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Cooling is a cost-efficient way to adapt to heatwaves even in high-latitude cities

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Abstract
Heatwaves pose a direct threat to human health and well-being, particularly in cities, but there is little evidence of how much adaptation is needed at high northern latitudes. Drawing on IPCC's notion of climate risk, we develop an integrated approach to determine the economic viability of adaptation to growing mortality caused by increasing heatwaves via improved cooling of residential buildings. Accounting for the stochasticity of temperatures using Monte Carlo simulations, we estimate that the mortality will increase by tenfold relative to current mortality caused by heatwaves in Southern Finland. We carry out a cost–benefit analysis and show that adaptation to heatwaves via cooling is a feasible but costly solution in all studied cities and under all climate change scenarios. Given the high value of statistical life, lack of adaptation to increasing frequency of heatwaves would be costly to society. Adaptation to heatwaves by cooling is an effective solution: costs are 38 200 – 416 000 €/life saved, and benefits exceed the costs by 1.8 to 18 times in alternative warming scenarios. Our results suggest that it is optimal to avoid any additional heatwave-related fatalities, implying that all the people belonging to the vulnerable population should be added to a district cooling network. The net present value of the adaptation by cooling is especially affected by the choice of the value of statistical life and more research is needed to ascertain the relevant value in the Finnish society.

Keywords Climate change adaptation · Cost–benefit analysis · Heatwave-related mortality · Cooling

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1 Introduction

Climate change negatively affects human health, and will increasingly do so over time, unless global GHG emissions are radically and rapidly reduced (Hobbhahn et al. 2019; Lüthi et al. 2023). Heatwaves have caused thousands of deaths. For instance, a severe heatwave in 2003 in Europe caused over 70,000 premature deaths (Robine et al. 2008), and in the summer of 2022, over 61,000 individuals lost their lives due to the unprecedented heatwave that swept across Europe (Ballester et al. 2023). Climate change increases the likelihood of heatwaves globally (Greene et al. 2011; Huang et al. 2011; de Coninck et al. 2018; Vautard et al. 2020; Ballester et al. 2023), and Europe is undergoing notable warming trends, with temperature increases occurring at a rate that is double the global average (Hermand et al. 2024), and an increase of heat-related mortality and morbidity (Menne and Ebi 2006; Confalonieri et al. 2007; Smith et al. 2014).

Past research suggests that heatwaves have significant economic consequences (García-León et al. 2021). Climate change has already led to more intense and longer heatwaves (IPCC 2014; Kiarsi et al. 2023). Throughout heatwaves, indoor temperatures rise both during the day and at night, resulting in prolonged exposure to elevated temperatures that may persist for several days, which can cause notable effects on public health, leading to considerable expenses related to healthcare (Beugin et al. 2023). Exposure to heat will substantially contribute to increased morbidity and mortality, especially in urban environments, where the urban heat island effect increases exposure (Zhao et al. 2018; Keith et al. 2019; Ellena et al. 2020), and especially among the vulnerable groups. Elderly individuals are often identified as particularly vulnerable to the negative impacts of high temperatures (Hajat et al. 2010; Sampson et al. 2013; Gronlund et al. 2014). The rising elderly population will elevate the percentage of individuals vulnerable to certain health-related risks (Kovats and Hajat 2008; Luber and McGeehin 2008; O'Neill and Ebi 2009).

With global temperatures on the rise and populations aging, heat-related health effects will continue to increase in the future (Huang et al. 2011; Gasparrini et al. 2017; Guo et al. 2018; Ebi et al. 2021; García-León et al. 2024). A study of 164 cities in 36 countries found that about 48% of the world's population would be exposed to deadly thresholds of heat for at least 20 days annually by 2100 even with the most ambitious GHG emission reductions projected (Mora et al. 2017). Guerreiro et al., (2018) studied future changes in droughts, heatwaves and floods for 571 European cities. They found that heatwaves increase across all cities, and particularly in Southern Europe, whereas the greatest temperature increases are expected in central European cities. Heatwave frequency and the heat-related mortality increase also in high-latitude areas (Russo et al. 2015; Ruuhela et al. 2018; Zhao et al. 2021; Lüthi et al. 2023). For example, in Finland (ca. 60–70°N), even in the current climate, heatwaves significantly increase mortality among the vulnerable groups (Kollanus et al. 2021; Vicedo-Cabrera et al. 2021; Kivimäki et al. 2023). Past major heatwaves in Finland have each resulted in hundreds of excess deaths (Kollanus and Lanki 2014; Ruuhela et al. 2021).

Cities are already developing adaptation strategies to address the potentially significant welfare losses from heatwave-related mortality. Heatwave-related mortality can be reduced through health care staff increase, heat warning systems and prevention plans, and building code revisions (Ebi et al. 2021; Lee et al. 2024). For minimizing the economic consequences of heatwave-related mortality, it is crucial to promptly implement adaptation measures. The practical implications of adaptation necessitate a careful consideration of the

benefits in comparison to opportunity costs and trade-offs (Wilby and Dessai 2010). Adaptation through the cooling of buildings provides potentially large benefits (Attia et al. 2021; Hu et al. 2023), but there is little evidence of how cost-effective cooling is, particularly in northern latitude cities. Adapting cities to heat waves is more complicated than adapting to e.g., flood risk, both in design and with respect to quantifying benefits and costs (Guerreiro et al. 2018).

Managing and understanding uncertainty and complexity represent the greatest challenges also in forecasting future mortality related to heat (Huang et al. 2011). Despite the uncertainty, previous research has indicated that it is essential to implement adaptation measures to minimize the impact of heatwaves on all levels and demographic groups (Rauf et al. 2017). In addition, understanding of the costs and benefits associated with adaptation measures is essential, as well as an analysis of the costs of adaptation in relation to the costs incurred from inaction. To determine the economic viability of a proposed policy, a cost–benefit analysis (CBA) framework is often employed.

Adger et al. (2005) have argued that elements of effectiveness and efficiency, among equity and legitimacy, are important normative evaluative criteria in judging successful adaptation. It has also been suggested in the past literature, that cost-effectiveness and cost efficiency can be used to evaluate the success of the climate change adaptation (CCA) policies and measures, but they have been sparingly applied so far (Nassopoulos et al. 2012; WHO 2013; Zou et al. 2013; Ryan and Stewart 2017; Chiabai et al. 2018; Hunt et al. 2017; Reguero et al. 2018; Junqueira et al. 2022). CBA is the preferred economic evaluation approach for guiding investment decisions aimed at assessing the overall impact on society, although cost-effectiveness analysis (CEA) serves as the primary method for conducting economic evaluations, e.g., within the healthcare sector (Brent 2023).

We develop a framework that integrates the framing of climate risk as a function of hazard, exposure and human or ecological system's vulnerability (Fig. 1b), and economic modeling. We apply the framework to examine the impact of mechanical cooling provision as a CCA policy three Finnish cities along the south-north gradient: Helsinki, Turku, and Oulu (Fig. 1a). We limit our analysis on mechanical cooling, acknowledging that there are other adaptation measures and that comprehensive adaptation to heatwaves requires the use of multiple different measures. We use CBA to answer the following research questions: 1) is the planned adaptation by cooling economically viable way to reduce heat-related mortality? 2) how costly is adaptation by cooling for society?, and 3) what are the costs of inaction? We determine projections on heatwave frequencies and demographics of vulnerable populations drawing on alternative Representative Concentration Pathways (RCPs) and combine this information with the estimated equations of mortality. Furthermore, we focus on the two oldest age groups: 65–74 and $\geq$75. We consider them as the vulnerable age groups, because in only those age groups heatwaves significantly increase the mortality risk (Kollanus et al. 2021). No-adaptation policy provides the baseline projection of heatwave mortality.

At the individual level, mechanical air cooling offers the clearest safeguard against the negative health effects associated with extreme heat (Bureau 2021; Sera et al. 2020), and air conditioning has proven to be the most efficient means of decreasing mortality (Semenza et al. 1996) and morbidity (Ostro et al. 2010) rates, as well as enhancing thermal comfort during periods of extreme heat (Morris et al. 2021). Thus, the climate response to reduce mortality, i.e., planned adaptation, is to promote cooling by air conditioning (AC) and dis-

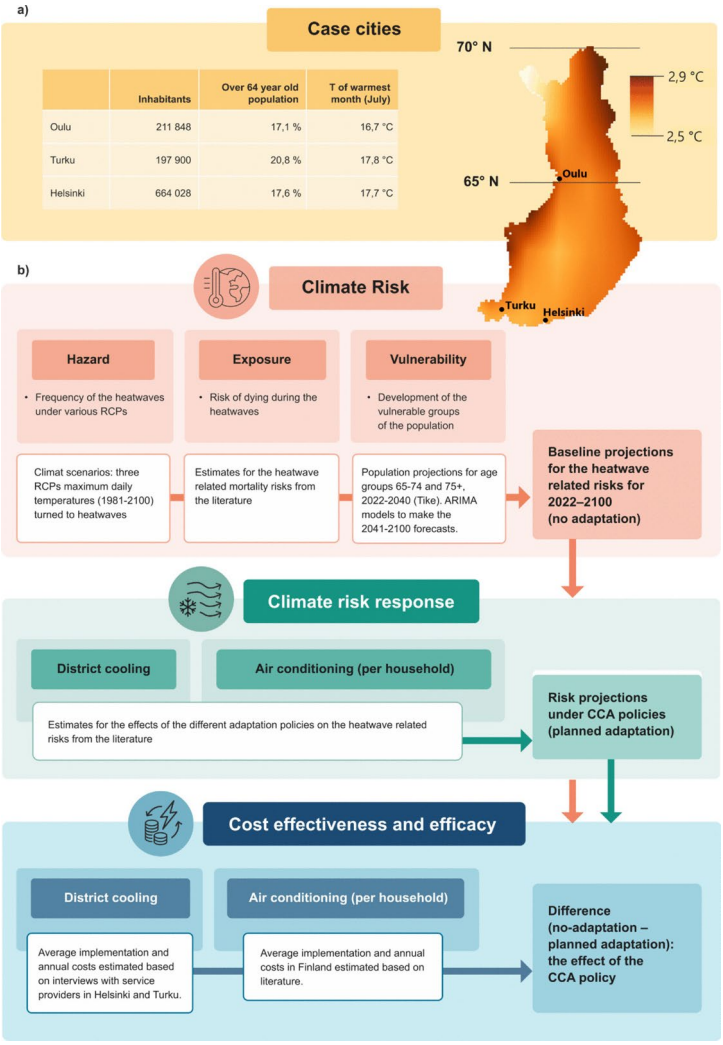

Fig. 1 Case cities and the applied framing of climate risk. **a**) The map represents July average temperature change (°C) from 1991–2020 to 2085 within the SSP2-RCP4.5 scenario, based on the dataset produced by the Finnish Meteorological Institute (2023a). The table includes basic information of the target cities. The inhabitant/population information describes the situation at the end of year 2022 (Statistics Finland 2023a), and the temperature data represents the average temperature of the period 1991–2020 (Finnish Meteorological Institute 2023b). **b**) The figure shows the IPCC's framing of climate risk (Ara Begum et al. 2022) and how it has been applied here to analyse the cost effectiveness and efficiency of the climate change adaptation (CCA) policy. The arrows indicate the process of data flow in the analysis, i.e., orange arrows indicate the climate risk factor data used for baseline projections (orange horizontal arrow) that were further used for the economic simulations of risks under CCA policies (upper vertical orange arrow), and the effect of CCA policies in terms of costs and lives saved together with the economic simulations of risks under CCA policies (lower vertical orange arrow and vertical green arrow respectively); horizontal green arrow indicates the response effect data used for the economic simulation of risks under CCA policies; blue arrow indicates the response cost data used for the simulation of effect of CCA policies in terms of costs

trict cooling (DC), both of which entail costly adaptation. How much mortality should be reduced, is a value choice. Therefore, we employ alternative target levels for saved lives (from 20 to 98%) and determine the efficiency of adaptation in two alternative ways: cooling costs per saved lives (cost-effectiveness) and value of the lives saved per cooling costs (benefit/cost ratio), and the net present value (NPV) criterion to evaluate the overall economic viability of the CCA policy (see, e.g., Brent 2023). The NPV of a project is defined as the total of the discounted values of all incoming cash flows, subtracted by the total of the discounted values of all outgoing cash flows, when discounting is performed to the project's beginning. According to the NPV criterion, projects that yield a positive NPV are considered worthwhile, whereas those that result in a negative NPV are deemed unworthy of pursuit (Bey et al. 1981).

2 Data and methods

2.1 The economic model

We use an economic model to determine the cost/effectiveness and the net present values of the adaptation policies. For each city, we formulate the planner's problem as a constrained adaptation cost minimization problem:

$$\begin{gathered} \min_{\sigma_{DC,t},\sigma_{AC,t}} \sum_{t=1}^{T} \beta^t C_t \\ \text{subject to} \\ f_t \leq \overline{f_t} \\ P_{t+1} = P_t + \Delta \overline{P}_t - f_t \end{gathered} \tag{1}$$

where $\sigma_{DC,t}$ and $\sigma_{AC,t}$ are the decision variables, i.e., the adaptation intensities (i.e., the share of the population that is provided the adaptation measure) of the DC and AC implementation, C_t is the total adaptation cost, $\beta^t = (1+\rho)^{-t}$ is the discount factor, ρ is the discount rate, and T is the final period of the planning horizon. In the context of CBA, it is essential to discount health effects at the same rate as costs when they can be quantified in monetary terms. Time horizon of the analysis is 2022–2100. We use a long planning horizon because this way we can observe the effect of climate change on the annual heatwave frequency.

Turning to constraints, f_t is the risk, i.e., the number of mortalities from heatwaves in a year t, defined by a multiplicative function

$$f_{it} := n_t e_t \mu_i P_{it}, \tag{2}$$

Where symbols denote: the annual number of heatwaves, n_t, vulnerable population, P_{it}, and exposure to heatwaves, $e_t \mu_i$, and i denotes an age group. Since we focus only on vulnerable population, $i = \text{age group } < spanclass =' convertEndash' > 65-74 < /span >$ or $i = \text{age group } \geq 75$. The exposure is a product of the age group-dependent probability of dying during a heatwave, $\mu_i \in [0,1]$, and the effective share of population exposed to heatwaves, e_t, with

$$e_t = 1 - \varepsilon_{DC}\sigma_{DCt} - \varepsilon_{AC}\sigma_{ACt}\left(1 - \sigma_{DCt}\right), \tag{3}$$

where $\varepsilon_j \in [0,1]$ is the efficiency parameter with cooling of type $j \in \{AC, DC\}$, i.e., it defines how much the mortality risk decreases by applying a certain kind of cooling mechanism. Denote the total population by $P_t = \sum_i P_{it}$ and total mortalities from heatwaves $f_t = \sum_i f_{it}$ as sums over age groups. The population dynamics in each age group is modelled as follows:

$$P_{t+1} = P_t + \Delta\overline{P}_t - f_t, \tag{4}$$

where $\Delta\overline{P}_t = \overline{P}_{t+1} - \overline{P}_t$ is the baseline population growth. The effect of adaptation is given by changes in heatwave-related mortality: $f_t - f_t^0$, where f_t^0 is the mortality without adaptation measures (i.e., the baseline mortality). The term $\overline{f_t}$ is the annual targeted upper limit of the expected number of mortalities. We define the target as $\overline{f_t} = (1-\delta)\, f_t^0$, with $\delta \in [0,1]$. Thus, δ defines the target reduction in mortality relative to the baseline. This implies that the target changes annually as a linear function of the baseline mortality; the annual target, $\overline{f_t}$ defines the maximum number of annual heatwave-related mortalities in a planned adaptation trajectory.

The adaptation cost structure consists of investment costs, C_{Ij} and annual costs C_{Aj} as follows:

$$\begin{gathered} C_t = C_{I,DC}\left(1+\sigma_{DCt}\right) I_t^{DC} + C_{I,AC} I_t^{AC} + C_{A,DC}\left(1+\sigma_{DCt}\right)\sigma_{DCt} P_t + C_{A,AC}\left(\sigma_{ACt}\left(1-\sigma_{DCt}\right) P_t\right) \\ I_t^{DC} = \sigma_{DCt} P_t - \sigma_{DCt-1} P_{t-1} \\ I_t^{AC} = \sigma_{ACt}\left(1-\sigma_{DCt}\right) P_t - \sigma_{ACt-1}\left(1-\sigma_{DCt-1}\right) P_{t-1} \end{gathered} \tag{5}$$

where C_I is the investment cost and C_A the annual cost (including the energy costs). We assume that investment and annual costs of DC are a linear increasing function of the distance from the power plant, and hence, increasing functions of the adaptation intensity. Instead, the investment and the annual costs of AC are constant.

By solving Eq. (1), we obtain the optimal CCA policy path, denoted by $\sigma_t^* = (\sigma_{ACt}^*, \sigma_{DCt}^*)$, and the corresponding expected number of mortalities f_t^*, which is defined by the annual targeted upper limit of the expected number of mortalities, $\overline{f_t}$. The benefits of a CCA policy can be determined by comparing the economic costs of climate change in the baseline, no adaptation scenario with the costs under the policy scenario. The difference between these two scenarios reveals the benefits of a policy intervention (Chambwera et al. 2014).

In our case, benefits of the optimized CCA policy path are obtained by taking the difference between the number of mortalities in the baseline and the mortalities in the optimized adaptation path, i.e., the number of avoided mortalities, $f_t^* - f_t^0$ (the effect of the optimized CCA policy), and multiplying this difference with the value of a statistical life (VSL). Monetary valuation of a human life – VSL – is used in multiple policy areas resulting in a wide range of VSL estimates (Keller et al. 2021). The VSL quantifies the value individuals place on a slight decrease in the risk of mortality or the economic significance of reducing the overall occurrence of fatal incidents within the population by one (Colmer 2020; Hammitt 2023). The monetary VSL is frequently employed to assess policies aimed at minimizing mortality risks, such as health interventions. Any evaluation of a policy that alters mortality risks necessitates an estimation of how society values a statistical life in monetary terms

(Wijnen et al. 2009). By denoting the VSL as v, we may define the expected net present value (ENPV) of the adaptation for each target:

$$ENPV = \mathbb{E}\left\{\sum\nolimits_{t=1}^{T} \beta^t \left[\left(f_t^* - f_t^0\right) v - C_t\right]\right\}, \tag{6}$$

where $f_t^* := \widehat{n}_t \mu_i e_t(\sigma_t^*) P_t$ is the risk associated with the optimized vector for adaptation measures. Here $\widehat{n}_t$ is the random variable: realized annual number of the heatwaves. Therefore, the ENPV, is also a random variable, which is calculated with 10,000 Monte Carlo simulations. Thus, we treat the number of heatwaves, n_t, differently in optimization and simulations: in optimization n_t is the average annual number of heatwaves representing the trend of heatwaves in each RCP, whereas in simulations $\widehat{n}_t$ is a stochastic random variable which takes a realization from a non-homogeneous Poisson process in each simulation. Thus, in this setup the planner derives the optimal adaptation strategies drawing on the expected number of heatwaves and determines the adaptation decision paths over the time horizon. Then the planner uses these optimized decision paths in Monte Carlo simulations to obtain distributions for the output variables of interest, i.e., ENPV.

We also examine alternative output variables that are typically used in the evaluation of a project or policy. When a cost-effectiveness analysis is resorted instead of CBA, we study what is the ratio between discounted costs and the effect of cooling, over the planning horizon, with the help of expected cost/effect ratio (ECER). In this case the ECER is defined as follow:

$$ECER = \mathbb{E}\left\{\frac{\sum_{t=1}^{T} \beta^t C_t}{\sum_{t=1}^{T} f_t^* - f_t^0}\right\}, \tag{7}$$

Finally, we also use the benefit/cost ratios for the evaluation of the adaptation policies. The expected benefit/cost ratio (EBCR) is defined as follows:

$$EBCR = \mathbb{E}\left\{\frac{\sum_{t=1}^{T} \beta^t \left(f_t^* - f_t^0\right) v}{\sum_{t=1}^{T} \beta^t C_t}\right\}. \tag{8}$$

Thus, with EBCR we study what is the expected ratio between the discounted value of the effect of cooling and the discounted costs, over the planning horizon. A project/policy with a benefit–cost ratio (BCR) exceeding 1.0 is anticipated to yield a positive net present value (NPV).

2.2 Data

For the numerical application of the model described by the equations [1]-[8], we need data on 1) the evolution of the hazard, i.e., the heatwaves in different climate scenarios, 2) the evolution of the vulnerability, i.e., the population projections for the two oldest age groups, 3) the exposure, i.e., mortality risk estimates for the vulnerable age groups, and on 4) adaptation costs and benefits, i.e., the cooling costs and VSL.

2.3 Hazard: frequency of heatwaves under different climate scenarios

To construct future projections for the annual number heatwaves, we first need to define what is meant by the heatwave in this study. Heatwave refers to the period when the temperature is notably above the average in a particular region (Xu et al. 2016). Nevertheless, there is no single definition of a heatwave because its intensity, area, and length can differ greatly by location (Kiarsi et al. 2023). The World Meteorological Organization characterizes a heatwave as a period of five or more consecutive days where the daily maximum temperature surpasses the average maximum temperature by a minimum of 5 °C (Kiarsi et al. 2023). The United States characterizes a heat wave as a duration exceeding three consecutive days during which daily maximum temperatures surpass 32.2 °C (Agel et al. 2021), whereas under Korean criteria, a heat wave advisory is issued when the maximum daily temperature will exceed 33 °C for two consecutive days according to weather forecasts (Lee et al. 2019). We apply the similar kind of definition of a heatwave in Kollanus et al. (2021) with slight modifications: the maximum temperature must exceed the standard definition of a hot day in Finland (the threshold of 25 °C) (Finnish Meteorological Institute 2023b) for four consecutive days. To obtain the number of annual heatwaves, we first organized the daily maximum temperature data from 1981 to 2100 to annual periods, from which we picked the periods of at least four consecutive days when the maximum temperature exceeds the threshold of 25 °C. We note that this means that all the different heat metrics relevant for health have not been considered in the epidemiologic assessment, since, for example, the average daily temperature and the minimum temperature are also important for the health.

To estimate the projections of the future heatwaves, we use maximum daily temperatures for three different climate scenarios (Representative Concentration Pathways, RCPs): RCP2.6, RCP4.5, and RCP8.5 (van Vuuren et al. 2011). RCP2.6 is a "very stringent" pathway, RCP4.5 is described by the IPCC as an intermediate scenario, whereas RCP8.5 is generally taken as the basis for worst-case (i.e., the warmest) climate scenarios. By using different climate scenarios, we aim to quantify and demonstrate the uncertainty related to the future climate development and the associated health risks. The timeframe for the scenarios reaches to the end of the century.

Our scenarios for the daily maximum temperatures are from the project called Pathways linking uncertainties in model projections of climate and its effects (Finnish Meteorological Institute 2019) (raw data is provided in the Supplementary material). Data consists of the maximum temperatures measured in each day from January 1st 1981 to December 31st 2010 and maximum temperatures modeled in each day from Jan 1st 2011 to Dec 31st 2100 for each scenario, and in each city, which have been interpolated to a 10 km grid. The effect of topography and water areas on the data has been considered in producing the observation grid data. There is no separate urban modeling component involved. The raw data is divided into four separate episodes: the years 1981–2010 are based directly on weather observations, and in these years the temperatures corresponding to the different climate scenarios are the same. During the period 2011–2040, it is as if the previous 30 weather years were lived again, however, so that temperatures were generally higher than in that period based on observations. The same is repeated in the periods 2041–70 and 2071–2100, so that the warming is the stronger the greater the expected climate change, e.g., the warmer the climate scenario. Results from 13 GCM simulations participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) were used in this study. The

GCMs were: BCC-CSM1-1, CanESM2, CCSM4, CNRM-CM5, EC-EARTH, GFDL-CM3, GFDL- ESM2M, IPSL-CM5AMR, MIROC5, MIROC-ESM, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M).

The heatwave projections in RCP scenarios show little variation between the RCPs, especially between RCP2.6 and RCP4.5, and considerable annual variation within the RCP projections. However, because these projections are simulations, and therefore provide only one realization of the stochastic phenomenon, we fit linear regressions to these projections to describe the evolution of the annual heatwaves on average. Thus, we consider a typical case where a social planner bases annual adaptation decisions on the expected number of annual heatwaves. Therefore, we use the linear trends, fitted to the applied simulation data, in the optimization, without any stochastic elements. However, then we simulate the model, using the optimized adaptation trajectories as inputs, we use non-homogeneous Poisson distribution from which we draw the realizations for the number of the annual heatwaves to add the stochasticity back to the analysis and to obtain the expected net present values (ENPVs) described in Eq [6]. We use a non-homogeneous Poisson distribution, because although the annual number of heatwaves can be considered independent from each other, the average frequency of heatwaves increases in time. We employ the estimated linear regressions to illustrate the progression of the annual mean number of heatwaves over time. For each year, we generate a random value from the Poisson distribution that corresponds to the calculated mean.

2.4 Vulnerability: population projections

For the population projections for the people in vulnerable age groups, we use the Statistics Finland's statistical database (Statistics Finland 2023a) on past observations (2004–2021) and the forecasts (2022–2040) and continue these nonlinear trends to 2100 with forecasts developed with ARIMA models (Box and Jenkins 1976). Thus, for both age group in each city, we fit a set of ARIMA models, rank then with the help of an Akaike's information criteria (AIC) (Akaike 1974), choose the best model from this set of models, and use that to forecast the development of the population up to year 2100.

2.5 Exposure: the risk estimates

For the exposure, we use Kollanus et al. (2021), according to which mortality increases by 6.7% (95% CI of 2.9–10.8) in the age group of 65–74 and by 12.8% (95% CI: 9.8–15.9%) in the age group of≥75 during the heatwaves. Kollanus et al. (2021) found no significant increase in mortality risk during the heatwaves in other age groups. To estimate heatwave-related mortality parameter, μ_{ci}, we turn these relative probabilities into absolute probabilities. We start from the Eq. (2), from which we can write

$$\mu_{ci} = \frac{f_{cit}}{n_{ct} e_{cit} P_{cit}}, \tag{9}$$

where the index c denotes city. The data does not directly give the number of heatwave related mortalities, f_{cit}. These need to be derived from the data using the estimates of the heatwave-related mortality increment, ω_{ci}, by Kollanus et al. (2021). Note that in Kollanus

et al. (2021) the increment does not depend on the city, as they use only one age-group specific estimate for the whole nation, i.e., $\omega_{ci} = \omega_i$. We assess the number of heatwave-related mortalities from the observed number of deaths, d_{cit}, using the heatwave-related mortality increment. The observed number of deaths is

$$d_{cit} = d^0_{cit} + f_{cit} = (1 + n_{ct}\omega_i)\, d^0_{cit}, \tag{10}$$

where d^0_{cit} is the unobserved number of deaths other than the ones caused by heatwaves and n_{ct} is the number of heatwaves. From Eq. (10) we can derive the number of heatwave-related mortalities

$$f_{cit} = n_{ct}\omega_i d^0_{cit} = \frac{n_{ct}\omega_i d_{cit}}{1 + n_{ct}\omega_i}. \tag{11}$$

Inserting this into definition of μ_{ci}, and assuming that in the calibration data all citizens are vulnerable, $e_{cit} = 1$, we get

$$\mu_{cit} = \frac{1}{1 + n_{ct}\omega_i} \times \frac{n_{ct}\omega_i d_{cit}}{n_{ct} P_{cit}} = \frac{\omega_i}{1 + n_{ct}\omega_i} m_{cit}, \tag{12}$$

where the mortality

$$m_{cit} := \frac{d_{cit}}{P_{cit}} \tag{13}$$

can be simply calculated from the data. We obtain the number of mortalities and the population data from Finland's Statistic Center (pxdata.stat.fi, b). It is reasonable to assume that the heatwave-related mortality parameter is time invariant. Since there are several years of data, we can construct a following estimator for the heatwave-related mortality parameter:

$$\overline{\mu}_{ci} = \frac{\omega_i}{T} \sum_t \frac{m_{cit}}{1 + n_{ct}\omega_i}. \tag{14}$$

2.6 Adaptation costs – costs of cooling

To calculate the ENPV of cooling we also need estimates for the costs of cooling, i.e., the adaptation costs. Adaptation takes place via individual choices and, here, we assume that all those in vulnerable position would make the choice of adapting. The costs of investing in air conditioning (AC) consists of the installation costs. The average installation costs of AC are 3275 € (Kodinplaza n.d.). The average lifespan of the machine is 20 years. Thus, we divide the installation costs with 20 and add those to the annual use costs. The average energy consumption for cooling is 200 kWh/a (GlobalPetrolPrices n.d.). We take the current (2023) energy price in Finland, which is 0.222 €/kWh. Thus, the annual cost is 44.4 €/a. Since it is difficult to come up with price projections for the energy prices, we treat those as sensitivity parameters and study the sensitivity of the results to the adaptation costs. To prevent heat

wave related mortality, cooling is relevant during the mid-summer months when heatwaves occur in Finland i.e., June–August. During these months, the energy prices are typically low in Finland. Therefore, the annual costs of AC are rather low. However, in many southern countries, where the heatwaves are already big problem, energy costs are high during the summer months. To increase the generalizability of our analysis, we also study sensitivity of our results for the high adaptation costs.

District cooling (DC) has been produced in Finland since 1998. The main limitation in the production and distribution of DC is the slow and expensive construction of DC networks. The costs of DC include the connection charge and the investment (connection) costs, which vary across the cities, and household annual costs. In Helsinki, the household cost for DC implementation per building includes the connection charge (1500–1800 €) (Helen, personal communication). In 2023, approximately 100 housing units in Helsinki and 50 real estates in Turku have a direct DC interface. Investment cost of a DC, i.e., the cost of connecting a building to a DC network, is around 150 000€ (Helen, personal communication). In 2022, there were 11 401 apartment buildings in Helsinki, with around 333 481 dwellings in these buildings (Statistics Finland 2023b). By dividing the number of apartments with the number of buildings, the average number of apartments per building is 29.25. Therefore, the average investment cost per apartment is 150,000€/29.25 = 5128€ in Helsinki. The number of apartment buildings in Turku is 2 946, and the number of dwellings in these buildings is 93 919, whereas the corresponding numbers in Oulu are 2 572 and 65 141 (Statistics Finland 2023b). Using the investment cost values from Helsinki, as they were not available for Turku and Oulu, the investment costs are 150000/31.88 = 4705€ in Turku and 150000/25.33 = 5922€ in Oulu. Note that we assume that capital depreciation is included in the price, and it needs no special description. According to the service providers Helen and Turku Energia, direct DC is not available for all residential areas, but an indirect DC mechanism with a heat pump installed in a building working with the district heat is basically available for all residential buildings. With the current price of energy, the average household annual cost of DC is 100-240€ (based on the information from the service providers webpages and personal communication, estimate made for an 85 m^2 apartment). We use the average of this range, i.e., 170 €. We assume that there are two people living in a household in the age group 65–74, but only one person living in a household in the age group ≥ 75. On the other hand, many people in the oldest age group live in the retirement homes shared by many individuals. These two assumptions may balance each other at least to a certain degree. We divide the investment and the annual cost by two for the age group 65–74.

2.7 The effect of cooling

We need also a numerical estimate for the efficiency parameter, i.e., the reduction in mortality risk caused by a certain cooling mechanism. Having air conditioners (AC) at home has been associated with a relative risk reduction for heat-related death of 77% (OR = 0.23, 95% CI = 0.1–0.6) (Bouchama et al. 2007; Kenny et al. 2010).[1] DC offers economies of scale, higher energy efficiency than AC, lower climate emissions and other benefits (Inayat and Raza 2019). We assume that DC can reduce the heat hazard by 98% (if the resident stays at home during the heat wave, he/she is fully protected from the heatwaves, because the

[1] In a large data study from the US between 1960–2004 the reduction was 86% (Barreca et al. 2016). We apply the lower estimate, 77% in our empirical application.

temperature of the apartment can be adjusted freely). This simplest case, the assumption that all mortality and morbidity could be avoided by adaptation, is typical in the absence of better information (WHO 2013). Once the household is connected to the DC net, indoors temperature can be lowered below the health threatening levels. However, we use an estimate that is slightly under 100% for the technical reasons associated with the optimization (with 100% a global solution was not found). In addition, it is reasonable to assume that not all, even though almost all, of the mortalities could be avoided with DC, mainly because of the human errors related to the old age of the individuals (such as dementia) and in providing the service.

2.8 Adaptation benefits – value of statistical life

Finally, we need an estimate for the VSL. Unfortunately, there is no VSL estimate specific to Finland. However, for Sweden, a review conducted by Hultkrantz and Svensson (2012) indicates an average estimate of €3.7 million, while official authorities in Sweden recommend a lower estimate of €2.4 million. For our purposes, we will adopt the lower figure. It is also important to note that previous literature has presented significantly higher estimates. Keller et al. (2021), in their comprehensive review of 120 studies on VSL methodologies and estimates across various sectors, determined that the median midpoint VSL estimate for the health sector was €6.4 million.

2.9 Costs of inaction

When studying the economic benefits of a CCA policy (or planned adaptation), it is illustrative to first look at the costs of inaction, which represent the overall economic burden of climate change when planned adaptation measures are not implemented (Nicklin et al. 2019). Thus, they are the costs associated with the baseline. In this context those are obtained by multiplying the number of mortalities in the baseline with VSL. In this case the costs of inaction equal the health costs (alternatively called "health damage costs" or "the health costs of inaction"). WHO (2013) defines the health costs as "the costs associated with climate change in the absence of planned adaptation or mitigation responses".

2.10 Discounting

The choice of a discount rate is essential for the analysis, because adaptation costs and benefits unfold gradually (Chambwera et al. 2014). Unfortunately, there is no unique definition of the social discount rate. Most cost-effectiveness studies commonly apply a discount rate ranging from 3 to 5% per year when evaluating future health benefits (Evans and Hurley 1995). For instance, the United States Public Health Service, through a committee appointed by them (Gold et al. 1996), recommends that future Quality-Adjusted Life Years (QALYs) gained should be discounted at a rate of 3%. Similarly, the World Bank (Jamison et al. 1993) suggests that Disability-Adjusted Life Years (DALYs) averted through interventions should be discounted at a 3% per year rate in cost-effectiveness studies. Therefore, we use a 3% discount rate. However, we study the sensitivity of the results to the choice of the discount rate (cf. Basu and Ganiats 2017). All the parameters, their estimates, and their corresponding symbols in the economic model, and the data sources are shown in Table 1.

Table 1 Parameters and their estimates used in the numerical application, the corresponding symbols in the economic model, and the sources

Parameter	Estimate	Symbol	Source
Mortality increase during the heatwaves in the age group of 65–74	6.7%	μ_i, with $i = 1$	Kollanus et al. (2021)
Mortality increase during the heatwaves in the age group of≥75	12.8%	μ_i, with $i = 2$	Kollanus et al. (2021)
Relative risk reduction for heat-related death by air conditioners (AC)	77%	ε_j, with $j = AC$	Bouchama et al. (2007); Kenny et al. (2010)
Relative risk reduction for heat-related death by district cooling (DC)	98%	ε_j, with $j = DC$	WHO (2013)
The average installation costs of AC	3275 €	C_{Ij}, with $j = AC$	Kodinplaza (n.d.)
The annual cost of AC	44.4 €/a	C_{Aj}, with $j = AC$	Own calculations
The average installation costs of DC	1500–1800 €	C_{Ij}, with $j = DC$	Helen, personal communication
The annual cost of DC	100- 240 €	C_{Aj}, with $j = DC$	Own calculations
Value of statistical life (VSL)	2.4 M€	v	Hultkrantz and Svensson (2012)
Discount rate	3%	ρ	-

2.11 Sensitivity analysis

We used sensitivity analysis to study how changing the uncertain parameters affects the NPVs and the benefit/cost-ratios of the cooling by DC and AC. We assign values to key parameters above and below their baseline value and study how the NPV react to these changes. We studied whether changes in the uncertain parameters can turn the positive NPVs to negative ones, and thus change the policy implication from recommending the adaptation by cooling to not recommending such adaptation strategy. We studied only two city/RCP combinations: Helsinki/RCP4.5 and Oulu/RCP2.6, because Helsinki-RCP4.5 can be considered as an average case and Oulu-RCP2.6 as the case with adaptation may be less beneficial. In addition, we studied only three target levels: 20%, 60%, and 98%.

3 Results

3.1 Estimated risk estimates

The numerical values for the absolute risk estimates are shown in Fig. 2. The vulnerability clearly increases with age, because the risk of dying during a heatwave is notably higher in age group≥75 than in age group 65–74. Furthermore, the risk is highest in Turku, and lowest in Oulu, independently of the age group. It is intuitive that the risk is lowest in Oulu because it is the northernmost city. However, the difference between Helsinki and Turku is not explained by the geographical location, since Helsinki is more southern city than Turku, but rather on unobserved factors. Nevertheless, the difference between these southern cities is rather marginal. All in all, the probability of dying during a heatwave is low, i.e., notably less than one percentage.

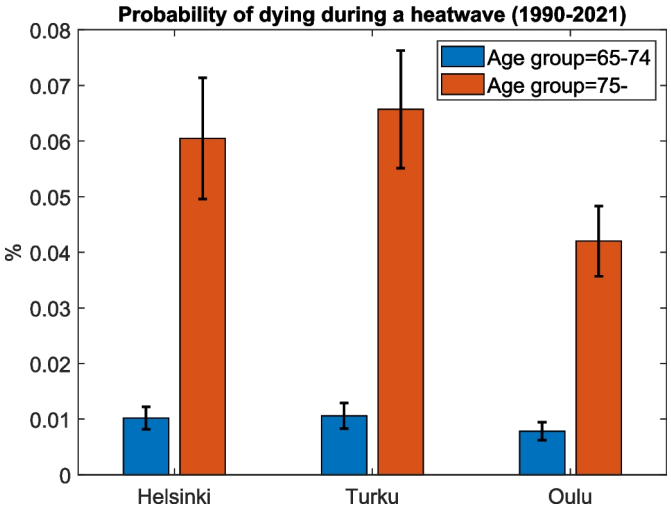

Fig. 2 Estimated mean probabilities of dying during the heatwaves in Helsinki, Turku, and Oulu, in age groups 65–74 and over 75 years, and the associated standard deviations

3.2 Costs of no-adaptation

Currently, there are approximately two heatwaves annually in Finland all together. Our projections suggest that heat wave frequency increases from the current level by 24%, 48%, and 112% in Helsinki, by 18%, 36%, and 79% in Turku and by 4%, 44%, and 112% in Oulu, by 2050, with RCP2.6, RCP4.5, and RCP8.5, respectively. This implies that there are 2–6 heatwaves annually in 2050, depending on the city and the climate scenario (Fig. 3a). In 2100, there will be 2–10 heatwaves annually. The frequency of heatwaves increases almost by the same amount in Helsinki and Oulu in relative terms in RCP4.5 and RCP8.5, although in absolute terms there are notably more heatwaves in Helsinki than Oulu, because Helsinki is a southern city whereas Oulu is northern city. It is also notable that in RCP8.5 the absolute number of heatwaves is highest in Turku, which is also located in the south. Thus, geographical location explains the number of heatwaves but not the relative increase in the frequency of heatwaves.

In all cities, the older age group increases towards the end of the century (Fig. 3b). In Oulu the increasing trend is steepest, whereas in Helsinki the growth stabilizes towards the end of the century. At the same time, the population in the age group 65–74 decreases, mostly in Oulu, and least in Helsinki. Thus, the vulnerability to the heatwaves increases the most in Oulu and least in Helsinki. In absolute terms, however, there is more population in vulnerable age groups in Helsinki than in Oulu or Turku. Combining the heatwave projections with the projections for the vulnerable age groups, and the probability of dying during the heatwaves (Fig. 2), yields the heatwave-related risk projections showing that the south-north gradient is the most important factor explaining the differences in the annual mortality risks. In the case of no-adaptation, i.e. in the baseline, mortality increases from the current by 86%, 123%, and 213% in Helsinki, by 64%, 89%, and 145% in Turku and by 105%, 184%, and 315% in Oulu, by 2050, with RCP2.6, RCP4.5, and RCP8.5, respectively (Fig. 3c, target = 0%). These results are in the same order of magnitude as the results in the

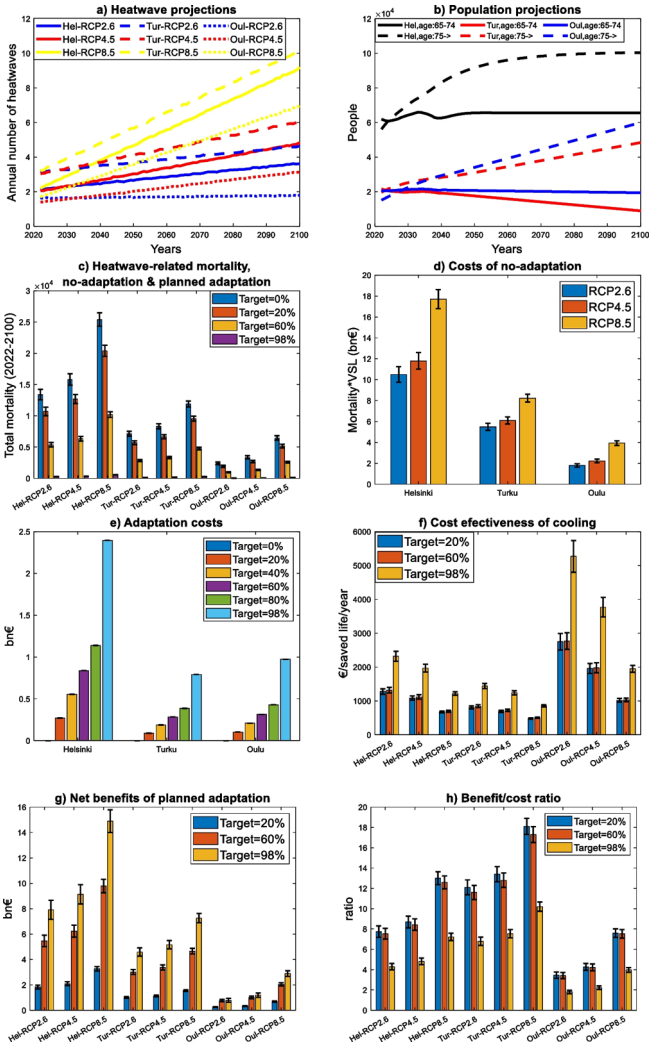

Fig. 3 Costs of no-adaptation and planned adaptation. (**a**) The annual number of heatwaves, which are averaged over the Monte Carlo simulations, for the years 2022–2100, (**b**) projections for the vulnerable age groups (65–74 and over 75) consisting of the forecasts given by the Statistics Finland for the years 2022–2040 and the forecasts obtained with the ARIMA models for the years 2041–2100, (**c**) the total mortality over the planning horizon (2022–2100) with different targets for the mortality reduction compared to the baseline, (**d**) the sum of annual discounted costs in the baseline scenario with no adaptation for 2022–2100, which are obtained by multiplying annual number of heatwave related mortalities with the VSL (2.4 M€), (**e**) the sum of annual discounted adaptation costs for 2022–2100 for different target levels, averaged over the RCPs (costs are nearly identical for the RCPs), (**f**) the cost/effect ratios of cooling for the years 2022–2100, (**g**) the net present values of the planned adaptation for 2022–2100, h) the benefit/cost ratios of cooling for the years 2022–2100 and for the cities Helsinki, Turku, and Oulu, and the targets (0.2, 0.6, and 0.98). In all the subplot with targets, a target means a reduction in mortality relative to the baseline. Thus, a 0%-target means that the number of mortalities is the same that in the baseline, and a 98%-target means that almost all the lives are saved that would have been lost in the baseline

previous literature considering Canada (Doyon et al. 2008; Cheng et al. 2009). Thus, in relative terms the risk increases the most in Oulu, despite being the city located in the north. In absolute terms, however, the risk associated with a no-adaptation scenario is highest in Helsinki, second highest, but notably lower in Turku, and lowest in Oulu.

The costs of no-adaptation policy, determined by the mortality times VSL, increase over time because inaction allows the heatwave mortality to increase. The discounted total costs of no-adaptation over the whole planning horizon (2022–2100) increase rapidly with RCPs and are clearly the highest in Helsinki due to the greatest vulnerable population (Fig. 3d). These costs range from 11–18 bn € in Helsinki, 5.5–8.0 bn € in Turku, 1.8–3.9 bn € in Oulu, depending on the RCP.

3.3 Cost effectiveness of the planned adaptation

The planned adaptation actively promotes cooling. In Helsinki, the 98%-target saves about 13000 – 25000 lives over the planning horizon (2022–2100), depending on the RCP, in Turku half of this, and in Oulu four times less (Fig. 3c). Increasing the target to 98% entails the highest investment and annual costs in cooling (Fig. 3e). These costs increase linearly as a function of the target and have a kink at roughly 80% to even higher adaptation costs. The kink emerges because AC provides on average only 78% survival and reaching higher survival rates requires extending DC to everywhere. Furthermore, the need for cooling increases over time, because the amount of vulnerable people and the number of heatwaves increases in time. The total costs of cooling (i.e., the sum of annual discounted costs over the planning horizon 2022–2100) rise roughly to 2.5 bn € in Helsinki, 0.9 bn € in Oulu, and 0.8 bn € in Turku for the 98%-target (Fig. 3e).

The cost/effect ratios of cooling decrease for higher warming implying that adaptation is more effective, or more needed for warmer climate scenarios. Naturally, for higher targets, costs increase more (Fig. 3f). The cost/effect ratio ranges from 53,500 (std = 2190) to 183,000 (std = 11,500) €/saved life in Helsinki, from 38,200 (std = 1390) to 114,000 (std = 6150) €/saved life in Turku, and from 80,600 (std = 4230) to 416,000 (std = 37,000) €/saved life in Oulu. The notably highest costs/saved life in Oulu reflect the fact that the expected annual number of mortalities is relatively low (due to the low mortality probabilities), while the costs of increasing cooling become high. Thus, adaptation to heat waves by cooling is clearly most cost effective in Helsinki.

Despite the high adaptation costs, when saved lives are valued by VSL, net present values (NPV) are positive for all cities and the climate scenarios suggesting full adaptation, as the employed VSL value exceeds the cooling costs for all targets by a wide margin (Fig. 3g). Interestingly, the net benefits of planned adaptation are highest in RCP8.5 and lowest in RCP2.6. This is because the number of heat-related mortalities is highest in the warmest climate scenario, and therefore RCP8.5 entails more saved lives in absolute terms for the same target levels when compared to RCP2.6. In addition, NPV is an increasing function of the target level, implying that avoiding as many heatwave-related additional mortalities as possible is socially optimal. Benefit/cost-ratios show that in Helsinki, the benefits of cooling exceed by 13 (std = 0.64) times its costs in RCP8.5 and the target of 20%, while they are 4.3 (std = 0.3) times the costs in RCP2.6 with the target of 98% (Fig. 3h). In Turku, the benefits of cooling exceed the costs by 18 (std = 0.8) times in RCP8.5 and the target of 20%, and by 6.8 (std = 0.4) times in RCP2.6 and the target of 98%. Finally, the corresponding benefit/cost

ratios are 7.6 (std = 0.42) and 1.8 (std = 0.17) in Oulu. Given that benefit/cost-ratios are > 1, the previous conclusion re-emerges. In other words, cooling is a socially optimal strategy for the adaptation to heatwaves, and the benefits of adaptation exceed the cost by the most in Turku, second in Helsinki, and last in Oulu. In addition, the adaptation is the most beneficial in RCP8.5 and least beneficial in RCP2.6. All in all, these results imply that the way we measure the costs and benefits do have an impact on the ranking of the cities, but using NPV criteria leads to the same conclusion that the adaptation is recommendable regardless of the city or the RCP, or even of the target level.

3.4 Sensitivity analysis

Changing the uncertain parameters above and below their baseline value affects the NPVs of the cooling by DC and AC (Fig. 4). Most importantly, the positive NPVs can turn to negative ones, and thus change the policy implication from recommending the adaptation by cooling to not recommending such CCA strategy.

The NPV can be negative if VSL falls below certain thresholds, with Oulu-RCP2.6 having critical thresholds even at lower targets (Fig. 4). In Helsinki, under the RCP4.5 scenario, the net present value (NPV) is negative for the 98% target when the value of a statistical life (VSL) is less than 0.5 million euros (Fig. 4a). In Oulu, for the RCP2.6 scenario, the NPV remains negative even at the 20% target if the VSL is below 0.8 million euros (Fig. 4b). Furthermore, to achieve social acceptability for the adaptation at the 98% target in Oulu, the VSL must exceed 1.3 million euros.

For changing discount rate, the NPVs are decreasing functions of the discount rate, and eventually turn negative for a high enough discount rate. This happens for instance in Oulu with RCP2.6 and target 98% when the discount rate exceeds 7% (Fig. 4d). However, discounting affects benefits more than costs, because most cooling costs appear in the early phase of the planning horizon, whereas most benefits appear in the later phase of the planning horizon when the climate becomes warmer. This indicates that the more impatient the planner is, the less acceptable the adaptation to heatwaves becomes, i.e., the higher discount rate the planner uses, the less desirable adaptation to heatwaves by cooling becomes.

The applied parameter values for the cooling costs are also highly uncertain, because, for example, the price of energy varies notably in time and geographically. The NPV of cooling is a decreasing function of the costs of cooling. In Helsinki, where the adaptation is more cost effective than in Oulu, the costs have surprisingly minor effects on the NPV (Fig. 4e). In the case of Oulu, on the other hand, high cooling costs can turn the NPVs negative if the costs of cooling are about 1.7-times the baseline costs in RCP2.6 and for the 98%-target (Fig. 4f). Thus, if the adaptation by cooling is the recommended strategy, then even large increases in the cooling costs do not change this policy recommendation. On the hand, in the cases where this adaptation strategy is barely recommendable, large increases in the cooling costs can make the cooling an unrecommended adaptation strategy. Hence, in southern countries where the heatwaves are even bigger challenge than in Finland, and therefore the cooling is clearly a recommendable adaptation strategy, even high cooling costs would not change the policy recommendation.

Finally, the mortality-decreasing effect of cooling has a minor influence on the NPVs (Fig. 4g, h). In this case, scaling of the effect of DC upwards has no effect because it is

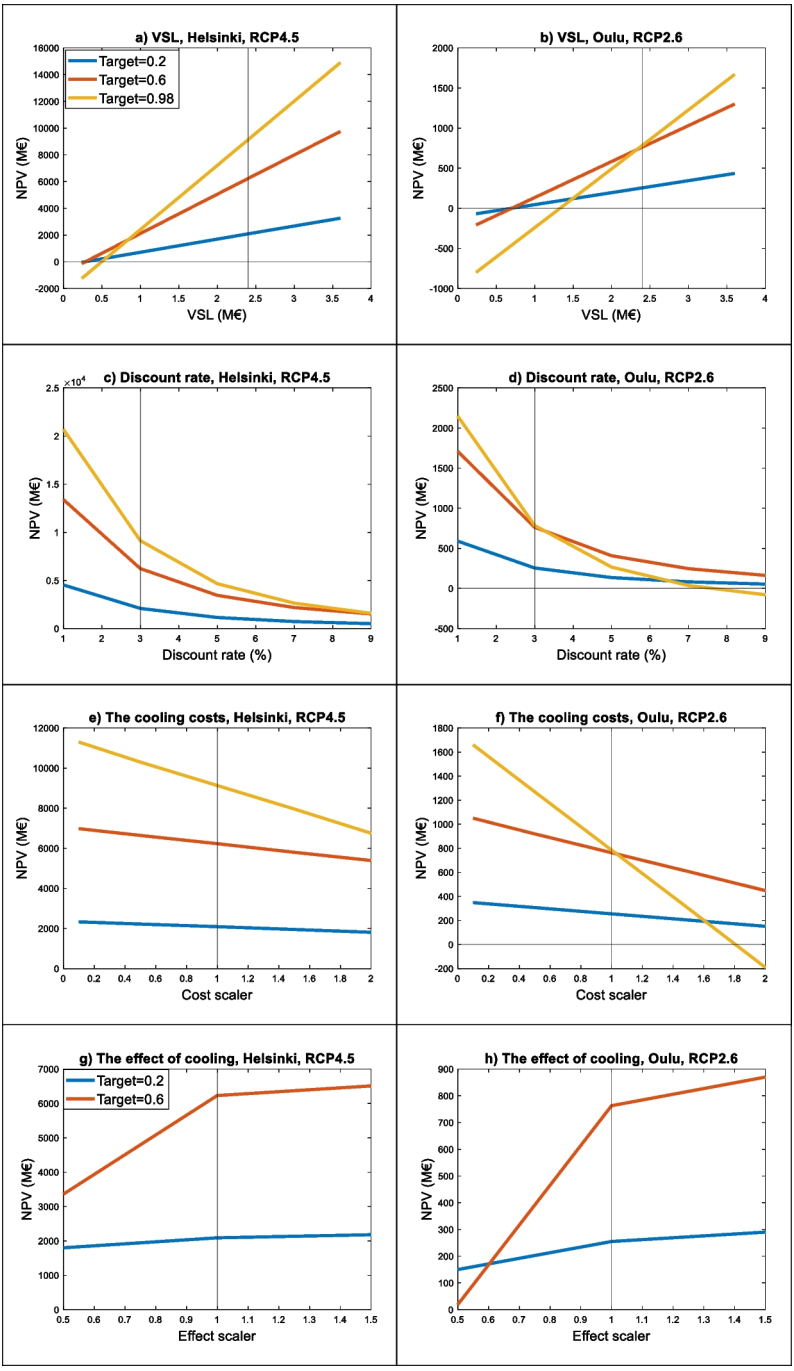

Fig. 4 Sensitivity of the NPVs for the VSL (**a**) and (**b**), for the discount rate (**c**) and (**d**), for the cooling costs (**e**) and (**f**), and for the effect of cooling (**g**) and (**h**). The scaler on the x-axis scales the baseline costs (**e**) and (**f**) and the effect of cooling (**g**) and (**h**) up and down

already practically 100% at the baseline. Therefore, we observe a notable impact on the NPV only for the effects below the baseline.

4 Discussion

We developed a framework for determining cost effective ways for reaching adaptation targets relating to heatwaves. We adopt the IPCC's framing of climate risk as a function of hazard, exposure, and human or ecological system's vulnerability. We use the data of these risk components as inputs to an economic model, which is used as a tool in cost–benefit-analysis determining the economic viability of the adaptation measures. This framework can be used to compare different adaptation measures, and to determine whether a certain CCA policy is economically viable or not. By applying the framework, we derived net benefits of two adaptation measures, district cooling (DC) and the implementation of air conditioners (AC) in apartments, aiming to reduce mortality associated with the increased heatwaves for three climate scenarios in three different cities in Finland, of which two are in southern part of the country and one in northern part of the country. Although it has been suggested in previous literature that the number of heatwaves and their costs increases more for cities in Southern Europe (Guerreiro et al. 2018; EEA 2023; García-León et al. 2024), studying the increasing heatwave risks in our case cities we find that the costs of not adapting to climate change are very high also in northern latitude cities, ranging from 1.8 bn € in Oulu for RCP2.6 to 18 bn € in Helsinki for RCP8.5.

The high costs of not adapting suggest that it is always optimal to avoid any additional heatwave-related mortality with cooling. Therefore, a determined effort is needed to promote the extension of the DC network to prevent the increasing mortality, particularly by extending the DC network to everyone belonging to the vulnerable population group. This could be done by promoting actions in public buildings (hospitals, senior homes, and kindergarten). When planning for cooling in municipalities, it should be noted that the increasing cooling needs may burden the citizens unequally (see, e.g., Igawa et al. 2022). Hence, promoting private adaptation by providing a subsidy to boost investments in cooling in apartment houses is necessary. Some municipalities make advantageous CCA policy in comparison to the national CCA policy, but their measures may be limited, for example, by lack of necessary financial support for retrofitting buildings for cooling. Advancing adaptation to heat risks in municipalities in a truly cost-efficient way requires support and governance from the state (Lake et al. 2017). In addition, more information is needed to help communities, city planning and individuals to choose effective approaches for reducing or avoiding exposure to heat (Tong and Ebi 2019) including strategies for avoiding the overheating of apartments (see Farahani et al. 2024).

We found that the frequency of heatwaves increased in all cities, and mostly in Turku and Helsinki, implying that geographical location explains the number of heatwaves but not the relative increase in the frequency of heatwaves, since in the two warmest climate scenarios the relative increase was as great in Helsinki and Oulu, despite being the northernmost case city. In absolute values, however, the risk associated with the no-adaptation scenario was highest in Helsinki. Our results suggested also that the warmer the climate change scenario, the more cost effective the adaptation by cooling is, and that the cooling is the most cost effective in Helsinki and the least cost effective in Oulu. These results are explained by the

development of the vulnerable population in the cities. Since there are more vulnerable people in Helsinki than in Oulu or Turku, the cost of inaction is highest there, and the adaptation costs per reduced mortality are slightly lowest in Helsinki, implying that the cost effectiveness is highest in Helsinki. Our results on the cost/benefit and benefit/cost ratios imply that the way we measure the costs and benefits have an impact on the ranking of the cities, but using NPV criteria leads to the same conclusion that the adaptation is economically viable despite of the city or the RCP, or even of the target level.

Our sensitivity analysis showed that the choice of value of statistical life (VSL) has a great impact on the question of whether the adaptation by cooling is economically viable or not. For northern cities, like Oulu, and for the milder climate scenarios, the VSL has to be quite high for the adaptation by cooling to be economically viable. The significant effect of the VSL on the cost benefit analysis results in health economics has been raised in past literature (Dionne and Lanoie 2002; Hutton et al. 2006; WHO 2013). We found that the discount rate also had a great impact on the NPVs, and those can eventually turn negative for a high enough discount rate. In Oulu with RCP2.6 and target 98% the discount rate exceeding 7% led to negative NPV. Discounting affects benefits more than costs, because most cooling costs appear in the early phase of the planning horizon, whereas most benefits appear in the later phase of the planning horizon when the climate becomes warmer.

Future studies could be extended to cover a wider geographical area and different climate regions, for example, all the biggest cities in Europe, to study how the net benefits of the adaptation policies differ across Europe. This would be interesting, because although heatwaves are a serious cause of concern in cooler regions such as in Finland (Perkins 2015; Perkins-Kirkpatrick and Gibson 2017), they are even more so in warmer regions (Russo et al. 2017; Raymond et al. 2020; Im et al. 2017; Pal and Eltahir 2016). Furthermore, research is needed on the environmental impacts of cooling and how to reduce them by introducing environmentally sound adaptation options, for instance with urban greening (Graça et al. 2022). The use of air conditioners results in higher electricity demand, increased GHG emissions, and diminished local air quality, implying that ignoring systemic effects increases risk of encouraging behaviors that are personally compatible in the short term, but it may be personally, socially, and environmentally incompatible in the long term (Jay et al. 2021; Kiarsi et al. 2023). Hence, another important extension of this study would be to broaden the selection of adaptation measures as heatwave related mortality in cities can also be lowered by increasing green infrastructure in the cities or by favoring white or light colors and reflective materials in buildings (Georgi and Dimitriou 2010; Peng et al. 2012; Kim and Ryu 2015; Wang and Akbari 2015; Araos et al. 2016; Alaci 2017; Bai et al. 2018; Viguié et al. 2020). Sufficient and sustainable reduction of the urban heat risks requires early and fast adoption of a diverse set of cooling measures as already shown in other parts of Europe (see, e.g., Vigué et al. 2020).

We also acknowledge that the current exposure–response functions may have limitations in projecting future heat-related mortality levels, as the correlation between heat and mortality could potentially evolve over time (Huang et al. 2011). We also ignored the ancillary impacts of adaptation, which can be either positive (co-benefits) or negative (maladaptation) and may or may not include cascading effects. Maladaptation arises when an effort to adjust to a specific location or sector ends up raising the risk of adverse effects on a different location, sector, or target group (Noble et al. 2014). IPCC (2022) notes that maladaptive behaviours, such as opting for air conditioning systems over sustainable cooling methods,

can create persistent challenges that are both expensive and challenging to rectify in the long run. In addition, district cooling requires energy, and the demand for energy related to air conditioning is anticipated to rise significantly throughout the entire period from 2000 to 2100, primarily influenced by increases in income levels (Isaac and van Vuuren 2009). Colelli et al. (2023) suggests that by the year 2050, under a high-warming scenario, the prevalence of air conditioning (AC) is projected to double in Europe and quadruple in India, ultimately reaching approximately 40% in both areas, revealing a trade-off between mitigation and adaptation. In Finland, however, most of the district heating is produced using renewable energy: in county with Helsinki as it's centre, the share of renewable energy sources is 72%, and the corresponding figures for Turku and Oulu are 95% and 71%, respectively, with the share of renewable energy expected to increase in the future (Energiateollisuus 2025). As a final note, our analysis omitted other health impacts of heatwaves than mortality. There are many additional health and societal benefits potentially associated with the cooling interventions, such as decreases in cardiovascular disease, ischemic heart disease, ischemic stroke, respiratory disease, pneumonia, dehydration, heat stroke, diabetes, and acute renal failure (Ostro et al. 2010), mental symptoms, skin disorder, gastrointestinal disorder, renal and urinary disorder, neurological disorder, sleep disorder (Lee et al. 2019) and many others. Their inclusion would strengthen the case for adaptation by cooling.

5 Conclusions

By evaluating the costs and benefits of district cooling (DC) and air conditioner (AC) implementation in three Finnish cities under different climate change scenarios, we discovered high costs of not adapting to rising heatwaves, even in northern cities like Oulu. We recommend promoting the expansion of the DC network, particularly to vulnerable populations, and encouraging private investments in cooling solutions. More information is needed to guide communities and individuals in mitigating heat exposure risks. Research on environmentally friendly cooling options, such as urban greening, is also recommended.

Heatwave frequency increased in all cities, with the greatest relative increase in Oulu despite its northern location. Cooling adaptation was found to be most cost-effective in Helsinki and least in Oulu, influenced by the vulnerable population distribution. Sensitivity analysis revealed the impact of values on statistical life (VSL) and discount rates on cost–benefit analysis results. Adaptation by cooling may not be economically viable in northern cities like Oulu without high VSL values.

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Author contributions Dr. Matti Hyyrynen did all the coding and model building, run the results, draw all the result figures and tables, analyzed the results, and wrote the manuscript. Prof. Ollikainen Markku came up with the research idea, analyzed results, and wrote the manuscript. Prof. Jussi Lintunen helped with the model building, analyzing the results, and drawing the figures, and participated in writing the manuscript. Dr. Janina Käyhkö helped with building the modelling framework and with finding the model parameters, and wrote the manuscript, and draw the framework figure. Dr. Groundstroem Fanny Marie helped with building the modelling framework and with finding the model parameters. Dr. Juuso Suomi helped with building the modelling framework and with finding the model parameters, and wrote the manuscript, and draw the figure describing the geographics of the study area. Prof. Jukka Käyhkö wrote the manuscript and helped with analyzing the results. Dr. Antti Mäkelä provided the raw data and participated in writing the manuscript. Prof Sirkku Juhola helped with analyzing the results and wrote the manuscript.

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Data availability Raw data is provided in supplementary material. Codes can be asked from the corresponding author.

Declarations

Ethical approval All authors have consent for ethical approval and participation, and for publication.

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