In the cascade, internal variability is represented by the range between different realizations from the same climate model (Fig. 4) and for the 2046–2065 period this range is 0.5 million km^2 on average across models and scenarios (0.6 million km^2 across the full CMIP5 ensemble; also see Supplementary Information). Internal variability on even shorter timescales, shown in the cascade by the range of pentads of a single realization, is 1.4 million km^2 on average, and reaches up to 4.6 million km^2. Variability in 5-year means is largest when the sea-ice extent reaches near ice-free levels. This pattern is most clearly shown using the CESM1 LE, in which variability increases as the sea-ice retreats, before dropping to close to zero when ice-free conditions are reached (Supplementary Fig. 6).

For the 20 year mean sea-ice extents over 2046–2065, model uncertainty is the dominant term (CMIP5 range of 9.4 million km^2), followed by scenario uncertainty (1.3 million km^2) and then internal variability (0.6 million km^2). It is worth noting that for the sea-ice extent trends considered in the previous sections, inter-realization spreads were not much smaller than the inter-model spread, even for multi-decadal trends (see Supplementary Information). For the multi-decadal means of sea-ice extent considered here, inter-realization spread is however much smaller than inter-model spread. Nonetheless, within any single model, internal climate variability can play a significant role in determining sea-ice extent on decadal timescales, and it plays an even more important role on shorter timescales.

Conclusions

When accounting for internal climate variability, observed and simulated September Arctic sea-ice extent trends over 1979–2013 are not inconsistent. Internal variability can also either mask or enhance human-induced changes for decades at a time. Thus, pauses in sea-ice loss, such as seen over the past eight years, are not surprising and are fully expected to occur from time to time. Additional single model large ensembles that capture this variability would be valuable for advancing our understanding. Further evaluating the physical processes responsible for decadal variability in sea-ice extent in both observations and simulations will also improve our ability to understand how sea-ice is likely to evolve in the next few years and decades. ❐

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COMMENTARY:

Connecting the Seas of Norden

Øyvind Paasche, Henrik Österblom, Stefan Neuenfeldt, Erik Bonsdorff, Keith Brander, Daniel J. Conley, Joël M. Durant, Anne M. Eikeset, Anders Goksøyr, Steingrímur Jónsson, Olav S. Kjesbu, Anna Kuparinen and Nils Chr. Stenseth

The Nordic Seas are highly sensitive to environmental change and have been extensively monitored and studied across a broad range of marine disciplines. For these reasons, the Nordic seas may serve as a pilot area for integrated policy development in response to ongoing climate change.

The northern high-latitude seas and their coastal waters are among the most sensitive to climate change on Earth. Salinity, temperature and oxygen gradients will become steeper, wind patterns will shift, and the rapid increase in atmospheric CO_2 will continue to acidify the ocean. The critical question — not only for scientists across all disciplines, but also for policymakers and society in general — is how the combination of all these stressors will impact the interdependent ecosystems as well as the social systems within this region.

These seas of Norden[1] are defined here as the Norwegian, Barents, Greenland and Iceland seas, as well as the Baltic and the North seas together with the ocean areas connecting them. Recognizing that they are interconnected, not only with each other, but also with human well-being and health, is a critical step in creating a chart to navigate science and policy towards a common goal of sustainability. Collaboration across scientific disciplines, between science,

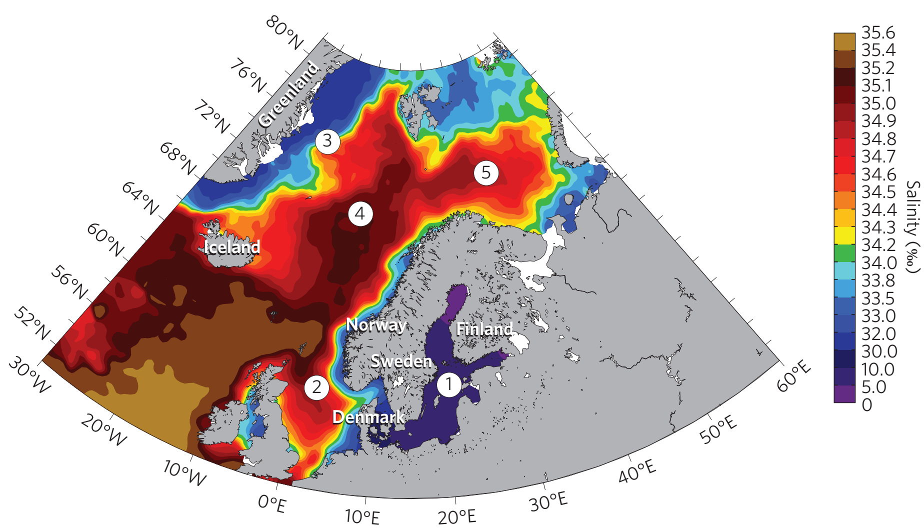

Figure 1 | The seas of Norden represent widely different water masses that are now undergoing far-reaching changes. Large salinity gradients can be observed both in an east–west and north–south direction. The seas of Norden are currently becoming fresher due to changes in inflow from the Atlantic Ocean[13], but also due to increased run-off, especially in the Arctic Ocean. Many predictions suggest a continued freshening and warming of surface waters in this region, which are changing the physical preconditions for key ecosystems. Note that the Baltic Sea has water masses with salinity that goes down below 5‰. 1, Baltic Sea; 2, North Sea; 3, Greenland Sea; 4, Norwegian Sea; 5, Barents Sea. Salinity data comes from the Norwegian Iceland Seas Experiment (NISE)[14] and the International Council for the Exploration of the Seas (ICES)[15]. See ref. 13 for an in-depth explanation of salinity changes. Figure courtesy of Kjetil Våge, University of Bergen.

policy, commerce and civil society and across international borders is a prerequisite for developing such a chart. It requires willingness on the part of the scientific community and others to shake off inherent conservatism and embrace new and broader perspectives.

Global sustainability challenge

The global community is facing unprecedented challenges related to climate change, food security and political conflicts. A fundamental component of human well-being is sustainable and resilient ecosystems[2] that are able to adapt to the challenges posed by increasing temperatures and provide food for a growing population with increasingly protein rich diets. Despite the growing awareness that the global community needs to address the pertinent challenge of managing international commons[3], multidisciplinary teams of scientists are only now beginning to unravel the social and ecological factors that will determine successful outcomes of common resource management at the local level[4]. The global sustainability challenge requires an understanding of complex and interacting social–ecological dynamics at larger and combined spatial and temporal scales. We argue that the seas of Norden are one of the few regions on Earth that carries the potential to successfully exemplify such a case.

Pilot region

There a number of reasons why the seas of Norden are good place to learn how to navigate towards large-scale cooperative sustainability**.** The region is diverse**,** ranging from oceanic to coastal and with the largest semi-enclosed sea in the world. Its academic, social and political infrastructures are strong, mature, and well connected. The study of the physical, biological, economic and social processes that characterize the region are equally well developed.

Better long-term data are available for the Nordic seas than for any other ocean region. These seas have experienced more rapid climate changes than any other ocean over the past century, and the predictability of future regional climate is probably higher than for other oceans. The area is also key for the global thermohaline circulation and CO_2 drawdown.

Holistic approaches

The demand for multi- and trans-disciplinary science is strong, as is the need for closing the science–policy gap[5]. Clear political statements[6] underline the importance of managing Norden with a holistic ecosystem approach, but what are the required characteristics for successful management? Integrated and adaptive management strategy requires multidisciplinary science as crucial support, yet progress in this field is limited, due to several factors, including limitations in biophysical models, nonlinear dynamics of ecosystems and their food webs, and realistic models of social behaviour[7].

Interconnected water masses

The seas of Norden, as they were named by the Norwegian oceanographer Johan Blindheim in the 1980s[1], include some of the ecologically richest, most diverse and best understood water masses on the planet (Fig. 1). Ideas and management strategies tested in this area can provide guidance that extends far beyond the region itself. The first wave of pioneering scientists conducted transect and point station measurements, which is why we now have some of the longest timeseries in the world[8]. This wealth of data, collected through periods of marked environmental and ecological fluctuations, provides us with a rare advantage when it comes to exploring the long-term effects of climate change and the influence of humans on the ocean.

The seas of Norden form a continuum where nutrients, plankton, pollutants and terrestrial sediments get entrained, mixed and transported by wind and buoyancy-driven ocean currents and modified by river and glacial freshwater runoff, before eventually being deposited along undulating seabeds, in trenches and offshore. The coasts, which are bordered by these waters, are home to millions of inhabitants that benefit daily from the ecosystem goods and services they represent, and the existence of which we tend to take for granted — be it fisheries, energy, transport or sandy belts for recreation.

From pristine to polluted

As with other water masses on the planet, those forming the seas of Norden were once considered pristine, with a barely detectable human imprint. This has changed rapidly as the list of stressors has increased and the level of impact has intensified. The stressors are many and the list is ever growing, while few (if any) are eliminated, which complicates management plans. Nevertheless, there are also some successes in curbing impacts of fishing, dredging, marine litter, nutrient run-off and pollution and these can and should be built on.

This aggregated effect of human impact on the oceans is challenging the science community across disciplines. Increased pressure compels cross-disciplinary solutions that seek to approach the present day seas of Norden not as a puzzle with individual compartments, but rather as a 'meta-ecosystem', defined by its connectivity and physical, ecological, anthropogenic and social attributes.

As an example, atmospheric circulation patterns over the North Sea, Skagerak and Kattegat have a direct impact on the structure and function of the Baltic Sea through its regulating role on saltwater inflow and thereby on harmful deep water hypoxia. Seabirds breeding in the Baltic and Barents seas conduct seasonal migrations and interact in the North Sea. Norwegian spring spawning herring *Clupea harengus* larvae drift along coastal regions of the eastern Norwegian Sea before serving as important food for top predators in the Barents Sea. The adult part of this stock also makes feeding migrations into Faroese and Icelandic waters during spring and sometimes has overwintered in the area. The seas of Norden are not only connected through biophysical and biological interactions, but also through scientific networks and political dynamics, affecting the regional inhabitants, and people across much of the Northern Hemisphere.

Prospects and pitfalls

The scientific community in the Nordic countries is strong, with seven universities in the Shanghai Ranking of the world's top-100 universities in a population of 25 million people. Several world-leading marine institutes are located within the same region, strengthening the prospects of mutually undertaking ground-breaking research. A long common history of exploring, sampling, mapping, monitoring and modelling individual seas of Norden has generated a substantial source of knowledge. Even so, this profusion of data has yet to be fully connected and communicated across national borders, across and between scientific disciplines, and between science, policy and practitioners, such as fishermen. The abundance of data covering the seas of Norden thus opens several potential avenues for research, but because they transcend national marine science priorities they also require fresh thinking and transnational funds.

We posit that the scientific community and the underlying funding structures have to be considerably more open to broad, multidisciplinary approaches at a far more advanced and dedicated level than it has been so far. The conservatism of science has its advantages, but it comes with a price. High transaction costs are associated with multidisciplinary collaboration, which takes a long time to establish and nurture. Academic structures and university faculties rarely encourage collaboration across scientific disciplines. Disciplinary language barriers, a lack of trust and interest, and different ways of formulating scientifically relevant questions all work against the type of multidisciplinary cooperation that the seas of Norden and other regions and systems require for an in-depth understanding of social–ecological dynamics[9]. However, if the politically stable, wealthy and relatively homogenous countries bordering the seas of Norden, with their scientific and financial capacities, are not able to address the sustainability challenge in their own back yard, how could the global scientific community be expected to do so elsewhere, where resources, capacity, and existing infrastructure may be much more limited?

The aptitude of the international community to effectively address shared global environmental challenges has proven limited. We hold that scientists and governments in the Nordic countries are in a unique position to showcase a new and innovative way to address the global challenges of sustaining the resilience of marine ecosystems, their resources and associated societies. The seas of Norden can constitute a global test-bed for innovative approaches, where science across disciplines, policy and governance are closely linked, and where binding management actions are closely monitored and enforced. The European Marine Strategy Framework Directive[6] provides a possible platform for this approach, but we believe that the Nordic countries share a common interest and responsibility to take the lead, which will serve as inspiration for other regions and seas.

The highly successful Oceans and Human Health initiative[10] launched by the National Institute of Environmental Health Sciences and National Science Foundation in the USA a decade ago has paved the way for truly cross-disciplinary approaches. It is based on a concept that specifically targets the intricate links between the marine environment, human health and well-being. The program has revealed how marine and coastal ecosystems benefit public health, by reducing the burden of human disease linked to marine environmental causes, and by building a capacity to anticipate new threats to public health before they unfold[10]. As of now, Europe and the Nordic countries in particular lack a corresponding mechanism[11].

Now is the time to move from global attempts to study the Earth system from disconnected natural and social science perspectives[12] to focus on integrated social–ecological science at the regional level. It is time to move away from an emphasis on problems as identified by narrow sector-specific scientists, and increasingly work across disciplinary boundaries to understand possible ways to address challenges. Science initiatives oriented towards sustainability are gaining traction in the international community, and the recent launch of the Future Earth initiative[12] is likely to generate substantial incentives for such collaboration, as well as interest from policymakers and practitioners. We argue that the scientific community working within the seas of Norden is willing and able to take on this challenge.

Opportunity

Our combined knowledge of long-term social, ecological and physical dynamics in and around the seas of Norden represents a unique opportunity for combining quantitative and qualitative analysis, across ecological and physical-biogeochemical gradients, between seas, and across periods of both rapid and long-term change. Scientists from the Baltic, Kattegat, Skagerrak, and the North seas, the Norwegian, Iceland, Greenland, and the Barents seas, have different and complementary insights and experiences to how we should understand the transformation of this vast region. We foresee that in order to progress we need to shake off any unnecessary conservatism, develop and foster transnational collaboration that not only tracks and describes change — which is necessary in its own right — but also provides an analytical framework for interpreting those changes. Such an effort would deliver an indispensable case study for the many changing systems on Earth. It would provide new insight accessible to society at large, which is imperative if we are to manoeuvre near-future possibilities and pitfalls. ❐

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Correction

In the Commentary 'Characterizing loss and damage from climate change' (*Nature Clim. Change* **4,** 938–939; 2014) it is incorrectly implied that the UNFCCC has an official definition for loss and damage. Whilst the definition is correctly quoted from a UNFCCC literature review, this was a working definition for the purpose of that review. There has been no formal discussion under the UNFCCC on what the term 'loss and damage' signifies. This correction notice has been published after print 7 January 2015.

Correction

In the Commentary 'Institutional coordination of global ocean observations' (*Nature Clim. Change* **5,** 4–6; 2015) ref. 18 was omitted from the reference list. This has been corrected after print 7 January 2015.