

Contents

List of Figures	x
List of Tables	xii
List of Plates	xiii
Key to Symbols	xiv
Foreword	xix
Preface	xxi
Chapter	Page
1 The Problem of Sea and Swell Forecasting	1
1.1 Introduction	1
1.2 The nature of the problem.....	2
1.3 The speed of waves.....	2
1.4 Breaking waves and surf.....	3
1.5 The constraints - duration or fetch.....	3
1.6 The problems of prediction.....	3
1.7 The requirement to consider currents and tides.....	4
1.8 Numerical models for sea and swell forecasts.....	4
1.9 Need for small - mesh models.....	5
1.10 Forecasts for specific operations.....	6
2 Observing and Measuring Sea and Swell.....	7
2.1 Observing sea and swell.....	7
2.2 Wave heights.....	7
2.3 Wave periods.....	7
2.4 Wave lengths.....	8
2.5 Measuring sea and swell with wave recorders.....	8
2.6 Other methods of measuring sea and swell.....	9
2.7 Definitions of wave heights in common use.....	9
2.8 Sea and swell reports transmitted by ships at sea.....	11
2.9 The quality of the data.....	11
2.10 Measurements from satellites.....	12
2.11 Descriptions of "freak" waves	12
2.12 Giant wind waves and swells.....	13
2.13 Killer waves.....	13
2.14 "Holes" in the ocean	14
3 The Structure of the Atmosphere Overlying the Sea Surface.....	17
3.1 Introduction	17
3.2 Stratification in the atmosphere.....	18
3.3 Convection in the lower atmosphere -arctic sea smoke.....	18
3.4 Smoke trails in a stratiform atmosphere.....	21
3.5 Smoke trails in a convective atmosphere.....	23
3.6 The density structure in the upper layers of the sea.....	24
3.7 Surface currents generated by wind stress.....	26
3.8 The application to sea and swell forecasting.....	29
4 The Effects of Variations in Air and Water Density on Sea and Swell Generation	29
4.1 Introduction	29

Chapter		Page
4.2	Energy and momentum transfer.....	29
4.3	The variations of air density with temperature	30
4.4	The adjusted virtual temperature T_v	30
4.5	The density of partially saturated air.....	34
4.6	Approximation for density difference ($\rho_a - \rho_s$) using temperatures and ignoring pressure changes	34
4.7	Relative importance of pressure, temperature, and humidity changes.....	35
4.8	The effect of air density differences in cases of limited fetch or duration.....	36
5	The Dynamics of the Boundary Layer in the Atmosphere.....	39
5.1	Surface wind	39
5.2	The geostrophic wind	41
5.3	The relationship between the geostrophic wind and the effective wind at sea level.....	41
5.4	The gradient wind.....	42
5.5	Corrections according to the atmospheric stability.....	44
5.6	Ratios of effective wind to the gradient wind.....	44
5.7	Plotting and analyzing an effective wind field chart.....	45
5.8	Procedure for analyzing the effective wind field chart.....	47
5.9	Example of straight isobar situation.....	47
6	Destructive Waves and Their Causes.....	50
6.1	Introduction	50
6.2	The effects of bottom topography.....	50
6.3	Chances of unusual occurrences.....	51
6.4	Physical explanation for "holes"	52
6.5	Forecasting "freak" waves and "holes".....	52
7	Empirical Formulas and Diagrams for Sea State Forecasting.....	61
7.1	Introduction	61
7.2	Diagrams for coastal waters.....	64
7.3	Diagrams taking into account air mass/sea surface temperature characteristics.....	70
7.4	Modifications to Lumb's diagrams taking into account synoptic thermal structure of the atmosphere and the sea surface temperature gradient	71
7.5	Limitations of the technique.....	73
7.6	Forecasts of wave periods.....	73
8	The Dynamics of the Boundary Layer in the Ocean.....	75
8.1	Introduction	75
8.2	Currents.....	76
8.3	Sea surface temperature charts.....	76
8.4	Measuring sea surface temperature.....	76
8.5	Some examples of sea surface temperature charts.....	77
8.6	Sea surface temperature charts from satellite measurements.....	77
8.7	Tides	77
8.8	Wind-driven currents.....	80
8.9	Summary	83
9	Ocean Thermal Forecasting.....	85
9.1	Introduction	85

Chapter		Page
9.2	The use of satellite imagery.....	86
9.3	Thermoclines	90
9.4	Heat budgets for the ocean.....	91
9.5	Incoming solar radiation.....	92
9.6	Back radiation.....	93
9.7	Evaporation loss.....	93
9.8	Sensible heat transfer.....	94
9.9	Advection terms.....	94
9.10	Heat budget equation.....	94
9.11	The effects of spray on the evaporation rate	95
9.12	Suggested modifications to existing empirical formulas for evaporation rates	96
10	Wave Steepness - Forecasting Slamming and Harbor Bar Conditions.....	99
10.1	Momentum of the sea surface layer.....	99
10.2	Contrary currents to winds in the Gulf of Alaska.....	99
10.3	Changes in the steepness factor caused by currents or tides and ship's speed.....	100
10.4	Estuary and harbor bar forecasting.....	101
10.5	The basic requirements for a sea state forecast at a river mouth.....	102
10.6	Theoretical considerations.....	103
11	Wave Spectra.....	107
11.1	Introduction	107
11.2	The energy spectra.....	107
11.3	Basic interpretations from spectral energy curves.....	108
11.4	The significant wave height	111
11.5	The significant wave period	112
11.6	Further statistical interpretations of spectral energy diagrams.....	113
11.7	Messages of spectral energy data from buoys	114
11.8	Co-cumulative spectra	117
11.9	The properties of the co-cumulative power spectra	117
12	The Use of Wave Spectral Data in Marine Synoptic Analyses.....	119
12.1	Introduction	119
12.2	Spectral diagram sequences from buoy reports.....	119
12.3	Environmental factors and wave generation at EB03 and PAPA	123
12.4	The establishment of statistical relationships between significant wave height and meteorological elements.....	124
12.5	Statistical analysis of sequences at Ocean Weather Station INDIA and Ocean Station PAPA127	127
13	The Effect of Fronts on Sea and Swell Generation	133
13.1	Introduction	133
13.2	Classification of fronts.....	133
13.3	The task of the forecaster.....	134
13.4	The effects of rainfall.....	135
13.5	Rainfall measurements over the oceans.....	136
13.6	Assessments of rainfall amount and rates at sea	136
13.7	Sequence weather affecting sea and swell development.....	136
13.8	Sea and swell in pack ice.....	148

Chapter		Page
14 Basic Considerations for Predicting Movement of Weather Fronts		149
14.1 Introduction		149
14.2 Rossby waves.....		149
14.3 Anticyclones		150
14.4 Blocking anticyclones.....		151
14.5 Satellite analysis.....		151
14.6 Surface synoptic charts.....		152
14.7 Isallobaric charts.....		152
14.8 Pressure and dew point.....		152
14.9 Forecasting katabatic winds.....		153
15 Monitoring Cold Air Outbreaks Over the Ocean.....		155
15.1 Introduction		155
15.2 A plotting technique for detecting and monitoring cold air outbreaks in the South Atlantic....		155
15.3 The variations in intensity of blocking anticyclones and the subtropical high pressure systems		157
15.4 A plotting technique for detecting and monitoring cold air outbreaks in the North Pacific....		158
15.5 The subtropical anticyclone.....		159
15.6 The frozen land masses and ice shelves of the North Pacific.....		159
15.7 The main depression tracks.....		159
15.8 The significant station reports for a grid.....		159
15.9 Semi-systematic variations in the pressure and temperature graphs at stations in northern Alaska		171
16 Environmental Services to Shipping.....		173
16.1 Introduction		173
16.2 Specialized requirements of users of marine forecasts.....		174
16.3 Oceanographic services.....		174
16.4 The limitations of pressure analyses for sea and swell forecasts.....		174
16.5 Weather routing.....		175
16.6 Some suggestions for improving services to shipping.....		176
Appendix A - The Theoretical Treatment of Waves.....		178
A-1 Sinusoidal wave motion.....		178
A-2 The speed of movement of waves.....		179
A-3 Approximations for movement of waves in deep and shallow water.....		180
A-4 Interpretation in practical applications		181
A-5 The movement of the water particles in a wave.....		182
A-6 The movement of waves in groups (the group velocity).....		183
A-7 The drag coefficient.....		185
A-8 The energy involved in surface waves.....		185
Appendix B - Deep Ocean Buoy Systems.....		189
Appendix C - Teletype Spectral Energy Data Formats from Buoys.....		192
Appendix D - Glossary.....		195
D-1 Beaches.....		195
D-2 The Coriolis effect		195

Chapter		Page
D-3	Gyres	195
D-4	Isopleths, isobars, isallobars.....	196
D-5	Seiches.....	196
D-6	Spring and neap tides.....	196
D-7	Storm tide surges	196
D-8	Tsunamis	197
D-9	Upwelling	197
	Selected Bibliography.....	198
	Index	201

List of Figures

Fig. No.		Page
1	Representative wave rider buoy wave trace.....	9
2	Sea state with a listing of visual and tactile clues.....	10
3	Low level radiosonde plots for 5 September 1969	20
4	Shallow depth temperature profiles for 5 September 1969.....	21
5	Low level radiosonde plots (unstable atmosphere).....	23
6	Variation in sea surface temperature at OWS JULIET and OWS INDIA.....	25
7	Two hypothetical contrasting situations in the North Sea.....	37
8	Graph of water vapor pressure versus temperature.....	44
9	Modified plotting models for synoptic observations from ships.....	46
10	Synoptic chart for 1200 GMT 30 March 1975.....	49
11	Wave traces with opposing currents of 0.34 meters/second (0.7 knots approx.) and 1.51 meters/second (3 knots approx.), respectively	53
12	Wave recorder trace taken on lightship <i>Daunt</i> off Cork.....	54
13	Ocean Weather Station INDIA wave record 23 January 1975.....	54
14	Synoptic situation 1200 GMT 22 January 1975 Northeast Atlantic.....	57
15	Ocean Weather Station JULIET 0600/21 to 0600/23 January 1975.....	58
16	Ocean Weather Station INDIA 0600/21 to 0600/23 January 1975.....	59
17	Synoptic situation 0600 GMT 2 January 1977 Northeast Pacific.....	60
18	Wave forecasting diagram - ordinates duration and significant wave height	62
19	Wave forecasting diagram - ordinates duration and fetch.....	63
20	Graph relating wind speed to maximum wave height with constraints of duration and fetch - oceanic waters	65
21	Graph relating wind speed to maximum wave height with constraints of duration and fetch - coastal waters (depth 100-150 feet).....	66
22	Graph relating wind speed to wave period with constraints of duration and fetch - oceanic waters....	67
23	Graph relating wind speed to wave period with constraints of duration and fetch - coastal waters (depth 100-150 feet).....	68
24	Graph relating wave length to wave period and depth.....	69
25	Lumb's graphical method of forecasting maximum wave height in North Atlantic.....	70
26	Britton's modification to Lumb's diagram.....	72
27	Graph relating significant wave period to wave speed and wave length	74
28	Ten day mean SST chart 21-30 May 1972.....	78
29	Mean monthly SST chart for October.....	79
30	Five-day mean SST analysis for 17-21 Aug. 1969 gridded onto analysis for 12-16 Aug. 1969.....	81
31	Five-day mean SST analysis for 21-25 Aug. 1969 gridded onto analysis for 16-20 Aug. 1969.....	82
32	Thermoclines.....	91
33	Bathythermograph trace.....	92
34	Effect of current on wave steepness.....	101
35	Effect of ship's speed on wave steepness.....	101
36	Wave spectrum.....	108
37	Continuous wave spectrum for fully arisen seas at wind speeds of 20, 30, and 40 knots.....	109
38	Typical spectral energy curve.....	111
39	Wave spectrum diagram.....	112
40	Spectral graph at EB03, 0000 GMT, 22 February 1975	115
41	Co-cumulative spectrum.....	116

Fig. No.		Page
42	Spectral data, EB03, 21 February 1975.....	122
43	Plot of significant wave height at EB03 with wind speed, temperature, and dew point for 16-28 February 1975.....	125
44	Significant wave height versus wind and wave direction at Station PAPA (1969-1973).....	128
45	Significant wave height versus wind speed at Station PAPA (1969-1973)	128
46	Significant wave height versus wind speed at Station INDIA.....	129
47	Measured significant wave height versus observed wave height at Station PAPA (1969-1973).....	130
48	Significant wave height versus observed wave height at Station INDIA (1969-1973).....	130
49	Significant wave height versus average wave period at Station PAPA (1969-1973).....	131
50	Significant wave height versus average wave period at Station INDIA (1969-1973).....	131
51	Ocean Station PAPA, 20-25 January 1975	138
52	Ocean Station PAPA, 25-29 January 1975	139
53	Ocean Station PAPA, 29 January - 1 February 1975	140
54	Ocean Station PAPA, 1-5 February 1975	141
55	Ocean Station PAPA, 5-8 February 1975	142
56	Ocean Station PAPA, 8-14 February 1975	143
57	Ocean Station PAPA, 14-17 February 1975	144
58	Ocean Station PAPA, 17-21 February 1975	145
59	Ocean Station PAPA, 21-25 February 1975	146
60	Ocean Station PAPA, 25 February - 1 March 1975	147
61	Various types of Rossby waves.....	150
62	Cold air outbreaks from Antarctica	156
63	Chart showing stations and the time staggers used to allow for mean movement of lows and fronts	160
64	Staggered graphs of pressure, temperature and dew point for 15-22 February 1975.....	162
65	Plotted weather observations, 15-21 February 1975 (staggered dates).....	163
66	Synoptic sequences for 16 February 1975.....	164
67	Synoptic sequences for 17 February 1975.....	165
68	Synoptic sequences for 18 February 1975.....	166
69	Synoptic sequences for 19 February 1975.....	167
70	Synoptic sequences for 20 February 1975.....	168
71	Synoptic sequences for 21 February 1975.....	169
72	Synoptic sequences for 22 February 1975.....	170
73	Pressure graphs for Point Barrow, Barter Island, and Nome, Alaska	172
A-1	A simple sinusoidal wave.....	178
A-2	Trochoidal motion typical of simple swell progression	179
A-3	Wave motion deformed by a strong wind stress.....	179
A-4	Orbital motions in "deep" and "shallow" water.....	182
A-5	Combinations of waves of equal amplitude but slightly different wave lengths.....	184
A-6	Symmetrical wave form.....	186
B-1	Environmental buoy locations for October 1979	190

List of Tables

Table No.		Page
1	Increments in degrees Celsius to apply to T_A for saturated air to obtain the adjusted virtual temperature	31
2	Density of air in kg/m^3	32
3	Beaufort wind scale.....	40
4	Gradient winds (Latitudes 30° - 37°).....	43
5	Gradient winds (Latitudes 38° - 47°).....	43
6	Gradient winds (Latitudes 48° - 60°).....	43
7	Multiplication factors to apply to gradient wind values.....	48
8	Comparative values of important environmental factors at Ocean Weather Stations JULIET (J) and INDIA (I) 21-23 January 1975.....	56
9	Maximum period of the dominant band in the spectrum where highest proportion of energy is concentrated	109
10	Useful spectral information.....	110
11	Wave spectral information from EB03, 0000 GMT, 22 February 1975	115
12	Minimum fetch and minimum duration needed to generate a fully developed sea for various wind speeds.....	117
13	EB03 spectral data for 21 February 1975.....	120
14	EB03 spectral data for 22 February 1975.....	121
15	Wave parameters derived from spectral data at Ocean Station PAPA for 21-22 February 1975.....	123
16	Comparative values of important environmental factors at EB03 and Ocean Station PAPA for 21-22 February 1975.....	124
17	Correlation coefficients between significant wave height and wind speed at staggered intervals of 3 hours at Ocean Station PAPA.....	126
18	Correlation coefficients between significant wave height and wind speed at staggered intervals of 3 hours at EB03.....	126
19	Correlation coefficients between significant wave heights and various factors involving wind and temperature at Ocean Station PAPA.....	127
A-1	Values of $e^{-2\pi d/L}$ and $\tanh(2\pi d/L)$ corresponding to ratios of depth to wave length between 0.05 and 2.0.....	180
B-1	Environmental buoy sensors.....	191
C-1	Wave spectral data from buoy 46001 for 0000 GMT 20 August 1980.....	194

List of Plates

Plate No.		Page
1	Smoke trails in stratiform situations.....	19
2	Smoke trails in convective situations.....	22
3	Echo sounder trace taken in the Strait of Gibraltar.....	86
4	Ship's radar scope showing the Strait of Gibraltar with internal waves created by incoming tide breaking the sea surface	87
5	Satellite picture of the Pacific Northwest Coast showing upwelling areas and aircraft contrails	88
6	Satellite picture of the Pacific Northwest Coast showing upwelling areas and aircraft contrails with grid and data superimposed	89
7	Sea state conditions off Alsea Bay, Oregon	105
8	Sea state conditions off Coquille River, Oregon	106
9	Environmental buoy	189