
THERMODYNAMIC AND FLUID-DYNAMICAL
PROCESSES IN SEA ICE

Dirk Notz
Trinity College



A dissertation submitted to the University of Cambridge
for the degree of Doctor of Philosophy

May 2005



ABSTRACT

In this thesis, new experimental and modelling approaches are used to study the growth of sea ice and the associated loss of salt into the underlying ocean. It is shown that in winter salt is only lost from sea ice by so-called gravity drainage and that the bulk-salinity and solid-fraction fields are continuous across the ice–ocean interface during ice growth. The concept of an effective distribution coefficient is therefore not warranted in the context of sea ice. It is further shown that so-called brine expulsion does not lead to any net loss of salt from sea ice, and that flushing with melt water during summer is the only other process that has any impact on the salinity evolution of sea ice.

These results are obtained theoretically, using the so-called mushy-layer equations and an enthalpy-based numerical model. The numerical model allows the study of sea-ice growth and its interaction with radiative processes, melt ponds, oceanic heat and salt fluxes, internal density changes, and surface heat fluxes on a single domain.

The theoretical predictions are confirmed by laboratory and field experiments, using a new instrument developed in this study, which allows the *in situ* measurement of the salinity distribution in growing sea ice with a very high temporal and spatial resolution. The instrumental technique is based on impedance measurements, and solid fraction profiles measured with the instrument in artificial sea ice in laboratory experiments are in very good agreement with theoretical predictions. During several field campaigns in the Arctic the salinity distribution of newly forming ice was measured and compared with results from traditional coring methods. It is shown that the latter are inaccurate, because significant amounts of brine are lost from the lower parts of the cores. The instrument also allows the direct measurement of the total salt flux from growing sea ice and provides new insight into the interior structure of general mushy layers.

CONTENTS

Overview	1
1 Sea Ice in the Climate System	5
1.1 The formation, growth and decay of sea ice	6
1.2 Salt in sea ice	9
1.3 Sea ice in the climate system	11
1.3.1 Impact of sea ice on the thermodynamics of the ocean and the at- mosphere	11
1.3.2 Sea ice and the thermohaline structure of the ocean	14
1.4 The biological importance of salt in sea ice	19
1.5 Sea ice in a changing climate	23
1.6 Summary	25
2 Desalination Processes in Sea Ice	27
2.1 Initial salt entrapment	28
2.2 Brine-pocket diffusion	29
2.3 Brine expulsion	30
2.4 Gravity drainage	31
2.5 Flushing	33
2.6 Summary	34

3	Fundamental Properties of Sea Ice and Mushy Layers	35
3.1	Liquidus temperature	36
3.2	Density	38
3.3	Heat conductivity of the solid and the liquid phase	39
3.4	Heat capacity of the solid and the liquid phase	40
3.5	Heat of solution	42
3.6	Some basic equations for the solid fraction	43
3.7	The enthalpy of mushy layers	45
3.8	The latent heat of fusion	46
3.9	The heat capacity of a mushy layer per unit mass	48
3.10	The heat capacity of a mushy layer per unit volume	50
3.11	The heat conductivity of a mushy layer	52
3.12	Summary	54
4	Analytical Modelling of Sea Ice and its Salinity Evolution	57
4.1	Earlier analytical models	58
4.2	The mushy-layer equations	59
4.3	Solution for the non-convective case	61
4.4	Brine expulsion for constant boundary conditions	65
4.5	The ice–ocean interface for constant boundary conditions	66
4.6	The temperature profile in thin sea ice	68
4.7	Importance of brine movement on ice growth and temperature field	69
4.8	Salt diffusion in sea ice	70
4.9	Summary	71
5	Numerical Modelling of Sea Ice and its Salinity Evolution	73
5.1	Classical numerical models of sea ice	74
5.2	Overview of the enthalpy-based sea-ice model	77
5.3	Basic model layout	78
5.4	The enthalpy method	81
5.5	Solidification of a pure liquid	82
5.6	Solidification of a multi-component liquid	84
5.6.1	Constant density	84
5.6.2	Non-constant density	86
5.7	Sensitivity studies	89
5.8	Brine expulsion for non-constant boundary conditions	93
5.9	Implementation of further desalination processes	94
5.9.1	Brine diffusion	95
5.9.2	Flushing	96

5.9.3	Gravity drainage	100
5.9.4	Initial brine entrapment	100
5.10	Summary	100
5.A	Numerical implementation of the model	101
6	Measuring the Salinity Evolution of Sea Ice	105
6.1	Methods previously used	106
6.1.1	Ice cores	106
6.1.2	Radioactive tracers	108
6.1.3	Time-domain spectroscopy and capacitance measurements	108
6.2	Methods used in this work	110
6.2.1	Temperature-only approach	110
6.2.2	Impedance measurements	112
6.3	Theoretical background for the impedance measurements	114
6.3.1	Equivalent circuit of a conductivity cell	114
6.3.2	Validity of the Poisson–Boltzmann model for AC-systems	116
6.3.3	Measuring the solid fraction with the wire harp	120
6.4	Data analysis for the impedance instrument	120
6.5	Summary	123
6.A	Mechanical design of the instrument	124
6.B	The power-supply and measurement electronics	125
7	Laboratory Experiments: Cooling from Below	129
7.1	General observations and raw data	130
7.2	Solid-fraction profiles: Comparison of the two versions of the instrument	133
7.3	Solid-fraction profiles: Measurements and comparison with theory	133
7.4	A mass-balance approach for the measuring of mean solid fractions	135
7.5	Discussion	139
7.6	Summary	141
8	Laboratory Experiments: Cooling from Above	143
8.1	Experimental setup	144
8.2	General observations	145
8.3	Constant cooling from above	149
8.4	Non-constant cooling from above	153
8.4.1	Mass-balance measurements	154
8.4.2	Impedance measurements	156
8.5	Discussion	159
8.6	Summary	160

9	Field experiments: Desalination of Natural Sea Ice	163
9.1	Field campaign in Svalbard, 2003	164
9.2	Field campaign in Svalbard, 2005	169
9.2.1	Experiment 1	172
9.2.2	Experiment 2	177
9.3	Discussion	179
9.4	Summary	182
10	External Fluxes in an Enthalpy Model	183
10.1	Ice–ocean heat and salt fluxes	184
10.1.1	A review of the current understanding of heat and salt fluxes across the ice–ocean interface	184
10.1.2	Implementation of ice–ocean fluxes into the single-domain model . .	187
10.1.3	Test of the numerical implementation	188
10.2	Atmosphere–ice heat fluxes	191
10.3	A simple test case	193
10.4	Summary	197
11	Discussion and Outlook	199
11.1	Physical processes governing the salinity evolution in sea ice	199
11.1.1	Salt entrapment at the ice–ocean interface	200
11.1.2	Diffusion	200
11.1.3	Brine expulsion	200
11.1.4	Gravity drainage	201
11.1.5	Flushing	202
11.2	Measuring the salinity evolution of sea ice	203
11.3	Modelling the salinity evolution of sea ice	205
11.4	Thermodynamic properties of sea ice	207
11.5	Summary	207
	Bibliography	209