12.3 BEAUFORT SEA ICE MELT POND COVERAGE FROM MODIS OBSERVATIONS

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1. INTRODUCTION

Melt ponds are ubiquitous on arctic sea ice during the summer melt season. During melt onset, the appearance of ponds transforms sea ice from a relatively homogeneous, snow-covered pack to a variegated surface with large spatial variation in albedo. The radiative and thermal properties of ponds differ greatly from the surrounding ice pack.

Recent observations have established that melt ponds play a central role in the summer evolution of ice pack albedo [*Perovich et al.,* 2002a; *Eicken et al.,* in press]. The albedo of bare, multiyear ice changes little during the melt season, because a surface scattering layer continually renews itself [*Perovich et al*., 2002a]. However, the behavior of melt ponds is quite different. Throughout the summer, melt pond albedos continually decrease as the ponds grow wider and deeper and the underlying ice thins. The reduction in the average albedo of individual floes during summer is due primarily to changes in the areal coverage and optical properties of the melt ponds.

Pond *coverage* also evolves through the melt season. During the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment, the pond fraction increased from melt onset until late July, then decreased until fall freeze-up [*Perovich et al.,* 2002b; *Tschudi et al.,* 2001]. It is therefore important not only to quantify the ponding that occurs on a given day during summertime, but also to characterize the evolution of pond fraction through the melt season. Since the evolution of pond fraction and pond characteristics is a function of ice conditions, air temperature and atmospheric radiation, variations in the pond fraction provides insight into the interannual and regional variations in these underlying forcings.

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Ice concentration during the arctic summer is underestimated using passive microwave observations, as melt ponds appear radiometrically similar to open water [*Fetterer and Untersteiner*, 1998; *Cavalieri et al*., 1984]. Estimates of pond fraction are therefore required to assess the overestimation of open water fraction using passive microwave retrievals during the melt season. Improvements in retrievals of summertime ice coverage will enhance the use of passive microwave ice concentration estimates for assimilation into sea ice and climate models, model evaluation, as well as real-time ice coverage forecasting.

Melt pond areal coverage has been measured in several arctic locations during field experiments [*Tucker*, 1999; *Perovich and Tucker*, 1997; *Eicken at al.*, 1994; *Maykut et al.*, 1992] and has been observed from aircraft [*Perovich et al.,* 2002b; *Tschudi et al.,* 2001, 1997; *El Naggar et al.*, 1998] and high-resolution satellite imagery [*Fetterer and Untersteiner*, 1998]. *Markus et al*. [2002] investigated the use of Landsat imagery to characterize arctic sea ice conditions, and most recently [*Markus et al*., in press] combined satellite and airborne video observations to estimate pond fraction in Baffin Bay. The application of Moderate Resolution Imaging Spectroradiometer (MODIS) observations to quantify the evolution of pond coverage permits the cover to be characterized throughout the Beaufort and Chukchi Seas, and is the first attempt to classify melt ponds from EOS data.

2. SURFACE SPECTRAL REFLECTANCE

To properly ascertain the coverage of open water, ponded ice, and unponded ice, the spectral reflectance of each feature must be estimated. Surface measurements of spectral reflectance were made from late May to late June, 2002 near Barrow, Alaska, as part of the Arctic Coastal Ice Processes study [Perovich *et al.*, 2001]. Spectral reflectance measurements of a blue melt pond and bare melting ice (June 5 at the Chukchi Sea site), as well as a green pond and white ice (June 8 at the Elson Lagoon site), were obtained (Figure 1).

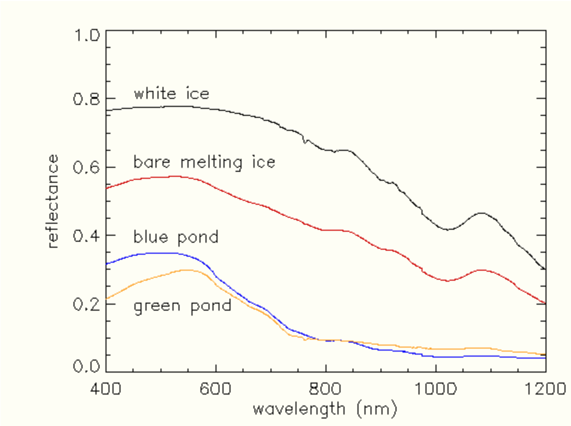

Figure 1: Surface reflectance during early June, 2002 near Barrow, Alaska.

These observations provide a basis for classifying ponds and sea ice in a nearby region during a similar time of observation. The spectral reflectance of open water was not measured at these sites, but observations by *Pegau and Paulson* [2002] are utilized (the reflectance is roughly 0.08 across this spectral region). The spectral reflectance (R) within a sensor's field of view is given by:

$$R = \Sigma A_i R_i, \text{ where } \Sigma A_i = 1. \qquad (1)$$

A_i is the fractional coverage of each surface feature and R_i the feature's spectral reflectance. A system of linear equations is built using (1) for multiple MODIS bands and solved for A_i.

Surface reflectance varies spatially and temporally in the arctic. It will therefore be necessary to adjust the spectral albedo of the surface features according to other observations that were taken during similar time periods and/or locations, when possible. For example, *Perovich et al.* [2002b] measured the evolution of spectral albedo through the melt season during the SHEBA field experiment (Figure 2).

To derive pond fraction, it is beneficial to utilize MODIS bands that distinguish ponded from unponded sea ice and open water. Bands 1 (620-670 nm), 3 (459-479 nm) and 4 (545-565 nm) are well suited for this purpose (Figure 2). These data are available in products that represent surface reflectance as would be measured on the ground. The algorithm that produces the band reflectance products corrects for removal of gases, aerosols, and cirrus clouds, as well as accounting for the effects of the BDRF [*Strahler and Muller*, 1999]. These products are built at resolutions of 250 and 500 m, although only bands 1 and 2 (841-876 nm) are available at 250 m. For this study, 500 m data was analyzed, so bands 3 and 4 could be included.

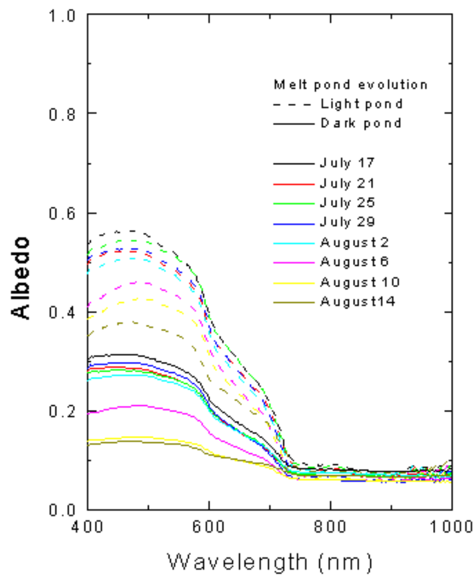

Figure 2: Spectral reflectance of two melt ponds at SHEBA [Perovich et al., 2002a*].*

3. POND FRACTION

The intent of this work is to provide a gridded dataset of pond fraction for the Beaufort and Chuckhi Seas during the summers of 2002 – 2004. For this paper, a prototype algorithm was developed from (1) to apply the MODIS band 1, 3, and 4 surface reflectance products with the spectral reflectance surface measurements (Figure 1) to obtain a melt pond, ice (which is unponded), and open water coverage estimate for each 500 m pixel in the boxed region of a MODIS scene (Figure 3) that was observed near to and in the same time period as the surface measurements. Cloud-covered pixels accounted for roughly one third of the scene, and were excluded from this analysis.

Pond, ice, and open water fractions calculated by this algorithm for the region are shown as histograms in Figure 4. The most common pond coverage was about 15%, open water 5% and ice 60%. For each pixel, ice + ponds + open water = 1 (so there is no pixel that exhibited all of the most common coverages). Mean pond coverage was

24.5%, with a standard deviation of 15.5%. Bare and melting ice are grouped into one category (ice), which is the same as unponded ice. It is evident in this region that open water comprises less than 20% of the pixel area in the majority of the region, although a secondary maximum of open water fraction suggests that there are leads or broken ice in some areas.

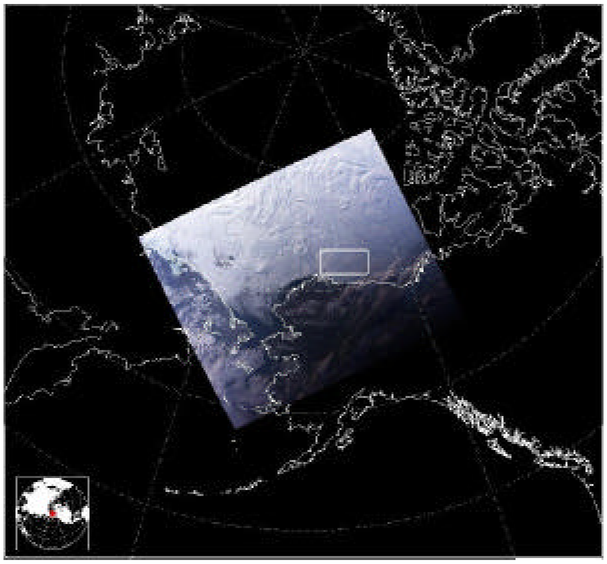

Figure 3: Composite MODIS 1 km resolution image from bands 1, 3, and 4 on June 2, 2002. Image by Mark Gray and Bill Ridgway (NASA GSFC).

A source of error for this estimate is the assumption that all ponds exhibit the same spectral signature as the ponds observed in June near Barrow. Pond reflectance can vary dramatically (Figure 2), even in a localized area on a particular day. For this analysis, an average reflectance of the blue and green pond (Figure 1) was used, but there is no justification to use a mean value. This will be an ongoing challenge for this work: how best to represent the pond (and ice) reflectance in different regions and time periods? Whenever possible, surface observations will serve this purpose. MODIS surface reflectance product errors, which include at-sensor radiance and atmospheric corrections errors, are detailed by *Strahler and Muller* [1999].

4. AEROSONDE OBSERVATIONS

The main method of evaluating the EOS-derived pond fractions will be through comparisons to pond coverage derived from observations collected during Aerosonde flights over the Beaufort Sea during the same time period. The Aerosonde is a small, robotic aircraft designed to undertake a wide range of operations in a highly flexible and inexpensive mode [*Holland et al.,* 2001]. The aircraft, developed by a US-Australian consortium, entered limited operations in 1999. Current operations and further development are being undertaken by *Aerosonde Robotic Aircraft* and *Aerosonde North America* (See www.aerosonde.com for details.) The Aerosonde conducts a defined mission in a completely robotic mode. However, all flights are under the command of a ground controller who can change missions and respond to air traffic control requests, etc. An NSF-funded effort (Office of Polar Programs' Long Term Observations [LTO] effort) is now underway at Barrow to deploy Aerosondes for routine mapping and atmospheric sounding missions (*J. Curry*, PI; *J. Maslanik*, Co-PI). Development and validation of the MODIS melt pond retrieval methodology will take advantage of these operations.

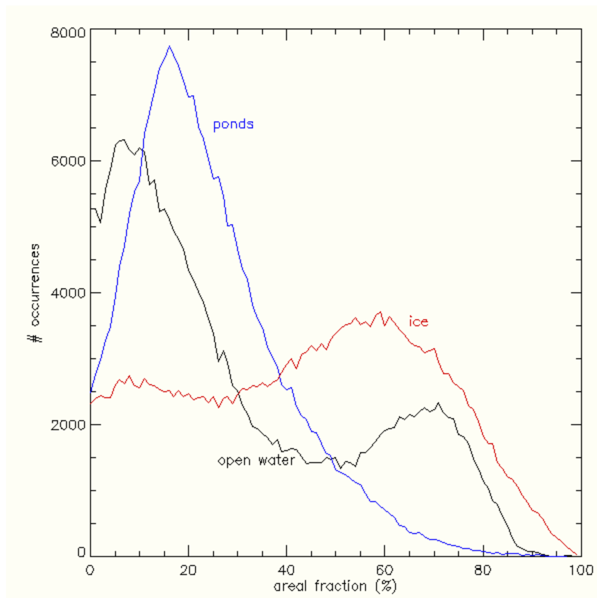

Figure 4: Estimated melt pond fraction over boxed area shown in figure 3.

Digital images acquired by the Aerosonde's downward-looking camera will be analyzed to determine pond, ice, and open water fraction. The routine for generating pond statistics where the pure pixel assumption is reasonably valid has already computed these feature coverages from images obtained in past Aerosonde missions based in Barrow. In addition to the digital camera, the possibility exists that a miniature spectrometer will be available during Aerosonde flights in 2003 or 2004. This would provide detailed spectral data over a broader area of the ice pack than can be sampled using in-situ field measurements, and thus help improve the accuracy of spectra prescribed in the unmixing algorithm.

5. SUMMARY

The MODIS surface reflectance product for a region in the Beaufort Sea on June 2, 2002 was analyzed to determine pond fraction, using surface observations of melt pond and ice spectral reflectance at a nearby site within a few days of the satellite overpass. The intent of this paper is to demonstrate the approach for building datasets of pond, ice and open water fraction over the Beaufort and Chukchi Seas for the summers of 2002-2004, which is currently being undertaken by the authors.

Past and future surface observations of pond and ice reflectance are critical to the success of this project, since pond reflectance varies spatially and temporally during the melt season. Aerosonde surface observations will quantify the accuracy of satellite-derived pond fraction estimates, and may also provide surface spectral reflectance that would be used with and compared to the MODIS products.

6. ACKNOWLEDGEMENTS

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