9.6 MELT POND COVERAGE ON ARCTIC SEA ICE FROM MODIS

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1. INTRODUCTION

Sea ice extent in the Arctic Ocean has been decreasing an estimated 2-3% per decade over the course of the satellite record [*Comiso and Parkinson*, 2004]. Recent evidence suggests that the ice has also been thinning [*Rothrock et al.,* 2003]. The reduction of sea ice extent and thickness is enhanced by the ice-albedo feedback [*Curry et al.*, 1995] by accelerating the rate of ice melt in the Arctic summer. The formation of melt ponds on sea ice during melt onset has a significant impact on the strength of this positive feedback mechanism by lowering the surface albedo.

Arctic melt pond coverage has been measured in several Arctic locations during separate field experiments [e.g. *Eicken et al.*, 1994] and has been observed aerially [*Perovich et al.*, 2002; *Tschudi et al.*, 2001, 1997] and with high-resolution satellite imagery [*Fetterer and Untersteiner*, 1998]. Pond fraction over Baffin Bay sea ice has been estimated from Landsat imagery by *Markus et al.* [2003]. However, this study is the first attempt to characterize the evolution of pond cover over a significant portion of the Beaufort and Chukchi Seas (Figure 1).

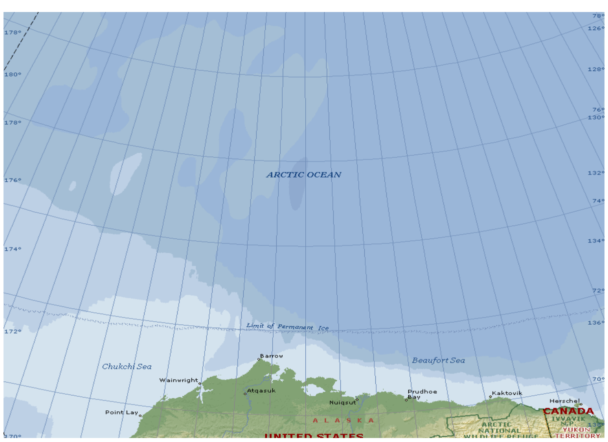

Figure 1: Study region.

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2. POND COVERAGE USING MODIS

Melt ponds exhibit a unique spectral reflectance compared to white ice and open water, enabling pond coverage to be estimated using observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) [*Tschudi et al.*, 2003]. The MODIS Land Group provides a product (MOD09) that estimates the surface reflectance for several MODIS bands at resolutions of 250m (for 2 bands), 500m, and 1km. This product has been produced by applying MODIS-derived corrections for atmospheric aerosols, gases and water vapor, as well as cirrus clouds and BRDF [*Vermote and Vermeulen*, 1999].

To derive pond fraction, we use

$$[\Sigma\, a_i \alpha_i = R]_j,\ \Sigma\, a_i = 1. \qquad (1)$$

R is the reflectance for each MODIS pixel over band *j*; a_i the area covered by pond, bare ice, or open water (i = 1, 2, or 3); α_i the individual reflectance for each of these surface features over band *j*. We solve (1) for a_i, using an on-ice measured reflectance [*Perovich et al.*, 2001] (α_i) and the MODIS surface reflectance (*R*), yielding a unique melt pond fractional coverage for each MODIS pixel.

3. AIRBORNE VERIFICATION OF POND COVERAGE

Several unmanned aerial vehicles (UAVs) were deployed by Aerosonde, Inc. (aerosonde.com) during June 2004 at Barrow, Alaska. The Aerosondes [*Holland et al.,* 2001] carried a variety of instruments during this deployment, including a downward-looking color digital camera, which took hundreds of photographs of the sea ice, typically from an altitude of 1km (Figure 2). After the deployment, the photographs were classified for pond, ice and open water coverage using an interactive computer program.

On June 13, 2004, an Aerosonde flew a 10km x 10km grid pattern during clear-sky conditions, approximately 100km NNW of Barrow. Overlapping digital sea ice photographs were acquired and subsequently classified. The set of classifications is compared to MODIS-derived pond coverage over the same area (Figure 3). Aerosonde image locations for this set are superimposed over a MODIS 250m band 1 (620-670 μm) radiance image, including the MODIS cloud mask, in Figure 4. The cloud mask verifies that the grid pattern was flown without intervening clouds.

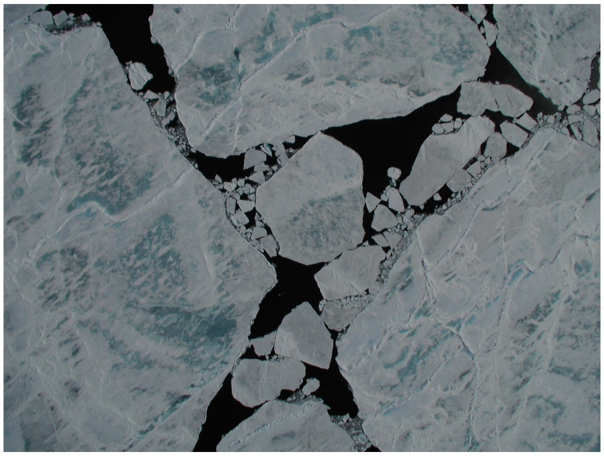

Figure 2: Digital photograph of sea ice near Barrow, taken from an Aerosonde on June 13, 2004.

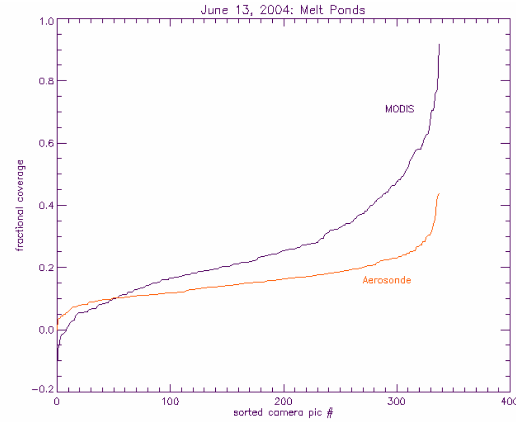

Figure 3: Sorted melt pond fractions for Aerosonde digital camera images and from MODIS.

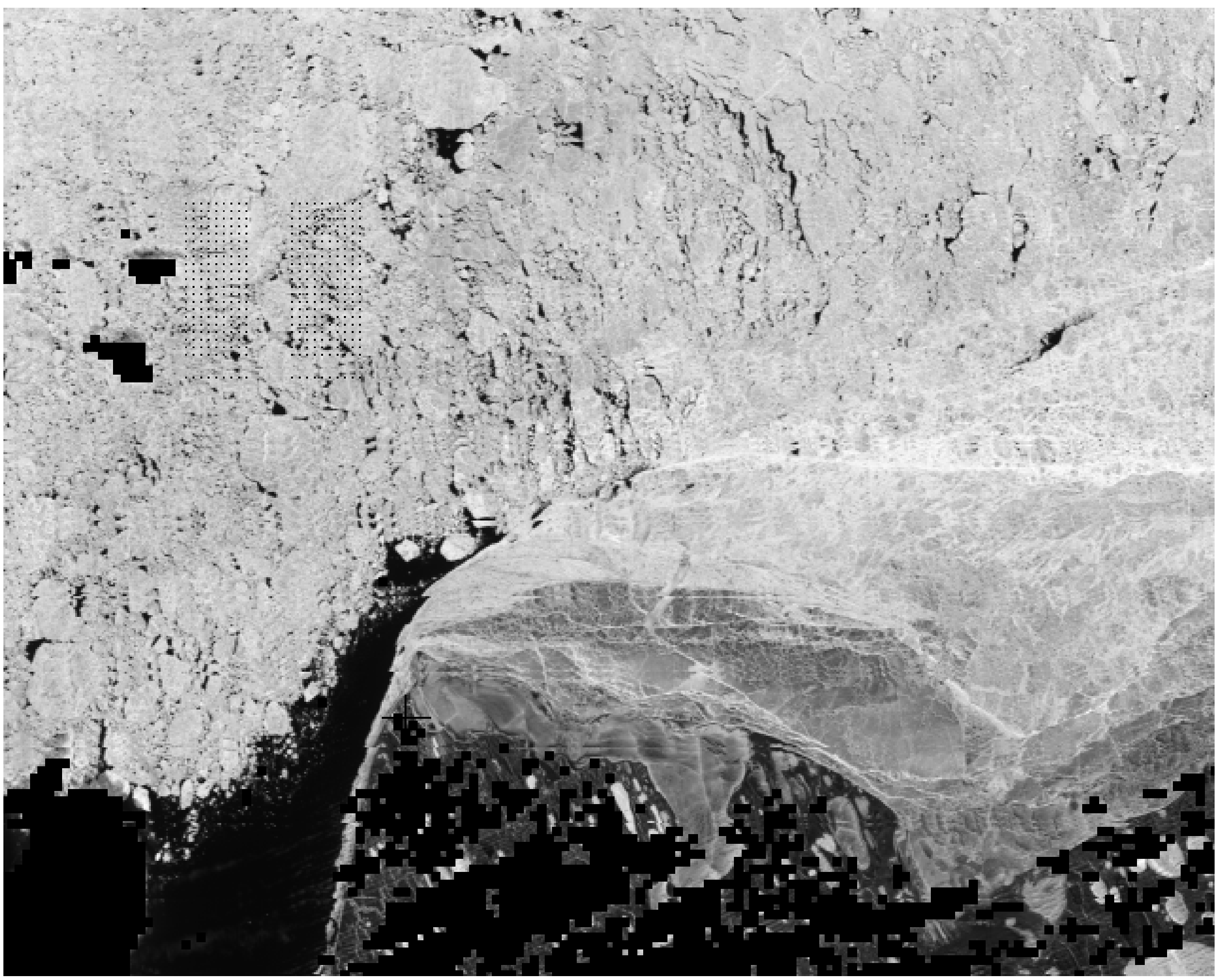

Figure 4: MODIS band 1, 250m resolution, June 13, 2004. Black dots are Aerosonde digital camera image locations (center points), black squares are from the MODIS cloud mask. Barrow is marked by a black +.

4. DISCUSSION

Melt pond coverage (Figure 3 and Table 1) was typically larger using (1) with the MODIS surface reflectance product than the coverage estimated from the Aerosonde digital camera photos. Variability about the mean (i.e. standard deviation) was higher with the MODIS-based estimates than for the Aerosonde. The discrepancy in pond coverage between the two techniques can be explained in part by the mismatch in coverage between the photos and the MODIS pixels, as areal dimensions do not exactly match. However, this only explains why the pond coverages *differ*, rather than why the MODIS pond coverage has a greater mean.

Technique	Sfc Type	Mean %	St Dev
MODIS	Ponds	18.0	0.084
Aerosonde	Ponds	15.6	0.063
MODIS	Open Water	8.6	0.065
Aerosonde	Open Water	9.4	0.011
MODIS	White Ice	73.3	0.070
Aerosonde	White Ice	75.9	0.092

Table 1: Surface feature coverage over area observed by both MODIS and Aerosonde.

Aerosonde photographs were classified by visually identifying the "best" result for each photograph, which corresponds to the classifier's interpretation of where ponding exists. However, areas of bare ice and flooded ice may not have been classified as ponds by the user, although they most likely contributed a spectral signature that was different from ponds, white ice, or open water (Figure 5).

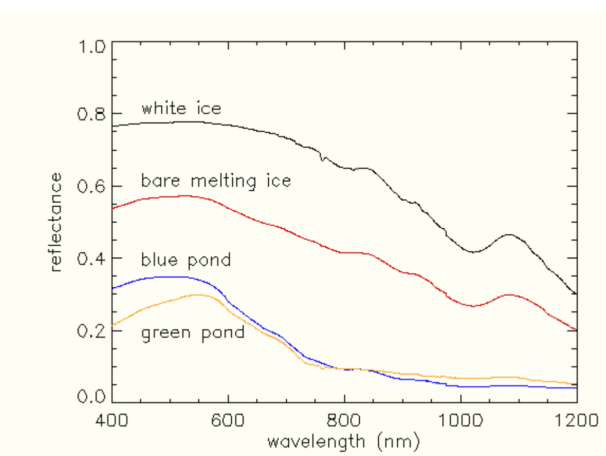

Figure 5: Spectral reflectance of ice and ponds measured during summer, 2001 near Barrow, Alaska

Fortunately, (1) allows for as many surface types as needed, given that *i-1* MODIS bands are applied, where *i* is the number of surface types. Therefore the next step in this work is to use an additional MODIS band and add "bare ice" as a fourth surface type. Adding a second class of melt ponds is also planned, due to the variability between ponds in their spectral signature (e.g. Figure 5).

Figures 6 and 7 illustrate the distribution of ice and open water coverage computed from the MODIS and Aerosonde techniques (see also Table 1). The overestimation of pond fraction by MODIS, compared to the Aerosonde photo classifications, results in an underestimation of ice and open water by MODIS. In almost 1/3 of the cases, MODIS open water coverage was less than zero, indicating that an improvement in the MODIS technique (as suggested in the previous paragraph) is necessary. It is encouraging, however, that the agreement in the mean coverages are within a few percent, which suggests that our approach can be extended to quantify pond, ice, and open water coverage throughout the study area (Figure 1) and eventually over the entire Arctic Basin.

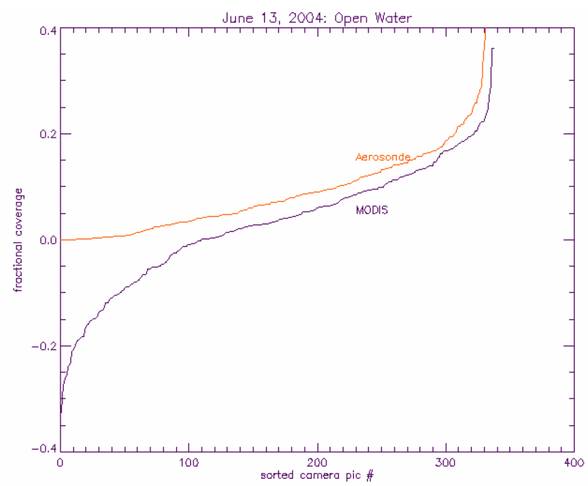

Figure 6: Open water coverage using each technique.

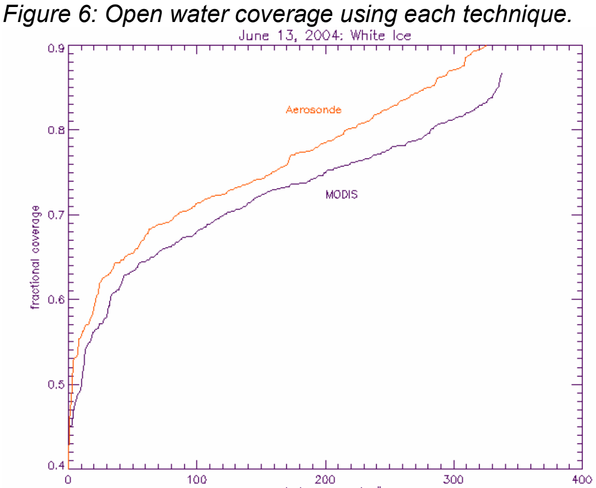

Figure 7: White ice coverage using each technique.

5. ACKNOWLEDGEMENTS

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