

CLIMATE CHANGE

The IPCC Scientific Assessment



WORLD METEOROLOGICAL ORGANIZATION/UNITED NATIONS ENVIRONMENT PROGRAMME

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

CLIMATE CHANGE

The IPCC Scientific Assessment

Report Prepared for IPCC by Working Group 1

Edited by J.T.Houghton, G.J.Jenkins and J.J.Ephraums
(Meteorological Office, Bracknell, United Kingdom)



WMO



UNEP

Contents

<i>Preface</i>	<i>iii</i>
<i>Foreword</i>	<i>v</i>
<i>Policymakers Summary</i>	<i>vii</i>
<i>Introduction</i>	<i>xxxv</i>
1 Greenhouse Gases and Aerosols R.T. WATSON, H. RODHE, H. OESCHGER AND U. SIEGENTHALER	1
2 Radiative Forcing of Climate K.P. SHINE, R.G. DERWENT, D.J. WUEBBLES AND J-J. MORCRETTE	41
3 Processes and Modelling U. CUBASCH AND R.D. CESS	69
4 Validation of Climate Models W.L. GATES, P.R. ROWNTREE AND Q-C. ZENG	93
5 Equilibrium Climate Change J.F.B. MITCHELL, S. MANABE, T. TOKIOKA AND V. MELESHKO	131
6 Time-Dependent Greenhouse-Gas-Induced Climate Change F.P. BRETHERTON, K. BRYAN AND J.D. WOODS	173
7 Observed Climate Variations and Change C.K. FOLLAND, T. KARL AND K.YA. VINNIKOV	195
8 Detection of the Greenhouse Effect in the Observations T.M.L. WIGLEY AND T.P. BARNETT	239

9 Sea Level Rise	257
R.A. WARRICK AND H. OERLEMANS	
10 Effects on Ecosystems	283
J.M. MELILLO, T.V. CALLAGHAN, F.I. WOODWARD, E. SALATI AND S.K. SINHA	
11 Narrowing the Uncertainties	311
G. McBEAN AND J. McCARTHY	
Annex	329
<i>Appendix 1 Emission Scenarios</i>	341
<i>Appendix 2 Organisation of IPCC and WGI</i>	343
<i>Appendix 3 Contributors to the WGI Report</i>	345
<i>Appendix 4 Reviewers of the WGI Report</i>	353
<i>Appendix 5 Acronyms - Institutions</i>	359
<i>Appendix 6 Acronyms - Programmes and Miscellaneous</i>	361
<i>Appendix 7 Units</i>	363
<i>Appendix 8 Chemical Symbols</i>	365

CONTENTS

Executive Summary	xi	<i>a. If emissions follow a Business-as-Usual pattern</i>	xxii
		<i>b. If emissions are subject to controls</i>	xxii
Introduction: what is the issue?	xiii	What will be the patterns of climate change by 2030?	xxiii
What factors determine global climate?	xiii	How will climate extremes and extreme events change?	xxiii
What natural factors are important?	xiii	Will storms increase in a warmer world?	xxv
How do we know that the natural greenhouse effect is real?	xiv	Climate change in the longer term	xxvi
How might human activities change global climate?	xiv	Other factors which could influence future climate	xxvii
What are the greenhouse gases and why are they increasing?		How much confidence do we have in our predictions?	xxvii
Concentrations, lifetimes and stabilisation of the gases	xv	Will the climate of the future be very different?	xxvii
How will greenhouse gas abundances change in the future?	xvii	Has man already begun to change the global climate?	xxviii
Greenhouse gas feedbacks	xvii	How much will sea level rise?	xxix
Which gases are the most important?	xviii	What will be the effect of climate change on ecosystems?	xxx
How can we evaluate the effect of different greenhouse gases?	xix	What should be done to reduce uncertainties, and how long will this take?	xxxi
How much do we expect climate to change?	xx		
How quickly will global climate change?	xxii	Annex	xxxiv

Based on
the
redu-
over
levels
to be
the
redus-
over
levels
under
emis-

CONTENTS

Greenhouse Gases and Aerosols

Executive Summary

1.1 Introduction

1.2 Carbon Dioxide

1.2.1 The Cycle of CO₂

1.2.1.1 The role of the ocean

1.2.1.2 The role of the land

1.2.1.3 The role of the atmosphere

1.2.2 Anthropogenic CO₂1.2.2.1 Historical CO₂ emissions1.2.2.2 Long-Term CO₂ trends

1.2.2.3 The Consequences

R.T. WATSON, H. RODHE, H. OESCHGER, U. SIEGENTHALER

1.2.3 Feedbacks from the Climate System

1.2.3.1 The CO₂-climate system1.2.3.2 The CO₂-ocean system1.2.3.3 The CO₂-atmosphere system

Contributors:

M. Andreae; R. Charlson; R. Cicerone; J. Coakley; R. Derwent; J. Elkins; F. Fehsenfeld; P. Fraser; R. Gammon; H. Grassl; R. Harriss; M. Heimann; R. Houghton; V. Kirchhoff; G. Kohlmaier; S. Lal; P. Liss; J. Logan; R. Luxmoore; L. Merlivat; K. Minami; G. Pearman; S. Penkett; D. Raynaud; E. Sanhueza; P. Simon; W. Su; B. Svensson; A. Thompson; P. Vitousek; A. Watson; M. Whitfield; P. Winkler; S. Wofsy.

1.2.4 Feedbacks from the Land Surface

1.2.4.1 The CO₂-climate system1.2.4.2 The CO₂-ocean system1.2.4.3 The CO₂-atmosphere system

1.2.4.4 Modifying the carbon cycle

1.2.4.5 UV-B radiation

1.2.4.6 Terrestrial ecosystems

1.2.4.7 Carbon sinks

1.2.4.8 European climate

1.2.4.9 Temperature

1.2.4.10 Water

1.2.4.11 Changes in vegetation

1.2.4.12 UV-B radiation

1.2.4.13 Conclusions

1.3 Methane

1.3.1 Atmospheric Methane

1.3.1.1 Palaeo-atmospheric methane

1.3.1.2 Contemporary methane

CONTENTS

Executive Summary	5	1.3.1.3 Isotopic composition of methane	19
1.1 Introduction	7	1.3.2 Sinks of Methane	19
1.2 Carbon Dioxide	8	1.3.3 Sources of Methane	20
1.2.1 The Cycle of Carbon in Nature	8	1.3.3.1 Natural wetlands	20
1.2.1.1 The role of the atmosphere	9	1.3.3.2 Rice paddies	20
1.2.1.2 The role of the ocean	9	1.3.3.3 Biomass burning	21
1.2.1.3 The role of terrestrial vegetation and soils	10	1.3.3.4 Enteric fermentation (animals)	21
1.2.2 Anthropogenic Perturbations	10	1.3.3.5 Termites	21
1.2.2.1 Historical fossil fuel input	10	1.3.3.6 Landfills	21
1.2.2.2 Historical land use changes	10	1.3.3.7 Oceans and freshwaters	21
1.2.3 Long-Term Atmospheric Carbon Dioxide Variations	11	1.3.3.8 Coal mining	21
1.2.4 The Contemporary Record of Carbon Dioxide - Observations and Interpretation	11	1.3.3.9 Gas drilling, venting and transmission	21
1.2.4.1 The carbon dioxide increase from pre-industrial period	11	1.3.4 Feedbacks from Climate Change into the Methane Cycle	21
1.2.4.2 Uptake by the ocean	12	1.3.4.1 Tropical methane sources	22
1.2.4.3 Redistribution of anthropogenic carbon dioxide	13	1.3.4.2 High latitude methane sources	22
1.2.4.4 Seasonal variations	14	1.3.5 Conclusions	22
1.2.4.5 Interannual variations	14		
1.2.4.6 Temporal variations of carbon isotopes	14	1.4 Halocarbons	23
1.2.5 Evidence that the Contemporary Carbon Dioxide Increase is Anthropogenic	14	1.4.1 Atmospheric Distribution of Halocarbons	23
1.2.6 Sensitivity Analyses for Future Carbon Dioxide Concentrations	14	1.4.2 Sinks for Halocarbons	24
1.2.7 Feedbacks from Climate Change into the Carbon Dioxide Cycle	14	1.4.3 Sources of Halocarbons	24
1.2.7.1 Oceanic feedback effects	15	1.4.4 Future Atmospheric Concentration of Halocarbons	24
1.2.7.1.1 Ocean temperature	16	1.4.5 Conclusions	24
1.2.7.1.2 Ocean circulation	16		
1.2.7.1.3 Gas exchange rates	16	1.5 Nitrous Oxide	25
1.2.7.1.4 Modification of oceanic biogeochemical cycling	16	1.5.1 Atmospheric Distribution of Nitrous Oxide	25
1.2.7.1.5 UV-B radiation	16	1.5.2 Sinks for Nitrous Oxide	25
1.2.7.2 Terrestrial biospheric feedbacks	16	1.5.3 Sources of Nitrous Oxide	25
1.2.7.2.1 Carbon dioxide fertilization	16	1.5.3.1 Oceans	25
1.2.7.2.2 Eutrophication and toxification	16	1.5.3.2 Soils	26
1.2.7.2.3 Temperature	16	1.5.3.3 Combustion	26
1.2.7.2.4 Water	16	1.5.3.4 Biomass burning	26
1.2.7.2.5 Change in geographical distribution of vegetation types	17	1.5.3.5 Fertilizer / ground-water	27
1.2.7.2.6 UV-B radiation	17	1.5.4 Conclusions	27
2.8 Conclusions	17		
1.3 Methane	17	1.6 Stratospheric Ozone	27
1.3.1 Atmospheric Distribution of Methane	18	1.6.1 Stratospheric Ozone Trends	27
1.3.1.1 Palaeo-atmospheric record of methane	18	1.6.1.1 Total column ozone trends	27
1.3.1.2 Contemporary record of methane	19	1.6.1.2 Changes in the vertical distribution of ozone	28
		1.6.2 Future Changes	28
		1.7 Tropospheric Ozone and Related Trace Gases (Carbon Monoxide, Non-Methane Hydrocarbons, and Reactive Nitrogen Oxides)	28
		1.7.1 Tropospheric Ozone	28
		1.7.1.1 Atmospheric distribution	28
		1.7.1.2 Trends	29
		1.7.1.3 Relationships between ozone and its precursors	29

1.7.2 Carbon Monoxide	30	Non-Methane Hydrocarbon / Carbon Monoxide / Oxides of Nitrogen / Tropospheric Ozone System	31																		
1.7.2.1 Atmospheric distribution of carbon monoxide	30	1.7.6 Conclusions	31																		
1.7.2.2 Sources and sinks for carbon monoxide	30																				
1.7.3 Reactive Nitrogen Oxides	30																				
1.7.3.1 Atmospheric distribution of nitrogen oxides	30	1.8 Aerosol Particles	31																		
1.7.3.2 Sources and sinks of nitrogen oxides	30	1.7.4 Non-Methane Hydrocarbons	31	1.8.1 Concentrations and Trends of Aerosol Particles in the Troposphere	31	1.7.4.1 Atmospheric distribution of non-methane hydrocarbons	31	1.8.2 The Atmospheric Sulphur Budget	32	1.7.4.2 Sources and sinks for non-methane hydrocarbons	31	1.8.3 Aerosol Particles in the Stratosphere	33	1.7.5 Feedbacks Between Climate and the Methane /	31	1.8.4 Conclusions	33			References	34
1.7.4 Non-Methane Hydrocarbons	31	1.8.1 Concentrations and Trends of Aerosol Particles in the Troposphere	31																		
1.7.4.1 Atmospheric distribution of non-methane hydrocarbons	31	1.8.2 The Atmospheric Sulphur Budget	32																		
1.7.4.2 Sources and sinks for non-methane hydrocarbons	31	1.8.3 Aerosol Particles in the Stratosphere	33																		
1.7.5 Feedbacks Between Climate and the Methane /	31	1.8.4 Conclusions	33																		
		References	34																		

Radiative Forcing of Climate

K.P. SHINE, R.G. DERWENT, D.J. WUEBBLES, J-J. MORCRETTE

Contributors:

A.J. Apling; J.P. Blanchet; R.J. Charlson; D. Crommelynck; H. Grassl; N. Husson; G.J. Jenkins; I. Karol; M.D. King; V. Ramanathan; H. Rodhe; G-Y. Shi; G. Thomas; W-C. Wang; T.M.L. Wigley; T. Yamanouchi

CONTENTS

Executive Summary	45	2.3 Other Radiative Forcing Agents	61
2.1 Introduction	47	2.3.1 Solar Radiation	61
2.2 Greenhouse Gases	47	2.3.1.1 Variability due to orbital changes	61
2.2.1 Introduction	47	2.3.1.2 Variability due to changes total in solar	
2.2.2 Direct Effects	49	irradiance	
2.2.3 Indirect Effects	50	2.3.2 Direct Aerosol Effects	63
2.2.4 Relationship Between Radiative Forcing and	51	2.3.3 Indirect Aerosol Effects	64
Concentration	51	2.3.4 Surface Characteristics	65
2.2.5 Past and Present Changes in Radiative Forcing	54	2.4 The Relative Importance of Radiative Forcing	
2.2.6 Calculations of Future Forcing	55	Agents in the Future	66
2.2.7 A Global Warming Potential Concept for		References	67
Trace Gases	58		

Processes and Modelling

3.1 Introduction

3.2 Climate

3.2.1 The climate system

3.2.2 The climate system

3.2.3 The climate system

3.2.4 The climate system

3.2.5 The climate system

3.3 Radiative forcing

3.3.1 Direct effects

3.3.2 Indirect effects

3.3.3 Global warming potential

U. CUBASCH, R.D. CESS

3.3.4 Other effects

Contributors:

F. Bretherton; H. Cattle; J.T. Houghton; J.F.B. Mitchell; D. Randall; E. Roeckner; J.D. Woods; T. Yamanouchi.

CONTENTS

Executive Summary	73	3.5.1.1 Estimate of temperature sensitivity to CO ₂ changes	83
3.1 Introduction	75	3.5.1.2 Construction of the analogue patterns	83
3.2 Climate System	75	3.5.2 Atmospheric General Circulation Models	84
3.2.1 The Atmosphere	75	3.5.2.1 Physical parameterizations	84
3.2.2 The Ocean	75	3.5.2.2 Radiation and the effect of clouds	84
3.2.3 The Cryosphere	76	3.5.2.3 Sub grid-scale transports	85
3.2.4 The Biosphere	77	3.5.2.4 Land surface processes	85
3.2.5 The Geosphere	77	3.5.2.5 Boundary conditions	86
3.2.6 Timescales	77	3.5.3 Ocean Models	86
	77	3.5.4 Carbon Cycle Models	86
	79	3.5.5 Chemical Models	87
	77	3.5.6 Coupled Models of the Atmosphere and the Ocean	87
3.3 Radiative Feedback Mechanisms	77	3.5.7 Use of Models	87
3.3.1 Discussion of Radiative Feedback Mechanisms	77	3.5.7.1 Equilibrium response experiments	88
3.3.2 Water Vapour Feedback	78	3.5.7.2 Time-dependent response experiments	88
3.3.3 Snow-ice Albedo Feedback	78		
3.3.4 Cloud Feedback	79		
		3.6 Illustrative Equilibrium Experiments	88
3.4 Predictability of the Climate System	80	3.7 Summary	89
3.5 Methods of Predicting Future Climate	80		
3.5.1 The Palaeo-Analogue Method	83	References	90

4

Validation of Climate Models

4.1.1.

4.1.2.

4.2.1.

4.3.1.

4.3.2.

4.3.3.

W.L. GATES, P.R. ROWNTREE, Q.-C. ZENG

Contributors:

*P. Arkin; A. Baede; L. Bengtsson; A. Berger; C. Blondin; G. Boer; K. Bryan;
R. Dickinson; S. Grotch; D. Harvey; E. Holopainen; R. Jenne; J. Kutzbach;
H. Le Treut; P. Lemke; B. McAvaney; G. Meehl; P Morel; T. Palmer; L. Prahm;
S. Schneider; K. Shine; I. Simmonds; J. Walsh; R. Wetherald, J. Willebrand.*

CONTENTS

Executive Summary	97	4.5 Simulation of Regional Climate Anomalies	116
4.1 Introduction	99	4.5.1 Response to El Niño SST Anomalies	116
4.1.1 Model Overview	99	4.5.2 Sahelian Drought	118
4.1.2 Methods and Problems of Model Validation	100	4.5.3 Summer Monsoon	119
4.2 Simulation of the Atmospheric Circulation	102	4.6 Simulation of Extreme Events	119
4.2.1 Sea-Level Pressure	102	4.7 Validation from Operational Weather Forecasting	120
4.2.2 Temperature	102	4.8 Simulation of Ocean Climate	120
4.2.3 Zonal Wind	104	4.8.1 Status of Ocean Modelling	121
4.2.4 Eddy Kinetic Energy	105	4.8.2 Validation of Ocean Models	121
4.3 Simulation of Other Key Climate Variables	107	4.9 Validation of Coupled Models	122
4.3.1 Surface Air Temperature	107	4.10 Validation from Palaeo-Climate	124
4.3.2 Precipitation	108	4.10.1 Observational Studies of the Holocene	124
4.3.3 Soil Moisture	108	4.10.2 Model Studies of Holocene Climate	124
4.3.4 Snow Cover	112	4.10.3 Other Validation Opportunities	125
4.3.5 Sea-Ice	113	4.11 Conclusions and Recommendations	126
4.3.6 Clouds and Radiation	113	References	127
4.4 Simulation of Regional Seasonal Cycle	115		
4.4.1 Surface Air Temperature	115		
4.4.2 Precipitation	115		

Equilibrium Climate Change - and its Implications for the Future

5.1 Introduction	5.1.1 What is Equilibrium Climate Change?	5.1.2 What is the Greenhouse Effect?	5.1.3 How does the Greenhouse Effect Work?	5.1.4 Recent Developments in Climate Change Theory
5.2 Equilibrium Climate Change - and its Implications for the Future	5.2.1 What is the Greenhouse Effect?	5.2.2 What is the Greenhouse Effect?	5.2.3 What is the Greenhouse Effect?	5.2.4 What is the Greenhouse Effect?

J. F. B. MITCHELL, S. MANABE, V. MELESHKO, T. TOKIOKA

Contributors:

A. Baede; A. Berger; G. Boer; M. Budyko; V. Canuto; H. Cao; R. Dickinson; H. Ellsaesser; S. Grotch; R. Haarsma; A. Hecht; B. Hunt; B. Huntley; R. Keshavamurty; R. Koerner; C. Lorian; M. MacCracken; G. Meehl; E. Oladipo; B. Pittock; L. Prahm; D. Randall; P. Rowntree; D. Rind; M. Schlesinger; S. Schneider; C. Senior; N. Shackleton; W. Shuttleworth; R. Stouffer; F. Street-Perrott; A. Velichko; K. Vinnikov; D. Warrilow; R. Wetherald.

CONTENTS

Executive Summary			
5.1 Introduction			
5.1.1 Why Carry Out Equilibrium Studies ?	135	5.3.1.3 Diurnal range of temperature	153
5.1.2 What are the Limitations of Equilibrium Climate Studies ?	137	5.3.2 Precipitation	153
5.1.3 How Have the Equilibrium Experiments Been Assessed ?	137	5.3.3 Winds and Disturbances	153
5.2 Equilibrium Changes in Climatic Means due to Doubling CO₂			
5.2.1 The Global Mean Equilibrium Response	137	5.4 Regional Changes - Estimates for 2030	155
5.2.2 What are the Large-Scale Changes on Which the Models Agree ?	137	5.4.1 Introduction	155
5.2.2.1 Temperature changes	137	5.4.2 Limitations of Simulated Regional Changes	155
5.2.2.2 Precipitation changes	137	5.4.3 Assumptions Made in Deriving Estimates for 2030	155
5.2.2.3 Soil moisture changes	137	5.4.4 Estimates of Regional Change; Pre-industrial to 2030 (IPCC "Business-as-Usual" Scenario)	157
5.2.2.4 Sea-ice changes	138		
5.2.2.5 Changes in mean sea-level pressure	138	5.5 Empirical Climate Forecasting	158
5.2.2.6 Deep ocean circulation changes	138	5.5.1 Introduction	158
5.3 Equilibrium Changes in Variability due to Doubling CO₂		5.5.2 Results	158
5.3.1 Temperature	150	5.5.2.1 Temperature	158
5.3.1.1 Day-to-day variability	152	5.5.2.2 Precipitation	158
5.3.1.2 Interannual variability	152	5.5.3 Assessment of Empirical Forecasts	158
	153	5.6 The Climatic Effect of Vegetation Changes	159
	153	5.6.1 Introduction	159
	153	5.6.2 Global Mean Effects	160
	153	5.6.3 Regional Effects: Deforestation of Amazonia	160
	153	5.7 Uncertainties	160
	153	References	162

Time-Dependent Greenhouse-Gas-Induced Climate Change

6.1 Introduction

6.1.1 What is a greenhouse gas?

6.1.2 The greenhouse effect

6.1.3 Models of the greenhouse effect

6.2 Expected climate change

6.3 Expected climate change from greenhouse gases

6.4 Summary

6.4.1 Climate change from greenhouse gases

6.4.2 Summary

F.P. BRETHERTON, K. BRYAN, J.D. WOODS

Contributors:

J. Hansen; M. Hoffert; X. Jiang; S. Manabe; G. Meehl; S.C.B. Raper; D. Rind; M. Schlesinger; R. Stouffer; T. Volk; T.M.L. Wigley.

CONTENTS

Executive Summary	177	6.5 An Illustrative Example	183
6.1 Introduction	179	6.5.1 The Experiment	183
6.1.1 Why Coupled Ocean-Atmosphere Models ?	179	6.5.2 Results	184
6.1.2 Types of Ocean Models	179	6.5.3 Discussion	185
6.1.3 Major Sources of Uncertainty	180	6.5.4 Changes in Ocean Circulation	187
6.2 Expectations Based on Equilibrium Simulations	180	6.6 Projections of Future Global Climate Change	187
6.3 Expectations Based on Transient Simulations	181	6.6.1 An Upwelling Diffusion Model	187
6.4 Expectations Based on Time-Dependent Simulations	181	6.6.2 Model Results	188
6.4.1 Changes in Surface Air Temperature	181	6.6.3 Discussion	190
6.4.2 Changes in Soil Moisture	183	6.7 Conclusions	191
		References	192

Observed Climate Variations and Change

7.1. Introduction

7.2. Palaeoclimates

7.2.1. The Quaternary

7.2.2. The Holocene

7.2.3. The Recent Past

7.2.4. Summary

7.3. The Present Climate

C.K. FOLLAND, T.R. KARL, K.YA. VINNIKOV

Contributors:

J.K. Angell; P. Arkin; R.G. Barry; R. Bradley; D.L. Cadet; M. Chelliah; M. Coughlan; B. Dahlstrom; H.F. Diaz; H. Flohn; C. Fu; P. Groisman; A. Gruber; S. Hastenrath; A. Henderson-Sellers; K. Higuchi; P.D. Jones; J. Knox; G. Kukla; S. Levitus; X. Lin; N. Nicholls; B.S. Nyenzi; J.S. Oguntoyinbo; G.B. Pant; D.E. Parker; B. Pittock; R. Reynolds; C.F. Ropelewski; C.D. Schönwiese; B. Sevruk; A. Solow; K.E. Trenberth; P. Wadhams; W.C. Wang; S. Woodruff; T. Yasunari; Z. Zeng; and X. Zhou.

CONTENTS

Executive Summary	199	7.6 Tropospheric Variations and Change	220
7.1 Introduction	201	7.6.1 Temperature	220
7.2 Palaeo-Climatic Variations and Change	201	7.6.2 Comparisons of Recent Tropospheric and Surface Temperature Data	222
7.2.1 Climate of the Past 5,000,000 Years	201	7.6.3 Moisture	222
7.2.2 Palaeo-climate Analogues for Three Warm Epochs	201	7.7 Sub-Surface Ocean Temperature and Salinity Variations	222
7.2.2.1 Pliocene climatic optimum (3,000,000 to 4,300,000 BP)	203	7.8 Variations and Changes in the Cryosphere	223
7.2.2.2 Eemian interglacial optimum (125,000 to 130,000 years BP)	203	7.8.1 Snow Cover	223
7.2.2.3 Climate of the Holocene optimum (5000 to 6000 years BP)	204	7.8.2 Sea Ice Extent and Thickness	224
7.3 The Modern Instrumental Record	206	7.8.3 Land Ice (Mountain Glaciers)	225
7.4 Surface Temperature Variations and Change	207	7.8.4 Permafrost	225
7.4.1 Hemispheric and Global	207	7.9 Variations and Changes in Atmospheric Circulation	225
7.4.1.1 Land	207	7.9.1 El Niño-Southern Oscillation (ENSO) Influences	226
7.4.1.2 Sea	207	7.9.2 The North Atlantic	228
7.4.1.3 Land and sea combined	209	7.9.3 The North Pacific	229
7.4.2 Regional, Seasonal and Diurnal Space and Timescales	212	7.9.4 Southern Hemisphere	229
7.4.2.1 Land and sea	214	7.10 Cloudiness	230
7.4.2.2 Seasonal variations and changes	214	7.10.1 Cloudiness Over Land	230
7.4.2.3 Day-time and night-time	217	7.10.2 Cloudiness Over the Oceans	230
7.5 Precipitation and Evaporation Variations and Changes	217	7.11 Changes of Climate Variability and Climatic Extremes	230
7.5.1 Precipitation Over Land	218	7.11.1 Temperature	231
7.5.2 Rainfall Over the Oceans	218	7.11.2 Droughts and Floods	232
7.5.3 Evaporation from the Ocean Surface	220	7.11.3 Tropical Cyclones	232
	220	7.11.4 Temporales of Central America	232
		7.12 Conclusions	233
		References	233

Detection of the Greenhouse Effect in the Observations

8.1 Introduction	1
8.1.1 The greenhouse effect	1
8.1.2 The greenhouse effect in the atmosphere	1
8.1.3 Computer models	1
8.1.4 What is detected?	1
8.2 Detection	1
8.2.1 Changes in the atmosphere	1
8.2.1.1 The greenhouse effect	1
8.2.1.2 The greenhouse effect in the atmosphere	1
8.2.1.3 The greenhouse effect in the ocean	1

T.M.L. WIGLEY, T.P. BARNETT

Contributors:

T.L. Bell; P. Bloomfield; D. Brillinger; W. Degefu; C.K. Folland; S. Gadgil; G.S. Golitsyn; J.E. Hansen; K. Hasselmann; Y. Hayashi; P.D. Jones; D.J. Karoly; R.W. Katz; M.C. MacCracken; R.L. Madden; S. Manabe; J.F.B. Mitchell; A.D. Moura; C. Nobre; L.J. Ogallo; E.O. Oladipo; D.E. Parker; A.B. Pittock; S.C.B. Raper; B.D. Santer; M.E. Schlesinger; C.-D. Schönwiese; C.J.E. Schuurmans; A. Solow; K.E. Trenberth; K.Ya. Vinnikov; W.M. Washington; T. Yasunari; D. Ye; W. Zwiers.

CONTENTS

Executive Summary	243		
8.1 Introduction	245	8.2.3.2 Enhanced high-latitude warming, particularly in the winter half-year	250
8.1.1 The Issue	245	8.2.3.3 Tropospheric warming and stratospheric cooling	251
8.1.2 The Meaning of "Detection"	245	8.2.3.4 Global-mean precipitation increase	251
8.1.3 Consistency of the Observed Global-Mean Warming with the Greenhouse Hypothesis	245	8.2.3.5 Sea level rise	251
8.1.4 Attribution and the Fingerprint Method	247	8.2.3.6 Tropospheric water vapour increase	251
8.2 Detection Strategies	248	8.3 Multivariate or Fingerprint Methods	252
8.2.1 Choosing Detection Variables	248	8.3.1 Conspectus	252
8.2.1.1 Signal-to-noise ratios	248	8.3.2 Comparing Changes in Means and Variances	252
8.2.1.2 Signal uncertainties	248	8.3.3 Pattern Correlation Methods	252
8.2.1.3 Noise uncertainties	248	8.4 When Will the Greenhouse Effect be Detected ?	253
8.2.1.4 Observed data availability	249	8.5 Conclusions	254
8.2.2 Univariate Detection Methods	249	References	254
8.2.3 Evaluation of Recent Climate Changes	249		
8.2.3.1 Increase of global-mean temperature	249		

Sea Level Rise

Executive Summary

1 Sea Level Rise

2 Future Effects

3 The Sea Level

40 Years?

and Components

5 Land Accretion

6 Possible Causes

R. WARRICK, J. OERLEMANS

Contributors:

P. Beaumont; R.J. Braithwaite; D.J. Drewery; V. Gornitz; J.M. Grove; W. Haeberli;
A. Higashi; J.C. Leiva; C.S. Lingle; C. Lorius; S.C.B. Raper; B. Wold;
P.L. Woodworth.

CONTENTS

Executive Summary	261	9.4.3 Glaciers and Small Ice Caps	268
9.1 Sea Level Rise: Introduction	263	9.4.4 The Greenland Ice Sheet.	269
9.2 Factors Affecting Sea Level	263	9.4.5 The Antarctic Ice Sheet.	271
9.3 Has Sea Level Been Rising Over the Last 100 Years ?	263	9.4.6 Possible Instability of the West Antarctic Ice Sheet.	273
9.3.1 Comparison of Recent Estimates	264	9.4.7 Other Possible Contributions	274
9.3.2 Possible Sources of Error	265	9.4.8 Synthesis	274
9.3.3 Accelerations in Sea Level Rise	266	9.5 How Might Sea Level Change in the Future ?	275
9.5.1 Methods and Assumptions		9.5.2 Discussion	276
9.4 Possible Contributing Factors to Past and Future Sea Level Rise	266	9.6 Summary and Conclusions	278
9.4.1 Thermal Expansion of the Oceans.	266	References	279
9.4.2 Land Ice	268		

10

Effects on Ecosystems

J.M. MELILLO, T.V. CALLAGHAN, F.I. WOODWARD, E. SALATI, S.K. SINHA

Contributors:

J. Aber; V. Alexander; J. Anderson; A. Auclair; F. Bazzaz; A. Breymeyer; A. Clarke; C. Field; J.P. Grime; R. Gifford; J. Goudrian; R. Harris; I. Heaney; P. Holligan; P. Jarvis; L. Joyce; P. Levelle; S. Linder; A. Linkins; S. Long; A. Lugo, J. McCarthy, J. Morison; H. Nour; W. Oechel; M. Phillip; M. Ryan; D. Schimel; W. Schlesinger; G. Shaver; B. Strain; R. Waring; M. Williamson.

CONTENTS

Executive Summary	287			
10.0 Introduction	289	10.2.2.2.3 Decomposition	295	
10.1 Focus	289	10.2.2.2.4 Models of ecosystem response to climate change	296	
10.2 Effects of Increased Atmospheric CO₂ and Climate Change on Terrestrial Ecosystems	289	10.2.2.3 Large-scale migration of biota	298	
10.2.1 Plant and Ecosystem Responses to Elevated CO ₂	289	10.2.2.3.1 Vegetation-climate relationships	298	
10.2.1.1 Plant responses	289	10.2.2.3.2 Palaeo-ecological evidence	298	
10.2.1.1.1 Carbon budget	289	10.2.2.4 Summary	299	
10.2.1.1.2 Interactions between carbon dioxide and temperature	290			
10.2.1.1.3 Carbon dioxide and environmental stress	290	10.3 The Effects of Terrestrial Ecosystem Changes on the Climate System	300	
10.2.1.1.4 Phenology and senescence	291	10.3.1 Carbon Cycling in Terrestrial Ecosystems	300	
10.2.1.2 Community and ecosystem responses to elevated carbon dioxide	291	10.3.1.1 Deforestation in the Tropics	300	
10.2.1.2.1 Plant-plant interactions	291	10.3.1.2 Forest regrowth in the mid-latitudes of the Northern Hemisphere	301	
10.2.1.2.2 Interactions between plants and animals	291	10.3.1.3 Eutrophication and toxification in the mid-latitudes of the Northern Hemisphere	301	
10.2.1.2.3 Interaction between plants and microbes	291	10.3.2 Reforestation as a Means of Managing Atmospheric CO ₂	301	
10.2.1.2.4 Decomposition	291	10.3.3 Methane and Nitrous Oxide Fluxes	301	
10.2.1.2.5 Whole-ecosystem exposure to elevated carbon dioxide	292	10.3.3.1 Methane	302	
10.2.1.3 Summary	292	10.3.3.2 Nitrous oxide	302	
10.2.2 Plant and Ecosystem Responses to Changes in Temperature and Moisture	294	10.3.4 Ecosystem Change and Regional Hydrologic Cycles	303	
10.2.2.1 Plant responses to changes in temperature and moisture	294	10.3.5 Summary	304	
10.2.2.1.1 Carbon budget	294	10.4 Marine Ecosystems and Climate Change	304	
10.2.2.1.2 Phenology and senescence	294	10.4.1 Climate Change and Community Response	304	
10.2.2.2 Community and ecosystem responses	295	10.4.2 Interaction Between the Land and the Ocean	305	
10.2.2.2.1 Plant community composition	295	10.4.3 Interactions Between the Ocean and the Atmosphere	305	
10.2.2.2.2 Interactions between plants and animals	295	10.4.4 The Carbon System and the Biological Pump	305	
		10.4.5 Summary	306	
		References	306	

Narrowing the Uncertainties: A Scientific Action Plan for Improved Prediction of Global Climate Change

G. MCBEAN, J. MCCARTHY

Contributors:

K. Browning; P. Morel; I. Rasool.

CONTENTS

Executive Summary	315	11.3 Requirements for Narrowing Uncertainties in Future Climate Change	322
11.1 Introduction	317	11.3.1 Improvement of the Global Atmosphere and Land Surfaces Observing System	322
11.2 Problem Areas and Scientific Responses	317	11.3.2 Development of a Global Ocean and Ice Observing System	323
11.2.1 Control of the Greenhouse Gases by the Earth System	318	11.3.3 Establishment of a Comprehensive System for Climate Monitoring	323
11.2.2 Control of Radiation by Clouds	318	11.3.4 Development of Climate Models	324
11.2.3 Precipitation and Evaporation	320	11.3.5 International Research on Climate and Global Change	325
11.2.4 Ocean Transport and Storage of Heat	320		
11.2.5 Ecosystems Processes	321	11.3.6 Time-scales for Narrowing the Uncertainty	325
