Fluid flow through sea ice governs a broad range 3 of geophysical and bi-

4 ological processes in the polar marine environment. For example, the evo-

5 lution of melt ponds and sea ice albedo, which is important in climate mod-

6 eling, is constrained by drainage through the porous brine microstructure.

7 However, for brine volume fractions below about 5%, columnar sea ice is ef-

8 fectively impermeable to fluid flow. In two different experiments conducted

9 in the Arctic and Antarctic, we have found that this critical fluid transition exhibits a strong electrical signature, with sea ice resistivity 10 rising sharply

11 over three orders of magnitude near the brine connectivity threshold. The

12 data are accurately explained by percolation theory, with the same univer-

13 sal critical exponent which captures fluid permeability. These results enable

14 us to connect specific electrical profiles to important processes such as melt

15 pond formation and drainage, CO2 pumping, and the flux of nutrients which

16 sustain biomass build-up.

Polar sea ice is a key component of Earth’s climate system, and a leading indicator of

climate change [Thomas and Dieckmann, 2009; Serreze et al., 2007]. As a material sea ice

is a composite of pure ice with brine and air inclusions. The brine phase hosts extensive

microbial communities which sustain life in the polar oceans [Thomas and Dieckmann,

2009; Fritsen et al., 1994]. Fluid flow through the porous microstructure mediates key

processes impacting the climatology and biology of sea ice. Improving projections of the

fate of Earth’s sea ice cover and its ecosystems depends on a better understanding of these

important processes and feedback mechanisms.

For example, the evolution of sea ice albedo represents a fundamental problem in climate

modeling and a significant source of uncertainty in climate projections [Flocco et al., 2010;

Polashenski et al., 2012]. The albedo of sea ice floes is determined by melt pond evolution

[Perovich et al., 2002; Polashenski et al., 2012]. Drainage of the ponds, with a resulting

increase in albedo, is largely controlled by the fluid permeability of the porous sea ice

underlying the ponds [Eicken et al., 2004; Golden et al., 2007]. As ice recedes with

melting, more water surface is exposed, which increases solar absorption, leading in turn to more melting, and so on. This ice–albedo feedback has played 37 a significant role in the

38 decline of the summer Arctic ice pack [Perovich et al., 2007].

39 Fluid flow through sea ice governs the evolution of the salt budget and salinity profiles

40 [Thomas and Dieckmann, 2009], convection-enhanced thermal transport [Lytle and Ack-

41 ley, 1996], ocean-ice-atmosphere CO2 exchanges [Rysgaard et al., 2009], and the build-up

42 of algal biomass fueled by nutrient fluxes [Thomas and Dieckmann, 2009; Fritsen et al.,

43 1994]. It also drives snow-ice formation, accounting for a significant portion of the ice pro-

44 duced in the Southern Ocean [Maksym and Markus, 2008]. Sea water percolates upward

45 through the porous microstructure, flooding the snow layer, and subsequently freezing.

46 While fluid flow is substantially restricted for brine volume fractions \_ below about 5%,

47 columnar sea ice is increasingly permeable for \_ above 5% [Golden et al., 1998]. For a

48 typical bulk salinity of 5 ppt, the critical porosity \_c \_ 5% corresponds to a temperature

Tc \_ −5\_ 49 C. This critical behavior of the fluid permeability, which is known as the rule

50 of fives, results from a connectivity or percolation threshold in the brine microstructure

51 [Golden et al., 1998, 2007; Pringle et al., 2009].

52 If the fluid transport properties of sea ice can be linked to its electrical properties, which

53 is the aim of this paper, then new approaches can be brought to bear in monitoring the

54 state of sea ice. For example, it could open the door to the development of sensors to

55 enhance existing buoy networks, provide information on key ice processes, and improve

56 integration with satellite data.

57 The electrical conductivity of sea ice has been studied over the past five decades [Fujino

58 and Suzuki , 1963; Addison, 1969; Thyssen et al., 1974; Buckley et al., 1986; Reid et al., 2006; Ingham et al., 2008]. However, there have been no observations 59 of critical behavior

60 in electrical properties corresponding to the microstructural transition encapsulated in the

61 rule of fives. Here we report on two types of experiments where electrical resistivity data

62 clearly display critical behavior at the brine percolation threshold. The mathematical

63 description we develop provides a rigorous link between fluid and electrical transport in

64 sea ice, with both displaying the same type of universal critical behavior, thus laying the

65 foundation for the techniques referred to above. In fact, we further develop this foundation

66 by partitioning the range of resistivity values of our data into intervals which correspond

67 to distinct regimes of fluid permeability characteristics and related process behavior, such

68 as melt pond development, and fluxes of nutrients and CO2.

69 One of the goals of this work is to obtain data on the linkages between electrical and

70 hydraulic properties [Wong, 1988]. The value of such an approach lies in the potential

71 to then extract information about other key variables describing the state of sea ice,

72 e.g., pertaining to its rheology or potential to harbor microbial communities. Our results

73 indicate that such information could potentially be obtained from measurements of electric

74 properties via in situ drifting sensors that can monitor the evolution of sea ice non-

75 destructively (Figure 1 d).

76 The findings presented here also have implications for measuring ice thickness, an im-

77 portant gauge of the impact of global warming. Not only is thickness data important in

78 comparing climate model predictions to observed behavior, but in specifying the initial

79 conditions necessary for long-term numerical simulations. Promising techniques for ad-

80 vanced airborne or surface-based measurements of ice thickness depend on the interaction of electromagnetic (EM) fields with sea ice. For example, there has 81 been significant inter-

82 est in the development of EM induction devices [Haas, 2004; Reid et al., 2006] mounted

83 on ships, planes and helicopters. These techniques, and the interpretation of the data to

84 obtain thickness information, rely on knowledge of the electrical properties of sea ice, and

85 how they vary with depth, temperature, salinity, and ice type. The results presented here

86 shed significant light on such issues.

2. Measuring the electrical properties of sea ice

87 Sea ice is an anisotropic composite with vertically elongated brine inclusions and corre-

88 sponding anisotropy in the effective fluid permeability and electrical conductivity tensors.

89 Most methods for measuring sea ice conductivity involve indirect or inverse techniques,

90 such as surface-based geoelectric profiling using a Wenner array of electrodes [Fujino and

91 Suzuki , 1963; Thyssen et al., 1974; Buckley et al., 1986; Reid et al., 2006; Ingham et al.,

2008; Sampson et al., 2011]. Generally with these methods the vertical conductivity \_\_

v 92 is

inherently mixed with the horizontal components. Here we are most interested in \_\_

v 93 due

94 to its connection with vertical fluid flow.

95 During the Sea Ice Physics and Ecosystem Experiment (SIPEX) in September and

October of 2007, we made direct measurements of \_\_

v 96 in Antarctic pack ice by adapting

97 a four probe Wenner array for use in cylindrical ice cores, as shown in Figure 1 a and b.

The study area was located off the coast of East Antarctica, between 115\_ E and 130\_ 98 E,

and 64\_ S and 66\_ 99 S. At 8 of the 15 ice stations along the cruise track of the Australian

100 icebreaker Aurora Australis, we extracted vertical cores from thin first-year sea ice, with

101 lengths ranging from 34 cm to 86 cm. Thermistor probes were inserted into small holes drilled every 5 cm. We used aWenner electrode array along sections 102 of the cores, connected

103 to a YEW Earth Resistance Tester operating at 38 Hz. This set-up yields the resistance

104 along the axis of the cylindrical ice core between probes P1 and P2, corresponding to the

105 vertical direction in situ, with a = L = 10 cm (or a = L = 5 cm in some cases). We

106 obtained 26 averaged data points from 67 raw measurements of the resistance between the

107 inner probes. After the temperature and resistance measurements were taken, which took

108 about 10 to 20 minutes, we cut each core into 10 cm sections which were later melted, so

109 that we could obtain bulk salinity measurements for each section. The temperature and

110 salinity measurements allowed us to calculate a brine volume fraction profile for each core

111 [Eicken, 2003]. In the auxiliary material we demonstrate that the Wenner array deployed

112 along the core axis is a viable field method for measuring conductivity, yielding values of

113 the vertical component very close to the results of classical, parallel plate experiments.

114 In the Arctic, we used the technique of cross-borehole DC resistivity tomography [In-

115 gham et al., 2008; Jones et al., 2010], as shown in Figure 1 c and d. The ice is probed

116 in its natural state, utilizing two or four vertical strings of electrodes frozen into the ice.

117 It has been shown that this method can be used to derive the horizontal component of

118 the anisotropic resistivity profile. Moreover, it has been demonstrated that the vertical

component of \_

\_ 119 can be obtained as well [Jones et al., 2010; Ingham et al., 2008]. If a

120 minimum of four electrode strings are used, the geometric mean of the vertical and hor-

izontal components of \_

\_ 121 can be derived, along with the horizontal component [Ingham

122 et al., 2008], yielding the vertical component.

Measurements of the temporal variation in the resistivity structure 123 of first-year Arctic

124 sea ice through spring warming have been made approximately 1 km off the coast of

Barrow, Alaska at 71\_ 210 56.4500 N, 156\_ 320 39.0100 125 W. Electrode strings were installed in

126 landfast first year ice in late January 2008. Cross-borehole measurements were made on 6

127 separate occasions between early April and mid June 2008, allowing both the horizontal

128 and vertical components of the ice resistivity to be derived. A sea ice mass balance

129 site and an ice core sampling program at the same location [Druckenmiller et al., 2009]

130 provided ice temperature and salinity data, allowing the variation in resistivity structure

131 to be correlated with brine volume fraction \_.

3. Modeling the electrical conductivity of sea ice

132 Lattice and continuum percolation models [Stauffer and Aharony, 1992] have been used

133 to study a broad range of disordered materials where the connectedness of one phase

134 dominates effective transport behavior. In sea ice, the fluid and electrical transport prop-

135 erties are largely determined by the connectedness of the brine phase − an electrically

136 conducting fluid. Here we briefly describe a lattice percolation model which provides the

137 theoretical framework for predicting the electrical conductivity of sea ice, as well as its

138 fluid permeability. This model, and how it is adapted to the microstructure of sea ice, is

139 covered in more detail in the auxiliary material.

Consider the two dimensional square network of bonds (edges) joining nearest neighbor

sites (vertices) in the integer lattice Z2, as shown in Figure 2 a and b. The bonds are

assigned electrical conductivities \_0 > 0 (open) or 0 (closed) with probabilities p and

1−p, so that a relative proportion p of the bonds are open (on average). The percolation threshold pc is the smallest value of p for which an infinite, connected cluster of open

bonds forms. In two dimensions (d = 2), pc = 1

2 , and in three (d = 3), pc \_ 0.25. For p

just above the percolation threshold, p > pc, where conducting pathways span the infinite

lattice, the effective or bulk conductivity \_\_(p) is believed to display power law behavior,

\_\_(p) \_ \_0(p − pc)t , (1)

where t is the conductivity critical exponent. For lattices, t is believed 140 to be universal,

141 depending only on dimension and not, for example, on whether the lattice is square or

142 triangular. In d = 2, t \_ 1.3, and in d = 3, t \_ 2.0 [Stauffer and Aharony, 1992]. The

effective resistivity is given by \_\_(p) = 1/\_\_143 (p).

In applying percolation theory to sea ice, it is useful to consider the vertical conductivity

formation factor F = \_\_

v/\_b, which removes the dependence of the effective parameter on

the changing conductivity \_b of the brine. In view of (1),

F(\_) \_ F0 (\_ − \_c)2, (2)

144 where the brine percolation threshold is \_c \_ 0.05 [Golden et al., 1998, 2007; Pringle

145 et al., 2009], and t \_ 2.0, the d = 3 universal lattice value. Sea ice is a continuum whose

146 percolation threshold of 0.05 can be explained with a continuum percolation model, known

147 as a “compressed powder” model. Surprisingly, however, the lognormal distribution of

148 brine inclusion cross-sectional areas leads to the universal, lattice critical behavior for

149 transport near the percolation threshold in sea ice [Golden et al., 2007; Berkowitz and

150 Balberg, 1992], as displayed in (2).

151 The scaling factor F0 is obtained by relating the electrical conductivity to the fluid

152 permeability of sea ice through a critical (or bottleneck) radius rc [Friedman and Seaton, 1998]. By measuring the radii of vertical pathways in X-ray tomography 153 images [Golden

154 et al., 2007; Pringle et al., 2009], we estimate a range in mm of 0.1 \_ rc \_ 0.2, yielding a

155 range for F0 of 6 \_ F0 \_ 24. The relations between fluid and electrical transport in sea

156 ice, and the formula for F0, are developed in the auxiliary material.

4. Comparison of theory and data

157 In order to compare our conductivity measurements with percolation theory, we must

158 exclude data below \_c \_ 0.05 [Golden et al., 2007], since the theory is only valid for \_ > \_c.

It is more illustrative to display the data in terms of the reciprocal G = 1/F = \_\_

v159 /\_b,

160 which is the vertical resistivity formation factor. As the conductivity F becomes very

161 small near \_c, its reciprocal G becomes very large, with its behavior approximating a

162 vertical asymptote near \_ = \_c. In Figure 2 c and d we show the two data sets from the

163 Antarctic and Arctic. By fixing the exponent t = 2 and the threshold value \_c = 0.05 in

164 the above expression for F(\_), a statistical best fit of the data yields a value of F0 \_ 9,

which lies inside our predicted range, so that F(\_) \_ 9 (\_ − 0.05)2165 .

166 We see that the data agree well with the theory, and that they both exhibit divergent

167 behavior with a vertical asymptote at the percolation threshold. Moreover, in the variables

168 x = log (\_ − 0.05) and y = log F, the line predicted by percolation theory is y = 2x +

169 log F0, with log F0 = 0.95, F0 = 9. Critical path analysis yields the bounds 0.8 \_ log F0 \_

170 1.4, and the best fit for the Antarctic data in f is y = 1.99x + 0.93, where 0.93 lies inside

171 these bounds. In logarithmic variables, the error of the regression is 0.38 for the Arctic

172 data and 0.22 for the Antarctic data (that is, approximately 68% of the Antarctic data is within 0.22 of the regression line). The increased scatter 173 in the Arctic data is not

174 surprising given the inverse computation required.

To model \_\_

v175 (\_) over all porosities, we consider features of the brine phase present over

176 the full range − some degree of small−scale connectivity, and self-similarity. Hierarchical

177 models of spheres or other grains surrounded by smaller spheres, and so on, with brine

in the pore spaces [Golden et al., 2007], were used to model k\_

v 178 (\_). The simplest model

yields a result of k\_

v(\_) = k0 \_3 and an Archie’s law F(\_) = F0 \_3179 . A statistical best fit of

180 our Antarctic data yields a value of F0 \_ 16, which is in the estimated range. In Figure 3

181 a, our Antarctic data is shown along with fits derived from both models, and in b, Arctic

182 permeability data [Golden et al., 2007] is shown relative to predictions from both models.

5. Discussion

183 Figure 4 illustrates how we can derive information about the permeability structure and

184 relevant transport processes from resistivity soundings of Arctic sea ice with in situ elec-

185 trode strings [Jones et al., 2010]. Thus, the different formation factor regimes shown cor-

186 respond to different permeability classes, with the lowermost ice layers permeable enough

187 to allow for gas and nutrient exchange conducive to biomass build-up and CO2 pumping

[Rysgaard et al., 2007], based on a critical permeability of 4×10−11 m2188 , corresponding to

189 a resistivity formation factor of 31.3 for rc = 0.1 mm. This permeable base layer increases

190 in vertical extent as the ice warms and thins due to bottom and surface melt. The ice

191 interior is permeable enough to allow for meltwater flushing and reduction of ice salinity

192 at surface ablation rates of 10 cm/d or less even prior to the onset of melt [Freitag and

193 Eicken, 2003], corresponding to a resistivity formation factor of 625. High resistivity formation factors near the top in Figure 4 b are in part explained 194 by such percolation of

195 freshwater below accumulations of surface melt water.

196 Let’s further examine how these results may be used to improve our understanding of

197 key processes like melt pond evolution. Incorporating such processes into climate models is

198 critical to improving projections of climate change and the fate of the Earth’s sea ice packs.

199 Development and tuning of advanced climate models could be significantly enhanced by

200 ground truth information on these key processes and the state of the underlying sea ice.

201 This information could be provided by arrays of sensors frozen into the sea ice giving the

202 time evolution of the electrical conductivity and fluid permeability profiles, along with

203 corresponding satellite or airborne imagery of melt pond evolution.

204 For example, there is recent evidence from Arctic sea ice experiments (conducted by C.

205 Polashenski and K. M. Golden in 2014) that the above mentioned percolation of freshwa-

206 ter from snowmelt into the upper layers of sea ice, and its subsequent freezing, could be

207 fundamental to the very formation of melt ponds. This process reduces the permeability

208 − thus increasing the electrical resisitivity, a process likely to have a recognizable elec-

209 trical signature, as evidenced in Figure 4. Gauging the impact, for example, of changing

210 Arctic snowfall on the availability of freshwater for melt pond formation could be made

211 possible with methods based on our results. Melt pond drainage events, which can have

212 a significant impact on sea ice albedo, often follow an increase in permeability through

213 its percolation threshold, which has a strong electrical signature. Specific information on

214 electrical and fluid transport profiles would enable estimates of drainage rates, duration

215 of events, rate of change of albedo, etc. The resulting input of fresh water into the up-

per ocean is also an important process which could then be remotely 216 monitored, making

217 possible estimates on the rate of freshwater influx and net amounts of freshwater input.

218 In the Antarctic snow-ice formation is a significant component of sea ice production.

219 Knowledge of the time evolution of the conductivity−permeability profile in Antarctic

220 sea ice could tell us when the conditions needed for snow-ice formation were present. For

221 example, knowing how long the entire sea ice layer was permeable so that it could flood

222 through upward percolation, and how permeable it was, would let us estimate how much

223 snow ice formed during a storm event. Like melt ponds in the Arctic, incorporating snow-

224 ice formation into Antarctic sea ice and climate models is critical to improving projections.

Laboratory and field work [Zhou et al., 2013; Loose et al., 2011] have demonstrated the

204 importance of permeability changes in spring in driving a key seasonal transition asso-

205 ciated with disproportionate increases in gas transfer, nutrient exchange and biological

206 activity in sea ice. Zhou et al. [2013] demonstrated how this important transition en-

207 hances primary production within the ice and under the ice through seeding of under-ice

208 waters. Since there is no clear surface expression of these processes, in situ measurement

209 of electrical conductivity (e.g., through arrays sampling large volumes [Jones et al., 2010])

210 may serve as an important proxy and help track changes in the timing and magnitude of

211 seasonal increases in gas, nutrient and biomass transfer.

6. Conclusions

225 It has been demonstrated in field experiments conducted in both the Arctic and Antarc-

226 tic that sea ice exhibits critical behavior in its electrical transport properties at a per-

227 colation threshold. Such behavior provides the electrical signature of a key transition in

228 fluid transport properties, known as the rule of fives, which determines whether or not

229 fluid can flow through sea ice. This transition constrains a broad range of processes which

230 are important in the geophysics and biology of the polar regions. The phenomenon is

231 explained theoretically using percolation theory, which provides a universal power law

232 describing the data from both poles, as well as a rigorous link between the fluid and elec-

233 trical transport properties of sea ice. Our findings open the door to a new generation of

234 techniques for in situ analysis and remote monitoring of transport processes, which can

235 improve projections of the fate of Earth’s ice packs and the response of polar ecosystems.