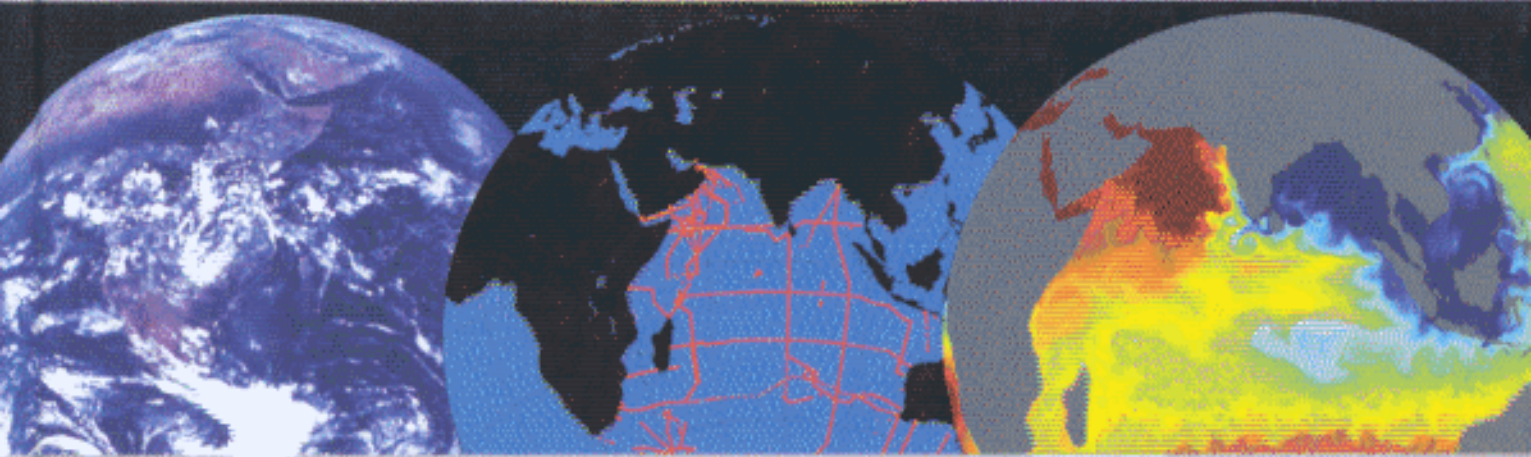


Ocean Circulation & Climate

Observing and Modelling the Global Ocean



Gerold Siedler John Church John Gould



INTERNATIONAL GEOPHYSICS SERIES, VOLUME 77



Contents

Contributors	xiii
Foreword	xvii
Preface	xviii
Acknowledgment	xx

Section 1: The Ocean and Climate

Section 1 plates appear between pages 44 and 45

1.1 Climate and Oceans	3
<i>Hartmut Grassl</i>	
1.1.1 WOCE and the World Climate Research Programme	3
1.1.2 The scientific approach to the complex climate system	4
1.1.3 Ocean–atmosphere interaction and climate	5
1.1.4 Rapid changes related to the oceans	6
1.1.5 Cryosphere and the oceans	7
1.1.6 Anthropogenic climate change and the oceans	7
1.1.7 Future climate research and ocean observing systems	8
1.2 Ocean Processes and Climate Phenomena	11
<i>Allyn Clarke, John Church and John Gould</i>	
1.2.1 A global perspective	11
1.2.2 Air–sea fluxes	12
1.2.3 Ocean storage of heat and fresh water	17
1.2.4 Ocean circulation	17
1.2.5 Ocean transport of heat, fresh water and carbon	23
1.2.6 Climatic and oceanic variability	24
1.2.7 Impacts of ocean climate	27
1.2.8 Conclusion	30
1.3 The Origins, Development and Conduct of WOCE	31
<i>B. J. Thompson, J. Crease and John Gould</i>	
1.3.1 Introduction	31
1.3.2 Large-scale oceanography in the 1960s and 1970s	31
1.3.3 Ocean research and climate	32
1.3.4 Implementation of WOCE (SSG initiatives)	36
1.3.5 Implementation and oversight	41
1.3.6 Was WOCE a success and what is its legacy?	43

Section 2: Observations and Models

Section 2 plates appear between pages 76 and 77

2.1 Global Problems and Global Observations	47
<i>Carl Wunsch</i>	
2.1.1 Different views of the ocean	47
2.1.2 The origins of WOCE	48
2.1.3 What do we know?	51
2.1.4 The need for global-scale observations	52
2.1.5 Where do we go from here?	56

2.2	High-Resolution Modelling of the Thermohaline and Wind-Driven Circulation	59
	<i>Claus W. Böning and Albert J. Semtner</i>	
2.2.1	The improving realism of ocean models	59
2.2.2	Historical perspective	60
2.2.3	Basic model design considerations: equilibrium versus non-equilibrium solutions	62
2.2.4	Examples of model behaviour in different dynamical regimes	64
2.2.5	Concluding remarks	77
2.3	Coupled Ocean-Atmosphere Models	79
	<i>Richard A. Wood and Frank O. Bryan</i>	
2.3.1	Why coupled models?	79
2.3.2	Formulation of coupled models	79
2.3.3	Model drift and flux adjustment	84
2.3.4	Initialization of coupled models	86
2.3.5	Coupled model simulation of present and past climates	87
2.3.6	Coupled model simulation of future climates	93
2.3.7	Climate models, WOCE and future observations	94
2.3.8	Summary and future developments	95
Section 3: New Ways of Observing the Ocean		
Section 3 plates appear between pages 172 and 173		
3.1	Shipboard Observations during WOCE	99
	<i>B. A. King, E. Firing and T. M. Joyce</i>	
3.1.1	The role of hydrographic measurements	99
3.1.2	CTD and sample measurements	102
3.1.3	Current measurements in the shipboard hydrographic programme	111
3.1.4	Shipboard meteorology	120
3.1.5	Summary and conclusions	121
3.2	Subsurface Lagrangian Observations during the 1990s	123
	<i>Russ E. Davis and Walter Zenk</i>	
3.2.1	Determining currents in the ocean	123
3.2.2	Historical aspects: Stommel's vision to the WOCE Float Programme	123
3.2.3	The WOCE Float Programme	127
3.2.4	WOCE float observations	129
3.2.5	The future	137
3.3	Ocean Circulation and Variability from Satellite Altimetry	141
	<i>Lee-Lueng Fu</i>	
3.3.1	Altimeter observations	141
3.3.2	The ocean general circulation	143
3.3.3	Large-scale sea-level variability	148
3.3.4	Currents and eddies	162
3.3.5	Concluding discussions	170

3.4	Air–Sea Fluxes from Satellite Data	173
	<i>W. Timothy Liu and Kristina B. Katsaros</i>	
3.4.1	Forcing the ocean	173
3.4.2	Bulk parameterization	173
3.4.3	Wind forcing	174
3.4.4	Thermal forcing	177
3.4.5	Hydrologic forcing	179
3.4.6	Future prospects	179
3.5	Developing the WOCE Global Data System	181
	<i>Eric J. Lindstrom and David M. Legler</i>	
3.5.1	Organization and planning for WOCE data systems	181
3.5.2	Elements of the WOCE Data System	185
3.5.3	The WOCE Global Data Set and future developments	189

Section 4: The Global Flow Field

Section 4 plates appear between pages 300 and 301

4.1	The World Ocean Surface Circulation	193
	<i>Peter Niiler</i>	
4.1.1	Background	193
4.1.2	Methodology	195
4.1.3	The global mean velocity and velocity variance	198
4.1.4	The wind-driven Ekman currents	201
4.1.5	Future global circulation observations	203
4.2	The Interior Circulation of the Ocean	205
	<i>D. J. Webb and N. Sugimoto</i>	
4.2.1	Processes in the ocean interior	205
4.2.2	Observational evidence	206
4.2.3	Theory of gyre-scale circulation	209
4.2.4	The abyssal circulation	211
4.2.5	Conclusions	213
4.3	The Tropical Ocean Circulation	215
	<i>J. S. Godfrey, G. C. Johnson, M. J. McPhaden, G. Reverdin and Susan E. Wijffels</i>	
4.3.1	Flow and water mass transformation patterns	215
4.3.2	Equatorial phenomena in the Pacific Ocean	216
4.3.3	Equatorial Atlantic	226
4.3.4	Near-equatorial circulation in the Indian Ocean	233
4.3.5	Overall conclusions	245
4.4	Tropical–Extratropical Oceanic Exchange Pathways	247
	<i>Zhengyu Liu and S. G. H. Philander</i>	
4.4.1	The role of diffusion and advection	247
4.4.2	Tropical–subtropical exchanges of thermocline waters	248
4.4.3	Tropical–subpolar exchange of Intermediate Waters	252
4.4.4	Summary and further issues	254

4.5	Quantification of the Deep Circulation	259
	<i>Nelson G. Hogg</i>	
4.5.1	Deep circulation in the framework of WOCE	259
4.5.2	Deep Western Boundary Currents	260
4.5.3	The interior: The Deep Basin Experiment	266
4.5.4	Summary	269
4.6	The Antarctic Circumpolar Current System	271
	<i>Stephen R. Rintoul, Chris W. Hughes and Dirk Olbers</i>	
4.6.1	Flow in the zonally unbounded ocean	271
4.6.2	Observations of the Antarctic Circumpolar Current	274
4.6.3	Dynamics of the ACC	280
4.6.4	Water mass formation and conversion	291
4.6.5	The Southern Ocean and the global overturning circulations	296
4.6.6	Conclusions	300
4.7	Interocean Exchange	303
	<i>Arnold L. Gordon</i>	
4.7.1	Interocean links	303
4.7.2	Bering Strait	306
4.7.3	Indonesian Seas	307
4.7.4	The Agulhas Retroflexion	310
4.7.5	Discussion	313

Section 5: Formation and Transport of Water Masses

Section 5 plates appear between pages 428 and 429

5.1	Ocean Surface Water Mass Transformation	317
	<i>William G. Large and A. J. George Nurser</i>	
5.1.1	The problem	317
5.1.2	Theory of surface water mass transformation	318
5.1.3	Ocean surface temperature, salinity and density	321
5.1.4	Surface fluxes of heat, fresh water and density	326
5.1.5	Surface water mass transformation and formation	332
5.1.6	Summary	335
5.2	Mixing and Stirring in the Ocean Interior	337
	<i>John M. Toole and Trevor J. McDougall</i>	
5.2.1	Scales of mixing and stirring	337
5.2.2	Background	338
5.2.3	The Temporal-Residual-Mean circulation	340
5.2.4	Lateral dispersion between the mesoscale and the microscale	345
5.2.5	Diapycnal mixing in and above the main thermocline	346
5.2.6	Mixing in the abyss	352
5.2.7	Discussion	354
5.3	Subduction	357
	<i>James F. Price</i>	
5.3.1	A little of the background on oceanic subduction	357
5.3.2	Surface-layer dynamics and thermodynamics of the subduction process	360
5.3.3	Development of steady, continuous models: Application to numerical model analysis and observations	361
5.3.4	Transient response of the thermocline to decadal variability	365
5.3.5	Summary and outlook	370

5.4	Mode Waters	373
	<i>Kimio Hanawa and Lynne D. Talley</i>	
5.4.1	Ventilation and mode water generation	373
5.4.2	Definition, detection and general characteristics of mode waters	374
5.4.3	Geographical distribution of mixed-layer depth and mode waters in the world's oceans	376
5.4.4	Temporal variability of mode water properties and distribution	384
5.4.5	Summary	386
5.5	Deep Convection	387
	<i>John Lazier, Robert Pickart and Peter Rhines</i>	
5.5.1	Convection and spreading	387
5.5.2	Plumes – the mixing agent	391
5.5.3	Temperature and salinity variability	393
5.5.4	Restratification	396
5.5.5	Summary and discussion	398
5.6	The Dense Northern Overflows	401
	<i>Peter M. Saunders</i>	
5.6.1	The sources	401
5.6.2	Overflow paths	402
5.6.3	Observed transport means and variability	404
5.6.4	Processes in the overflows	411
5.6.5	Analytical models of the overflow	412
5.6.6	Numerical models of the overflow	414
5.6.7	Overflow variability	416
5.6.8	What have we learnt in WOCE?	416
5.7	Mediterranean Water and Global Circulation	419
	<i>Julio Candela</i>	
5.7.1	Marginal seas	419
5.7.2	Formation of Mediterranean Water	421
5.7.3	Outflow of Mediterranean Water at the Strait of Gibraltar	422
5.7.4	The effect of Mediterranean Water outflow on the circulation of the North Atlantic and the World Oceans	427
5.8	Transformation and Age of Water Masses	431
	<i>P. Schlosser, J. L. Bullister, R. Fine, W. J. Jenkins, R. Key, J. Lupton, W. Roether and W. M. Smethie, Jr</i>	
5.8.1	Background	431
5.8.2	Tracer methodology and techniques	432
5.8.3	Exemplary results	433
5.8.4	Outlook	450

Section 6: Large-Scale Ocean Transports

Section 6 plates appear between pages 492 and 493

6.1	Ocean Heat Transport	455
	<i>Harry L. Bryden and Shiro Imawaki</i>	
6.1.1	The global heat balance	455
6.1.2	Bulk formula estimates of ocean heat transport	456
6.1.3	Residual method estimates of ocean heat transport	458
6.1.4	Direct estimates of ocean heat transport	459
6.1.5	Discussion	466
6.1.6	Challenges	470
6.1.7	Summary	473
6.1.8	Outlook for direct estimates of ocean heat transport	474

6.2	Ocean Transport of Fresh Water	475
	<i>Susan E. Wijffels</i>	
6.2.1	The importance of freshwater transport	475
6.2.2	Indirect estimates of oceanic freshwater transport	475
6.2.3	Impacts of uncertainties on model development	476
6.2.4	Direct ocean estimates of freshwater transport	478
6.2.5	Comparison of direct and indirect flux estimates	483
6.2.6	Mechanisms of oceanic freshwater transport	486
6.2.7	Global budgets	487
6.2.8	Summary	488
6.3	Storage and Transport of Excess CO₂ in the Oceans: The JGOFS/WOCE Global CO₂ Survey	489
	<i>Douglas W. R. Wallace</i>	
6.3.1	Introduction	489
6.3.2	Background	489
6.3.3	The JGOFS/WOCE Global CO ₂ Survey	495
6.3.4	Synthesis of Global CO ₂ Survey data: Review	503
6.3.5	Conclusions and outlook	520

Section 7: Insights for the Future

Section 7 plates appear between pages 588 and 589

7.1	Towards a WOCE Synthesis	525
	<i>Lynne D. Talley, Detlef Stammer and Ichiro Fukumori</i>	
7.1.1	Exploiting the WOCE data set	525
7.1.2	Data-based analyses	526
7.1.3	Model evaluation and development	535
7.1.4	Ocean state estimation	535
7.1.5	Summary and outlook	542
7.2	Numerical Ocean Circulation Modelling: Present Status and Future Directions	547
	<i>J. Willebrand and D. B. Haidvogel</i>	
7.2.1	Remarks on the history of ocean modelling	547
7.2.2	Space-time scales of ocean processes and models	548
7.2.3	Modelling issues	549
7.2.4	Atmospheric forcing and coupling	553
7.2.5	Organization of model development	554
7.2.6	Concluding remarks	556
7.3	The World during WOCE	557
	<i>Bob Dickson, Jim Hurrell, Nathan Bindoff, Annie Wong, Brian Arbic, Breck Owens, Shiro Imawaki and Igor Yashayaev</i>	
7.3.1	Assessing the representativeness of the WOCE data set	557
7.3.2	The state of the atmosphere during WOCE	558
7.3.3	The analysis of decadal change in intermediate water masses of the World Ocean	563
7.3.4	Climatic warming of Atlantic Intermediate Waters	565
7.3.5	Spin-up of the North Atlantic gyre circulation	567
7.3.6	Altered patterns of exchange in Nordic Seas	569
7.3.7	System-wide changes in the Arctic Ocean	571
7.3.8	Interdecadal variability of Kuroshio transport	573
7.3.9	Evidence of water mass changes in the Pacific and Indian Oceans	576
7.3.10	Summary and Conclusions	580

7.4	Ocean and Climate Prediction – the WOCE Legacy	585
	<i>Neville Smith</i>	
7.4.1	The long-term context	585
7.4.2	Building from WOCE	588
7.4.3	WOCE observations	589
7.4.4	WOCE and climate prediction	592
7.4.5	The mean state and long-term change	595
7.4.6	Ocean variability and prediction: GODAE	597
7.4.7	Institutionalizing the benefits of WOCE	600
7.4.8	Conclusions	601
	References	603
	Acronyms, abbreviations and terms	686
	Index	693