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Technical Background – Part I

1.1 Climate Impact Assessments in British Columbia: Climate Model Selection and Data Analysis Methods

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1.2 Introduction

Decision makers are increasingly using climate change impact and risk assessments to understand current and future hazards, impacts, and economic costs (J.-C. C. Ciscar et al., 2019; ESSA, 2019; United States Environmental Protection Agency, 2020). Impact assessments can provide information to support adaptation planning to numerous hazards, particularly if the analyses use climate models to examine how risks may change over time.

Detailed and locally grounded climate impact modelling frequently require daily timeseries of projected climate variables. Daily timeseries are generally used as inputs into complex damage functions to determine social, economic, or ecological impacts (J.-C. Ciscar et al., 2014; ESSA, 2019; Fant et al., 2020). For climate modelling to be useful to decision makers it frequently needs to be at the spatial scale of relevant government jurisdictions (e.g., municipal, health authorities) and at a temporal scale that aligns with policy and capital planning horizons. Requirements for these precisions mean that climate inputs need to have a high spatial resolution to account for micro-climates and inter-regional variation and need to capture uncertainty across various GCMs and global emissions scenarios.

Low-resolution climate analyses in Canada frequently uses ensembles of 20 to 30 statistically downscaled general circulation models (GCMs) to determine the possible worlds under various greenhouse gas emissions pathways. These models represent a subset of all the available GCMs for Canada and are at a gridded resolution of 300 arc-seconds (roughly 10 km) (PCIC, 2019). Further, low resolution analyses commonly use ensemble median or mean values and standard deviations to capture the range of uncertainty.

High-resolution climate impact analyses, however, require a different approach. First, using ensemble median or mean and distributions to capture a range of model outputs can produce incongruent physical realities. For example, the low-resolution ensemble approach could result in daily max temperature from *model A* being selected for day 1 of a timeseries and precipitation amount from *model B* being selected for day 1; while *model A* and *model B* physical assumptions may in-fact contradict one another. Instead, high resolution climate impact analyses usually need to run damage functions separately for each GCM.

Further, 10km gridded data are not a high enough resolution to estimate climate impacts in most high-resolution assessments. In a province like British Columbia where mountain valleys and coasts create large local variation, 10-kilometre gridded data may underestimate summer temperatures at valley floors – where communities are usually located – and may overestimate winter temperatures in coastal communities that are influenced by ocean temperatures (Murdock, T.Q., S.R. Sobie, H.D. Eckstrand, 2016). Numerous approaches are used to downscale climate models including development of regionally specific models that embed micro-climate dynamics. In British Columbia, the Pacific Climate Impact Consortium has published gridded 30 arc-second (roughly 800 metre) gridded observation data which can be used to locally correct 10-kilometre gridded climate projections.

The objective of this analysis is to: 1) identify a subset of GCMs that capture the range of temperature realities under SSP5-8.5 for British Columbia; 2) develop daily tasmin and tasmax timeseries for each Population Centre[1] in British Columbia that have high spatial resolution.

1.3 Methods

1.3.1 GCM selection

Because we were using the climate data to drive health and labour productivity damage functions, our primary interest was with the frequency and distribution of warm temperatures. Specifically, we wanted to find GCMs which produced the greatest variation in mean daily temperature and select GCMs which had various distributions of extreme heat. Due to computing power, we were constrained to five GCMs. We used statistically downscaled CMIP6 climate models available through the Pacific Climate Impacts Consortium for this study (Pacific Climate Impacts Consortium University of Victoria, 2022). CMIP6 climate models reflect the most recent climate science and have been statistically downscaled for SSP1-2.6, SSP2-4.5; and SSP5-8.5 radiative forcing pathways.

First, we downloaded gridded index climate projections for all 19 statistically downscaled CMIP6 GCMs used by Environment Climate Change Canada at the time of this analysis. We selected two indexes to proxy exposure to moderate temperatures and extreme temperatures: number of days per year with temperatures over 30^{o}C SU30); and growing season length (GSL). Because our climate impact modelling only used SSP5-8.5, we only analyzed GCMs using this radiative forcing pathway. All data were downloaded in netCDF format for years 2000 through 2100.

Next, we cut climate projection data to Population Centre boundaries and collated annual averages (Statistics Canada, 2021). Using R Cran, we developed code to loop through temporal layers of each climate projection (netCDF file) (see supplemental materials). For each year, we recorded the average value for all grid cells in each shapefile polygon. To capture inter-provincial variation, we used Prince George and Vancouver boundaries for this study.

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[1] Population Centres are defined by Statistics Canada. At the time of this study, there were 108 Population Centres for British Columbia. For our climate impact assessment, we re-aggregated Vancouver into three distinct polygons resulting in a total 111 distinct Population Centres. A shapefile is available on GitHub here.

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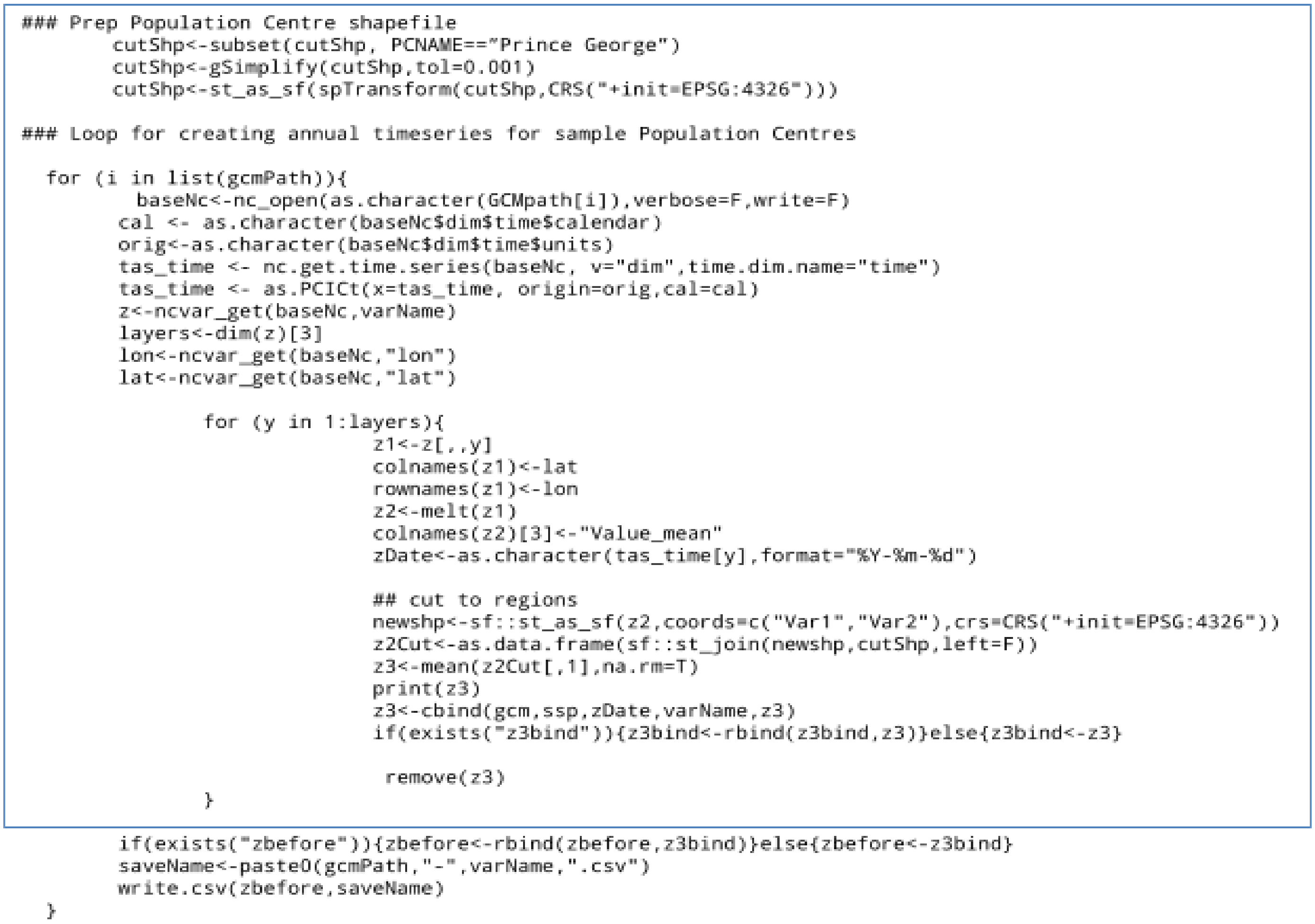

```
### Prep Population Centre shapefile
       cutShp<-subset(cutShp, PCNAME==”Prince George")
       cutShp<-gSimplify(cutShp,tol=0.001)
       cutShp<-st_as_sf(spTransform(cutShp,CRS("+init=EPSG:4326")))

### Loop for creating annual timeseries for sample Population Centres

  for (i in list(gcmPath)){
         baseNc<-nc_open(as.character(GCMpath[i]),verbose=F,write=F)
        cal <- as.character(baseNc$dim$time$calendar)
        orig<-as.character(baseNc$dim$time$units)
        tas_time <- nc.get.time.series(baseNc, v="dim",time.dim.name="time")
        tas_time <- as.PCICt(x=tas_time, origin=orig,cal=cal)
        z<-ncvar_get(baseNc,varName)
        layers<-dim(z)[3]
        lon<-ncvar_get(baseNc,"lon")
        lat<-ncvar_get(baseNc,"lat")

               for (y in 1:layers){
                            z1<-z[,,y]
                            colnames(z1)<-lat
                            rownames(z1)<-lon
                            z2<-melt(z1)
                            colnames(z2)[3]<-"Value_mean"
                            zDate<-as.character(tas_time[y],format="%Y-%m-%d")

                            ## cut to regions
                            newshp<-sf::st_as_sf(z2,coords=c("Var1","Var2"),crs=CRS("+init=EPSG:4326"))
                            z2Cut<-as.data.frame(sf::st_join(newshp,cutShp,left=F))
                            z3<-mean(z2Cut[,1],na.rm=T)
                            print(z3)
                            z3<-cbind(gcm,ssp,zDate,varName,z3)
                            if(exists("z3bind")){z3bind<-rbind(z3bind,z3)}else{z3bind<-z3}

                             remove(z3)
               }
        if(exists("zbefore")){zbefore<-rbind(zbefore,z3bind)}else{zbefore<-z3bind}
        saveName<-paste0(gcmPath,"-",varName,".csv")
        write.csv(zbefore,saveName)
  }
```

Finally, after developing a timeseries of annual projected SU30 and GSL for both Prince George and Vancouver, we plotted each GCM on a two-by-two matrix. Then, again using code developed in R Cran, we calculated the convex hull for 2030s, 2050s, and 2090s horizons.

This method for selecting a sub-set of GCMs draws from the United States Environmental Protection Agency’s (EPA) approach to model selection for the Climate Impact and Risk Analysis (EPA, 2017; United States Environmental Protection Agency, 2020). This approach was also used by the Canadian Climate Institute to select a national CMIP5 sub-ensemble in 2019 (Clark et al., 2021; Under Water: The Costs of Climate Change for Canada’s Infrastructure, 2021).

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```
### Organize data

       pull<-Data %>%
         dplyr::select(gcm, era, Temp.su30, Temp.gsl) %>%
         filter(era==i)

       pull<-pull %>%
         dplyr::group_by(gcm) %>%
         summarise(across(where(is.numeric), ~mean(.x,na.rm=T)))

         pull$x<-pull$Temp.su30
         pull$y<-pull$Temp.gsl
         index<-chull(pull$x,pull$y)
         boundaryGCM<-(paste(as.character(gcm[index]), sep=", ", collapse=", "))
         Title<-paste0("ssp585 for Vancouver", i)

###Save output
         save<-cbind(i,boundaryGCM)
         if(exists("chullOut")){chullOut<-rbind(save,chullOut)}else{chullOut<-save}


###Draw diagram
         rownames(pull)<-pull$gcm
         xAxis<-"days over 30C"
         yAxis<-"growing degree days"
         hpts <- chull(pull$x, pull$y)
         hpts <- c(hpts, hpts[1])
         tempPlot<-ggplot(d=pull, aes(x,y))+ geom_point(shape=1,color="blue") +
           geom_text(aes(x,y,label=rownames(pull)),
                     position = position_dodge(width=0.5), size=2.5)+
           geom_path(data=pull[hpts,], color="blue")+
           labs(title = Title, x=xAxis,y=yAxis)
```

1.3.2 Data transformations and scaling

After selecting the five GCMs for our climate impact modelling, we created daily timeseries of min and max temperature for all Population Centres in British Columbia. This involved a three-step process which we streamlined through a R Cran loop (supplemental materials).

First, we downloaded raw data from the PCIC server (Pacific Climate Impacts Consortium University of Victoria, 2022). We downloaded daily minimum and maximum temperature projections (tasmin and tasmax) from 1981 to 2100 for British Columbia for each of the five selected GCMs. Data were only downloaded for SSP5-8.5 radiative forcing pathway. The data were structured on the PCIC server such that we pulled one netCDF file per year for each GCM – each netCDF having between 365 and 365.25 temporal layers.

```
##### Download data from PCIC server

#HadGEM GCM: Gregorian
"https://data.pacificclimate.org/data/downscaled_cmip6/tasmin_day_BCCAQv2+ANUSPLIN300_CanESM5_historic
al+ssp126_r1i1p2f1_gn_19500101-21001231.nc.nc?tasmin[21900:22264][84:352][0:328]"

#EC-Earth GCM: fixed 360
"https://data.pacificclimate.org/data/downscaled_cmip6/tasmax_day_BCCAQv2+ANUSPLIN300_EC-Earth3_histor
ical+ssp585_r4i1p1f1_gr_19500101-21001231.nc.nc?tasmax[18262:55151][0:510][0:1068]"

#FGoals-G3: fixed 365
"https://data.pacificclimate.org/data/downscaled_cmip6/tasmax_day_BCCAQv2+ANUSPLIN300_FGOALS-g3_histor
ical+ssp585_r1i1p1f1_gn_19500101-21001231.nc.nc?tasmax[18250:55113][0:510][0:1068]"

#UKESM1-0-L: fixed 360
"https://data.pacificclimate.org/data/downscaled_cmip6/tasmax_day_BCCAQv2+ANUSPLIN300_UKESM1-0-LL_hist
orical+ssp585_r1i1p1f2_gn_19500101-21001230.nc.nc?tasmax[18000:54359][0:510][0:1068]"

#ACCESS ESM1: Gregorian
"https://data.pacificclimate.org/data/downscaled_cmip6/tasmax_day_BCCAQv2+ANUSPLIN300_ACCESS-ESM1-5_hi
storical+ssp585_r1i1p1f1_gn_19500101-21001231.nc.nc?tasmax[18262:55151][0:510][0:1068]"


######## Download function
websearch<- function (URLbase){

  library(rvest)
  library(plyr)
  library(stringr)

  options(timeout=1000)
  cnt1<-0

    t1<-seq(18262,55151,by=360)
    cnt2<-0
    for(i in t1){
      t2<-i+359
      cnt2<-cnt2+1

u<-paste0("https://data.pacificclimate.org/data/downscaled_cmip6/tasmax_day_BCCAQv2+ANUSPLIN300_",URLb
ase,"_historical+ssp585_r1i1p1f1_gn_19500101-21001231.nc.nc?tasmax[",i,":",t2,"][84:352][0:328]")
      if(cnt2>1.1){U<-c(U,u)}else{U<-u}
    }


  for (i in U){
      cnt1<-cnt1+1
      #retry::wait_until(Sys.time() - timeStamp > 120)

      name<-as.character(stringr::str_match(i,pattern="(?<=downscaled_cmip6/)(.*?)(?=.nc.nc)")[,1])
      fileDes<-paste0("D:/GIS/Climate Models/CMIP6/BC/SelectedGCMs/tasmax/",name,"_",cnt1,".nc")
      tryCatch({
        download.file(url=i,destfile =fileDes,mode="wb")
        print("waiting for download")
      },error =function(e){print("couldn't find file")
        Sys.sleep(30)
      },warning=function(e){print("couldn't find file")}
```

Second, we reprojected and cut the four-dimensional gridded data for each Population Centre. Again, using R Cran and packages RNetCDF; ncdf4; raster; PCICt; chron; sf; and rgeos, we iterated through each temporal dimension of each netCDF file to create a temporary raster projection of a given climate variable (i.e., tasmin or tasmax) (R Core Team, 2022). We then reprojected the raster to the same projection as our Population Centre shapefile. Then, we calculated the mean value for all grid cells within each population centre’s spatial boundary on a given day. After iterating through this looped process for each day, netCDF file (i.e., year), and climate variable, we had a daily timeseries for each GCM and Population Centre.

Finally, we scaled daily projections based on historic gridded high-resolution land-surface temperature observations. We used the PCIC's PRISM monthly minimum and maximum temperature data from 1981 to 2010 downloaded through the PCIC website (Pacific Climate Impacts Consortium University of Victoria, 2014). First, repeating steps described above, we calculated the monthly minimum and maximum temperatures for each Population Centre using the PRISM data. We then aggregated the daily tasmin and tasmax climate observations into monthly averages. This resulted in two timeseries: 1) PRISM monthly observations from 1981 to 2010; and 2) hindcast monthly climate projections from 1981 to 2010 (Sobie & Murdock, 2017). We then calculated the average monthly error between PRISM and climate projections for each Population Centre over the baseline period. As a last step, we corrected for the error by adding or subtracting from the daily climate projections. The PRISM-based adjustments allowed us to capture local climates more accurately (although it should be clear that it does not increase modelling precision).

1.4 Results

1.4.1 GCM selection

We identified wide variation between GCMs in both the number of days projected over 30°C and the number of growing degree days. We observed that there was a range of 39 growing degree days between the warmest and coolest GCM in Vancouver in the 2030s and 43 growing degree days during the 2050s. Because growing degree days are projected to reach near 365 days by mid century, the range between the warmest and coldest GCM decreased in the 2090s in Vancouver. However, we observed that the range continued to grow in Prince George, where there was a difference of 76 days between the warmest and coldest model by end of the century (Table 1).

		Vancouver			Prince George		
		2030s	**2050s**	**2090s**	**2030s**	**2050s**	**2090s**
Growing season length (days)	Max	337.8	360.4	361.2	205.3	236.6	299.5
	Min	298.9	317.4	348.6	183.7	190.5	223.4
	Mean	322.7	336.1	356.3	194.4	209.3	248.4
	Range	39.0	43.0	12.5	21.6	46.1	76.2

We observed that the range of projected extreme heat days also increased throughout the century across all 19 GCMs analyzed. The total range of uncertainty was similar in Vancouver and Prince George. We observed that the number of extreme heat days is projected to grow faster in Vancouver compared to Prince George among both the coldest and warmest GCMs (Table 2).

	Vancouver			Prince George		
Annual number of	**2030s**	**2050s**	**2090s**	**2030s**	**2050s**	**2090s**

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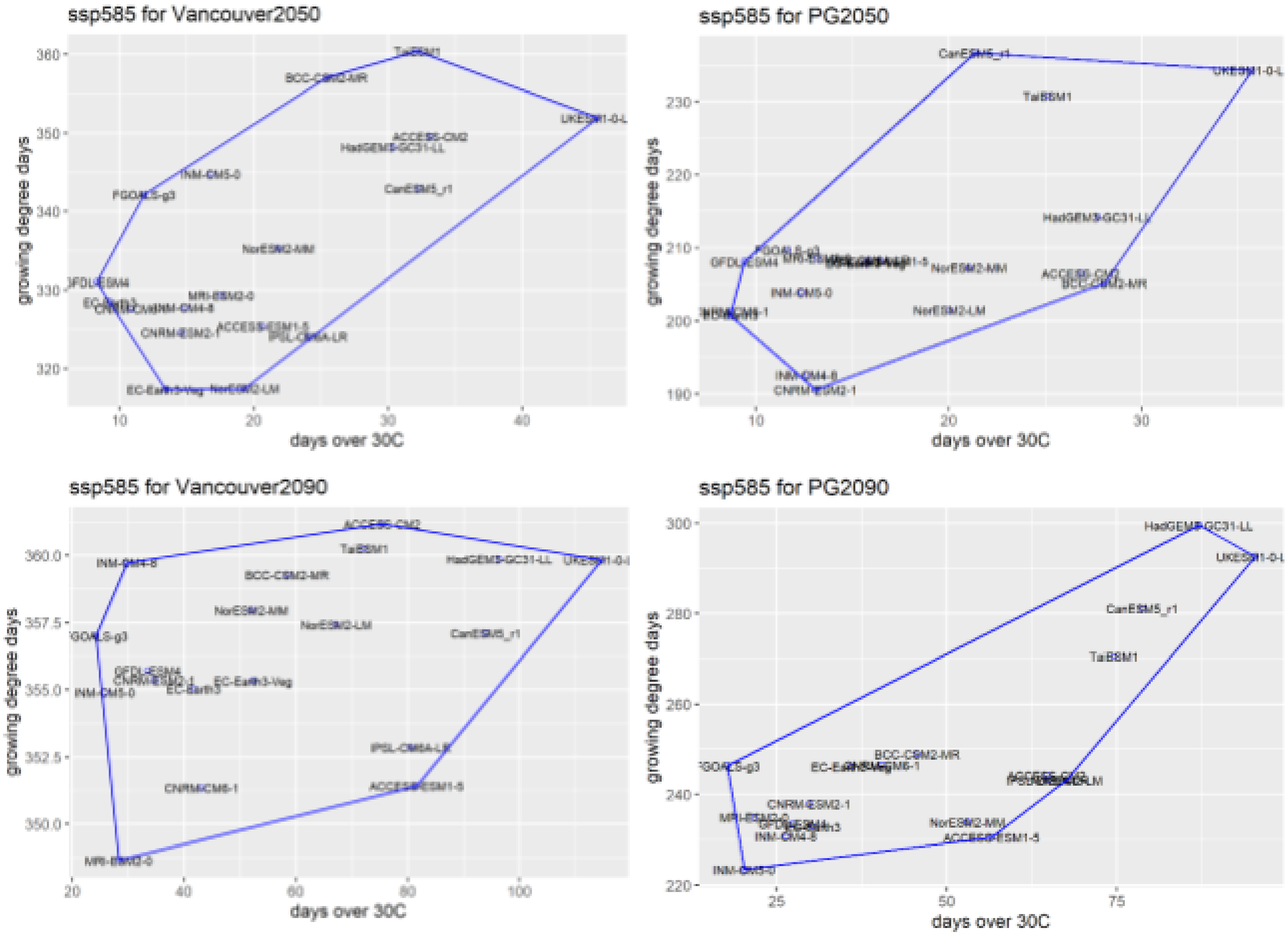
days above 30C	Max	20.9	45.6	114.7	19.7	35.7	95.3
	Min	5.6	8.3	24.3	4.0	8.7	17.8
	Mean	12.6	21.2	58.2	11.3	18.1	49.4
	Range	15.3	37.3	90.4	15.7	27.0	77.5

In plotting the GCMs on a two-dimensional matrix, we observed that while there was a correlation between SU30 and GSL, there were clearly models that had longer summers with shorter tailed extreme heat and models that had shorter summers but longer tailed extreme heat (Figure 1).



There was a clear set of GCMs which were on the periphery for both Vancouver and Prince George during all the time horizons. Based on the LASSO analysis, we selected five GCMs for use in the later part of the study. These were: EC-Earth3; FGOALS-g3; HadGEM3-GC31-LL; UKESM1-0-LL; and ACCESS-ESM1-5 (Figure 2).

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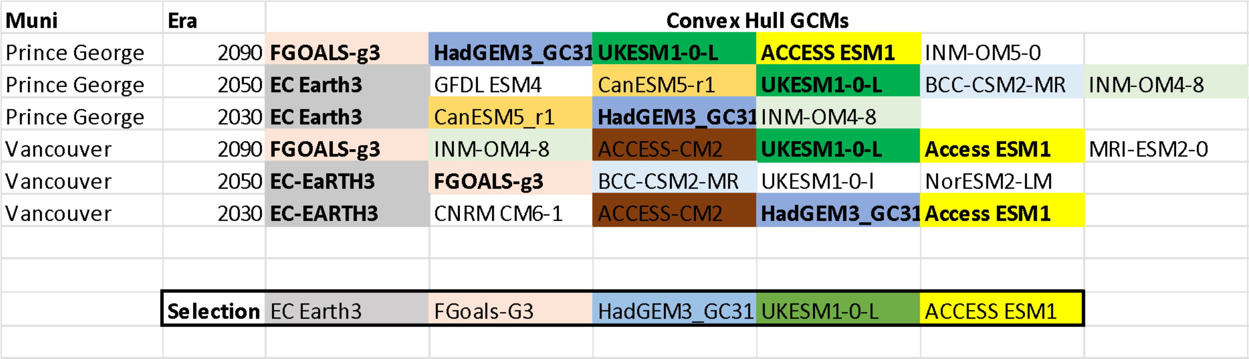
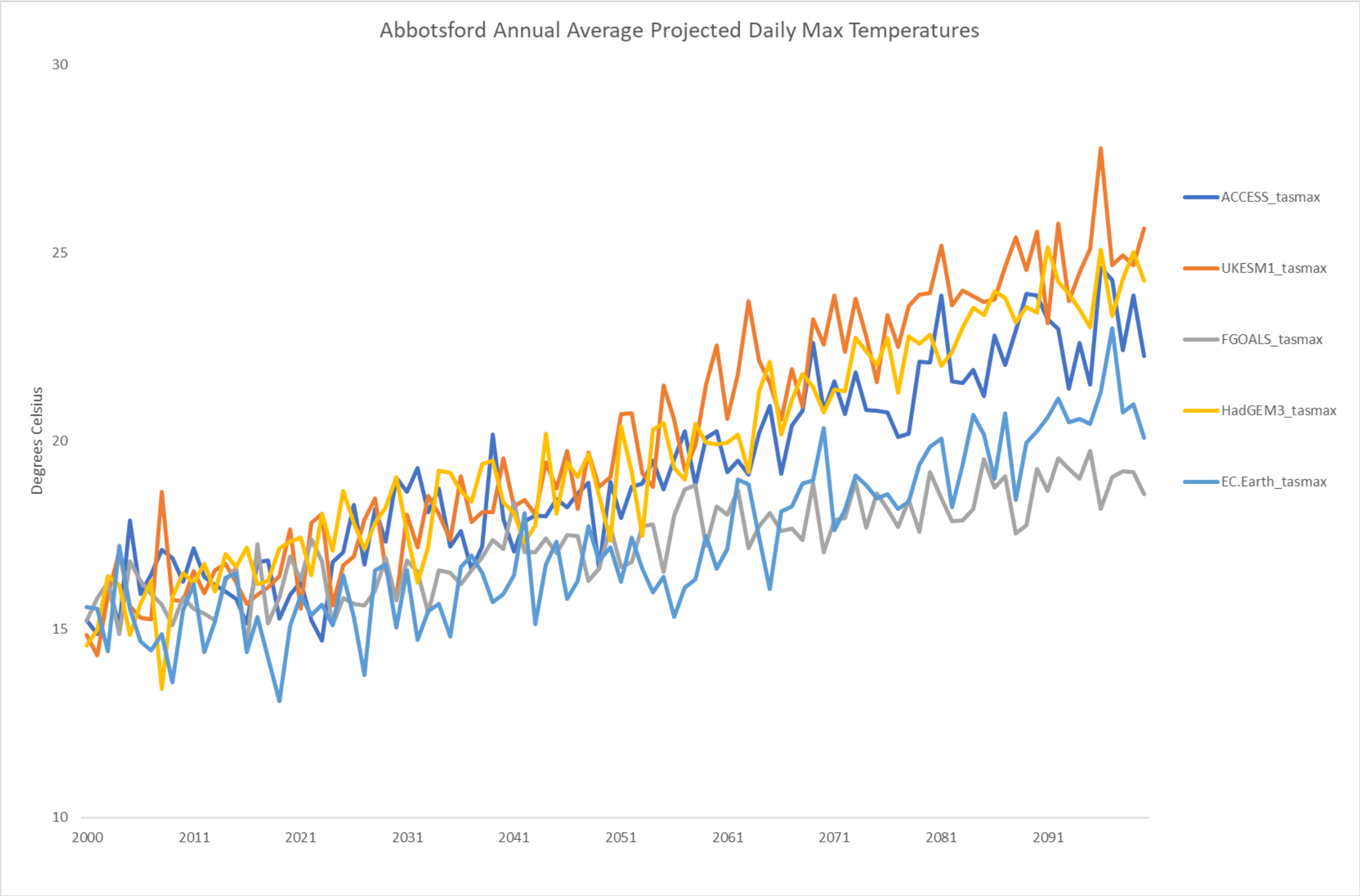


Muni	Era	Convex Hull GCMs					
Prince George	2090	**FGOALS-g3**	**HadGEM3_GC31**	**UKESM1-0-L**	**ACCESS ESM1**	INM-OM5-0	
Prince George	2050	**EC Earth3**	GFDL ESM4	CanESM5-r1	**UKESM1-0-L**	BCC-CSM2-MR	INM-OM4-8
Prince George	2030	**EC Earth3**	CanESM5_r1	**HadGEM3_GC31**	INM-OM4-8		
Vancouver	2090	**FGOALS-g3**	INM-OM4-8	ACCESS-CM2	**UKESM1-0-L**	**Access ESM1**	MRI-ESM2-0
Vancouver	2050	**EC-EaRTH3**	**FGOALS-g3**	BCC-CSM2-MR	UKESM1-0-l	NorESM2-LM	
Vancouver	2030	**EC-EARTH3**	CNRM CM6-1	ACCESS-CM2	**HadGEM3_GC31**	**Access ESM1**	
	Selection	EC Earth3	FGoals-G3	HadGEM3_GC31	UKESM1-0-L	ACCESS ESM1	

To verify the model selection and our approach of running individual climate impact assessments for each GCM, we reviewed projected monthly average temperature projections for select Population Centres in British Columbia. We noted that there was temporal variation (interannual and decadal) in terms of which GCM was the min, median, and max (Figure 3).

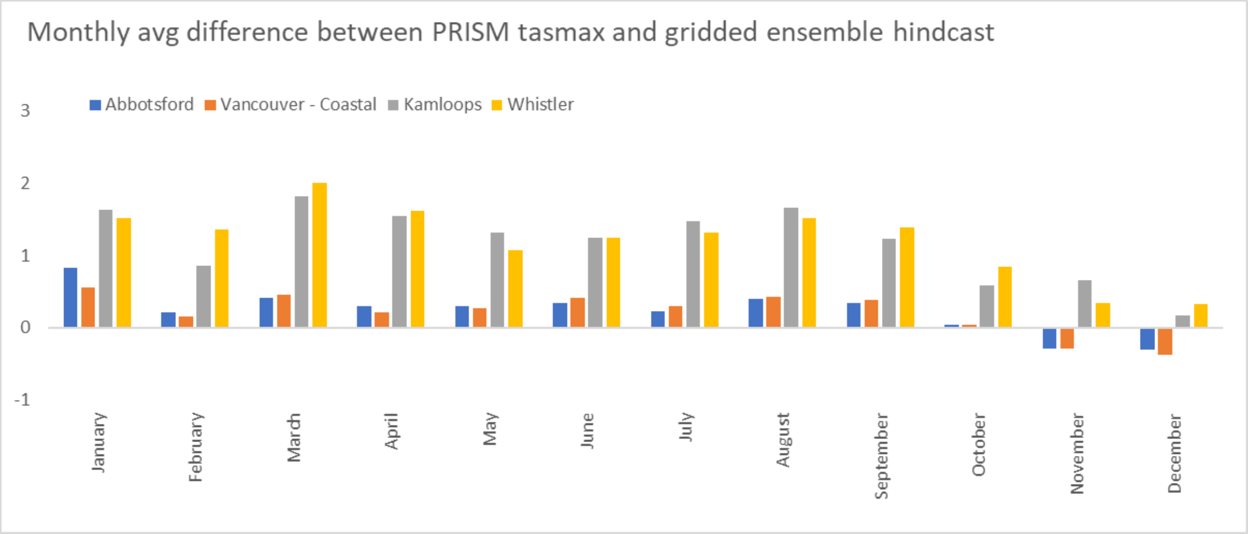


1.4.2 Data transformations and scaling

We found that there was seasonal variation in the difference between hind-cast climate projections (a 10-kilometre resolution) and the PRISM data (800-metre resolution)(Figure 4). We found that across all

British Columbia Population Centres, January had the largest differences (average 2.00°C) while the smallest difference was in October (average 0.59 °C). On average, climate models underestimated temperatures by 1.05 °C annually.

Climate models tended to overestimated temperatures during November and December in coastal communities – especially smaller communities which had lower grid sample sizes. For example, in Campbell River, climate models overestimated tasmin from October to December by an average of 0.24 °C and tasmax by an average of 0.21 °C. Similarly, climate models overestimated tasmax by 0.29 in the fall. These overestimates were not universal to all costal communities though, models underestimated temperatures year around in Sechelt, Tofino, Ucluelet, Port Hardy, Port Alberni, and Prince Rupert. Underestimates were largest in mountain communities. We observed the largest climate model underestimates in Cultus Lake, Hope, Keremeos, Lillooet, Lions Bay, Nelson, Naramata, Okanagan Falls, Penticton, Peachland, and Sicamous – all communities that have large topographical variation in the surrounding area. Many of these places also have small Population Centre boundaries, meaning that very few grid cells are sampled from the climate models.



After correcting for local climate variation using the PRISM data, we assessed general patterns across the five GCMs. All outputs are published (see supplemental data), however, we focus on model projections for Vancouver here.

The data suggests that the average daily minimum temperature will increase by 3.6°C in the next decade across Vancouver (including Richmond and Burnaby). Further, the five-model ensemble mean suggests that average daily maximum temperatures will increase by 3.8°C. We observe that the largest projected change is in the severity of extreme heat days; models suggest that the maximum annual temperature will increase by an average of 5.2°C over the next decade.

	Avg tasmin	**Avg tasmax**	**Min tasmin**	**Max tasmax**
Baseline ***(2000 to 2020)***	8.08	15.50	-1.03	27.43

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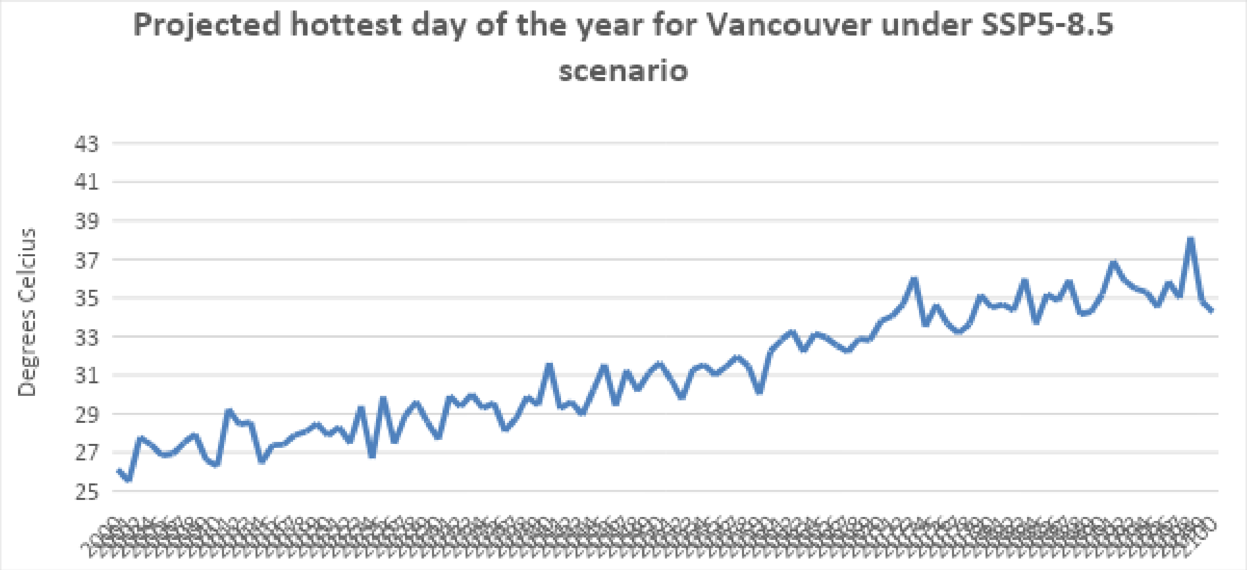
2030s	11.64	19.30	2.71	32.60
2050s	10.55	18.17	1.10	31.09
2090s	14.03	21.78	5.90	35.71

Later in the century under a SSP5-8.5 radiative forcing scenario, models suggest that the hottest day of the year could be 8.3oC warmer than the baseline average. Further, models suggest that by mid-century there will rarely be any year where temperatures drop below freezing in Vancouver.



Data shows the mean value of the five GCM sub-ensemble.

1.5 Conclusions

Climate impact modelling requires high spatial and temporal resolution. However, consultants, researchers, and analysts often have limited computing power and time to develop and run climate impact models. There are substantial limitations when running models on ensemble averages – a frequent work-around – instead of bottom-up functions for each GCM. Further, few regions around the world have higher spatial resolution than ~10 kilometre statistically downscaled models.
In this study we describe a toolkit for selecting a subset of GCMs for climate impact modelling and improving spatial accuracy. While these methods have their own limitations, the steps vastly improve workflow and reduce computational requirements. Further, the limitations can be mitigation through sensitivity analysis.

In our analysis we demonstrate the ability to select a subset of GCMs while still capturing the broad range of distributions across a larger climate model ensemble. We also show the importance of correcting for local climate variation – especially in coastal and mountainous regions – using historic high-resolution gridded observational data.

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Our analysis and the approaches described for climate impact modelling do not replace the use of broader ensemble runs for more complex, and multi-hazard climate impact analyses. For example, wildfire regime modelling that requires interlinked precipitation, temperature, and wind projections may need to use a broader sample of GCMs to capture the multi-variate interplay.

Further, correcting statistically downscaled climate models using PRISM data does not replace the need for regional climate models which account for the mechanisms which are driving variation between the statistically downscaled GCMs and PRISM data. For example, regional climate models that include local ocean currents, freshets discharge patterns, snowpack dynamics, and topographic variation would likely produce projections that are more closely aligned with the historic observations.

Climate change is increasingly affecting hazard dynamics and risks to society. It is critical that decision makers and researchers have a suite of tools to choose from to deploy regionally relevant climate impact models and inform adaptation decision making.

Funding

Government of BC contributed $250,000 for the Canadian Climate Institute to analyze the economic costs and impacts of the 2021 heatwave.

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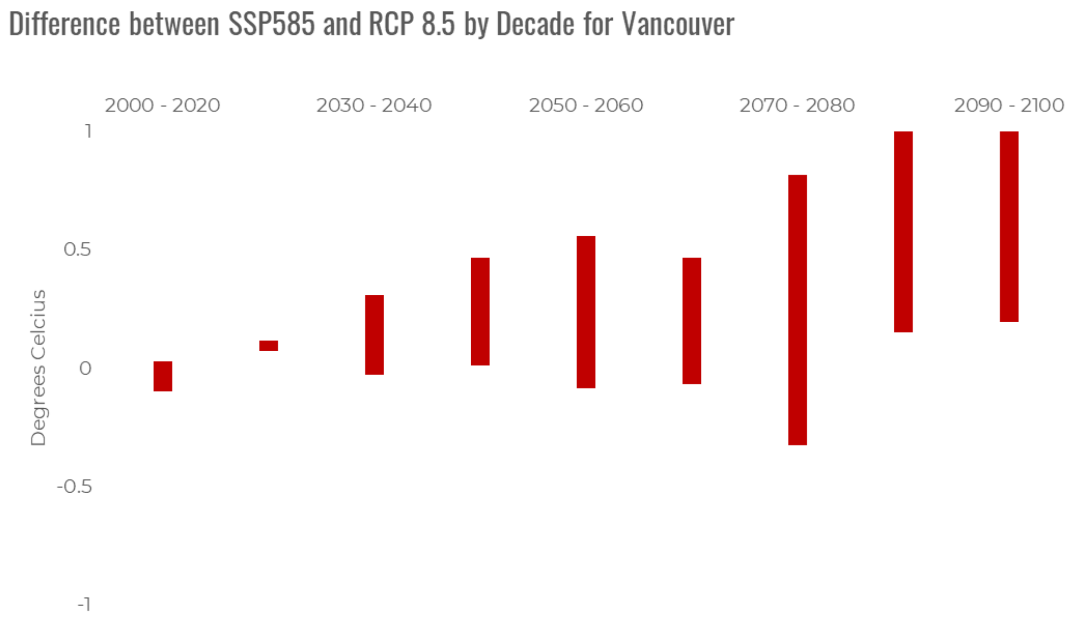
Data access and supplementary materials

- A shapefile of Population Centres adapted for this project is here.
- Programming code (developed in R Cran) used to select a sub-ensemble can be found on GitHub here
- Programming code (developed in R Cran) used for pulling and processing GCMs from the PCIC servers can be found on GitHub here.
- Daily timeseries for all 111 population centres in British Columbia can be found here developed with the methods described in this study are available here.

CMIP5 and CMIP6 comparison

We analyzed the difference between SSP5-8.5 and RCP8.6 (i.e., CMIP5 and CMIP6) ensemble range for Vancouver. We found that SSP5-8.5 is generally warmer, however this is not universal across all GCMs and our coldest GCM is less than or equal to the CMIP5 ensemble mean across the projection period.

FINAL UPDATES COMING SOON


Difference between SSP585 and RCP 8.5 by Decade for Vancouver

Technical Background – Part II

2 Mortality and Morbidity Impacts from Heat Exposure

Author: Richard Boyd, All One Sky Foundation

2.1 Introduction

Evidence of an association between ambient temperature and mortality or morbidity outcomes has been documented in many studies[2]. Those particularly at risk include older adults, pregnant women, children,

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[2] For a recent review of this literature for Canada see Section 3.4 in Gosselin, P., Campagna, C., Demers-Bouffard, D., Qutob, S., & Flannigan, M., 2022: Natural Hazards. In Berry, P. and Schnitter, R. (Eds.), Health of Canadians in a Changing Climate: Advancing our Knowledge for Action. Government of Canada, Ottawa, ON.

people with chronic health conditions, and populations with increased social vulnerability with less access to information, resources, healthcare, and other means to prepare for and avoid the health risks of high temperatures[3].

Below, we describe the approach used to estimate the future biophysical and economic impact of heat-related mortality and select morbidity outcomes under a “high-warming” scenario (SSP5-8.5) in B.C., with and without proactive planned adaptation.

2.2 Approach

2.2.1 Estimation of biophysical impacts—mortality

To quantify **mortality** impacts attributable to high temperatures under the “high-warming” scenario in the absence of new adaptation actions, we use the exposure-response functions (ERFs) estimated by Henderson et al. (2013)[4] for four different ecoregions in B.C. These functions relate changes in daily non-traumatic mortality rates to changes in daily maximum apparent temperature (AT) above a threshold (inflection) temperature for each ecoregion—shown in Figure 1. The “temperature-mortality slope” for each ecoregion is also provided. The inflection temperatures for each ecoregion are: +18.4°C (Coast); +16.2°C (Mountain); +22.2°C (Dry Plateau); +14.1°C (North).

As per similar studies, we assume that the general population autonomously adapts (acclimatizes) to rising temperatures over time to reflect physiological, behavioural and cultural changes[5]. For this study we follow the approach used by Kovats et al. (2011) and conservatively assume the estimated inflection temperature in each region increases by 0.5°C every three decades, starting from 1998 which is the central year of the data set underpinning the ERFs estimated by Henderson et al. (2013). By way of example, by 2028 the inflection temperature for the “North” is assumed to be +14.6°C—i.e., 14.1°C plus 0.5°C; by 2068 it is assumed to be +15.1°C—i.e., 14.1°C plus 1.0°C. Linear interpolation is used to adjust the inflection temperature for all intervening years.

Figure 1: Exposure-response functions for estimating heat-mortality outcomes by ecoregion

Coast	Mountain

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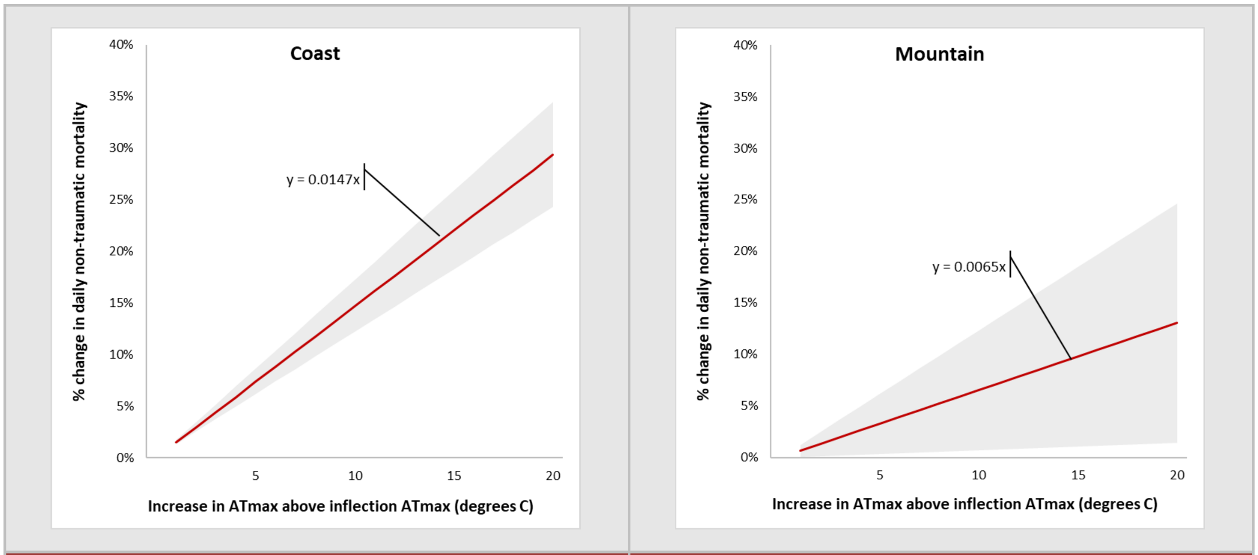
[3] See, for example, Death Review Panel, 2022: Extreme Heat and Human Mortality: A Review of Heat-Related Deaths in B.C. in Summer 2021. Report to the Chief Coroner of British Columbia; and Henderson, S., McLean, K., Lee, M. and Kosatsky, T., 2022: Analysis of community deaths during the catastrophic 2021 Heat Dome. Environmental Epidemiology, 6, 1, e189.

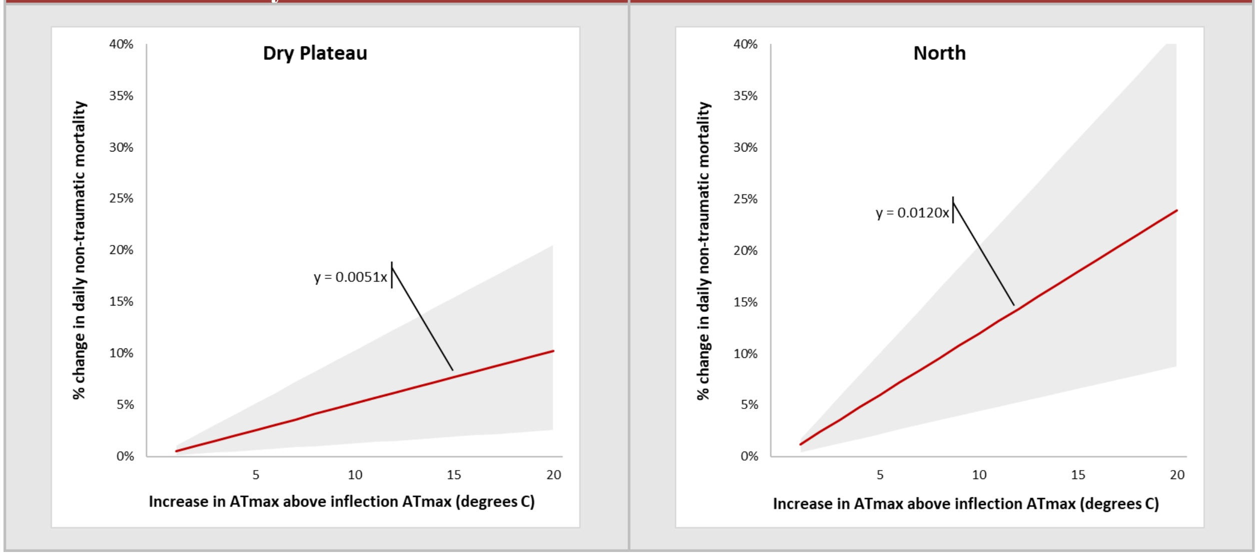
[4] Henderson, S., Wan, V. and Kosatsky, T., 2013: Differences in heat-elated mortality across four ecological regions with diverse urban, rural and remote populations in British Columbia, Canada. Health and Place, 23, 45-53.

[5] See, for example, Horricks, L., et al., 2009: Impacts of Climate Change in Human Health in Europe. PESETA-Human Health Study. Report for the PESETA I Project, JRC Technical Reports, Seville, Spain; Kovats, S., et al., 2011: Technical Policy Briefing Note 5: The Impacts and Economic Costs on Health in Europe and the Costs and Benefits of Adaptation. Results of the EC RTD ClimateCost Project. In: Watkiss, P. (Ed.) The ClimateCost Project. Final Report. Volume 1: Europe. Stockholm Environment Institute, Stockholm, Sweden; and Paci, D. (ed.), 2014: Human Health Impacts of Climate Change in Europe. Report for the PESETA II Project, JRC Technical Reports, Seville, Spain.

FINAL UPDATES COMING SOON



Dry Plateau **North**



Source: Based on Henderson et al. (2013)

Note: The solid red line shows the mean estimated temperature-mortality slope (the % change in the daily mortality rate per 1°C change in maximum apparent temperature (AT^{max}); the light grey shaded area shows the 95% confidence interval.

The analysis is performed separately for 111 distinct population centres in B.C. With the exception of the following three composite centres created for the lower mainland, the population centres are the same as those by Statistics Canada for 2021 Census of Population:

"Vancouver-NorthShore"	"Vancouver-Coastal"	"Vancouver-Inland"
North Vancouver	Richmond	Port Moody
Burrard Inlet	Great Vancouver A	Maple Ridge
Capilano	Vancouver	Delta
Lions Bay	Burnaby	Langley
North Vancouver, CY		Langley, CY
West Vancouver		White Rock

FINAL UPDATES COMING SOON

Belcarra	Surrey
	Anmore
	Port Coquitlam
	Pitt Meadows
	New Westminster
	Coquitlam

Estimated mortality impacts in population centre (p) in year (t) are calculated as follows:

$$\begin{array}{l|l} \text{If } \Delta AT^{max}_{p,d(t)} \leq 0 & MT^{RC}_{p,t} = 0 \\ \text{If } \Delta AT^{max}_{p,d(t)} > 0 & MT^{RC}_{p,t} = \sum_{d} P_{p,t} \times \frac{1}{100,000} \times \Delta AT^{max}_{p,d(t)} \times ERF_{p(h)} \times DM_{h(t)} \end{array}$$

Where $\Delta AT^{max}_{p,d(t)} = AT^{max}_{p,d(t)} - AT^{inf}_{p,t}$.

And MT is the annual sum of daily deaths under the (no adaptation) Reference Case (RC), $\Delta AT^{max}_{p,d(t)}$ is the change in daily maximum apparent temperature in population centre p on day d in year t above the inflection temperature in that year adjusted for acclimatization ($AT^{inf}_{p,t}$), ERF is the temperature-mortality slope coefficient assigned each population centre, and DM is the projected baseline daily (non-traumatic) mortality rate for Health Authority h in year t. DM was provided by the Institute for each of the five Health Authorities in B.C. for the period 2010-2012; the rate for all Health Authorities is assumed to increase at 0.56% per year, which is the average annual growth rate in the daily (non-traumatic) mortality rate in B.C. over the period 2000-2019. Each population centre was mapped onto one of the four ecoregions for the purpose of matching it up with an exposure-response functions (shown in Figure 1).

Mortality impacts for each population centre are calculated separately for temperature projections from five GCMs over the period 2000-2099. Estimated annual average deaths over the years 2000-2020 are treated as a baseline for estimating future changes in mortality from further climate change beyond today. Maximum daily temperature projections from the GCMs are converted to apparent temperature projections using a set of month-specific multipliers generated from daily data (2019-2021) from 16 weather stations across B.C.

2.2.1.1 Uncertainty surrounding the temperature-mortality slope at extreme values

The exposure-response functions (ERF) used to quantify mortality impacts—shown in Figure 1—have a constant slope across all temperatures above the threshold (inflection) temperature. However, segmented regressions of more recent 3-day average maximum temperatures and daily mortality (including the 2021 "heat dome") in the five Heath Authorities finds significantly higher temperature-mortality slopes at the 95th-99th percentile values than those estimated in Henderson et al.

(2013), which are the basis for ERFs in Figure 1[6]. In effect, there is a second inflection point at extreme temperatures after which the slope of the original ERFs increases considerably.

These findings came through towards the end of the project, so it was not feasible to re-run the entire mortality-impact analysis with updated ERFs. Instead, sensitivity tests are performed for the two most populus centres in each Health Authority (Abbotsford, Vancouver-Inland, Kamloops, Kelowna, Fort St. John, Prince George, Vancouver-Coastal, Vancouver NorthShore, Victoria and Nanaimo) using the GCM *ensemble* mean projections. For each of the 10 population centres, the sensitivity test involves:

1. Defining the 95th percentile AT^{max} for the 2000-2020 baseline period.
2. Estimating the cumulative unexpected deaths at or above the 95th percentile temperature over the projection period using the ERFs in Figure 1 (this is possible as the mortality models calculate both the change in AT^{max} above AT^{inf} and estimated unexpected mortality in 1-degree Celsius intervals).
3. Multiplying the outcome from (2) by a scaling factor (e.g., 5 times) to account for the steeper ERF beyond the 95th percentile AT^{max}.
4. Adding the outcome from (3) to estimated cumulative unexpected deaths *below* the 95th percentile temperature over the projection period using the ERFs in Figure 1.

The scaling factors and 95th percentile inflection temperatures used for the sensitivity tests are shown in Table 1; these were provided by the Canadian Climate Institute (the “Institute”). The results of the sensitivity test are summarized Table 2. Taking Vancouver-Coastal, for example, using the scaling factor to account for the steeper slope of the ERF above the 95th percentile temperature increases projected mortality over the period 2020-2100 by 1,535 unexpected deaths, relative to projections based solely on the ERF slope coefficient shown in Figure 1.

Table 1: Mortality scaling factors and threshold temperatures for applying the scaling factors, by population centre

Population centres	95th inflection temperature	Scaling factor for estimated mortality
Vancouver- Coastal	35.1	4.7
Vancouver- NS	35.2	4.7
Vancouver- Interior	35.9	6.1
Abbotsford	36.8	6.1
Kamloops	37.2	77.8
Kelowna	37.0	77.8
Nanaimo	34.8	8.5

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[6] Personal communication between the Institute and Dr. S. Henderson, Scientific Director, Environmental Health Services, B.C. CDC.

Victoria	33.4	8.5
Prince George	34.9	12.8
Ft. St. John	33.0	12.8

Source: Canadian Climate Institute, based on information provided by the B.C. CDC

Table 2: Impact of sensitivity test on estimated unexpected mortality (increase in projected mortality over the period 2020-2100 from application of scaling factor above 95th percentile inflection temperature)

Population centres	Change in projected mortality
Vancouver- Coastal	+1,535
Vancouver- NS	+340
Vancouver- Interior	+3,810
Abbotsford	+395
Kamloops	+16,750
Kelowna	+32,445
Nanaimo	+790
Victoria	+3,340
Prince George	+1,360
Ft. St. John	+190

2.2.2 Estimation of biophysical impacts—morbidity

To quantify **morbidity** impacts attributable to high temperatures under the "high-warming" scenario in the absence of new adaptation actions, we use the exposure-response functions (ERFs) estimated by Bai, L., et al. (2016) and (2017) for hospital admissions in Ontario[7]. These functions relate changes in daily hospital admissions for hypertensive diseases, diabetes, coronary heart disease, stroke, and ischaemic stroke to changes in daily mean temperature above a threshold (inflection) temperature for each morbidity outcome (see Figure 2). The inflection temperatures are: +18.6°C (hypertensive diseases); +11.0°C (diabetes); +18.0°C (coronary heart disease); +16.6°C (stroke); +17.2°C (ischaemic stroke); and +9.0°C (mental and behavioural disorders). The "temperature-hospitalization slope" coefficients for each morbidity outcome are also shown in Figure 2. In addition to the morbidity outcomes listed above, we use an ERF derived from Wang et al. (2014) to estimate emergency room visits (ERV) for mental and behavioural disorders in response to changes in mean daily temperature[8]. The "temperature-ERV slope" coefficient and inflection temperature used in this study to estimate mental and behavioural disorders are also shown in Figure 2.

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[7] Bai, L., et al., 2016: Hospitalizations from hypertensive disease, diabetes, and arrhythmia in relation to low and high temperatures: population-based study. Nature Scientific Reports, 6, 30283, DOI:10.1038/srep30283; and Bai, L., et al., 2017: Increased coronary heart disease and stroke hospitalizations from ambient air temperatures in Ontario. Heart, 104, 673-679.

[8] Wang, X., et al., 2014: Acute impacts of extreme temperature exposure on emergency room admissions related to mental and behavior disorders in Toronto, Canada. Journal of Affective Disorders, 155, 154-61, DOI: 10.1016/j.jad.2013.10.042.

Estimated morbidity impacts in population centre (p) in year (t) are calculated as follows:

$$\begin{array}{l|l} \text{If } \Delta T^{mean}_{p,d(t)} \leq 0 & MB^{RC}_{p,t,k} = 0 \\ \text{If } \Delta T^{mean}_{p,d(t)} > 0 & MB^{RC}_{p,t,k} = \sum_{d} P_{p,t} \times \frac{1}{100{,}000} \times \Delta T^{mean}_{p,d(t)} \times ERF_{k} \times DSC_{h,k} \end{array}$$

Where $\Delta T^{mean}_{p,d(t)} = T^{mean}_{p,d(t)} - T^{inf}_{p,t}$.

And MB is the annual sum of daily secondary care episodes (hospitalizations or emergency room visits) for morbidity outcome k under the (no adaptation) Reference Case (RC), $\Delta T^{mean}_{p,d(t)}$ is the change in daily mean temperature in population centre p on day d in year t above the inflection temperature in that year adjusted for acclimatization ($T^{inf}_{p,t}$)[9], ERF is the temperature-morbidity slope coefficient for morbidity outcome k, and DSC is the disease specific secondary care rate per 100,000 people (e.g., hospital admissions for diabetes) for Health Authority h. DSC is assumed to remain constant at 2020 levels over the projection period 2000-2099; disease specific DSC was provided by the Institute for each of the five Health Authorities in B.C. Morbidity impacts for each population centre are calculated for the GCM ensemble projections over the period 2000-2099 and not individually for each GCM.

2.2.3 Monetization of biophysical impacts

Consistent with other bottom-up economic studies of climate-related health impacts[10], projected biophysical health outcomes are converted to economic costs by multiplying the projected health outcome by an appropriate projected "unit value":

Economic cost in future year t

=

projected health outcome (physical units) in year t

x

projected "unit value" ($ per physical unit) of the health outcome in year t

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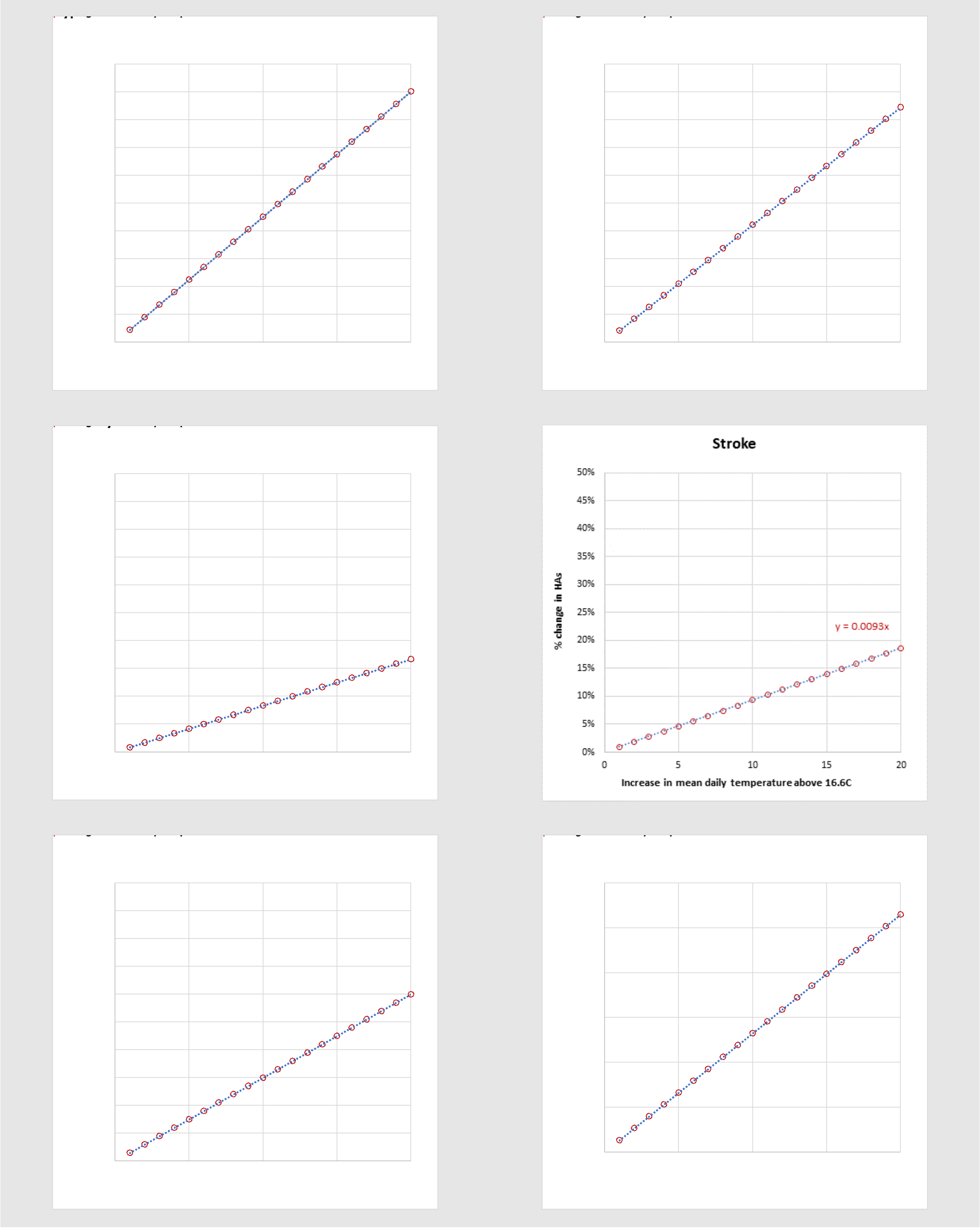
[9] The same autonomous adaptation (acclimatization) assumption used for the mortality calculations is also applied to the morbidity calculations.

[10] For example, Horricks et al. (2009); Kovats et al. (2011); and Paci (2014).

Figure 2: Exposure-response functions for estimating heat-morbidity outcomes



Source: Derived from Bai, L., et al. (2016) and (2017) and Wang et al. (2014)

2.2.3.1 Monetizing morbidity impacts

Ill-health can contribute to losses in individual utility or welfare directly (because people prefer to be more healthy than less healthy) and indirectly (by reducing satisfaction from the consumption of goods and services not related to health or by reducing earning potential and income that allows people to consume goods and services). Our interest here lies with determining the impact of heat-related ill-health on overall social welfare. The valuation of the full welfare impact of ill-health on individuals, including the value of reduced health itself, requires the application of willingness-to-pay (WTP) metrics[11]. WTP to avoid ill-health comprises three components[12]:

- Direct (resource) costs, which arise from the consumption of medical (primary and secondary care expenditures, drug purchases and formal home care costs) and non-medical resources (e.g., payments for transportation to access health care);
- Indirect (opportunity) costs, which arise from foregone leisure opportunities or lost production (from absenteeism or presenteeism) due to ill-health, premature mortality or informal caregiving; and,
- Disutility (human or quality of life) costs, which refers to the value individuals attribute to the emotional distress, pain and suffering that they, family and friends experience as a result of ill-health or loss of life.

In this study, the economic unit values applied to projected biophysical impacts (i.e., hospitalizations and ERVs) attributable to high temperature exposures comprise only the first two components. Moreover, the direct resource costs do not include non-medical expenses. Projected economic impacts are thus underestimated.

Direct (resource) costs for the six morbidity impacts of interest were provided by the Institute for 2022. Future resource costs are derived by inflating these estimates for projected real growth in the hourly wage rate of "health occupations" through 2099[13]; growth in wages is the most notable driver of health-care price inflation[14]. The same assumed real annual growth rate is used to back cast resource costs to 2000 as the period of analysis is 2000-2099. Regarding opportunity costs, the average Length of Stay (LOS) in hospital, in days, are first generated from the CIHI Patient Cost Estimator for each of the six diseases of interest for 2021; the LOS estimates are assumed to remain constant over time. Estimated LOS values for 2021 are adjusted to account for the proportion of the population unemployed in B.C. in 2021 and multiplied by daily payroll compensation costs in 2021 averaged across all industries in the

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[11] WHO (World Health Organization), 2009: WHO Guide to Identifying the Economic Consequences of Disease and Injury. Department of Health Systems Financing Health Systems and Services, World Health Organization (WHO), Geneva, Switzerland, p. 132.

[12] US EPA, 2007: Cost of Illness Handbook. 2007 Update. Washington, DC.; and PHAC, 2018: Economic Burden of Illness in Canada, 2010. Public Health Agency of Canada (PHAC), Health Economics Team, Ottawa, ON., p. 58.

[13] Hospitalization resource costs are assumed to grow at 0.06% per year in real terms = ((1 + 1.97%) / (1 + 1.91%)) - 1, where 1.97% is the average annual compound growth rate in total compensation payments (health occupations) in B.C. from 2001-2021 and 1.91% is the average annual compound growth rate in CPI (all-items) in B.C. from 2001-2021.

[14] CIHI, 2011: Health Care Cost Drivers: The Facts. Canadian Institute for Health Information (CIHI), Ottawa, ON., p 33.

province (converted to 2022 dollars) to derive disease-specific unit values for opportunity costs in 2021 attributable to hospitalization. Future unit values are derived by inflating the baseline estimates for assumed real growth in payroll compensation costs (average, all industries in B.C.) over the period 2020-2099[15]. The same assumed real annual growth rate is used to back cast opportunity costs to 2000. The unit values used to monetize projected morbidity impacts are shown in Table 3 for the years 2025, 2055 and 2058.

Table 3: Morbidity economic unit values ($ 2022 dollars per case)

	Hypertensive diseases	Diabetes	Coronary heart disease	Stroke	Ischaemic stroke	Mental and behavioural disorders
Direct costs						
2025	18,780	15,615	16,175	21,675	9,075	19,305
2055	19,145	15,920	16,490	22,095	9,250	19,680
2085	19,515	16,225	16,815	22,525	9,430	20,065
Indirect costs						
2025	1,185	900	1,495	1,625	620	2,755
2055	1,610	1,225	2,030	2,200	840	3,740
2085	2,180	1,660	2,750	2,990	1,140	5,075
Total costs						
2025	19,965	16,515	17,670	23,300	9,695	22,060
2055	20,750	17,140	18,520	24,300	10,090	23,420
2085	21,695	17,885	19,565	25,515	10,570	25,140

Estimated total morbidity costs (MBC) for residents of population centre (p) experiencing heat-related illness in year t is calculated as:

$$MBC^{RC}_{p,t} = \sum_{k} MB^{RC}_{p,t,k} \times TC_{t,k}$$

Where TC is the total resource and opportunity cost per case (in 2022 dollars) of morbidity outcome k in year t. Recall, the superscript RC denotes the Reference Case against which the performance of proactive adaptation actions is assessed. Projected total morbidity costs for B.C. in year t are given by:

$$MBC^{RC}_{BC,t} = \sum_{p} MBC^{RC}_{p,t}$$

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[15] Labour compensation payments are assumed to grow at 1.02% per year in real terms = ((1 + 2.95%) / (1 + 1.91%)) - 1, where 2.95% is the average annual compound growth rate in total compensation payments (all industries) in B.C. from 2001-2021 and 1.91% is the average annual compound growth rate in CPI (all-items) in B.C. from 2001-2021.

2.2.3.2 Monetizing mortality impacts

Two metrics are typically used to monetize unexpected mortality in health costing studies[16]: the value of a statistical life (VSL) and the value of a statistical life year (VSLY). An individual's VSL reflects their marginal rate of substitution between small changes in own mortality risk and own spending on non-health goods and services in a defined time period; it is not the value an individual, government or society places on life. For example, if an individual is willing-to-pay (WTP) $900 for a 1/10,000 annual change in the risk of death, then their VSL is equal to $9 million (i.e., $900 ÷ 1/10,000). Similarly, over a population of 10,000, if the average WTP for a 1/10,000 annual reduction in the risk of death is $900, then the number of statistical deaths avoided in the population is one (i.e., 10,000 x 1/10,000) and the VSL is $9 million (i.e., $900 x 10,000). The VSLY values a change in mortality risk in proportion to the corresponding change in life expectancy. With the VSLY, changing an individual's risk of dying today produces a gain equal to the increase in the chance of surviving the current year multiplied by the individual's life expectancy in years (conditional on surviving the year). The monetary value of this gain is given by the expected number of life-years saved times the VSLY. The VSLY thus provides a proxy means of accounting for differing lengths of life-expectancy at death than making direct adjustment to the VSL for age or future life-years lost.[17] In theory, the VSLY could be estimated directly; in practice, it is typically derived from the VSL[18]. For example, in the simplest case of a zero discount rate and a constant VSLY, the VSLY is calculated by dividing the VSL by the number of life years lost (saved) because of an increase (decrease) in mortality risk (calculated from the average remaining life expectancy of the affected population). In practice, remaining life years at death are discounted, such that the VSLY is given by the VSL divided by the present value sum of remaining life years.

It is outside the scope of this study to use both metrics to value unexpected mortality; projected deaths resulting from temperature stress exposures are valued using the VSL only. As a starting point we adopt the central VSL recommended by Chestnut and De Civita (2009)[19]; their recommended central value is $6.5 million (in 2007 dollars), which represents the average of the mean estimate from stated preference studies and the mean estimated from revealed preference studies for Canada. These values were

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[16] See, for example, Kovats et al. (2011) and Paci (2014). Also see: Boyd, R., Eyzaguirre, J., Poulsen, F., Siegle, M., Thompson, A., Yamamoto, S., Osornio-Vargas, Erickson, A. and Urcelay, A., 2020: Costing Climate Change Impacts on Human Health Across Canada. Technical report prepared by ESSA Technologies for the Canadian Institute of Climate Choices; and US HHS, 2016: Guidelines for Regulatory Impact Analysis. Office of the Assistant Secretary for Planning and Evaluation, U.S. Department of Health and Human Services (HHS), Washington, D.C.

[17] There is evidence that VSL estimates for children are higher than for the average-aged adult, values for adults of working age increase to middle age, peak and then decline, and that values for older adults may decline—see, for example, Robinson, L., et al., 2018: Valuing mortality risk reductions in global cost-benefit analysis. Guidelines for Benefit-Cost Analysis Project, Working Paper No. 7. Prepared for the Benefit-Cost Analysis Reference Case Guidance Project, Bill and Melinda Gates Foundation, 66 p.

[18] See, for example, Hammitt, J. et al., 2020: Premature deaths, statistical lives, and years of life lost: identification, quantification, and valuation of mortality risks. Risk Analysis, 40, 4, DOI: 10.1111/risa.13427; or Robinson, L., et al., 2018.

[19] Chestnut, L. and De Civita, P., 2009: Economic Valuation of Mortality Risk Reduction: Review and Recommendations for Policy and Regulatory Analysis. Research Paper. PRI Project, Regulatory Strategy, Government of Canada, Ottawa, 64 p.

converted to 2022 Canadian dollars by adjusting the 2007 dollar values for growth in real income and monetary inflation between 2007 and 2022 using the following formula[20]:

$$VSL^{2022} = VSL^{2007} \times \left(\frac{CPI^{2022}}{CPI^{2007}}\right) \times \left(\frac{Y^{2022}}{Y^{2007}}\right)^{\varepsilon}$$

Where:

CPI^{2022} = Consumer Price Index (CPI) level in 2022 for Canada

CPI^{2007} = CPI level in 2007 for Canada

Y^{2022} = Real income (constant dollar GDP per capita) in 2022 in Canada

Y^{2007} = Real income (constant dollar GDP per capita) in 2007 in Canada

ε = Income elasticity of the WTP

Based on a recent review of income elasticities for mortality valuation conducted for the US EPA's Office of Air and Radiation and Office of Policy, we adopt a central estimate of 0.7 for ε[21]. Projected future VSL values (in constant 2022 dollars) over the period 2022-2099 are adjusted for anticipated growth in real (per capita) incomes only. Projected growth in real GDP per capita through 2099 is taken from Boyd et al. (2020).

By way of example, estimated VSLs used to monetize projected temperature-related mortality impacts for 2025, 2055 and 2085 are, respectively, $9.5 million (2022 dollars per unexpected death), $10.6 million, and $11.8 million.

Estimated mortality costs (MTC) for residents of population centre (p) in year (t) is calculated as:

$$MTC^{RC}_{p,t} = MT^{RC}_{p,t} \times VSL_{t}$$

Where VSL is the Value of Statistical Life (in 2022 dollars) in year t. The same VSL is applied to all population centres across B.C. in any given year. All other notation is same as described above for morbidity costs. Projected total mortality costs for B.C. in year t are given by:

$$MTC^{RC}_{BC,t} = \sum_{p} MTC^{RC}_{p,t}$$

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[20] Robinson, L. et al., Appendix D: Updating Value per Statistical Life (VSL) Estimates for Inflation and Changes in Real Income, US HHS, 2016: Guidelines for Regulatory Impact Analysis. Office of the Assistant Secretary for Planning and Evaluation, U.S. Department of Health and Human Services (HHS), Washington, D.C.

[21] Recommended Income Elasticity and Income Growth Estimates: Technical Memorandum. February 5, 2016. Prepared by staff in EPA's Office of Air and Radiation and Office of Policy, US Environmental Protection Agency (EPA), Washington, DC., p 4.

2.3 Adaptation scenarios

There are multiple long-term preventative measures to mitigate the adverse health effects associated with the exposure of people to heat stress, either by managing the build-up of ambient heat or applying techniques to cool the air. In addition to the use of air (room, portable or central) conditioning, common examples of individual-level adaptations involve modifications to homes and property:

- Adding vegetation and water features to property—e.g., adding trees, leafy plants and shrubs, garden spaces or green roofs / walls, installing decorative water fountains or ponds.
- Enhancing shade and insulation, including external shading (e.g., awnings, shutters, external curtains), window glazing and smart (thermochromic or electrochromic) windows, internal shading (e.g., blinds, curtains), loft and wall insulation, seals on doors and windows to prevent heat ingress, and double- and triple-glazed windows.
- Increasing the use of cool materials, such as the application of reflective paints on roofs and exterior walls, and the use permeable pavement for driveways.

Municipalities can also directly invest in adaptation or use planning tools to reduce the build up of ambient temperatures by, for example:

- Increasing green infrastructure—e.g., increase the number of trees, vegetation, parks, green open spaces (with tree shading), tree canopy coverage and connectivity of greenspaces.
- The addition of water features—e.g., incorporate ponds, moving water and decorative fountains in public spaces to increase evaporative cooling.
- Increasing shading around and on buildings—e.g., artificial canopies can be strategically located over high-use outdoor areas to minimize radiative heat load.
- Improving thermal comfort in outdoor areas through the addition of shading structures, shaded seating, splash pads, and strategic tree planting.
- Increasing the use of cool materials—e.g., utilizing reflective paints on roofs and walls of civic buildings, or high albedo or porous materials for pavements, parking lots and road surfaces.

In this study, we evaluate several individual and municipal proactive adaptation strategies. Specifically, we subject the following “what-if” adaptation scenarios to cost-benefit analysis:

- **Households** install and use **air conditioning** consistent with: (1) a continuation of historical trends; (2) 1.5 times the historical rate of adoption; and (3) 2 times the historical rate of adoption. This set of scenarios is applied to all population centres in B.C.
- **Households** install **external screens** / **shading technologies** on south and west facing aspects; 50% of projected homes have external screens / shading technologies by 2050 and 100% of projected homes external screens / shading technologies by 2099. Likewise, this scenario is applied to the two most populus centres in each Health Authority.
- **Municipalities** use a portfolio of **urban planning measures** and **direct investment** to reduce ambient outside temperatures through increased use of cool materials (roads, pavements and

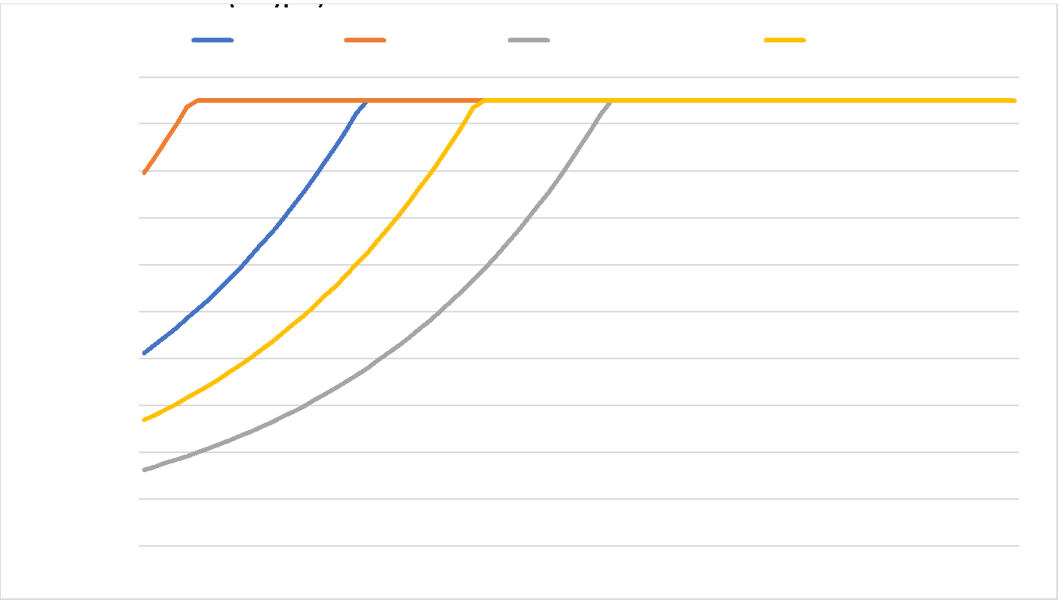
roofs) and green infrastructure (trees and vegetated roofs). Due to data limitations on existing land-use, this scenario is applied to population centres in the lower mainland only.

In all scenarios, impacts on both projected morbidity and mortality outcomes are quantified and monetized. Additionally for all scenarios, present value benefits (PVB) and present value costs (PVC) are calculated for the period 2020-2099 at two real annual discount rates; **3**% and **7**%, as per Canada's Cost-Benefit Analysis Guide for Regulatory Proposal. Estimated PVBs and PVCs are combined to calculate the adaptation scenarios' net present value (NPV = PBV – PVC), benefit-cost ratio (PVB ÷ PVC) and return on investment (NPV ÷ PVC). Additional key assumptions underpinning each cost-benefit analysis are provided below.

2.3.1 Air conditioning scenarios

- The prevalence of (proportion of all homes with) air conditioning (all types) in the residential sector in 2019 in each Health Authority is assumed to be 43% (Frazer), 83% (Interior), 17% (Northern), 28% (Coastal), and 17% (Vancouver Island)[22].
- The historical (annual average) change in the presence of space cooling stock in the residential sector in B.C. over the 15-year period 2005-2019 is +4.1% per year (Natural Resources Canada's Comprehensive Energy Use Database) (see Figure 3). The prevalence rates in each Health Authority in 2019 are assumed to change at this rate, 1.5 times this rate, or 2 times this rate through 2099.

Figure 3: Assumed up-take of air conditioning (AC) in homes by Health Authority in B.C. between 2019-2099 based on a continuation of historical trends



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[22] Derived from B.C. data in Statistics Canada's Table: 38-10-0019-01.

- The maximum prevalence of air conditioning in the residential sector in B.C. is assumed to be 95%.
- The average household size in B.C. in 2021 is 2.45 persons, which is assumed to decline at 0.17% per year through 2099 (this is the mean average annual rate of change between 2001-2021 after removing outliers). The projected average household size is used in conjunction with the projected population for each population centre in B.C. to determine the total stock of residential dwellings.
- The percentage change in projected unexpected mortality per percentage point change in the prevalence of air conditioning (all types) in homes is 0.49; the percentage change in projected unexpected morbidity per percentage point change in the prevalence of air conditioning (all types) in homes is 0.88[23].
- Mortality and morbidity impacts—both with and without the adaptation scenarios implemented—are quantified and monetized in accordance with the approach set out above.
- The assumed seasonal (June-September) operating costs of the air conditioning technologies are $32 (in 2022 dollars) for portable AC units; $39 for window AC units; $429 for central AC units; and $178 for heat pumps[24].
- The assumed installed costs of the air conditioning technologies are $475 ($250-$700) (in 2022 dollars) for portable AC units; $600 ($200-$1,000) for window AC units; $6,500 ($4,500-$8,500) for central AC units; and $10,000 ($6,000-$14,000) for heat pumps[25].
- The assumed expected useful life of the air conditioning technologies is 7.5 years for portable AC units; 9.0 years for window AC units; 17.5 years for central AC units; and 15.0 years for heat pumps[26].
- The assumed market share of each air conditioning technology in the residential sector in 2020 is 43% for portable AC units; 16% for window AC units; 19% for central AC units; and 22% for heat pumps. These shares are assumed to remain constant through 2099[27].

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[23] Derived from: Ostro, B., et al., 2010: The Effects of Temperature and Use of Air Conditioning on Hospitalizations. American Journal of Epidemiology, 172, 9, DOI: 10.1093/aje/kwq231. Barreca, A., et al., 2015: Adapting to Climate Change: The Remarkable Decline in the U.S. Temperature-Mortality Relationship over the 20th Century. Journal of Political Economy, 124, 1, DOI:10.1086/684582. Eisenman, D., et al., 2016: Heat death associations with the built environment, social vulnerability and their interactions with rising temperature. Health and Place, 41, 89–99. Sera, F., et al., 2020: Air conditioning and heat-related mortality: a multi-country longitudinal study. Epidemiology, 31, 6, 779-787.

[24] B.C. Hydro. Cold comfort: The rising use (and cost) of air conditioning in B.C. July 2018.

[25] B.C. Hydro; Central Air Conditioner Prices in Canada (Updated for 2023) [https://www.furnaceprices.ca/air-conditioners/central-air-conditioner-prices-canada/]; and Boyd, R. and Zukiwsky, J., 2021: Climate Resilient Home Handbook for Calgarians. Report prepared by All One Sky Foundation for the City of Calgary, Calgary, AB.

[26] The 2023 Buyer's Guide to Home Air Conditioners [https://www.enercare.ca/cooling/buyers-guide-air-conditioners].

[27] B.C. Hydro.

- Both installed and operating costs are assumed to increase in real terms at 0.31% per year[28].

2.3.2 Window shading (external screens) scenario

- Installed external screens are assumed to reduce projected daily maximum temperatures (when operational during the heat season) by 19.7% for single-detached, 11.8% for single-attached, and 15.7% for apartments[29]. A weighted average reduction in daily maximum temperature is calculated and applied to daily maximum temperature projections for each population centre—the weights are based on each building type's share of the total residential building stock in each population centre.
- The assumed installed cost of external window screens is \$295 per m^2 (\$180-\$410 per m^2) (in 2022 dollars). This was derived from RS Means 2020; costs in US\$ per square foot were converted to 2022 Canadian dollars per square metre for application in B.C. using the RS Means City Construction Index average for Kamloops, Prince George, Vancouver and Victoria.
- The assumed expected useful life of external window screens is 20 years (15-25 years)[30].
- External window screens are assumed to reduce projected baseline energy consumption in homes by 30% (21%-38%)[31].

2.3.3 Urban planning scenario

- This scenario combines multiple adaptations: 1. The current area of impervious surfaces at-grade in the lower mainland is transitioned to tree canopy (specifically, 50% and 100% of the estimated "treed potential" of impervious at-grade area in the lower mainland is assumed to be realised by 2050 and 2099, respectively); 2. The reflectivity of the residual fraction of impervious surfaces at-grade that is not treed is increased (specifically, 50% and 100% of the residual fraction not treed is assumed to be transformed to "light surfaces" by 2050 and 2099, respectively); 3. The current area of impervious surfaces above grade (roofs) are transitioned to "cool roofs" or "living (vegetated) roofs" (specifically, 25% and 50% of the total roof area is assumed to be converted to cool roofs by 2050 and 2099, respectively, and 25% and 50% of the total roof area is assumed to be converted to vegetated roofs by 2050 and 2099, respectively); and 5. The current area of vegetation (grasses) is transitioned to tree canopy (specifically, 50% and 100% of the estimated "treed potential" of vegetated area is assumed to be realised by 2050 and 2100, respectively). The current area of each land-use type and the treed potential of both at-grade impervious

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[28] 0.31% = ((1 + 2.22%) / (1 + 1.91%)) - 1, where 2.22% is the average annual compound growth rate in CPI (household equipment and energy) in B.C. from 2001-2021 and 1.91% is the average annual compound growth rate in CPI (all-items) in B.C. from 2001-2021.

[29] Derived from Laouadi A., et al., 2021, ibid.

[30] Consortium for Building Energy Conservation 2016.

[31] King and Perry ibid.

surfaces and vegetated areas for the lower mainland are sourced from Metro Vancouver (2019) Regional Tree Canopy Cover and Impervious Surfaces.

- The assumed responsiveness of daily maximum temperature to changes in land-use are as follows[32]: 1. minus 0.0201 change in daily maximum temperature per percentage point change in vegetation (grass) to tree canopy; 2. minus 0.0596 change in daily maximum temperature per percentage point change in at-grade impervious surface to tree canopy; 3. minus 0.0414 change in daily maximum temperature per percentage point change in conventional roofs to vegetated roofs; 4. minus 0.0329 change in daily maximum temperature per percentage point change in conventional roofs to cool roofs; and 5. minus 0.0329 change in daily maximum temperature per percentage point change in at-grade impervious surfaces to cool surfaces.
- The average incremental installed cost of cool roofs is \$1.86 per m^2 (2022 dollars) (representative of multiple cool roof technologies). The assumed expected useful life of cool roofs is 20 years. Annual maintenance costs are assumed to be 20% of installed costs[33].
- The average incremental installed cost of cool pavements (at grade surfaces) is \$38.80 per m^2 (2022 dollars) (representative of multiple cool pavement technologies). The assumed expected useful life of cool pavements is 12 years[34].
- The average incremental installed cost of vegetated roofs is \$103.40 per m^2 (2022 dollars) (representative of multiple vegetated roof technologies). The assumed expected useful life of vegetated roofs is 43 years. Annual maintenance costs are \$4.95 per m^2 per year (2022 dollars)[35]. Installed costs in 2022 are assumed to reduce by 33% and 50% by 2055 and 2085, respectively, due to learning effects[36].
- The average cost of an urban tree is \$490 (2020 dollars) or \$6.80 per m^2, assuming a tree canopy diameter of 2.5 metres and spacing between trees of 6 metres[37]. The assumed expected useful life of an urban tree is 65 (30-100) years[38].

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[32] Derived from Rosenzweig, C., et al., 2006: Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces. Columbia University, New York, NY, U.S.

[33] All assumptions are based on US EPA, 2008: Reducing Urban Heat Islands: Compendium of Strategies: Cool Roofs. U.S. Environmental Protection Agency, Washington, D.C. p. 28.

[34] Both assumptions are based on US EPA, 2012: Reducing Urban Heat Islands: Compendium of Strategies: Cool Pavements. U.S. Environmental Protection Agency, Washington, D.C. p. 37.

[35] GSA, 2011: The Benefits and Challenges of Green Roofs on Public and Commercial Buildings. A Report of the United States General Services Administration (GSA), Washington, D.C.; and Feng, H. and Hewage, K., 2017: Economic Benefits and Costs of Green Roofs. Nature Based Strategies for Urban and Building Sustainability, https://doi.org/10.1016/B978-0-12-812150-4.00028-8.

[36] Feng, H. and Hewage, K., 2017 ibid.

[37] Urban Systems, 2016: Urban Forestry Management Strategy. City of Kamloops, p.86; and Diamond Head Consulting Ltd., 2021: Urban Forestry Strategy: 2020-2045. City of Abbotsford, p. 51.

[38] Canadian Forest Service.

- The installed cost of each adaptation technology is assumed to increase in real terms at 0.54% per year[39].
- The co-benefits of cool roofs, vegetated roofs and urban tree canopy in 2022 are assumed to be, respectively, \$0.67 per m^2 per year, \$5.21 per m^2 per year and \$2.48 per m^2 per year[40]. Depending on the adaptation measure, co-benefits comprise a combination of building energy cost savings, carbon sequestration and avoided emissions, drought risk reduction, habitat provision, property value premiums, removal of air pollutants, and stormwater volume and quality. The co-benefit unit values are assumed to grow in real terms inline projected growth in real per capita income in B.C., adjusted for the income elasticity of WTP (see Section 2.2.3.2).

3 IMPACTS OF HEAT EXPOSURE TO WORKFORCE

Notwithstanding the significance of the health risks for the general public, climate change may present an even greater risk to the health and safety of the workforce. Employees are often exposed to the effects of climate change for longer durations and at greater intensities than the public. In part, because workers are less able to avoid exposure to adverse conditions than are the public, who can choose to stay indoors, in air-conditioned environments. And just as the health of some population groups are more affected by climate change than others—because of factors like where they live, their age, existing health status etc.—certain groups of workers are more vulnerable to climate-related impacts because of where they work, the type of work they do, or both.

In general, climate change can directly impact workers in two main ways:

1. By altering the severity or frequency of known climate-related workplace hazards experienced today, such as storms, high temperatures and heatwaves, wildfires, and air pollution. These hazards are likely already contributing to occupational injuries, illnesses and fatalities, reduced labour supply and productivity, and will only be made worse by climate change.
2. By creating unprecedented or unanticipated occupational hazards, such as widening the ranges of infectious disease vectors like ticks and mosquitos.

3.1 Labour supply and productivity and high temperatures

An emerging field of research on the macroeconomic consequences of climate change examines the impact of temperature and heat stress on the hours worked and productivity of workers across different

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[39] 0.54% = ((1 + 3.82%) / (1 + 3.26%)) - 1, where 3.82% is the average annual compound growth rate in the construction cost index for Vancouver from 2001-2021 and 3.26% is the average annual compound growth rate in the implicit price index (gross capital formation) in B.C. from 2001-2021.

[40] The units values for co-benefits are derived from FEMA, 2022: FEMA Economic Benefit Values for Green Infrastructure. Federal Emergency Management Agency (FEMA), Washington, D.C., p.90.

economic sectors.[41] There is an observable relationship between workplace temperatures and worker performance; beyond a certain temperature labour supply (i.e., the amount of labour supplied, typically measured in person-hours), the hourly productivity of workers, or both declines.[42] When an employee performs strenuous physical work, heat is generated by the body. The risk of overheating increases with the level of physical exertion required to perform a given task, the duration of the task, the experience of the worker in performing the task (i.e., their level of acclimatization), and the ambient temperature of the work environment.[43] Heat generated needs to be transferred to the external environment to avoid increases in the body's temperature. If the body is unable to dissipate the heat—perhaps because of prolonged exposure, or water or salt deficiencies—it begins to cause dizziness, muscle cramps, and fever. In the extreme, prolonged exposure to high temperatures can cause acute cardiovascular, respiratory, and cerebrovascular distress, which can require hospitalization or be life threatening. Before these serious health effects occur, workers can experience diminished "work ability". Temperatures beyond certain thresholds affect work ability in two ways:[44]

1. They may directly lower labour supply by reducing time allocated to work to avoid physical or psychological discomfort.
2. They may directly reduce task productivity or performance, altering the increment of effort exerted within any given hour or the marginal return of that effort.

Of course, these two impacts may occur concurrently. The combined impact of temperature stress on labour supply (the number of hours worked) and labour productivity (output per hour worked) has been referred to using the composite metric "effective labour supply".[45]

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[41] For a review see: Dell, M., Jones, D. and Olken, B., 2014: What do we learn from the weather? The new climate-economy literature. Journal of Economic Literature, 52 (3), 740-798; Heal, G. and Park, J., 2016: Temperature stress and the direct impact of climate change: a review of an emerging literature. Review of Environmental Economics and Policy, 10 (2), 1-17; Kjellstrom, T., et al., 2015: Heat impacts on work, human performance and daily life. In: Climate Change and Public Health [Levy, B. and Patz, J., (eds.)], Oxford University Press, New York, 73–86; or Newell, R., Prest, B. and Sexton, S., 2018: The GDP-temperature relationship: implications for climate change damages. RFF WP 18-17, Resources for the Future, Washington, DC, 61 pp.

[42] Dasgupta, S., et al., 2021: Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet Health, 5, 455-465; Zivin, J. and Neidell, M., 2014: Temperature and the allocation of time: implications for climate change. Journal of Labour Economics, 32, 1–26; and Dunne, J., Stouffer, R. and John, J., 2013: Reductions in labour capacity from heat stress under climate warming. Nature Climate Change, 3, 563–566.

[43] ESDC, 2018: Thermal stress in the workplace: Guideline 2018. Employment and Social Development Canada, Ottawa (available at https://www.canada.ca/en/employment-social-development/services/health-safety/reports/thermal-stress-work-place.html).

[44] See, for example, ILO, 2019: Working on a warmer planet: the impact of heat stress on labour productivity and decent work. International Labour Organization (ILO), Geneva, Switzerland, or Kjellstrom, T., et al., 2016: Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. Annual Review of Public Health, 37, 97–112.

[45] Heal, G. and Park, J., 2014: Feeling the heat: temperature, physiology and the wealth of nations. National Bureau of Economic Research, Working Paper 19725, DOI 10.3386/w19725.

For this study, we adapted the approach used by Boyd et al. (2020)[46] to estimate the future economic impact of temperature stress under a "high-warming" scenario (SSP5-8.5) on **labour supply** in B.C., with and without proactive planned adaptation.

3.2 Approach

3.2.1 Estimation of biophysical impacts

Boyd et al. used Zivin and Neidell's estimates of the response of labour supply to daily maximum temperatures to calculate incremental labour impacts and associated economic consequences for "high-risk" industries[47] in Canada under future climate and socioeconomic scenarios. As per Zivin and Neidell, "high-risk" industries are defined as: (North American Industrial Classification System (NAICS) Code 11) Agriculture, Forestry, Fishing, and Hunting; (NAICS 21) Mining, Quarrying, and Oil and Gas Extraction; (NAICS 22) Utilities; (NAICS 23) Construction; (NAICS 31-33) Manufacturing; and (NAICS 48-49) Transportation and Warehousing.

Using a panel data set created from the American Time-Use Survey, Zivin and Neidell examined the response of labour to daily maximum temperature across 5°F (roughly 2.8°C) increments, from >25°F (-3.9°C) to 105°F (40.6°C). They found that days with high temperatures were associated with significant changes in the time allocated to labour by individuals. On days when maximum temperatures exceeded 37.8°C (100°F), for example, workers in "high-risk" industries reduced time allocated to labour by nearly one hour compared to (inflection) temperatures in the 23.9-26.7°C range, which represents a 14% reduction in labour supply for the day (see Table 4). However, they found no statistically significant temperature-labour supply effects in other industries that are less exposed to weather (e.g., non-manufacturing, primarily indoor occupations). Due to the lack of statistically detectable effects on "low-risk" industries, they were not included in Boyd et al.; nor are they included in this study.

Table 4: Exposure-response functions for relationship between maximum daily temperature and time allocation (change in minutes allocated to working at each temperature interval relative to 23.9°C - 26.7°C)

Max daily temperature (degrees C)	**All individuals** (mins / worker / day)	**High-risk occupations** (mins / worker / day)	**Low-risk occupations** (mins / worker / day)
>23.9 to 26.7	---	---	---
>26.7 to 29.4	-3.769	+0.148	-10.061
>29.4 to 32.2	-4.642	-5.053	-3.364
>32.2 to 35.0	-6.621	-17.400	-0.633

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[46] Boyd, R., Eyzaguirre, J., Poulsen, F., Siegle, M., Thompson, A., Yamamoto, S., Osornio-Vargas, Erickson, A. and Urcelay, A., 2020: Costing Climate Change Impacts on Human Health Across Canada. Technical report prepared by ESSA Technologies for the Canadian Institute of Climate Choices.

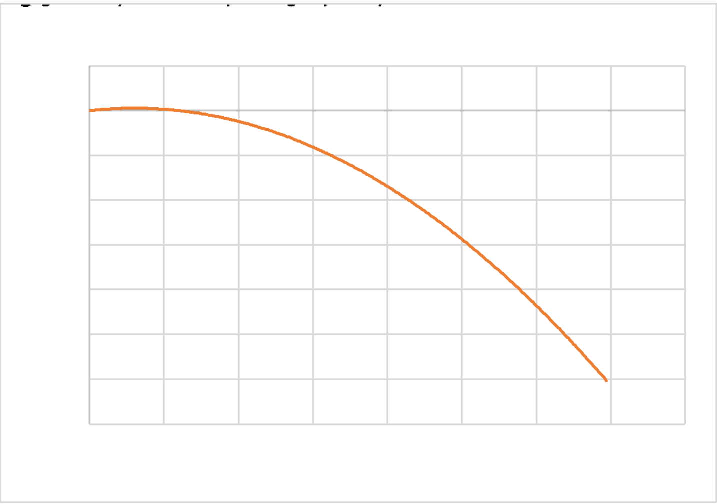
[47] High-risk industries are sectors where the work is performed primarily outdoors, as well as manufacturing, where facilities are sometimes not climate controlled, and the production processes often generate residual heat.

>35.0 to 37.8	-13.876	-41.417	-11.256
> 37.8	-18.327	-58.032	-14.951

Source: Zivin and Neidell (2014, Table A1)

A continuous exposure-response function for labour supply in “high-risk” industries was fitted to the Zivin and Neidell point estimates shown in Table 4. This function (see Figure 4) measures the change in minutes supplied per worker per day in response to changes in daily maximum temperature above 25.3°C (the mid-point of inflection temperature range used by Zivin and Neidell, 23.9-26.7°C).

Figure 4: Exposure-response function for labour supply in “high-risk” industries and maximum daily temperature above the inflection temperature of 25.3°C



Source: Derived from Boyd et al. (2020) based on Graff Zivin and Neidell (2014)

The function in Figure 4 was coupled with projections of (a) the workforce in each “high-risk” industry across all B.C. population centres included in the study and (b) changes in maximum daily temperature under the “high-climate” scenario (2000-2099), to estimate daily changes in labour hours supplied, which were subsequently monetized. In contrast to the quantification of future mortality impacts discussed above, daily labour supply impacts were estimated for the 5-GCM ensemble median, as opposed to separately for each GCM.

3.2.1.1 Determining the future workforce in “high-risk” industries

For each population centre, we use labour force data for each 2-digit NAICS industry from the 2021 Census to determine the base year labour force (i.e., the population aged 15 years and over) employed in each of the “high-risk” industries—denoted:

$$LF_{i,p,t}\ [workers]$$

Where i is the 2-digit NAICS industry, LF is the labour force (number of workers), p is the population centre and t is the base year; the base year for the analysis is t = 2021. The starting point for calculating the future labour force in B.C. exposed to temperature stress are projections of employment by 2-digit NAICS industry provided by the Institute for the Boyd et al. study; these projections covered the period 2015-2050. The Institute's projections were used to construct a growth index for employment in each "high-risk" industry in B.C. (denoted EI), with 2021 = 100. Values for years after 2050 were generated using the linear forecasting function in Excel, using the estimated values for the period 2021-2050. Values for the baseline period 2000-2020 were similarly generated.

The future labour force in year t (from 2000 to 2099) in each of the "high-risk" industries, by population centre, was calculated as:

$$LF_{i,p,t}[workers] = LF_{i,p,2021}[workers] \times EI_{i,t}\,[index\ number\ with\ 2021\ base\ year]$$

This represents the population centre-specific number of workers in "high-risk" industries exposed to temperature stress in each future year of interest, as well as the baseline period 2000-2020. The estimated labour supply response in population centre (p) for each industry (i) in year (t) was calculated as:

$$H^{RC}_{i,p,t} = \sum_{d} LF_{i,p,t} \times \Delta T^{max}_{p,d(t)} \times ERF \times 0.71 \times \frac{1}{60}$$

Where H is the annual sum of daily work hours lost under the (no adaptation) Reference Case (RC), $\Delta T^{max}_{p,d}$ is the change in daily maximum temperature above the inflection temperature of 25.3°C on day d in year t, and ERF is the corresponding coefficients of the labour supply exposure-response function. The likelihood of an individual working in population centre p on day d (and thus being exposed to ΔT^{max}_{d}) is given by the fraction 0.71, which is derived from the annual average number of hours worked by employees in B.C. across all "high-risk" industries. The second fraction converts minutes to hours (1/60). Note that we assume workers acclimatize to rising temperatures over time in line with the general population; the base year inflection temperature of 25.3°C is adjusted over time using the same approach described above for mortality and morbidity.

3.2.2 Monetization of biophysical impacts

The estimated direct climate induced changes in labour supply were monetized using two metrics:

1. **Total payroll compensation** ($ 2022 per hour worked). It is calculated as the ratio between total compensation payments and the number of hours worked in all jobs. Total compensation is a measure of the total payroll costs of producers. It consists of all payments, whether cash or in-kind, to workers for services rendered, including salaries and social contributions paid by employers, plus an imputed labour income for self-employed workers.

2. **Labour productivity** ($ 2022 GDP per hour worked). It is calculated as the ratio between value added generated and hours worked in all jobs. Labour productivity provides a measure of losses to society, differentiating it from the loss of compensation—a measure that more reflects losses for the individual worker. For a specific industry, value added is given by that industry's gross output (mainly sales) less purchases of intermediate goods and services supplied by other sectors. It corresponds to GDP at basic prices.

The above monetary metrics were calculated for each "high risk" 2-digit NAICS industry in B.C. for the 2021 base year using provincial-level data obtained from Statistics Canada (Table: 36-10-0480-01 and Table: 36-10-0489-01). Historic values for the baseline period 2000-2021—adjusted to 2022 dollars—were derived from the same sources. As per US EPA (2015 and 2017)[48], future values for each metric were generated by adjusting the 2021 base year values (in 2022 dollars) for projected growth in *real* GDP per capita. Using hourly compensation (LC) as an example, future values are calculated as:

$$LC_{i,t} = LC_{i,2021} \times \frac{\frac{GDP_t}{Population_t}}{\frac{GDP_{2021}}{Population_{2021}}}$$

Where GDP is projected Gross Domestic Product (constant dollars) in year t. The real GDP projections the Institute generated for Boyd et al. were used in this study—rebased to 2022 dollars. The industry-specific unit values generated using the above formula are assumed to apply across all population centres in B.C. Projected labour unit costs for 2025, 2055 and 2085 are provided in Table 5.

Estimated foregone labour compensation (LC) for "high-risk" workers residing in population centre (p) in year (t) is calculated as:

$$LC^{RC}_{p,t} = \sum_i H^{RC}_{i,p,t} \times LC_{i,t}$$

Estimated foregone labour productivity (LP) for "high-risk" workers residing in population centre (p) in year (t) is calculated as:

$$LP^{RC}_{p,t} = \sum_i H^{RC}_{i,p,t} \times LP_{i,t}$$

Where $LP_{i,t}$ is the value of labour productivity ($ 2022 GDP per hour) for industry i in year t.

Table 5: Projected labour compensation and labour productivity costs (2022 dollars per hour) for "high-risk" industries in B.C.

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[48] US EPA, 2015: Climate Change in the United States: Benefits of Global Action. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001. Washington, DC; and US EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-17-001.

Year	NAICS 11	NAICS 21	NAICS 22	NAICS 23	NAICS 31-33	NAICS 48-49
Compensation:						
2025	31	66	72	43	44	43
2055	34	73	79	47	49	47
2085	38	80	87	51	53	52
Productivity						
2025	65	196	383	60	60	66
2055	72	216	421	66	66	72
2085	79	237	463	72	73	79

3.3 Adaptation scenarios

There are three main approaches to managing heat-related impacts on the workforce:[49]

1. **Engineered controls**. For example, installing external shading devices and technologies on walls and windows (especially south-facing walls) at the workplace, increasing insultation levels on external walls and ceiling spaces, upgrading the ventilation system to increase air flow and velocity through the workplace and increase evaporative cooling, changing the location of work to cooler areas on site, purchasing and using fans ("spot cooling") to increase air movement over specific workspaces, decreasing humidity levels in the workplace., etc.
2. **Administrative controls**. For example, developing an acclimatization plan for new employees or employees returning to work after extended leave, developing and using a formal work-rest schedule, organizing work to minimize the exposure of employees to heat, like scheduling high and very high intensity tasks for cooler parts of the day, etc.
3. **Personal protective equipment or behaviours**. For example, encouraging workers to wear appropriate clothing that is breathable, light-colored and loose-fitting, or to wear heat-protective or temperature-controlled clothing like air-cooled suits, water-cooled suits, ice-cooled vests, etc.

In general, engineered controls are the most effective means to avoid heat-related illness and productivity losses in the workplace, followed by administrative controls; personal protective equipment is typically considered as a supplementary control method.[50] Despite their effectiveness, engineered controls can be practically impossible in an outdoor working environment typical of four of the five "high-risk" industries identified by Zivin and Neidell; the exception being manufacturing (NAICS 31-33). Boyd et al. performed a cost-benefit analysis of an engineered control to adapt manufacturing sites in

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[49] Boyd, R., Zukiwsky, J and Kwan, C., 2022: Climate Resilient Business Guide: Future-Proofing Your Business for a Changing Climate. Final Report prepared by All One Sky Foundation for the City of Edmonton, Edmonton, AB.

[50] ESDC, 2018: Thermal stress in the workplace: Guideline 2018. Employment and Social Development Canada (ESDC), Ottawa, ON.

Canada to reduce the impact of higher ambient temperatures on labour supply (see Box 1). In this study, we evaluate a proactive administrative control, which applies to all “high-risk” industries. Specifically, we subject the following two “what-if” adaptation scenarios to cost-benefit analysis:

1. **Shifting work to cooler times of the day (1)**: When the daily maximum temperature in the official “heat warning” for a population centre is forecast to be reached, employers re-schedule work to cooler times of day. The scenario is assumed to apply to only workers with “irregular hours, irregular shifts, on call, or other schedule”—which amounts to 22.6% of workers in Canada in 2020.[51] The scenario is applied to this percentage of workers in all five “high-risk” industries in B.C.
2. **Shifting work to cooler times of the day (2)**: As above, except the scenario is assumed to apply to workers with (a) “irregular hours, irregular shifts, on call, or other schedule” (22.6% of workers in Canada in 2020) *plus* (b) workers with “regular daytime hours or daytime shift” (69.3% of workers in Canada in 2020. The scenario is applied to 91.9% (22.6% + 69.3%) of workers in all five “high-risk” industries in B.C.

The only difference between the two scenarios is thus the size of the pool of workers to which the administrative control is applied.

Similar to heat-health adaptation scenarios, the analysis is performed only for the two most populous centres in each Health Authority: Abbotsford, Vancouver-Inland, Kamloops, Kelowna, Fort St. John, Prince George, Vancouver-Coastal, Vancouver NorthShore, Victoria and Nanaimo.

Box 1: Cost-benefit analysis of “engineered control” to adapt manufacturing sites for rising ambient temperatures due to climate change

Boyd et al. evaluated the following “what-if” proactive adaptation scenario for labour supply: 25% and 50% of manufacturing facilities in each province installed internal and external shading technologies by 2055 and 2085, respectively. Relative to the projected Reference Case in the absence of new adaption action, Boyd et al. found that if 25% of manufacturing facilities in B.C. had shading technologies installed in 2055, about 68,555 labour hours would be saved. The corresponding annual costs avoided amounted to $3.0 million (labour compensation) and $4.6 million (labour productivity) (both in 2015 dollars). Annual net energy savings amounted to about $1.1 million. Annualized investment costs were about $3.2 million, resulting in positive net annual benefits of about $0.9 million (based on labour compensation). In this case, estimated net annual benefits are positive—and the simulated adaptation investment can be justified on economic efficiency grounds. By 2085, however, annual net benefits associated with 50% of manufacturing facilities in B.C. adopting shading technologies was estimated at negative $1.9 million (labour compensation) and $0.0 million (labour productivity) (i.e., present value benefits = present value costs).

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[51] Table 5, Aspects of quality of employment in Canada, February and March 2020, Statistics Canada, Ottawa, ON.

Under Reference Case conditions—in the absence of the simulated administrative controls—workers were assumed to work from 09.00 to 17.00. Each adaptation scenario involves shifting work hours to 05.00 to 13.00—if and only if—the daily maximum temperature for a population centre is forecast to exceed the daily maximum temperature in the official "heat warning". The corresponding change in daily maximum temperature to which workers who shift work hours to cooler parts of the day are exposed is calculated as (ignoring the day, d, and year, t,notation):[52]

$$T_{RC}^{max} = \frac{3}{8} \times T^{mean} + \frac{2}{8} \times \frac{\left(T^{mean} + T^{max}\right)}{2} + \frac{3}{8} \times T^{max}$$

$$T_{AC}^{max} = \frac{3}{8} \times T^{min} + \frac{4}{8} \times T^{mean} + \frac{1}{8} \times \frac{\left(T^{mean} + T^{max}\right)}{2}$$

$$\%\ \Delta T_{AC}^{max} = \frac{T_{AC}^{max} - T_{RC}^{max}}{T_{RC}^{max}}$$

Both T_{RC}^{max} and T_{AC}^{max} (AC denotes the Adaptation Case) were calculated from the projected ensemble median daily minimum and maximum temperatures for each population centre. The estimated percentage change in daily maximum temperature generated from the above equations was subsequently used to adjust the projected daily maximum temperature used to estimate labour supply losses under the Reference Case, as follows:

$$H_{i,p,t}^{AC} = \sum_{d} LF_{i,p,t} \times \left(\Delta T_{d(t)}^{max} \times \%\ \Delta T_{AC}^{max}\right) \times ERF \times 0.71 \times \frac{1}{60}$$

The physical benefits of the adaptation scenarios—in terms of the change in the projected annual sum of daily work hours lost from exposure to heat—were then calculated as:

$$\Delta H_{i,p,t}^{AC} = H_{i,p,t}^{RC} - H_{i,p,t}^{AC}$$

Estimated physical benefits (hours saved per year) were subsequently valued using projected hourly labour compensation (LC) and labour productivity (LP):

$$\Delta LC_{p,t}^{AC} = \sum_{i} \Delta H_{i,p,t}^{AC} \times LC_{i,t} \text{ and } \Delta LP_{p,t}^{AC} = \sum_{i} \Delta H_{i,p,t}^{AC} \times LP_{i,t}$$

Present value benefits (PVB) are calculated for the period 2020-2099 at two real annual discount rates; **3**% and **7**%, as per Canada's Cost-Benefit Analysis Guide for Regulatory Proposal.

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[52] Our approach is adapted from the "4+4+4" method used in ILO (2019) to estimate hourly temperature distributions; informed by the shape of the average hourly temperature distribution for Vancouver.

Regarding the costs of the adaptation scenarios, it was assumed that employers could alter shift patterns without incurring additional costs other than paying a premium to workers for having to work outside of normal hours (assumed to be 09.00-17.00). Furthermore, it was assumed that employee performance (productivity) would be unaffected by shifting work to cooler parts of the day (assumed to be 05.00-13.00) and the risk of accidents and injuries would likewise be unaffected. The starting point for estimating industry-specific premiums for working non-routine hours was the shift premium paid B.C. Government employees ($1.46 per hour at the time of writing). An hourly premium of $1.46 represents about 3.5% of the average hourly compensation paid employees in NAICS 91 (Public Administration). The assumed hourly premiums paid workers in the five “high-risk” industries were determined by multiplying the hourly compensation paid employees in each industry in 2020 (expressed in 2022 dollars) by 3.5%. The resultant hourly premiums were inflated in *real* terms over the period 2020-2099; a *real* annual average compound rate was computed for each “high-risk” industry by deflating the *nominal* annual average compound rate over the period 2002-2022 using the CPI (all-items) for B.C. over the same 2002-2022 period. The estimated premiums used to calculate the costs of the adaptation scenarios are listed in Table 6. For each day when the daily maximum temperature is forecast to exceed the daily maximum temperature in the official “heat warning” for a population centre, it is assumed that each employee that starts work at 05.00 as opposed to 09.00 is paid the hourly premium for 2 hours only—i.e., for work between 05.00 and 07.00.

Table 6: Projected compensation premium (2022 dollars per hour) paid workers in “high-risk” industries in B.C. for working outside their routine hours

Year	NAICS 11	NAICS 21	NAICS 22	NAICS 23	NAICS 31-33	NAICS 48-49
2025	0.86	1.54	1.61	1.23	1.23	1.18
2055	1.38	2.30	2.07	1.57	1.58	1.38
2085	2.20	3.42	2.67	1.99	2.02	1.61

Present value costs (PVC) are calculated for the period 2020-2099 at two real annual discount rates; **3**% and **7**%. Estimated PVBs and PVCs are combined to calculate the adaptation scenarios’ NPV (NPV = PBV – PVC), benefit-cost ratio (PVB ÷ PVC) and return on investment (NPV ÷ PVC).

FINAL UPDATES COMING SOON