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Projected impact of heat on mortality and labour productivity under climate change in Switzerland

Zélie Stalhandske et al.

Correspondence to: Zélie Stalhandske (zelie.stalhandske@usys.ethz.ch)

Supplementary Information

1. Datasets used for the climate impact modelling

Table S1: Datasets used for the climate impact modelling.

	Mortality	Labour Productivity
Hazard	CH2018 climate scenarios data [1] (T_{max})	CH2018 climate scenarios data [1] (T_{min}; T_{max})
Exposure	Population statistics (STATPOP 2018 [2])	Companies' structure statistics (STATNET 2017 [3])
Vulnerability	RR functions from Ragettli *et al* (2017) [4]	Empirical studies (see Table 1 in paper)

2. Infer temperature inside buildings

To compute indoor temperature values, we use a dynamic thermal model. To be able to retrieve the operating temperature inside the building, we have to perform the energy analysis. We use the CH2018 climate scenarios for indoor climate data for the station of Zurich as input, considering dry bulb and dew point temperatures, relative humidity, atmospheric pressure, horizontal infrared radiation intensity from sky, direct and diffuse normal and horizontal radiation, wind direction and speed. The model represents a simplified office building with the typical thermal transmittance (see Table S2) located in the city area of Zurich. The extent of the area and the thermal properties of the building used in the model correspond to averages computed on the basis of the building stock constructed between 2001 and 2005 in Zurich. These are assumed to be valid also for the rest of Switzerland.).

3. Calculation of the Wet Bulb Globe Temperature at Stations

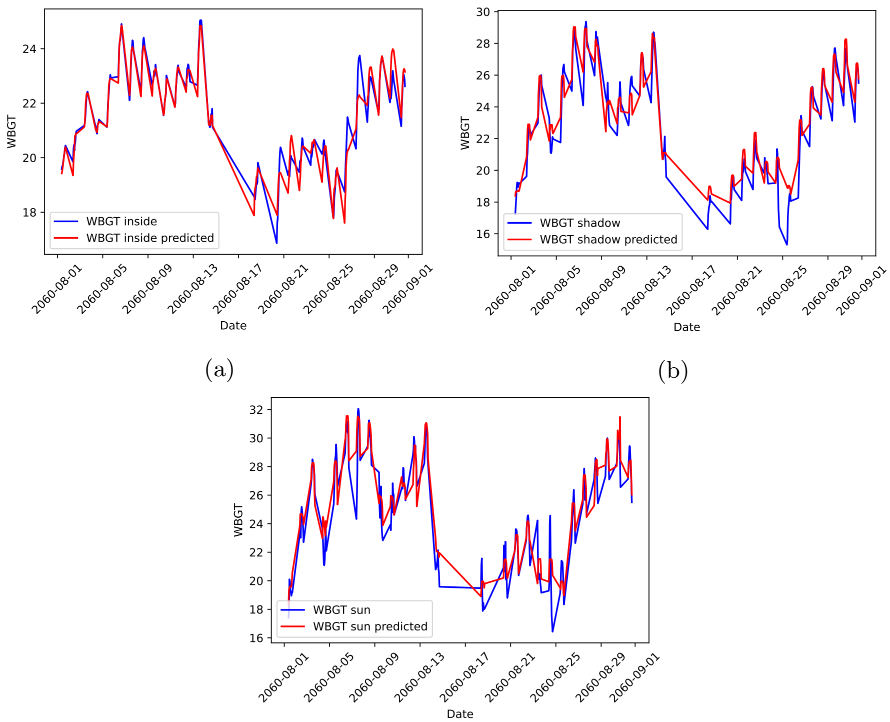
We calculate the Wet Bulb Globe Temperature (WBGT) at 45 stations, for 6 years in 2035 and 2060 under an RCP2.6 and RCP8.5 scenario. We use the R package *HeatStress* [6]. This package provides tools to calculate the WBGT from meteorological variables. Two functions are available: one to calculate WBGT based on temperature, humidity, radiation and wind speed based on Liljegren et al. (2008) [18], and the other one assuming no direct radiation and constant wind speed based on Bernard et al. (1999) [17]. We consider the equation by Liljegren et al. (2008) to model WBGT outside in the sun and in the shadow, by considering direct sun exposure or not. In order to calculate WBGT inside buildings, we first estimate the temperature inside using a building model as detailed in section 4 and then calculate the hourly WBGT based on the equation by Bernard et al. (1999) provided in the *HeatStress* R package, considering that the humidity is the same as outside the building.

Table S2: Assumptions at the basis of the dynamic thermal model.

	Surface area	206 m^2
	Windows area	109 m^2
Thermal properties	U-value wall	0.3 W/m^2K
	U-value window	1.4 W/m^2K
	U-value ground	0.4 W/m^2K
	U-value roof	0.3 W/m^2K

4. Prediction model of WBGT

As the CH2018 gridded datasets is available for minimum and maximum temperature, we predict the WBGT based on the WBGT previously calculated at stations. We use the minimum and maximum temperature, as well as the hour of the day as predictors and train three random forest regression (WBGT in the shadow, in the sun and inside a typical office building). Only days with maximum temperature reaching 22 ℃and hours between 8:00 and 18:00 are considered as these are used as input for the model. We cross validate the three models, separating the datasets in training and testing data. The distribution of possible WBGT for a given hour, and minimum and maximum daily temperature is then used in the Monte Carlo simulation.



(a) (b) (c)

Figure S1: Calculated and predicted WBGT at the Zurich Kaserne station in August for a statistical year corresponding to a 2060 climate under an RCP8.5 scenario inside a building (a), in the shadow (b) and in the sun (c). Only days with maximum temperature reaching 22 ℃and hours between 8:00 and 18:00 are shown.

5. Categorisation of the activity classes

The category *low physical activity* consists primarily of knowledge workers, such as accounting and servicing, which do not require to perform any major physical effort during the working day (metabolic rate of $200W$). The jobs of the category *moderate physical activity* are for example industry activities, which demand a moderate physical effort (metabolic rate of $300W$). The category *high physical activity* refers to occupations that are particularly demanding on a physical level (metabolic rate of $400W$), with agriculture and construction being the predominant sectors.

Table S3: Subdivision of the activity classes in the three occupation categories: low (L), moderate (M), and high (H) physical activity. In the third column of the table it is specified whether the tasks of each activity class are mostly carried out indoor (I) or outdoor (O). Swiss average hourly salaries are indicated in the last column, expressed in CHF/h. We calculate these from mean monthly gross salaries of 2018 for Switzerland [7].

Activity class	Occupation category	Work setting	Average hourly salary [CHF/h]
Agriculture, hunting, and related activities	H	O	26.50
Forestry and timber harvesting	H	O	45.02
Fishing and aquaculture	H	O	NaN
Coal mining	H	O	41.50
Extraction of oil and gas	H	O	41.50
Ore mining	H	O	41.50
Extraction of stone and soil, other mining activities	H	O	41.50
Supply of services to the mining and quarrying industry	H	O	NaN
Manufacture of food and feed products	M	I	36.57
Beverage production	M	I	43.39
Tobacco processing	M	I	74.94
Manufacture of textiles	M	I	37.03
Manufacture of clothing	M	I	33.21
Manufacture of leather and related products	M	I	32.52
Manufacture of wood, plaiting, wicker, and cork products (without furniture)	M	I	38.98
Manufacture of paper and paperboard and articles thereof	M	I	41.64
Manufacture of printed matter; Duplication of recorded sound, image, and data carriers	M	I	40.51
Coke and mineral oil processing	M	I	49.33
Manufacture of chemical products	M	I	54.37
Manufacture of pharmaceutical products	M	I	71.06
Manufacture of rubber and plastic products	M	I	40.04
Production of glass and glassware, ceramics, processing of stones and soils	M	I	41.98
Metal production and processing	M	I	40.57
Manufacture of metal products	M	I	40.22
Manufacture of data processing equipment, electronic and optical products	M	I	47.84
Manufacture of electrical equipment	M	I	46.31
Machinery manufacture	M	I	46.57
Manufacture of automobiles and automobile parts	M	I	39.66
Other vehicle manufacture	M	I	46.96
Furniture manufacture	M	I	39.86
Manufacture of other goods	M	I	43.36
Repair and installation of machinery and equipment	M	I	43.65
Energy supply	M	O	55.69

Water supply	M	O	46.43
Wastewater disposal	M	O	41.61
Collection, treatment and disposal of waste; Recovery	M	O	40.46
Pollution abatement and other disposal	M	O	NaN
Building construction	H	O	42.79
Civil engineering	H	O	43.91
Preparatory construction site work, building installation and other finishing trades	H	O	39.89
Trade, maintenance, and repair of motor vehicles	M	I	39.87
Wholesale trade (except of trade of motor vehicles)	M	I	53.26
Retail trade (except of trade of motor vehicles)	M	I	33.57
Land transport and transport by pipeline	M	O	42.14
Shipping	M	I	40.29
Aviation	M	I	46.86
Warehousing and support activities for transportation	M	I	45.46
Postal, courier and express services	M	O	39.14
Accommodation	M	I	29.41
Gastronomy	M	I	28.85
Publishing industry	L	I	50.16
Production, distribution and sale of films and television programs; Cinemas; Sound studios and music publishing	L	I	42.46
Broadcasters	L	I	53.73
Telecommunications	L	I	59.39
Supply of information technology services	L	I	60.02
Information services	L	I	86.68
Supply of financial services	L	I	73.12
Insurance, reinsurance, and pension funding (excluding social insurance)	L	I	64.12
Activities auxiliary to financial and insurance services	L	I	67.61
Real estate and housing	L	I	47.35
Legal and tax advice, auditing	L	I	56.62
Administration and management of companies and enterprises; Management consultancy	L	I	75.01
Architecture and engineering offices; Technical, physical, and chemical analysis	L	I	49.20
Research and development	L	I	70.32
Advertising and market research	L	I	48.89
Other freelance, scientific, and technical activities	L	I	50.11
Veterinary services	L	I	41.73
Rental of movable goods	L	I	42.19
Placement and transfer of workers	L	I	37.77

Travel agencies, tour operators, and other reservation services	L	I	39.99
Guard and security services, detective agencies	L	I	35.81
Building management; Gardening and landscaping	H	O	35.38
Supply of economic services to enterprises and individuals n.e.c.	L	I	42.77
Public administration and defence; Social insurance	L	I	53.67
Education and teaching	L	I	55.25
Healthcare	L	I	46.47
Homes (excluding recreational and holiday homes)	L	I	38.69
Social services (without homes)	L	I	41.63
Creative, artistic and entertainment activities	L	I	41.96
Libraries, archives, museums, botanical and zoological gardens	L	I	46.66
Gaming, betting, and lottery	L	I	36.41
Supply of sports, entertainment, and recreational services	L	I	42.64
Interest groups, church and other religious associations (excluding social services and sport)	L	I	49.03
Repair of data processing equipment and consumer goods	L	I	37.56
Supply of other predominant personal services	L	I	28.79

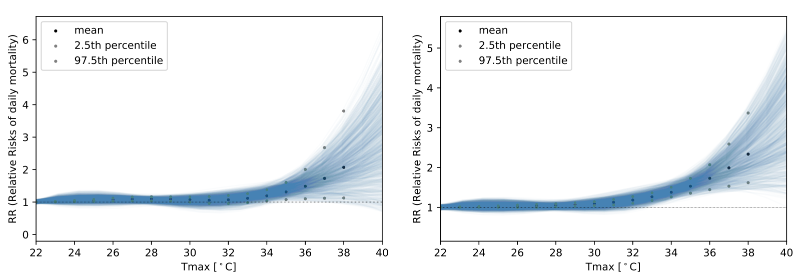
6. Sampling of the impact functions for mortality

6.1. Polynomial function

We assume the impact functions for mortality (RR functions) to be polynomial functions of the third order, with equation:

$$f(x) = ax^3 + bx^2 + cx + d \tag{1}$$

6.2. Sample distribution of probable impact functions for mortality



(a) (b)

Figure S2: Distribution of functions describing the relationship between daily maximum temperature and relative risk of daily mortality for (a) the people below the age of 75 and (b) with or above the age of 75. The mean curve and the confidence interval are taken from the study of Ragettli *et al* (2017) [4].

7. Sampling of the impact functions for labour productivity

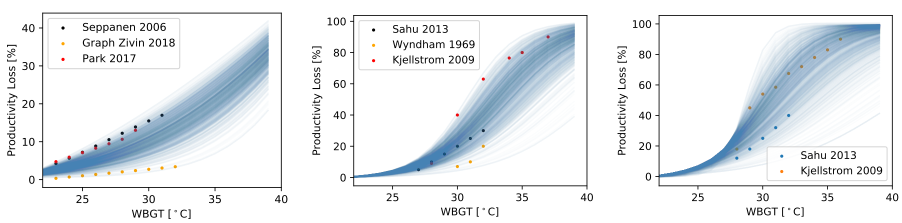
7.1. Sigmoid function

We assume the impact functions for labour productivity to be sigmoid functions, as for example some of the ones used in CLIMADA [8]. Also in other studies assessing the impact of heat on labour productivity sigmoid functions are used [9, 10]. The functions developed for the present study are logistic functions, with equation:

$$f(x) = \frac{L}{1 + e^{-k(x-x_0)}} \tag{2}$$

where x stands for the WBGT values and $f(x)$ is the percentage of labour productivity that get lost due to heat. L indicates the curve's maximum value (i.e. the maximum percent of labour productivity loss), k stands for the logistic growth rate (i.e. the steepness of the curve), and x_0 refers to the x-value of the sigmoid's midpoint.

7.2. Sample distribution of probable impact functions for labour productivity



(a) (b) (c)

Figure S3: Distribution of impact functions describing the relationship between WBGT and percentage of labour productivity loss for people working at a (a) low physical activity, (b) moderate physical activity, and (c) high physical activity.

8. Sources of uncertainties and shape of their distributions

8.1. Overview table

Table S4: Summary of the sources of uncertainties in both model and shapes of their distributions. The first group of uncertainties shows those which are common to both models, while the second shows the additional uncertainties which are embedded in the labour productivity model.

	Source of Uncertainty	Distribution
Common Uncertainties	Climate Model	Uniform
	Natural Variability	Uniform
	Impact Functions	Normal
Labour Productivity Uncertainties	hourly WBGT values	Normal
	Sun Exposition	Uniform

9. Sensitivity Analysis

The sensitivity analysis is performed for the labour productivity model, as shown in Figure S4. In the variables common to both models, the uncertainties stemming from the climate data (climate simulations and natural variability) play the most important role. In the example in Figure S4, the influence of the climate simulations can be up to 52% below and 41% above the median costs (95% confidence interval). The impact functions have a smaller contribution, with the impact being up to 28% below and 8% above the median costs. For the labour productivity model, the estimation of the WBGT contributes the most to the the uncertainty, where the cost can be up to 112% and 76% below the median estimate.

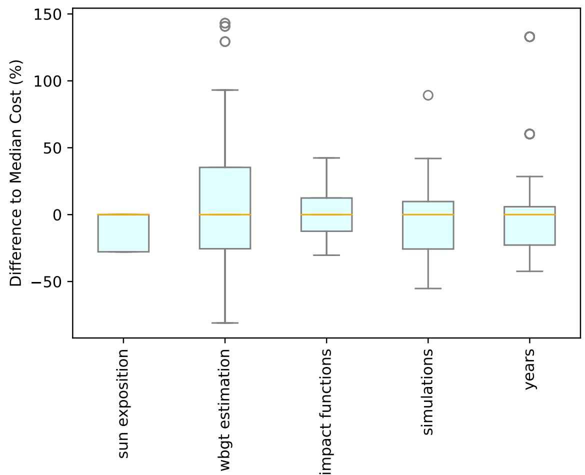


Figure S4: Sensitivity analysis for the labour productivity model. Results for the category *high physical activity* in the year 2050 and under the RCP8.5 scenario. The median is indicated by the orange line. The rectangles contain values from the 25th to the 75th percentile. The vertical lines span throughout the 95% confidence interval.

10. Spatially explicit results for mortality

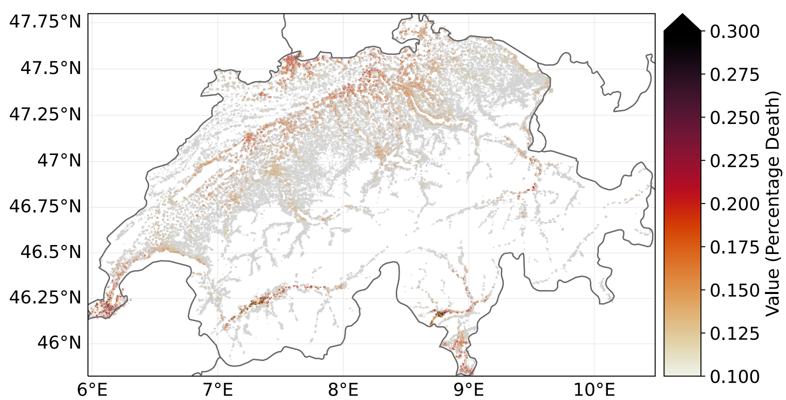
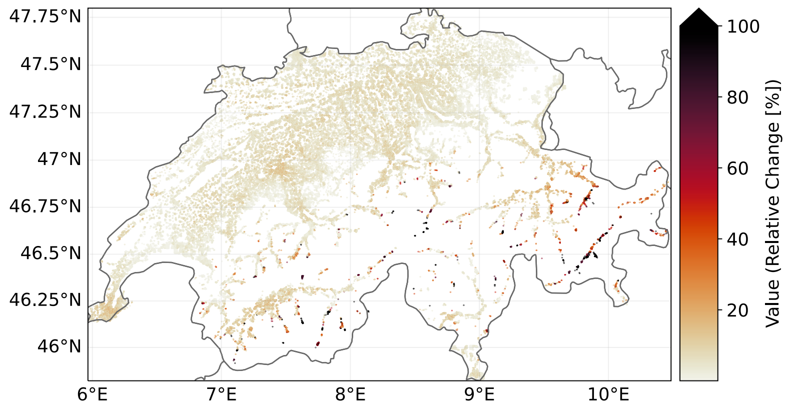
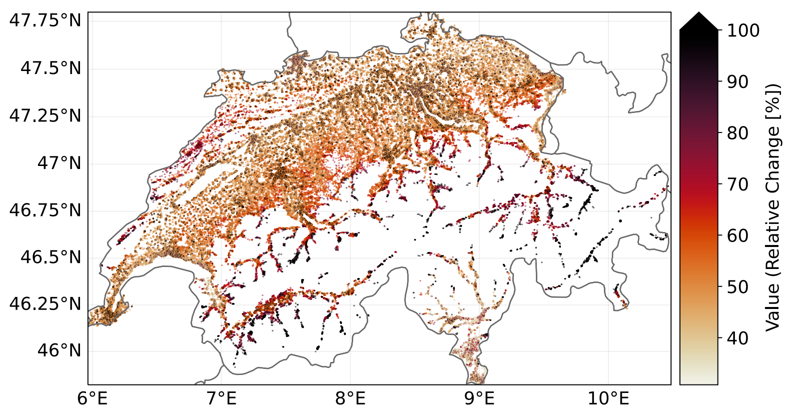


Figure S5: Map showing the spatial impact for mortality in percentage compared to the total exposure value for the year 2050, the RCP8.5 scenario, and the category of elderly people.



(a)



(b)

Figure S6: Maps showing the relative changes in number of heat-related deaths compared to the baseline for the year 2050 under an RCP2.6 (a) and an RCP8.5 scenario (b) for the category of elderly people.

11. Results at cantonal level

	Baseline (2020)	RCP2.6		RCP8.5	
		2050	2080	2050	2080
canton					
Aargau	58	62	62	82	133
Appenzell Ausserrhoden	2	2	2	3	6
Appenzell Innerrhoden	0	0	0	1	1
Basel-Landschaft	28	29	30	39	64
Basel-Stadt	16	17	17	22	36
Bern	81	87	87	116	193
Fribourg	21	23	23	31	51
Genève	42	46	44	61	100
Glarus	2	2	2	3	6
Graubünden	11	13	13	18	33
Jura	6	7	7	9	16
Luzern	28	30	30	40	67
Neuchâtel	10	11	11	15	25
Nidwalden	3	3	3	4	7
Obwalden	2	2	2	3	5
Schaffhausen	7	7	8	10	17
Schwyz	8	9	9	12	21
Solothurn	26	27	28	36	59
St. Gallen	33	34	35	46	76
Thurgau	20	21	22	28	46
Ticino	42	43	43	56	91
Uri	2	2	2	3	5
Valais	28	31	30	43	73
Vaud	55	58	58	77	125
Zug	7	7	7	10	16
Zürich	105	111	112	147	242
Total	653	695	698	925	1526

Table S5: Median estimate for the number of heat-related deaths for each canton for the baseline (2020, RCP8.5), and the years 2050 and 2080 under the climate scenarios RCP2.6 and RCP8.5.

	Baseline (2020)	RCP2.6		RCP8.5	
		2050	2080	2050	2080
canton					
Aargau	48.12	54.11	60.39	79.52	156.64
Appenzell Ausserrhoden	2.31	2.54	2.91	3.76	7.76
Appenzell Innerrhoden	0.73	0.82	0.92	1.19	2.56
Basel-Landschaft	22.47	24.66	27.61	37.18	71.32
Basel-Stadt	26.66	27.73	31.43	44.20	81.74
Bern	74.67	79.91	90.67	120.04	242.53
Fribourg	18.41	20.44	22.76	30.13	61.66
Genève	56.00	61.26	69.50	93.46	179.30
Glarus	2.21	2.45	2.68	3.61	7.97
Graubünden	12.29	14.36	14.81	21.25	48.61
Jura	5.10	5.47	6.21	8.22	16.27
Luzern	30.04	32.65	36.01	48.35	100.25
Neuchâtel	11.19	11.82	13.42	18.08	35.49
Nidwalden	2.77	3.03	3.30	4.38	9.27
Obwalden	2.35	2.70	2.88	3.76	8.77
Schaffhausen	6.12	6.82	7.62	10.20	19.60
Schwyz	9.33	10.23	11.40	15.21	32.11
Solothurn	19.71	21.69	24.68	31.83	62.76
St. Gallen	32.26	35.09	38.91	52.16	107.82
Thurgau	16.77	18.71	20.61	27.75	55.71
Ticino	36.32	39.29	44.21	58.53	116.02
Uri	1.75	2.06	2.18	2.90	6.81
Valais	22.38	26.82	27.08	39.60	85.91
Vaud	59.69	64.08	72.67	98.36	191.21
Zug	13.56	14.18	16.11	22.07	44.02
Zürich	131.34	139.30	159.67	217.50	425.55
Total	664.57	722.22	810.65	1093.26	2177.66

Table S6: Median estimate of the losses in labour productivity (in million CHF) for each canton for the baseline (2020, RCP8.5), and for the years 2050 and 2080 under the climate scenarios RCP2.6 and RCP8.5.

References

[1] NCCS 2018 *CH2018 – Climate Scenarios for Switzerland* National Centre for Climate Services, Zurich https://naturalsciences.ch/service/publications/107868-ch2018---climate-scenarios-for-switzerland

[2] Bundesamt für Statistik BFS 2019a *Statistik der Bevölkerung und Haushalte (STATPOP), Geodaten 2018* https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/gebaeude-wohnungen-haushalte-personen/bevoelkerung-haushalte-ab-2010.assetdetail.9947069.html

[3] Bundesamt für Statistik BFS 2019b *Statistik der Unternehmensstruktur (STATENT), Beschäftigte und Arbeitsstätten: Geodaten 2017* https://www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/arbeitsstaetten-beschaeftigung/statistik-unternehmensstruktur-statent-ab-2011.assetdetail.9526894.html

[4] Ragettli M S, Vicedo-Cabrera A M, Schindler C and Röösli M 2017 Exploring the association between heat and mortality in Switzerland between 1995 and 2013 *Environmental Research* **158** pp 703–709 https://doi.org/10.1016/j.envres.2017.07.021

[5] Chow D H C and Levermore G J 2007 New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models *Building Services Engineering Research and Technology* **28** pp 237–248 https://doi.org/10.1177/0143624407078642

[6] Casanueva A 2019 HeatStress: Calculate heat stress indices *R package version 1.0.7.* https://github.com/anacv/HeatStress

[7] Bundesamt für Statistik BFS 2020 *Swiss Earnings Structure Survey in 2018: initial findings* https://www.bfs.admin.ch/bfs/en/home/statistics/work-income/wages-income-employment-labour-costs.gnpdetail.2019-0502.html

[8] Aznar-Siguan G and Bresch D N 2019 CLIMADA v1: a global weather and climate risk assessment platform *Geoscientific Model Development* **12** pp 3085–3097 https://doi.org/10.5194/gmd-12-3085-2019

[9] Kjellstrom T, Freyberg C, Lemke B, Otto M and Briggs D 2018 Estimating population heat exposure and impacts on working people in conjunction with climate change *International Journal of Biometeorology* **62** pp 291–306 https://doi.org/10.1007/s00484-017-1407-0

[10] Kjellstrom T, Holmer I and Lemke B 2009 Workplace heat stress, health and productivity - an increasing challenge for low and middle-income countries during climate change *Global Health Action* **2** https://doi.org/10.3402/gha.v2i0.2047

[11] Seppänen O, Fisk W and Lei Q 2006 Effect of Temperature on Task Performance in Office Environment *Lawrence Berkeley National Laboratory* https://indoor.lbl.gov/sites/all/files/lbnl-60946.pdf

[12] Graff Zivin J, Song Y, Zhang P and Tang Q 2018 Temperature and high-stakes cognitive performance: Evidence from the national college entrance examination in China *Journal of Environmental Economics and Management* **104** https://doi.org/10.1016/j.jeem.2020.102365

[13] Park J 2017 Hot Temperature, Human Capital and Adaptation to Climate Change *Harvard University Economics Department* https://scholar.harvard.edu/files/jisungpark/files/paper_nyc_aer.pdf

[14] Sahu S, Sett M and Kjellstrom T 2013 Heat Exposure, Cardiovascular Stress and Work Productivity in Rice Harvesters in India: Implications for a Climate Change Future *Industrial Health* **51** pp 424–431 https://doi.org/10.2486/indhealth.2013-0006

[15] Wyndham C H 1969 Adaptation to heat and cold *Environmental research* **5** pp 442–469 https://doi.org/10.1016/0013-9351(69)90015-2

[16] Pérez L and Künzli N 2009 From measures of effects to measures of potential impact *International journal of public health* **54** pp 45–48 https://doi.org/10.1007/s00038-008-8025-x

[17] Bernard T. E. 1999 Prediction of Workplace Wet Bulb Global Temperature *Applied Occupational and Environmental Hygiene* **14** pp 126-134 https://doi.org/10.1080/104732299303296

[18] Liljegren JC, Carhart RA, Lawday P, Tschopp S, Sharp R 1999 Modeling the wet bulb globe temperature using standard meteorological measurements *J Occup Environ Hyg* **14** pp 645-55 https://doi.org/10.1080/15459620802310770