Meteosat-5 at the equator and 63°E in 1998, helped fill the void of geostationary data. This satellite was moved in support of the Indian Ocean Experiment (INDOEX), and was first incorporated into IMS in March 2001. This platform was preferred over other geostationary meteorological satellites such as the Feng Yun 2 (FY2) from China and the Indian National Satellite System 2 (INSAT 2) from India. The observation footprint is comparable for all these satellites, but only a single geostationary satellite is required. Meteosat-5 was chosen because FY2 is experimental and near the end of its serviceable period, while data from INSAT 2 are available for Indian national use. The inclusion of Meteosat-5 has provided a great boost to Asian snow mapping during the winter season.

Multifunctional transport satellite (MTSAT). The Japanese Meteorological Agency (JMA) Multifunctional Transport Satellite (MTSAT) series succeed the GMS series as the next generation satellite series covering East Asia and the Western Pacific. While MTSAT offers only marginal improvements in visible resolution over GMS, the improved calibration and correction algorithms provide improved detection of snow and ice. The IMS began using MTSAT in November 2005.

National operational hydrologic remote sensing center (NOHRSC). The inclusion of National Operational Hydrologic Remote Sensing Center (NOHRSC) maps into IMS analysis began in February 2004. The national analysis provided by NOHRSC, called the SNOw Data Assimilation System (SNODAS), provides a 1 km resolution estimation of snow cover for the conterminous United States. SNODAS is a system that amalgamates NCEP modeling, multisensor, station report, and airborne information into a single daily or subdaily product (Barrett, 2003). The output timing of this product corresponds to the IMS observation day and serves as an important winter input source when clouds blanket the conterminous United States. While the fine resolution and multisource data of SNODAS provides reliable data, its spatial extent is limited compared to the IMS, so it provides only a small but nationally important area for snow mapping.

MODIS looping. Soon after the inclusion of MODIS visible imagery as an IMS datasource, analysts found the utility of looping recent MODIS overpasses for a given location. Looping of this polar orbiter is available due in part to the Aqua and Terra satellites sharing the identical visible channel at 1 km and the poles having multiple daily overpasses. While the time span between images used in the loop is somewhat coarse compared with geostationary observations, these loops allow the analyst greater ability to distinguish between the surface cyrosphere and clouds. MODIS is an experimental satellite and will not be followed by a direct legacy product. The merger of the DoD and NOAA satellites in the future, known as the national polar-orbiting operational environmental satellite system (NPOESS), will provide a similar product as that of MODIS and hopefully can be exploited for image looping once NPOESS is launched and declared operational.

Marine modeling and analysis branch (MMAB) sea ice analysis. The tracking of sea ice cover presents many difficulties. The IMS relies primary on visible imagery but this method is contingent on clear sky or thin cloud during the observation periods. When weather or low illumination obscures visual interpretation of sea ice, microwave observations play a greater role. IMS analysts often apply a 1/16 mesh Northern Hemispheric grid of sea ice concentrations from the Marine Modeling and Analysis Branch (MMAB) to demarcate those locations with >50% ice cover. The MMAB sea ice analysis is solely based on Special Sensor Microwave Imager (SSM/I) and applies a modified version of the National Aeronautics and Space Administration (NASA) team algorithm to derive sea ice concentrations (Grumbine, 1996). All SSM/I based products suffer from melt water attenuation, coastal contamination, poor thin ice detection, and difficulties in identifying concentration along the marginal ice zone. While analysts rely on the MMAB product as their primary sea ice concentration source in the winter months, analysts will slightly vary the IMS ice cover when other external sources suggest the MMAB may be contaminated with a false emissivity.

Daily NIC ice edge. In its inception, the IMS was designed to exploit the NIC weekly ice charts for the Northern Hemisphere. The NIC produced detailed sea ice maps coded in an ice charting nomenclature (known as egg code) once a week, usually updating the product on Friday afternoons, until 2001. Since that time, the NIC switched from weekly to biweekly hemispheric coverage. This decreased the utility of the charts for daily operational ice mapping. Furthermore, ice charts released on Fridays would use input data typically three to seven days old for the analysis. While the NIC charts could still provide a general outlook of ice thickness and ice distribution, the dynamic nature of ice made the charts too old for the IMS analysis.

Since February 2004, a daily vector sea ice edge has been incorporated into the IMS. The NIC daily sea ice vector product applies visible, infrared, passive microwave, and radar data to outline those areas with >10% ice cover. This product differs from the IMS product in three key ways. First, the NIC product is vector-based and attempts to enclose amorphous polygons, while the IMS defines ice cover within predefined pixels. The NIC ice cover has no set size requirements on the polygon size or shape, thus, the scale of what areas enclose >10% is at the NIC analyst's discretion. This often leads to smoothing along the ice edge in some areas, while other areas may be more detailed than the IMS. Experience has revealed more of the former than the latter. A second difference in the products is the ice concentrations captured by each product. The NIC outlines areas with >10% ice cover, while the IMS demarcates areas with >50% ice cover. IMS analysts must adjust for this difference when using the NIC daily ice edge for IMS input. A third difference in the ice analysis output is the IMS's inclusion of lake ice. The NIC vector ice edge only outlines sea ice and lake ice in the Great Lakes. Other significant lake bodies that freeze (Great Bear, Great Slave, Caspian Sea, Lake Baikal, Aral Sea, among many others) are not included within the NIC product.

Despite the differences, IMS analysts will bridge the analysis outputs and methodologies to use NIC data as an input source. NIC data is often applied with or taken in the context of the MMAB sea ice product to provide a best guess approach for the IMS sea ice mapping. Figure 2 shows how the NIC ice cover product is able to suggest ice cover in the Hudson Bay even when imagery has cloud contamination. One can notice that each product suggests a different ice cover pattern,

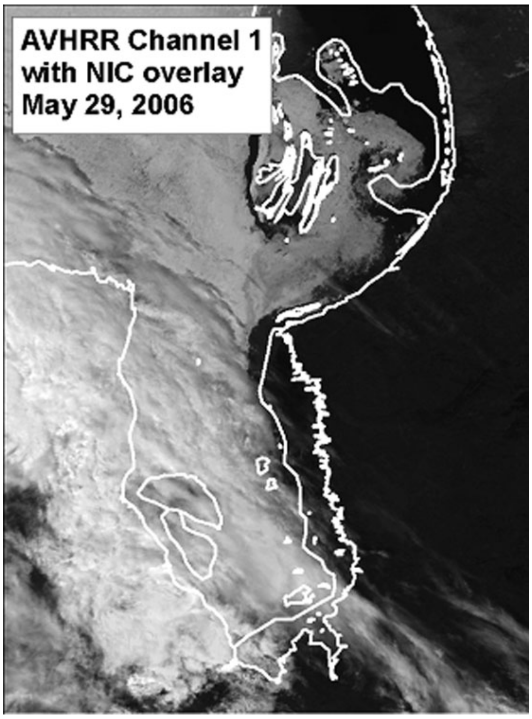

Figure 2. A VHRR Channel 1 with the NIC ice edge overlaid for 29 May 2006. The NIC ice edge is a vector file with shorelines. White lines represent shoreline and 10% ice cover isopleth

perhaps due to observational methodological differences. But the NIC ice edge is able to provide IMS analysts information regarding the shape of the lead in James Bay, even though the southern part of James Bay is cloud covered. Plans are being developed to bring the radar data available to NIC analysis into the IMS and to have an NIC ice-edge product that outlines using similar criteria as that of the IMS. This will be discussed later in this paper in greater detail.

Automated snow and ice cover products. In August 1999, NOAA/NESDIS began the production of automated snow maps over North America. The product generates daily maps of 4 km resolution based on visible, near-infrared, middle-infrared, infrared and microwave imagery. This imagery comes from both polar orbiting and geostationary satellites. The algorithm applies a series of decision-trees to bin pixels containing either a majority of the area snow covered or having less then a majority of area snow covered (Romanov *et al*., 2000). While the midlatitudes maps are generally mapped using GOES imagery, the higher latitudes rely on polar orbiter spectral differences and microwave signals. Microwave retrievals are the default observation when shorter wavelength data is attenuated by clouds for several days. Since being declared operational the product has expanded beyond North America to the Southern Hemisphere and the remainder of the Northern Hemisphere, though the spatially expanded versions of the automated snow maps remain experimental at the present time (Romanov and Tarpley, 2003). Examples of the Northern Hemisphere multisensor product are demonstrated in Figure 3. The pattern closely resembles that of the IMS for the same date (IMS not shown). Figure 4 displays an example of the experimental automated Southern Hemisphere product. Validation efforts remain ongoing for both hemispheric products.

Other comparison studies using automated snow cover mapping versus IMS suggest that IMS may have underestimation problems in the transition seasons but outperform automated products in cloudy areas with new snow cover and during winter (Brubaker *et al*., 2005). The validation efforts will help determine how these products will be incorporated with the IMS. Without a current Southern Hemisphere IMS product, an automated product could serve as the NOAA NESDIS Southern Hemisphere output in the future. However, should the product be unable to provide a serviceable input for EMC or CPC modeling efforts, the output will merely serve as one input to a southern hemispheric IMS analysis that will need

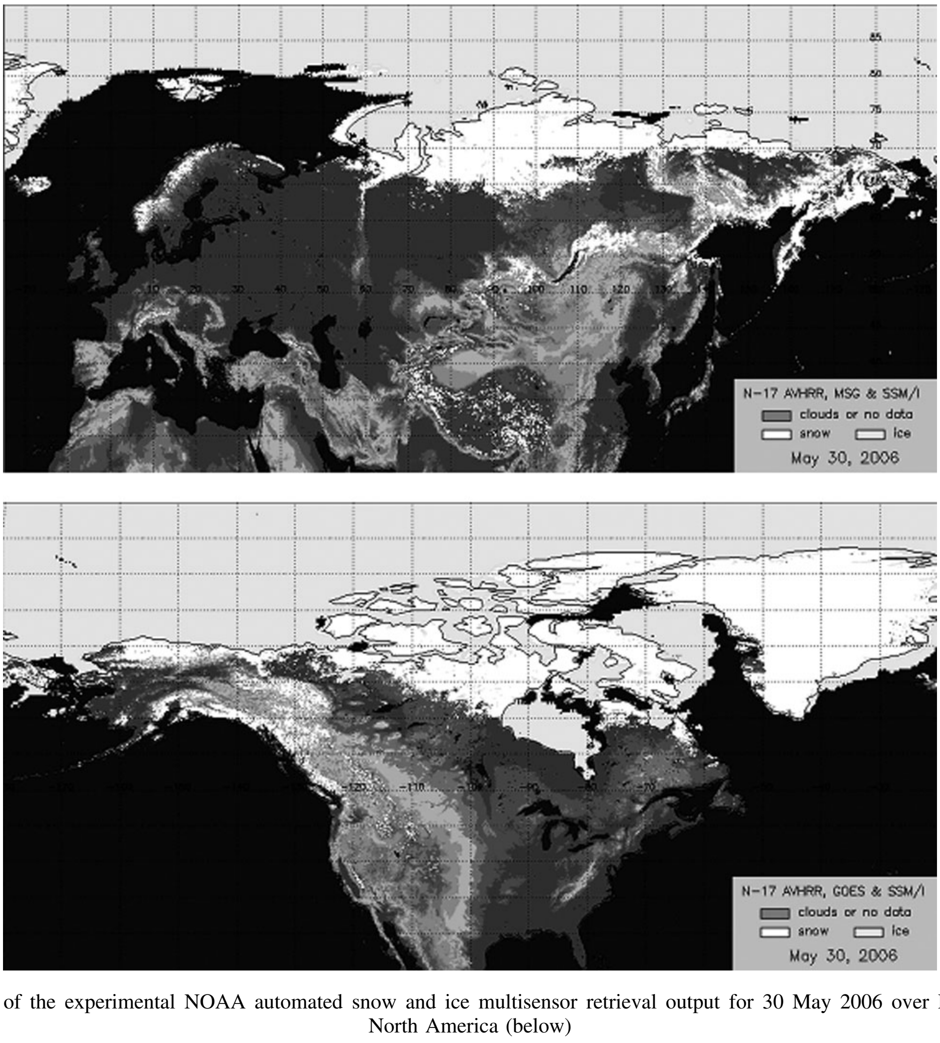

Figure 3. Examples of the experimental NOAA automated snow and ice multisensor retrieval output for 30 May 2006 over Eurasia (above) and North America (below)

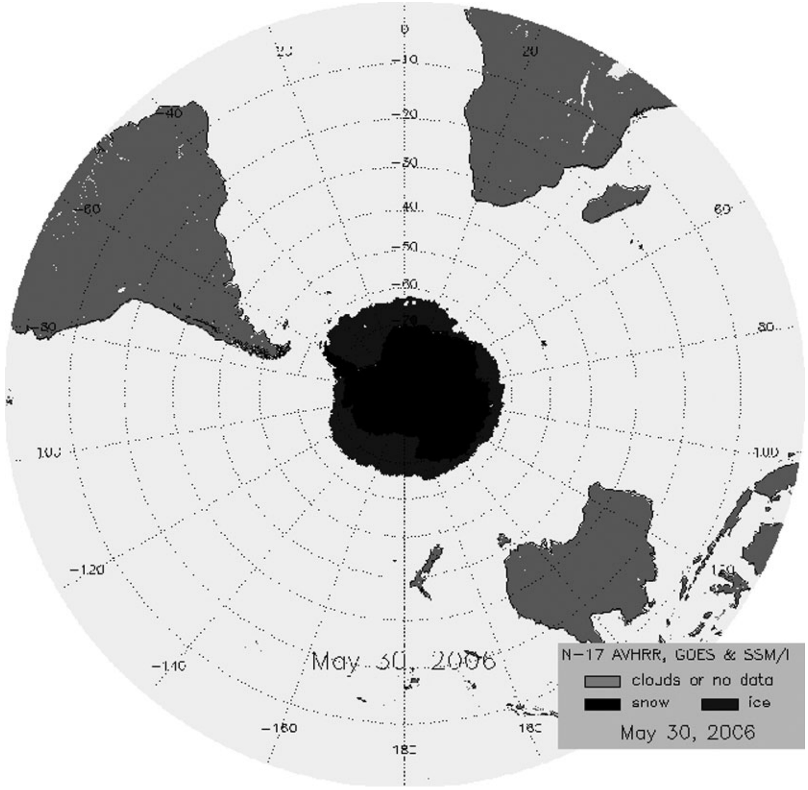

Figure 4. Examples of the experimental NOAA automated snow and ice NOAA-17 retrieval output for 30 May 2006 over the Southern Hemisphere. This product is at 4 km resolution and could expand IMS from the Northern Hemisphere to global coverage

to be created. Likewise, the role the Northern Hemispheric automated analysis product plays in the IMS will be determined based on the validation results and the customer requirements. Possible scenarios include serving as another layer in the IMS (much like the North American product does now), serving as the initial state of the IMS, or even replacing the current Northern Hemispheric IMS product.

Current production methodology for IMS

Since the inception of the IMS, production methodologies and image preferences have become more transparent. The production of the IMS has evolved over time, with inclination in which imagery types are applied at certain times of year and how long the production process takes. This section will provide a greater insight into the production methodology used to make multisensor IMS outputs. Production of the IMS products is not tremendously time consuming for analysts, who spend anywhere from 1 to 5 h generating a daily product depending on the season, analyst familiarity, and satellite data available. The month of August requires the lowest average time to conduct an analysis, averaging between 70 and 75 min. Production time during the accumulation season (Oct–Apr) averages about 120 min. The ablation season (May–Sep) averages approximately 90 min for production time. Products are due to the primary customer by 2300 h GMT. The IMS analysis currently starts with the previous day's analysis as the initial state. The analyst then reconfigures the current IMS based snow extent on the input data available at the time of the analysis.

Seasons determine not only just how much time is required to generate a chart, but also what data will be used as input into the IMS. Geostationary data looping is the primary tool for determination of snow cover (Ramsay, 1998). The geostationary looping represents an estimated 60% of the snow analysis examination areas during the winter (Dec–Feb). This decreases to an estimated 30% of the snow examination area during the summer (Jun–Aug). During the summer months, polar orbiting satellites' visible channels (bands) characterize an estimated 65% of the snow analysis.

Analysts generally prefer using visible imagery for snow extent mapping, but will use microwave data in the event light is unavailable due to cloud occlusion or low solar illumination angles. The combination of high albedo, static motion, and meteorological conditions provides the analyst with 80 to 90% of input data used in the analysis of observed snow cover. Even during winter, microwave derived snow data generally only represents 5% of an analysis. Microwave snow extent data have well documented snow misidentification errors due to signal obstructions, snow grain size, land cover influences, and algorithm limitations (Chang *et al.*, 1996; Foster *et al.*, 1999, 2004).

Analysts rely more on snow climatology to estimate snow cover in the high latitudes during the winter than pure microwave data. Where and when various data sources are available the IMS uses METAR and cooperative meteorological observations, NOAA NWS' NOHRSC, and SNODAS data, and automated snow cover maps from both NOAA's Center for Satellite Applications and Research (STAR) and the MODIS Land Science Team, NASA Goddard Space Flight Center (GSFC). These external data sources are often used to validate an area having snow or snow obscured with clouds. Often, the IMS analyst must use a consensus of several data sources to provide an optimal 'best-guess' approach to determining the presence of snow.

Ice cover analysis relies on a different approach than snow cover for charting. Ice cover determination must rely less on high albedo, stagnate cover, and meteorological conditions. Sea ice in the Northern Hemisphere winter is primarily located in areas with low solar illumination. New ice formation often has a low albedo until the ice thickens, becomes more opaque, and albedo increases (Wadhams, 2000). Furthermore, sea ice is a dynamic surface making it less distinguishable from clouds using image loops. The presence of lake and sea ice can be unrelated to current meteorological conditions due to ice transport, ice thickness, and water temperatures among other factors. The prominence of low-level stratus clouds over polar and subpolar region also preclude the use of visible imagery as the primary source of ice observation.

While these problems reduce the efficiency of albedo-based observation of ice, it is still a valuable input. On average, about 60% of changes in winter ice cover are noted via geostationary, AVHRR or MODIS observations. Much of the higher latitude areas are verified as being ice-covered using microwave-based retrievals. Microwave-based observations often represent 30 to 35% of the winter and autumn (Sep–Nov) ice cover input. Ice climatology is another tool for estimating ice cover in places where observations are unavailable. Since ice cover often exists in remote and dangerous areas, no station data is currently incorporated into the analysis. The NIC produces a sea ice edge vector file that provides the IMS with an external source for ice cover information. Currently, the NIC ice edge encompasses total polygons with greater than 10% ice cover. The IMS analyst attempts to identify whether each 4 km × 4 km pixel contains more than 50% ice cover. These products do not correspond directly due to each product requiring different output specifications. Despite the differences between products, the NIC ice edge is used when other sources of data fail to provide any clear input on ice-covered ocean or Great Lakes waters. This represents about 2 to 10% of the time, depending on the season.

Montane snow mapping

Elevation plays an important role in snow generation due mostly to orographic lifting and temperature decreasing with increasing height. Snow often outlines higher elevation areas during the transition season and during the winter in semiarid, midlatitude regions. To mimic this effect in mapping snow, the IMS allows analysts to chart areas dynamically as having snow based on a digital elevation model (DEM). The DEM resolution is 4 km and matches the IMS, thus providing the elevation of each IMS pixel. This provides the analyst with the ability to toggle the pixels within a given polygon to match the outline of snow revealed through imagery. The analyst can optimize the snow cover pattern based on elevation, local geography, and reflectance revealed through imagery. This has become a frequently applied tool in IMS snow mapping.

The strengths and shortcomings of this DEM-based mapping are considered by the analyst while applying this tool. The strength is a more detailed and realistic mapping technique than previously available based on a physiographic relationship of snow with elevation. One weakness is that the DEM-based mapping does not account for other known states or physiographic factors that play a role in snow cover distribution, such as slope and aspect. Nor does it take solar, vegetation, or climatologic wind variations and storm patterns into account.

Studies reveal that physiographic features such as radiation, elevation, slope, and aspect account for between 50 to 80% of snow depth variability in the Rocky Mountains, Sierra Nevadas, and Alps (Balk and Elder, 2000; Marchand and Killingtveit, 2001). Elevation tends to be the second largest influence on snow cover distribution next to radiation, but the weight of this influence is dependent on spatial scale (Balk and Elder, 2000, Marks *et al.*, 2002). Elevation and radiation appear to be greater factors at increasing spatial scales, likely playing a large role in distribution variability at the 4 km scale in semiarid and mountainous environments. Despite the shortcoming of this tool, it is just a methodology for mapping, with analysts basing snow distribution on numerous input data, not merely elevation. Analysts can compensate for inhomogeneous spatial patterns noted with regional elevation due to the other state factors that influence snow cover distribution.

THE FUTURE OF IMS

Enhancements to the IMS will continue to push the bounds of cryospheric observation and charting. Requirements for snow and sea ice extent differ for climate studies versus numerical weather prediction. Since surface cryospheric climate datasets are constrained by past data with the historic scale limitations, snow maps need to be maintained at historical spatial resolutions to preserve the climate record integrity (Robinson, 2003). Downscaling of older datasets would be required to blend the old and new snow maps into a common 4 km grid with interpolated daily values from weekly values.

Fox and Ghan (2004) point out another limitation that fine resolution climate grids would need to overcome as well. While the IMS's 4 km resolution for global climate outlooks and monitoring exceeds the current resolution requirements at one observation per day, improvements in weather prediction are predicated on the prediction grid resolutions and prefer up-to-date observations. The need for global snow information at improved spatial and temporal resolutions for numerical weather prediction models is driving the advancements in the IMS. A 4 km resolution snow and ice cover has the spatial resolution to initialize models such as the NCEP North American Mesoscale (NAM) model with a 12 km resolution and could even provide improved ice and snow initialization for finer resolution models such as the Fifth-Generation Penn State/National Center for Atmospheric Research Mesoscale Model (MM5) (Dudhia *et al.*, 1999; Rogers *et al.*, 2001).

The temporal resolution of once a day could improve model results since afternoon (Eastern Standard Time, EST) model runs may be up to 21 h removed from the last snow and ice cover initialization. With daily snow depth depletions of over 12 in reported at snow telemetry (SNOTEL) stations, spatial distribution of snow cover may change drastically over one day, given ideal weather conditions for ablation. IMS will attempt to respond to this need for more timely information by introducing a second IMS observation each day over North America at the 4 km resolution. This will be challenging given the time constraints of Satellite Analysis Branch (SAB) analysts and the window of visible imagery available for analysis by the late afternoon EST model run, particularly, in the western United States during winter.

In addition to a second IMS daily product, the IMS will be expanding to provide global coverage. While the IMS provides adequate coverage in the Northern Hemisphere, the current product fails to capture the snow and ice extent in the Southern Hemisphere. Like the improved temporal resolution North American IMS product, this presents a challenge to the resources required to provide such data. As previously mentioned, the automated snow and ice product is likely to play a large role in the production of southern hemispheric analysis. The completion of the Southern Hemisphere IMS will complete the global snow and ice coverage for model initialization.

The IMS currently employs over 15 separate sources of data for input. This number can seem daunting to navigate, but each source is expertly selected to provide an optimal snow analysis. Still, NOAA is looking to exploit new technologies for understanding the current state of the surface cryosphere. To improve the output and to meet future product requirements, several new products are being tested for implementation into the IMS.

In the short term, these products include snow and sea ice cover from the Advanced Microwave Scanning Radiometer - EOS (AMSR-E), the Northern and Southern Hemisphere automated snow mapping systems, NASAs Quick Scatterometer (QuikSCAT), and ESAs Environmental Satellite (Envisat) Advanced Synthetic Aperture Radar (ASAR) operating in Global Monitoring Mode (GMM), and MetOps Advanced Scatterometer (ASCAT). MetOps impending launch will also offer an expansion in the platforms carrying the AVHRR and Advanced Microwave Sounding Unit (AMSU) sensors. Recent improvements to the Air Force Weather Agency (AFWA) snow depth and MMAB sea ice products will also be incorporated in the near future.

The IMS output product has been available to users for almost ten years. Archival and archived product dissemination has been done through cooperation with the National Snow and Ice Data Center (NSIDC). The NSIDC currently provides users with American Standard Code for Information Interchange (ASCII) output data at the original 24 km resolution as well as the recently added 4 km output. While these products have been a popular data source, the formatting of the output can be complex to novice users. To promote a broader user community, NOAA NESDIS has begun to generate GIS GeoTiff outputs at the 4 km resolution. This product will be archived and disseminated at the NSIDC. The GeoTiff archive will span from February 2004 until the latest day, with completed analysis.

Snow and ice extent and coverage have both been the primary outputs for IMS. However, this is far from the lone variable needed for modeling snow and ice behavior at regional and global scales. NOAA/NESDIS is at the cusp of introducing new snow products that work in conjunction with the IMS to improve initialization in atmospheric models. A common problem reported with IMS has been that of continuing to maintain observation of snow cover during cloud-obscured periods. The IMS analysts apply many tools and images to produce a 'best guess' approach to snow observation. However, when clouds obscure visibility, or the snow is too thin for microwave detection, and if there are no station reports, IMS analysts leave reports on snow conditions as they were since the last observation. This can be problematic when snow has actually melted. Atmospheric models contain algorithms to estimate snow depth throughout the day and to predict ablation of the snow cover. However, snow ablation in atmospheric models is reinitialized with the current snow cover obtained from IMS. If the snow in the IMS is merely the result of continuance and held in the IMS output because there is not enough evidence to remove snow cover, this reinitialization can lead to false snow observations and thus propagate errors throughout the NCEP model. To address this issue, a file of last observation time for the IMS has been developed and is undergoing testing. This will allow modelers to choose between using IMS or modeled estimates for their observations on snow cover.

SWE has been produced by SSM/I measurements for many decades, and is a valuable snow variable for atmospheric and hydrologic modelers. NOAA NESDIS is currently testing a combined AMSU and IMS SWE product that will merge the reliable IMS snow cover observations with AMSU's capacity for estimating SWE (Kongoli *et al.*, 2006). An example of the premerged and merged products is demonstrated in Figure 5. Additional snow variables including snow depth and fractional snow covered area are being experimented with to improve model initialization in combination with IMS output (Romanov *et al.*, 2003). Future NOAA efforts for mapping sea and lake ice variables utilizing IMS, such as ice concentration and ice thickness, are in the planning stage.

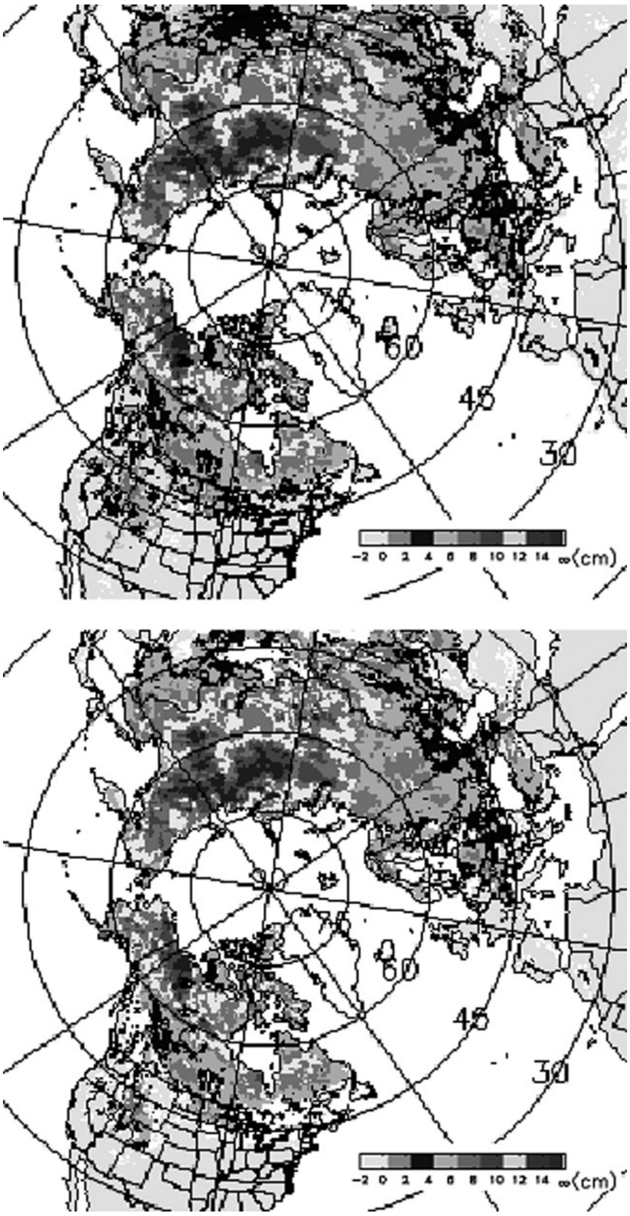

Figure 5. Examples of the experimental NOAA merged AMSU SWE-IMS output (bottom) for 1 February 2006 over the Northern Hemisphere. The premerged AMSU SWE (top) has erroneous or questionable signals masked by using the IMS

These input and output enhancements are not the only short-term changes planned for the product's future. Current plans are to relocate the operational production of the IMS from its current location within SAB to the NIC. This transition from one agency within NESDIS to another is being done with the hope of producing an improved product at a reduced cost for NESDIS. This should lead to less duplication in sea ice monitoring within NESDIS by parallel offices, consolidate network systems and imagery storage, free SAB personnel time for other products, and allow time for NIC personnel trained in IMS analysis to help meet NCEP requirements of two IMS observations per day. All NIC personnel will undergo the same training as the current SAB personnel to achieve IMS qualifications before being assigned to IMS product generation. Parallel product generation will be performed at the SAB and NIC until comparable output products are obtained between offices. After evaluation and duplication of the IMS has been achieved, production of the IMS will transition fully to the NIC. No production methods other then personnel will change during this process.

Longer-term plans for enhancements to the IMS input data revolve around the future deployment of NPOESS and GOES-R. NPOESS will be a joint military and civilian satellite replacing many of the existing U.S. polar orbiting sensors with improved sensors such as the Visible Infrared Imager Radiometer Suite (VIIRS), Conical Scanning Microwave Imager/Sounder (CMIS), and Advanced Technology Microwave Sounder (ATMS).

GOES-R will be the next generation of NOAA geostationary satellites that will aid snow and ice observations. Geostationary satellites are regarded by analysts as the most valuable input source. IMS analysts assessing surface cryospheric coverage will benefit greatly by the advancements in remote sensing provided on GOES-R, particularly the Advanced Baseline Imager (ABI). The ABI will have 16 spectral bands, compared with five on the current GOES imagers. The ABI will improve the spatial coverage from 1 to 0·5 km at its nadir for broadband, and from 4 to 2 km for the infrared bands. For snow and ice detection this will improve the ability of the analyst to confirm the presence of ice on the surface through recognition of spatial patterns more discernable at higher resolutions, such as dendritic spatial patterns of snow on mountains, ice floe shapes that indicate certain ice thickness, or ice fractures. The ABI also includes spectral information never before present on GOES imagers. One band of particular relevance to snow and ice detection will be centered at 1·61 μm, which would expand the ice/cloud discrimination sampling beyond the temporally coarse polar orbiters (Schmit *et al.*, 2005). This should improve the IMS accuracy and reduce the amount of time required for detection. This channel differencing would also improve automated snow and ice detection. GOES-R will increase the coverage acquisition rate nearly five-fold, allowing closer to real-time observations and increased discrimination of relatively static surface features from highly dynamic atmospheric features.

SUMMARY

The IMS has undergone significant enhancements to the product's spatial resolutions, its data inputs, processing methodology, and output formats that have augmented the product's utility. These changes have been largely beneficial to the NCEP EMC model (Mitchell, K., 2006, professional conversation). The changes involve an improved architecture, superior output resolution, expanded input sources, and topographic mapping capabilities. The current system architecture allows IMS analysts to quickly map snow and ice, thus speeding the production time. The advanced resolution product begun in February 2004 allows for greater details of snow and ice

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information to be conveyed to the user community. While product evaluations are still ongoing at NCEP, improvements in the product's spatial resolution are likely to have a positive impact on numerical weather prediction. The expanded input imagery from which the analyst may choose allows for an increase in the likelihood of correct snow and ice identification. The more accurately the surface cryosphere is depicted, the better the forecast by the weather prediction model.

The enhancements made to the IMS have been mostly driven by the need for better NCEP EMC initializations. Planned future changes to the product are also geared to improving NCEP EMC forecasts. Unfortunately, the impacts of the enhancements to NCEP CPC climate evaluation remain unknown. The product has likely become more accurate due to improved spatial resolution, enhanced mapping methodologies, and improved input sources. However, the extent of impact of an improved product, which may cause heterogeneity in the snow and ice extent record, is still under evaluation. While consultation of change impacts is sought by the CPC and nonfederal researchers, formal examinations are to date forthcoming. This concern is not without note and is in need of further investigation.

Providing IMS outputs in new, easier-to-use formats and with accompanying products (SWE, snow fraction, ice age, etc.) will expand the user community for the products. Further advances in the products are predicated on customer requirements, new sensors, and advanced technologies. The advancements in the IMS, as well as links to past snow mapping, should continue to make this a viable snow mapping system for years to come.

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