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OPERATIONAL SYNTHETIC APERTURE RADAR HIGH RESOLUTION WINDS IN THE ARCTIC

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1. INTRODUCTION

As the Arctic Ocean* becomes more ice free over longer periods of the year, transit and other marine activities will become more common. Hence, there is a need for more complete monitoring of the Arctic environment. This growing need corresponds to increasing abilities for such monitoring. Over the last decade, the ability to use spaceborne, high-resolution (< 500 m) synthetic aperture radar (SAR) radar cross section measurements to derive wind speed measurements to better than 2 m/s accuracy has matured. SAR wind measurements have been validated against buoy measurements, model predictions, and other remote sensing techniques.

In light of this maturation, the NOAA National Environmental Satellite, Data, and Information Service (NESDIS) and National Ice Center (NIC) are commissioning an operational near real-time SAR wind speed product in May 2013. Currently, data are being received at NIC from the Radarsat-2 SAR for the primary purpose of sea ice location and identification. SAR winds are now routinely produced from this imagery. We anticipate that the availability of SAR wind imagery over the Arctic will be significantly augmented with the launch of Sentinel-1 this year. Other SAR satellites such a TerrasSAR-X and the COSMO SkyMed constellation offer still more opportunities. In the future, we also anticipate data from the Radarsat constellation.

2. RADAR CROSS SECTION TO WIND SPEED

If the ocean surface were perfectly flat, all the radar energy would be reflected away and the SAR image would appear dark. As the surface gets rougher, more energy is reflected back to the radar and the image is brighter. The first-order theory explaining this is called "Bragg" scattering (Bragg 1913). When the projected wavelength of the radar matches the same roughness scale on the surface, there is a resonance increasing

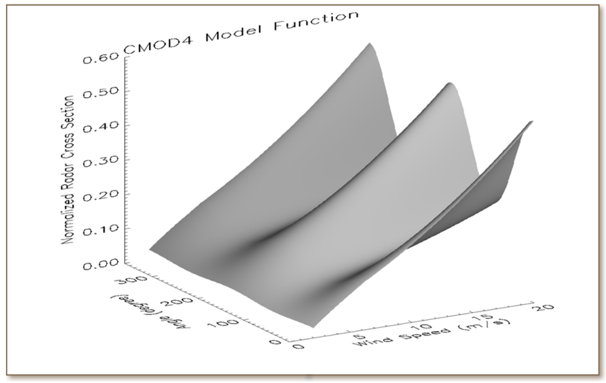

FIG. 1. Model function relating wind speed and direction to radar cross section.

the power returned to the radar. For microwave radars, this means the that brightness of the ocean surface is proportional to roughness on the surface from roughly 2 to 30 cm depending on the particular spaceborne SAR.

Although there has been significant effort and progress in modeling the response of the ocean surface to local winds and the scattering from the surface, wind speed retrievals are more accurate when based on empirical model functions. These functions model the normalized radar cross section (NRCS) as a function of wind speed and direction, the local incident angle, and the aspect angle of the radar with respect to the local wind direction. A notional version of such model functions takes the form:

$$\sigma^0 = A(\theta)U^{\gamma}(\theta)[1 + B(\theta)\cos\phi + \cos 2\phi] \qquad (1)$$

where σ^0 is NRCS, U is wind speed, θ is the local incident angle, and ϕ is the angle between the radar look direction and the wind direction. A, B, C, and γ are coefficients dependent upon the incident angle and the radar wavelength and polarization.

Fig. 1 is an illustration the the CMOD4 (Stoffelen and Anderson 1997) model function for C-band (5 cm wavelength). Note that NRCS increases with increasing wind speed and, for a given wind speed, is the

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TABLE 1. Civilian SAR systems

Satellite	Launch	Freq. Band.	Res. (m)
Seasat	1978	L	25
SIR-B	1984	L	16–58
ERS-1	1991	C	25
JERS-1	1991	L	18
SIR-C	1994	L,C,X	10-50
ERS-2	1995	C	25
Radarsat-1	1995	C	25-50
SRTM	2000	C, X	30
Envisat	2002	C	30-1000
ALOS	2006	L	7-88
Radarsat-2	2007	C	3-100
COSMO SkyMed	2007	X	3
Sentinel-1A	2013	C	5-20

highest when the radar look direction and the wind direction are aligned and a minimum when these directions are orthogonal.

There are other proposed model functions (Hersbach 2003, 2008; IFREMER 1996) but the key feature of these functions is that given a wind speed and direction it is possible to estimate the corresponding NRCS. However the inverse is not true. A particular radar cross section may correspond to a number of different wind sped and direction pairs. In order to invert Eq. 1 we must have an *a priori* estimate of wind direction.

Wind directions to initialize SAR wind speed retrievals can come from two sources: numerical weather model estimates or linear features in the SAR image associated with wind streaks. The former has the advantage that the directions are always available and dynamically reasonable. However, high-resolution variations in direction might be missed. The latter might pick up high resolution variations, they are sometimes not present and are encumbered with a 180° ambiguity. We have chosen to use former approach with GFS (Center for Environmental Modeling 2003) model winds.

3. SAR SYSTEMS

Table 1 is a listing of civilian SARs. Over time they have grown more complex, with greater resolution and some with multi-polarization capabilities. The frequencies listed give the letter designation for the frequency band with associated wavelengths of: $\sim$ 23 cm for L-band, $\sim$ 5 cm for C-band, and $\sim$ 2.5 cm for X-band.

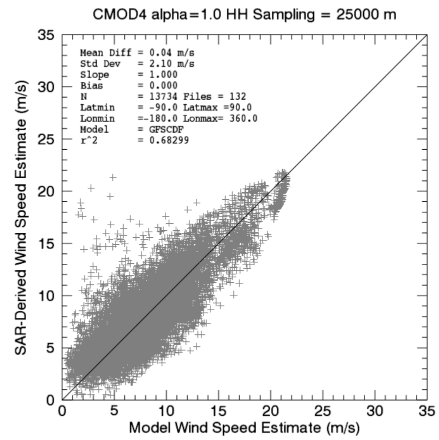

FIG. 2. Comparison of Radarsat-2 SAR-retrieved winds versus GFS model winds for the period 2013 Jan 16 to 2013 Feb 28 UTC.

4. ANSWRS

ANSWRS, or the APL/NOAA SAR Wind Retrieval System, is a set of software and protocols for the near real-time estimate of high-resolution wind speed from SAR imagery. The system will be officially operational at NOAA/NESDIS in May 2013 and is running in a beta mode at the National Ice Center. Currently, Radarsat-2 is the primary source of data.

ANSWRS can processes SAR imagery, within 10 minutes of when an image is available, into wind speed data at 500-m resolution or better. Wind speed estimates can be processed to the actual SAR resolution, sometimes on the order of meters. However, radar cross section variations associated with other phenomena such as ocean surface waves complicate interpretation of data. We recommend averaging SAR data to between 250 and 500 m for wind speed retrieval.

When compared against buoy and QuikSCAT scatterometer measurements, SAR wind speed retrievals agree to better than 2 m/s (Horstmann 1997; Monaldo et al. 2001, 2004; Horstmann et al. 2003). Typically, comparisons with models shows slightly larger differences due to model errors. However, regular comparisons with models provide many data points and a way to continually monitor the stability of SAR wind measurements. Fig. 2 is a scatter plot of Radarsat-2 SAR wind speed retrievals versus GFS wind speeds over the same area ant time. The mean difference is 0.04 m/s with a standard deviation of 2.10 m/s. The Radarsat-2 data considered was that used by the National Ice Center during the time period 2013 Jan 16 to 2013 Feb 28 UTC.

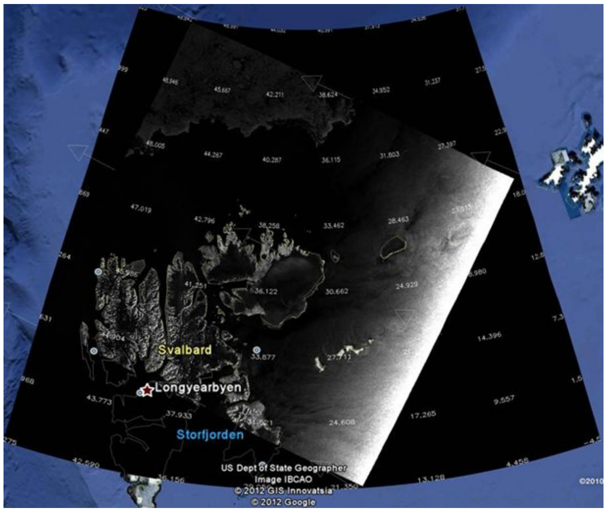

FIG. 3. Radarsat-2 NRCS image projected onto Google Earth, acquired 2012 Aug 08 05:57:54 UTC.

5. EXAMPLES

The actual wind speed values are available and stored in the NOAA-standard netCDF format. In addition, color-coded wind speed imagery are provided in PNG, KMZ, and GeoTIFF formats to aid the analysts at NIC. Here are some examples to illustrate the output. Fig. 3 is a Radarsat-2 NRCS image acquired near Svalbard, Norway. Note the rapid fall off in NRCS associated with increasing incident angle going from the right to left portion (east to west) of the image. Careful examination will reveal sea ice in the northwestern portion of the image.

Fig. 4 represents the corresponding wind speed image, color-coded from 0 m/s (dark blue) to 25 m/s (red). Land is represented by the a shaded-relief grayscale map. The wind speed processing has essentially flattened out the image. Now the sea ice area (for which the wind speed retrievals are not valid) is more conspicuous. Hence, the wind speed processing not only provides estimates of wind speed, but makes the identification of sea ice areas clearer.

A KMZ file of the latest 48 hours of wind speed retrievals can be found at:

http://www.natice.noaa.gov/

Click on "Products" and follow the links to "SAR Wind KML Files."

At this NIC site, the SAR wind data are combined in the KMZ files with and ice mask layer from the 4-km resolution Interactive Multisensor Snow and Ice Mapping System (IMS) data (Helfrich et al. 2007). Fig. 5 shows a screen shot of a Google Earth display of wind

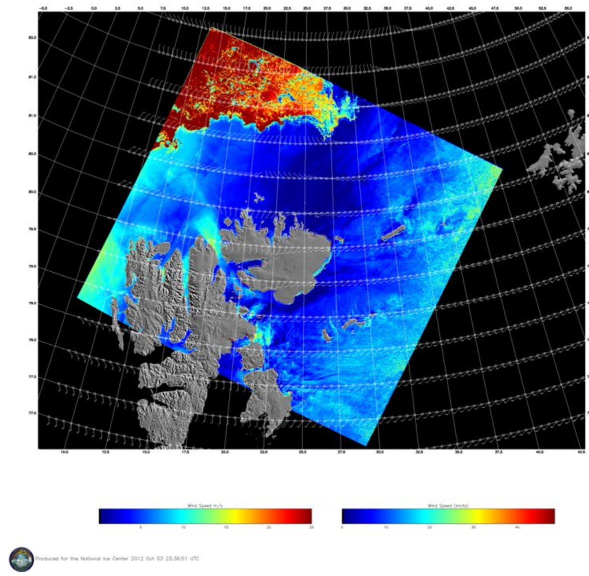

FIG. 4. Radarsat-2 wind image 2012 Aug 08 05:57:54 UTC.

speed off the eastern coast of Greenland. The western part of the image has sea ice. Fig. 6 is the same image, where the grey scale represents the IMS sea ice mask from the latest analysis. Again, this aids in the interpretation of the SAR wind imagery and the separation of open ocean from sea ice.

6. CONCLUSIONS

The use of synthetic aperture radar to make high-resolution estimates of wind speed is now a mature technology. It will soon be operational at NOAA NESDIS. A test version of the software including an ice

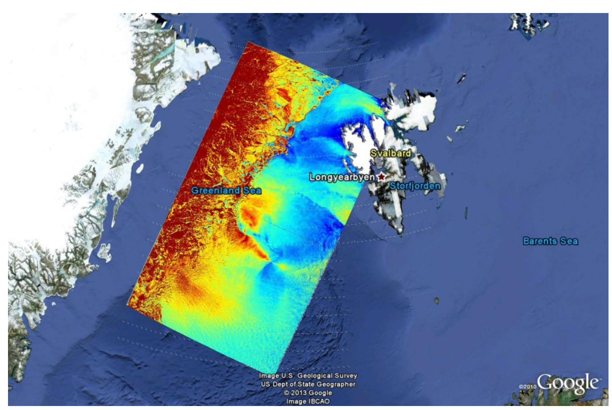

FIG. 5. Radarsat-2 wind image 2013 Mar 28 07:14:49 UTC.

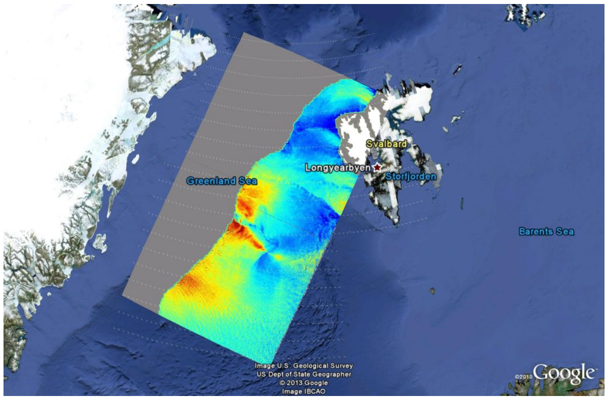

FIG. 6. Radarsat-2 wind image 2013 Mar 28 07:14:49 UTC with sea ice mask in gray.

mask layer is now being provided routinely by the National Ice Center. These wind images not only provide wind information, but aid in the discrimination of open water from sea ice.

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