

CLIMATE CHANGE

Past, Present and Future

Marie-Antoinette Mélières and Chloé Maréchal

This book is designed for first- and second-year university students (and their instructors) in earth science, environmental science, and physical geography degree programmes worldwide. It provides a simple but masterly account, with a minimum of equations, of how the Earth's climate system works, of the physical processes that have given rise to the long sequence of glacial and interglacial periods of the Quaternary, and that will continue to cause the climate to evolve. The summaries at the end of each section constitute essential reading for policy makers and planners. Its straightforward and elegant description, with an abundance of well chosen illustrations, focuses on different time scales, and includes the most recent research in climate science by the United Nations Intergovernmental Panel on Climate Change (IPCC). It shows how it is human behaviour that will determine whether or not the present century is a turning point to a new climate, unprecedented on Earth in the last several million years.



Marie-Antoinette Mélières, Docteur d'Etat in physics, taught basic physics and, later, climate and environmental science at Joseph Fourier University of Grenoble 1 and at the University of Savoie. Her research has covered various areas ranging from molecular spectroscopy and atmospheric physics to environmental and climate science. In 1995 she established the newsletter *Global Change*, published by the French National Committee on Climate Change, under the authority of the Academy of Sciences. The Committee is the French branch of the four international programs IGBP, WCRP, IHDP and Diversitas. She continued to edit this publication until 2008.



Chloé Maréchal, PhD, geochemist, is Maître de Conférences in the Observatoire des Sciences de l'Univers at Université Claude Bernard Lyon 1, where she teaches Earth Sciences at first university degree level and at Masters level. In her research into the biogeochemical cycles of copper and zinc in the Earth's outer layers, she established a protocol for using isotopes of these elements by plasma-source mass spectrometry and investigated their isotopic fractionation in marine sediments, as well as in soils affected by human activity. She also worked on the geochemical cycle of boron, using its isotopic signal in marine biogenic carbonates as a tool in paleo-oceanographic reconstructions.



Also available
as an e-book



www.wiley.com/go/melieres/climatechange

Cover image: Banded iceberg drifting a couple of miles off the French station, Dumont d'Urville (Terre Adélie), Antarctica, © Emmanuel Lemeur, 2008/9

WILEY Blackwell

FONDATION
NICOLAS
HULOT
POUR LA NATURE
ET L'HOMME

CNL
Centre national
du livre

Rhône-Alpes 

ISBN 978-1-118-70851-4



Contents

Foreword	xiii	5. <i>Atmosphere and ocean: key factors in climate equilibrium</i>	33
Acknowledgements	xv	5.1. Driving forces	34
About the companion website	xvii	5.2. The atmosphere	34
Introduction	1	5.2.1. Composition, pressure and temperature	34
PART I: THE CLIMATE ENGINE OF THE EARTH: ENERGY	5	5.2.2. The zonal pattern of atmospheric circulation	37
1. <i>Why are there many different climates on Earth?</i>	7	5.3. The oceans	42
2. <i>Different climates . . . such diversity of life</i>	11	5.3.1. Ocean circulation	43
2.1. The different climates on Earth	11	5.3.2. CO ₂ equilibrium between atmosphere and ocean	50
2.2. Climates, biomes and biodiversity	13	5.4. Heat transport from the Equator to the poles	51
2.2.1. Distributions	13	Part I: Summary	53
2.2.2. Biodiversity	16	Part I: Notes	54
2.3. Climate and society	17	Part I: Further reading	54
3. <i>From a patchwork of climates to an average climate</i>	19	PART II: MORE ON THE ENERGY BALANCE OF THE PLANET	55
3.1. Temperature and thermal equilibrium	19	6. <i>Thermal radiation, solar and terrestrial radiation</i>	57
3.1.1. Temperature, a measure of average energy	20	6.1. Thermal radiation from a <i>black body</i>	57
3.1.2. Thermal equilibrium – energy equilibrium	21	6.2. The laws of black-body radiation	58
3.2. The average temperature of the Earth's surface	21	6.3. Solar and terrestrial radiation	59
3.3. Precipitation	24	7. <i>The impact of the atmosphere on radiation</i>	61
3.4. Wind	25	7.1. Scattering and reflection	61
3.5. Three major items in energy consumption	26	7.2. Absorption by a gas – the <i>cut-off approximation</i>	62
4. <i>The global mean climate</i>	27	7.2.1. The Beer–Lambert absorption law	62
4.1. The Sun, source of energy	27	7.2.2. The cut-off approximation	64
4.2. The energy equilibrium at the Earth's surface	28	7.3. Absorption of solar and terrestrial radiation by atmospheric gases	64
4.2.1. Case 1: a totally absorbing Earth without an atmosphere	28	7.3.1. Estimates	64
4.2.2. Case 2: a partly reflecting Earth without an atmosphere	29	7.3.2. Absorption of solar and terrestrial radiation	66
4.2.3. Case 3: Earth with an atmosphere	29		

7.4. Direct transfer by the atmosphere	68	9.3. The impact of human activity	91
7.5. Major atmospheric constituents involved in radiative transfer	69	9.4. The present unbalanced global energy budget	91
8. Radiative transfer through the atmosphere	73	10. Climate forcing and feedback	93
8.1. Three radiative mechanisms that heat or cool the Earth's surface	73	10.1. Climate forcing	93
8.1.1. Reflection of solar radiation	73	10.1.1. Internal processes	93
8.1.2. Absorption of solar radiation in the atmosphere: the <i>anti-greenhouse effect</i>	74	10.1.2. External forcing and radiative forcing	94
8.1.3. Absorption of terrestrial radiation by the atmosphere: the greenhouse effect	76	10.2. Feedbacks	95
8.1.4. Comments	78	10.2.1. Slow feedbacks	95
8.2. The greenhouse effect	78	10.2.2. Fast feedbacks	96
8.2.1. The greenhouse effect: the bathtub analogy	79	10.3. Climate sensitivity	98
8.2.2. Venus and the greenhouse effect	82	11. Climate modelling	99
8.3. Radiative transfer: the roles of the different constituents	83	11.1. The Energy Balance and Radiative–Convective Models	99
8.3.1. Reflection of solar radiation: principal factors	83	11.1.1. Energy Balance Models (EBMs)	99
8.3.2. Absorption of solar radiation by the atmosphere: the <i>anti-greenhouse effect</i>	83	11.1.2. Radiative–Convective Models (RCMs)	101
8.3.3. Absorption of terrestrial radiation by the atmosphere: the greenhouse effect	84	11.2. Three-dimensional Atmosphere Global Circulation Models	101
8.3.4. The multiple roles of the components	85	11.2.1. The structure of the model	101
8.4. The radiation balance of the Earth	86	11.2.2. Meteorological models versus climate models	103
9. The energy balance	87	11.2.3. Coupled Atmosphere–Ocean Global Circulation Models (AOGCMs)	103
9.1. The energy balance at the surface of the Earth in the <i>single-layer model</i>	87	11.3. Three-dimensional models: ever-increasing refinements	103
9.1.1. The single-layer approximation	87	11.4. Climate models – what for?	104
9.1.2. Surface temperature as an adjustable parameter	88	Part II. Summary	105
9.2. The Earth's energy balance at equilibrium	89	Part II. Notes	106
9.2.1. The different pieces of the puzzle	89	Part II. Further reading	107
9.2.2. A brief summary	90	PART III: THE DIFFERENT CAUSES OF CLIMATE CHANGE	109
		12. The choice of approach	111
		13. The Sun's emission	115
		13.1. The impact on the climate	115
		13.2. How emission varies	115
		13.2.1. Over a decade	115

13.2.2. Decades and centuries	116	Part III. Summary	145
13.2.3. The past millennia	117	Part III. Notes	146
13.3. What are the consequences?	117	Part III. Further reading	147
14. <i>The position of the Earth with respect to the Sun</i>	119	PART IV: LEARNING FROM THE PAST ...	149
14.1. An overview	119	18. <i>Memory of the distant past</i>	151
14.2. Irradiance, determined by orbital parameters	120	18.1. Over billions of years ...	151
14.3. Changes in obliquity: the impact on the seasons	120	18.2. The past tens of millions of years: slow cooling	152
14.4. Changes in the Earth's orbit and eccentricity: the impact on the Earth–Sun distance	122	18.3. The entry of Northern Hemisphere glaciations	156
14.5. Precession of the axis of rotation: the impact on the Earth–Sun distance at different seasons	124	19. <i>Since 2.6 million years ago: the dance of glaciations</i>	161
14.6. Changes in irradiance	127	19.1. The archives of the dance	161
15. <i>The composition of the atmosphere</i>	129	19.1.1. Marine sediment records: the isotope signal and the nomenclature of the climate stages	161
15.1. The effect on the climate: the mechanism	129	19.1.2. Ice records: isotopes and air bubbles	163
15.2. How the composition has changed, and why	130	19.1.3. Continental records	167
15.2.1. Greenhouse gases and dust	130	19.2. The glacial–interglacial cycles	168
15.2.2. Volcanic aerosols and water vapour	131	19.2.1. Since 2.6 million years ago: the various relevant periods	168
15.2.3. Recent changes	133	19.2.2. The duration of glacials and interglacials	168
15.3. What are the consequences?	133	19.2.3. Asymmetric transitions	169
16. <i>Heat transfer from the Equator to the poles</i>	135	19.3. Glacials and interglacials: very different climate stages	169
16.1. The impact on the climate: the mechanism	135	19.3.1. The glacial stage	169
16.2. How and why can the transfer vary?	135	19.3.2. The interglacial stage	171
16.3. What are the consequences?	136	19.3.3. The change in temperature between glacial and interglacial stages	172
17. <i>Oscillations due to ocean–atmosphere interactions</i>	137	19.3.4. Changes in atmospheric composition between glacial and interglacial stages	172
17.1. The impact on the climate: the mechanism	137	19.4. Glacials and interglacials: similar but never identical	173
17.2. The El Niño Southern Oscillation and trade wind fluctuations	138	19.4.1. Glacial stages	173
17.3. The North Atlantic and Arctic Oscillations	142	19.4.2. Interglacial stages	174
17.3.1. The North Atlantic Oscillation	142		
17.3.2. The Arctic Oscillation	143		

19.5. Abrupt climate changes in the last climate cycle	174	21.2.4. Changes in greenhouse effect gases	197
19.5.1. Chaotic climate and iceberg melting in the last glaciation	174	21.2.5. Earlier interglacials: was the sea level higher than now?	197
19.5.2. The end of the last glaciation	177	21.3. When will the next glaciation come?	198
20. Glacial–interglacial cycles and the Milankovitch theory	181	22. The past 12,000 years: the warm Holocene	201
20.1. The leading role of the Northern Hemisphere	182	22.1. The Holocene	201
20.2. Seasonal irradiance, the key parameter in Quaternary glaciations	182	22.2. Deciphering climate changes during the Holocene	202
20.3. Two types of configuration	183	22.3. Slow changes in irradiance (Timescale 1: millennia)	203
20.4. The climate in the past 250,000 years	184	22.4. Slow cooling at middle and high latitudes in the Northern Hemisphere	203
20.4.1. Past records	184	22.5. Strong monsoon in the Early Holocene: the ‘Green Sahara’ episode	206
20.4.2. The onset and development of warm phases	185	22.5.1. The three continents	206
20.4.3. The onset and development of glacial phases	187	22.5.2. The ‘Green Sahara’ episode	207
20.5. Glacials and interglacials: similar situations, never identical	188	22.5.3. Intense monsoons long before the Holocene	209
20.6. The energy budget: radiative forcing and feedback	189	22.5.4. Monsoon and glacial cycles	212
21. The glaciation dance: consequences and lessons	191	22.5.5. $\delta^{18}\text{O}_{\text{atm}}$, a proxy for the water cycle in the tropics	213
21.1. The impact on life of glacial–interglacial cycles	191	22.5.6. The impact of future warming on the Sahara	213
21.1.1. Change in habitat from glacials to interglacials	191	22.6. Solar fluctuations (Timescale 2: centuries)	214
21.1.2. The impact on biodiversity: taxa, ‘climate refugees’ and so on	192	22.6.1. The Little Ice Age of the last millennium	214
21.1.3. Each interglacial: a succession of similar vegetation	193	22.6.2. Neo-glaciations in the Holocene	220
21.2. Lessons to be drawn	196	22.6.3. The warm phases of the last millennia	221
21.2.1. The significance of an ‘average’ degree	196	22.7. The Holocene and the birth of agriculture and animal husbandry	222
21.2.2. Disparity between latitudes	196	23. Global and regional fluctuations (Timescale 3: decades)	225
21.2.3. The difference between continent and ocean	196	23.1. From global ...	226
		23.1.1. ENSO episodes (El Niño and la Niña)	226

23.1.2. Volcanic eruptions	228	26.1.2. The retreat of Arctic sea ice: why is it so important?	258
23.1.3. El Niño and volcanic activity, two key sources of inter-annual variability	229	26.1.3. Sea ice in the Arctic Ocean over the 20th century	258
23.2. ... to regional: the North Atlantic Oscillation	229	26.1.4. A comparable change in the Southern Hemisphere?	259
23.3. The Sun, the other source of change	230	26.2. Changes in glaciers	261
24. Future warming and past climates	231	26.2.1. The relationship between glaciers and climate	261
24.1. The global 'hot flush' of 55 million years ago	231	26.2.2. Observations of changes in glaciers	262
24.2. Three million years ago	233	26.3. Ice-sheet changes	264
24.3. Warmer periods in the past 2 million years?	233	26.4. Changes in frozen soils	267
Part IV. Summary	235	26.4.1. Permafrost and frozen soils	267
Part IV. Notes	236	26.4.2. Recent changes	267
Part IV. Further reading	239	26.4.3. Consequences	269
		26.5. Freeze-up and snow cover	271
PART V: CLIMATE CHANGE IN RECENT YEARS	241	27. The impact of warming on the ocean	273
25. Recent climate change	243	27.1. Change in sea level	274
25.1. Changes in temperature	243	27.1.1. What changes the average sea level?	274
25.1.1. Observed changes	243	27.1.2. Observed changes	274
25.1.2. Measuring the global mean temperature: implausible accuracy?	247	27.1.3. Is sea-level rise uniform over the planet?	275
25.1.3. How do the different components of the Earth's climate system warm?	248	27.2. Regional changes in ocean salinity	278
25.2. Changes in precipitation, water vapour and extreme events	249	27.3. Is deep ocean circulation slowing?	279
25.2.1. Changes in precipitation	249	27.4. Changes in dissolved carbon dioxide and ocean acidification	280
25.2.2. Changes in atmospheric water vapour	249	27.4.1. Changes in dissolved carbon dioxide	280
25.2.3. Changes in 'extreme' events	250	27.4.2. Ocean acidification	281
25.3. An overview of the past few decades	255	27.5. In summary: consistency over the globe	283
25.4. The impact of global warming: the key issue	255	28. The impact of warming on the biosphere	285
26. The impact of global warming on the cryosphere	257	28.1. Ongoing changes	285
26.1. Sea ice, the 'canary' of our planet	257	28.2. Oceans	286
26.1.1. Sea ice	257	28.2.1. Migration in the North Atlantic	286
		28.2.2. Coral bleaching	286
		28.2.3. Ocean acidification	288

28.3. Land	289	Part V. Summary	320
28.3.1. Warming and migration	290	Part V. Notes	321
28.3.2. Warmer, earlier	291	Part V. Further reading	322
28.3.3. Changes in development and life cycles	294		
28.4. Portents of dysfunction	295		
29. Warming in the 20th century: natural or human-induced?	297	PART VI: CLIMATE IN THE 21ST CENTURY: DIFFERENT SCENARIOS	323
29.1. The carbon cycle prior to the industrial era	298	30. Two key factors	325
29.1.1. The key role of carbon in the universe	298	30.1. Greenhouse gas emissions	325
29.1.2. Carbon reservoirs	298	30.1.1. The leading role of CO ₂	325
29.1.3. Exchange between reservoirs	301	30.1.2. CO ₂ emissions and global energy production	326
29.1.4. The carbon cycle in glacial periods	302	30.1.3. Emissions vary from country to country	327
29.1.5. Year-to-year variations in carbon sinks and sources	303	30.1.4. Accumulation of CO ₂ and CH ₄ in the atmosphere	328
29.2. The impact of human activity on the carbon cycle	305	30.2. Population growth	328
29.2.1. The increase of atmospheric CO ₂ and CH ₄ in the 'Anthropocene'	305	31. Projections: economic scenarios and climate models	329
29.2.2. Changes in the carbon cycle	306	31.1. Successive steps in a projection	329
29.2.3. The signature of anthropogenic emissions	309	31.2. Climate models	331
29.3. Changes related to human activity	310	32. Simulations: a survey	333
29.3.1. Greenhouse gas emissions from human activity	310	32.1. Long-term scenarios	333
29.3.2. Other changes resulting from human activity	312	32.1.1. Climate stabilization: the last stage of the scenario	333
29.4. Natural causes: solar and volcanic activity	313	32.1.2. The coming centuries	333
29.5. An overview of all the causes: the major role of human activity	314	32.1.3. Over several millennia	335
29.5.1. Human-induced radiative forcing	314	32.2. IPCC 2007 scenarios for the 21st century	336
29.5.2. Twentieth-century global warming: natural versus anthropogenic origin	315	32.2.1. Different economic scenarios	336
29.5.3. Is anthropogenically induced warming now detectable? If so, since when?	318	32.2.2. Modelling and scenarios	336
		32.2.3. Global mean temperature change	338
		32.3. IPCC 2013 scenarios for the 21st century	339
		32.3.1. Modelling in IPCC 2007 and 2013	339
		32.3.2. Scenarios	340
		32.3.3. Global mean temperature change	342
		33. Future warming and its consequences	343
		33.1. Global warming	343
		33.2. The water cycle and precipitation	344

33.3. Extreme events	347	34.2. Which choice of scenario?	356
33.4. Snow and ice	347	34.2.1. The impact on life: the fundamental issue	356
33.5. The sea level	348	34.2.2. The size of the change compared to the past	358
33.6. Ocean acidification	349	34.3. Global warming: no more than 2°C	360
33.7. Climate predictions: what degree of confidence?	350	34.4. The 'Triple Zero' challenge	360
33.7.1. Sources of uncertainty in the projected global mean temperature	350	35. <i>Climate change in the present state of the planet</i>	363
33.7.2. Improvements to the models	351	35.1. Environmental degradation	363
33.7.3. Are the economic scenarios outdated?	351	35.2. Depletion of energy resources	364
33.7.4. Tipping points and the possibility of an abrupt climate event	351	35.3. Inexorable world population growth?	364
33.8. In summary, the future is already with us	354	35.4. A new type of development?	364
34. <i>The choice</i>	355	Part VI. Summary	366
34.1. Can future warming be counteracted naturally?	355	Part VI. Notes	367
		Part VI. Further reading	368
		Conclusion	369
		References	373
		Index	383