

# Contents

<b>1</b>	<b>An Integrated Earth System</b> .....	<b>1</b>
1.1	A Research Agenda to Meet the Challenge of the Future .....	1
1.2	The Earth as a System .....	3
1.3	The Nature of Global Change .....	4
1.4	Objectives and Structure of the Book .....	7
	References .....	9
<b>2</b>	<b>Planetary Machinery:</b>	
	<b>The Dynamics of the Earth System Prior to Significant Human Influence</b> ..	<b>11</b>
2.1	The Natural Dynamics of the Earth System .....	11
2.2	New Insights in Temporal Variability of the Earth System .....	12
2.2.1	The Long-Term Envelope of Natural Self-Regulation .....	12
2.2.2	Millennial-Scale Oscillations and Abrupt Changes .....	13
2.2.3	Climate Variability in Interglacial Periods .....	16
2.2.4	Temporal Variability in the Biota .....	23
2.3	New Insights into the Role of Biology in Earth System Functioning .....	24
2.3.1	Biogeophysical Processes .....	24
2.3.2	Biogeochemical Processes .....	28
2.3.3	The Role of Biodiversity .....	33
2.4	New Insights into Spatial Variability of the Earth System .....	35
2.4.1	Spatial Patterns of Land Cover .....	36
2.4.2	Spatial Patterns of Carbon Sources and Sinks .....	44
2.4.3	Trace Gas Exchanges Between Earth's Surface and the Atmosphere ....	47
2.5	New Insights into the Connectivity of the Earth System over Space and Time .	51
2.5.1	Connectivity via the Oceans and their Currents .....	51
2.5.2	Connectivity via Atmospheric Transport .....	52
2.5.3	Connectivity via Hydrologic Transport .....	57
2.5.4	Connectivity via the Biota .....	58
2.5.5	Teleconnections in the Climate System .....	60
2.5.6	Connectivity through Time: The Legacy of Past Disturbance .....	63
2.6	New Insights into Non-linearities, Surprises and Thresholds in the Earth System .....	64
2.6.1	Glacial Terminations .....	64
2.6.2	Heinrich and Dansgaard-Oeschger Events .....	64
2.6.3	Mega-droughts and Other Extreme Events .....	66
2.6.4	The Browning of the Sahara .....	67
2.7	The Earth System in a Pre-Human Dominated State .....	68
	References .....	73
<b>3</b>	<b>The Anthropocene Era: How Humans are Changing the Earth System</b> ....	<b>81</b>
3.1	A Human-Dominated Planet? .....	81
3.2	Drivers of Change .....	83
3.2.1	Sectoral Activities as Drivers of Change .....	83
3.2.2	A Systems Approach to the Drivers of Earth System Change .....	90

3.3	Characterisation of Changes in the Earth System .....	93
3.3.1	The Earth's Land as Transformed by Human Activities .....	93
3.3.2	The Atmosphere as Transformed by Human Activities .....	100
3.3.3	The Hydrological Cycle as Transformed by Human Activities ....	111
3.3.4	Coastal and Marine Environments as Transformed by Human Activities .....	115
3.3.5	Biological Diversity as Transformed by Human Activities .....	118
3.3.6	Alteration of Carbon, Nitrogen, Phosphorus and Sulphur Fluxes ...	119
3.4	Putting Human-Driven Changes into an Earth System Perspective .....	123
3.4.1	Socioeconomic and Cultural Teleconnections .....	123
3.4.2	Interaction Between Human-Driven Changes and Natural Variability .....	129
3.4.3	Global Change: Magnitudes, Rates and Significance of Human Changes .....	131
	References .....	135
<b>4</b>	<b>Reverberations of Change: The Responses of the Earth System to Human Activities</b> .....	<b>143</b>
4.1	Reverberations of Change .....	143
4.2	Responses of the Earth System to Fossil Fuel Combustion .....	143
4.2.1	Non-Reactive Gases .....	144
4.2.2	Reactive Gases .....	160
4.2.3	Aerosols .....	164
4.3	Response of the Earth System to Land-Use and Land-Cover Change .....	168
4.3.1	The Conversion Process .....	170
4.3.2	Effects of Changed Land Cover .....	174
4.3.3	Intensification of Agriculture .....	182
4.4	Multiple and Interacting Changes .....	189
4.4.1	Fires in Southeast Asia .....	189
4.4.2	Coral Reefs .....	189
4.5	Integrated Responses of the Earth System to Human Forcing .....	192
4.5.1	The Carbon Cycle .....	192
4.5.2	Nitrogen, Phosphorus, Sulphur Cycles .....	193
4.5.3	The Hydrological Cycle .....	194
4.5.4	The Climate System .....	195
	References .....	196
<b>5</b>	<b>Living with Global Change: Consequences of Changes in the Earth System for Human Well-Being</b> ...	<b>203</b>
5.1	Consequences of Global Change .....	203
5.2	General Approaches for Anticipating the Consequences of Global Change .....	203
5.2.1	The Scenario-Driven Approach .....	203
5.2.2	Assessment of Consequences Based on Vulnerability .....	205
5.2.3	Assessment of Vulnerability Using Palaeo-Data .....	209
5.3	Risks to Key Resources for Human Well-Being .....	213
5.3.1	Quality and Sufficiency of Food .....	214
5.3.2	Water Resources .....	221
5.3.3	Air Quality .....	227
5.3.4	Pests and Diseases .....	229
5.3.5	Amplifying, Damping and Multiple Effects .....	232
5.4	Risks Facing the Earth System as a Whole .....	235
5.4.1	Catastrophic Failures .....	235
5.4.2	Past Changes, Extreme Events and Surprises .....	244
5.4.3	Human Perceptions of Global Change .....	247
	References .....	249

<b>6</b>	<b>Towards Earth System Science and Global Sustainability</b> .....	255
6.1	From Climate Change to Earth System Science .....	255
6.2	The Knowledge Base .....	255
6.2.1	Biology in the Earth System .....	256
6.2.2	The Nature of Global Change .....	257
6.2.3	Cascading Impacts of Global Change .....	260
6.2.4	Thresholds and Abrupt Changes .....	261
6.2.5	A No-Analogue State .....	262
6.3	Making Earth System Science .....	264
6.3.1	Questions at the Frontier .....	264
6.3.2	Coping with Complexity and Irregularity .....	265
6.4	The Earth System Science Toolkit .....	267
6.4.1	Palaeo-Science .....	267
6.4.2	Contemporary Observation and Monitoring .....	271
6.4.3	Earth System Experimentation .....	274
6.4.4	Global Networks .....	276
6.4.5	Integrated Regional Studies .....	277
6.4.6	Simulating Earth System Dynamics .....	279
6.4.7	Global Integration, Synthesis and Communication .....	283
6.5	Towards Global Sustainability .....	285
6.5.1	Advancing Sectoral Wisdom .....	285
6.5.2	Stewardship of the Earth System .....	285
6.5.3	Challenges of a Changing Earth .....	299
	References .....	299
	<b>Appendix</b> .....	305
	<b>Acknowledgements</b> .....	307
	<b>Index</b> .....	311