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Towards a holistic climate service: Addressing all four climate risk determinants

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HIGHLIGHTS

- We provide a climate service that provides information about how future climate will affect future society.
- We provide a service considering all four risk determinants used by IPCC: hazard, exposure, vulnerability, and response.
- Developing response indicators is challenging because of limited data on adaptation efforts.
- Climate risk varies spatially. The service identifies the most impacted places that also have the lowest response levels.
- Climate risk varies temporally. The service demonstrates climate change impacts for the near and far futures.

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ABSTRACT

This article presents a newly developed climate service designed to monitor climate risk in Norwegian municipalities using a variety of indicators. The service is accessible through a publicly available multimedia platform. With the expected increase in extreme weather events, many climate services have emerged focusing solely on future climate conditions, thus addressing only the hazard component of climate risk. As a result, most current local climate services evaluate how future climate will impact today's society. The Intergovernmental Panel on Climate Change (IPCC), however, recently developed a risk framework consisting of four determinants: hazard, exposure, vulnerability, and response. Following this framework, our climate service incorporates all four risk determinants. It presents geographically and temporally varying indicators expressing current, near-future, and far-future projections or scenarios on hazard, exposure, and vulnerability, and maps these against current response levels. This approach enables us to identify which municipalities in Norway are most at risk and currently have the least adequate responses.

Practical implications
chapter

The adverse impacts of climate change are expected to escalate the frequency and severity of extreme weather events. Consequently, there is a growing demand for climate services that project future climate scenarios. This information is crucial for local governments that need to prepare for the challenges a changing climate may pose. However, traditional climate services primarily focus on the hazard dimension of climate risk, essentially informing how future climate will affect today's society. We argue that it is important for climate services to provide information not only about how the climate may change in the future, but also how society may change regarding vulnerability and exposure, and how these processes together may affect municipalities if their current adaptation responses to climate change remain unchanged.

This article describes a new and innovative Norwegian climate service we have produced as a delivery from the Norwegian Center for Sustainable Climate Change Adaptation (NORADAPT). The first version of the climate service was launched in August 2023, and an improved second version one year later (Rød et al. 2024a). This climate service will be updated annually, incorporating the latest improvements and innovations, providing information on how the climate as well as society may change in the future.

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Additionally, updated information about current responses to climate change adaptation is included, covering all 357 Norwegian municipalities.

Our climate service follows the IPCC's framework where climate risk is described by four risk determinants: hazards, exposure, vulnerability, and response. IPCC (2022, p. 5) defines the first three of these as follows:

(1) Hazard is the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources.
(2) Exposure is the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.
(3) Vulnerability is the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

The use of risk in the context of response to climate change is new and was applied for the first time by the IPCC in the 6th main report (IPCC, 2022). Although the IPCC has not formally defined 'response', it relates to both mitigation and adaptation (Reisinger et al., 2020). Risk related to response includes adaptation options being less effective than anticipated or creating conflicts with other societal objectives, including the Sustainable Development Goals (IPCC, 2022). The inclusion of response as a risk determinant signifies that if the responses from institutions, communities, and individuals aimed at reducing climate risks are not adequate, risk will increase or (at best) decrease less than anticipated.

We position this article as a step towards holistic climate services, integrating indicators for all four determinants of climate risk. In addition to the specific climate-related information (hazards), we include information on exposure, vulnerability, and response. The indicators are scalable – if one or more of them increases – climate risk will increase. The unfortunate point of departure is that climate-related hazards are increasing around the globe, and a reduction in greenhouse gases is needed for this element to be reduced. Many countries have therefore established greenhouse gas accounting and reporting standards (ICLEI, 2014) and there are several examples of how such inventories are downscaled to various sectors. However, to our knowledge, there are few, if any, comprehensive monitoring systems that provide municipalities with sufficient information to understand how climate risk develops, which goes beyond presenting downscaled predictions of climate change.

Reflecting on the adage "The proof of the pudding lies in the eating," we assess the societal impact of our climate service. The first gained media coverage nationally and even internationally (Rød et al. 2023). This exposure prompted regional authorities in Nordland and Troms to commission specific regional analyses based on our national system. The municipalities in each region were assessed in similar ways – but with additional local indicators – for Nordland (Rød et al. 2024b) and Troms (Rød et al. 2024c), with supplementary handbooks to guide county administrations in conducting detailed climate risk analyses, addressing both public services and private businesses.

1 Introduction

Risk related to natural hazards typically depends on the interplay of three risk determinants: hazard, exposure, and vulnerability (Wolf, 2012). Until the 1970s, the hazard determinant was predominant, describing risk solely as the probability of physical damage, which can generally be assessed spatially and put on a map (Hilhorst and Bankoff, 2013). The concept of vulnerability emphasizes that damage also stems from the fragility of societal elements at risk (Cardona, 2013). Crichton (1999) further developed this framework by including exposure, a term commonly used by the insurance industry, and used a triangle to illustrate risk as a function of the combined effects from hazard, vulnerability, and exposure. Crichton's risk triangle illustrates two important properties of risk: if one or more of the sides of the triangle increases, risk increases, and if any side has no length, there is no risk.

The IPCC adopted a similar approach in their 2012 framework, where the intersection between hazard, exposure, and vulnerability (displayed as three scalable propellors) represents risk (IPCC, 2012). In the 6th main report, IPCC introduced response as a fourth risk determinant signifying that if responses from institutions, communities and individuals aimed at reducing climate risks are not adequate, risk will increase or (at best) decrease less than anticipated (IPCC, 2022). Fig. 1. shows the proposed expansion of the IPCC risk framework from the existing three-propellant framework (hazard-vulnerability-exposure) applied in the 5th and 6th main assessment reports to a four-propellant framework to be applied in the coming 7th main assessment report.

The IPCC's risk framework utilizes a spatial approach where a set of indicators can be used to represent various aspects of the risk determinants. Using spatial indicators, one can map out the geography of climate risk to identify places most at risk, which may be places where a response is most needed. Whereas hazards such as a flood or storm surges is tangible and thus rather easy to represent as an indicator, vulnerability is a more complex phenomenon and therefore more challenging to measure (Patt et al., 2008), mainly because "it involves a combination of factors that determine the degree to which someone's life, livelihood, property, and other assets are put at risk by a discrete and identifiable event (or series or 'cascade' of such events) in nature or in society" (Wisner et al., 2004, p. 11). It is nevertheless rather common to operationalize vulnerability using indicators (Hinkel, 2011).

Unlike vulnerability, exposure is tangible and easier to measure. Common ways to measure exposure include counting the number of assets situated inside a flood zone, storm surge zone, or any other hazard zone (Rød et al., 2015). These assets could be numbers of dwellings, kilometers of roads or other kinds of infrastructure, or areas of cultivated land.

Fig. 1. A simplification of IPCC's risk framework to be applied in the 7th main assessment report (IPCC, 2022).

Climate change adaptation is represented by the concept of response, the fourth proposed addition to the framework in Fig. 1. Whereas mitigation performance is gauged by greenhouse gas emissions, adaptation lacks a straightforward outcome variable (Dupuis and Biesbroek, 2013). As a result, how to 'gauge' effectiveness in climate change adaptation is contested. What is considered effective by some may not be considered effective by others, and actions may have trade-offs across spatial and temporal scales, sectors, and development goals (Juhola et al., 2016; Dilling et al., 2019; Selseng et al., 2021). Measuring success depends on avoided impacts being observable, measurable, and attributable to adaptation (Singh et al., 2022).

Available data and metrics that can be used to proxy adaptation success, while also being consistent, coherent, comparable, and comprehensive, as Ford and Berrang-Ford (2016) emphasize, do not exist. To circumvent this issue, researchers focus on the institutional settings where adaptation action takes place. At the local government level, this effort includes investigating and ranking the quality of local climate action plans (Reckien et al., 2023; Aboagye and Sharifi, 2024), measuring various socio-economic and physical determinants of places' or institutions' readiness or capacity to adapt (Tilleard and Ford, 2016; Siders, 2019), and surveying municipalities about their institutional context and adaptation efforts (Patterson, 2021; Selseng and Gjertsen, 2024).

The official guidance for IPCC authors on the concept of risk states that "the more clearly you can characterize the adverse consequence (in terms of magnitude, scale, distribution, reversibility, etc.) and the nature of uncertainty, by providing the respective narrative, the more useful the risk concept will be" (Reisinger et al, 2020, p. 10). It is particularly useful to show how climate risk varies geographically (Rød et al., 2015), and descriptions of future climate risk, commonly provided by climate services, may therefore play an important part in answering questions on how and where to prioritize adaptation efforts with respect to the type, location, and timing (Vaughan and Dessai, 2014).

Indeed, climate services is defined as "the provision and use of climate data, information, and knowledge to assist decision-making" (GFCS, 2025). Many view climate services as an integral part of improving our capacity to manage climate-related risks, aimed at informing about adaptation to climate variations and changes (Vaughan and Dessai, 2014). However, in most cases, climate services have been limited to addressing only climate variability and climate change (Street et al., 2019). Effective adaptation strategies require a broader range of information, including vulnerability to climate-related impacts (Vaughan and Dessai, 2014).

Since the knowledge of vulnerabilities and climate change impacts on human well-being is less advanced than the knowledge of climate systems (Goosen et al., 2014), climate information should be integrated with other kinds of knowledge to mainstream climate risk management into decision-making (Lemos and Rood, 2010). For climate services to substantially provide better decision support for an improved climate risk management, such services should not only cover the hazard determinant of risk but also provide information on other equally important risk determinants (Vaughan and Dessai, 2014).

We argue that it is crucial for local governments and others to receive information not only about how the climate may change in the future but also about how societal vulnerability and exposure may evolve, and how this will affect municipalities if their current responses to climate change remain unchanged. Our aim is to provide a climate service that encompasses relevant information beyond the common hazard component of the IPCC framework for analyzing physical climate risks.

This article reports from our approach towards creating a holistic climate service that provides information about societal vulnerability, exposure, and response, in addition to hazard. We do so by utilizing available data with sufficient coverage and geographic resolution, enabling the establishment of an indicator set representing various, but essential, characteristics of the four risk determinants from the IPCC's climate risk framework. To disseminate our climate service, we have produced an interactive StoryMap application,[1] displaying the method and results in an accessible language with interactive graphics and illustrative examples (Rød et al., 2024a).

2 Material and methods

2.1 Workflow

The selection of indicators for our climate service was driven by four considerations: 1) to ensure transparency and reproducibility, we should be able to develop all indicators based on publicly available data, 2) to enable construction of indicators for the future, a variable used to develop an indicator should be part of time-series data, 3) including an indicator should not alter the balance between the number of indicators across the various risk elements, and 4) each new included indicator should represent a critical, but distinct facet, of climate risk. The method we used to construct climate risk indices involved four main steps, ultimately resulting in indices for each risk determinant. These were subsequently normalized and combined to form composite climate risk indices, as depicted in Fig. 2.

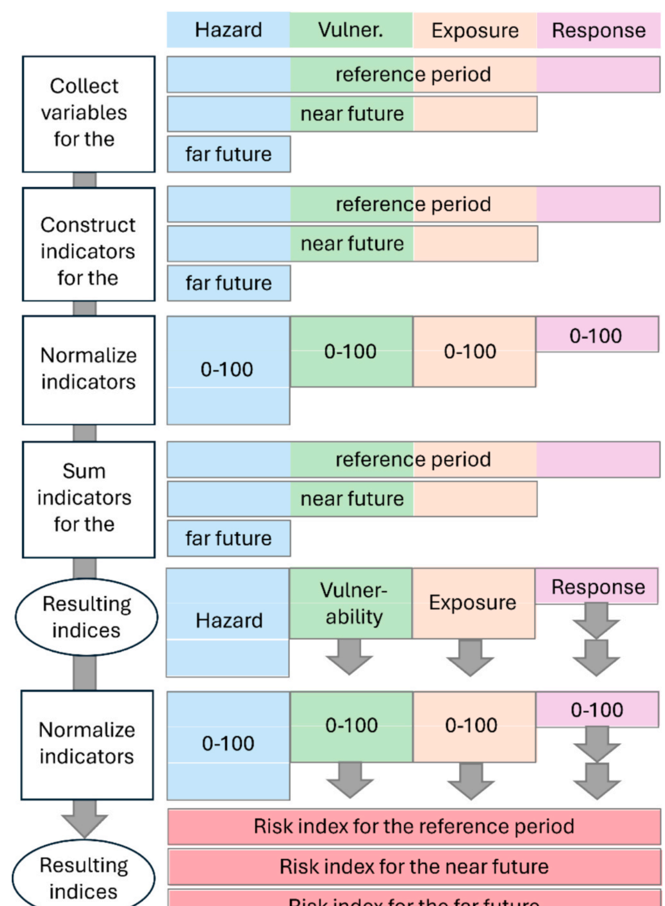

Fig. 2. The workflow for the method used consists of four steps before arriving at the resulting indices for each of the risk determinants, which is normalized before ending up with the final climate risk indices for the reference period and the future periods.

[1] A web-based multimedia platform with text, images, videos, graphics, and interactive maps.

2.2 Spatial and temporal resolution

The hazard indicators are based on gridded datasets with 1 km spatial resolution and are represented as a historical baseline (1971–2000), projections for the near future (2031–2060), and the far future (2071–2100). However, a similar spatial and temporal resolution for the other indicators proved difficult to generate since these are based on data collected for the lowest level of government (the municipality level). As spatial resolution, we therefore used the municipality level for all four groups of indicators. Regarding temporal resolution, these differ for the various groups of risk elements as outlined in Table 1. Vulnerability and exposure indicators generated for the near future involve uncertainty, and we therefore call these scenarios rather than projections. We base the scenarios on linear trends, which construct very similar indicators for the near and far future, and we therefore chose to use the near future indicators also as the far future indicators.

We constructed indicators for each of the four risk determinants contributing to an increase or decrease in risk. An overview of the chosen indicators is provided in Table 2. This is not a final list, in the sense that the current list of indicators can be supplemented in new editions of the climate service with new indicators as better data and new knowledge arise.

All 17 indicators are constructed for municipalities in Norway according to the 2024 division (n = 357). Details on how each indicator was constructed are provided below.

2.3 Hazard indicators

Norwegian authorities recommend using the precautionary approach for the choice of emission scenario, i.e., choosing the 'worst' alternative (Miljøverndepartementet, 2013). We therefore use RCP 8.5 as a basis for constructing the various hazard indicators. In our climate service, we allow users to investigate the projected changes regarding hazard indicators for the near future and the far future relative to the reference period.

2.3.1 Rot decay

Norway is among the countries in the world with a particularly high proportion of the use of wood as a primary building material. However, wood structures can be negatively affected by weather and climate conditions. Precipitation and temperature combined with wind are crucial in determining the probability of wood constructions being affected through rot decay. In a wetter and warmer climate, the risk of rot decay increases in most of Norway (Tajet and Hygen, 2017). Tajet and Hygen (2017) constructed a rot index as a measure of how exposed wooden buildings are to rot. For the reference period (1971–2000), the rot index ranges from 1 to 73 but varies from 3 to 87 and 10 to 108 for the periods 2031–2060 and 2071–2100, respectively. To construct the indicators, we calculated the average rot risk for each Norwegian municipality for the three periods.

2.3.2 Storm surge

Given its long coastline and direct exposure to the North Atlantic Ocean, flooding due to coastal storm surge presents a significant threat to life and property in Norway (Kristensen et al., 2023). To assess the impact of storm surges in Norwegian municipalities, we used the Norwegian Mapping Authority's zones for 1000-year storm surges for the current situation and for the situations in 2050 and 2090. For each municipality, we calculated the area covered by the storm surge zone – the larger the inundated area, the larger the score on the indicators. Sea level rise, and thus future storm surge events, will be most dramatic where the post glacial isostatic land uplift is least, which is in Western part of Norway (Bakkelid, 1986).

Table 1
Temporal resolution for indicators by risk element.

Risk determinant	Base line (2000)	Near future (2050)	Far future (2100)
Hazard	X	X	X
Exposure	X	X	
Vulnerability	X	X	
Response	X		

Table 2
Overview of the chosen indicators in the 2024-version of our climate service.

Risk determinant	Indicator	Data source
Hazard	Rot decay	Norwegian Climate Service Senter
	Storm surge	Norwegian Mapping Service
	Riverine flooding	Norwegian Climate Service Senter
	Diminishing winter land	Norwegian Climate Service Senter
Exposure	Compensation from the Norwegian Natural Perils Pool for house damage due to riverine floods, storm surges, storms, landslides, and pluvial flooding	Finance Norway
Vulnerability	Population density	Statistics Norway
	Vulnerable demographic groups	Statistics Norway
	Employment in primary sector	Statistics Norway
	Mobility	NILU
Response	Planning for climate change	Norwegian Directorate for Civil Protection's (DSB)
	Mobilizing resources for action	Norwegian Environmental Agency
	Implementing adaptation measures	Norwegian Climate Monitor
	Taking a sustainable approach	Norwegian Climate Monitor

2.3.3 Riverine flooding

The Norwegian Water Resources and Energy Directorate (NVE) has carried out flood zone mapping for more than 150 river sections but has prioritized the major watercourses close to existing buildings. Currently, flood hazard maps are available for 138 out of 357 municipalities in Norway. The fact that just under 40 % of municipalities have flood zone mapping, and only for some parts of certain rivers, makes it unfeasible to assess the flood risk for all Norwegian municipalities based on mapped flood hazard zones in a similar way as done for storm surges. Instead, we use the projected changes in 200-year flood zones for the near and far future periods prepared by NVE (Lawrence, 2016). The projected changes have considerable regional differences reflecting the geographical variation in snowmelt and heavy rain events. Western and northern parts of Norway will experience the highest increase (up to 59 %), whereas the southern inland and the extreme north will experience a decrease in flooding (down to −54 %) for the period up to 2100.

2.3.4 Snow depth

A reduced number of days with snow cover due to climate change highlights an important gradual change for Norway as a "winter country." Most of the population in the northern areas lives at low elevations, where the projected decrease in snow accumulation will be particularly visible and lead to darker winters, possibly followed by an increase in mental health problems (Raza et al., 2024). Also important, less snow will make the reindeer herders less mobile (Riseth et al., 2011) and there will be less favorable conditions for recreational winter activities (Dyrrdal et al., 2012). Snow cover will be considerably reduced in low elevations and close to coastline ski resorts. If a ski resort experiences several snow-free winters, it may no longer be considered a destination for ski tourism (O'Brien et al., 2006). Hence, these ski resorts must adapt either through artificial snow production or, in the worst case, move the lifts to a more snow-reliable area to stay in business (Scott et al., 2020). Snow depth is therefore considered of general human interest for every Norwegian and has been measured in Norway since 1950 (Kravtsova, 1972).

A snow depth of 30 cm is considered acceptable for cross-country skiing (Aall and Høyer, 2005). For this indicator, we therefore use 'days with snow depth over 30 cm' for each of the three periods. The range of values is from 0 to 354 for the reference period and from 0 to 224 for the far future. By subtracting the values representing the situation for the far future from the values representing the situation for the reference period, the range is from 0 to −350. This means that there is no place in Norway where snow cover will increase, but there are places where days with snow cover of 30 cm or more will be reduced, on average, by more than three days each year.

As the indicator is meant for municipalities, we calculated the mean of the grid values located within each municipality. On average, Norwegian municipalities may have 19 days with more than 30 cm of snow by 2100 if climate emissions continue as today, compared to an average of 89 days in the reference period.

2.4 Exposure indicators

Although extreme weather events rarely threaten people's lives in Norway, they have significant economic consequences by damaging exposed houses, i.e., buildings in places where they have been adversely affected. Norway has one of the most comprehensive insurance schemes in Europe regarding damage to people's homes from natural perils (Sandberg et al., 2020). The Norwegian Natural Perils Pool was established in 1979 and has registered compensations since 1980. According to data from the Norwegian Natural Perils Pool, storms, storm surges, floods, and landslides have resulted in payments totaling NOK 26.31 billion in the period 1980 to 2023 (adjusted to the 2015 value of the krone). Pluvial flooding is not part of the Norwegian Natural Perils Pool arrangement, but as the cost of pluvial flooding is alarming in urban areas (Venvik et al., 2019), Finance Norway also collects these compensations from various insurance companies selling insurance in Norway. The dataset consists of data from 2008 until 2023, and during this period, pluvial flooding has resulted in payments totaling NOK 17.20 billion (adjusted to the 2015 value of the krone).

We use five exposure indicators based on the compensations for house damages due to storms, storm surges, floods, landslides, and pluvial floods. For pluvial flooding, we used the mean of the 16 annual summed compensations when constructing indicators for the historical and near-future periods. However, since storm surges, floods, and landslides are rather rare events, to build these exposure indicators, we started off by using the medians of the compensations since the median is less sensitive to rare event peaks than the mean. However, as the median became zero for almost 70 % of municipalities' flood exposure indicator (since more than half of the years, there were no compensations), we used the 75th percentiles instead. We used the 75th percentiles also for the exposure indicators for landslides, storm surge, and storms.

Further, for the Natural Perils Pool-based indicators (flood, surge, storm, and landslide), we used linear regression to calculate the intercept and slope for a trend line we extended to 2067. We calculated the 75th percentiles for the extrapolated values for the period 2024–2067. A majority of the municipalities have a positive slope for the trend, such as for Voss municipality (see Fig. 3a). This may signify that, due to climate change, extreme events become more costly but also that many inhabitants in these municipalities live in exposed zones. However, it may also be a result of randomness: if one extreme event happens towards the end of the period (as shown in Fig. 3a), the trend becomes positive. Likewise, if one or more extreme events happen in the middle of the period, the trend becomes flat (as shown for Sandnes municipality in Fig. 3b). Finally, if an extreme event happens at the start of the period, the trend becomes negative (as in Fig. 3c). We found a negative trend for

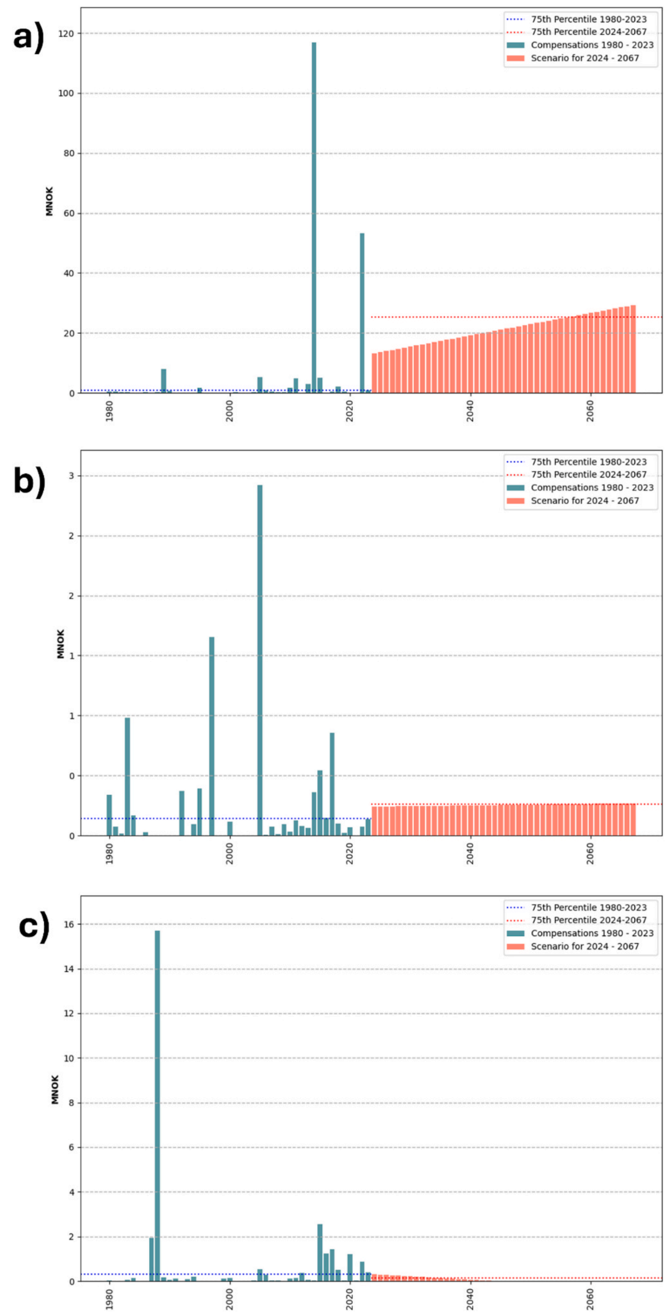

Fig. 3. Flood compensations in three municipalities with: (a) positive trend, (b) flat trend, and (c) negative trend.

66 municipalities (approx. 18.5 %). Fig. 3c shows the plot for Stavanger municipality, which indeed has had a considerable response regarding climate change adaptation. The indicator value for Stavanger is thus likely not entirely arbitrary.

2.5 Vulnerability indicators

The factors that influence vulnerability range from the characteristics of individuals (e.g., age, health, income, dwelling, employment) to attributes of whole communities or regions (population growth, urbanization, economic vitality, robustness of the built environment, quality of infrastructure) (Holand et al., 2011). Here, we follow the early work of Selstad (2008), who proposed five indicator themes to describe local climate vulnerability: population, business profile, mobility, physical infrastructure, and mentality. At this stage, we used the first three proposed themes and measured four indicators commonly used to express vulnerability.

2.5.1 Population density

If an extreme event happens in a less populated area, the consequences will appear smaller than if an extreme event occurs in a densely populated area. High population density exposes many people to hazards while simultaneously making evacuation and emergency help more difficult to organize and administer, and it may increase economic and human losses since more people and property are affected (Holand et al., 2011). Population density is therefore one of the most important indicators of vulnerability.

For the population density indicator, we used data from Statistics Norway collected for municipalities for the year 2024, and we used the current and most detailed land use dataset for built-up land in Norway. These datasets were combined to calculate population density for the historical period. Statistics Norway has made projections for population changes up to and including 2050 (Tømmerås and Thomas, 2024). There is no projection of the land use dataset, but as the land use dataset is available as time series data, we calculated the trend of changes for built-up area and estimated the area of urbanized area for each municipality. Finally, the projected population count was combined with projected built-up areas to generate an indicator for population density for the near future.

2.5.2 Vulnerable demographic groups

Heiberg et al. (2008) assume from a general perspective that a high percentage of economically active individuals and a low percentage of children and young people are among the conditions that improve adaptation capacity. To measure vulnerability due to age structure, Holand et al. (2011) included variables for the proportion of the population that is older than 67 years and under 5 years old. We follow Holand et al.'s approach and constructed a similar indicator for the historical period. As the population projection from Statistics Norway also includes age structure, we used their projected data for the near future period.

2.5.3 Mobility

Data on population counts people where they sleep, but people are often elsewhere. In the same manner as population density expresses how vulnerable people are when they are at home, the mobility indicator expresses people's vulnerability while traveling. The higher the traffic volume is on the roads within a municipality, the more vulnerable it may be to the negative consequences of climate change. We have obtained data for the mobility indicator from NILU, the Norwegian Environmental Agency, and TØI, who have measured the volume of traffic on Norwegian roads over a 14-year period from 2009 to 2022. We aggregated the traffic volume for 2022 to the municipality level and used this for the historical or current indicator and designed an indicator for the near future based on the linear trend obtained from the historical time series data.

2.5.4 Employment in primary sector

The primary sector includes fishing, aquaculture, agriculture, and forestry. Although climate change may bring about some new opportunities for the primary sector, there will also be negative effects. Crop losses are commonly associated with natural hazards (Cutter et al., 2000). With only a modest rise in sea temperature (i.e., 1–3 degrees), the optimal location for fishing the current common species (e.g., cod, herring, capelin, pollock) will move northward, but other new species from southern waters could also be introduced (Stenevik and Sundby, 2007). Harmful algal blooms are a possible threat that climate change brings to the aquaculture industry (Karlson et al., 2021). Forests may be damaged by extreme storms, and the clearance work is dangerous (Ochsner et al., 2018). Employment in the primary sector is therefore a relevant indicator of vulnerability, as municipalities with a high proportion of local employment in primary industries will face more challenges and/or need to be able to adapt to new opportunities than municipalities with a different business structure. Additionally, the primary sector is usually impaired when a disaster strikes, making people working in these sectors vulnerable to losing their jobs (Scherzer et al., 2019).

To calculate this indicator, we use data from Statistics Norway: employees aged 15–74 years old, by industry and sector. We calculated the proportion of people employed in agriculture, forestry, and fishing for 2023, and use this as an indicator for the historical period. Using backdated time series data, we calculated the trend and estimated values for an indicator for the near future. We consider municipalities that have (or will have) a high proportion of employees in primary industries the most vulnerable municipalities.

2.6 Response indicators

In line with current research, we focus on the institutional settings that constitute a likely effective adaptation response (Singh et al., 2022; Selseng and Gjertsen, 2024). We have chosen four dimensions when constructing response indicators, namely the extent that municipalities are: i) planning for climate change (Olazabal and Ruiz De Gopegui, 2021; Reckien et al., 2023), ii) mobilizing resources for action (Olazabal and Ruiz De Gopegui, 2021), iii) implementing adaptation measures (Rogers et al., 2023; Selseng and Gjertsen, 2024), and iv) taking a sustainable approach, i.e., aiming to preempt adverse side-effects and promote win–win adaptation action (Jacobs and Street, 2020; Singh et al., 2022, Aall et al., 2023).

2.6.1 Planning for climate change

The Directorate for Civil Protection (DSB) has conducted municipal surveys in 2018, 2022, and 2023 asking to what extent risk and vulnerability to serious natural hazards, as well as an increase in this risk because of climate change, are considered in municipal planning. Municipalities may answer 'to a great extent', 'to some extent', 'to a small extent', 'not at all', and 'not sure', which we have coded '3′, '2′, '1′, '0′, '0′. All municipalities except 11 participated in the surveys. We have taken the mean of the response options for the three surveys. The lower the value, the more we consider the response to be inadequate and thereby possibly contributing to an increased risk.

2.6.2 Mobilizing resources for action

The Norwegian Environment Agency has a grant scheme for municipalities and county administrations to support local adaptation to climate change (Norwegian Environment Agency, 2024). The indicator is based on an overview of all municipalities that have applied for funding and all those who have received funding to implement climate adaptation measures for the period 2015–2023. Not all good applications are rewarded with grants, partly due to limited budgets. However, we have constructed the indicator so that all municipalities that have applied for funding, or that are partners in an application, or that belong to a county where the county administration has applied for funding, receive a positive score. Applying for funding represents a willingness to mobilize resources for climate change adaptation and contributes to increased knowledge of how climate change affects the municipality's areas of responsibility. The highest scores are awarded to municipalities that have applied for and received funding.

2.6.3 Implementing climate change adaptation

From the Norwegian Climate Monitor,[2] we have one indicator that describes the extent to which municipalities have implemented climate

[2] Norwegian Climate Monitor is a research project led by Western Norway Research Institute that collects and disseminates data on climate change adaptation efforts in Norway (https://klimamonitor.no/).

adaptation measures. The score for the indicator is based on eight item responses from surveys conducted in 2021 and 2024 (Tandberg and Selseng, 2024) where municipality representatives answered the questions reproduced in Table 3. The eight items were subject areas or other areas of responsibility where the municipalities could have implemented both organizational and physical climate change adaptation measures, only physical measures, only organizational measures, or no measures. We consider physical measures more important than organizational measures and score the alternatives accordingly. The municipalities picked the alternatives that appropriately described the situation, and the alternatives selected were transformed into numbers. A municipality could get a score of up to 40 (20 x 2), but the highest score obtained was 38.

2.6.4 Sustainable approach to climate change adaptation

The second indicator constructed from the Norwegian Climate Monitor describes the extent to which municipalities have a sustainable adaptation policy. The score for the indicator is based on answers the municipalities provided, from surveys conducted in 2021 and 2024 (Tandberg and Selseng, 2024), on eight items in a question battery as well as one other question, as shown in Table 4. The municipalities marked the cells that appropriately described the situation and marked cell locations were transformed into numbers. A municipality could get a score of up to 72 (36 x 2), but the highest score obtained was 61.

3 Results

The 17 indicators are combined into their respective composite indices (i.e., hazard, vulnerability, exposure, and response). We thus have an index for each risk determinant, as well as an overall climate risk index where these four are combined. Furthermore, we also combine hazard, vulnerability, and exposure into an index we call impact and plot municipalities' scores on this against scores on the response index.

3.1 Composite indices

The simple idea behind composite indices is to combine different types of hazard, exposure, vulnerability, and response indicators in the evaluation instead of assessing these individually. Because we combine different indices, we need to transform these to a common scale before they can be added, which is achieved by a minimum–maximum transformation (see Formula 1):

$$x' = \frac{x - min}{max - min} \times 100 \quad (1)$$

where x' is the transformed value, x is the original value, and *min* and *max* are the minimum and maximum values, respectively, of the indicators that are to be transformed. Finally, we multiply the result by 100 to bring the transformed values between 0 and 100.

3.2 Categorization of municipalities based on scatter plot quadrats

We plot the scores on a composite impact index based on the hazard, exposure, and vulnerability indicators against a composite response index. This is done for each of the three periods, and Fig. 4 shows the far future. Each dot in the scatter plot represents a municipality, and they are placed in one of four squares formed by the average values for impact and response. This enables us to identify, for instance, whether municipalities that will have the largest impact from climate change also respond appropriately. The colors indicating different municipalities in

Table 4
The question battery used to generate an indicator for adaptation as a cross-sector topic.

To what extent do you see climate change adaptation in connection with other policy areas, e.g., by identifying conflicts or win–win measures?	Not at all	To a small extent	To some extent	To a large extent	To a very large extent	Do not know/ not relevant
Emission reduction	0	1	2	3	4	0
Protection of natural areas and biodiversity	0	1	2	3	4	0
Energy measures	0	1	2	3	4	0
Health (e.g., changes in drinking water quality, increased incidence of vector diseases)	0	1	2	3	4	0
Agriculture (e.g., increased rot damage, introduction of new species, etc.)	0	1	2	3	4	0
Cultural heritage sites (e.g., rot damage in buildings, flood damage, etc.)	0	1	2	3	4	0
Transport (e.g., green space and rain beds related to roads and parking)	0	1	2	3	4	0
Stormwater (e.g., blue-green infrastructure)	0	1	2	3	4	0
What is the time perspective for the climate adaptation work in the municipality?						
Future climate change impacts (based on projections, e.g., climate profiles by county)?	0	1	2	3	4	0

Table 3
The question battery used to generate an indicator of local adaptation measures.

What kind of climate change adaptation measures have you implemented in the following areas of expertise or responsibility?	Both organizational and physical measures	Only physical measures	Only organizational measures	No measures	Do not know/ not relevant
Waste-/storm water	4	3	2	1	0
Roads and parks	4	3	2	1	0
Energy supply	4	3	2	1	0
Nature management	4	3	2	1	0
Agriculture	4	3	2	1	0

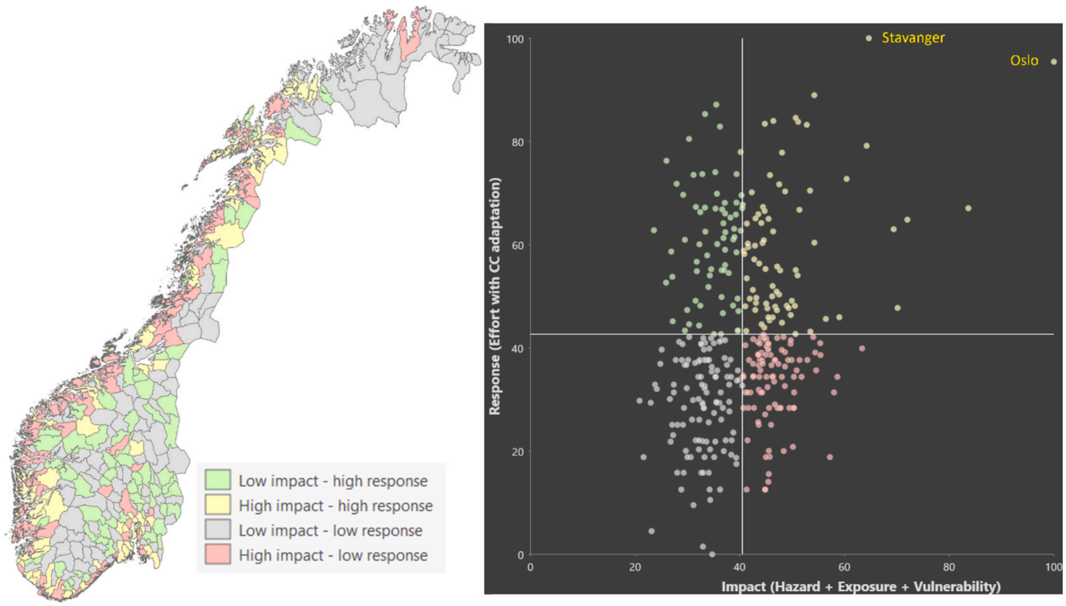

Fig. 4. Map and scatter plot of how Norwegian municipalities score on the composite indices for impact and response (n = 357). The municipality having the highest score on response and impact, respectively, are Stavanger and Oslo.

the scatter plot correspond with the coloring of the municipalities in the map:

(1) Quadrat I (top left, green): These are municipalities whose responses are high, and the impact is low.
(2) Quadrat II (top right, yellow): These are municipalities whose responses are high, and the impact is high.
(3) Quadrat III (bottom left, grey): These are municipalities whose responses are low, but so is the impact.
(4) Quadrat IV (bottom right, red): These are municipalities whose responses are low, and the impact is high.

From the scatter plot, we can observe that there is no clustering of points in the lower right corner of quadrat IV. The red dots represent municipalities that we would prefer to have a higher score on the response index, but most of these are rather close to the means. The municipalities most impacted by climate change (thus towards the right side of the diagram) are also the municipalities with the highest response – these are shown in quadrat II.

3.3 Climate risk

A second result is the composite climate risk index, where all 17 indicators are combined after being transformed using the

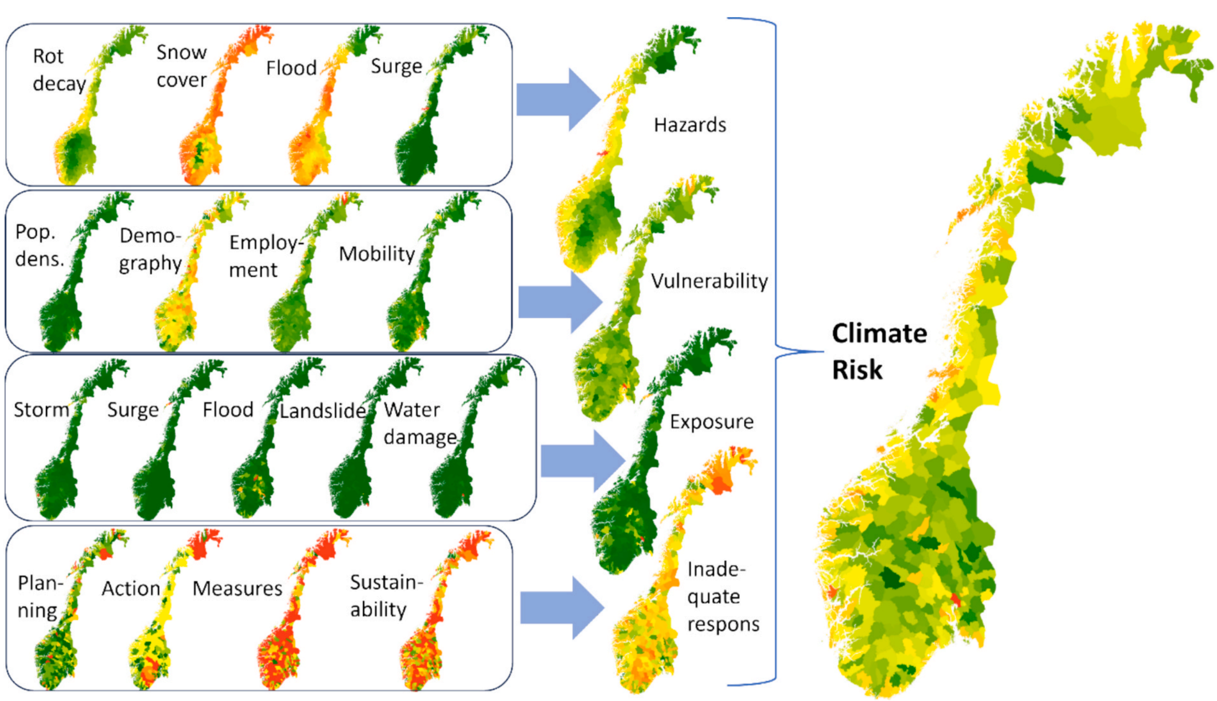

Fig. 5. Maps for the Climate Risk index, risk determinants, and their indicators.

minimum–maximum method. Fig. 5 shows the hazard indicator scores for 2100, the exposure and vulnerability scores for 2050, and the historical response indicators. The values for the response indicators are inverted since an inadequate response contributes to an increased risk. The final map is available from the StoryMap application as an interactive map, enabling users to investigate a municipality's indicator scores for the three periods (Rød et al., 2024a). Next year, we plan to enhance this feedback service, making it easier to understand why a municipality has, for instance, a particularly high score on the climate risk index (see Discussion).

4 Discussion

4.1 Better data for climate services

Findlater et al. (2021) argue that there is a key tension between focusing on better data and focusing on better decisions related to the development of climate services. We have made a modest start with 17 indicators representing various aspects of the four determinants of climate risk. Representing all aspects of climate risk with a set of indicators is impossible. However, our experience has shown that more and better data is often desired by municipality and county administrators, and this wish is also related to a recognized need to make better decisions. For instance, many have expressed a need for an indicator for climate change induced landslide hazard. Since this is so far not provided by the Norwegian Climate Services, we have therefore (so far) not included a landslide hazard indicator. There are maps of landslide hazard zones available, but not yet providing information on how these landslide hazard zones will change in the near and far future.

A similar argument can be made for the response index, which we have designed to only represent the reference period. Due to its status as a relative newcomer in the risk framework, it is arguably the risk determinant that has gained the least attention (Andrews et al., 2023). There is still a distance until researchers reach a shared understanding of what effective adaptation entails (Singh et al., 2022; Selseng and Gjertsen, 2024), and although there are mounting calls for better and more specific response data (Canales et al., 2023), few attempts at moving beyond the input and output stages of the adaptation process at a comprehensive level have been made (Berrang-Ford et al., 2021).

4.2 Indicator values for the near future

Regarding the estimation of indicator values for the near future for exposure and vulnerability, we have been reluctant to call these projections due to the large uncertainty involved. We have used a simplistic approach, employing linear regression to find near-future indicator values. Although other, and probably better, statistical methods would provide 'better data' – data that is more precise – (Findlater et al., 2021), using a linear trend is simple and easy to understand, and it may correspond to the second Shared Socioeconomic Pathways (SSP2) as it represents current development (IPCC 2022). Furthermore, seeing how the future may look in terms of exposure and vulnerability may trigger engagement that aligns the climate service with the needs of climate-sensitive decision-makers, as Findlater et al. (2021) call for.

4.3 Vulnerability indicators

Since vulnerability is a complex term, it is common to use several indicators that each represent various aspects of the notion of vulnerability. For instance, Cutter et al. (2003) used 42 indicators in the first version of the social vulnerability index (SOVI), and Holand et al. (2011) used 33 indicators when replicating the SOVI for Norway. Using only four vulnerability indicators does not, of course, cover the complete picture of vulnerability.

4.4 Weights for indicators

A main challenge is determining the weight that each of the indicators should have within the combined index (Rød et al., 2012). Cutter et al. (2000) considered all indicators as making equal contributions to the social vulnerability index, and we do the same for the climate risk index. Clearly, additional research is needed to develop weighting schemes for the four risk determinants, and this could be a subject for group discussion on the relative importance between paired indicators, as done using the analytical hierarchical process for multi-criteria decision support (Hanssen et al., 2018). Another approach is to use an online tool to crowdsource opinions on how a weighting scheme for indicators used for a particular index should be (Opach and Rød, 2018). These approaches are, however, beyond the scope of this article and the current version of the climate service provided, but something we consider for future releases.

4.5 Collinearity

An issue related to weighting schemes is the presence of collinearity. If there is a high correlation between two indicators, they should either be merged into one indicator or one of them should be dropped. With 17 indicators, there are 136 possible pairs of indicators, and Fig. 6 shows a scatter plot matrix of these. The mean value of the correlation coefficients (Pearson's R squared) is 0.05, while the median value is 0.01, indicating a skewed distribution of correlation coefficients. Unfortunately, we did not test for collinearity before the launch of the 2024 version of the climate service, but we will need to reconsider some of the indicators used. The highest correlation is highlighted and enlarged in Fig. 5 and is between two of the response indicators: 'Implementing adaptation measures' and 'Taking a sustainable approach' with an R2 = 0.74. Other paired indicators with high R2 are: 'Population Density' and 'Mobility' (R2 = 0.5), 'Population Density' and 'Water Damage' (R2 = 0.43), and 'Decay' and 'Number of days with Snow Depth 30 cm or more' (R2 = 0.31). Interestingly, the correlation between the hazard indicator for flood and the exposure indicator for flood is next to zero (R2 = 0.00), indicating that we have succeeded in measuring different aspects of how flooding contributes to climate risk.

4.6 Decision support

Also important for climate services to assist decision support is an understanding of the information provided, which is one possible dimension of whether a climate service is successful (Boon et al., 2022). Seeing a map showing where the most exposed or vulnerable places are does not provide an understanding of why these places are exposed or vulnerable. From Riach and Glaser (2024), we have learned that developing municipal climate profiles will support the need for localized climate information. Riach and Glaser (2024) developed a map interface where clicking on a municipality provides information on the chosen parameter as well as a link to the profile, which is a three-page informative document. Our thought for a municipality profile is to apply geographic visualization techniques with linked windows showing related information using maps, diagrams, table views, etc., since previous research has found this to be beneficial (Bohman et al., 2015; Glaas et al., 2016; Neset et al., 2016). We can find an example of how this could be implemented from the ViewExposed tool (Opach and Rød, 2013; Slocum et al., 2022) shown in Fig. 7. If a user clicks on a municipality in the map (A), the index scores for the municipality are shown in the plot with a brown line (C), crossing the vertical bars (B) representing the indices. The municipality scores can be evaluated against the national mean shown with a white line (D), or other selected neighboring municipalities (not shown here).

A user could then investigate how the municipality scores relate to the scores of neighboring municipalities. Knowledge from psychology on human sustainable behavior indicates that a descriptive normative

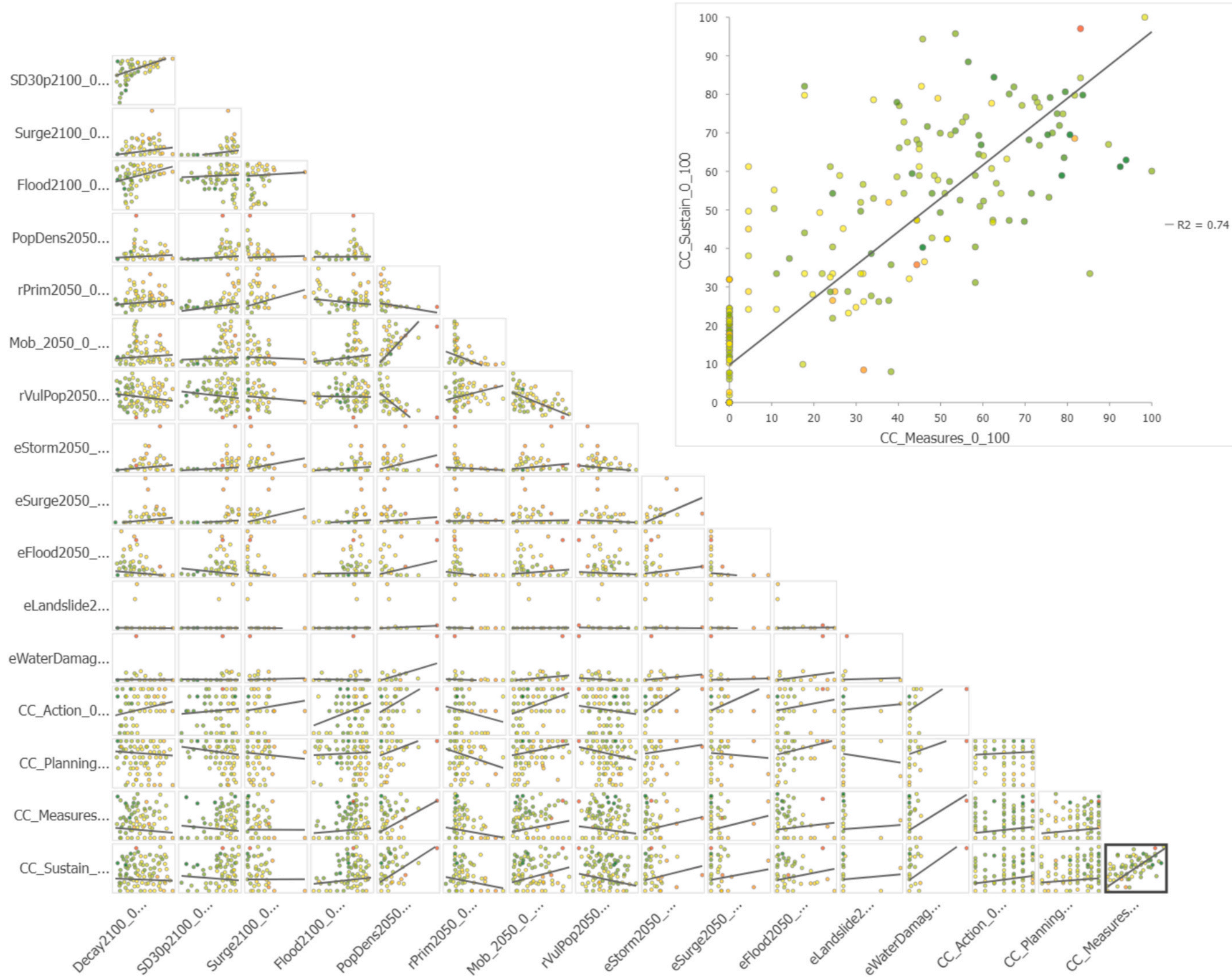

Fig. 6. Scatter plot matrix of the 136 possible paired combinations of 17 indicators.

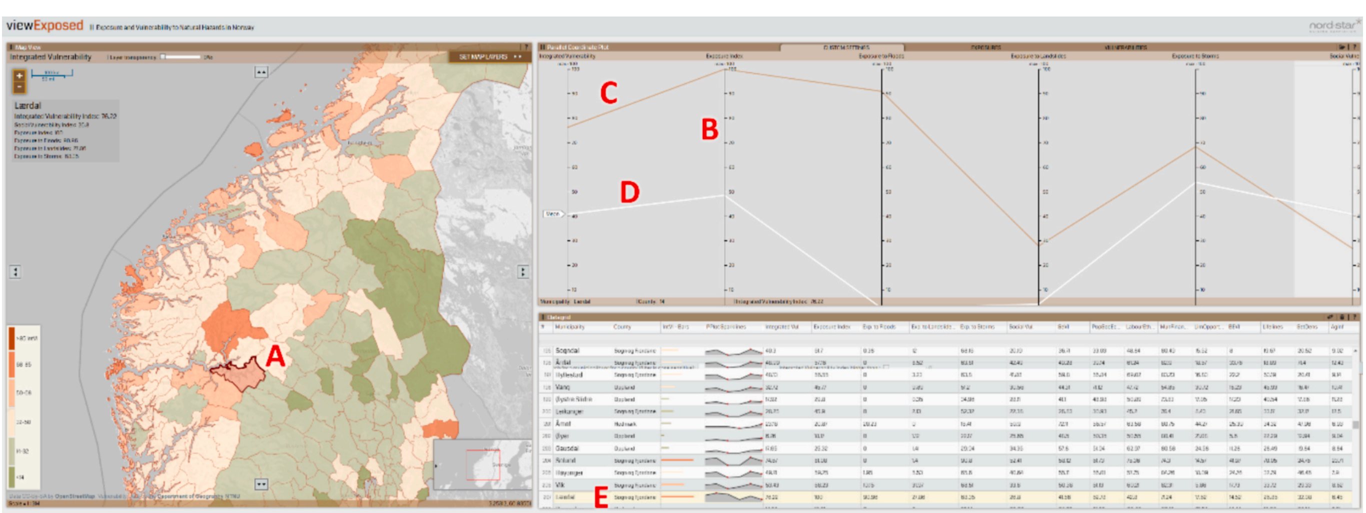

Fig. 7. Screen dump from the ViewExposed tool consisting of three linked views: map view, plot view, and table view.

message – a message merely containing information about the conservation behavior of most of one's neighbors – spurs people to conserve more energy than other kinds of influence or appeals that are traditionally accorded motivational power (Nolan et al., 2008). We are not aware of any study showing similar effectiveness in spurring climate change adaptation efforts on a municipality level, but there is evidence for increased attention to adaptation if a municipality participates in a network with its neighbors (Hauge et al., 2019).

Climate changes and societal changes are uncertain, and any decisions regarding climate change adaptation will therefore be made under uncertainty. Although the Norwegian authorities recommend using the precautionary approach (Miljøverndepartementet, 2013), there are alternatives for decision-making under uncertainty. Robust decision-making is becoming one such alternative, describing a variety of approaches by characterizing uncertainty with multiple representations of the future (Lempert and Collins, 2007; Dittrich et al., 2016). Future versions of our climate service could approach robust decision-making by constructing future hazard indicators based on low, medium, and high emission scenarios, and future vulnerability and exposure indicators based on SSP2 (current development), SSP1 (more optimistic societal development), and SSP3 (more pessimistic societal development.

5 Concluding remarks

Having an indicator framework representing aspects of all four climate risk determinants is a useful service, enabling a more efficient measurement and assessment of municipalities' need to engage in climate change adaptation as well as their performance in doing so. Dashboard functionality is on our wish list for the 2025 version of our climate service because we have learned from feedback that municipality workers (and others) would like to know why their municipality has a high score on the climate risk index. Providing dashboard functionality would offer a better understanding of contributing factors for a certain risk level by providing a profile outlining which indicators a municipality has high or low scores on. Such a profile of the contributing factors to risk may further support decisions on what kind of response the municipality should carry out. If neighboring municipalities score better, that may initiate the formation of climate networks for knowledge sharing and increased efforts.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Jan Ketil Rød: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Carlo Aall:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Torbjørn Selseng:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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