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Network modeling of Arctic melt ponds

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ABSTRACT

The recent precipitous losses of summer Arctic sea ice have outpaced the projections of most climate models. A number of efforts to improve these models have focused in part on a more accurate accounting of sea ice albedo or reflectance. In late spring and summer, the albedo of the ice pack is determined primarily by melt ponds that form on the sea ice surface. The transition of pond configurations from isolated structures to interconnected networks is critical in allowing the lateral flow of melt water toward drainage features such as large brine channels, fractures, and seal holes, which can alter the albedo by removing the melt water. Moreover, highly connected ponds can influence the formation of fractures and leads during ice break-up. Here we develop algorithmic techniques for mapping photographic images of melt ponds onto discrete conductance networks which represent the geometry and connectedness of pond configurations. The effective conductivity of the networks is computed to approximate the ease of lateral flow. We implement an image processing algorithm with mathematical morphology operations to produce a conductance matrix representation of the melt ponds. Basic clustering and edge elimination, using undirected graphs, are then used to map the melt pond connections and reduce the conductance matrix to include only direct connections. The results for images taken during different times of the year are visually inspected and the number of mislabels is used to evaluate performance.

1. Introduction

Sea ice is a critical component of Earth's climate system and a sensitive indicator of climate change. The dramatic losses of summer Arctic sea ice observed in the past few decades have a substantial impact on Earth's climate system, yet most global climate models have significantly underestimated the rate of decline (Boé et al., 2009; Serreze et al., 2007; Stroeve et al., 2007). One of the fundamental challenges of climate science is to develop more rigorous representations of sea ice in climate models and to incorporate important small scale processes and structures into these large scale models. For example, during the melt season the Arctic sea ice cover becomes a complex evolving mosaic of ice, melt ponds on the sea ice surface, and open water. While white snow and ice reflect most incident sunlight, melt ponds and the ocean absorb most of it. The overall reflectance or albedo of sea ice floes – the ratio of reflected to incident sunlight – is determined by the evolution of melt pond coverage and geometry (Perovich et al., 2002; Polashenski et al., 2012; Scott and Feltham, 2010). As melting increases, the albedo is lowered, which increases solar absorption, leading to more melting, and so on. This key mechanism is called *ice–albedo feedback* (Curry et al., 1995), and has played a significant role in the decline of the summer Arctic ice pack (Perovich et al., 2008; Pistone et al., 2014). Sea ice albedo is a significant source of uncertainty in climate projections and one of the most important parameters in climate modeling (Flocco et al., 2010; Pedersen et al., 2009; Polashenski et al., 2012; Scott and Feltham, 2010).

While melt ponds form a key component of the Arctic marine environment, comprehensive observations or theories of their formation, coverage, and evolution remain relatively sparse. Available observations of melt ponds show that their areal coverage is highly variable. This is particularly true for first year ice early in the melt season, with rates of change as high as 35% per day (Polashenski et al., 2012; Scharien and Yackel, 2005).

Such variability, as well as the influence of many competing factors controlling melt pond and ice floe evolution, makes the incorporation of realistic treatments of albedo into climate models quite challenging (Polashenski et al., 2012). Small and medium scale models of melt ponds which include some of these mechanisms have been developed (Flocco and Feltham, 2007; Scott and Feltham, 2010; Skyllingstad et al., 2009), and melt pond parameterizations are being incorporated into global climate models (Flocco et al., 2010; Flocco et al., 2012; Hunke and Lipscomb, 2010; Hunke et al., 2013; Pedersen et al., 2009).

As melting progresses during the season, the evolution of melt ponds from small isolated structures into large interconnected networks is responsible for a number of processes that help control the rate at which the ice pack melts. It is believed (Hohenegger et al., 2012) that this evolution of connectedness is an example of a percolation transition

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(Christensen and Moloney, 2005; Stauffer and Aharony, 1992). Such a transition occurs when one phase in the microstructure of a composite material, for example, becomes connected on macroscopic scales as a controlling parameter exceeds a critical value called the *percolation threshold* (Broadbent and Hammersley, 1957; Christensen and Moloney, 2005; Stauffer and Aharony, 1992).

In the case of melt ponds the controlling parameter which gives rise to critical behavior is thought to be the fraction of the area of the sea ice surface covered by melt ponds.

An important example of critical behavior related to percolation theory as applied to sea ice, and important for melt pond drainage, comes from the study of fluid flow through the porous microstructure of sea ice. Specifically, the brine microstructure displays a percolation threshold at a critical brine volume fraction of around 5 % in columnar sea ice (Golden et al., 1998; Golden et al., 2007; Pringle et al., 2009), which corresponds to a critical temperature $T_c \approx -5\ ^\circ$C for a typical bulk salinity of 5 ppt. Below this threshold the brine phase of the sea ice consists primarily of isolated, disconnected pockets. It is only above the threshold where the brine phase becomes connected over large scales. This threshold acts as an on-off switch for fluid flow through sea ice, and is known as the *rule of fives*. It leads to critical behavior of fluid flow, where sea ice is effectively impermeable to fluid transport for brine volume fractions below 5 % and increasingly permeable for volume fractions above 5 %.

In addition to identifying the critical behavior of fluid transport in sea ice, the percolation theory of fluid and electrical transport through lattices (Christensen and Moloney, 2005; Stauffer and Aharony, 1992) was used to produce models of the fluid permeability of sea ice as a function of brine volume fraction (Golden et al., 2007). In this work X-ray computed tomography images of the brine microstructure of sea ice were analyzed and mapped onto random graphs of nodes and edges, in order to establish the percolative behavior of the system (Golden et al., 2007; Pringle et al., 2009), and the rule of fives in particular.

Other types of network models have also been used to describe both fluid and electrical transport in the brine phase of sea ice. For example, in the random pipe model, the diameters of random pipes, which represent brine channels in the ice, are chosen from lognormal probability distributions that describe the cross-sectional areas of the brine inclusions in sea ice and then assigned to the edges in a square lattice (Zhu et al., 2006). The fluid permeability of the model is then computed by using a random resistor network representation of the system and employing a fast multigrid method to find its effective conductivity which can then be related to the permeability. This same approach can also be used to directly model the electrical conductivity of the ice, an important parameter in remote sensing of sea ice thickness, fluid transport properties, and microstructural transitions (Addison, 1969; Buckley et al., 1986; Fujino and Suzuki, 1963; Ingham et al., 2008; Reid et al., 2006; Thyssen et al., 1974). Network models have been used extensively in analyzing the transport properties of composite materials (Milton, 2002; Torquato, 2002).

It has been suggested that percolative behavior occurs for melt ponds on the sea ice surface, As they cover more of the surface, disconnected, isolated ponds begin to evolve into large connected structures with complex boundaries, presumably achieving large scale connectivity above a critical area fraction (Hohenegger et al., 2012).

Increased connectivity of melt ponds promotes further melting through increased heat transport, contributes to the break-up of ice floes, and allows increased horizontal transport of meltwater toward drainage avenues such as large vertical brine channels, cracks, leads, and seal holes (Polashenski et al., 2012; Scharien and Yackel, 2005). Other melt pond models including both vertical and horizontal transport of melt water, such as a type of cellular automata, have been developed elsewhere, as in Scott and Feltham (2010).

In this work we begin to develop techniques for network modeling of melt ponds, their connectivity, and horizontal flow characteristics. Some of the groundwork for this type of modeling was laid in Hohenegger et al. (2012). Images of melting Arctic sea ice collected during two Arctic expeditions – the 2005 Healy-Oden Trans Arctic Expedition (HOTRAX) (Perovich et al., 2009) and the 1998 Surface Heat Budget of the Arctic Ocean (SHEBA) expedition (Perovich et al., 2002) – were analyzed for area–perimeter data on thousands of individual melt ponds. Algorithmic methods of distinguishing melt ponds from the ocean in leads between the sea ice floes were developed. This data was used to discover that pond fractal dimension transitions from 1 to 2 around a critical length scale of 100 m^2 in area (Hohenegger et al., 2012). Pond complexity was found to increase rapidly through the transition as smaller ponds coalesce to form large connected regions, reaching a maximum for ponds larger than about 1000 m^2 whose boundaries resemble space filling curves.

In earlier work on melt ponds and sea ice albedo, image processing has been used to measure the area fractions of melt ponds and leads from aerial and satellite images. In Perovich et al. (2002) these area fractions from June to October, using SHEBA images taken in 1998 (Perovich et al., 2002), show how the area fraction of melt ponds increases as summer progresses, and starts decreasing again at the end of summer as new ice forms. A probability distribution for the size of melt ponds is also derived from the data, which depends on the progress of the melt season.

In the work reported here, the connectivity of these melt pond networks is determined using aerial images of Arctic sea ice from the SHEBA and HOTRAX databases. We develop an algorithmic method of mapping a configuration of melt ponds onto a graph of nodes and edges. These melt pond configurations may be disconnected individual components, or partially or completely connected across an image. The edges are assigned values which indicate the width of "bottlenecks" separating larger pools of melt water, which are identified with the nodes of the graph.

The horizontal flow of water between melt ponds depends on the narrowest bottlenecks between them and the width of these bottlenecks is inversely proportional to the fluid conductance between them.

Mathematical morphology based image processing techniques (Gonzalez and Woods, 2008) are used with a clustering algorithm and graph theory to find a conductance graph associated with each melt pond configuration studied. Further work will explore the relationship of these graphs and associated conductance networks with the actual flow of fluid in the pond network, and the effect on sea ice albedo.

2. Method

The images of melt ponds from the SHEBA and HOTRAX expeditions are in color. The intensity and color of each pixel in the image are encoded using the intensities of the Red, Green and Blue colors that make up each pixel. The image is represented as a matrix of pixels, with each pixel being a vector of three variables — red, green and blue color values. These are called, respectively, the red, green and blue channels of the image.

These images are converted to gray-scale to reduce each pixel to only one intensity and lessen the number of computations required. The gray scale image is derived using the red channel as we see the largest difference between ice and water there.

A simple thresholding operation, as described in the Appendix A, is sufficient to segment the melt pond water from ice and produce a binary image. Otsu's method (Gonzalez and Woods, 2008) is used to determine this threshold individually for each image, which is then segmented based on this threshold. Fig. 1 shows a histogram of the intensity levels of a gray-scale aerial image with Otsu's threshold. After having segmented water from ice, it is also possible to use the blue color intensity in the images to distinguish between the ocean water leads and melt pond water. However, in this paper, we have selected images that do not contain any ocean water leads.