



SCIENCES

GEOGRAPHY AND DEMOGRAPHY



Physical Geography, Construction of Environments and Landscapes

Spatial Impacts of Climate Change

**Coordinated by
Denis Mercier**

ISTE

WILEY

Spatial Impacts of Climate Change

SCIENCES

Geography and Demography, Field Director – Denise Pumain

Physical Geography, Construction of Environments and Landscapes,
Subject Head – Étienne Cossart

Spatial Impacts of Climate Change

Coordinated by
Denis Mercier

ISTE

WILEY

First published 2021 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms and licenses issued by the CLA. Enquiries concerning reproduction outside these terms should be sent to the publishers at the undermentioned address:

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

© ISTE Ltd 2021

The rights of Denis Mercier to be identified as the author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

Library of Congress Control Number: 2020947184

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78945-009-5

ERC code:

LS8 Ecology, Evolution and Environmental Biology

LS8_1 Ecosystem and community ecology, macroecology

LS8_2 Biodiversity, conservation biology, conservation genetics

LS9 Applied Life Sciences, Biotechnology, and Molecular and Biosystems Engineering

LS9_4 Applied plant sciences (including crop production, plant breeding, agroecology, forestry, soil biology)

Contents

Introduction	xiii
Denis MERCIER	
Chapter 1. Climate Change at Different Temporal and Spatial Scales	1
Denis MERCIER	
1.1. Contemporary global climate change.	1
1.2. Contemporary Arctic-wide climate change	6
1.3. Future global climate change	9
1.4. Future Arctic-wide climate change	11
1.5. The causes of climate change	13
1.5.1. Solar radiation	13
1.5.2. Anthropogenic greenhouse gas emissions	14
1.5.3. Volcanism	16
1.5.4. Albedo and the radiation balance.	17
1.6. Conclusion	19
1.7. References	19
Chapter 2. Climate Change and the Melting Cryosphere	21
Denis MERCIER	
2.1. Introduction.	21
2.2. The sensitivity of the cryosphere to climate change	22
2.3. Melting of the marine cryosphere.	24

2.3.1. The melting of the Arctic sea ice	24
2.3.2. Antarctic sea ice.	27
2.4. Melting of the Earth’s cryosphere.	28
2.4.1. Melting ice sheets.	28
2.4.2. The melting of mountain glaciers	32
2.4.3. Decreasing permafrost	35
2.4.4. Melting snow	35
2.5. Consequences of the melting cryosphere	36
2.5.1. On a global scale: rising sea levels.	36
2.5.2. Regionally: paraglacial risks	38
2.6. Conclusion	40
2.7. References	40

Chapter 3. Between Warming and Globalization: Rethinking the Arctic at the Heart of a Stakes System. 43

Éric CANOBBIO

3.1. Spatial impacts of climate change in the Arctic	43
3.1.1. Clarifying the terms of the subject in their polar contexts	44
3.2. The manufacture of polar issues, between global warming and globalization	52
3.2.1. Warming and space production, a decade of confusion off the Arctic coasts	53
3.2.2. Three interacting contexts	57
3.3. The production of polar doctrines: rhetoric and frameworks for action	59
3.3.1. Factors of convergence and consensus	60
3.3.2. Differentiation factors	61
3.3.3. The strategic dimensions of Arctic policies, the complex issue of polar militarization	62
3.4. Geography of a new system of stakeholder relations in the Arctic	65
3.5. Conclusion: polar metamorphisms	67
3.6. References	68

Chapter 4. Coastlines with Increased Vulnerability to Sea-level Rise. 71

Axel CREACH

4.1. Introduction.	71
4.2. Coastlines under the influence of sea-level rise.	72
4.2.1. The pressures of climate change on coastlines	72

4.2.2. Consequences of sea-level rise on coastlines	76
4.3. Increasingly attractive coastlines for societies	78
4.3.1. The coastalization process	78
4.3.2. A densification of activities on the coastlines	79
4.3.3. A closer approach to the sea	81
4.4. Towards the necessary adaptation of coastal areas	83
4.4.1. The coastline, an area at risk	83
4.4.2. Possible coping strategies	84
4.4.3. The example of the Netherlands	86
4.5. Which coastline for tomorrow?	87
4.6. References	89

Chapter 5. The Consequences of Climate Change on the Paraglacial Sedimentary Cascade 93

Denis MERCIER and Étienne COSSART

5.1. The paraglacial sedimentary cascade: elements of definition	93
5.1.1. General principles of the concept of a paraglacial sedimentary cascade	93
5.1.2. Paraglacial spatial boundaries	98
5.1.3. The temporal limits of the paraglacial sedimentary cascade	99
5.2. Sediment inputs to the paraglacial sedimentary cascade	102
5.2.1. Landslides	102
5.2.2. Remobilization of slope deposits	105
5.3. Sediment fluxes within the paraglacial sedimentary cascade	108
5.3.1. The evolution of ice margins on a decadal scale	108
5.3.2. Paraglacial fluvial metamorphoses on a secular scale	109
5.4. Sedimentary stocks or the end of the paraglacial sedimentary cascade	110
5.4.1. Temporary storage areas on a secular scale	110
5.4.2. Interglacial-scale temporary storage areas	112
5.4.3. Final storage areas	115
5.5. Conclusion	115
5.6. References	116

Chapter 6. Spatial Impacts of Climate Change on Periglacial Environments 119

Denis MERCIER and Étienne COSSART

6.1. Introduction	119
6.1.1. Definition of periglacial	120

6.1.2. Present and past spatial extent of periglacial environments	121
6.2. Melting permafrost and paraperiglacial geomorphological crises	125
6.2.1. Definition of paraperiglacial	125
6.2.2. Paraperiglacial processes and forms	127
6.3. Periglacial coastal environments in high latitudes in the face of climate change.	129
6.4. Periglacial environments at high altitudes in the face of climate change.	131
6.4.1. Gravity dynamics and permafrost wall degradation.	132
6.4.2. Gravity dynamics and permafrost degradation in loose formations	134
6.4.3. The impact of global warming on high-mountain practices	136
6.5. Conclusion	137
6.6. References	138

Chapter 7. The Impacts of Climate Change on the Hydrological Dynamics of High Latitude Periglacial Environments 143

Emmanuèle GAUTIER

7.1. Periglacial regions strongly affected by recent climate change	143
7.1.1. Much warmer winters	143
7.1.2. Permafrost and its sensitivity to air temperatures	144
7.2. The influence of permafrost on hydrological functioning.	146
7.2.1. Numerous wetlands in periglacial environments.	147
7.2.2. The knock-on effects of climate change on slope hydrology	148
7.3. The response of Arctic fluvial hydrosystems to ongoing climate change.	150
7.3.1. River ice	153
7.3.2. Increasing winter low water levels	155
7.3.3. Spring flooding and breakup	157
7.3.4. The rapid evolution of water discharge	159
7.4. Conclusion	163
7.5. References	163

Chapter 8. The Impacts of Climate Change on Watercourses in Temperate Environments 167

Gilles DROGUE

8.1. What is at stake?	167
8.1.1. Spatial dynamics of climate zoning and river regimes	167

8.1.2. Watercourses: resource, vector and living environment	169
8.1.3. The (dis)equilibrium between precipitation, evapotranspiration and flow in temperate environments	171
8.1.4. The study of past climate impacts	173
8.1.5. The study of future climate impacts	173
8.1.6. Summary	174
8.2. Hydrological changes already “observable”.	176
8.2.1. The case of metropolitan France	176
8.2.2. Continental trends: Western Europe	179
8.3. Hydrological projections	180
8.3.1. For French rivers	180
8.3.2. For continental Europe.	181
8.4. Conclusion	184
8.5. References	184

Chapter 9. Spatial Impacts of Melting Central Asian Glaciers: towards a “Water War”? 187

Alain CARIOU

9.1. Societies and economies dependent on the cryosphere	187
9.1.1. The possibility of water scarcity and “water war”?	187
9.1.2. “Water tower” mountains for arid depressions.	188
9.1.3. Tensions between riparian and rival states	194
9.2. The impact of climate change on water resources	198
9.2.1. Recession of the cryosphere.	198
9.2.2. The consequences of cryosphere retreat on hydrology	200
9.2.3. Human societies facing the challenge of climate change.	202
9.3. Conclusion	205
9.4. References	206

Chapter 10. Spatial Impact of Climate Change on Winter Droughts in the Mediterranean and Consequences on Agriculture. 209

Florian RAYMOND and Albin ULLMANN

10.1. Climate variability and change in the Mediterranean basin	209
10.2. Droughts during rainy seasons	211
10.2.1. Rainfall drought: the absence of rain in time and space.	211
10.2.2. Detection of very long dry events in the Mediterranean Sea	212

10.2.3. Spatial and temporal characteristics of the main event patterns of very long dry spells.	213
10.3. Rainfall droughts in the Mediterranean: impacts on Spanish agrosystems	216
10.4. Rainfall droughts in the Mediterranean: projections for the future	218
10.5. Conclusion	221
10.6. References.	222

Chapter 11. The Spatial Impacts of Climate Change on Viticulture Around the World. 225

Hervé QUÉNOL and Renan LE ROUX

11.1. Introduction	225
11.2. Recent climatic trends in the world’s wine-growing regions	226
11.3. Climate zoning in viticulture.	227
11.4. Impact of climate change: anticipating changes in the spatial distribution of vines	230
11.4.1. Towards climate change modeling in wine-growing regions.	231
11.4.2. The need to take into account local factors	236
11.5. Conclusion	238
11.6. References.	239

Chapter 12. Climate Change in the Amazon: A Multi-scalar Approach 243

Vincent DUBREUIL, Damien ARVOR, Beatriz FUNATSU, Vincent NÉDÉLEC and Neli DE MELLO-THÉRY

12.1. Introduction	243
12.2. The Amazonian climate system	244
12.2.1. Heat, humidity and regional diversity	244
12.2.2. Radiation balance and general circulation.	247
12.2.3. The forest-climate interaction issue	248
12.3. A changing system: deforestation, warming and drying?	250
12.3.1. Pioneering dynamics: rise and (provisory?) decline	250
12.3.2. Increase in temperature and decrease in rainfall	252
12.3.3. The dynamics of the start and end dates of the rainy season	252
12.3.4. Local effects of land-use changes.	254
12.4. Uncertainties of future changes, perceptions and adaptations	257
12.4.1. Savanization and tipping points	257

12.4.2. An overall impact which is certain, but which remains to be specified.	258
12.4.3. Perceptions and adaptations by local populations	259
12.5. Conclusion: a stake in the global negotiations.	261
12.6. References.	263

Chapter 13. The Impacts of Climate Change on the Distribution of Biomes 267

Delphine GRAMOND

13.1. Biomes, a representation of life on a global scale.	268
13.1.1. The biome, an indicator of climatic context: what are the realities?	269
13.1.2. From the roots of a globalizing concept to the emergence of an operational scale	270
13.2. Structural and functional impacts of climate change on terrestrial biomes	274
13.2.1. From bioclimatic bathing to modification of ecological processes	274
13.2.2. Identifying changes: from global diagnosis to biological responses.	275
13.3. Spatializing change: biome modeling.	279
13.3.1. Observed and projected global impacts	279
13.3.2. Observed and projected impacts for the Arctic region.	282
13.4. Conclusion	284
13.5. References.	286

Chapter 14. Spatial Impacts of Climate Change on Birds. 289

Laurent GODET

14.1. Introduction	289
14.2. Contemporary distributional changes.	291
14.2.1. Latitudinal shifts.	292
14.2.2. Altitudinal shifts.	293
14.2.3. Spatial manifestations of range changes.	295
14.3. Different responses for different species	297
14.3.1. Dispersion capabilities	297
14.3.2. Reproductive capacity	298
14.3.3. Generalist nature.	299

14.4. Conservation implications	299
14.4.1. Ecological consequences	299
14.4.2. Conservation measures	300
14.5. Conclusion	302
14.6. References.	303
List of Authors	311
Index	313

Introduction

Spatial Impacts of Climate Change: Multi-scale Issues

Denis MERCIER

Sorbonne University, Paris, France

Climate change involves a change in the elements of what is known as the climate machine, often summarized in the press as a change in the temperature variable alone. However, the Earth's climate is a complex system inducing interactions between its different components: atmosphere, hydrosphere, cryosphere, pedosphere, biosphere, lithosphere and noosphere.

1.1. The impact of contemporary climate change on forest fires in Australia in 2019–2020: a systemic approach

There is no shortage of examples in the recent past to illustrate the systemic interactions related to climate change in recent decades. Gigantic fires in Australia had destroyed more than 10 million hectares (ha) in the southeast of the country by early January 2020. This is more than five times the area of the California fires of 2018 (1.8 million ha) and ten times the area of the high-profile fires in the Amazon rainforest in the summer of 2019 (0.9 million ha, see Chapter 12). Global warming increases the likelihood that fires may occur by accentuating the expansion potential of these fires, which are devastating for fauna, flora and sometimes also for human life. Indeed, the fire seasons in Australia now begin earlier in September and last longer. Climate change in Australia is measured by a reduction in annual precipitation, which contributes to the drying out of soils, vegetation and thus the potential for fires. The year 2019 was the driest year on record since 1900 according

to the Australian Bureau of Meteorology¹. At the same time, temperatures have been rising, and 2019 was also the warmest year on record in Australia since 1910. These same climate changes can be understood on another spatial scale by combining ocean and atmospheric circulation. In the Indian Ocean, the dipole reflects the temperature differential between the western and eastern parts of this ocean basin. During the positive phases of this dipole, ocean temperatures are higher in the west than in the east, favoring rainfall over East Africa and reducing rainfall over Australia and Indonesia (Kämpf *et al.* 2019). These positive phases have become more frequent and intense since the 1950s. When the Antarctic Oscillation enters a negative phase, the westerly winds surrounding the Antarctic continent, the so-called Roaring Forties and Howling Fifties, move away from the continent and move up towards mid-latitudes, generating strong winds towards land areas such as Australia (Feng *et al.* 2019). When these two phenomena occur in time, dry air masses over the eastern Indian Ocean are propelled towards Australia, which then receives less precipitation and experiences strong winds. These air masses then cross Australia's interior deserts and fall back down over the eastern part of the Australian Cordillera, which reinforces the local drying of these air masses over the southeastern part of the country by the foehn effect. In addition, these Australian fires generate dust in the atmospheric circulation and result in dust fallout on New Zealand glaciers, particularly those of Fox and Franz Josef, whose melting is likely to be accelerated by the lowering of their surface albedo, which is brownish in color due to ash and soot fallout. At its scale, this local melting of the cryosphere contributes to a global rise in sea level.

Beyond the Australian case and on a more global scale, recent research shows that a warmer planet increases the risk of forest fires (Johns *et al.* 2020). Increasing temperatures, decreased precipitation and soil moisture, combined with drying strong winds, contribute to an increase in the frequency and severity of fire-prone periods.

1.2. The impacts of contemporary climate change: a multi-scalar approach

The issues are therefore systemic and multi-scale. Societies, whatever they are and wherever they are found, must and will have to adapt to the following changes for which they are not necessarily individually responsible. This book therefore presents the different impacts of climate change according to the areas and territories under consideration.

¹ <http://www.bom.gov.au/>.

On a global scale, all the fundamental elements of the Earth system and their interactions are mobilized by climate change: water cycle, carbon cycle, atmospheric circulation, thermohaline circulation. Although general mechanisms make it possible to understand and explain climate change, regional and local nuances show that geographical elements such as the distribution of land and oceans, the layout of landforms, coastal dynamics and human activities can minimize or, on the contrary, exacerbate the spatial consequences of general physical laws. The example of contemporary climate warming on a global scale and its amplification in the Arctic illustrate the importance of these changes in spatial scales (see Chapter 1). The melting of the marine and terrestrial cryosphere, discussed in Chapter 2, is not spatially uniform. It contributes to changing geopolitical and economic issues in the Arctic (see Chapter 3). The melting of the terrestrial cryosphere induces a rise in global sea and ocean levels, which will not affect coastlines in the same way according to their own typology (cliff coasts, deltas, etc.) or their own dynamics (subsidence, stability or uplift) and according to the way they are occupied by societies (see Chapter 4).

At the regional scale, the spatial impacts of contemporary climate change are being addressed using a variety of approaches. By modifying the cryosphere in high latitudes and high mountains, changes in climate induce changes in the paraglacial sedimentary cascade (see Chapter 5) and periglacial environments (see Chapter 6). River organisms in cold environments (see Chapter 7) and temperate environments (see Chapter 8) record climate change in different ways. The melting glaciers of Central Asia place the consequences of climate change at the heart of geopolitical issues in this region (see Chapter 9).

At the local level, the impact of rainier season droughts in the western Mediterranean basin on Spanish rain-fed agriculture provides a link between regional climate dynamics and local impacts (see Chapter 10).

Multi-scalar approaches also make it possible to show the stakes of contemporary climate change on viticulture (see Chapter 11), on the scale of the Amazon basin (see Chapter 12), on the distribution of biomes (see Chapter 13) or on the distribution of birds (see Chapter 14).

In all the chapters, the examples analyzed underline the importance of geographical approaches for the study of the impacts of contemporary climate change.

I.3. References

- Feng, J., Zhang, Y., Cheng, Q., San Liang, X., Jiang, T. (2019). Analysis of summer Antarctic sea ice anomalies associated with the spring Indian Ocean dipole. *Global and Planetary Change*, 181 [Online]. Available at: <https://doi.org/10.1016/j.gloplacha.2019.102982>.
- Jones, M.W., Smith, A., Bettes, R., Canadell, J.G., Prentice, C., Le Quéré, C. (2020). Climate change increases the risk of wildfires. *ScienceBrief* [Online]. Available at: <https://sciencebrief.org/topics/climate-change-science/wildfires>.
- Kämpf, J. and Kavi, A. (2019). SST variability in the eastern intertropical Indian Ocean – On the search for trigger mechanisms of IOD events. *Deep Sea Research Part II: Tropical Studies in Oceanography*, 166, 64–74.

1

Climate Change at Different Temporal and Spatial Scales

Denis MERCIER

Sorbonne University, Paris, France

1.1. Contemporary global climate change

Contemporary climate change refers to the period from 1850 to the present day and covers the period from the Industrial Revolution to the digital revolution. It also covers a period during which humanity experienced a population explosion, reaching 1 billion people for the first time in 1820. On January 1, 2020, the human population was estimated at 7.7 billion and is expected to reach 11 billion by 2100, according to the UN.

Through the use of fossil fuels (coal, oil, gas) and increased agricultural production to feed the world's growing population, these elements contribute to increasing humanity's role in the climate machine.

Since the mid-19th Century, the average global air temperature has increased by 1.1°C. This increase has not been linear over time and Figure 1.1 illustrates the stages of this evolution. Two warming sequences help to understand this increase: the first from 1910 to 1940 and the second from 1980 to the present day, during which the increase in temperature was 0.18°C per decade. According to the World

Spatial Impacts of Climate Change,
coordinated by Denis MERCIER. © ISTE Ltd 2021.

Meteorological Organization¹, the year 2019 was the second warmest year recorded since 1850. It comes after the year 2016, which experienced a particularly intense El Niño episode, with abnormally high ocean surface water temperatures in the eastern South Pacific. These two periods of warming are interspersed by temporal sequences of cooling (from 1880 to 1910, then from 1940 to 1980).

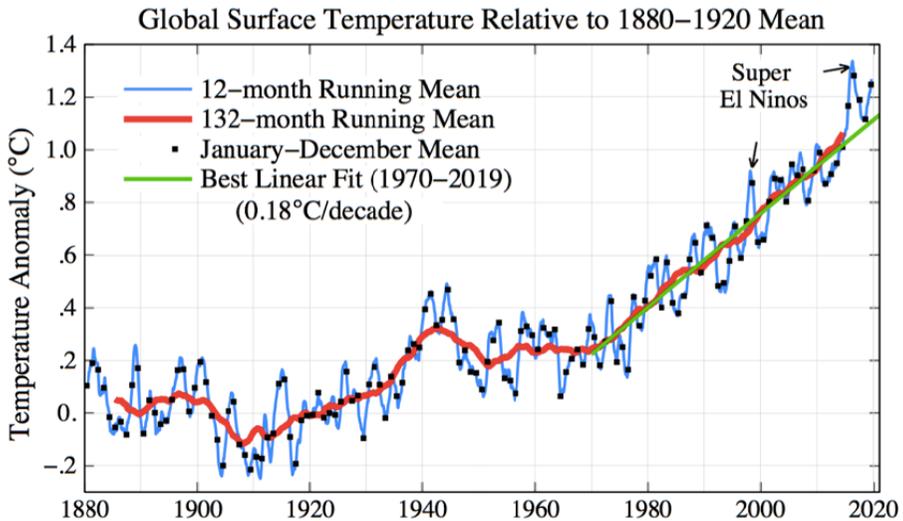


Figure 1.1. Annual mean surface temperature from 1880 to 2019 compared to the 1880–1920 mean (source: Sato and Hansen, *Climate Science, Awareness and Solutions at Columbia University Earth Institute*, 2020). For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

This non-linear temperature evolution over time is not spatially homogeneous (see Figure 1.2). These maps illustrate general trends. Continental land areas record this contemporary global warming better than ocean surfaces; of these continental land surfaces, those with a hypercontinental climate such as Siberia are experiencing the greatest temperature increases.

Although the map projection is not very favorable, Figure 1.2 shows that high latitude regions, especially the Arctic basin and its surroundings, have experienced the greatest increases in temperature.

¹ <https://public.wmo.int/fr>.

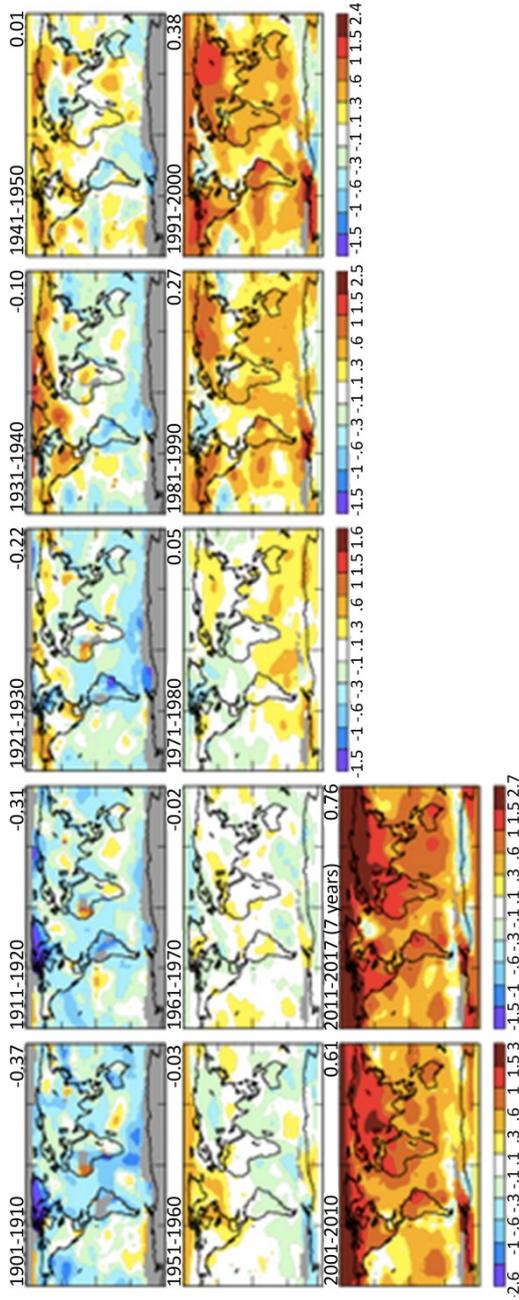


Figure 1.2. Average surface temperature per decade from 1910 to 2017 compared to the 1951–1980 average (source: 2018 NASA-GISS temperature data, downloaded from <https://data.giss.nasa.gov/gistemp/>). For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

Although the oceans are warming less than land areas, they are still warming and store 93% of the excess heat. The last 10 years are the warmest recorded for ocean surface waters since 1955 with a linearly increasing temperature trend since the 1980s (see Figure 1.3) (Cheng *et al.* 2020). For the first period, the warming was relatively constant of approximately 2.1 ± 0.5 Zetta Joules² per year. However, the warming in the more recent period is greater than that of the previous warming (9.4 ± 0.2 Zetta Joules per year, or 0.58 watt per m² on average on the Earth's surface), hence the significant increase in the rate of global climate change at the ocean scale (Cheng *et al.* 2020).

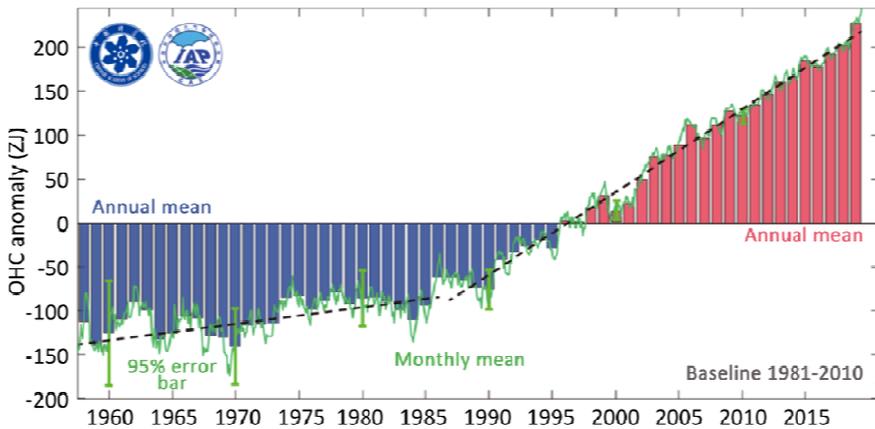


Figure 1.3. Ocean heat content (OHC) in the upper water section above 2,000 m from 1955 to 2019. For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

COMMENT ON FIGURE 1.3.– *The histogram represents annual anomalies (ZJ: Zetta Joules, where 1 ZJ = 10^{21} Joules) where positive anomalies relative to a mean calculated between 1981 and 2010 are shown as red bars and negative anomalies are shown in blue. The two dashed black lines represent linear trends for the periods 1955–1986 and 1987–2019 (source: Cheng et al. 2020).*

The increase in ocean surface temperatures affects all oceans. Although some ocean areas, such as the North Atlantic, experienced a decrease in temperature between 1960 and 2019 (Cheng *et al.* 2020), the penetration of heat into the deep ocean is clear in Figure 1.4, mainly in the Atlantic and Southern Oceans (Cheng

2 Zetta: one triilliard (10^{21}), or one thousand trillion, according to the international system of units.

et al. 2020). These two ocean basins, especially near the Antarctic Circumpolar Current (40° 60° S) show greater warming than most other basins (Cheng *et al.* 2020).

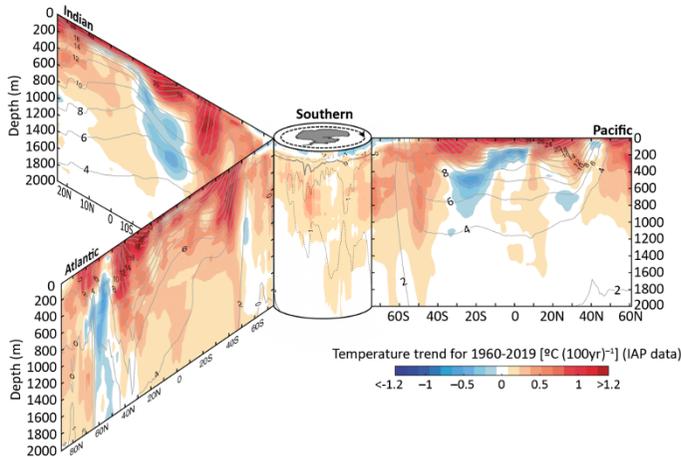


Figure 1.4. Vertical cross-section of ocean temperature trends from 1960 to 2019 from the sea surface to 2,000 m (60-year ordinary least squares linear trend). For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

COMMENT ON FIGURE 1.4.— *The zonal mid-sections of each ocean basin are organized around the Southern Ocean (south of 60° S) in the center. The black outlines show the associated mean temperature with 2°C intervals (in the Southern Ocean, 1°C intervals are shown as dashed lines) (source: Cheng et al. 2020).*

This increase in global ocean surface temperatures leads, through thermal expansion, to a rise in sea level, as an increase in air temperature contributes to the melting of the Earth's cryosphere and thus to the increase in the amount of water in the global ocean (see Chapter 2 on melting of the cryosphere). Similarly, rising ocean temperatures reduce dissolved oxygen in the ocean and significantly affect marine life, especially corals and other organisms sensitive to temperature and water chemistry (IPCC 2019; see Chapter 4 on coasts). Increasing ocean surface water temperature promotes evaporation over the oceans and moisture in the atmosphere, which logically can promote heavy rainfall, and can be associated with more frequent and/or more intense cyclones, and can, depending on the case, lead to flooding (IPCC 2019). The consequence of this change in ocean temperatures is prolonged contemporary warming simply because of the thermal inertia of these gigantic ocean masses.

1.2. Contemporary Arctic-wide climate change

Global warming is not always visible to some, but it is most easily illustrated in the Arctic, particularly with the melting of the cryosphere (see Chapter 2). Indeed, the high latitudes of the boreal regions have recorded an increase in temperature of around 2.5°C since the beginning of the 20th Century, with temperature sequences comparable to those recorded on a global scale. Globally, this temperature increase is mainly due to the last few decades. Seasonally, the winter months (November to April) recorded the greatest temperature increases (see Figure 1.5), although the warmer months also experienced higher temperatures.

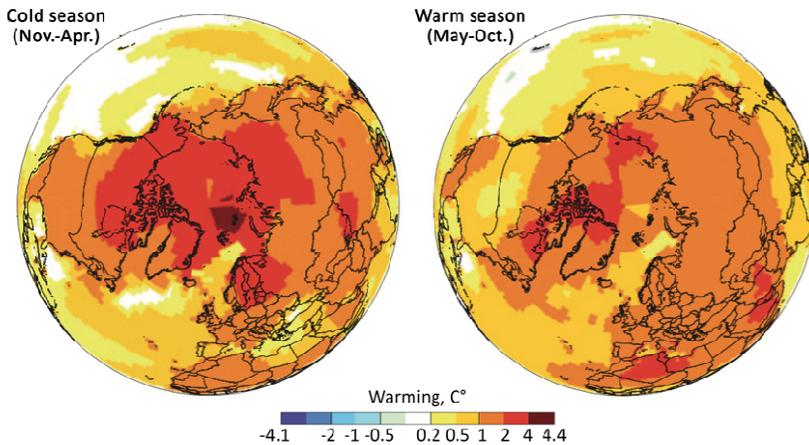


Figure 1.5. Spatial distribution of Arctic warming for the period 1961–2014 for the cold season (November to April) and the warm season (May to October) (source: AMAP 2017). For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

In the Arctic Basin, the Svalbard Archipelago is located in the area with the greatest warming. The curves in Figure 1.6, showing the evolution of temperature since the end of the 19th Century, illustrate both this climate warming on all time scales (annual and seasonal, especially winter) and the increase in annual precipitation. The average temperature in Longyearbyen, (Svalbard archipelago) has increased by 4 to 5°C since the beginning of the 20th Century. Like all the meteorological stations of this archipelago, Longyearbyen, being in a coastal position, is all the more sensitive to the spatial retraction of the winter sea ice in recent years, which explains the more significant increase in winter temperatures in recent decades in particular. Temperature trends are not linear, and cycles of different lengths and amplitudes have been obtained by statistical analyses (Fourier and wavelet, see Humlum *et al.*

2011). The similarities between the thermal evolutions at the Longyearbyen station and the North Atlantic Multidecadal Oscillations (AMO) underline the importance of the influence of ocean temperatures on that of the lower layers of the atmosphere (Humlum *et al.* 2011).

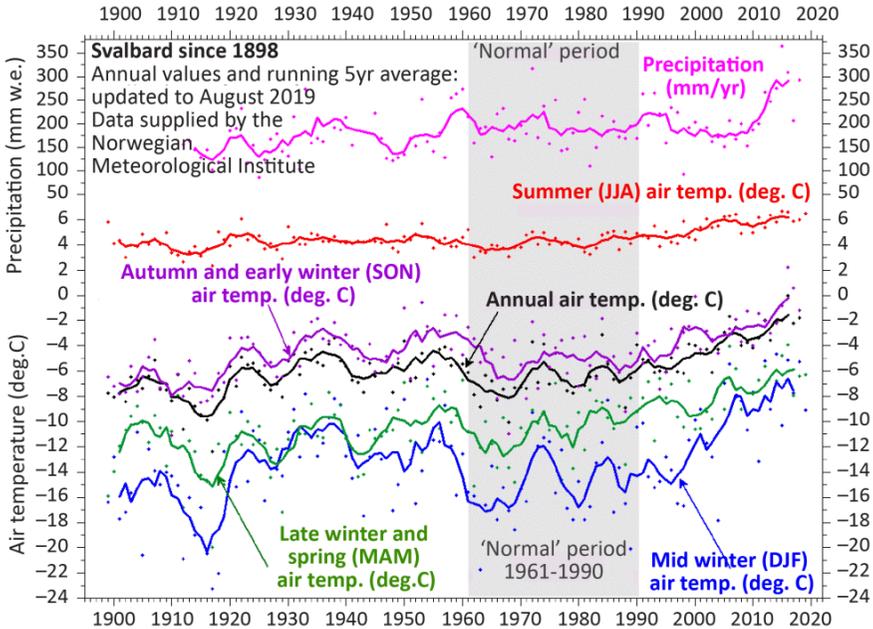


Figure 1.6. Temporal distribution of air temperature warming at Longyearbyen, 78° 25' N, 15° 47' E, capital of the Svalbard archipelago, for the period 1898–2019 at different time scales, annual in black, summer (June, July, August) in red, autumn (September, October, November) in purple, winter (December, January, February) in blue, spring (March, April, May) in green. For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

COMMENT ON FIGURE 1.6.– *The baseline average is calculated for the period 1961–1990. Change in mean annual precipitation with a five-year sliding average (in pink) (source: based on data from the Norwegian Meteorological Institute³).*

For the Ny-Ålesund station, located on the northwestern coast of the Svalbard archipelago (78° 55' N, 11° 55' E), Figure 1.7 shows an increase in mean annual temperatures of 4°C from 1969 to 2016 and the increase in predominantly rainy

3 <http://www.climate4you.com/SvalbardTemperatureSince1912.htm>.

precipitation from 356 mm per year in 1969 to 546 mm per year in 2016. The increase in temperatures largely explains the increase in precipitation due to an increase in the hygrometric capacity of the air, by the increase in the frequency of oceanic disturbances caused by the North Atlantic drift; in winter, in connection with periods when the North Atlantic Oscillation (NAO) index is positive, and in relation to the reduction of the ice pack in the Arctic basin, which allows open sea water to release heat into the lower layers of the atmosphere (see Chapter 2).

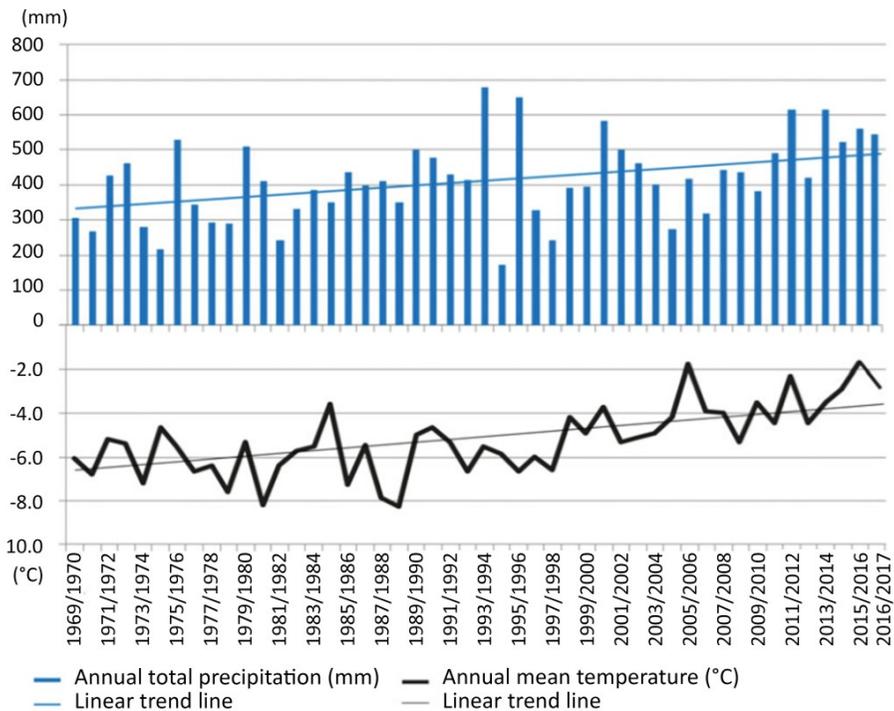


Figure 1.7. Annual mean precipitation and annual mean temperatures from 1969 to 2016 at the Ny-Ålesund weather station (northwestern Spitsbergen, Svalbard) (source: Bourriquen et al. 2018, based on data from the Norwegian Meteorological Institute). For a color version of this figure, see www.iste.co.uk/mercier/climate.zip

Thus, whatever the spatial scales used here, contemporary climate change is illustrated by an increase in temperatures and an associated increase in precipitation.

J, K, L

jökulhlaups, 39
 Köppen, 269
 La Niña, 248
 landslides, 102
 Lena, 153
 Levant, 214
 Little Ice Age (LIA), 14, 99
 Longyearben, 6
 low water, 169

M

Maghreb, 214
 Maunder, 14
 Mediterranean
 basin, 209
 climate, 210
 monsoon, 247
 morphogenic crises, 96
 mountaineering, 136
 Multi-decadal Atlantic Variability
 (MAV), 178

N

nordicity, 48
 North Atlantic, 4
 drift, 8
 Oscillation (NAO), 8
 Ny-Ålesund, 7

O, P

ocean
 Atlantic, 4
 Southern, 5
 periglacial, 120
 para-, 125

permafrost, 35, 119, 144
 phenological stages, 225
 plant formation, 270
 plasticity, 291
 Pleistocene, 21
 polar
 doctrines, 59
 regional economy, 60
 space, 46

R

radiative
 exchanges, 125
 forcing, 218
 rainy season, 246
 relative sea level, 74
 Representative Concentration
 Pathway (RCP), 219
 retrogressive thaw slump, 131
 riparian, 55, 154, 194, 197
 risk expertise, 66
 river metamorphosis, 109
 runoff, 93

S

savannah process, 257
 sea ice, 24
 sedimentary cascade, 96
 Siberia, 143
 solar radiation, 14
 Spain, 216
 specialist, 299
 storms, 83
 submersion, 76
 Svalbard, 6
 Syr Darya, 191

T

talik, 147

thermal

 expansion of the oceans, 36

 thresholds, 269

thermo-estatism/thermal expansion,
 72

thermokarst, 127

trade winds, 247

tundra/taiga, 267

U, V

urban heat island, 255

variability, 246

viticulture, 225

vulnerability, 85

W, Y

Walker, 247

water

 resources, 210

 stress, 218

Winkler, 227

Yakutsk, 143

Yedoma, 148

WILEY END USER LICENSE AGREEMENT

Go to www.wiley.com/go/eula to access Wiley's ebook EULA.

