Methods used in Klimaatlas, the Danish Climate Atlas (v2025a)

DMI Report 25-16

DMI Report
v2025a

National Centre for Climate Research (NCKF) at DMI

Colophon

Content

Changes in this version

Klimaatlas v2025a adds an additional set of indicators focused on the theme "Winters of the Future", including indicators of wet winters, ice days, freeze-thaw days and snowfall. In addition, an important technical change has been made to the way that bias adjustment of atmospheric indicators is performed, that improves the expected realism of extreme temperatures in particular, but that has little direct effect on most indicators related to averages.

Improvements have also been made to the final products, including a new product to enable comparison of a given indicator across all previous versions of *Klimaatlas*, improved metadata in the NetCDF files, and the addition of a limited set of English language products. The methods report (this document) has also been restructured and heavily revised in preparation for publication as a scientific article.

Methods

- **Improvement of the bias-adjustment approach.** The non-parametric bias-adjustment approach employed in *Klimaatlas* for atmospheric data is based on a discretization of the relevant model and observation data into bins from the 1st to the 99th percentile. However, this approach raises the question of how to extrapolate beyond these values e.g. when dealing with temperatures outside the range of the observational training set. The previous approach in *Klimaatlas* extrapolated the bias-relationship using a fitted slope of the relationship between observational and model-based quantiles, starting from either the 1st or the 99th percentile as relevant. However, experience has shown that this approach breaks down in some situations, particularly with regard to extreme high temperatures and grid-points with relatively low variability (e.g. near the coast) – the bias adjustment in these cases can be in excess of 10 or even 15 degrees C, resulting in unrealistically high projected temperatures.

- The revised approach replaces the fitted slope with a simple 1:1 slope beyond the 1st and 99th percentiles i.e. with a constant bias adjustment. A literature review showed this approach appears to be more common amongst climate services and is the default (and only) approach in common tools such as the XSDBA package (Dupuis et al., 2025) (previously part of Xclim (Bourgault et al., 2023)). The effect of this change is generally minor and is only detectable in indicators looking at the extremes of the distribution: bulk indicators, such as average temperature or precipitation are unaffected, as values beyond the 1st/99th percentile play a minimal role. However, the revised approach has the advantage of removing unrealistic

values from the analysis and is particularly beneficial for the quality of the daily bias-adjusted variables that *Klimaatlas* also publishes.

- **Impacted indicators**: The effect is only detectable in indicators of extreme warm temperature (004, 006), extreme precipitation that is not based on fitting an extreme value distribution (102, 106), extreme wind (302), and fire-weather index (501, 502, 503).

Indicators

- Addition of four new indicators
    - *Isdøgn* – Ice days (Indicator 014), i.e., days with a maximum temperature below freezing.
    - *Dage med frysepunktspassager* – Zero-crossing days (Indicator 016)
    - *Andel år / årstider som er "meget våde"* – Proportion of years / seasons that are "very wet" (Indicator 111)
    - *Dage med snefald* - Days with snowfall (Indicator 116)
- Clarification of three indicators
    - Indicator 110 (*Andel år / årstider som er "meget tørre"* – Proportion of years / seasons that are "very dry") has been renamed from *Klimaatlas* v2024a and v2024b, where it was called *Andel år / årstider som er "tørre"* - Proportion of years /seasons that are "dry". The change from "dry" to "very dry" has been made to ensure consistency with the standardised language used in DMI's communication around unusually wet and dry seasons and years. No changes have been made to the calculation of the indicator, and the values remain therefore unchanged.
    - Indicator 006 (*Årets temperatur-interval* – annual temperature interval) has been clarified to highlight that the calculation is based on the daily mean temperature, and not the daily minimum / maximum.

Products

Four changes have been made to the suite of *Klimaatlas* products

- **Addition of a version archive product** for advanced users. *Klimaatlas* has experienced that there are many users that have a need to understand how the indicators presented have changed over time and between updates e.g. in connection with updating of a climate adaptation plan. A spreadsheet has therefore been generated that contains all indicators presented in each version, for all spatial areas (municipalities, drainages and coastal stretches), percentiles, emission scenarios and time periods. Due to the large size of this spreadsheet, it is not recommended for regular usage, but only on an as-needed basis. Grid-point data is not included in this spreadsheet, due to its large size, but previous versions of this

data are available through the version history (*versionshistorik*). The version archive spreadsheet is available in both the version history and as part of the data for expert users.

- **Metadata in NetCDF files** (both indicators and daily bias-adjusted variables) have been homogenised and updated.
- **Wider use of indicator IDs**. Indicator IDs are used internally within *Klimaatlas* to refer unambiguously to an indicator, and we would like to see this practice also extended to our users. All excel spreadsheets have been updated to include the indicator ID together with the indicator name. Furthermore, indicator IDs have also been incorporated into the map viewer, as part of the indicator description.
- **Addition of English-language products**. For the first-time, *Klimaatlas* now includes English-language products: the report for all of Denmark has been translated, together with the Excel spreadsheet containing all indicators.

Documentation

This document, the *Klimaatlas* technical methods description, has been extensively revised from version v2024b, to align the document with common practices for documenting scientific data by submission to a peer-reviewed scientific journal.

1 Introduction

Responding to the challenge of the climate crisis requires scientific information to support decision making that is relevant, reliable and actionable. Unfortunately, much of the data produced by the climate science community are difficult for stakeholders to utilise directly, due to mismatches in scale (global vs local), lack of direct relevance or applicability and the large data volumes involved that are often impractical for stakeholders. Climate services are an attempt to bridge this gap, by converting climate data from models and observations into climate information that can support climate-relevant decision making, particularly with regard to climate adaptation.

The primary climate service in Denmark is *Klimaatlas*, the Danish Climate Atlas, produced by the Danish Meteorological Institute (DMI). *Klimaatlas* aims to provide municipalities (*kommuner*) in Denmark with an authoritative and geographically complete dataset that can be used as the basis for adaptation planning. *Klimaatlas* is funded directly from the central government via the national finance act (*Finansloven*), with the initial round of funding for four years starting in 2018, with subsequent renewals in the financial acts for 2022 and 2026. The initial version of the service was launched on 6 October 2019 with 17 indicators, and has evolved through multiple releases, each building on the previous version by adding improved datasets, new indicators and improved products.

The development of *Klimaatlas* has been, and continues to be, driven by the needs of stakeholders and decision makers in Denmark. Co-design approaches have been used throughout, with frequent workshops, user surveys and focused meetings with individual users shaping the climate service and ensuring that the information delivered both addresses user needs and is in a usable format. The primary target group of users are the 98 municipalities that are legally mandated to develop climate action and adaptation planning within Denmark: a recent review documented a high degree of uptake amongst these users, with at least 90% of municipalities reporting use of *Klimaatlas* in connection with the development of their climate action plans (Lind & Hansen, 2023). However, the pool of users has also broadened over the years, and today *Klimaatlas* is used by all tiers of government in Denmark, together with civil society, researchers, and increasingly in the private sector as well as part of environmental, social and governance (ESG) reporting.

Klimaatlas focuses on providing information on indicators and variables that are relevant for Danish society. This entails a focus on mean meteorological

conditions, but also sea level rise and indicators describing extreme and impactful events (e.g. cloudbursts, heatwaves, and storm surges). *Klimaatlas* is based primarily on regional climate models derived from EURO-CORDEX (Jacob et al., 2014) (https://euro-cordex.net), but multiple other data sources, both modelled and observed, also make important contributions, particularly for sea level rise, storm surge and extreme-precipitation indicators.

Klimaatlas products are provided in multiple data-formats, including Excel spreadsheets, NetCDF files and data layers suitable for use in GIS clients. These data are intended for users requiring download of material for further processing, but *Klimaatlas* also provides an online display of the information (http://www.dmi.dk/klimaatlas), with documentation and user guides in Danish. Furthermore, reports are generated for each of the 98 municipalities in Denmark, summarizing the key findings from *Klimaatlas*, together with a report covering the entire country.

While many climate services only produce major releases every 5-7 years where all indicators are updated (e.g. Dyrrdal et al., 2025; MeteoSwiss & ETH Zürich, 2025), *Klimaatlas* uses a "rolling-release" model. Updates of selected parts of *Klimaatlas* occur 1-2 times a year, in combination with full documentation of all releases, enabling a smoother updating frequency. Trustworthiness and timeliness of the service therefore remain high, even when some indicators are derived from datasets with differing or out-of-phase update cycles (e.g. global vs. regional datasets). The update cycle for *Klimaatlas* is thus a balance between effective communication of new information and the need for stable communication to and dialogue with stakeholders making decisions on long time horizons.

In this report we provide a technical description of the data processing steps leading to the results presented in the *Klimaatlas* climate service. The goal is to provide a reference for users of *Klimaatlas* and its datasets characterising the generation of the data, thereby aiding in both its potential use and interpretation, as well as allowing developers of other climate service to be inspired by the methods and choices behind *Klimaatlas*. Where appropriate, a brief justification for the choices made is provided and elaborated as necessary, but the focus is on providing a description of how the data were generated.

2 Overview

Klimaatlas links three processing pipelines, to produce 1) Atmospheric indicators, 2) Extreme precipitation indicators and 3) Sea-level rise and storm surge indicators (Figure 1). These pipelines are then integrated to produce output for use in society. The structure of this manuscript reflects this construction, describing each of the pipelines and processing steps in turn.

As a preliminary step, we define two types of data in *Klimaatlas:*

- *Climate variables* are climate data in their source time resolution. Variables can include the output obtained from a climate model (either global or regional) or observations, often, but not always, in the form of gridded datasets. As a further gradation, we consider *primary variables* as those obtained from the source (e.g. temperature and precipitation) and *derived variables* that are produced as a combination of other variables from the same data source, or in interaction with other data sources (e.g. as in bias adjustment) e.g. the Canadian Fire Weather Index (FWI) (Wagner, 1987), which is produced as a function of the primary variables temperature, precipitation, wind and humidity
- *Climate indicators* are metrics based on climate variables that have been modified via a processing scheme involving the generation of some form of summary statistic (e.g. a mean) over time. Examples include annual mean temperature, return level of an extreme rain event (e.g. a 10 year event) and the number of days per year with an extreme FWI.

The key distinction between a variable and an indicator is the act of time-averaging. Climate variables have a higher time resolution (e.g. days or hours) than the corresponding indicators (e.g. annual averages, 30-year averages). The information delivered by a climate service, including *Klimaatlas*, and that commonly serves as the basis for further decision making, is most commonly in the form of indicators. It is also important to note, however, most variables have already undergone a degree of time-aggregation away from the native time-resolution of the climate model (e.g. daily mean temperature): in our definition, climate variables are the input to the *Klimaatlas* processing chain, the precursor for indicators and often an intermediate step in the processing chain.
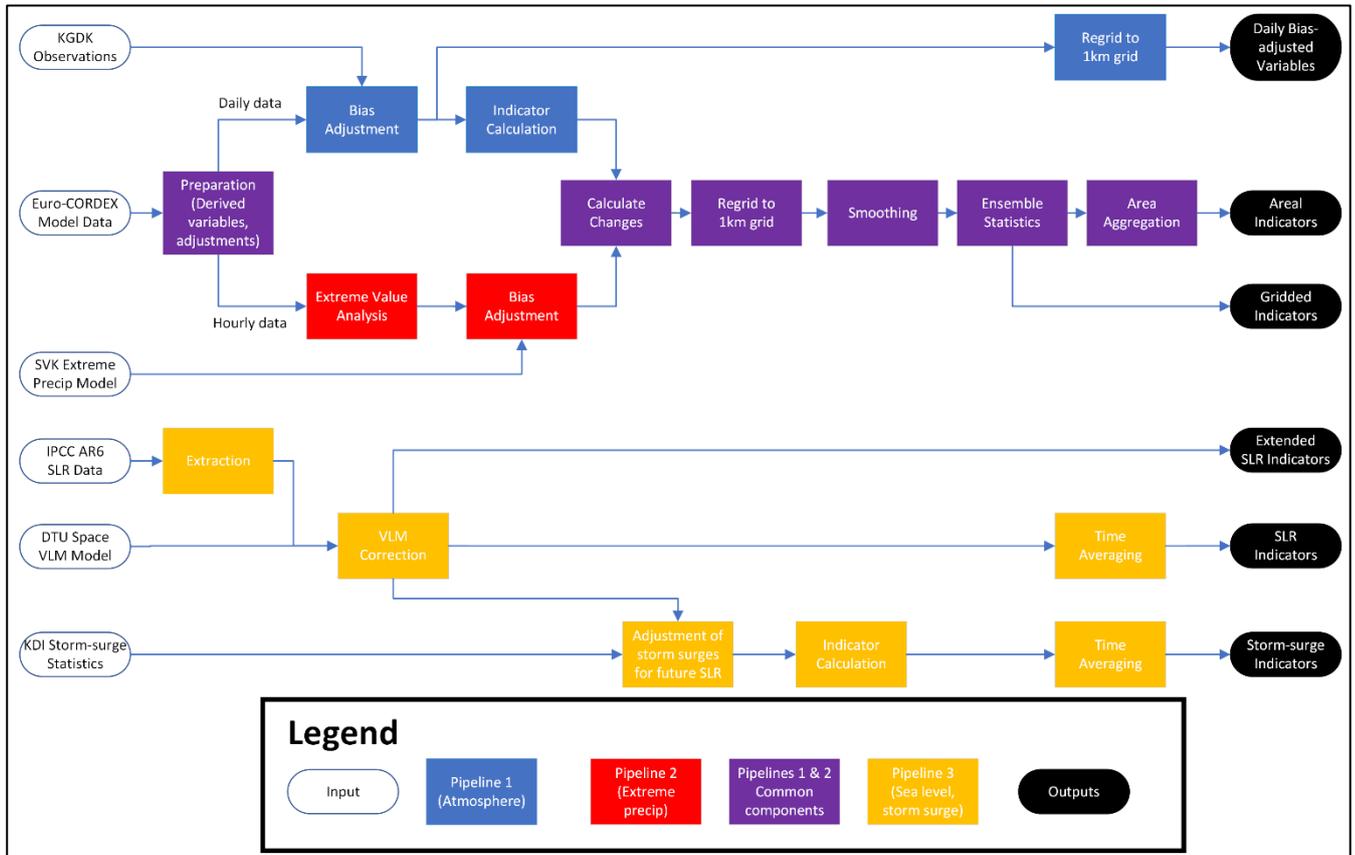
Figure 1 Overview of *Klimaatlas* processing pipelines. Abbreviations**:** KDI (*Kystdirektoratet*; Danish Coastal Authority); KGDK (*Klimagrid Danmark*); SLR (Sea Level Rise); SVK (*Spildevandskommiteen*; Water Pollution Committee of the Society of Danish Engineers); VLM (Vertical land motion).

3 Atmospheric indicators

3.1 Data

3.1.1 EURO-CORDEX Climate projections

The regional EURO-CORDEX collaboration (Jacob et al., 2014) (www.euro-cordex.net) is a European initiative building on the international CORDEX collaboration (www.cordex.org). The aim is to construct a multi-model ensemble of regional climate model simulations covering Europe in high resolution and making output with high temporal frequency available to the public. As a part of the initiative, the domain size, resolution, and output variable list have been coordinated between participating institutions.

The current EURO-CORDEX ensemble is based on selected simulations from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) global model ensemble: global models were selected based on their ability to reproduce the historical period of the simulation (McSweeney et al., 2015). The emission/concentration scenarios underlying the CMIP5 simulations downscaled in EURO-CORDEX are the RCP scenarios RCP2.6, RCP4.5, and RCP8.5(Van Vuuren et al., 2011). Eleven regional climate models (RCMs) have been employed with boundary conditions provided by a total of 12 different CMIP5 global climate model simulations (GCMs): the "matrix" of GCM, RCM and scenario combinations is, however, not complete and the total number of simulations (a single combination of GCM, RCM and RCP scenario) available is around 120 out of the 396 possible combinations (11 RCMs, 12 GCMs, three RCPs). The simulations have been run on a domain covering Europe, the Mediterranean Sea and the North Atlantic in around 12 km horizontal grid point distance. Output data in multiple temporal resolutions are available to the public through the ESGF distributed network, e.g., https://esgf-metagrid.cloud.dkrz.de/

The models we use in *Klimaatlas* are a subset of the available ensemble, several simulations were excluded as follows:

- The CNRM-CERFACS-CNRM-CM5 global simulation has a recognized issue with inconsistency of lateral boundary conditions (Meteo France, 2018). While some members of the EURO-CORDEX ensemble are still affected by this error (typically denoted by version 1), others have accounted for the problem (typically, denoted with the v2 or v3 identifier). Only simulations not affected by this lateral boundary condition error for an RCM have been included in the *Klimaatlas* ensemble.

- Output from the old regional climate models ALADIN5.3 and WRF331 are excluded. These models have been superseded by newer versions in the CORDEX ensemble, which have been used in preference.
- Due to the use of a different geographical projection, the ALADIN and RegCM regional climate models have been re-gridded to the EUR-11 standard grid (12km horizontal resolution) as the first step prior to the processing steps described below.

The final set consists of a total of 72 GCM-RCM combinations (Table 1): again, however, the "matrix" is not complete, and not all variables are available for all models or emissions scenarios (Table 2).

Table 1. List of the regional model simulations used for the climate indices produced within *Klimaatlas*. Each row represents one model simulation with a forcing global climate model (GCM) with the associated realisation identifier (realisation), a downscaling regional climate model (RCM) and version number. Columns represent one variable used, split up into Primary variables (those obtained directly from the model outputs) and derived variables (those calculated from one or more primary variables): see Table 3 for an explanation of variable codes. For each variable and model simulation we denote the scenarios available by h (historical period), 2 (RCP2.6), 4 (RCP4.5) and 8 (RCP8.5).

Global Climate Model (GCM)		Regional Climate Model (RCM)		Primary Variables								Derived Variables	
Institution and Model	Realisation	Institution and Model	Version	hurs	pr	rsds	sfcWind	sfcWindmax	tas	tasmax	tasmin	fwi	potevap
CCCma-CanESM2	r1i1p1	CLMcom-CCLM4-8-17	v1	h8	h8	h8	h8		h8	h8	h8	h8	h8
CCCma-CanESM2	r1i1p1	GERICS-REMO2015	v1		h8	h8	h8	h8	h8	h8	h8		h8
CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
CNRM-CERFACS-CNRM-CM5	r1i1p1	CNRM-ALADIN63	v2		h48	h48	h48	h48	h48	h48	h48		h48
CNRM-CERFACS-CNRM-CM5	r1i1p1	DMI-HIRHAM5	v2	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
CNRM-CERFACS-CNRM-CM5	r1i1p1	GERICS-REMO2015	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
CNRM-CERFACS-CNRM-CM5	r1i1p1	ICTP-RegCM4-6	v2	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
CNRM-CERFACS-CNRM-CM5	r1i1p1	IPSL-WRF381P	v2		h8	h8	h8	h8	h8	h8	h8		h8
CNRM-CERFACS-CNRM-CM5	r1i1p1	KNMI-RACMO22E	v2	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
CNRM-CERFACS-CNRM-CM5	r1i1p1	MOHC-HadREM3-GA7-05	v2	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r12i1p1	CLMcom-CCLM4-8-17	v1		h248	h248	h248	h248	h248	h248	h248		h248
ICHEC-EC-EARTH	r12i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r12i1p1	DMI-HIRHAM5	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r12i1p1	GERICS-REMO2015	v1		h248	h248	h248	h248	h248	h248	h248		h248
ICHEC-EC-EARTH	r12i1p1	ICTP-RegCM4-6	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r12i1p1	IPSL-WRF381P	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8

Global Climate Model (GCM)		Regional Climate Model (RCM)		Primary Variables								Derived Variables	
Institution and Model	Realisation	Institution and Model	Version	hurs	pr	rsds	sfcWind	sfcWindmax	tas	tasmax	tasmin	fwi	potevap
ICHEC-EC-EARTH	r12i1p1	KNMI-RACMO22E	v1	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
ICHEC-EC-EARTH	r12i1p1	MOHC-HadREM3-GA7-05	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
ICHEC-EC-EARTH	r12i1p1	SMHI-RCA4	v1	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
ICHEC-EC-EARTH	r12i1p1	UHOH-WRF361H	v1		h8		h8		h8	h8	h8		
ICHEC-EC-EARTH	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r1i1p1	DMI-HIRHAM5	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E	v1	h48	h48	h48	h48	h48	h48	h48	h48	h48	h48
ICHEC-EC-EARTH	r1i1p1	SMHI-RCA4	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r1i1p1	UHOH-WRF361H	v1		h8	h8			h8				h8
ICHEC-EC-EARTH	r3i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r3i1p1	DMI-HIRHAM5	v2	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
ICHEC-EC-EARTH	r3i1p1	KNMI-RACMO22E	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
ICHEC-EC-EARTH	r3i1p1	SMHI-RCA4	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
IPSL-IPSL-CM5A-MR	r1i1p1	DMI-HIRHAM5	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
IPSL-IPSL-CM5A-MR	r1i1p1	GERICS-REMO2015	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
IPSL-IPSL-CM5A-MR	r1i1p1	IPSL-WRF381P	v1		h48	h48	h48	h48	h48	h48	h48		h48
IPSL-IPSL-CM5A-MR	r1i1p1	KNMI-RACMO22E	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	v1	h48	h48	h48	h48	h48	h48	h48	h48	h48	h48
MIROC-MIROC5	r1i1p1	CLMcom-CCLM4-8-17	v1	h28	h28	h28	h28		h28	h28	h28	h28	h28
MIROC-MIROC5	r1i1p1	GERICS-REMO2015	v1		h28	h28	h28	h28	h28	h28	h28		h28
MIROC-MIROC5	r1i1p1	UHOH-WRF361H	v1		h8	h8	h8		h8				h8
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	v1		h48	h48	h48	h48	h48	h48	h48		h48
MOHC-HadGEM2-ES	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MOHC-HadGEM2-ES	r1i1p1	CNRM-ALADIN63	v1		h8	h8	h8	h8	h8	h8	h8		h8
MOHC-HadGEM2-ES	r1i1p1	DMI-HIRHAM5	v2	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
MOHC-HadGEM2-ES	r1i1p1	GERICS-REMO2015	v1		h248	h248	h248	h248	h248	h248	h248		h248
MOHC-HadGEM2-ES	r1i1p1	ICTP-RegCM4-6	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
MOHC-HadGEM2-ES	r1i1p1	IPSL-WRF381P	v1		h8	h8	h8	h8	h8	h8	h8		h8
MOHC-HadGEM2-ES	r1i1p1	KNMI-RACMO22E	v2	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
MOHC-HadGEM2-ES	r1i1p1	MOHC-HadREM3-GA7-05	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
MOHC-HadGEM2-ES	r1i1p1	SMHI-RCA4	v1	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248

Global Climate Model (GCM)		Regional Climate Model (RCM)		Primary Variables								Derived Variables	
Institution and Model	Realisation	Institution and Model	Version	hurs	pr	rsds	sfcWind	sfcWindmax	tas	tasmax	tasmin	fwi	potevap
MOHC-HadGEM2-ES	r1i1p1	UHOH-WRF361H	v1		h8	h8	h8		h8	h8	h8		h8
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	v1		h248	h248	h248	h248	h248	h248	h248		h248
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r1i1p1	DMI-HIRHAM5	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r1i1p1	ICTP-RegCM4-6	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
MPI-M-MPI-ESM-LR	r1i1p1	IPSL-WRF381P	v1	h8	h8	h8	h8	h8	h8	h8	h8		h8
MPI-M-MPI-ESM-LR	r1i1p1	KNMI-RACMO22E	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
MPI-M-MPI-ESM-LR	r1i1p1	MOHC-HadREM3-GA7-05	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r1i1p1	MPI-CSC-REMO2009	v1		h248	h248	h248	h248	h248	h248	h248		h248
MPI-M-MPI-ESM-LR	r1i1p1	SMHI-RCA4	v1a	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
MPI-M-MPI-ESM-LR	r1i1p1	UHOH-WRF361H	v1		h28	h28	h28		h28	h28	h28		h28
MPI-M-MPI-ESM-LR	r2i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC-REMO2009	v1		h248	h248	h248	h248	h248	h248	h248		h248
MPI-M-MPI-ESM-LR	r2i1p1	SMHI-RCA4	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r3i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r3i1p1	GERICS-REMO2015	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
MPI-M-MPI-ESM-LR	r3i1p1	SMHI-RCA4	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
NCC-NorESM1-M	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
NCC-NorESM1-M	r1i1p1	DMI-HIRHAM5	v3	h48	h48	h48	h48	h48	h48	h48	h48	h48	h48
NCC-NorESM1-M	r1i1p1	GERICS-REMO2015	v1	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248
NCC-NorESM1-M	r1i1p1	ICTP-RegCM4-6	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
NCC-NorESM1-M	r1i1p1	IPSL-WRF381P	v1		h8	h8	h8	h8	h8	h8	h8		h8
NCC-NorESM1-M	r1i1p1	KNMI-RACMO22E	v1	h28	h28	h28	h28	h28	h28	h28	h28	h28	h28
NCC-NorESM1-M	r1i1p1	MOHC-HadREM3-GA7-05	v1	h8	h8	h8	h8	h8	h8	h8	h8	h8	h8
NCC-NorESM1-M	r1i1p1	SMHI-RCA4	v1	h248	h248	h248	h248	h248	h248	h248	h248	h248	h248

Table 2. Breakdown of regional model ensemble size in *Klimaatlas*. For each climate variable and emissions scenario, the number of CORDEX models used in *Klimaatlas* is given. See Table 3 for an explanation of variable codes.

Variable	Number of models per scenario			
	Historical	RCP2.6	RCP4.5	RCP8.5
hurs	52	19	13	52
pr	72	27	22	72
rsds	71	27	22	71
sfcWind	71	27	22	71
sfcWindmax	65	25	22	65
tas	72	27	22	72
tasmax	70	27	22	70
tasmin	70	27	22	70
fwi	51	19	13	51
potevap	71	27	22	71

3.1.2 Observational data

Climate models differ systematically from observations because of imperfect physics, limited resolution, and uncertain parameter choices, so their raw output has biases in mean, variability, and extremes. Observations can, however, be used to "bias-adjust" model data to be more consistent with the observed climate and more suitable for impact studies and decision making.

In *Klimaatlas*, bias adjustment is based on data derived from measurement stations operated across Denmark by the Danish Meteorological Institute (DMI). These observational data are used to generate evenly spaced grids (e.g. 10×10 km for precipitation and 20×20 km for temperature) known as *Klimagrid Danmark* (KGDK) (Scharling, 1999; Scharling & Kern-Hansen, 2012; Wang & Scharling, 2010). The KGDK grid is aligned with the system *det Danske kvadratnet* (Danmarks Statistik, 2024) (Figure 2).

To align with DMI's official climate normals for mean precipitation, KGDK precipitation data that are not corrected for undercatch are employed as the basis for bias adjustment. Undercatch correction refers to adjustments applied because rain gauges are known to miss parts of the precipitation that actually falls: wind around the gauge, snow drifting over the gauge orifice, wetting loss, evaporation, and splash-out all cause recorded amounts to be too low. In Denmark undercatch bias is typically 5–10% in summer, 15–20% in winter, and larger for snowfall (Allerup & Madsen, 1980). Undercatch-corrected precipitation is based on statistical modelling and using it as the observational

reference would therefore result in a mixture of measurements and assumptions regarding wind, precipitation phase, shelter, and gauge behaviour, which may not hold everywhere or every year. Many historical records and climate normals are based on raw gauge data, so replacing them with corrected values would reduce comparability over time and complicate trend analysis and communication. Furthermore, if metadata on wind, exposure, gauge changes, or snow fraction are incomplete or inaccurate, the correction can introduce larger and less transparent errors than leaving the measurements uncorrected. All this does not, however, remove the fact that using non-corrected observations may introduce spurious biases and therefore unreliable future projections.

For each climate variable selected from the CORDEX ensemble (Table 1), a corresponding observational data product was obtained to serve as the basis for bias adjustment and calibration. Bias adjustment is carried out over a period in which model simulations and observations overlap, but observational datasets are not always available for identical years or with complete records: the temporal range of the observational product used therefore varies by climate variable (Table 3).
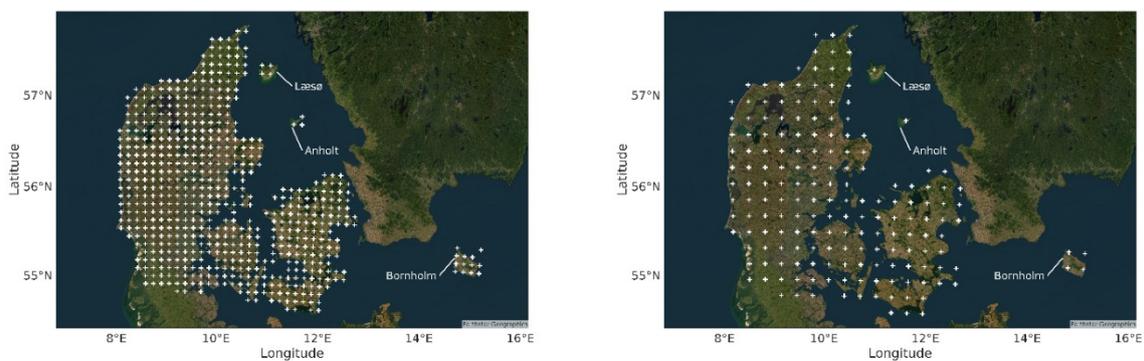
Figure 2. The *Klimagrid Danmark* grid with a 10 by 10 km resolution (left) and a 20 by 20 km resolution (right). Note the small islands of Anholt and Læsø are explicitly represented in this grid.

Table 3. Observational data used for the various climate variables in *Klimaatlas*.

ClimateVariable		Observational Product Details
Code	Name	
hurs	Relative humidity	KGDK 10x10km, Daily mean, 2011– 2022
pr	Daily total precipitation amount	KGDK 10x10km, Daily sum, 2004– 2019
potevap	Daily potential evaporation	KGDK 20x20km, Daily sum, 1989– 2019
rsds	Daily mean downward shortwave radiation	KGDK 20x20km, Daily mean,1989– 2019
sfcWind	Daily mean wind speed	KGDK 20x20km, Daily mean, 1989– 2019
sfcWindMax	Daily maximum wind speed	KGDK 20x20km, Daily mean, 2011– 2019
tas	Daily mean surface air temperature	KGDK 20x20km, Daily mean, 1989– 2019
tasmax	Daily maximum temperature	KGDK 10x10km, Daily mean, 2011– 2019
tasmin	Daily minimum temperature	KGDK 10x10km, Daily mean, 2011– 2019

3.2 Derived variables

Two additional variables are calculated based on the primary climate variables and used in further processing steps.

The Canadian Fire Weather Index System (FWI) provides information about the state of the landscape from a forest-fire-related perspective and the ability of an ignition source to spread and grow into a larger fire (Wagner, 1987). The FWI is based on time series of temperature, precipitation, relative humidity and wind, and can be calculated on a daily gridpoint-by-gridpoint basis given daily time-series of these variables. This calculation has been done in *Klimaatlas* using the xclim package (Bourgault et al., 2023) in Python, using the function `xclim.indicators.atmos.cffwis_indices()`, applying the function to both modelled and observational data.

Information about the rate of potential evaporation from a wet surface is also included in *Klimaatlas* for use by downstream users in e.g. water-balance and hydrological models. Potential evaporation is estimated from the daily solar shortwave irradiation (rsds in Table 1 and Table 3) and the daily average temperature (tas) based on the Makkink formulation employed in-house at DMI (Aslyng & Hansen, 1982; Scharling, 2001) – see "*Bilag 2*" on page 13 of this reference for the exact formulation. Note that there is a typographical error in this report that has been corrected in *Klimaatlas*: the value of the constant β_{M1} used is 0.7, not 7 as is printed in the text.

Both derived variables are bias-adjusted in the same manner as is done for the primary variables.

3.3 Bias adjustment

Model bias adjustment deals with the reality that the statistical distributions of climate model data are not identical to distributions that are reported by observational systems. The differences can lie in different mean values, or, usually, in distributions that neither have the same mean nor the same shape (spread, for instance). Methods designed to remedy this problem are called "bias-adjustment" methods here and will be discussed below.

Bias-adjustment methods generally determine a mapping between model and observations from the calibration period. The calibration period is a period where the observed and modelled time series overlap (Figure 3) and may be different for different climate variables due to observational data constraints. The mappings are based on the distributional properties of the data, but will be applied to the time-series themselves. As the mappings used here are all monotonic, the resulting series preserves the main temporal characteristics of the model: this may be important to some users as the temporal characteristics of the model are not always realistic. Bias adjustment methods can also vary based on the variable being considered. The methods are based on using observational data from, e.g., measurement stations but analyses and model-based reanalyses are also commonly used in climate services.

In *Klimaatlas* two families of bias-adjustment methods are applied. In this section, we focus on the calibration of the core and shoulders of the distribution (hereafter referred to as the non-extreme part of the distribution), which is relevant for non-extreme indicators: the second case, for indicators of extreme precipitation, is detailed in Section 4.2.1. A significant amount of work was performed in the establishment of *Klimaatlas* to investigate the choice of calibration method (DMI, 2024). Cross-validation experiments examining the performance of bias-adjustment techniques showed that bias adjustment should be performed on daily data even if only monthly means are wanted. Results were also found to be sensitive to the length of the calibration period, but in *Klimaatlas* the impact is minor since 30-year periods of calibration data are available for most variables.

The following section describes how bias adjustment for non-extreme cases is currently implemented in *Klimaatlas*, based on a combination of these initial investigations and subsequent experience with using the techniques in practice.

3.3.1 Empirical Quantile-Quantile Mapping

Klimaatlas uses an empirical quantile-quantile matching approach for bias adjustment of non-extreme aspects of a climate variable's distribution. For a model variable denoted by M, the variables M_c, M_r, and M_f refer to model values in the calibration period (c), the reference period (r), and the future period (f), respectively (Figure 3). In the calibration period we have both values for the model M_c and observations O. The calibrated model values in the reference period and the future period are denoted $\tilde{M}_r$, and $\tilde{M}_f$. Bias adjustment involves generating a mapping $M_c \rightarrow O$ which is then used to transform M_f to get $\tilde{M}_f$: $M_f \rightarrow \tilde{M}_f$.
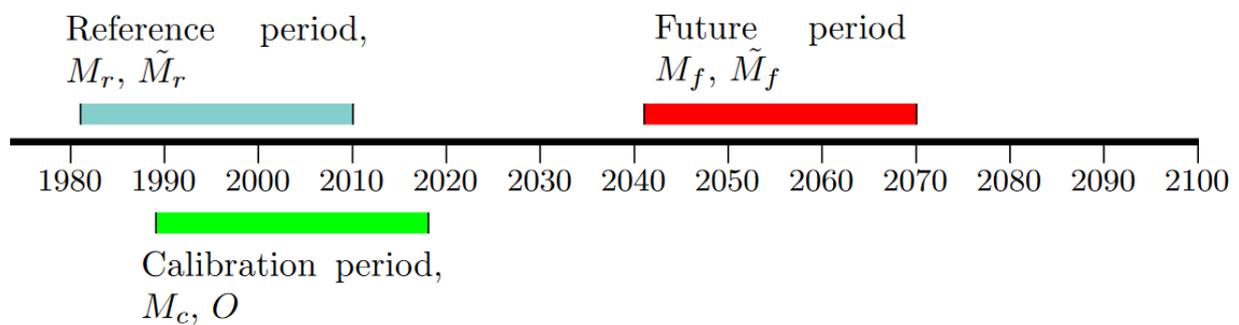
Figure 3. Time periods used in this work in connection with bias adjustment. M_c, M_r, and M_f refer to model values in the calibration period (c), the reference period (r), and the future period (f), observations are denoted by O, while $\tilde{M}_r$, and $\tilde{M}_f$ denote bias-adjusted model values in the reference and future periods respectively. Note that the time periods used here in bias-adjustment differ from those over which the final output indicators are calculated (Table 6).

Quantile-quantile (q-q) mappings are one implementation of this approach. Let F_O and F_{M_c} be the cumulative distribution functions of observations and the corresponding model variable in the calibration period, respectively. Then $\Xi = F_O^{-1}(F_{M_c})$ is the mapping for the bias-adjustment method and the calibrated values are $\tilde{M}_f = \Xi(M_f)$. Note that the distribution of $\Xi(M_c)$ is per definition identical to the distribution of O. While the q-q mapping approach can also be based on (fitted) parametric distributions of the data sets, *Klimaatlas* employs an entirely non-parametric approach, approximating each cumulative distribution function based on empirical quantiles.

3.3.2 Implementation details

The following generic procedure describes the implementation of quantile-quantile matching in *Klimaatlas*. However, in several instances there are important deviations from this approach: these are detailed in subsequent sections.

Firstly, for each model we identify "land" points in the model grid. A model grid cell is classified as land if it has at least 50% land in the specific model's land-sea fraction grid. We also specifically ensure that small islands (specifically the islands of Anholt and Læsø - Figure 2) are included by manual modification where necessary, even though the model land-sea mask may indicate a value of less than 50%.

Observational data are then regridded to the model grid. For all model grid points identified as "land", the nearest KGDK grid-point is found, and this 'nearest neighbour' time series is used as the assigned observational data point for that model grid point. We use the nearest neighbour method, rather than interpolation, to avoid the smoothing of data associated with most interpolation methods. Distance is calculated in the straight line in the RCM rotated latitude-longitude system, without accounting for "great-circle" effects.

Data quantiles are then setup. For each model, and for each of the four seasons, empirical quantiles from the 1st to 99th inclusive in steps of 1% are determined, interpolating where necessary, using daily data from both the observed and modelled datasets. A 1:1 slope is then used to extend the 99-point sequence beyond its range to higher and lower values, starting at the first and last points of the sequence (Figure 4). In earlier versions of *Klimaatlas*, this extension was based on the slope of a regression line between the model and observational quantiles: however, experience has shown that this approach breaks down in some situations, particularly with regard to extreme high temperatures and in near-coast pixels: the bias adjustment in these cases can be in excess of 10 and even 15 degrees C, resulting in unrealistically high projected temperatures. The simpler 1:1 approach avoids this problem. For wind (max and mean), precipitation, shortwave radiation, fire weather index and evaporation, the negative-side extrapolation is forced through zero to maintain physically meaningful values.

Quantile-quantile transformation is now performed using the constructed relationship. The mapping is based on linear interpolation between points on the 99-pair percentile sequence if the model value is between the maximum and minimum percentiles: if the model value falls outside this range, the linear extensions are used. The transformation is performed for each of the four seasons individually, and the results combined to provide the full time series.
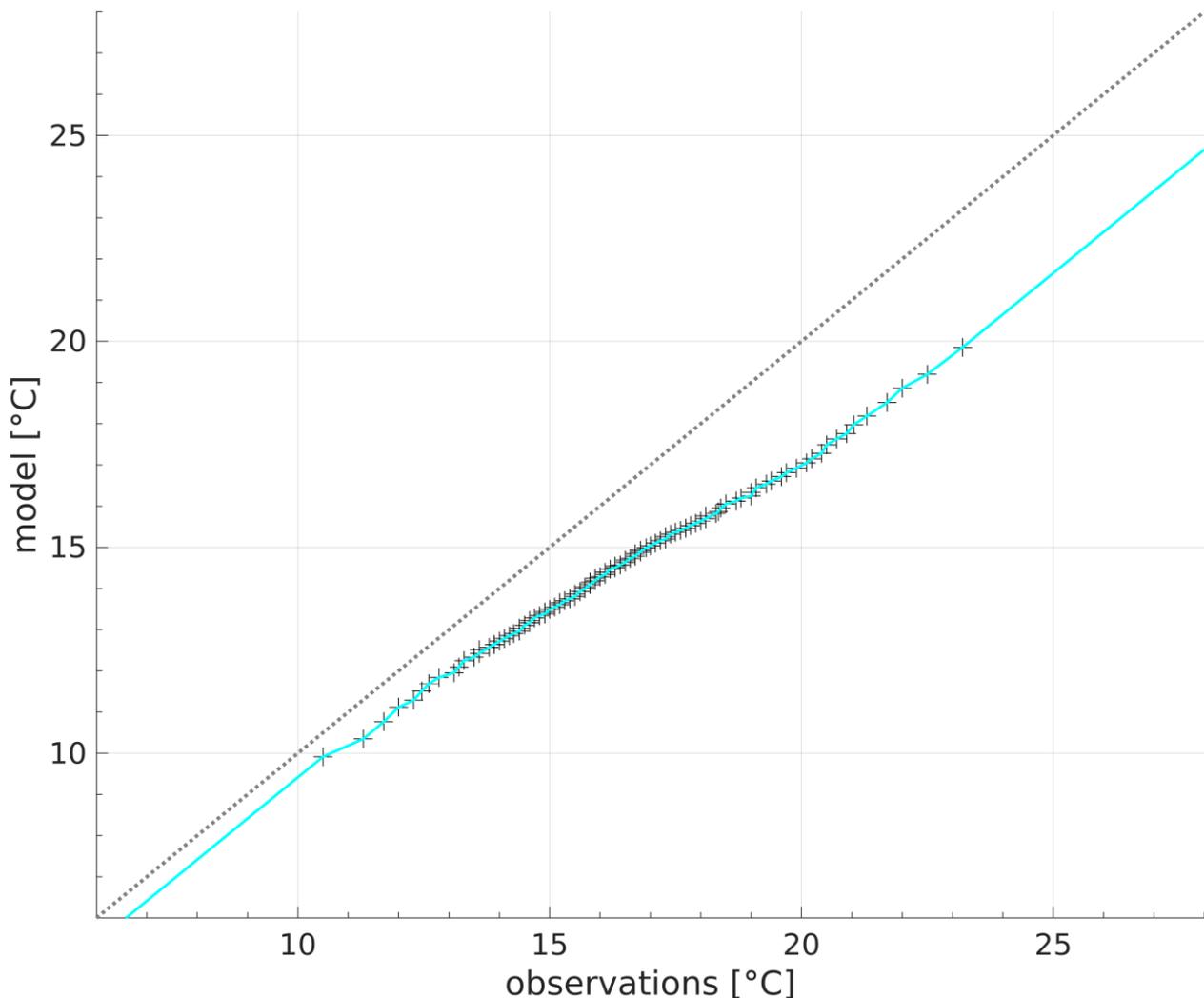
Figure 4 Example of Q-Q mapping in practice. Points correspond to the 99 pairs of empirical percentiles (from the 1st to the 99th in steps of 1%) derived from model and observational datasets. The first and last points are then extended with a straight line slope of 1. In this individual case, the model is clearly low-biased compared to observations but with a greater bias at high temperatures than in low temperatures. Data shown are for the daily mean temperature for the summer (JJA) period for the RCA/SMHI model forced by the NorESM GCM for a single grid cell with coordinates 55.8173°N, 11.5655°E.

3.3.3 Bias adjustment of temperature maxima and minima

Initial explorations in the development of *Klimaatlas* revealed that the model-fields for temperatures, their maxima and their minima – which are delivered from CORDEX as separate variables – did not all fulfil such basic requirements as $T_{min} < T_{mean} < T_{max}$. Before starting the bias-adjustment procedure for modelled daily minimum and maximum temperature, we made corrections for each model, each day and each grid cell so that T_{min} is set to the lowest value of T_{min}, T_{mean}, T_{max}, and T_{max} is given the highest value of the three variables and T_{mean} is given the middle value of the three.

For the bias adjustment of the daily maximum (T_{max}) and minimum (T_{min}) temperatures also represent a special case where there is a need to maintain the order of the two variables. While multi-dimensional bias-adjustment methods could be considered, *Klimaatlas* uses a simpler approach by calibrating the daily temperature-range and skewness as two independent variables, and then reconstructing the maximum and minimum temperatures from the bias-corrected variables. The procedure applied is as follows:

- The daily temperature range (DTR = Tmax − Tmin) is calculated for both the model and observed data sets.
- The daily skewness Z = Tmean − (Tmax + Tmin)/2 is calculated for both the model and observed data sets.
- Both DTR and Z are then bias-corrected using the generic q-q bias adjustment described above, resulting in DTRBC and ZBC. All instances where DTRBC < 0 were set to 0.
- Bias corrected Tmin and Tmax are then reconstructed using the equations Tmin,BC =Tmean,BC − ZBC − DTRBC/2 and Tmax,BC = Tmean,BC − ZBC + DTRBC/2.

3.3.4 Bias adjustment for precipitation

Three minor modifications to the bias-adjustment procedure described above are used specifically for the case of precipitation

- o Prior to application of the bias-adjustment algorithm all zero values are set to a small random number between 0 and 10^{-12} in model and observations. This approach avoids having a large proportion of the quantiles associated with zero precipitation, which can be problematic for the implementation of the quantile-quantile algorithm: however, the net effect on precipitation indicators is insignificant, due to the small size of the random number that is added.
- o As noted above, extrapolation of the quantile-quantile plot in the negative direction is done with a line passing through (0,0) which helps avoid unphysical negative values.
- o After bias adjustment, all adjusted model numbers smaller than $0.1\ \mathrm{mm\ /\ day}$ are set to zero, reflecting the limited ability of observational products to resolve precipitation below this level.

3.4 Indicators

Bias-adjusted variables (Table 3) are then used as the basis for generating indicators. Each indicator (Table 4) is associated with a three-digit code, which is used throughout *Klimaatlas* to refer to an indicator in an unambiguous manner. An individual indicator is first calculated for each member of the CORDEX model ensemble, and for each available scenario, using daily bias-

corrected values on the native EUR-11 CORDEX grid. The calculation takes place on an annual basis, and in many cases also on a seasonal basis (

Table 5), as relevant for the individual indicator. The annual/seasonal indicators are then aggregated by averaging across 30-year climatological periods (Table 6), to extract the climatological value and remove the effect of interannual variability. Finally, all indicators are calculated for all emissions scenarios available in the dataset (Table 7).

Notes regarding the implementation of individual indicators can be found in the following sections.

Table 4. Atmospheric indicators available in the current version of *Klimaatlas*.

Indicator ID	Name	Description
001	Mean temperature	Mean temperature over a year or a season.
002	Daily maximum temperature	The mean daily maximum temperature seasonally or annually. Describes the highest temperature to be expected on a typical day.
003	Daily minimum temperature	The mean daily minimum temperature seasonally or annually. Describes the lowest temperature to be expected on a typical day.
004	Maximum temperature	The maximum temperature in the season/annually, calculated as the mean of the 30 years' occurrences seasonally/annually.
005	Minimum temperature	The minimum temperature in the season/annually, calculated as the mean of the 30 years' occurrences seasonally/annually.
006	Annual temperature range	Average annual difference between highest and lowest daily-average temperature
007	Diurnal temperature range	Seasonal/annual average of the range between daily maximum and minimum temperatures.
008	Heatwave days	Number of heat-wave days annually. A 'heatwave day' is indicated when the average of the maximum temperature, over at least three consecutive days, is above 28 °C, not counting the first two days of each heatwave.
009	Warm-wave days	Number of warm-wave days annually. A 'warm-wave day' is indicated when the average of the maximum temperature, over at least three consecutive days, is above 25 °C, not counting the first two days of each warm-wave.
010	Frost days	Number of days seasonally/annually where the lowest temperature is below freezing (0 °C).
011	Growing season length	Number of days between the year's first six consecutive days of daily mean temperature above 5 °C to the year's last six consecutive days of daily mean temperatures above 5 °C.
014	Ice days	Number of 'ice days' seasonally/annually where the highest temperature doesn't exceed freezing (0 °C).
016	Zero-crossing days	Number of days where there are temperatures both above and below freezing point.
101	Mean precipitation	Mean daily precipitation across a year or a season.
102	Max daily precipitation	Maximum daily precipitation for a year or season.
103	5-day max precipitation	Maximum precipitation over any 5-day period.
104	14-day max precipitation	Maximum precipitation over any 14-day period.
105	Number of days with over 10 mm precipitation per day.	Number of days in a year/season with more than 10 mm precipitation
106	Number of days with over 20 mm precipitation per day.	Number of days in a year/season with more than 20 mm precipitation
108	Number of dry days	Number of days of the year or season with precipitation below 1 mm.

Indicator ID	Name	Description
109	Maximum dry spell length	Length of the longest period of the year or season with consecutive days with precipitation below 1 mm.
110	Fraction of years/seasons that are 'very dry'	Proportion of 'very dry' years / seasons, defined by total precipitation that would be amongst the lowest five values in the reference period (1981-2010).
111	Fraction of years/seasons that are 'very wet'	Proportion of 'very wet' years / seasons, defined by total precipitation that would be amongst the highest five values in the reference period (1981-2010).
112	Number of 5-day dry spells	Number of periods of minimum length 5 days with less than 1 mm precipitation per day
115	Number of 10-day dry spells	Number of periods of minimum length 10 days with less than 1 mm precipitation per day
116	Snowy days	Number of days over the year / season where there is a possiblity of snowfall, based on temperature and precipitation.
301	Mean wind speed	Average wind speed over a year or a season.
302	Extreme wind	Number of days in a year or season with a maximum wind speed above 25 m/s.
401	Solar radiation	Seasonal/annual average of the daily sum of the direct and diffuse radiation from the Sun reaching the (horizontal) surface.
402	Potential evaporation	The seasonal/annual average potential evaporation that could evaporate, as given by the Makkink formula
501	Mean Fire Weather Index	Mean FWI across seasons and year
502	Days with very high fire risk	Number of days with fire weather index above 18.5 ('very high')
503	Days with extremely high fire risk	Number of days with fire weather index above 29.5 ('extreme')

Table 5 Season definitions used in *Klimaatlas*.

Id	Name	Months
ann	Annual	1,2,3,4,5,6,7,8,9,10,11,12
DJF	Winter (DJF)	12,1,2
MAM	Spring (MAM)	3,4,5
JJA	Summer (JJA)	6,7,8
SON	Autumn (SON)	9,10,11

Table 6. Time periods used in *Klimaatlas*. Indicators are averaged over each of the time periods.

PeriodCode	Description (English)	Description (Danish)	Start_year	End_year
1981-2010	Reference	Reference	1981	2010
2011-2040	Beginning of century	Start århundrede	2011	2040
2041-2070	Mid century	Midt århundrede	2041	2070
2071-2100	End of century	Slut århundrede	2071	2100

Table 7. Emission scenarios used in *Klimaatlas*, across both atmospheric and sea-level/storm surge indicators. The scenario description used follows that of the IPCC and attempts to form a linkage between the relative concentration pathways (RCPs) of IPCC AR5 and CMIP5, and the shared socioeconomic pathways (SSPs) of IPCC AR6 and CMIP6

Scenario description in *Klimaatlas*	RCP Scenario used for Atmospheric indicators	SSP Scenarios used for sea-level and storm surge indicators
Very high	RCP 8.5	SSP 5-8.5
High	-	SSP 3-7.0
Medium	RCP 4.5	SSP 2-4.5
Low	RCP 2.6	SSP 1-2.6
Very Low	-	SSP 1-1.9

3.4.1 Frequency of "very wet" and "very dry" seasons / years (Indicators 110 and 111)

For use as indicators of seasonal extremes, *Klimaatlas* includes the frequency of "very wet" and "very dry" seasons. The "very wet" and "very dry" classification follows that used internally at DMI and as part of their external communication and corresponds to the 83rd and 17th percentiles of precipitation respectively. i.e. amongst the five wettest and five driest years in a 30-year climatological period. This indicator also corresponds approximately to three-month standardised precipitation indices (SPI-3) of +1 and -1 respectively, although in many cases the descriptions used in the SPI community differ. The indicators are calculated by first calculating the 83rd and 17th percentiles of precipitation during the "Reference" period (Table 6): the frequency with which precipitation in a season lies outside these threshold values is then calculated for future periods. The procedure is duplicated for annual indicatorsusing annual precipitation in place of seasonal.

3.4.2 Snowy-days indicators (Indicator 116)

While snowfall is not directly considered as a climate variable in *Klimaatlas* due to a lack of suitable data to bias-adjust against, snowfall can be inferred from temperature and precipitation. Daily snowfall amounts, *sf*, expressed as liquid-water equivalents, are calculated using daily mean temperatures *tas* and daily sums of precipitation *pr* using the equation sf = pr × α, where α is 1 for *tas* ≤ 0 °C, 0 for *tas* ≥ 2°C and -0.5 × tas + 1 for 0°C < *tas* < 2°C (Førland et al., 1996; Vejen et al., 2014). A day is considered to be a snowfall-day if more than 1mm liquid-water equivalent falls as snow (Frei et al., 2018), corresponding to approximately 1cm of snowfall.

3.5 Ensemble statistics

Each indicator is calculated for the entire ensemble of model data available, generating an ensemble of indicator values. Further processing is then performed to generate model statistics.

3.5.1 Calculation of changes

Changes in each indicator are calculated relative to the Reference period (Table 6). All indicators based on temperature (including snowfall) and the indicator for extreme-wind days are calculated as absolute changes (change=future - reference) while all other indicators (precipitation, radiation, potential evaporation, mean wind and FWI) we calculate relative changes in percent (change = 100*(future-reference)/reference). All subsequent processing steps are applied to both the absolute and relative versions of the indicators.

3.5.2 Regrid indicators to the KGDK 1x1 km grid.

Indicators on the native EUR-11 CORDEX 12km grid are regridded to the KGDK 1km grid prior to the calculation of ensemble statistics. The interpolation uses the Matlab routine `scatteredInterpolant` which uses a Voronoi triangulation of the scattered sample points to perform interpolation (Amidror, 2002; Mathworks, 2026b): natural neighbour interpolation is used between points (via setting the `Method` argument to `natural`), while linear extrapolation is used beyond these points where necessary (via setting the `ExtrapolationMethod` argument to `linear`).

3.5.3 Smoothing

Smoothing of the resulting 1x1 km grid is performed to remove small-scale artefacts that are thought to be unrealistic. We expect that the spatial structure in the reference period (i.e. the target for bias adjustment) to be more credible than modelled future spatial structures in changes and therefore use a differentiated smoothing scheme: averages over moving box-windows of size 25×25 km are used for the reference period while a 75x75 km window is used for future projections. However, due to large gradients in wind speed inland from the coasts, the smoothing is reduced for wind speed indicators (Indicators 301 and 302) compared to other indices: a 25 x 25 km filter is used for all time periods. Smoothing is implemented using the MATLAB routine `smooth2a` (Reeves, 2026). As data is only available over land, the number of grid cells available for use by the smoothing algorithm around coastal regions and for islands is naturally reduced and can potentially lead to artefacts in these regions.

3.5.4 Calculation of percentiles

The ensemble of smoothed and interpolated indicator fields is then collated and percentiles calculated for each grid cell, season (including annual values), time period, scenario and absolute and relative indicator values. The 10th, 50th, and

90th percentiles are extracted using the MATLAB routine `prctile` (Mathworks, 2026a) (with `Method` argument set to "`exact`"), which interpolates in the values presented to it.

However, a modification is applied to the directly calculated percentiles to ensure consistency. The number of RCP2.6 and RCP4.5 simulations from EURO-CORDEX can be up to a factor of 3 or more less than for RCP8.5, depending on the climate variable (Table 2), and this leads to unfortunate effects due to small sample size and model correlations (as many of the modelling systems are closely related (Kuma et al., 2023)). The error bars for RCP2.6 and RCP4.5 results therefore show a tendency to vary a lot between future time periods, as well as occasionally being unrealistically narrow. This prompts us to apply an adjustment scheme so that we can present estimated error bars for RCP2.6 and RCP4.5 results that are realistic. We ensure that:

- The RCP2.6 and RCP4.5 error bars in near future and mid-century are adjusted so that the smaller one is scaled to the width of the larger one
- the end of century error bar is scaled so that it is never the smallest of the error bars for the time periods.

The scaling algorithm applies a factor on the error bars, when scaling is called for, which retains the ratio of the upper (50 to 90 percentile interval) error bar to that of the lower (10 to 50 percentile) error bar, while keeping the median value unchanged.

A larger ensemble of models would remedy this problem from the root, but the EURO-CORDEX ensemble of models is limited in scope for the RCP 2.6 and RCP4.5 scenarios.

3.6 Area-aggregation

Indicators are aggregated over both municipalities (*kommuner*) and watersheds (*vandoplande*) for use in subsequent products targeted to these regions. For each municipality or watershed area, the 1x1 km grid-points inside the corresponding boundary polygon are first identified by finding all grid-points with centre-coordinates inside the given polygon. The mean of the 10, 50 and 90 percentiles of all pixels that fall inside the polygon are then calculated and used in subsequent products.

The following shapefiles were used as the basis for spatial averaging:

- The boundaries for municipalities (kommuner) are defined by the Danish Agency for Climate Data (Klimadatastyrelsen, KDS), as downloaded in May 2018. The shapefile can be downloaded from:
  https://www.dmi.dk/fileadmin/klimaatlas/municipalities.json
- The boundaries for main watershed areas (vandoplande) are given by the Danish Environment Protection Agency (Miljøstyrelsen), as downloaded in May 2018. The shapefile can be downloaded from:
  https://www.dmi.dk/fileadmin/klimaatlas/DK_hovedvandoplande_klimaatlas_UTM32N.json

In addition to indicators of specific regions, *Klimaatlas* also includes a region "Denmark" intended to function as a single representative value across the entire domain. For atmospheric values calculated on a regular grid, this is simply the mean of land-points within the borders of Denmark.

4 Extreme precipitation indicators

Extreme events occur rarely and both model and observations typically have only a few realisations of these events. This situation is particularly problematic for the empirical quantile-quantile bias-adjustment technique described in Section 3.3 as the tail of the empirical cumulative distribution function (CDF) is poorly defined. For extreme precipitation, an alternative approach based on extreme value analysis is therefore applied in *Klimaatlas*. This approach is implemented as an appreciably different workflow from that described above for other non-extreme indicators and is therefore considered, and documented, as a separate processing pipeline.

4.1 Data

4.1.1 EURO-CORDEX Climate runs

EURO-CORDEX climate hourly precipitation data (Table 8) have been used for the calculation of extreme-precipitation indicators in *Klimaatlas*. Data obtained directly from ESGF have been complimented with data obtained bilaterally from modelling institutions.

Table 8. List of the regional model simulations with 1 hourly precipitation used for calculating extreme precipitation indicators in *Klimaatlas*. Each row represents one model simulation with a forcing global climate model (GCM) with the associated realisation identifier (Realisation), a downscaling regional climate model (RCM) and version number (Version). For each model simulation we denote the scenarios available by a cross (x) for Historical, RCP2.6, RCP4.5 and RCP8.5 scenario experiments. The number of ensemble members associated with each scenario are given in the bottom row.

Global Climate Model (GCM)		Regional Climate Model (RCM)		Scenario			
Institution and Model	Realisation	Institution and Model	Version	Historical	RCP2.6	RCP4.5	RCP8.5
CCCma-CanESM2	r1i1p1	CLMcom-CCLM4-8-17	v1	x			x
CCCma-CanESM2	r1i1p1	GERICS-REMO2015	v1	x			x
CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
CNRM-CERFACS-CNRM-CM5	r1i1p1	CNRM-ALADIN63	v2	x		x	x
CNRM-CERFACS-CNRM-CM5	r1i1p1	DMI-HIRHAM5	v2	x			x
CNRM-CERFACS-CNRM-CM5	r1i1p1	GERICS-REMO2015	v2	x	x		x
CNRM-CERFACS-CNRM-CM5	r1i1p1	ICTP-RegCM4-6	v2	x			x
CNRM-CERFACS-CNRM-CM5	r1i1p1	MOHC-HadREM3-GA7-05	v2	x			x
ICHEC-EC-EARTH	r12i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
ICHEC-EC-EARTH	r12i1p1	DMI-HIRHAM5	v1	x			x

| Global Climate Model (GCM) | | Regional Climate Model (RCM) | | Scenario | | | |
Institution and Model	Realisation	Institution and Model	Version	Historical	RCP2.6	RCP4.5	RCP8.5
ICHEC-EC-EARTH	r12i1p1	GERICS-REMO2015	v1	x		x	x
ICHEC-EC-EARTH	r12i1p1	ICTP-RegCM4-6	v1	x			x
ICHEC-EC-EARTH	r12i1p1	MOHC-HadREM3-GA7-05	v1	x	x		x
ICHEC-EC-EARTH	r12i1p1	SMHI-RCA4	v1	x	x	x	x
ICHEC-EC-EARTH	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
ICHEC-EC-EARTH	r1i1p1	DMI-HIRHAM5	v1	x			x
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E	v1	x		x	x
ICHEC-EC-EARTH	r1i1p1	SMHI-RCA4	v1	x			x
ICHEC-EC-EARTH	r3i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
ICHEC-EC-EARTH	r3i1p1	DMI-HIRHAM5	v2	x	x	x	x
ICHEC-EC-EARTH	r3i1p1	SMHI-RCA4	v1	x			x
IPSL-IPSL-CM5A-MR	r1i1p1	DMI-HIRHAM5	v1	x			x
IPSL-IPSL-CM5A-MR	r1i1p1	GERICS-REMO2015	v1	x			x
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	v1	x		x	x
MIROC-MIROC5	r1i1p1	CLMcom-CCLM4-8-17	v1	x			x
MIROC-MIROC5	r1i1p1	GERICS-REMO2015	v1	x			x
MOHC-HadGEM2-ES	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
MOHC-HadGEM2-ES	r1i1p1	CNRM-ALADIN63	v1	x			x
MOHC-HadGEM2-ES	r1i1p1	DMI-HIRHAM5	v2	x	x	x	x
MOHC-HadGEM2-ES	r1i1p1	GERICS-REMO2015	v2	x		x	x
MOHC-HadGEM2-ES	r1i1p1	KNMI-RACMO22E	v2	x		x	x
MOHC-HadGEM2-ES	r1i1p1	MOHC-HadREM3-GA7-05	v1	x	x		x
MOHC-HadGEM2-ES	r1i1p1	SMHI-RCA4	v1	x	x	x	x
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	v1	x			x
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
MPI-M-MPI-ESM-LR	r1i1p1	DMI-HIRHAM5	v1	x			x
MPI-M-MPI-ESM-LR	r1i1p1	ICTP-RegCM4-6	v1	x	x		x
MPI-M-MPI-ESM-LR	r1i1p1	MOHC-HadREM3-GA7-05	v1	x			x
MPI-M-MPI-ESM-LR	r1i1p1	MPI-CSC-REMO2009	v1	x		x	x
MPI-M-MPI-ESM-LR	r1i1p1	SMHI-RCA4	v1a	x	x	x	x
MPI-M-MPI-ESM-LR	r2i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC-REMO2009	v1	x		x	x
MPI-M-MPI-ESM-LR	r2i1p1	SMHI-RCA4	v1	x			x
MPI-M-MPI-ESM-LR	r3i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x
MPI-M-MPI-ESM-LR	r3i1p1	GERICS-REMO2015	v1	x			x
MPI-M-MPI-ESM-LR	r3i1p1	SMHI-RCA4	v1	x			x
NCC-NorESM1-M	r1i1p1	CLMcom-ETH-COSMO-crCLIM-v1-1	v1	x			x

Global Climate Model (GCM)		Regional Climate Model (RCM)		Scenario			
Institution and Model	Realisation	Institution and Model	Version	Historical	RCP2.6	RCP4.5	RCP8.5
NCC-NorESM1-M	r1i1p1	DMI-HIRHAM5	v3	x		x	x
NCC-NorESM1-M	r1i1p1	GERICS-REMO2015	v1	x	x	x	x
NCC-NorESM1-M	r1i1p1	ICTP-RegCM4-6	v1	x	x		x
NCC-NorESM1-M	r1i1p1	MOHC-HadREM3-GA7-05	v1	x			x
NCC-NorESM1-M	r1i1p1	SMHI-RCA4	v1	x	x	x	x
		Ensemble members per scenario		52	12	16	52

4.1.2 Observation-based model of extreme precipitation in Denmark

As the observational basis for bias adjustment of extreme precipitation in *Klimaatlas*, we use an observation-based model (Madsen et al., 2017) developed by the Water Pollution Committee of the Society of Danish Engineers (*Spildevandskomiteen,* SVK). This model gives estimates of the exceedance frequency, scale- and shape- parameters for a generalized Pareto distribution on a 10x10 km grid (on *det Danske Kvadratnet*, cf. Figure 2) for both 1-hour and 24-hour durations. The model consists of three steps, carried out with hourly and 24-hourly durations separately. Firstly, an extreme value analysis (peak-over-threshold) is applied to all available stations, estimating parameters (exceedances frequency, scale and shape). For all stations, the exceedance frequency and scale parameters for each station separately are then linearly regressed against the predictors mean annual precipitation and mean exceedance of daily precipitation for that station. For the shape parameter, one common value (the average) is used for the entire country. Finally, these linear regression relations are used to give values of the parameters on all grid points in KGDK, using predictors calculated from the daily KGDK precipitation. From these parameters, any return level can be calculated for any location on the grid: these return values are used as reference values ("observations") in the subsequent bias adjustment approach. This somewhat indirect approach was used out of necessity, since stations with hourly precipitation measurements are unevenly distributed throughout Denmark, with large areas being unobserved.

4.2 Extreme value analysis

In extreme value analysis (EVA) one considers a time series, and the aim is to estimate the frequency of occurrence of rare events. In *Klimaatlas* we use the peak-over-threshold (POT) method, where all peak values above a specified

threshold x_0 and separated by a minimum time span are considered. It is assumed that peak occurrences are independent and Poisson-distributed with parameter λ_0, which is the average number of exceedances (events) per year. Alternatively, λ_0 can be specified, in which case x_0 is a stochastic variable: for our purpose, we specify λ_0, which has the advantage that it can be applied to all climate model data. Specifying a threshold would be more cumbersome, since individual climate models may have different peak heights and the threshold would therefore have to be tailored individually.

It can be shown that the distribution of the peak exceedances $x-x_0 > 0$ are approximately distributed as a Generalised Pareto distribution (GPD), with cumulative distribution function given by:

$$G(x - x_0) = 1 - \left(1 + \xi \frac{x - x_o}{\sigma}\right)^{-1/\xi}, x > x_o \qquad 4.1$$

where σ is the scale parameter and ξ the shape parameter. The frequency, λ_x, with which x is exceeded is then

$$\lambda_x = \lambda_0(1 - G(x - x_o)) \qquad 4.2$$

where λ_o is the exceedance frequency corresponding to the threshold x_o. The T-year return level, x_T, is determined as the level exceeded on average once in T years, and therefore:

$$1 = \lambda_x T = \lambda_o T[1 - G(x_T - x_0)] \qquad 4.3$$

from which we get

$$x_T = G^{-1}\left(1 - \frac{1}{\lambda_o T}\right) + x_o \qquad 4.4$$

We use the method of probability weighted moments (PWM) for estimating the parameters from data. This method gives unbiased estimates even for small samples. For more details see (Coles, 2001).

4.2.1 Analytical quantile matching

The theoretical framework above allows estimation of extreme value distributions and associated return levels. This can be applied to perform a form of bias adjustment on the extreme value distributions and thereby obtain future projected values (Schmith et al., 2021).

We make use of Equation 4.3 above, which is valid both for M_c and for O and for any return period T. If we apply this to O and M_c we obtain the expression

$$\lambda_{M_c} T(1 - G_{M_c}(M_{c_T} - M_{c_0})) = 1 = \lambda_O T(1 - G_O(O_T - O_o)) \qquad 4.5$$

relating M_{c_T} and O_T. After some manipulation, we arrive at

$$O_T = G_O^{-1}\left(1 - \frac{\lambda_{M_c}}{\lambda_O}\left[1 - G_{M_c}(M_{c_T} - M_{c_0})\right]\right) + O_o \qquad 4.6$$

Equation 4.6 defines a mapping from $M_{c,T}$ to O_T, which is then applied to $M_{f,T}$ to obtain $\tilde{M}_{f,T}$.

4.2.2 Implementation details

The following procedure is applied to all land-grid points in all available EURO-CORDEX models (Table 8), for each scenario (Table 7) and for each future period (Table 6).

- Apply nearest-neighbour interpolation from the CORDEX model grid to the 10x10 km KGDK grid. The nearest-neighbour interpolation assigns the model series in the nearest CORDEX grid point to det Danske Kvadratnet point under consideration.
- Perform extreme-value analysis (POT) for 1 and 24-hour precipitation windows covering each time period. The 24-hour analysis is performed with sliding windows covering 24 hours but advancing one hour each step. Peaks used in the analysis are required to be separated by at least 24 hours. The largest 3n peaks, where n is the number of years in the dataset, are used in the analysis.
- Use the analytical quantile matching approach (Equation 4.6) to bias adjust the return levels estimated for each return period.

4.2.3 Cloudbursts (Indicator 107)

A key and commonly used measure of extreme precipitation in Denmark is the concept of a "cloudburst", defined as more than 15 mm of precipitation within a 30-minute period. According to this definition, a cloudburst occurs roughly once in three years at a given location in Denmark, as an average across Denmark (Arnbjerg-Nielsen et al., 2023), although there is evidence of spatial variation in the frequency of cloudbursts (Antoniadou et al., 2025; Madsen et al., 2017; Schmith et al., 2023). While having such an indicator in *Klimaatlas* would be highly desirable, the extremely high resolution (sub-hourly) temporal resolution required to calculate is not available from current CORDEX model runs.

A workaround has therefore been employed, assuming that 1) a cloudburst corresponds to a return period of three years and 2) a cloudburst can be associated with an extreme in hourly precipitation. This means that the methodology from above can also be used to generate indicators of the frequency of cloud bursts. Table 8We use the hourly precipitation data from

CORDEX in *Klimaatlas* (Table 8) and identify the precipitation threshold with a return period of three years in the calibration period, x_{CB}: note that this can vary in space. The frequency of cloudbursts in can therefore be determined from the corresponding extreme value distribution for each grid point, model, time period and scenario using Equation 4.2.

4.3 Subsequent post-processing

The bias-adjusted return levels and frequency of cloudbursts calculated above can be used directly as indicators of extreme precipitation (Table 9) without the need for further modifications.

The indicators produced by this pipeline are then handled in the same way described for the atmospheric indicators for incorporation in *Klimaatlas*: see the descriptions in Sections 3.5 and 3.6.

Table 9. Extreme precipitation indicators available in the current version of *Klimaatlas*.

Indicator ID	Name	Description
107	Number of cloudbursts per year	Number of days with more than 15 mm precipitation in 30 minutes
151	2-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of two years.
152	5-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of five years.
153	10-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of ten years.
154	20-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of 20 years.
155	50-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of 50 years.
156	100-year event hourly precipitation	Precipitation-sum for one hour that occurs with a return-period of 100 years.
157	2-year event in 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of two years.
158	5-year event 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of five years.
159	10-year event 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of 10 years.
160	20-year event 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of 20 years.
161	50-year event 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of 50 years.
162	100-year event 24-hour precipitation	Precipitation-sum over 24 hours that occurs with a return-period of 100 years.

5 Sea-level rise and storm surge indicators

Klimaatlas provides projections of mean sea level rise and associated extreme sea level statistics for selected coastal stretches around the coast of Denmark. These indicators use an entirely separate processing chain from the two described above, reflecting both the inherent differences in the data upon which they are based and the different approach required to calculate these indicators. Generally, this pipeline can be viewed as consisting of two linked parts. The first part corresponds to estimates of future sea level rise, which are then used to adjust the return level curve for storm surges in the second part and calculate derived indicators. This processing pipeline is described below.

5.1 Data

Klimaatlas uses coastal stretches (*kyststrækninger*) defined by the Danish Coastal Authority (*Kystdirektoratet*, KDI) as the basic unit of analysis for its sea-level rise and storm-surge indicators. Each of these 34 stretches (Table 10) corresponds to a coastal tide-gauge station chosen for having the highest quality present day high water statistics: however, two of these coastal stretches, Ringkøbing Fjord and Nissum Fjord, are regulated by lock gates (Codes VK2 and VK3) and are therefore not included into *Klimaatlas*. The coastal stretch polygons can be downloaded from: https://www.dmi.dk/fileadmin/klimaatlas/DK_kystinddeling_klimaatlas_UTM32N.json

Sea level indicators in *Klimaatlas* are based on the sea level projections data set (Garner et al., 2021) associated with the Intergovernmental Panel for Climate Change Sixth Assessment Report (IPCC AR6) (IPCC, 2023). The IPCC AR6 sea level projections dataset contains global and regional total sea level change projections, as well as projections of individual physical processes contributing to sea level rise, each with the associated probability distribution, created using the "Framework for Assessment of Changes To Sea-level" (FACTS) (Kopp et al., 2023). The projections include contributions to sea level rise from Antarctic and Greenland ice sheets, glaciers, land water storage, ocean dynamics (including thermal expansion of the ocean), and vertical land motion. Projections are made on a regular 1°×1° grid, as well as for the locations of all tide gauge stations in the Permanent Service for Mean Sea Level database (PSMSL) (Holgate et al., 2012).

The IPCC AR6 dataset includes two types of sea level rise projections: medium and low confidence projections. Medium confidence projections rely solely on

relatively well understood processes driving sea level rise that can be simulated with medium or high confidence, while low confidence projections also include the potential impact of deeply uncertain ice sheet processes about which there is currently a low level of agreement and limited evidence, but if they occur they could significantly increase sea level (Van De Wal et al., 2022). Medium confidence projections are provided for five scenarios: SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 every 10 years from 2020 to 2150, while low confidence projections exist only for three: SSP1-2.6, SSP2-4.5, and SSP5-8.5 and are given until 2300. All projections are given as change relative to the 1995-2014 reference period. *Klimaatlas* uses the low confidence projections preferentially when available because, as noted in IPCC AR6, stakeholders with a low risk tolerance such as those planning for coastal safety, may wish to consider the estimates above the *likely* range. The corresponding medium confidence projections are available in the extended yearly dataset.

Extreme sea level statistics (*Højvandsstatistikker*) are calculated based on tide gauge records and provided by the Danish Coastal Authority (*Kystdirektoratet*, KDI) approximately every five years. The latest statistics were published in 2024 (Kystdirektoratet, 2024) and contain return levels for 20, 50, and 100-years return periods, including the uncertainties, determined from a generalized Pareto distribution based on 40 highest observed water levels at each station from the beginning of the observations at that location until 1st January 2024. 1-year return levels are obtained from an earlier version of this dataset (Kystdirektoratet, 2013), in which they are computed by directly counting the events in the tide gauge records.

Klimaatlas uses local estimates of the contribution of vertical land motion (VLM) to sea level rise instead of the one contained in the IPCC AR6 dataset. The main contribution to vertical land motion is the land uplift due to glacial isostatic adjustment (GIA), which has a strong signal in Denmark and varies significantly across the country. A VLM model specifically made for Denmark with a much higher spatial resolution (0.1° latitude and 0.2° longitude) than the IPCC dataset, and thus covering the local and regional differences better, has been developed by DTU Space (Knudsen et al., 2024). However, the 2024 KDI *Højvandsstatistikker* (Kystdirektoratet, 2024) predates the publication of this model and is based on a preliminary version: to ensure consistency between *Klimaatlas* and the KDI extreme sea level statistics, *Klimaatlas* has chosen to use the VLM rates as given in the 2024 *Højvandsstatistikker,* including the KDI

estimate of the VLM rate for the island of Bornholm (Figure 2), which is not covered by the DTU Space model.

Table 10 Coastal stretches used in *Klimaatlas*. The number, name and location (longitude, latitude) of the corresponding representative station from the 2024 KDI *Højvandsstatistikker* (Kystdirektoratet, 2024) are given. Also given is the local warning level for that coastal stretch, which serve as a threshold for DMI's storm-surge warning system.

Code	Coastal stretch	KDI 2024 *Højvandsstatistikker* Station				Warning Level (m)
		Number	Name	Longitude	Latitude	
VH1	Vadehavskyst syd	1	Vidå	8,65	54,96	2,40
VH2	Vadehavskyst central	6	Ribe	8,65	55,34	2,40
VH3	Vadehavskyst nord	7	Esbjerg	8,43	55,48	2,00
VK1	Vestkyst central	12	Hvide Sande Kyst	8,12	55,98	1,90
VK4	Vestkysten ud for Limfjorden	19	Thyborøn Kyst	8,21	56,73	1,90
VK5	Skagerrakkyst syd	20	Hanstholm	8,62	57,18	1,30
VK6	Skagerrakkyst nord	21	Hirtshals	9,96	57,63	1,30
LF1	Limfjord øst	31	Ålborg Øst	9,90	57,10	1,30
LF2	Limfjorden ved Skive	25	Skive	9,10	56,60	1,30
LF3	Limfjorden ved Lemvig	24	Lemvig	8,30	56,60	1,30
LF4	Limfjorden ved Thisted	27	Thisted	8,70	57,00	1,30
OJ1	Kattegatkyst nord	23	Frederikshavn	10,56	57,43	0,90
OJ2	Ålborg Bugt	33	Hals	10,46	56,96	1,30
OJ3	Randers Fjord og Mariager Fjord	34	Randers	10,26	56,58	1,25
OJ4	Djurslands østkyst og Anholt	35	Grenå	10,94	56,42	1,25
OJ5	Århus Bugt	36	Århus	10,21	56,14	1,25
OJ6	Lillebælt nord	38	Juelsminde	10,02	55,71	1,50
OJ7	Lillebælt central	40	Fredericia	9,75	55,56	0,84
SD1	Lillebælt syd	45	Fynshav	9,99	55,00	1,25
SD2	Sydfynske Øhav	46	Fåborg	10,23	55,10	1,00
SD3	Storebælt sydvest	51	Slipshavn	10,83	55,28	0,90
SD4	Femern Bælt	67	Gedser	11,92	54,57	1,25
SD5	Smålandsfarvandet	53	Karrebæksminde	11,65	55,17	0,95
SD6	Falsters og Møns Østersøkyst	66	Hesnæs	12,13	54,80	1,25
SD7	Faxe Bugt	64	Rødvig	12,38	55,25	1,25
SJ1	Storebælt nordvest og Odense Fjord	50	Kerteminde	10,67	55,45	1,00
SJ2	Storebælt nordøst	55	Kalundborg	11,09	55,67	1,10
SJ3	Sejrø Bugt	37	Ballen	10,65	55,82	1,25
SJ4	Nordsjællands kyst	60	Hornbæk	12,46	56,10	1,10
SJ5	Isefjord	57	Holbæk	11,70	55,73	1,00
SJ6	Roskilde Fjord	58	Roskilde	12,08	55,65	0,90
SJ7	Øresunds kyst	61	København	12,60	55,70	1,40
SJ8	Køge Bugt	63	Køge	12,20	55,45	1,10
SJ9	Bornholms kyst	69	Tejn	14,87	55,28	1,25

5.2 Sea level change

Sea level rise in *Klimaatlas* is based on the IPCC data set, modified by improved estimates of land rise rates. The projections for individual sea level change contributions from the Greenland and Antarctic ice sheets, glaciers, land water storage, and ocean dynamics (incl. thermal expansion) at the 34 stations across Denmark are extracted from the IPCC dataset (Figure 5). For locations that are in the PSMSL database and those close to a grid point (less than 5 km), nearest neighbour interpolation is used to find and extract the data, while for the remaining locations data is obtained using bi-linear interpolation from the four closest grid points. The 10th, 50th (median) and 90th percentile projections are extracted for all relevant scenarios for the 2020-2150 timespan.

Early explorations of this dataset showed that the ocean dynamics contribution for the SSP2-4.5 (medium emission) climate scenario contains spurious peaks of extremely high values at a few grid points in Denmark, most likely a numerical artefact as they are significantly higher than not only the surrounding area but also than the projections in the SSP5-8.5 (very high emission) scenario. To mitigate the impact of these extreme outliers, the spatial median of the area between 7°E to 16°E and 54°N to 58°N of the ocean dynamics contribution to sea level rise is used at all locations, as the ocean dynamics contribution is expected to have low spatial variability at these scales. Even though only one scenario contains these artefacts, the spatial median is used for all emission scenarios to maintain consistency.

The VLM contribution to sea level change relative to the 1995-2014 reference period is used from the KDI *Højvandsstatistikker* (Kystdirektoratet, 2024), which are based in turn on the DTU Space VLM model. As this model does not include uncertainties, they are considered to be zero, and consequently the 10th, 50th, and 90th percentile projections are identical.

Total sea level change is then calculated from its contributions (e.g. Figure 5) by adding their medians and combining the uncertainties:

$$SLR_{tot}^{50} = \sum_i SLR_i^{50} \qquad\qquad 5.1$$

$$\Delta SLR_{tot} = \sqrt{\sum_i (\Delta SLR_i)^2} \qquad\qquad 5.2$$

where SLR_{tot}^{50} and ΔSLR_{tot} are the median and the uncertainty of the total sea level change, SLR_i^{50} median of contribution *i*, and ΔSLR_i the corresponding

uncertainty. The lower (ΔSLR^{10}) and the upper (ΔSLR^{90}) uncertainties differ and are defined as:

$$\Delta SLR^{10/90} = \left| SLR^{50} - SLR^{10/90} \right|$$

5.3

where $SLR^{10/90}$ are the 10th and the 90th percentiles of sea level change. Equations used to calculate the 10th and the 90th percentile of total sea level change are therefore:

$$SLR_{tot}^{10} = SLR_{tot}^{50} - \sqrt{\sum_i \left(SLR_i^{50} - SLR_i^{10} \right)^2}$$

5.4

$$SLR_{tot}^{90} = SLR_{tot}^{50} + \sqrt{\sum_i \left(SLR_i^{50} - SLR_i^{90} \right)^2}$$

5.5

As *Klimaatlas* uses a different reference period (1981-2010) than the IPCC sea level dataset, the projections are adjusted to match it. First, yearly values are computed from the 10-year temporal resolution by linearly interpolating the time series, including between 2005, when sea level change is by definition zero as it is the centre of the dataset's reference period, and 2020, when the projections start. Values between 1995 and 2005 are obtained by linear extrapolation. Finally, the time series are shifted such that values are zero in 1995, the central year of the *Klimaatlas* reference period.
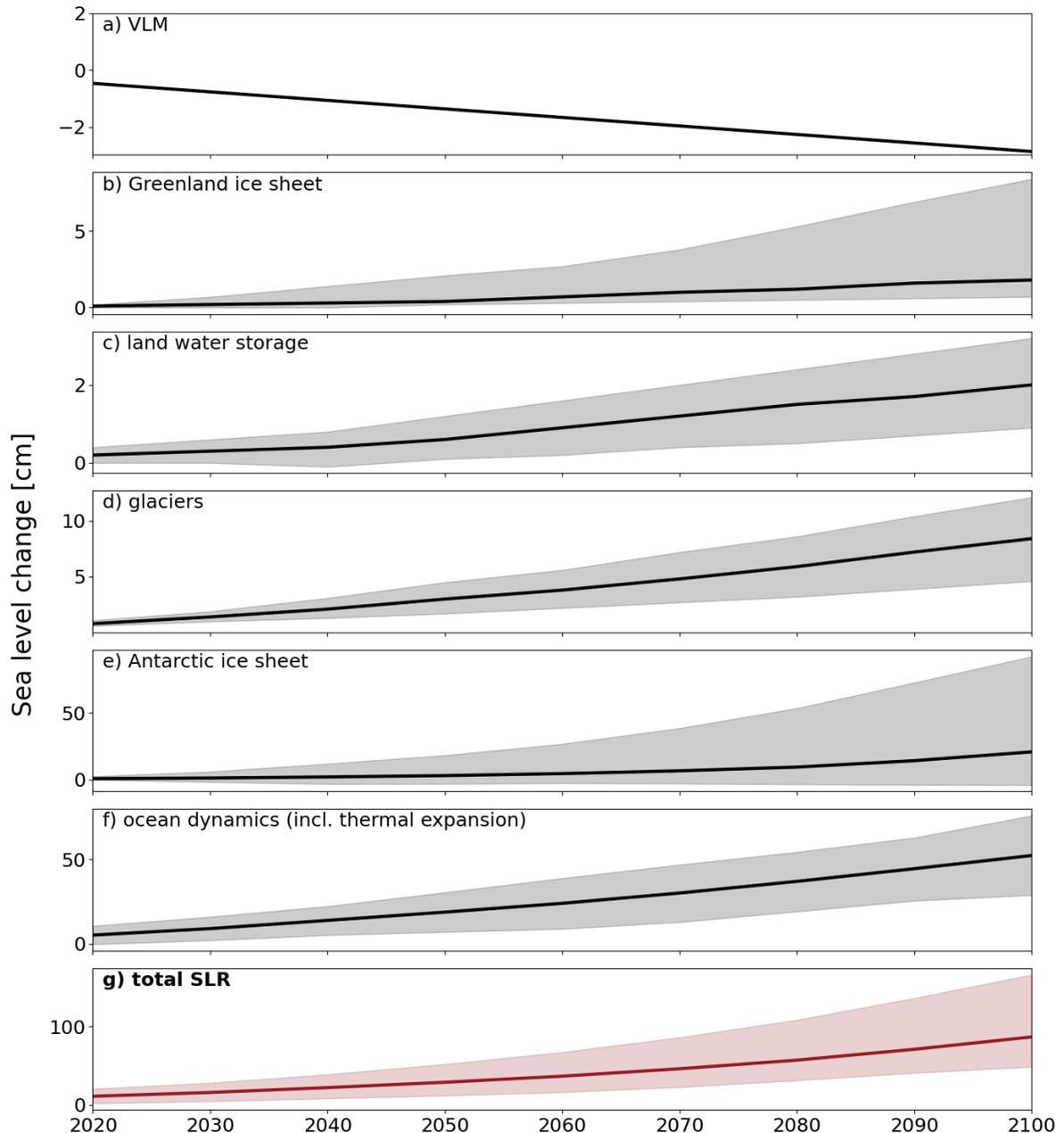
Figure 5 Sea level change contributions (a-f) and total sea level change (g) relative to the 1995-2014 reference period for the Vadehavskyst nordlig coastal stretch (represented by the station Esbjerg) in SSP5-8.5 scenario. Shading spans the 10th – 90th percentiles, while the solid line is the median (50th percentile).

5.3 Return levels of extreme sea level events

For each of the 34 coastal stretches in *Klimaatlas*, the 20, 50, and 100-year return levels are extracted for the appropriate station from the 2024 *Højvandsstatistikker* (Kystdirektoratet, 2024), while the 1-year return levels are taken from an earlier version (Kystdirektoratet, 2013). Return levels from both datasets are adjusted to the *Klimaatlas* 1981-2010 reference using the sea

level change rates provided for each station, also provided in the 2024 *Højvandsstatistikker* (Kystdirektoratet, 2024). The 5-year return level at each location is then obtained by interpolating between 1-year and 20-year return levels in the log-period space.

Observations at the station Fåborg, representative for the Sydfynske Øhav coastal stretch, only started in 2000, so it is included in the 2024 version of *Højvandsstatistikker*, but the observed time series was too short to be included in the 2012 version, from which *Klimaatlas* draws the 1-year return levels, necessitating an alternative source for it. Typically, the 40 highest observed sea levels used to find the return level distribution are well above the 1- or even 5-year return periods, making this method unsuitable for the calculation of the 1-year return levels. However, the relatively short Fåborg series in the 2024 dataset has enough data points with short return periods, allowing reliable extraction of high frequency return levels from the fitted distribution. Therefore, the 1- and 5-year return levels for Fåborg are taken directly from the return level distribution given in the 2024 *Højvandsstatistikker* (Kystdirektoratet, 2024).

Future projections of extreme sea levels are computed by combining the historical storm surge statistics with sea level rise projections using the same principles as in the previous section:

$$RL^{50}_{proj} = RL^{50}_{hist} + SLR^{50}_{tot} \qquad\qquad 5.6$$

$$RL^{10}_{proj} = RL^{50}_{proj} - \sqrt{\left(RL^{50}_{hist} - RL^{10}_{hist}\right)^2 + \left(SLR^{50}_{tot} - SLR^{10}_{tot}\right)^2} \qquad 5.7$$

$$RL^{90}_{proj} = RL^{50}_{proj} + \sqrt{\left(RL^{50}_{hist} - RL^{90}_{hist}\right)^2 + \left(SLR^{50}_{tot} - SLR^{90}_{tot}\right)^2} \qquad 5.8$$

where RL^{10}_{proj}, RL^{50}_{proj}, and RL^{90}_{proj} are the 10th, 50th, and 90th percentiles of the projected future return levels, RL^{10}_{hist}, RL^{50}_{hist}, and RL^{90}_{hist} represent the historical storm surge statistics, and SLR^{10}_{tot}, SLR^{50}_{tot}, and SLR^{90}_{tot} are the median and uncertainties of the total sea level change calculated above (e.g. Figure 6). This calculation is performed for the 34 stations representing coastal stretches in *Klimaatlas*, for every year between 1995 and 2150 and for all scenarios provided in the IPCC dataset.

a) Sea level change projections

b) Projections of return levels in SSP585 for year 2085
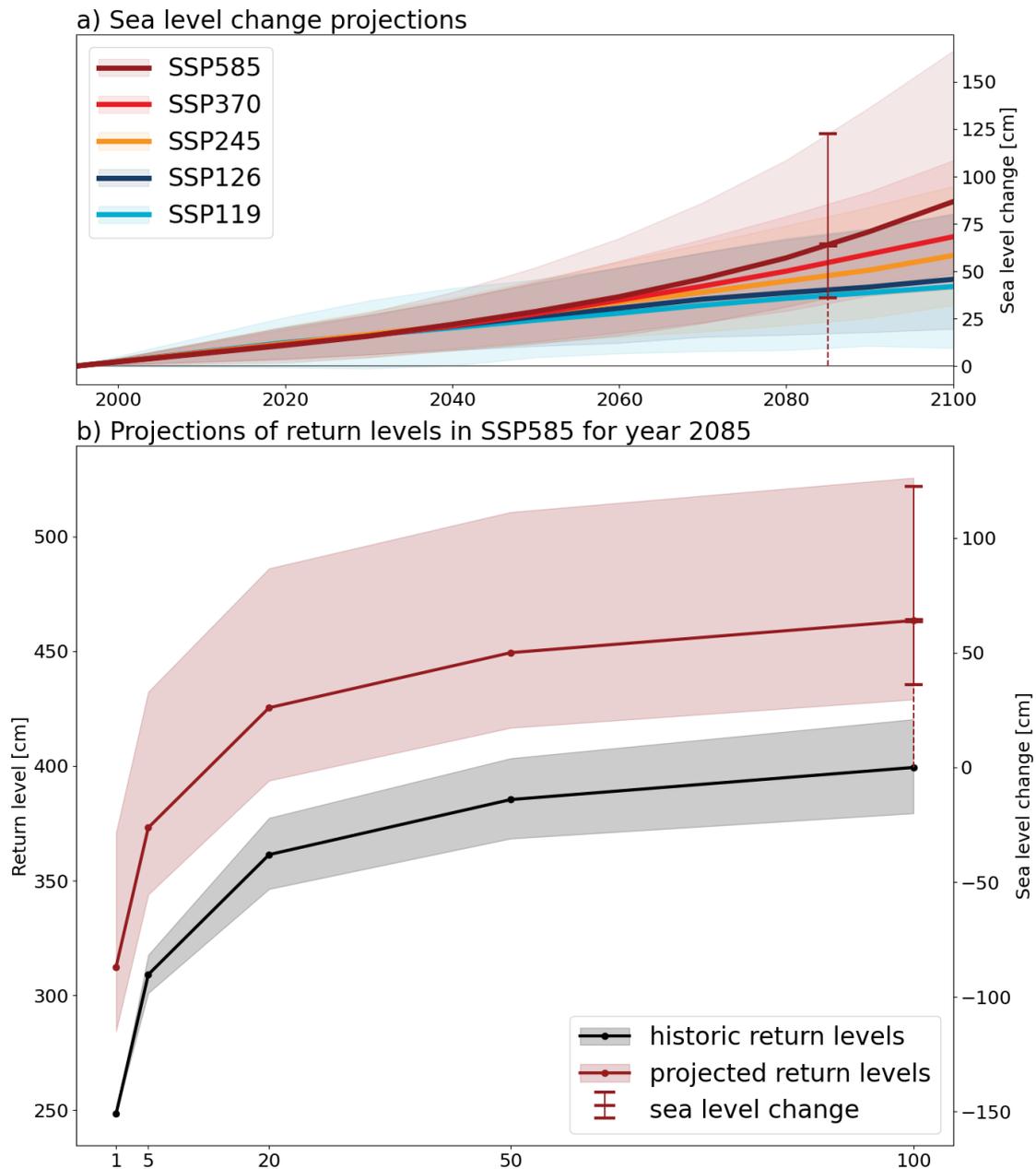
Figure 6 Calculating return levels for the *Vadehavskyst nordlig* coastal stretch (represented by the station Esbjerg) for year 2085 in the SSP5-8.5 scenario. (a) Projected sea level changes relative to the 1995-2014 reference period for the SSP scenarios, with the red vertical line showing the median and the uncertainties of the sea level change in year 2085 in SSP5-8.5. (b) Adding the sea level change to the historical return levels to obtain the return level projections in year 2085 in the SSP5-8.5 scenario. Shading spans the 10th-90th percentiles, while the solid lines depict the median (50th percentile).

5.4 Frequency of extreme sea level events

Frequency indicators represent the future frequency with which a threshold water level will be exceeded in the future. These indicators take their point of departure, for example, in the water levels associated with 20- and 100-year

events in the "reference" climate period (1981-2010) (Table 10). Such indicators are calculated by first converting the return periods to logarithmic scale, and then for each of the levels, interpolating the projected return level curve to obtain the future return period (Figure 7). If the future frequency of extreme event is less than 1 event per year (lowest value in the return level curve), the return level curve is linearly extrapolated using the 1- and 5-year return levels. The same process is applied to the median and the 10th percentile. However, this process can result in extremely large values for the 90th percentile and in some cases for the median, which fall outside the reliable range of the datasets they are based on: a limit is therefore set to 3 extreme events per year. The future return periods are then converted to frequency of events in 20 years for the 20-year event, and 100 years for the 100-year event.
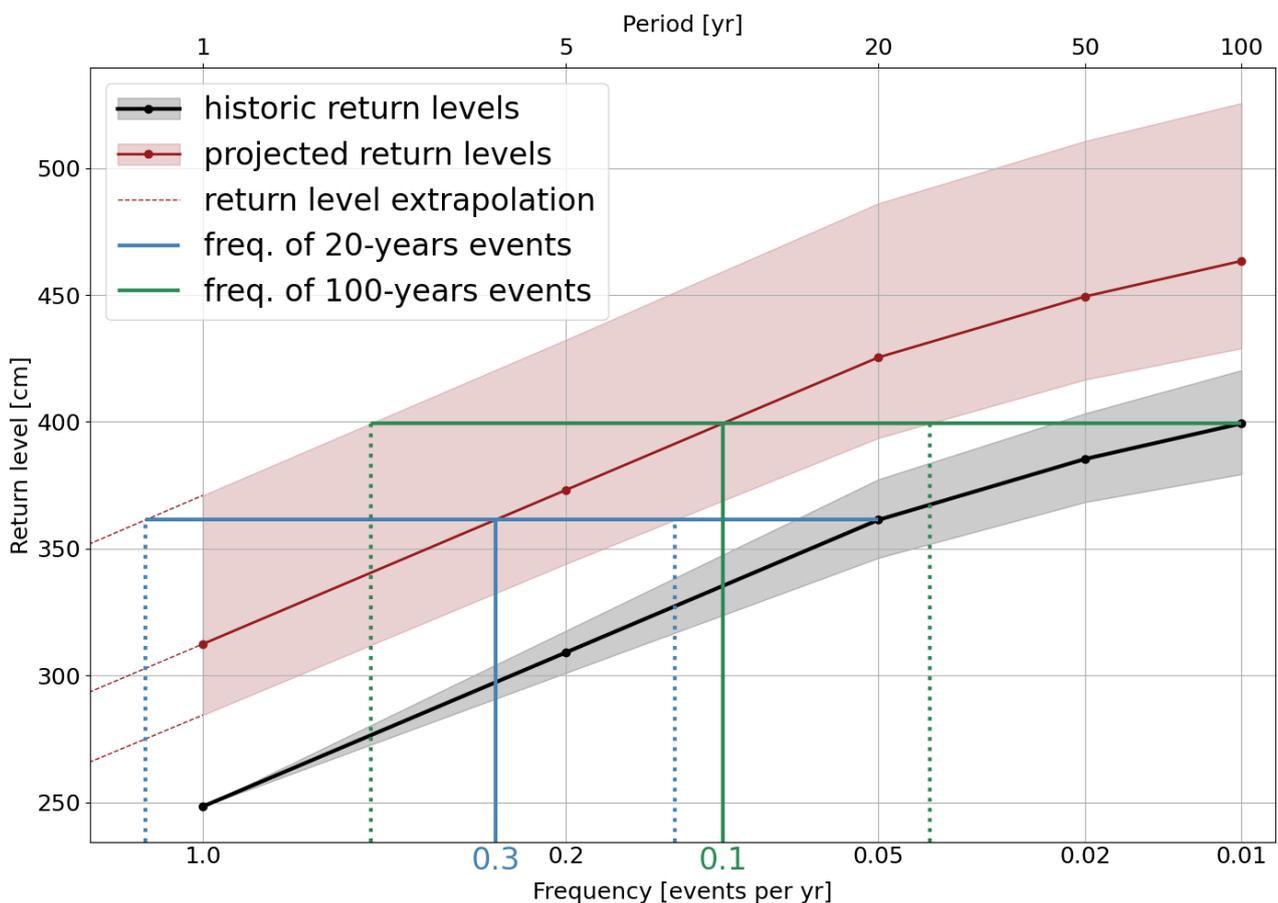
Figure 7 Calculating frequency indicators for the *Vadehavskyst nordlig* coastal stretch (represented by the station Esbjerg) for year 2085 in the SSP5-8.5 scenario. Shading spans the 10th-90th percentiles, while the solid line depicts the median (50th percentile).

5.5 Implementation details

Temporal averages are calculated from the yearly projections for each period used in *Klimaatlas* (Table 6) and for each coastal stretch, indicator and emission scenario.

In addition to indicators of coastal stretches, *Klimaatlas* also includes a region "Denmark" intended to function as a single representative value across the entire domain. Defining a representative value for coastal stretches is not as straightforward as it is for atmospheric indicators, due to the varying sizes and amount of coastline associated with these polygons. The decision was therefore made to use a simple mean across the 34 coastal stretches for sea level rise and most storm surge indicators. However, indicator 210, "Frequency of storm surge 20-year event", shows an asymmetrical distribution with a long tail: in this case the use of a median was clearly more representative of the centre of the distribution and was employed instead of a mean.

5.6 Indicators

An overview of the sea-level and storm-surge indicators present in *Klimaatlas* can be found in Table 11.

Table 11 Sea-level and storm-surge indications in *Klimaatlas*.

Indicator ID	Name	Description
201	Mean sea level	Mean sea-level with respect to coastline
202	Storm surge 20-year events	Height of storm surge of the 20-year event, relative to reference level.
203	Storm surge 50-year event	Height of storm surge of the 50-year event, relative to reference level.
204	Storm surge 100-year event	Height of storm surge of the 100-year event, relative to reference level.
206	1-year sea level event	Height of the sea level of the 1 year event, relative to reference level.
208	5-year sea level event	Height of the sea level of the 5 year event, relative to reference level.
210	Frequency of storm surge 20-year event	Frequency with which the historical 20-year storm surge level will be exceeded in a future climate
213	Frequency of storm surge 100-year event	Frequency with which the historical 100-year storm surge level will be exceeded in a future climate

6 Output formats

Klimaatlas data are brought together in a webpage, www.klimaatlas.dk, used to both disseminate data and provide the necessary supporting information and documentation. The primary language of the webpage is in Danish: however, experience has shown that online tools that allow translation of browsed websites work extremely well with *Klimaatlas*, allowing the user to view the website in other languages.

This section provides an overview of the output formats.

6.1 Data explorer

The core of the *Klimaatlas* website is the data explorer, which provides direct and easy access to all indicators for all regions across Denmark: https://www.dmi.dk/klima-atlas/data-i-klimaatlas (Figure 8). At the top of the page the user is presented with menu dropdowns giving the ability to select a grouping of climate variables (e.g. Precipitation, Temperature), the spatial scheme (e.g., municipalities, major watersheds), the region within that scheme (e.g. Copenhagen municipality), the season (e.g.

Table 5), and whether to present the data as an absolute value or relative to the historical period (1981-2010). Below the dropdowns, the user can see a map of Denmark, with the appropriate spatial scheme and a background raster showing the change in the indicator of choice, zoomable to the native 1 km resolution of *Klimaatlas*: here the user can select the emissions scenario (e.g. Table 7), time period (Table 6) or the indicator to show.

Below the map viewer, a bar chart presents the same data as that selected above, but with all emissions scenarios and time periods, rather than the single scenario – period combination presented as a map. The user can switch between spatial regions of interest by clicking on each polygon. Roll-over tool-tips provide the value of the corresponding indicator, with uncertainties.

Finally, at bottom right, links are provided to download data products that correspond to the selection.
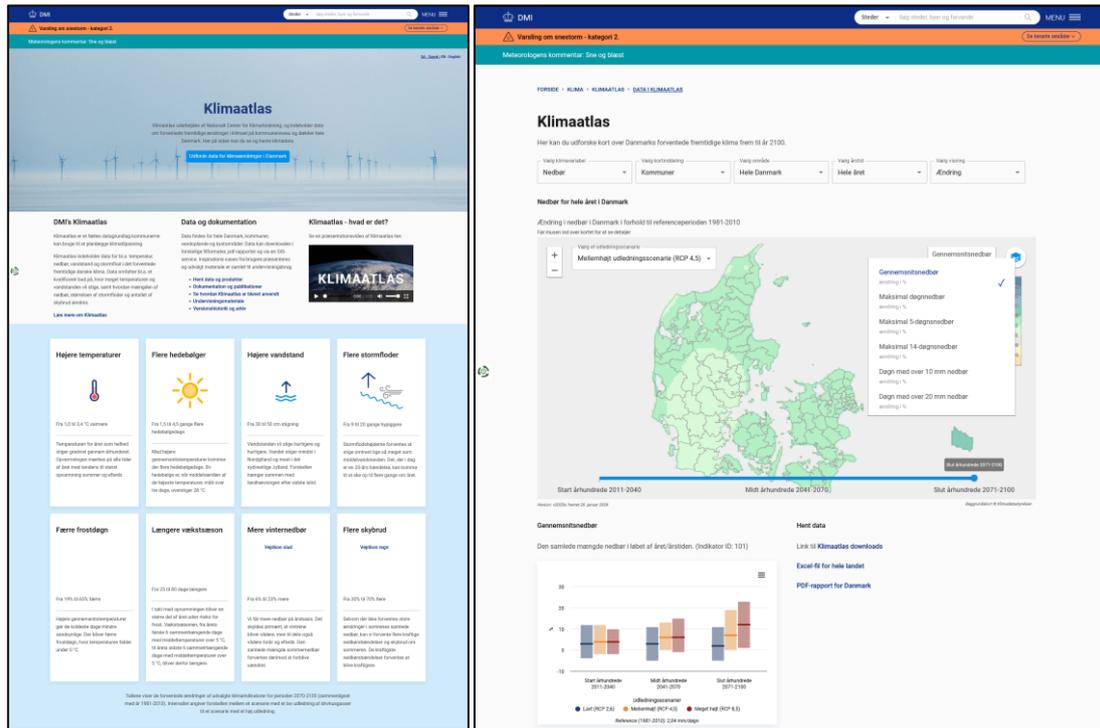
Figure 8 (Partial) screen shots of the *Klimaatlas* webpage. At left, the front land-page, providing access to the data explorer (blue button), links to various pages, and a brief overview of the main results. At right, the data explorer (https://www.dmi.dk/klima-atlas/data-i-klimaatlas), shows changes in the annual average precipitation across Denmark in a medium-high emissions scenario (RCP 4.5) (top figure) and a bar chart showing the same change under different scenarios (bottom left). Screenshot taken 26 January 2026.

6.2 Municipality (Kommune) reports

Klimaatlas presents reports tailored to users in the 98 Danish municipalities (*kommuner*), in the form of tailored summary reports, together with a report covering the entire country of Denmark. Although the reports are written in Danish, an English-language version of the "Denmark" report has also been developed. Each report contains the following elements:

- An introduction to Klimaatlas and its use, including interpretation and use of emissions scenarios, time periods, uncertainties and in the interpretation of Klimaatlas figures
- Highlights of Denmarks future climate (Denmark report only)
- An overview of indicators relating to future changes in temperature in the municipality/Denmark
- An overview of indicators relating to future changes in precipitation in the municipality/Denmark

- In cases where the municipality has a coastline, an overview of indicators relating to future sea level rise and storm surges. For the Denmark report, three representative coastal stretches are chosen.
- A half-page description of the current climate in each municipality, noting certain key climatic and weather features, derived from (Scharling & Cappelen, 2017) (Municipality reports only).
- A summary table showing all of the indicators included as figures in numeric form.

Each report is machine-generated based on an R-markdown template. While figures showing changes in each indicator for the three time-periods and all emissions scenarios, in the style of the data explorer (Figure 8), are included and tailored to the municipality, the actual textual content of the reports is generic (with the exception of the description of the climate in each municipality). The goal of the reports is to provide an overview of the important changes that will result as a function of climate change, without being exhaustive: reports are typically 10-14 pages in length.
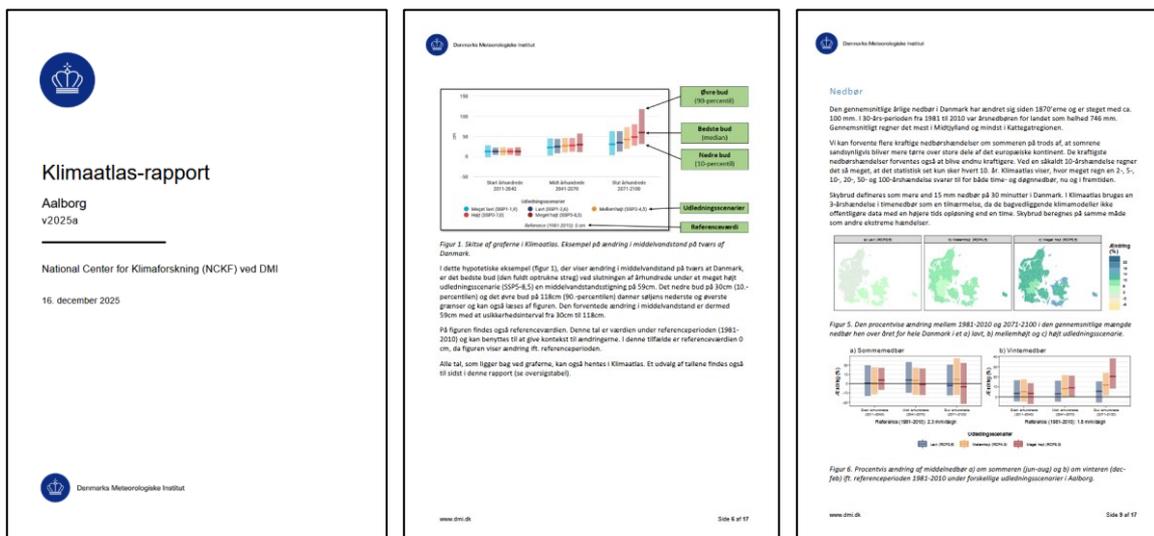
Figure 9 Example pages from the municipality (*kommune*) report for Aalborg Kommune v2025a. Title page (left panel). Example of introductory material, explaining how figures should be interpreted (centre panel). Example of the section on precipitation (*Nedbør*), with introductory text, a panel-plot showing systematic changes for Denmark as a whole, and changes in specific indicators for Aalborg (right panel).

6.3 Excel spreadsheets

The most comprehensive format for the distribution of *Klimaatlas* data is in the form of Microsoft Excel spreadsheets. Over 150 different spreadsheets are available, each representing different subsets of the data that are relevant to individual users, as follows:

- A spreadsheet that covers all Klimaatlas core data, with Danish metadata and descriptions
- A spreadsheet that covers all Klimaatlas core data, with English metadata and descriptions
- A spreadsheet that only contains indicators for coastal stretches
- A spreadsheet that only contains indicators for watershed areas,
- A spreadsheet that only contains indicators for municipalities.
- 23 watershed spreadsheets, one for each individual watershed area and one for all of Denmark
- 35 coastal stretch spreadsheets, one spreadsheet for each individual coastal stretch and one for all of Denmark
- 98 municipality spreadsheets, one for each municipality including both atmospheric indicators averaged over the municipality's region and sea-level and storm surge indicators from neighbouring coastal stretches, as appropriate.
- One spreadsheet only containing indicators for all of Denmark

All spreadsheets are in Danish, with the exception of an English language-version containing all *Klimaatlas* data. The structure of each spreadsheet is broadly similar, consisting of three sheets. The first sheet is an introduction to the data, defining the contents and providing background information, including how to cite *Klimaatlas* data. The second sheet provides details about the indicators presented, including a description of their calculation (see e.g. Table 4, Table 9 and Table 11). The final sheet provides the data itself in the form of a large flat table that can be filtered using Excel's built-in filtering functions.

Figure 10 Screenshot of the English language Excel spreadsheet from v2025a containing all indicators for all area types.

Excel spreadsheets are used here as the main dissemination format as they reflect the usage patterns of users of *Klimaatlas*: however, Excel spreadsheets can also be opened in non-commercial spreadsheet software such as LibreOffice, in R via the readxl package (Wickham & Bryan, 2025) and in python via the pandas library (Pandas development team, 2020).

6.4 GIS-oriented data layers

Many early users expressed an interest in getting *Klimaatlas* data in a format that could be used in conjunction with GIS (geographic information systems) clients. Developing such a delivery format has proved challenging, as it is not a customary format within climate science and the procedure has been refined several times since the launch of *Klimaatlas*. The current GIS service consists of two components:

- Publication of all indicators averaged over polygons (municipalities, watersheds and coastal stretches) as a web feature service via the ArcGIS open data portal: https://klimaatlas-dmidata.opendata.arcgis.com/ (Figure 11).
- Publication of indicators on a 1 km raster grid as GeoTIFF files covering all of Denmark for direct download and importing into a GIS client via https://download.dmi.dk/Research_Projects/klimaatlas/latest/geotiff_indicators/

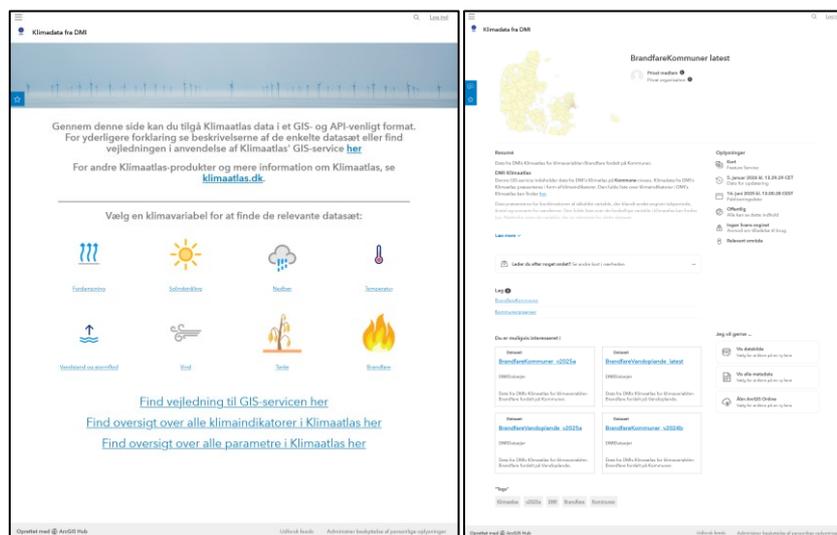Documentation for the use of these products is included on the ArcGIS open data portal.

Figure 11 Screenshots of the *Klimaatlas* ArcGIS open data portal. Left panel: landing page, providing a link to document and to the individual groups of indicators. Right panel: example of data page for fire weather indicators.

6.5 Products for specialist users

6.5.1 Version archive tool

Many users of *Klimaatlas* have, on occasion, the need to understand how data in *Klimaatlas* has changed over time e.g. in connection updating of climate action plans and climate adaptation plans at the municipal level. While *Klimaatlas* features a version history (*Versionshistorik*), providing access to data in previous versions (https://www.dmi.dk/klima-atlas/versionshistorik), a version archive tool has also been developed to enable a direct comparison between versions. This spreadsheet contains the values of the median estimates of all indicators produced in *Klimaatlas* for all regions, scenarios, time periods and seasons over all versions, allowing a quick and easy way to quantify the differences between versions of indicators. Due to size limitations associated with the Microsoft Excel spreadsheet format, it has not been possible to include the 10th and 90th percentiles: these values are available on request from the *Klimaatlas* team.

6.5.2 NetCDF indicators

Gridded values of *Klimaatlas* indicators on a 1km UTM grid covering Denmark are available for all indicators as NetCDF files. These products are otherwise identical to the GeoTIFF products described above.

6.5.3 Extended sea-level rise dataset

Klimaatlas provides an extended sea-level-rise dataset for expert users with higher time resolution, more scenarios and a longer temporal coverage. The dataset is extracted from the sea-level rise processing pipeline detailed above (Section 5.2), prior to averaging over 30-year periods. The dataset includes estimates of sea level rise annually from 1995 to 2150, as well as all medium confidence and low-confidence scenarios.

6.5.4 Daily bias-corrected data

Klimaatlas also publishes bias-corrected atmospheric climate variables for all ensemble members for use by expert users. The dataset is extracted from the processing pipeline after bias adjustment (Section 3.3) but prior to atmospheric indicator calculation (Section 3.4) for which it forms the input. All climate variables used in *Klimaatlas* (Table 2) are made available, with the exception of humidity and the fire-weather index, for all models, emissions scenarios and time periods. In addition to the native EURO-CORDEX 12km grid employed at this stage of the pipeline, the data is also interpolated using bilinear interpolation onto the 1km grid "*Det Danske Kvadratnet*" (Figure 2) used

elsewhere in *Klimaatlas*. The dataset can be used for further calculations or as boundary conditions in a users' own models, e.g. impact models.

The dataset is large (multiple TBs in size), and a spreadsheet has been created to provide an easy overview. This spreadsheet contains seasonal and annual averages across all of Denmark for each file, which can be used as a basis for subsetting the ensemble if relevant (e.g. to identify the warmest or wettest models). URLs, filesizes and MD5 checksums are also provided for each file to enable automated downloading of a large set of files.

6.5.5 Education material

With the development of *Klimaatlas* and a growing public interest in climate change, a demand emerged for more easily accessible climate data for educational purposes. The aim was to enable students in primary and upper secondary schools to work with the same data that form the basis of *Klimaatlas* and for municipal climate adaptation strategies. This approach provides a way to integrate socially relevant issues into the teaching of geography, mathematics, and physics.

For educational and training purposes, *Klimaatlas* data used to calculate the climate indices and associated uncertainties are compiled and provided in an Excel dataset. This dataset allows users to recalculate or modify any temperature- or precipitation-based climate index, along with its corresponding uncertainty, for specific exercises. The dataset includes annual time series of temperature and precipitation averaged over Denmark for the period 1981-2100 for each of the 72 climate models contributing to *Klimaatlas*, and for each of the three emission scenarios: Low, Medium High and Very High (RCP2.6, RCP4.5, and RCP8.5, respectively).

The demand for climate data comes from both primary and upper secondary schools, but also from companies and organisations that develop targeted teaching material for these educational levels. Two examples of teaching material developed for primary and upper secondary schools and which draw on data from *Klimaatlas*, are:

- A teaching programme entitled "*Vandkamp*", developed by NOVO LIVE in collaboration with DMI https://undervisning.life.dk/vk
- Teaching material prepared through a collaboration between Rysensteen Gymnasium and DMI https://lru.praxis.dk/Lru/microsites/virksomhederiundervisningen/dmi_film.html.

7 Dataset Availability

Data described in this manuscript can be accessed in the Zenodo repository under the DOIs given in Table 12. While *Klimaatlas* data is primarily delivered to users through the website www.klimaatlas.dk, Zenodo provides a DOI and permanent archive of all versions. Archived versions include all municipality reports and excel spreadsheets together with the corresponding technical description of the data and gridded indicators as NetCDF and, more recently, GeoTIFF files (see Section 6). Note that due to the large size, daily bias-corrected data are not included in the Zenodo archive. An overview of all *Klimaatlas* versions with the main changes and DOIs for the data is given here (Table 12).

Version	Main changes in this version and DOI

v2025a (latest) Dec 2025	• Addition of four new indicators that provide a more nuanced picture of future winters
	   ○ 014. Days with ice cover
	   ○ 016. Freezing point passages
	   ○ 111. Proportion of years/seasons that are 'very wet'
	   ○ 116. Days with snowfall
	• All other indicators from previous editions are also included in this dataset.
	• Addition of a new version archive with indicators from all previous versions of *Klimaatlas* dating back to the first version enabling comparison across editions.
	• Technical improvements to bias adjustment calculations for atmospheric variables. All relevant indicators have been recalculated, and the changes are generally minor.
	• DOI: https://doi.org/10.5281/zenodo.17491764

v2024b Nov. 2024	• All sea level and storm-surge indicators have been updated in line with the latest version of the Danish Coastal Authority's "*Højvandsstatistikkerne*" from July 2024, revised 5th November 2024.
	• Addition of two new SSP emissions scenarios, SSP1-1.9 and SSP3-7.0, for sea level and storm surge indicators
	• Addition of 1 indicator
	   ○ Frequency of current 100-year storm surge event
	• Removal of 3 indicators
	   ○ Total duration of high-water warnings
	   ○ Frequency of high-water warnings
	   ○ Height of a 10 000 year storm surge event
	• All other indicators from previous versions can also be found in this dataset.
	• The reference year for sea level is moved from 1990 to 1995, giving a minor shift across all stations of around 2cm.
	• Addition of two new climate models to the dataset for the maximum and minimum daily temperatures. All relevant indicators have been recalculated with the expanded ensemble.
	• DOI: https://doi.org/10.5281/zenodo.13753022

Version	Main changes in this version and DOI
v2024a Jun. 2024	• Addition of three new indicators for fire danger o Average of the fire danger index. o Days with 'very high' fire danger. o Days with 'extreme' fire danger. • Addition of three new indicators for dry periods o Dry periods of minimum 5 days. o Dry periods of minimum 10 days. o Proportion of years/seasons that are 'dry'. • All indicators from previous versions are also available in this dataset. • 7 new climate models have been added to the ensemble, increasing the number of models to 72. All indicators have been recalculated with the extended ensemble. • The format of the Excel spreadsheets has been updated with a focus on machine readability. • DOI: https://doi.org/10.5281/zenodo.11402836
v2022a	• Addition of a third emission scenario, RCP2.6. • Update of sea level indicators to the latest IPCC report (AR6). • The model ensemble has been expanded to include up to 65 climate models. • DOI: https://doi.org/10.5281/zenodo.18416944
v2021a	• Addition of two new indicators for storm surges o Frequency of storm-surge warnings o Duration of storm-surge warnings • Release of daily bias-corrected data • Investigation of the possibility of new, high-resolution model calculations of selected indicators. • DOI: https://doi.org/10.5281/zenodo.18417556
v2020b	• Addition of 19 new indicators o Temperature: Daily maximum temperature, Daily minimum temperature, highest temperature, lowest temperature, annual temperature interval, daily temperature interval, heatwave days, warm-wave days, frost days, growing season o Radiation o Potential evaporation o Wind: Average wind, Frequency of wind over 25 m/s. o Sea level and storm-surge: Height of 100 and 10 000 year storm surges, Height of 1 and 5 year water levels, frequency of current 20 year event • DOI: https://doi.org/10.5281/zenodo.18417703
v2020a	• Addition of eight new indicators: o Precipitation (return values): 5, 20, and 50-year events for hourly and daily precipitation o Precipitation: Dry days and longest dry period. • Model ensemble expanded for indicators in the groups: Precipitation, Precipitation (return values) and Temperature. These climate indicators are now based on up to 57 models. • DOI: https://doi.org/10.5281/zenodo.18417815

Version	Main changes in this version and DOI
v2019a	- First release of *Klimaatlas* 17 indicators: - Precipitation: Average precipitation, Maximum daily, 5-day, 14-day precipitation, Days with more than 10, 20 mm precipitation - Extreme precipitation: Cloudbursts, 2-, 10-, 100-year event hourly precipitation, 2-, 10-, 100-year event daily precipitation - Temperature: Average temperature - Sea level and storm surge: Mean sea level, 20-, 50-year event storm surge - Two emissions scenarios: RCP 4.5 and 8.5 - Four time periods: 1981-2010, 2011-2040, 2041-2070, 2071-2100 - An initial model ensemble of 36 models. - DOI: https://doi.org/10.5281/zenodo.11402538

Table 12 Overview of *Klimaatlas* versions, with links to archived versions.

8 Acknowledgements

Klimaatlas has been developed over many years based on a close collaboration with users from across a broad span of Danish society. We wish to recognise all of those that have contributed to the development of *Klimaatlas*, both within DMI and amongst our users, and helped to make it a success.

We also wish to acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We thank the climate modelling groups (listed in Table 1) for producing and making available their model output. We acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP). We thank the projection authors for developing and making the sea-level rise projections available, multiple funding agencies for supporting the development of the projections, and the NASA Sea Level Change Team for developing and hosting the IPCC AR6 Sea Level Projection Tool.

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10 Appendix A Previous versions

Release notes describing previous versions of *Klimaatlas* can be found in this section. Data associated with each version is also found in the version archive on the webpage (https://www.dmi.dk/klima-atlas/versionshistorik) and in Zenodo archive (https://zenodo.org/communities/klimaatlas/).

10.1 Version 2024b, November 2024

Klimaatlas v2024b represents a significant update of indicators associated with sea level rise and storm surges in Denmark. The release updates existing storm surge indicators based on upon new data (*Højvandsstatistikker*) from *Kystdirektoratet* released in July 2024 and updated again in November 2024. In addition, a rewrite of the sea-level and storm-surge processing code has aligned this part of the pipeline with the rest of the *Klimaatlas* processing chain. The resulting changes in indicators are generally minor, and within the uncertainty associated with estimates: notable changes may occur in some instances and are highlighted below.

In addition, the number of emissions scenarios available for sea-level rise and storm-surge indicators has been increased. This reflects the increasing focus on scenarios beyond the core set previously used in *Klimaatlas*, and particularly on SSP3-7.0.

10.1.1 Sea Level Rise and Storm Surge Statistics

Input data

- **Update of *Højvandsstatistikker* from 2017 to 2024 version**. There is generally good agreement between the resulting storm-surge indicators, with revisions generally being minor.
  Impacted indicators: 202-204, 206, 208, and 210.
- **Use of land-rise rates as reported in *Højvandsstatistikker***, rather than from the source report from DTU as done previously. This change ensures coherency between *Højvandsstatistikker* and *Klimaatlas*.
  Impacted indicators: all sea-level and storm surge indicators (201-204, 206, 208, 210, 213).
- **Improved utilization of sea-level rise projections from IPCC AR6**. Previous versions of *Klimaatlas* built upon a simplified version of the available sea-level rise projections as inputs that required the uncertainties of interest (10th and 90th percentiles) to be inferred from the data available (83rd and 95th percentiles).

v2024b uses the full set of sea-level rise projection data, allowing the relevant uncertainties to be extracted directly.

Impacted indicators: all sea-level and storm surge indicators (201-204, 206, 208, 210, 213).

Methods

- The **reference year for sea-level rise** calculations has been moved to 1995, whereas it was previously 1990. This change resolves a minor inconsistency between the choice of reference year and the average sea level rise over the historical period. The resulting net change in sea level indicators is less than 2cm averaged across all stations.
  Impacted indicators: all sea-level and storm surge indicators (201-204, 206, 208, 210, 213).
- **Removal of DKSS storm-surge model based variance contributions**. The calculation of future storm-surge indicators in Klimaatlas previously used a limited set of simulations using the DKSS storm surge model under two RCPs to estimate uncertainties in future storm surges associated with changes in wind patterns. However, while v2024b now presents five SSP-based emissions scenarios for sea-level rise and storm-surges, there are no corresponding SSP-based simulations available using the DKSS model system. The use of DKSS simulations in estimating the variance of future storm surge statistics has therefore been discontinued. The impact on the indicators is minor.
  Impacted indicators: all storm surge indicators (202-204, 206, 208, 210, 213).
- **Rewrite of the calculation** of sea-level rise and storm-surge indicators using Python. Agreement between indicators calculated with the old and new code with the same input data was generally excellent.
  Impacted indicators: all sea-level and storm surge indicators (201-204, 206, 208, 210, 213).

Indicators

- **Addition of a new indicator (213)**, frequency with which the current 100 year storm surge level will be exceeded in the future.
  Removal of indicator 205 (height of 10 000 year storm surge). Recent work in relation to the protection of Copenhagen against storm surges concluded that the use of statistical extrapolation to such long return periods was not supported by the (comparatively short-duration) time series available (Su et al 2024). This indicator has therefore been removed. The last published version of this indicator can be found in the *Klimaatlas* archive in version v2024a:
  https://zenodo.org/doi/10.5281/zenodo.11402835

- **Suspension of indicator 211** (Frequency of storm surge events exceeding current local warning level). Indicator 211 was previously calculated on the basis of DKSS simulations and cannot therefore be calculated as previously. A new calculation method, similar to that used for 210 and 213 is being developed, and indicator 211 has therefore been suspended for the meantime. A new version of the indicator will be released in a future update. The last published version of this indicator can be found in the *Klimaatlas* archive in version v2024a:
  https://zenodo.org/doi/10.5281/zenodo.11402835

- **Removal of indicator 212** (Accumulated duration of sea level exceeding current local warning level). Together with indicator 211, this indicator was previously calculated based on a limited set of DKSS model runs. It was not possible to find a new method to calculate this indicator with the new set of scenarios and it has therefore been removed. The last published version of this indicator can be found in the *Klimaatlas* archive in version v2024a:
  https://zenodo.org/doi/10.5281/zenodo.11402835

- **Indicator 210 shows the greatest change** as a result of the above changes to methods and input data. Indicator 210 describes the frequency with which the level of a 20-year storm-surge in the current climate will be exceeded in the future and therefore integrates both changes in storm-surge statistics and sea level rise. The agreement between v2024b and v2024a is however good (R^2 between v2024a and v2024b = 0.79, mean difference between v2024a and v2024b = 0.4 events per 20 years).

Webpage and Documentation

- **Addition of extra SSP scenarios and time periods** to the map viewer for sea level rise and storm surge statistics. Previously only three SSP scenarios were presented in the core *Klimaatlas* products (SSP1-2.6, SSP2-4.5 and SSP5-8.5), covering the last two periods (2041-2070 and 2071-2100). In line with the increased focus that SSP3-7.0 is receiving in an adaptation context, the set of scenarios has now been extended to include all five major SSP scenarios (i.e. addition of SSP3-7.0 and SSP1-1.9). Furthermore, the removal of DKSS data from the processing pipeline now makes it possible to generate *Kommune* reports and excel spreadsheets have also been updated accordingly.

10.1.2 Other Changes

Input data

- **Two additional atmospheric models** that were previously excluded from calculations involving Tmax and Tmin have been incorporated into *Klimaatlas*, increasing the ensemble size for indicators derived from these two variables. While

there are subsequent revisions to estimates of both the median and the uncertainties, the changes are generally minor.
Impacted indicators: 002-005,007-010

10.2 Version v2024a, June 2024

This version introduces a new indicators related to fire, dry periods and meteorological drought. In addition, several existing precipitation indicators have been moved into a new "tørke" (drought) group. The new groupings and indicators (with their corresponding IDs) are:

- Fire danger (*brandfare*)
    - Average fire danger across years / seasons
    - Number of days with "very high" fire danger
    - Number of days with "extreme" fire danger
- Drought (tørke)
    - Number of dry days (moved from *Nedbør* (precipitation) group) (108)
    - Longest dry period (moved from *Nedbør* (precipitation) group) (109)
    - Number of years / season that are "dry" (110)
    - Number of periods of minimum five consecutive dry days (112)
    - Number of periods of minimum ten consecutive dry days

The number of ensemble members has been expanded from 65 to 72.

Klimaatlas data is now archived in the Zenodo archive. As a result, *Klimaatlas* data and reports now have a Digital Object Identifier (DOI) associated with them. This version of *Klimaatlas* can therefore be referenced as:

Danish Meteorological Institute. (2024). DMI Klimaatlas v2024a - Projections of climate indicators over Denmark [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11402836

Previous versions of *Klimaatlas* data have also be archived retrospectively. The full archive can be found at: https://zenodo.org/communities/klimaatlas

Excel spreadsheets have been converted to a new format that is intended to be both human-readable and machine readable. The medium emissions scenario (RCP4,5 / SSP2-4,5) were added to the Kommune reports, together with overview "cartoon-strips" showing changes under different emissions scenarios.

10.3 Version v2022a, February 2023

In this update of *Klimaatlas*, we added (1) the low emission climate scenario RCP2.6, (2) sea level projections from the latest IPCC report, and (3) additional climate model data for the RCP4.5 and RCP8.5 scenarios.

Regarding (1) and (3), the list of models used in the current data set can be found in Tables 7 and 8.

Regarding (2), we updated the mean sea level data regionalized from IPCC AR6, which means it is now based on the new generation of emission scenarios, "Shared Socioeconomic Pathways" (SSPs). The scenarios used in this report for sea level rise assessment are SSP12.6/RCP2.6, SSP2-4.5/RCP4.5 and SSP5-8.5/RCP8.5. As something new, our uncertainty estimates now include the expert judgement of potential contributions from melting ice sheets not well-captured by the climate models; often called low confidence processes, as part of "deep uncertainty" related to sea level rise. The inclusion of this estimate from the latest IPCC report results in a larger uncertainty interval, especially through an increased 90-percentile of the high-emission scenario RCP8.5.

Improved calculation methods have given rise to minor changes with this update. Among the atmospheric indices, we change the order of statistical processing and interpolation for some of the indices, with only small changes discernible in the mean. We have added an updated flow-chart of the processing used for the atlas, on page 30. Looking at the change in median values expressed as a percentage of the width of the old confidence interval from the 10 to the 90 percentile, we note some changes, mainly of minor sizes. Indices of wind and extreme precipitation show the most pronounced local changes.

With the method update, it appears that the older versions of *Klimaatlas* underestimated the widths of confidence intervals for indexes related to extremes, compared to the present version of *Klimaatlas*. Hence, these have increased - again - especially for extreme precipitation and winds.

Lastly, while the regional climate model projections of the SSP-scenarios are still being prepared by the international research community, we have performed a first assessment of the new generation of global climate model projections (CMIP6, based on the SSP-scenarios) over Northern Europe and how they compare to the previous projections (CMIP5, based on RCP-scenarios) – for details see (Christiansen, 2023).

10.4 Version v2021a, December 2021

In this version we release high resolution time series for 8 variables, namely - tas, tasmin, tasmax, pr, sfcWind, sfcWindmax, rsds, potevap, which are used to produce a range of indexes in *Klimaatlas*. These time-series are released at a 1x1 km grid as daily values, and are made available as netcdf files for download by the users.

Users of these expert-only data should be aware that the files are large and download times long. Use of the wget solution is recommended.

We have changed the algorithm for calculating indexes 008 and 009 (i.e. heat-wave days and warm-wave days) and now release corrected versions of these indexes in *Klimaatlas*, which are consistent with the calculations applied to DMI's climatological data. This means that both data and figures are updated. Compared to the updated numbers, the previous method resulted in too many days being counted by several in the mean, and up to 12 days in some models.

We introduced a new bias-adjustment method of handling (low) extremes which influenced, to a small degree, indexes 301, 302, 401 and 402. New values for these were calculated and are part of version 2021a release. The change had to do with ensuring that small negative values are not produced during the bias-adjustment.

Two new sea level and storm surge indicators: frequency and accumulated duration of sea level exceeding current local warning level. The 10.000 year storm surge events are still subject to research, and an update is underway – read section 6.1.2 for details. We have changed the unit of the frequency of 20-year storm surge events to number of events per 20 year period.

The present data release, version 2021a, is identical to version v2020b, except for the indices 008, 009, 301, 302, 401 and 402 and the ocean information indexes 210, 211 and 212, which are updated.

Section 4 of the older versions of this report has been shortened and edited for clarity and the text therein now only details the procedures actually applied – see, e.g. version 20-20, for the older material.

10.5 Version v2020b, December 2020

With the update to version 2020b in December 2020, *Klimaatlas* has been expanded with 19 new indicators. The new data presents more details on the

future changes in temperature, winds, evaporation, sunshine, frequent and rare storm surges.

Fourteen new atmospheric indicators: Daily high and low temperatures, maximum and minimum temperatures, annual and diurnal temperature intervals, heatwaves (hedebølger og varmebølger), frost days, growing season length, mean wind speed, number of storm events, potential evaporation, and solar radiation.

Five new sea level and storm surge indicators: 100- and 10,000-year storm surge events, 1and 5-year sea level events, and the change in frequency of current 20-year storm surge events.

10.6 Version v2020a, June 2020

With version v2020a, *Klimaatlas* has been updated to include 8 new indicators: the mean number of dry days, the mean duration for the longest dry period, and 5, 20, and 50 year events for hourly and daily precipitation. Furthermore, *Klimaatlas* is now based on data from more climate models; up to 57 models for daily values and 35 models for hourly values. Data for sea level and storm surges is unchanged since v2019a.

Note that some index numbers have changed since the previous version: the indices for2, 10, and 100-year events for hourly precipitation are now 151, 153, and 156 (previously 108, 109, and 110), and the indices for 2, 10, and 100-year events for 24-hour precipitation are now 157, 159, and 162 (previously 111, 112, and 113).

10.7 Version 2019a, October 2019

Klimaatlas was initially released on 6th October 2019 with 17 indicators:

- Precipitation
  - Average precipitation
  - Maximum daily, 5-day and 14 day precipitation
  - Days with more than 10-, and 20mm precipitation
  - Cloudburst frequency
  - 2-, 10-, and 100 year events for hourly precipitation
  - 2-, 10-, and 100 year events for daily precipitation
- Temperature
  - Average temperature
- Sea level and storm surge
  - Sea level rise

- 20 and 50 year storm surge events