

ICE IN THE OCEAN

Peter Wadhams



Gordon and Breach Science Publishers

ICE IN THE OCEAN

Peter Wadhams

*Scott Polar Research Institute
University of Cambridge, UK*

L III 63

DK:551.467

345/4168
INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHÄUSER STR. 2 - 30419 HANNOVER

GORDON AND BREACH SCIENCE PUBLISHERS
Australia • Canada • France • Germany • India • Japan
Luxembourg • Malaysia • The Netherlands • Russia
Singapore • Switzerland

CONTENTS

PREFACE	xiii
1. THE FROZEN OCEANS	1
1.1. A world of white	2
1.2. The physical structure of the polar oceans	2
1.2.1. The topography	2
1.2.2. The water masses	5
1.2.3. The current systems	9
1.2.4. Water mass transformations	17
1.3. The distribution of ice in the oceans	22
1.3.1. The Arctic	22
1.3.2. The Antarctic	24
1.3.3. Icebergs	30
1.4. Mapping the frozen oceans	31
1.5. Sea ice and the history of exploration	34
2. FORMATION, GROWTH AND DECAY OF SEA ICE	37
2.1. The structure of the ice crystal	37
2.2. The density and freezing point of sea water	39
2.3. The initial stages of ice formation	40
2.3.1. Ice formation in calm water	40
2.3.2. Ice formation in rough water: The frazil-pancake cycle	41
2.4. Crystal growth and brine rejection	46
2.4.1. Crystal fabric	46
2.4.2. Brine cells	49
2.4.3. Brine cell migration and drainage	49
2.4.4. Solid salts in ice	53
2.4.5. Lake and river ice	54
2.5. Snow loading and meteoric ice formation	54
2.6. Summer melt processes	56
2.7. Multi-year ice	57
2.8. Formation of leads and pressure ridges	64
2.9. Ice in shallow water	69
2.9.1. Grounded landfast ice	69
2.9.2. Ice scour	72
2.10. Polynyas and their role	73

3. THE THERMODYNAMICS OF SEA ICE	81
3.1. Thermophysical properties of sea ice	81
3.1.1. Thermal conductivity	82
3.1.2. Specific heat	84
3.1.3. Latent heat of fusion	84
3.1.4. Radiation extinction coefficient	86
3.2. Early models of ice growth and decay	88
3.3. The Maykut-Untersteiner model	92
3.3.1. Formulation	92
3.3.2. Input parameters	99
3.3.3. Results	100
4. ICE IN MOTION	109
4.1. The momentum balance	110
4.1.1. Air stress	110
4.1.2. Water stress	112
4.1.3. Coriolis force	114
4.1.4. Internal ice stress	115
4.1.5. Sea surface tilt	115
4.2. A free drift solution	116
4.2.1. Inertial motion	116
4.2.2. Free drift in response to geostrophic wind	118
4.3. The motion of compact ice	122
4.3.1. Ice rheology	122
4.3.2. Sea ice models	125
4.4. Dynamics and thermodynamics of coastal polynyas	127
4.5. Tidal ice motion	133
4.5.1. Tidal amplitudes and currents	133
4.5.2. Effect of sea ice on tides	134
4.5.3. Effect of tides on sea ice	135
5. PRESSURE RIDGES AND THE ICE THICKNESS DISTRIBUTION	139
5.1. Statistical properties of a sea ice cover	140
5.1.1. Importance of the ice thickness distribution	140
5.1.2. Ice thickness distribution — Definitions	141
5.1.3. Ice thickness distribution — Typical shapes	143
5.1.4. The distribution of morphological features	145
5.1.5. Pressure ridge depths	146
5.1.6. Pressure ridge spacings	147
5.1.7. Pressure ridge slopes and widths	151
5.1.8. Lead widths and spacings	152
5.1.9. Fractal properties of ice surfaces	154
5.1.10. Summary	156
5.2. The measurement of ice thickness	158

5.2.1. Current techniques	158
5.2.2. Possible future techniques	167
5.3. Present knowledge of ice thickness distribution	170
5.3.1. Mean ice thickness in the Arctic	170
5.3.2. Mean ice thickness in the Antarctic	177
5.3.3. The differences between Arctic and Antarctic sea ice	182
5.4. Applications of the ice thickness distribution	183
5.4.1. Sound propagation	183
5.4.2. Microwave signatures	184
5.4.3. Stimulation of internal waves by ice keels	185
5.4.4. The under-ice drag coefficient	185
5.4.5. Differential melt rates	186
5.4.6. Ice scour rates and pipeline burial depths	187
6. THE MARGINAL ICE ZONE	193
6.1. The structure of the ice margin	194
6.2. Marginal ice zones of the world	198
6.2.1. Greenland Sea	198
6.2.2. Labrador Sea	200
6.2.3. Bering Sea	201
6.2.4. Antarctic Ocean	201
6.3. Wave-ice interaction and the floe size distribution	202
6.3.1. A review of observations	202
6.3.2. Models of wave attenuation	203
6.3.3. Wave decay and floe break-up	215
6.4. Ice edge bands	219
6.5. Eddies and meanders	228
6.5.1. Some eddy observations	229
6.5.2. Generating mechanisms	234
6.6. Ambient noise at the ice edge	234
6.7. The Odden ice tongue and Greenland Sea convection	236
7. ICEBERGS	239
7.1. Mode of formation	240
7.2. Physical characteristics	244
7.2.1. Sizes	244
7.2.2. Shapes	245
7.2.3. Geographical distribution	249
7.3. Glaciological properties	251
7.4. Iceberg dynamics and drift	253
7.4.1. Iceberg motion	253
7.4.2. Patterns of iceberg drift	254
7.5. Decay mechanisms	258
7.5.1. Erosion and melt	258
7.5.2. Breakup by flexure	261

7.6. Iceberg scour	265
7.7. Climatic role of icebergs	266
7.8. Icebergs as a fresh water source	267
8. SEA ICE, CLIMATE AND THE ENVIRONMENT	273
8.1. Sea ice and biology	274
8.2. Sea ice and environmental threats	277
8.2.1. Oil spills and blowouts	277
8.2.2. The transport of pollutants by sea ice	281
8.3. Sea ice and climate	284
8.3.1. Climate change and the polar regions	284
8.3.2. Climate change and sea ice extent	287
8.3.3. Climate change and fast ice thickness	291
8.3.4. Climate change and moving pack ice thickness	292
8.3.5. Recent changes in the Arctic Ocean	294
8.4. The future course of research on sea ice	298
FURTHER READING	301
REFERENCES	305
INDEX	335