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The North Sea region as seen from satellite on 16 April 2003. *Sensor* Terra-Modis. *Credit* Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC; Saharan dust signals have been removed

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North Sea Region Climate Change Assessment

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Foreword

Climate change is a major threat for the 21st century and beyond as recognised by the world's governments who have funded the five assessments of the Intergovernmental Panel on Climate Change (IPCC) and numerous special reports since the 1980s. These efforts have been important in supporting global climate policy, culminating in the recent Paris Agreement on reducing future greenhouse gas emissions. In contrast, adaptation happens on smaller scales than climate mitigation and very different and more detailed information is required to support such decisions. A number of regional and local assessments have been produced with these issues in mind. As examples, in North America there have been several national assessments of the implications of climate change as well as city level studies such as for New York. In Europe there have been assessments at the EU scale such as the ACACIA and CLIMSAVE projects, the Baltic Sea region, national assessments such as the Delta Commission in the Netherlands, and city assessments such as for London and Hamburg.

The international North Sea Region Climate Change Assessment (NOSCCA) contributes substantial new insight into these efforts for the greater North Sea Region, constituting the first such assessment for this region. While North Sea societies have always faced climatic risk, the challenges are growing due to human-induced climate change mainly forced by enhanced greenhouse gas emissions, and often other significant non-climate drivers are in operation. At the same time, the available knowledge of climate change and its implications has expanded impressively over the past few decades. However, there is a challenge to synthesise and communicate this information in accessible and useful forms. The present assessment rises to these challenges to provide science-based information on climate change on the scale of adaptation decision-makers.

The independent and voluntary assessment team come from across the North Sea region. The component chapters have all been subject to extensive peer review and modification to promote wide and inclusive perspectives. Collectively, the chapters address a range of issues embracing climate science, ecosystems and socio-economics providing a unique integrated perspective which can support decision-makers and policy development. The authorship and editorship team are to be commended for their supreme efforts, establishing a platform for further assessments and updates as needed. The approach is readily transferable and might be transferred to other interested regions.

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Preface

Climate change impacts show wide regional variability; their strength, nature and evolution depending on the principal features of the area in which they are occurring. To cope responsibly with its impacts, decision-makers and authorities need sound information on the specifics of climate change in their region. The science community would also benefit from a comprehensive analysis of the state-of-knowledge on regional climate change and its effects.

The North Sea region is a precious natural and cultural environment and a major economic entity within Europe. The North Sea is one of the world's richest fishing grounds as well as being one of the busiest seas with respect to marine traffic and its related infrastructure, oil and gas extraction is also of high economic value. More recently the area has become a major site for wind energy, with many large offshore wind farms. Climate change impacts are expected to have profound effects on North Sea ecosystems and economic development. Despite its importance, until now a comprehensive analysis of climate change and its impacts for the region as a whole had not been attempted. Some nationally-focused studies with an emphasis on climate change projections have been published in recent years, such as the UK Climate Projections—Marine and Coastal Projections and the KNMI'14 Climate Scenarios for The Netherlands to name but two examples,[1] and these have all been considered in the present study.

A few years ago, inspired by our colleague Hans von Storch, we initiated an international climate change assessment of the North Sea region. We adopted a similar approach to that successfully employed for reviews of knowledge on climate change in the Baltic Sea basin, published in 2008 and 2015.[2] This activity was named the North Sea Region Climate Change Assessment—NOSCCA—and has involved around 200 climate scientists in different research areas from all countries around the North Sea, as well as a few from more distant localities. NOSCCA developed into an independent international initiative, with all scientists involved contributing their time and effort on a voluntary basis as there was no extra funding available.

Present knowledge of climate change in the North Sea region has been evaluated mainly using peer-reviewed publications on climate change in the physical systems and its effects on land and marine systems. Two types of impact studies were envisaged: those concerning specific ecosystems and those related to specific human activities causing degradation of the environment.

After an introductory chapter on the North Sea region and its characteristics in terms of geography, geology, hydrography, present-day climate and ecology, Part I describes the climate change experienced over the past 200 years, described separately in each of three chapters on the atmosphere, the North Sea and river flow. Part II examines projections of

[1]Lowe, JA, Howard TP, Pardaens A, Tinker J, Holt J, Wakelin S, Milne G, Leake J, Wol J, Horsburgh K, Reeder T, Jenkins G, Ridley J, Dye S, Bradley S. (2009) UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK; KNMI (2015): KNMI'14 climate scenarios for the Netherlands; A guide for professionals in climate adaptation, KNMI, De Bilt, The Netherlands, 34 pp.

[2]The BACC Author Team (2008), Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies, Springer-Verlag, 473pp; The BACC II Author Team (2015) Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies, Springer, 501pp.

future climate with separate chapters on the atmosphere, the North Sea, and river flow and urban drainage. The impacts of recent and future climate change on marine, coastal, lake and terrestrial ecosystems are presented in Part III. The report concludes with a consideration of climate change impacts on socio-economic sectors, Part IV contains chapters on fisheries, agricultural systems, offshore activities related to the energy sector, urban climate, air quality, recreation, coastal protection and finally coastal management and governance. Important background information is presented in five annexes to the report. An overall summary containing key statements from the different chapters precedes the main body of the book.

Climate change and its impacts on ecosystems has received much attention for many years. However, assessing the impacts of climate change on natural systems is far from straightforward. Environmental impacts resulting from non-climate drivers often make it very difficult to clearly establish the specific effects of climate change, which are already hard to attribute due to the difficulties of discriminating between natural variability and human interventions and their potential interactions. As a result, for many of the topics addressed in this assessment, other drivers have also been discussed, especially those that may mask potential climate change signals. Strict detection and attribution has not been undertaken here, mainly due to the lack of relevant published work. This could be the subject of a follow-up activity.

This assessment is a joint effort of 35 Lead Authors and a large group of contributing authors, who were willing to share their knowledge on many different aspects of the North Sea region and to contribute to compiling the different chapters. The process has been overseen by an international Scientific Steering Committee; the members are listed in the section 'About NOSCCA'. A review phase involving a sovereign review editor and more than 60 external reviewers was crucial to establishing an independent and scientifically sound product. All authors worked without financial support for this book and were supported by their respective institutions. We are extremely grateful for their contributions. Authors and reviewers are acknowledged and listed by name on the following pages. The open access publication of this report was made possible by funds provided by various institutions, which are listed in the acknowledgements section.

We consider this assessment to be the most comprehensive study of climate change in the North Sea region to date. It is hoped that NOSCCA will be of use to decision-makers in the many countries surrounding the North Sea as well as to those who are responsible for planning and implementing climate change adaptation in the region. We hope this assessment will stimulate further monitoring and topical studies on climate change in this ecologically and economically important region of Europe and as a result will increase the effectiveness of decision-making at the local level.

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Acknowledgements

Book Production, Meetings, and Talks

A comprehensive and thorough assessment of climate change in the North Sea region would not be possible without the tremendous effort of many experts analysing regional climate change and its impacts and compiling dedicated topical chapters or reviewing manuscripts. Therefore, our thanks go primarily to the lead authors and contributing authors, who through excellent teamwork have produced the most comprehensive assessment of climate change in the North Sea region to date. We also thank the many reviewers, whose work has been crucial in ensuring the high scientific standard of this assessment report. Lead authors, contributing authors and disclosed reviewers are listed by name and institution on the following pages.

The entire review process was defined and overseen by an independent review editor. We are extremely grateful to Prof. Robert J. Nicholls of the University of Southampton, UK, for taking on and so competently accomplishing this important function.

The NOSCCA initiative was advised and supported, throughout the entire process, by an international Scientific Steering Committee (SSC), whose contributions are greatly appreciated. The members of the SSC are introduced in the section ‘About NOSCCA’ of this front matter.

Working efficiently with a large group of experts from many different institutes and countries in Europe profits from face-to-face exchange. Therefore several meetings of NOSCCA lead authors and members of the SSC were held during the writing and revision phases. The support—including financial—of some of our colleagues is greatly appreciated. Monika Breuch-Moritz of the Federal Maritime and Hydrographic Agency (BSH), Germany, hosted the first meeting of the SSC in close proximity to Hamburg harbour. The initial gathering of the NOSCCA lead authors together with the members of the SSC took place in the Royal Netherlands Academy of Arts and Sciences in Amsterdam. This meeting was made possible by Hein J.W. de Baar from the Royal Netherlands Institute for Sea Research and the University of Groningen, The Netherlands. The second lead author meeting took place in the Carlsberg Academy in Copenhagen, Denmark, and was arranged by Eigil Kaas of the Niels Bohr Institute, Denmark. Jaap Kwadijk from Deltares, The Netherlands, arranged the third lead author meeting at the Deltares subsidiary in Delft. The final lead author meeting took place in the Chile House in Hamburg and was hosted by Daniela Jacob from the Climate Service Centre Germany of the Helmholtz-Zentrum Geesthacht.

The various topics of the envisaged climate change assessment were introduced during our meetings by invited keynote speakers. For their inspiring talks we thank Bas Amelung (Wageningen University, The Netherlands), Peter Burkill (Plymouth University, UK), Jens Hesselbjerg Christensen (Danish Meteorological Institute), Ken Drinkwater (Institute of Marine Research, Norway), Kirstin Halsnæs (Technical University of Denmark), Daniela Jacob (Climate Service Centre Germany), Albert Klein Tank (Royal Netherlands Meteorological Institute), Jaap Kwadijk (Deltares, The Netherlands), John K. Pinnegar (Centre for Environment, Fisheries and Aquaculture Science, UK), Marcus Reckermann (Baltic Earth), Markku Rummukainen (Lund University, Sweden), Lesley Salt (Royal Netherlands Institute for Sea Research), Corinna Schrum (University of Bergen, Norway, and Helmholtz-Zentrum Geesthacht, Germany), Hendrik M. van Aken (Royal Netherlands Institute for Sea Research), and Hans von Storch (Helmholtz-Zentrum Geesthacht, Germany).

Producing such an extensive book is not possible without the technical support of particular individuals, to whom we are extremely grateful. Special thanks go to our colleague Ingeborg Nöhren; Ingeborg was deeply involved in technical editing, obtaining reproduction permissions and improving most of the many graphics. Graphical expertise was also provided by Beate Gardeike and Bianca Seth. Merja Helena Tölle, Marcus Lange, and Sabine Hartmann supported us in coordinating NOSCCA during its initial phase. Sönke Rau helped formatting the chapters. Insa Puchert conducted an actor analysis for the North Sea region. Thanks to Ina Frings for maintaining the NOSCCA homepage.

Last but by no means least, we thank Carolyn Symon (UK) for professional language editing and many useful editorial suggestions.

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Open Access

To foster a wider outreach and to enhance the availability of our climate change review to young researchers and students, it was recently decided to release the NOSCCA report as an open access publication. This was made possible by shared funding with contributions provided by the following institutions and programmes: Cluster of Excellence 'Integrated Climate System Analysis and Prediction' at the University of Hamburg (CLISAP; Germany), Danish Meteorological Institute (DMI; Denmark), German Meteorological Service (DWD; Germany), Met Office (UK), Royal Netherlands Meteorological Institute (KNMI; The Netherlands), Swedish Meteorological and Hydrological Institute (SMHI; Sweden), Technical University of Denmark (DTU; Denmark), University of Bergen (Norway), and the Library and Institute of Coastal Research of the Helmholtz-Zentrum Geesthacht (Germany). Thank you very much for the essential support at short notice.

We sincerely hope that we have not forgotten anyone. Thank you so much to all of you for your tremendous effort and support, which together has made this assessment possible.

Geesthacht, Germany

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Acronyms and Abbreviations

20CR	20th century reanalysis
AGCM	Atmospheric general circulation model
AH	Azores high
AMO	Atlantic multidecadal oscillation
AMOC	Atlantic meridional overturning circulation
AMSL	Absolute mean sea level
AO	Arctic oscillation
AOGCM	Atmosphere–Ocean general circulation model
AR4	Fourth assessment report (IPCC)
AR5	Fifth assessment report (IPCC)
A_T	Total alkalinity
AVHRR	Advanced very high resolution radiometer
Bft	Beaufort scale
CH_4	Methane
CMIP3	Coupled model intercomparison project phase 3
CMIP5	Coupled model intercomparison project phase 5
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CPR	Continuous plankton recorder
CPUE	Catch-per-unit-effort
CTD	Conductivity-temperature-depth profiler
DGVM	Dynamic global vegetation model
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DON	Dissolved organic nitrogen
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Environment Agency
EEZ	Exclusive economic zone
ENSO	El Niño Southern Oscillation
ENW	Equivalent neutral wind
EOF	Empirical orthogonal function
ESM	Earth system model
ETM	Estuarine turbidity maximum
EU	European Union
EUR	Euro
GCM	General circulation model/Global climate model
GEV	Generalised extreme value
GHG	Greenhouse gas
GIA	Glacial isostatic adjustment

GNP	Gross national product
GPS	Global positioning system
HAT	Highest astronomical tide
H_s	Significant wave height
ICES	International Council for the Exploration of the Sea
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ICZM	Integrated coastal zone management
IL	Icelandic low
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ka	Thousand years ago
LW	Longwave (radiation)
ma	Million years ago
MHT	Mean high tide
MSL	Mean sea level
MSLP	Mean sea-level pressure
N	Nitrogen
N_2O	Nitrous oxide
NAM	Northern annular mode
NAO	North atlantic oscillation
NCEP	National Centers for Environmental Prediction
netPP	Net primary production
NH_3	Ammonia
NH_4	Ammonium
NMAT	Night marine air temperature
nmVOC	Non-methane volatile organic compounds
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
NO_3	Nitrate
NO_X	Nitrogen oxides
NPP	Net primary productivity
O_3	Ozone
OA	Ocean acidification
OGCM	Ocean general circulation model
P	Phosphorus
PAH	Polycyclic aromatic hydrocarbon
PAN	Peroxyacetyl nitrate
PBL	Planetary boundary layer
PCB	Polychlorinated biphenyl
$p\text{CO}_2$	Partial pressure of carbon dioxide
PEA	Potential energy anomaly
$PM_{2.5}$	Particles of less than 2.5 µm in diameter
PM_{10}	Particles of less than 10 µm in diameter
PM_{coarse}	Particles between PM_{10} and $PM_{2.5}$ in diameter
POC	Particulate organic carbon
RCM	Regional climate model
RCP	Representative concentration pathway (IPCC)
RCSM	Regional climate system model
RMSL	Relative mean sea level
ROFI	Region of freshwater influence
S	Sulphur
SBT	Sea-bed temperature

SD	Standard deviation
SEC	Surface elevation change
SLP	Sea-level pressure
SLR	Sea-level rise
SO_2	Sulphur dioxide
SPM	Suspended particulate matter
SRES	Special Report on Emission Scenarios (IPCC)
SSB	Spawning stock biomass
SSC	Suspended sediment concentration
SSS	Sea-surface salinity
SST	Sea-surface temperature
Sv	Sverdrup, 10^6 m^3/sec
SW	Shortwave (radiation)
T	Annual wave period
TAC	Total allowable catch
TAR	Third assessment report (IPCC)
UHI	Urban heat island effect
UK	United Kingdom
USD	US dollar
VOC	Volatile organic compound
VOS	Voluntary observing ship
WETCHIMP	Wetland and Wetland CH_4 Intercomparison of Models Project
WHO	World Health Organization
WMO	World Meteorological Organization

About NOSCCA

Ongoing and future anthropogenic climate change is widely recognised as a major scientific and societal issue, with huge economic consequences. The North Sea and its adjacent land areas is one of the major economic regions of the world and a place for settlement and commerce for millions of people. Like many other areas, this region is already facing a changing climate and projections indicate that impacts will become even stronger in the coming decades.

Knowledge of climate change has increased massively over the past few decades, which enables a more strategic response to climate-related risk. For example, the Intergovernmental Panel on Climate Change (IPCC) has released a series of major climate change assessments; the first in 1990 and the latest in 2013/2014. But although reliable information on the characteristics and impacts of climate change at a regional scale is essential for scientists, responsible authorities and stakeholders in the regions, it is arguably still limited. Even the most recent IPCC assessment (AR5, published in 2013 and 2014) could not report the desired level of detail for many regions of interest—including the North Sea.

In 2010, the Institute of Coastal Research of the Helmholtz-Zentrum Geesthacht in Germany initiated a comprehensive climate change assessment for the Greater North Sea region and adjacent land areas, referred to as the 'North Sea Region Climate Change Assessment' (NOSCCA). The purpose of this assessment is to review and analyse the scientifically legitimised knowledge of climate change and its impacts across the entire region. The NOSCCA approach is similar in format to the IPCC approach and close to that of a climate change assessment compiled for the Baltic Sea Basin (BACC).[3]

The challenges for NOSCCA as a full assessment of climate change in the North Sea region were first to get access to the scattered information, second to render it comparable, and finally to prepare an assessment of climate change based on the entire body of material. This synthesis is based entirely on scientifically legitimate published work, with the emphasis on peer-reviewed journal articles or book chapters wherever possible. Conference proceedings and reports from scientific institutes and governmental agencies (such as meteorological services or oceanographic centres) have also been evaluated. Reports from bodies with a mainly non-scientific agenda were excluded. In cases where a clear consensus on a climate change issue could not be found in the literature this is clearly stated and if appropriate different views are reported or knowledge gaps highlighted.

The 'North Sea region' as envisaged in the NOSCCA context comprises the Greater North Sea, as defined by OSPAR and the land domains of the bounding countries, which are part of the catchment area and which have a coastline along the Greater North Sea. Thus the Skagerrak, Kattegat and English Channel belong to the area of interest.

From the start, NOSCCA has been an independent international initiative involving scientists from all countries in the region. NOSCCA authors are predominately from universities and public research institutes. There was no special or external funding for NOSCCA activities, all contributions were made on a voluntary basis and scientists relied on

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[3]The BACC Author Team (2008), Assessment of Climate Change for the Baltic Sea Basin. Regional Climate Studies, Springer-Verlag, 473pp; The BACC II Author Team (2015) Second Assessment of Climate Change for the Baltic Sea Basin, Regional Climate Studies, Springer, 501pp.

their institutional resources and support. Writing teams guided by Lead Authors compiled the chapters. Lead Authors have played a crucial role in the overall process as they were responsible for the respective writing teams and are responsible for the content as well as the overall quality of their chapters. All climate change chapters were subject to independent scientific review. NOSCCA cooperates with the *International Council for the Exploration of the Sea* (ICES) and is a *Land-Ocean Interactions in the Coastal Zone* (LOICZ) affiliated project, information exchange with the OSPAR Commission was agreed upon. The entire process was coordinated by a team based at the Institute of Coastal Research at the Helmholtz-Zentrum Geesthacht.

From initialisation to the final product, the NOSCCA process was overseen by an international Scientific Steering Committee (SSC), whose members were selected to represent the North Sea countries and a wide range of expertise relevant to marine and terrestrial climate change. The role of the SSC was to formulate and determine the procedure leading to the final assessment report and to outline the topics to be addressed. Another important responsibility of the SCC was to select Lead Authors for the different chapters. The SSC was also involved in initialising the external review process. The NOSCCA SSC members are Hein J.W. de Baar (Royal Netherlands Institute for Sea Research and University of Groningen, The Netherlands), Monika Breuch-Moritz (Federal Maritime and Hydrographic Agency, Hamburg, Germany), Peter Burkill (Plymouth University, UK), Franciscus Colijn (Chair; Helmholtz-Zentrum Geesthacht, Germany), Ken Drinkwater (Institute of Marine Research, Bergen, Norway), Kevin Horsburgh (National Oceanography Centre, Liverpool, UK), Eigil Kaas (Niels Bohr Institute, Copenhagen, Denmark), Albert M.G. Klein Tank (Royal Netherlands Meteorological Institute, De Bilt, The Netherlands), Hartwig Kremer (United Nations Environment Programme, Copenhagen, Denmark), Georges Pichot (Management Unit of the North Sea Mathematical Models, Brussels, Belgium), Markus Quante (Helmholtz-Zentrum Geesthacht, Germany), Hans von Storch (Helmholtz-Zentrum Geesthacht, Germany), Göran Wallin (University of Gothenburg, Sweden) and Karen Helen Wiltshire (Alfred Wegener Institute, Bremerhaven, Germany).

To ensure an independent review process an external review editor was assigned, who is not involved in any other NOSCCA activity. The renowned climate change scientist Professor Robert J. Nicholls from the University of Southampton, Engineering and the Environment, UK, kindly agreed to take on this task. The review editor defined the overall review process and together with the SSC Chair, selected and invited the individual reviewers. The review process was overseen and undertaken with the assistance of the NOSCCA coordination team. Three independent reviewers, preferably from different countries were assigned to each climate change chapter. Only the introductory chapter and the annexes were reviewed by expert colleagues or authors of other chapters. The review editor had the final say in the case of conflicting opinions.

The NOSCCA process began in October 2010, when the SSC was formed during a meeting in Hamburg hosted by the Federal Maritime and Hydrographic Agency (BSH). The first meeting of Lead Authors together with the members of the SSC took place at the Royal Netherlands Academy of Arts and Sciences in Amsterdam in October 2011. The second Lead Author meeting took place at the Carlsberg Academy in Copenhagen in October 2012, where the Lead Authors agreed on the layout of the various chapters. The third Lead Author meeting was held in June 2013 at Deltares in Delft. The NOSCCA review phase began in spring 2014, and the external review was complete by the end of spring 2015. A final Lead Author meeting was held in June 2015 at the Climate Service Centre Germany in Hamburg. Key findings of all chapters were exchanged and discussed. All revised chapters were available by the end of 2015. All chapters were then subject to language editing before the final material was sent to the publisher in spring 2016. The final text was published as a print and open access book in summer 2016.

The NOSCCA initiative and process has been introduced at various meetings, symposia and conferences. Together with the Baltic Earth consortium a joint BACC-NOSCCA session *Climate change and its impacts in the Baltic and North Sea regions: Observations and model* *projections* was conducted during the European Geosciences Union General Assembly in 2015 and in 2016, where the first results were presented to the scientific public.

The assessment report comprises 19 chapters each allocated to one of four topical parts. Five annexes complement the climate change chapters with background knowledge. The assessment comprises past (the last 200 years) and current climate change, and climate change projections to the end of the century for the North Sea, the atmosphere and river flows; impacts of climate change on marine, coastal, and terrestrial ecosystems; and on socio-economic sectors, such as fisheries, agricultural systems, recreation, offshore activities, urban climate, air quality, coastal protection and coastal zone management. Long-term climate change was not an extensive theme of the present report; a few aspects are covered in the section *Geological and Climatic Evolution of the North Sea Basin* of the introductory chapter. Also *detection and attribution* and *adaptation measures* were not dealt with in depth in this first assessment but may be topics of follow-up activities. Concerning terminology, it should be noted that NOSCCA essentially follows the IPCC definition of the term "Climate change", and "anthropogenic" is explicitly added to that term when human causes are attributable. "Climate variability" is used, when referring to variations unrelated to anthropogenic influences.

The annexes cover the North Atlantic Oscillation (NAO), climate model simulations for the North Sea region, uncertainties in climate change projections, and emission scenarios for climate projections. The final annex provides facts about the Greater North Sea Region and geographical maps.

The NOSCCA report is written for a broad target readership ranging from scientists of different disciplines to authorities, agencies, decision makers and stakeholders acting in the North Sea region. It also aims to assist in the development of robust regional and local adaptation strategies.

Markus Quante

Overall Summary

The entire North Sea region is experiencing a changing climate and all available projections suggest the region will exhibit a wide range of climate change impacts over the coming decades. Among the robust results of this assessment are that the entire region is warming, and that the warming is almost certain to continue throughout this century; also that sea level is rising and will continue to rise at a rate close to the global average. Substantial natural variability in the North Sea region (from annual to multi-decadal time scales) makes it challenging to isolate regional climate change signals and impacts for some parameters. This is the case both for the observational period and for regional climate change projections and impact studies.

Projecting regional climate change and impacts for the North Sea region is currently limited by the small number of regional coupled model runs available and the lack of consistent downscaling approaches, both for marine and terrestrial impacts. The wide spread in results from multi-model ensembles indicates the present uncertainty in the amplitude and spatial pattern of the projected changes in sea level, temperature, salinity and primary production. For moderate climate change, anthropogenic drivers such as changes in land use, agricultural practice, river flow management or pollutant emissions are often more important for impacts on ecosystems than climate change.

The NOSCCA key findings that follow are provided as short statements. Quantifying the effects, changes or impacts has largely been avoided as this would require additional annotations or geographical specification. The aim here is to provide a concise summary of the major outcome of NOSCCA.

Recent Climate Change (Past 200 years)

Atmosphere

Temperature has increased everywhere in the North Sea region, especially in spring and in the north. Due to the lower heat capacity of land, land temperatures rise much faster than sea temperatures. The imbalance between the two is now nearly half a degree. Linear trends in the annual mean land temperature anomalies are about 0.17 °C per decade (for the period 1950–2010) and about 0.39 °C per decade (for the period 1980–2010). Generally, more warm and fewer cold extremes are observed.

There are indications that the persistence (duration) of circulation types has increased, with the consequence that ‘atmospheric blocking’ has become more frequent, thus contributing to the observation that extremes have become ‘more extreme’. It is unclear how this is related to the decline in Arctic sea ice.

An observed north-eastward shift in storm tracks agrees with projections from climate models forced by increased greenhouse gas concentrations. This is a new phenomenon that has not been observed before.

While the number of deep cyclones (but not the number of all cyclones) has increased, whether storminess as a whole has increased cannot be determined: although reanalyses show an increase in storminess over time, observations do not. Variability from decade to decade is large, and clear trends cannot be identified. Furthermore, reanalyses can suffer from homogeneity issues and observations from errors made during digitization, emphasising the need for a manual quality check for the latter.

Overall, precipitation has increased in the northern North Sea region and decreased in the south, summers have become warmer and drier and winters have become wetter. Heavy precipitation events have become more extreme.

North Sea

There is strong evidence of surface warming in the North Sea especially since the 1980s. Warming is greatest in the south-east, exceeding 1 °C since the end of the 19th century.

Absolute mean sea level in the North Sea rose by about 1.6 mm/year over the past 100–120 years, comparable with the global rise. Extreme levels rose primarily because of this rise in mean sea level.

The North Sea is a sink for atmospheric carbon dioxide (CO_2); uptake declined over the last decade owing to lower pH and higher temperatures.

Short-term variations in all variables (including sea-surface temperature and sea level) exceed climate-related changes over the past two centuries. This is especially true for salinity, currents (varying with tides, winds, and seasonal density), waves, storm surges and suspended particulate matter (varying with currents, river inputs and seasonal stratification).

Coastal erosion is extensive but irregular and some coastlines are accreting. Evidence for a link to climate change has not yet been established.

River Flow

Rivers draining into the North Sea show considerable interannual and decadal variability in annual discharge. In northern areas this is closely associated with variation in the North Atlantic Oscillation, particularly in winter.

Discharge to the North Sea in winter appears to be increasing, but there is little evidence of a widespread trend in summer inflow. Higher winter temperatures appear to have led to higher winter flows, as winter precipitation increasingly falls as rain rather than snow.

To date, no significant trends in response to climate change are apparent for most of the individual rivers discharging into the North Sea.

Future Climate Change

Atmosphere

A marked mean warming of 1.7–3.2 °C is projected for the end of the 21st century (2071–2100, with respect to 1971–2000) for different scenarios (RCP4.5 and RCP8.5, respectively), with stronger warming in winter than in summer and relatively strong warming over southern Norway. The overall warming is accompanied by intensified extremes related to daily maximum temperature and reduced extremes related to daily minimum temperature, both in terms of strength and frequency.

Simulations project marked future changes in some aspects of the large-scale circulation over the Atlantic-European region, of which the North Sea region is part.

Changes in the storm track with increased cyclone density over western Europe in winter and reduced cyclone density on the southern flank of the storm track over western Europe in summer are projected to occur towards the end of the 21st century.

A general tendency for more frequent strong westerly winds and for less frequent easterly winds in the central North Sea as well as in the German Bight in the course of the 21st century was projected using SRES A1B and SRES B1 scenarios.

Projections suggest an increase in mean precipitation during the cold season and a reduction during the warm season for the period 2071–2100 relative to 1971–2000, as well as a pronounced increase in the intensity of heavy daily precipitation events, particularly in winter and a considerable increase in the intensity of extreme hourly precipitation in summer.

North Sea

Consistent results are found for projections regarding a warming of the surface water to the end of the century (about 1–3 °C; A1B scenario). Exact numbers are not given due to differences in spatial averaging and reference periods from published studies.

Coherent findings from published climate change impact studies include an overall rise in sea level, an increase in ocean acidification and a decrease in primary production.

Larger uncertainties exist for projected changes in salinity, mostly a freshening was reported, but contrasting signals were also projected. Uncertainties for projected changes in extreme sea level and waves are large.

Model studies reveal large uncertainties in future changes in net primary production with decreases ranging from 1 to 36 % (and not statistically significant across all parts of the North Sea region).

Substantial natural variability in the North Sea region from annual to multi-decadal time scales is a particular challenge for isolating and projecting regional climate change impacts. Separating natural variations and regional climate change impacts is a remaining task for the North Sea.

River Flows and Urban Drainage

Increased hydrological risks due to more intense hydrological extremes in the North Sea region such as flooding along rivers, droughts and water scarcity, are projected by climate models and are of socio-economic importance for the region. Risk is particularly enhanced in winter due to increases in the volume and intensity of precipitation.

Models project that peak flow in many rivers may be up to 30 % higher by 2100, and in some rivers even higher.

The impacts projected lead both to opportunities and challenges in water management, agricultural practices, biodiversity and aquatic ecosystems.

The exposure and vulnerability of cities in the North Sea region to changes in extreme hydrometeorological and hydrological conditions are expected to increase due to greater urban land take, rising urban population growth, a concentration of population in cities and an aging population. Business-as-usual approaches are no longer feasible for these cities.

Impacts of Recent and Future Climate Change on Ecosystems

Marine Ecosystems

The marine ecosystem of the North Sea is highly productive, intensively exploited and well-studied. The changing North Sea environment is affecting biological processes and organisation at all scales, including the physiology, reproduction, growth, survival, behaviour and transport of individuals. The distribution, dynamics and evolution of populations and trophic structure are also affected.

Long-term knowledge and exploitation of the North Sea indicates that climate affects marine biota in complex ways. Climate change influences the distribution of all taxa, but other factors (fishing, biological interactions) are also important.

The distribution and abundance of many species have changed. Warmer water species have become more abundant and species richness (biodiversity) has increased. This will have consequences for sustainable levels of harvesting and other ecosystem services in the future.

Coastal Ecosystems

Accelerated sea-level rise, changes in the wave climate and storms may result in a narrowing of dunes and salt marshes where they cannot spread inland, particularly in the case of a narrow and steep foreshore. The relative importance of accelerated sea-level rise, changes in the wave climate, storms, and local sediment availability and their interactions are poorly understood. Human impacts on geomorphology and sediment transport interact with the potential impacts of climate change.

Estuaries and most mainland marshes will survive sea-level rise. Back-barrier salt marshes with lower suspended sediment concentrations and tidal ranges may be more vulnerable. Depressions away from salt-marsh edges and creeks on back-barrier marshes may be at particular risk.

Plant and animal communities can suffer habitat loss in dunes and salt marshes through high wave energy. Natural succession, and management practices such as grazing and mowing have a strong impact. Minor storm floodings in spring negatively affect breeding birds. Invasive species may change competitive interactions.

Plant and animal communities are affected by changes in temperature and precipitation and by atmospheric deposition of nitrogen. Their interactions result in faster growth of competitive species. Increased plant production may cause losses of slow-growing and low-statured plant species.

Lake Ecosystems

The North Sea region contains a vast number of lakes. These freshwaters and the biota they contain are highly vulnerable to climate change.

Lakes in the North Sea region have experienced a range of physical, chemical and biological changes due to climatic drivers over past decades. Lake temperatures have increased, ice-cover duration has decreased and major changes have occurred in the fluxes of dissolved organic matter and key elements such as nitrogen, phosphorus, silicate, iron and calcium.

Together, all physical and chemical changes have had a profound impact on the biota from algae to fish and biodiversity, and these impacts are predicted to proceed and intensify in the future.

Terrestrial Ecosystems

There is strong empirical evidence of changes in phenology in many plant and animal taxa and northward range expansions of mobile thermophilous animals.

There is limited empirical evidence of climate-induced changes in vegetation patterns and ecosystem processes (carbon cycling) in terrestrial ecosystems. Predictions concerning vegetation patterns and ecosystem processes are almost exclusively based on modelling approaches.

Climate change projections and impact studies suggest a northward shift in vegetation zones, enhanced carbon release from soils, and increased export of dissolved organic carbon to aquatic ecosystems.

Future climate change is likely to increase net primary production in the North Sea region due to warmer conditions and longer growing seasons, as long as future climate change is moderate and summer precipitation does not decrease as strongly as projected in some of the more extreme climate scenarios. The physiological effects of increasing atmospheric CO_2 levels and increasing N-mineralisation in the soil may also play a significant role, but to an as yet uncertain extent.

Climate Change Impacts on Socio-economic Sectors

Fisheries

North Sea fisheries may be impacted by climate change in various ways. Consequences of rapid temperature rise are already being felt in terms of shifts in species distribution and variability in stock recruitment.

Although an expanding body of research exists on this topic, there are still many knowledge gaps, especially with regard to understanding how fishing fleets themselves might be impacted by underlying biological changes and what this might mean for regional economies.

It is clear that fish communities and the fisheries that target them will almost certainly be very different in 50 or 100 years from now and that management and governance will need to adapt accordingly.

Agricultural Systems

Climate change impacts on agricultural production will vary across the North Sea region, both in terms of crops grown and yields obtained. Increased productivity and wider scope of crops is expected for northern areas. Larger risks of summer drought and associated effects will be a challenge in southern parts. In general, more extreme weather events may severely disrupt crop production.

Given adequate water and nutrient supply, a doubling of atmospheric CO_2 concentration could lead to yield increases of 20–40 % for most crops grown in the North Sea region.

Increased risks of nutrient (nitrogen and phosphorus) loadings from agricultural land to aquatic systems are likely with projected climate change.

The challenge in the North Sea region will be to ensure sustainable growth in agricultural production without negatively affecting the environment and natural resources.

Offshore Activities/Energy

There is no doubt that energy systems and offshore activities in the North Sea region will be impacted by climate change.

While most studies suggest an increase in hydropower potential, climate projections are highly uncertain regarding how much the future potential of other renewable energy sources such as wind, solar, terrestrial biomass, or emerging technologies like wave, tidal or marine biomass could be affected, positively or negatively.

Both offshore and onshore activities in the North Sea region (of which offshore wind, oil and gas dominate) are highly vulnerable to extreme weather events, in terms of extreme wave heights, storms and storm surges.

Urban Climate

About 80 % of the population within the North Sea countries lives in an urban area and this percentage is projected to rise. Some larger metropolitan areas in the region are generally located in low altitude areas. This is especially true for the urban areas of the Netherlands (Amsterdam, Rotterdam, The Hague and Utrecht), as well as for Antwerp, London and Hamburg.

There are indications that climate change in the North Sea region, potentially affecting urban climate and thus the health and welfare of city dwellers, is now apparent and includes drier and warmer summers, more intense precipitation, sea-level rise and hinterland flooding.

Cities must adapt to climate change. Despite broad similarities between urban areas, in terms of mitigation and adaptation to climate change there are large location-specific differences with regard to city planning needs. As cities themselves strongly contribute to greenhouse gas emissions, there is an opportunity for them to change both simultaneously: adapting to and mitigating climate change.

Air Quality

In the North Sea region, poor air quality has serious implications for human health and the related societal costs are considerable.

The effects on air quality of emission changes since preindustrial times are stronger than the effects of climate change. Model simulations suggest this is also the case for future air quality in the region, but substantial variation between model results implies considerable uncertainty.

If the reductions in air pollutant emissions expected through increasingly stringent policy measures are not achieved, any increase in the severity or frequency of heat waves may have severe consequences for air quality.

Recreation

Sea-level rise, coastal erosion and storms can destroy coastal infrastructure and alter coastal landscapes. Rebuild costs and a decline in tourism revenue can have significant economic impacts. Nevertheless, tourism in the North Sea area is expected to profit from rising temperatures, lower summer precipitation and a longer season. Destination attractiveness is largely determined by thermal environmental assets. However, landscape changes, natural and man-made, such as reduced beach width and higher sea walls, may decrease destination appeal.

Tourists are unlikely to change travel behaviour. Coping with climate change and its effects will require changes in government policy and innovative approaches from tourism suppliers. Investment cycles should be made on a long-term basis.

Coastal Protection

All countries around the North Sea with coastal areas vulnerable to flooding due to storm surges are ready to take up the challenges expected to occur as a consequence of climate change. Scenarios of accelerating sea-level rise leading to sea levels by 2100 of up to 1 m or more above present day, in some countries accompanied by increased storm surge set-up and wave energy, have been used as a basis for evaluation and planning of the adaptation of coastal protection strategies and schemes.

Coastal protection strategies differ widely from country to country, not only in terms of distinct geographical boundary conditions but also in terms of the length of planning periods, the amount of regulations and budgeting.

All countries, except Denmark and the UK, which allow coastal retreat at some stretches of their coasts, aim at keeping the current protection line in place to protect the hinterland. Combatting coastal erosion by nourishments is currently the most effective solution used for sandy coastlines and will continue to be a major tool for balancing climate change impacts in these environments.

Coastal Management and Governance

Broadly shared assessments of the urgency of adaptation are hampered by the difficulty of identifying the climate-driven component of observed change in the coastal zone. Due to uncertainty about the extent and timing of climate-driven impacts, current adaptation plans focus on no-regret measures.

The most considered no-regret measures in the North Sea countries are spatial planning in the coastal zone (set-back lines), coastal nourishment, reinforcement of existing protection structures and wetland restoration including managed realignment schemes.

In Germany, the Netherlands and Belgium coastal adaptation is steered by national and regional programmes and plans. The UK and the Scandinavian countries pursue active public involvement by transferring adaptation responsibilities to private stakeholders and partnerships.

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