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Urban SIS
D4.3 Indicators for urban assessments (revised)

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Urban SIS
D4.3 Indicators for urban assessments

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Background

The selection of Essential Climate Variables (ECV) and indicators is informed by the requirements identified by end-users and stakeholders. Notably those whose participated in two WP4 workshops that were held in Stockholm (17 December 2015) and Bologna (5 February 2016). Requirements from a broader European community have been added based on the contributions of experts and advanced end-users from Urban SIS partners such as University of Reading, UMU, UniBo and WSP.

There are two WP4 deliverables documenting end-user requirements on Urban (Sectoral Information System) SIS data:

- D4.2 Requirements on urban ECV data for use as input to local models (29 February 2016)
- D4.3 Impact indicators for use in urban assessments (31 October 2016, this report)

This document summarizes the indicators that have been selected for inclusion as output.

Introduction

What is an indicator?

An indicator is a data product for specific end-users needs. Indicators primarily use the available ECVs (Essential Climate Variables), but sometimes require additional data about the urban area, such as population density.

How have indicators been chosen?

Indicators were identified through end-users workshops in Bologna and Stockholm and expert panel meetings.

It is evident from the two workshops that there are many different indicators that are of interest by end-users of urban climate data. However, indicators do not have a consistent definition and/or method of calculation between end-user communities. For example, different thresholds, percentiles or statistical measures may be used. As this was apparent from a sub-set of end-users in just two cities (in two countries), it suggests that a more extensive evaluation across Europe would increase the list of desired indicators. Thus, priority was given to indicators expected to be applicable for large parts of Europe. Secondly, where a threshold is used, a percentile rather than an absolute value is selected, as this should permit a wider applicability across different climates.

Criteria for selection of indicators have been:

- Applicability for large parts of Europe
- A clear end-user need identified
- Quality of results

There is a wide range of sectors that end-users in urban area may have an interest in having an indicator for. However, as our current objectives are to demonstrate the proof-of concept, a more focussed (rather than exhaustive) approach is taken. Table 1 provides a summary of the sectors with the type of indicators.

Table 1. Sectors that indicators have considered for and an overview of indicators identified.

Health	Air quality	Air pollutant concentration Air pollution exposure Air pollution health impact
	Heat stress	Hot days Heat wave duration Heat-related deaths
	Discomfort	Thom Discomfort Index Universal Thermal Climate Index Frequency of tropical nights
Energy	Energy consumption	Heating and cooling degree days
	Solar energy	Solar insolation
Infrastructure	Flooding	Local and surface runoff Intense precipitation
	Soil	Soil temperature
	Green infrastructure	Growing season length Drought periods
	Transport infrastructure	Frost days Zero-crossings
Non-sector specific	Temperature	Maximum, minimum, and average air temperature
	Snow cover	Snow cover depth

Relation to Essential Climate Variables

Some indicators can be derived using only simple statistics of the essential climate variables (ECVs). These simple indicators are not listed in this document. The statistics that will be calculated for all Essential Climate Variables are:

- Mean over the full time-period
- Mean of yearly max, and min over the full time-period
- Yearly mean, max and min values
- Annual monthly mean, max and min for the full time-period
- Monthly mean, max and min values

Historical and Scenario Data

Indicators will be calculated for three ~5 year time-periods:

- *historical period*: results can be compared to measurements and indicators for the specific years
- *present* scenario: individual years taken from a climate scenario, representing todays climate
- one *future* scenario: individual years taken from a climate scenario, representing conditions around 2050

Where annual indicators are provided, the difference between the present time and future scenarios will be presented. The difference is calculated for the mean of the full 5 year window, as well as for the mean of yearly max and yearly min. These indicators are applied generally and are therefore not specified for each individual indicator in this document.

The difference between the indicator values for the future and the present scenario will indicate the changes in temperature and precipitation of the selected regional climate scenario RCP8.5 and its 30-year window (obtained by selecting 5 years with similar characteristics in temperature and precipitation as a full 30 year window).

Urban SIS will also output shorter adaptation scenarios over selected events. Adaptation events means that it will be possible to compare the impact of land-use changes on certain ECV variables, e.g. albedo changes affecting the urban heat island and vegetation changes affecting surface runoff. For those shorter events it will not be possible to calculate indicators based on long-term statistics.

How to interpret indicators and caveats

The main body of this document is an overview of the individual indicators that have been selected to be included in the demonstration portal. The intent is three fold:

a) To provide the details of the indicator to inform the developers of the portal (WP7) with the details of the indicator
b) To provide traditional end-users with the background to the indicator. It is anticipated that some of this material would be used as meta-data and web information in the portal.
c) To provide caveats that consultants or other users (who may be providing additional value) to the data should be aware of.

Table 2 provides an example of the template used for each indicator with the intent of each section. It is anticipated that the material within this will expand with usage. Table 3 provides caveats for interpreting, using, and calculating the indicators. There are also examples of specific ways the indicators could be used and visualized.

Table 2: Template used for each indicator (or set of indicators) with the intent of the content

Full indicator name in text

Sector	*Sector(s) that used this indicator*
ID	*Code(s) use for indicator(s) – when there are multiple closely related indicators there may be multiple listed (e.g. maximum, minimum, mean of a variable)*
Description	*Text description of the indicator*
End users	*Examples of those who have a requirement or a desire for this indicator*
Calculation method	Methods used to calculate the indicators. If the method is not a standard statistical metric the equation for calculation is given. 1: ID as above 2: Understandable unique title – this is provided when there are multiple closely related indicators 3: This is the period over which the [statistical] calculation has been undertaken (e.g. hourly, daily, annual) 4: Actual technique use to determine the indicator (e.g. maximum, minimum, average, 8-hour running average, 99-percentile, actual equation if not standard statistical techniques) 5: Units of the indicator (e.g. number of days, °C) 6: Many of the indicators have thresholds that have to be specified for the indicator to be determined. 7: Any comments about the indicator calculation

Id	Title	Period	Statistical processing	Unit	Threshold	Comment
1	2	3	4	5	6	7

Calculation caveats	For example: where the indicator should/shouldn't be applied, for whom is the indicator valid (e.g. a person indoors/outdoors, in shade/open) To what can the indicator be compared
Interpretation caveats	*Spatial representation* – Table 3a (Codes S**X**) describes what the data represent *Other caveats* – Table 3b *Could be compared to* – Table 3c *Could be used with* – Table 3d

Presentation

	Style	*Colour*
Map	Table 3e	Table 3f
Time Series		

Motivation	End-user need. Why this indicator is important.
Experience user	If someone was to use these data any additional things they should consider
References	References related to the indicator

Table 3: Codes Used in the templates (a) Spatial representation (b) Other Caveats (c) could be compared to (d) Examples of usage (e) presentation (f) colour ramps

TYPE	**(A) SPATIAL REPRESENTATION**
S1	This indicator is an average outdoor, street-level conditions for each grid cell at a resolution of 1 km. This means fine-scale variations resulting from *urban geometry* (building or tree heights, for example) are not resolved. Thus, there may be higher uncertainty in spatially complex settings such as city centres with a high degree of fine-scale spatial variation in surface geometry (e.g. from building shadows/reflections, anthropogenic heat sources). For example, 2 m outdoor urban air temperatures are affected by micro-scale urban geometry through sky-view factor and longwave radiation energy loss, thermal surface properties (via overnight storage heat releases), and anthropogenic heat emissions.
S2	Concentrations represent the urban background. This means that it does not reflect local extremes found close to roads or large emission sources.
S3	Applied relative risks originate from studies of both finer and coarser spatial resolution compared to exposure data used here.
S4	Future modelled changes in these indicators are predominantly due to atmospheric and climate processes operating on larger scales (regional, global) than urban areas. Thus, spatial variation within an urban area at 1 km x 1 km grid resolution is expected to be minimal.
S5	This is representative of selected points along the rivers.
S6	Average outdoor, street-level conditions for each grid cell (resolution: 1 km), so does not resolve fine-scale variations resulting from different *land uses*.

	(B) OTHER CAVEATS
O1	No physiological adaptation is assumed for the future scenario. Although it is likely that some physiological adaptation exists, its importance is unknown and therefore disregarded. This assumption might to some extent cause an overestimation of the number of heat related deaths in the future scenario.
O2	Percentiles are evaluated separately for the historical dataset and the scenarios. For the scenarios, the same 75-percentile is used for the present and the future scenario. The percentile is evaluated at the airport closest to the city and then used as a threshold in the evaluation for all grid cells.
O3	The scenario period is too short to be used for robust extreme value analysis.
O4	This is a threshold-based indicator that is dependent on choice of specific threshold. The threshold can vary from country to country and between climate regions. The thresholds selected here may not be for the individual geographic sub-region.
O5	For future scenarios, the change caused by trends in emissions can be expected to dominate over the change caused by the change in climate.
O6	The 75th percentile is a low threshold for hot days specification but is used to be consistent with health impact calculations presented for heat stress.

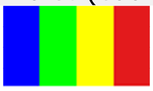
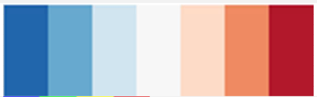
TYPE	**(C) COULD BE COMPARED TO**
C1	High-quality, long-term air temperature measurements (e.g. taken at airports, universities, air quality monitoring stations).
C2	Measured concentration at urban background stations, typically on a roof top, in a park or any other area a few hundred meters away from large roads and emission sources.
C3	Local runoff can theoretically be measured (or, rather, approximated) by using different discharge stations in the same river and, based on their differences, estimate the runoff contribution from the area draining to the river reach between the stations. In practice, however, such data are unavailable or only single-station

	data exist.
C4	Snow observations
C5	High-resolution precipitation observations from gauge or radar.
C6	Existing statistics and national guidelines.
C7	Soil-moisture based drought indicators are potentially comparable to observed estimates using soil moisture observations. Such observations are, however, both infrequent and uncertain. Single-site data from individual sensors are limited with respect to representing the large spatial scales involved in drought events. Satellite-based soil moisture products are promising but they may not be sufficiently accurate for this type of assessment.

	(D) EXAMPLES OF USAGE
U1	Grid average 2 m air temperatures could be used with high-resolution urban digital surface models, if available. This would allow downscaling or assessment of the likely impact of micro-scale variability of urban form (e.g. openness or sky view factor) on air temperature.
U2	Input data for micro-scale modelling of urban climate.
U3	Upstream background concentrations to be used together with local scale air quality modelling, allowing a more detailed description of air pollution levels.
U4	Flood risk and water balance assessments
U5	Solar resource assessment models, detailed urban solar radiation models, building energy models.

	(E) PRESENTATION
P1	Gridded with a resolution of 1 km * 1 km.
P2	Aggregated time series to visualize temporal variability and trends. A heavy line can be used to represent the spatial mean of all grid cells with a shaded region to represent max/min (or 10%/90%ile, etc.) of individual grid cell values.
P3	Time series and summary statistics representing a selected grid cell
P4	Wind rose plotted on the map at the position of a selected grid cell.
P5	PDF (Probability Density Function) representing a specific grid cell
P6	Annual total time series. Simple time series graph with 'Year' along x-axis and y-axis is the annual total (e.g. number of days above a certain threshold).
P7	Selected points along the rivers
P8	Time series and summary statistics representing selected points.
P9	Intensity-Duration-Frequency (IDF) curves (or tables), aggregated for the whole area. This is a compact statistical description of short-duration rainfall extremes, widely used in engineering. The curves provide the rainfall intensity associated with a certain duration and frequency, with the latter generally being expressed in the form of a return period. IDF-curves are applicable for small basins in which the spatial rainfall can be approximated by a single station; for larger basins ARFs (P10) are needed in addition.
P10	Areal Reduction Factors (ARFs), aggregated for the whole area. ARFs describe how local rainfall extremes become reduced when considering a gradually larger surrounding area. For small-scale rainfalls (e.g. convective events, generally produce highest local intensities) the ARF rapidly decreases with area, whereas for large-scale events (e.g. frontal) it is less reduced, and there is a corresponding dependence on the rainfall duration. The ARFs are used for hydrological design of large (urban) basins, which cannot be represented by a single station, and the ARFs may be provided as either curves or tables.

(F) COLOUR RAMPS[1]

TYPE	Colours	Specified limits	Example indicator
R1	blue (cool) ->red (warm)		Thom discomfort index
R2	rainbow violet (cool)->red (warm)		Air temperature
R3		VAL % COLOUR **≥100** Red **70** Yellow **50** Green **<50** Blue	Air pollutant concentrations. Corresponds to WHO & EU limit values and thresholds.
R4		VAL % COLOUR **≥100** Red **80** Yellow **65** Green **<65** Blue	Air pollutant concentrations. Corresponds to WHO & EU limit values and thresholds.
R5	yellow -> red, 0 is transparant.	range specified per indicator	Annual heat related deaths, persons exposed to air pollution above limit values
R6	dark blue -> light blue	range specified per indicator	HDD, CDD
R7	white –> dark blue	Minimum = 0, max = 30	Frost days, Ice days
R8	white -> green		Growing season length, leaf-off, leaf-on
R9		Minimum = 0, max	
R10		VAL % COLOUR **≥100** Red **80** Yellow **40** Green **<40** Blue	PM2.5 concentration and exposure. Corresponds to WHO & EU limit values.
R11		Levels adjusted to maximal value	Discharge, Runoff, precipitation
R12	White → Red	Minimum 0	

[1] Note that for many of these it may also be necessary to think about the implications for colour blind end users

Indicators (in alphabetical order)

Air temperature indicators

Sector	Non-specific, most
ID	*airtempmaxdaily, airtempmindaily, airtempevgdaily, airtemprangeyearly*
Description	describe daily maximum, minimum, average, and yearly range (max-min) of outdoor 2 m air temperatures
End user	Urban planners, health authorities, building engineers, landscape and building architects, general public

Calculation method

ID	*Title*	*Period*	*Statistical Processing*	*Unit*	*Threshold*	*Comment*
airtempmaxdaily	Daily max air temperature at 2 m above ground	daily	Max of 24 hours	°C		
airtempmindaily	Daily min air temperature at 2 m above ground	daily	Min of 24 hours	°C		
airtempavgdaily	Daily mean air temperature at 2 m above ground	daily	Average of 24 hours	°C		
airtemprangeyearly	Yearly maximum of daily temperature range at 2 m above ground	yearly	Max(airtempmaxdaily-airtempmindaily)	°C		

Calculation caveats

Interpretation caveats

Spatial representation:	S1
Could be compared to:	C1
Could be used with:	U1, U2

Presentation

	Style	*Colour*
Map	P1, P3	R1, R2
Time Series	P2	

Motivation	Air temperature is a base indicator for many applications including heat stress, energy use, planning, architectural design, etc. This can be used to calculate other indicators such as heating (cooling) degree days, tropical nights, and thermal comfort indices.
Experience user	These variables are of use for many additional applications.
References	

Air pollutant concentration indicators

Sector	Air quality
ID	*cEUNO2hourly, cEUNO2yearly, cEUPM2.5yearly, cEUPM10yearly cEUO3daily,* cO3SOMO35
Description	Concentrations of nitrogen dioxide (NO_2), particulate matter (PM) and ozone (O_3) evaluated as averages or percentiles to be comparable with WHO guidelines and EU limit values. Emissions data describing the historical time-period is acquired from regional or national sources. The emission data used for future scenarios is based on IASA-projections.
End users	Environmental authorities, air quality consultants, urban planners

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
cEUNO2hourly	99.8th percentile of hourly NO_2 concentration	yearly	99.8th percentile of hourly averages during a year (same as 18 exceedances per year)	$\mu g\ m^{-3}$	200 $\mu g\ m^{-3}$	
cEUNO2yearly	Yearly average NO_2 concentration	yearly	Average	$\mu g\ m^{-3}$	40	
cEUPM2.5yearly	Yearly average $PM_{2.5}$ concentrations	yearly	Average	$\mu g\ m^{-3}$	25	
cEUPM10yearly	Yearly average PM_{10} concentrations	yearly	Average	$\mu g\ m^{-3}$	40	
cEUPM10daily	90th percentile of daily average PM_{10} concentrations		90th percentile of daily averages during a year (same as 35 exceedances per year)	$\mu g\ m^{-3}$	50	
cEUO3daily	93.15th percentile of daily max of 8-hour running averages of ozone concentration	yearly	93.15th percentile of max of 8-hour running averages (same as 25 exceedances per year)	$\mu g\ m^{-3}$	120	
cO3SOMO35	SOMO35	yearly	Sum of excess of max daily 8-hour averages over 35 ppb (= 70 $\mu g\ m^{-3}$) calculated for all days in a year; SOMO35 (Sum Of Means Over 35 ppb)	days*$\mu g\ m^{-3}$	35 ppb	

Calculation caveats

Interpretation caveats	*Spatial representation*	S2			
	Other caveats	O5			
	Could be compared to				
	Could be used with				
Presentation		*Id*	*Style*	*Colour*	*Default range*
	Map	cEUNO2hourly,	P1	R3	0-200
	Map	cEUNO2yearly,	P1	R4	0-40
	Map	cPM25yearly	P1	R3	0-25
	Map	cPM10yearly	P1	R3	0-40
	Map	cEUO3daily	P1	R3	0-120
	Map	cO3SOMO35	P1	R3	0-70
	Time Series	-			
Motivation	EU air quality limit/target values are an essential legal instrument for air quality management in Europe. WHO 2005 guidelines provide strictly health based recommendations and is also a valuable reference. The presented exposure estimates are used for as basis for provided health impact indicators. A large part of the population is exposed to the urban background concentration of air pollutants. The urban background concentration is used for indicators related to population exposure and health impact due to air pollution. The concentration indicators provide an overview of the concentrations and can for example be used to identify areas with air pollution exceeding the air quality limits or guidelines.				
Experience user					
References	Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 summarized at http://ec.europa.eu/environment/air/quality/standards.htm WHO 2005: Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. ISBN 92 890 2192 6.				

Air pollution exposure indicators

Sector	Air quality
ID	*expEUNO2hourly, expEUNO2yearly, expEUPM2.5yearly, expEUPM10daily, expEUPM10yearly, expEUO3daily, expWHOO3daily, expWHONO2hourly, expWHONO2yearly, expWHOPM25yearly*
Description	Number of persons exposed to concentrations above EU standards or WHO 2005 guidelines.
End users	Environmental authorities, air quality consultants, city planners
Calculation method	Gridded population data is multiplied by a Boolean grid (True/False) representing exceedance of the corresponding limit value. Where no official population data exists with sufficient spatial resolution, a 1 * 1 km^2 disaggregated population grid is used (Gallego 2010).

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*
expEUNO2hourly	Persons exposed to NO_2 conc. > AQ EU hourly limit value	yearly	Pop*(99.8th percentile of hourly averages > 200)	persons	200 μg m^{-3}
expEUNO2yearly	Persons exposed to NO_2 conc. > AQ EU yearly limit value	yearly	Pop * (Average > 40)	persons	40 μg m^{-3}
expEUPM2.5yearly	Persons exposed to $PM_{2.5}$ concentrations > EU yearly limit value	yearly	Pop * (Average > 25)	Persons	25 μg m^{-3}
expEUPM10yearly	Persons exposed to PM_{10} concentrations > EU yearly limit value	yearly	Pop * (Average > 40)	Persons	40 μg m^{-3}
expEUPM10daily	Persons exposed to PM_{10} concentrations > EU daily limit value	yearly	Pop * (90th percentile of daily averages > 50)	Persons	50 μg m^{-3}
expEUO3daily	Persons exposed to O_3 concentrations > EU daily target value	yearly	Pop * (93.15th percentile of max of 8-hour running averages > 120)	persons	120 μg m-^{3}
expWHOO3daily	Persons exposed to O_3 concentrations > WHO guideline	yearly	Pop * (max of 8-hour running averages > 100)	persons	100 μg m^{-3}
expWHOPM2.5yearly	Persons exposed to $PM_{2.5}$ concentrations > WHO yearly limit value	yearly	Pop * (Average > 10)	Persons	10 μg m^{-3}
expWHOPM10yearly	Persons exposed to PM_{10} concentrations > WHO yearly limit value	yearly	Pop * (Average > 20)	Persons	20 μg m^{-3}
expWHONO2yearly	Persons exposed to NO_2 concentrations > WHO yearly limit value	yearly	Pop * (Average > 40)	persons	40 μg m^{-3}

Calculation caveats				
Interpretation caveats	*Spatial representation*	S2		
	Other caveats			
	Could be compared to			
	Could be used with			
Presentation		*Style*	*Colour*	*Default range*
	Map	P1	R5	0-1000
	Time Series	-		
Motivation	The number of people exposed to air pollution exceeding the air quality standards is often experienced as more intuitive than the concentration levels. The exposure information presented is used as part of the provided health impact indicators.			
Experience user				
References	Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 (summarized at http://ec.europa.eu/environment/air/quality/standards.htm) Gallego FJ 2010: A population density grid of the European Union. Population and Environment. 31, 460-473. WHO Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. ISBN 92 890 2192 6.			

Annual deaths due to NO_2 and $PM_{2.5}$ long-term exposure

Sector	Air quality, health
ID	mortNO2PM25yearly, mortO3yearly
Description	Number of deaths in age group 30+ associated with long-term exposure to urban background levels of $PM_{2.5}$ and NO_2. Relative risks based on recommendations from WHO HRAPIE Project (WHO, 2013b) regarding $PM_{2.5}$ and UK COMEAP (2015) regarding NO_2. Estimates are presented both separately and combined for both pollutants.
End users	Health authorities, environmental authorities, general public
Calculation method	High quality population data are primarily acquired each city (or country). Where no population data are available of sufficient spatial resolution, a 1 * 1 km^2 population grid disaggregated data is applied (Gallego 2010). Baseline mortality in age group 30+ for the city or region is used in combination with population exposure data for the city according to the HIA tool AirQ developed by WHO (2004), where the attributed mortality is calculated as $\Delta Y = (Y_0 * P) * (e^{\beta * X} - 1)$, where Y_0 is the baseline rate; P the number of exposed persons; β the exposure-response relationship (relative risk) and X the estimated mean exposure (with impact/above any assumed threshold). The data on baseline mortality are from national official sources (if possible) or from EHFAD (European Health for All Database) (WHO, 2016). When using EHFAD, average rates of crude non-standardised all-cause mortality rates for historical years and present time scenario years are calculated.

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
mortNO2PM25yearly	Mortality, all-cause, long-term NO_2 and $PM_{2.5}$ exposure	Yearly	See above	deaths per year		

Calculation caveats		
Interpretation caveats	*Spatial representation*	S2, S3
	Other caveats	
	Could be compared to	
	Could be used with	

Presentation		*Style*	*Colour*	*Default range*
	Map	P1	R5	0-5
	Time Series	-		

Motivation	It has long been recognized that particle concentrations correlate with mortality, both temporally (short-term fluctuations) and spatially based on mortality and survival (WHO 2003, WHO 2006a). Short-term effects are usually assumed to be included in the long-term impacts on mortality. Particles in ambient air (indicated by $PM_{2.5}$) are one of the major causes of preterm death in Europe, but also exposure to NO_2 and ozone has been associated with mortality. The WHO Review of evidence on health aspects of air pollution (REVIHAAP, WHO 2013a), concludes that recent long-term

studies are showing associations between PM and mortality at levels well below the current annual WHO air quality guideline level for $PM_{2.5}$ (10 µg m^{-3}). The WHO expert panel thus concluded that for Europe it is reasonable to use linear exposure-response functions, at least for particles and all-cause mortality, and to assume that any reduction in exposure will have benefits. The findings from REVIHAAP are used as a basis for the WHO Project Health risks of air pollution in Europe – HRAPIE (WHO 2013b). The conclusions from the HRAPIE project (Heroux et al. 2015) are implemented in cost-benefit calculations done by EMRC/IAASA for the European Union.

For the WHO HRAPIE impact assessment (WHO 2013b) for long-term exposure to $PM_{2.5}$ and all cause (natural) mortality in ages 30+ recommended use of exposure-response function from a meta-analysis of 13 cohort studies (Hoek et al. 2013). The RR for $PM_{2.5}$ from this meta-analysis was 1.062 (95% CI 1.040-1.083) per 10 µg m^{-3} is similar to the 1.06 per 10 µg m^{-3} increment of the annual average $PM_{2.5}$ of the American Cancer Society Cohort Study (Pope et al. 1995). This assumption (6% per 10 µg m^{-3}) has been used in many health impact assessments.

Although, different types of particles and reasoning explain the impacts on mortality (WHO 2007, WHO 2013a), the WHO REVIHAAP panel of experts consider current knowledge does not allow precise quantification of the health effects of PM emissions from different sources. Current risk assessment should consider particles of different: sizes, sources and composition, as equally hazardous to health (WHO 2007). Practice has treated both PM_{10} and fine fraction $PM_{2.5}$ (quite often considered to be more detrimental to health than the coarse fraction of PM_{10}) as being equally toxic by mass, irrespective of the origin. Thus, commonly exposure-response functions obtained using urban background $PM_{2.5}$ as the exposure indicator are converted to be used for PM_{10} through a factor based on their mass relation. In the new impact assessment HRAPIE no such conversion is recommended for PM_{10} and mortality.

Different types of PM have been assumed to influence mortality differently; e.g., ExternE3 (2005) includes assumptions about the toxicity of other different types of PM. This reflects results that indicate a higher toxicity of combustion particles, especially from internal combustion engines. They treat nitrates as equivalent to half the toxicity of $PM_{10,}$ sulphates as equivalent to $PM_{10,}$ primary particles from power stations as equivalent to $PM_{10,}$ and primary particles from vehicles as equivalent to 1.5 the toxicity of $PM_{2.5}$.

Effects of combustion-related particles have been studied using black smoke, black carbon (BC) or elemental carbon (EC) as the exposure variable. REVIHAAP (WHO 2013a) recommended that BC should be used as exposure variable in more studies, but did not recommend it to be used for the HRAPIE impact calculations (WHO 2013b).

A review of mortality and long-term exposure to the combustion-related particle indicators (Hoek et al. 2013) used different methods. Their relation and conversion factors have been described before (Janssen et al. 2011). All-cause mortality was significantly associated with EC, the meta-analysis resulted in a (relative risk) RR of 1.061 per 1 µg m^{-3} EC (95% CI 1.049-1.073), with highly non-significant heterogeneity of effect estimates. Most of studies assessed EC exposure without accounting for small-scale variation related to proximity to major roads. These results suggest that using the common RR for long-term exposure to $PM_{2.5}$ and mortality, may lead to an underestimation of impacts of particle mass from motor vehicle exhaust.

However, the REVIHAAP report concludes more studies have now been published showing associations between long-term exposure to NO_2 and mortality (WHO 2013a). This observation makes it more complicated for impact assessments from vehicle exhaust particles as the close correlation between long-term concentrations of NO_2 and exhaust particles make it difficult to separate the effects without measuring EC instead of $PM_{2.5}$.

The potential confounding problem of effects from NO_2 and $PM_{2.5}$ on mortality was the focus of 19 epidemiological long-term studies of mortality using both pollutants as exposure variable reviewed by Faustini et al. (2014). Studies with bi-pollutant analyses ($PM_{2.5}$ and NO_2) in the same models showed decrease in the effect estimates of NO_2, but still suggest partly independent effects. The greatest effect on natural or total mortality was observed in Europe for both NO_2 and $PM_{2.5}$. In Europe, there was a 7% increase in total mortality for both NO_2 and fine particles, the RR for NO_2 was 1.066 (95% CI 1.029-1.104) per 10 µg m^{-3} and RR for $PM_{2.5}$ was 1.071 (95% CI 1.021-1.124) per 10 µg m^{-3}.

After judging evidence (and introduction of a group B with more uncertainty), the HRAPIE project recommend to calculate a long-term effect on mortality of NO_2 in the age category 30+, added to the impacts estimated using the common RR associated with all $PM_{2.5}$ (WHO 2013b). HRAPIE recommend to calculate this impact over the annual mean 20 µg m^{-3}, applying a RR of 1.055 (95% CI 1.031-1.08) per 10 µg m^{-3} based on a meta-analysis of 11 studies (Hoek et al. 2013).

COMEAP (2015, UK Committee on the Medical Effects of Air Pollutants) provide interim recommendations on how to estimate the mortality effects associated with long-term average concentrations of NO_2 in UK using a RR of 1.025 (1.01-1.04) per 10 µg m^{-3} without any threshold (cut-off level). In addition, COMEAP discuss that it is possible that this RR should be reduced by up to 33% when impacts associated with $PM_{2.5}$ are added to the estimates for NO_2.

Experience user

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Annual deaths due to ozone short-term exposure

Sector	Air quality, health
ID	*mortO3y, mortO3ynorm*
Description	Annual number of preterm deaths due to ozone short-term exposure, in all ages and from all causes
End users	Health authorities, environmental authorities, general public
Calculation method	To estimate exposure, a 1*1 km^2 population grid disaggregated using land use data is applied (Gallego, 2010). Data on baseline mortality is acquired from national official sources (if possible) or from EHFAD (European Health for All Database) (WHO, 2016). When using EHFAD, average rates of crude non-standardised all-cause mortality rates for historical years and present time scenario years are calculated. Baseline mortality for all ages for the city or region is used in combination with population exposure data for the city according to the HIA tool AirQ developed by WHO (2004), where the attributed mortality is calculated as $\Delta Y = (Y_0 * P) \times (e^{\beta * X} - 1)$, where Y_0 is the baseline rate; P the number of exposed persons; β the exposure-response relationship (relative risk) and X here becomes the estimated annual mean exposure above the SOMO threshold). Calculations will build on the WHO HRAPIE recommendation assuming a 2.9% increase (95% CI 1.4 – 4.3) per 10 µg m^{-3} increase in daily maximum 8-hour ozone and cutoff at 35 ppb (70 µg m^{-3}) (SOMO35).

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
mortO3y	Annual deaths due to O_3 short-term exposure	yearly	See above	Deaths per year		
mortO3ynorm	Annual deaths per 100,000 inhabitants due to O3 short-term exposure	yearly	Divided by population*100000	deaths/100,000 inhabitants		

Calculation caveats	
Interpretation caveats	*Spatial representation* *Other caveats* *Could be compared to* *Could be used with*

Presentation

	Style	*Colour*	*Default range*
Map	P1	R5	0-5
Time Series	-		

Motivation	The WHO REVIHAAP project argues that despite the many respiratory outcomes associated with O_3, mainly adverse health outcomes with known baseline rates are suited for health impact assessments. Evidence from time-series studies of short-term exposure to O_3 suggest that health impact assessment calculations can be undertaken for a range of end-points, including all-age, all-cause mortality (WHO 2013a). There is still scientific debate whether the

effects on mortality of long-term exposure to O_3 are well enough documented to be included in health impact assessments.

Multi-pollutant models in the largest European study of short-term exposure (APHEA2) reported short-term exposure increases total mortality by approx. 0.3% per 10 µg m^{-3} using the daily 8-h or 1-h maximum, in a linear manner without a significant threshold (Gryparis et al. 2004). A WHO meta-analysis for the AQ guidelines (2003) reported a relative risk of 0.3% per 10 µg m^{-3} increase with the 95% (CI 0.1–0.4%) which we see as a robust exposure–response assumption to apply.

WHO REVIHHAP conclude that the epidemiological evidence supports calculations that use all-year coefficients for daily maximum 8-h O_3 (scaled from the 1-h measures reported in the literature), including adjustment for PM_{10}. It is also recommended that health impact calculations for short-term exposures assume linear concentration–response relationships. Since the epidemiological evidence on linearity does not extend down to zero, appropriate cut-off points for health impact assessments are therefore recommended: at 10 ppb (20 µg m^{-3}) for daily maximum 8-h O_3 and at 35 ppb (70 µg m^{-3}), for consistency with previous work using SOMO35 data (WHO 2013).

Given the uncertainties in the effects of long-term exposure to O_3 (see the REVIHAAP report) it was suggested that health impact assessments for long-term exposure and respiratory and cardiopulmonary mortality are undertaken as a sensitivity scenario. It is recommended the coefficients from single pollutant models from the American Cancer Society cohort study (Jerrett et al. 2009) are used, assuming an association exists within the range of O_3 concentrations studied.

The WHO HRAPIE Project recommended use of a meta-coefficient from The APHENA Study (results from 32 European cities) of a 2.9% increase (95% CI 1.4 – 4.3) per 10 µg m^{-3} increase in daily maximum 8-h O_3 (Katsouyanni et al. 2009) and cutoff at 35 ppb (SOMO60) as well as at 10 ppb (WHO 2013b).

Experience user

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Annual heat-related deaths

Sector	Health
ID	*Heatdeaths, heatdeathsnorm*
Description	Number of deaths associated with temperatures above the 75th percentile of daily mean temperature during summer months (Apr-Sep). Relative risks extracted from a European multi-city study (de' Donato et al. 2015) are used to describe the effect of high temperatures on mortality.
End users	Health authorities, environmental authorities, general public
Calculation method	emperature 75th percentile is calculated from Harmonie model output at the location of an official weather station and then used in the evaluation of each grid cell. The determination of the temperature 75th percentile is made separately for the historical period and for the present window of the climate scenario (for the future window of the climate scenario, the same temperature 75th percentile as calculated in the present window is used). The evaluation period for health impacts of temperatures above the 75th percentile is the full year (this since for the future climate scenario there are temperatures above the thresholds also outside the period Apr-Sep). Relative risks (RR) are recalculated to represent the risk associated with a 1°C increase in daily mean temperature. These risk coefficients were aggregated to two regions (Southern and Northern Europe) as well as the mean for Europe. Thus, each city must be classified as belonging to one of these groups. Population data have been obtained for each city, region or country. For Stockholm national data for 2012, with a spatial resolution of 100×100 m^2, have been obtained from Swedish statistics. For Bologna and Amsterdam/Rotterdam, a 1 * 1 km^2 population grid disaggregated data has been applied (Gallego 2010). Data on baseline mortality are acquired from national official sources (if possible) or from EHFAD (European Health for All Database) (WHO, 2016). When using EHFAD, average rates of crude non-standardised all-cause mortality rates for historical time-period and present time scenario years are calculated. The estimated number of deaths are calculated as $\Delta Y = (Y_0 * P) * (RR * T_{dd})$ where Y_0 is the baseline rate; P the number of exposed persons; RR the relative risk associated with a 1°C increase in temperature above the 75th percentile and T_{dd} is the number of degree days above the 75th percentile. he RR is scaled so that the total number of extra deaths for the entire city is equal to the number of deaths you would get if you used the daily temperatures from the location of the weather station for all the city population. This means that for present climate Urban SIS will just distribute spatially the impact to be stronger in more heated urban areas and lower in colder areas of the city. The scaling and the determination of the 75th percentile determined for the present climate is maintained for the future climate, thus allowing raising temperatures in the future to give a stronger health impact.

	Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
	heatdeaths	Annual heat-related deaths	Yearly	See above	Deaths/year	75^{th} percentile at position of an official weather station	Requires population data
	heatdeathsnorm	Annual heat-related deaths per 100,000 inhabitants	Yearly	Divided by population*100000	Deaths/(year *100,00 inhabitants)	75^{th} percentile at position of an official weather station	

Calculation caveats			
Interpretation caveats	*Spatial representation*		
	Other caveats	O1, O2	
	Could be compared to		
	Could be used with		
Presentation		*Style*	*Colour*
	Map	P1	R5
	Time Series	-	

Motivation

Derivation of risk estimates

Given the many studies showing a connection between high ambient temperatures and health, it is undisputable. However, scientific consensus as to the best climatological metric to describe or explain the connection between heat and health is missing. Studies use daily mean, maximum and minimum temperature (e.g. Medina-Ramon et al. 2006, de' Donato et al. 2015, Oudin et al. 2016) or a combination (Rocklov et al. 2011) to describe the temperature mortality relationship. Many combine temperature with humidity, given the human body's inability to cool in humid conditions but again the metrics differ (e.g. HUMIDEX, THOM index and apparent temperature). Although different temperature metrics are used to get the "best" predictor few evaluate the metric or the implications of the choice.

Barnett et al. (2010) consider a range of metrics (mean, minimum and maximum temperature with and without humidity, apparent temperature and HUMIDEX) with mortality but found none to be consistently the best predictor. They conclude the modelling method can be of greater importance than the metric itself and therefore the choice should be based on practical constraints. Similarly, Foroni et al. (2007) found the choice of Thom index if based on the maximum temperature or mean and maximum Thom wasn't critical.

Temperature mortality impact has been studied in a range of cities across Europe. However, Hajat and Kosatky's (2010) review found only Baccini et al. (2008) had multiple (15) European cities (e.g. Stockholm and Helsinki in the north and Athens and Valencia in the south). Baccini et al. (2008) established temperature thresholds for each city and a change in mortality for per degree increase above that threshold. These range from 1.84% K^{-1} (north-continental) to 3.12% K^{-1} in the Mediterranean region. However, the temperature thresholds in each city have different percentiles making it hard to generalize or extrapolate from, so unsuitable for this project.

Fortunately, newer studies have addressed multiple European cities. Guo et al. (2014) analysed 306 communities in 12 countries (e.g., Spain, Italy and United Kingdom). They conclude that Italy and Spain have higher temperature mortality risks than other countries based on accumulated risk over a 21-day lag of daily mean temperatures. Similarly, with Sweden (Stockholm) also included, an analysis of deaths attributable to the warm and cold season Gasparrini et al. (2015) found the lowest mortality was in the 80-90th percentile of annual mean temperatures for communities in a temperate region.

The health effects from high temperatures in 9 European cities across a wide geographical distribution using daily mean temperature were considered using cumulative risk over 40 days (de' Donato et al. 2015). The risk ratio (RR) used was the difference in risk for days with temperatures at the 75th percentile of summer temperatures compared to the 99th percentile. This use of relative increases in temperature to estimate the health effects makes the results more comparable between cities and easier to extrapolate beyond the study cities. The study controlled for factors such as barometric pressure, wind speed and NO_2 as confounders. The risks were estimated for two time periods to assess the possible effects of the 2003 heatwave. Here, the later period is used.

de' Donato et al. (2015) risks range from an 11% increase in mortality in Paris to a 35% increase in Athens. As these are associated with a relative increase in mortality comparison with similar studies is hard. If a linear increase in mortality between the 75^{th} and 99^{th} percentile is assumed, the increase per 1 K is from 1.7% (Paris) to 7.9% (Barcelona (mean increase of 4.6% all cities) is similar to previous studies of European cities.

If Europe is divided into two (North and South) a risk increase per 1 K above the 75th percentile based on the areal mean based on the similarity in estimated risks for the cities in the suggested regions (rather than geographical location *per se*). The suggested relative risks associated with 1 K increase above the 75^{th} percentile are:

Region	RR (range within region)
Europe	4.6% (1.7%-7.9%)
Northern	2.5% (1.7% – 3.5%)
Southern	6.2% (4.7% - 7.9%)

Using these RR for the **future scenario assumes no adaption.** Whereas, it is reasonable to expect individuals and populations will over time adapt to a changing climate. Temperature mortality relationships for a specific location change with adaptation, changes in population mortality rates or changing prevalence of chronic diseases, amongst other factors.

Adaptation over time to regional temperatures has been observed using historical registers for the 20th century. For Europe, declining vulnerability to heat, and cold, are observed in Germany (Lerchl, 1998), London, UK (Carson et al. 2006), Zeeland, The Netherlands (Ekamper et al. 2009) and Stockholm, Sweden (Astrom et al. 2013). Contributing factors include: medical and technological advances, demographical and epidemiological changes, improvements in the public health and health care sectors, improvements in housing standards with increased use of air conditioners and central heating. Individual physiological adaptation to higher than normal temperatures may occur through increased sweating and improved cardiovascular capacity (Parsons 2002). Furthermore, behavioural changes among population may alter the temperature mortality relationship as people may actively take measures to avoiding the heat when extremes occur. These relationships can change within a summer, with the impact of heat being higher earlier in summer than later (Gasparrini et al. 2016).

Impacts of heat and cold are regional, with heat-related mortality occurring at higher temperatures in warmer regions (Anderson and Bell 2009). Reduced vulnerability to heat before and after the 2003 heat wave was found in most cities but in northern cities (e.g. Stockholm, Helsinki) heat vulnerability increased (de'Donato et al. 2015).

Demographic change can be a driver of changing impacts on population health (Huang et al. 2011). The expected increase in elderly and other potentially vulnerable groups could make temperature extremes impact on human health more severe (Sierra et al. 2009), as the elderly and chronically ill are more vulnerable to high temperature (Basu 2009, Oudin Åström et al. 2011, Åström et al. 2015). Changing prevalence of chronic diseases (e.g. diabetes and Chronic Obstructive Pulmonary Disease (COPD)) and (in and out) migration must be considered. For example, in Italy the region of birth has been associated with heat sensitivity in adulthood (Vigotti et al. 2006).

Future winter mortality may modify the impacts on future summer mortality. High winter mortality reduces the effect of high temperatures the following summer in Stockholm (Rocklöv et al. 2009) and in warmer climates (Stafoggia et al. 2009). The mechanism may be that an increasing mortality during winter depletes the susceptible individuals pool who are most vulnerable to summer heat. Ebi and Mills (2013) suggest winter mortality rates are unlikely to decrease significantly.

Future heat waves may also be more intense and have longer duration (Field 2012). There may be increasing risks for more extreme heat waves but no increase in cold spells (Barnett et al. 2012). Gasparrini and Armstrong (2011) separate the risk during elevated temperature into a main effect due to the daily high temperatures and the added effect of the duration of the heat wave. The latter, found to occur after 4-days, was rather small compared to the main effect (Gasparrini and Armstrong 2011).

Todd and Valeron (2015) and Oudin Åström et al. (2016) reported that the minimum mortality temperatures were increasing over time in France and Sweden. This suggests that using a <u>fixed</u> percentile of current or future temperature distribution may be inappropriate.

Observed changes over time of the temperature mortality relationship as well as changes in population demographics, prevalence of chronic disease with a changing climate indicates estimating impacts of extreme temperatures on mortality is highly complex. Although it may be inappropriate to assume present relationships are representative of future responses at the European scale it may be necessary, as a limit to adaptation may exist among European countries that have recently experienced reduced risks and increased awareness in the northern

	regions, may reduce the risk in the future.
Experience user	
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Degree days

Sector	Energy, Agriculture
ID	*Heatingdegreedays, coolingdegreedays, degreedays*
Description	Heating (cooling) degree days [HDD (CDD)] are a measure to estimate energy demand for heating (cooling) building interiors. The indicator is calculated based on accumulated difference between outdoor air temperatures below (above) some reference base temperature (T_b).
End users	Energy companies, people working with evaluations of energy consumption, property owners
Calculation method	*For HDD, when hourly T_{air}<T_b:* $HDD_{Annual} = \sum_{d=1}^{365} HDD_D$, *where daily* $HDD_D = \frac{\sum_{j=1}^{24}(T_b - T_{air,j})}{24}$ *For CDD, when hourly T_{air}>T_b:* $CDD_{Annual} = \sum_{d=1}^{365} CDD_D$, *where daily* $CDD_D = \frac{\sum_{j=1}^{24}(T_{air,j} - T_b)}{24}$ (Formulae reference, Day 2006)

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
heatingdegreedays	Heating degree days	yearly	Based on hourly T_{air} values	°C day	*17*	Threshold used extensively by SMHI for Stockholm.
coolingdegreedays	Cooling degree days	yearly	Based on hourly T_{air} values	°C day	*20*	Threshold used extensively SMHI for Stockholm.
degreedays	Degree days	yearly	Effects on agriculture and also green areas in cities during heat waves	°C day		

Calculation caveats	O4
Interpretation caveats	*Spatial representation* S1 *Other caveats* O4 *Could be compared to* *Could be used with*
Presentation	*Style* / *Colour* *Map*: P1 / R1, R6 *Time Series*: P2
Motivation	HDD (CDD) provides a metric to estimate energy demand for building heating (cooling) (Christenson et al. 2006) and HDD are also correlated with local greenhouse gas emissions (Christen et al. 2011). HDD and CDD indicators can be used as inputs to estimate energy demand spatial variability for building heating and cooling. HDD and CDD indicators are provided on annual timescales for each grid cell, thus inter-annual variability or sub-annual trends cannot be assessed. Additional uncertainty arises from choice of threshold used to calculate HDD (CDD). This threshold is variable between countries and regions; for example HDD thresholds vary

	between 8-12° C in Switzerland (Christenson et al. 2006) and 14° C in Greece (Matzarakis 2004). In this calculation, T_b = 17 °C for HDD and T_b = 20 °C for CDD, is based on values used in Stockholm by SMHI. Degree days provide a proxy for energy demand, however in reality building energy consumption is also influenced by other variables such as occupant behaviour, building design, and type of heating/cooling system.
Experience user	Ideally calculated using appropriate threshold for area of interest.
References	Christenson M, H Manz, D Gyalistras 2006: Climate warming impact on degree-days and building energy demand in Switzerland. Energy Conversion and Management 47:6, 671-686. Christen A et al. 2011: Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements. Atmospheric Environment 45:33, 6057-6069. Day T 2006: Degree-days: theory and application, The Chartered Institution of Building Services Engineers, TM41: http://www.degreedaysforfree.co.uk/pdf/TM41.pdf, Accessed 18 October 2016. European Environment Agency 2012: http://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-1, Accessed 18 October 2016. Matzarakis A, C Balafoutis 2004: Heating degree‐days over Greece as an index of energy consumption. International Journal of Climatology 24:14, 1817-1828.

Discharge

Sector	Infrastructure
ID	*monthmaxdis, monthmindis*
Description	Monthly maximum and minimum discharge which includes contributions from upstream basins (if any).
End user	Base indicator for hydrological applications including water balance calculations, flood risk assessment, etc.

Calculation method

ID	*Title*	*Period*	*Statistical Processing*	*Unit*	*Threshold*	*Comment*
monthmaxdis	Maximum discharge in each month (annual cycle)	Monthly	Maximum discharge per month	m³/s	-	
monthmindis	Minimum discharge in each month (annual cycle)	Monthly	Minimum discharge per month	m³/s		

Calculation caveats

Interpretation caveats

Spatial representation:	S5
Could be compared to:	C3
Could be used with:	U4

Presentation

	Style	*Colour*	*Range*
Map	P7	R11	0 to range based on analysis of data
Time Series	P8		

Motivation	Fundamental indicator for flood risk and water resource management
Experience user	Of use for many additional applications
References	

Drought

Sector	Infrastructure
ID	*maxdroughtduration*
Description	Maximum number of days where the soil is dryer than a specific threshold.
End users	Managers of water resources, agriculture or green infrastructure.

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
maxdroughtduration	Drought duration	Yearly	Longest period (consecutive days) where the soil moisture is below the threshold	days	20% percentile	

Calculation caveats

Interpretation caveats

Spatial representation:	S6
Could be compared to:	C7
Could be used with:	U4

Presentation

	Style	*Colour*	*Range*
Map	P1, P3	R12	0 to range based on analysis of data

Motivation	Fundamental indicator for water resource management.
Experience user	Of use for many additional applications

References

Roudier P, Andersson JCM, Donnelly C, Feyen L, Greuell W, Ludwig F 2015: Projections of future floods and hydrological droughts in Europe under a +2°C global warming. Climatic Change, 135, 341-355 doi: 10.1007/s10584-015-1570-4.

Frost days

Sector	infrastructure and transport, Agriculture, Green infrastructure
ID	*frostdays*
Description	Number of days with daily minimum temperature below 0 °C.
End users	Agricultural sector, general public
Calculation method	*Id*: frostdays; *Title*: Frost days; *Period*: Yearly; *Statistical processing*: Number of days with daily minimum temperature less than 0°C.; *Unit*: days; *Threshold*: frostdays; *Comment*: Frost days
Calculation caveats	
Interpretation caveats	*Spatial representation*: S1 *Other caveats*: *Could be compared to*: *Could be used with*:
Presentation	*Map*: Style P1, Colour R7 *Time Series*: -
Motivation	Number of frost days provides a risk estimate for risk of frost damage to crops.
Experience user	
References	

Growing season length

Sector	Agriculture, green infrastructure
ID	*leafon, leafoff, GSL, GDD*
Description	Leaf-on (leaf-off) is the date of onset (offset) of deciduous vegetation greenness. The dates refer to the aggregate phenology of ecosystem-scale understory and overstory conditions. Growing season length (GSL) describes the number of days the deciduous vegetation is active and no freezing conditions are encountered (i.e. frost free days). These variables are important for agricultural applications as well as determining ecosystem services, functionality, and health of 'green' urban infrastructure (e.g. hydrologic and carbon related processes associated with urban vegetation, green roofs, and green walls).
End users	Urban planners, agricultural sector, landscape architects, gardeners
Calculation method	Growing season length (GSL) is calculated as the number of days between the first 5-day period with average temperatures above 5°C (leaf-on date) to the first 5-day period with temperatures below 5°C (leaf-off date) (Buitenwerf et al, 2015; Donat et al, 2013; Mueller et al, 2015).

Id	Title	Period	Statistical processing	Unit	Threshold	Comment
Leafon	Leaf on date	Yearly	Day corresponding to the end of the first 5-day period with average temperatures above or equal to 5°C	Day of year		Interpreted as leaf emergence
Leafoff	Leaf off date	Yearly	Day corresponding to the end of the first 5-day period with temperatures below or equal to 5°C	Day of year		Interpreted as beginning of autumn senescence
GSL	Growing season length	Yearly	*Leafoff – leafon*	Number of days		Interpreted as number of days between leaf-on and leaf-off dates

Calculation caveats	O4	
Interpretation caveats	*Spatial representation*	S1
	Other caveats	O3, O4 (thresholds also vary by vegetation

		species)	
	Could be compared to		
	Could be used with		
Presentation		*Style*	*Colour*
	Map	P1	R8
	Time Series	P2	
Motivation	Growing season length (GLS) has been shown to increase by 4-6 days for every 1 K increase in annual average air temperature (White et al. 1999). GSL is an important variable determining carbon assimilation and evapotranspiration from vegetation and soils (Euskirchen et al. 2006). GSL is also an important constraint on agricultural productivity, particularly in northern Europe (Olesen et al. 2002). There is a high degree of interannual variability in growing season length (GSL). Modelled GSL based on air temperature, soil moisture, and solar radiation in North America during the 20th century show a high degree of interannual variability (±15 days), primarily due to variations in air temperature.		
Experience user			
References	Buitenwerf R, L Rose, SI Higgins 2015: Three decades of multi-dimensional change in global leaf phenology. Nature Climate Change 5, 364-368. Donat MG et al. 2013: Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research: Atmospheres 118, 2098–2118. Euskirchen ES et al. 2006: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high - latitude ecosystems. Global Change Biology 12.4 (2006): 731-750. Mueller B et al. 2015: Lengthening of the growing season in wheat and maize producing regions. Weather and Climate Extremes 9, 47–56. Olesen JE, M Bindi 2002: Consequences of climate change for European agricultural productivity, land use and policy. European journal of agronomy 16:4, 239-262. White MA, SW Running, PE Thornton 1999: The impact of growing-season length variability on carbon assimilation and evapotranspiration over 88 years in the eastern US deciduous forest. International Journal of Biometeorology 42:3, 139-145.		

Heat wave duration

Sector	Heat stress and human discomfort
ID	*heatwaveduration*
Description	Heat waves are characterized as periods of sustained, extreme heat, although there is no universal definition of a heat wave. For this application, a heat wave is defined according to Meehl and Tebaldi (2004) based on daily maximum air temperature (T_{max}) and two percentile thresholds (*T1* and *T2*) from the distribution of daily T_{max} during the reference scenario period.
End users	General public, health authorities, urban planners
Calculation method	A heat wave is defined as a period of consecutive days that satisfy the following conditions: i) Daily T_{max} is above *T1* for at least three days, ii) the average T_{max} is above *T1* over the entire period, and iii) the daily T_{max} must be above *T2* every day of the period (the total heat wave period must be greater than or equal to 3 days). Here, *T1*=97.5th percentile and *T2*=81st percentile, following Meehl and Tebaldi (2004). The T1 and T2 percentiles are calculated from Harmonie model output at the location of an official weather station, both for the historical period and for the present window of the climate scenario. For the future window of the climate scenario, the same T1 and T2 percentiles as calculated in the present window are used.

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
heatwaveduration	Hot period duration	Yearly	Maximum number of consecutive days when: i) Daily T_{max} is above *T1* for at least three days, ii) the average T_{max} is above *T1* over the entire period, and iii) the daily T_{max} must be above *T2* every day of the period (the total heat wave period may be longer than three days).	days	*T1* = 97.5th percentile *T2* = 81st percentile	

Calculation caveats	O4

Interpretation caveats

Spatial representation	
Other caveats	O3, O4
Could be compared to	
Could be used with	

Presentation

	Style	*Colour*
Map	P1	R5
Time Series	-	

Motivation	Both duration and frequency of heat waves may increase in Europe (Perkins et al. 2011). The provided indicator can give planners a hint of changes to expect in their city. The selected method (Meehl and Tebaldi 2004) provides information about heat wave duration.
Experience user	Many methods to define a heatwave (Souch and Grimmond 2004, Perkins 2015).
References	Meehl GA, C Tebaldi 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305.5686, 994-997.

Perkins SE, Alexander LV, Nairn JR 2012: Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophysical research letters. 39:20

Perkins SE 2015: A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale. Atmospheric Research, 164, 242-267.

Souch C, CSB Grimmond 2004: Applied Climatology: Heat Waves. Progress in Physical Geography, 28, 599-606. **doi:** 10.1191/0309133304pp428pr

Hot days per year

Sector	heat stress & human discomfort
ID	*Hotdays*
Description	Number of days per year with a mean air temperature at 2 m above ground above the 75th percentile during summer months (Apr-Sep).
End users	Health authorities, environmental authorities, general public
Calculation method	Temperature 75th percentile is calculated from Harmonie model output during Apr-Sep at the location of an official weather station in the city and then used in the evaluation of each grid cell. The temperature 75th percentile is calculated separately for the historic period and for the present window of the climate scenario (the latter temperature threshold is used also for the future window of the climate scenario). Once the temperature 75th percentile is determined, the evaluation over the grid will performed for the whole year (this since it was observed that for the future climate scenario there are hot days outside the Apr-Sep period).

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
hotdays	Hot days > 75th percentile	Yearly	Number of days with mean temp > 75th daily percentile.	days		Percentile based on summer temperatures (Apr-Sep)

Calculation caveats		
Interpretation caveats	*Spatial representation*	
	Other caveats	O3, O6
	Could be compared to	
	Could be used with	

Presentation		*Style*	*Colour*	*Default range*
	Map	P1	R5	0-30
	Time Series	-		

Motivation	To be consistent with health impact calculations, the threshold that has been chosen to identify a hot day is the 75th percentile of daily mean temperature during summer (Apr-Sep). The term hot days has been chosen instead of the more commonly used heat-wave days since we focus on events that happen many times every year. The commonly used term heat wave is usually defined as a more extreme event.
Experience user	
References	

Ice days

Sector	Infrastructure and transport
ID	*icedays*
Description	Number of days per year with daily maximum temperature less than 0°C
End users	National road administrations, agricultural sector
Calculation method	see below
Calculation caveats	
Interpretation caveats	see below
Presentation	see below
Motivation	Cold conditions affect a large number of activities and sectors, including built infrastructure and agriculture.
Experience user	
References	

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
icedays	Ice days	yearly	Number of days with daily maximum temperature less than 0°C	days		

Interpretation caveats

Spatial representation	S1
Other caveats	
Could be compared to	
Could be used with	

Presentation

	Style	*Colour*	*Default range*
Map	P1	R7	0-30
Time Series	-		

Local runoff

Sector	Infrastructure
ID	*monthmaxrunoff, monthminrunoff*
Description	Monthly maximum and minimum local runoff. The total runoff generated inside a sub-basin and transported to the draining river or stream.
End user	Urban planners, hydrologists, civil engineers

Calculation method

ID	*Title*	*Period*	*Statistical Processing*	*Unit*	*Threshold*	*Comment*
monthmaxrunoff	Maximum local runoff in each month (annual cycle)	Monthly	Maximum local runoff per month	mm h^{-1}	-	
monthminrunoff	Minimum local runoff in each month (annual cycle)	Monthly	Minimum local runoff per month	mm h^{-1}		

Calculation caveats

Interpretation caveats

Spatial representation:	S6
Could be compared to:	C3
Could be used with:	U4

Presentation

	Style	*Colour*	*Range*
Map	P1, P3	R11	0 to range based on analysis of data
Time Series	P2		

Motivation	Fundamental indicator for flood risk and water resource management. A base indicator for hydrological applications including water balance calculations, flood risk assessment, etc.
Experience user	Of use for many additional applications
References	

Short-duration extreme precipitation

Sector	Infrastructure
ID	*maxprec*
Description	Statistical characterization of extreme short-duration precipitation
End users	water services, city planners and consultants dealing with design and management of infrastructure sensitive to pluvial flooding.

Calculation method	*Id*	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
	maxprec	Maximum precipitation intensity	Selected accumulation periods (AP) from 15 min to 24 h	Find the maximum value for each AP in each month during the 5-year period, calculate 5-year averages	mm AP^{-1}		

Calculation caveats		
Interpretation caveats	*Spatial representation*	S6 (grid cell average value)
	Other caveats	
	Could be compared to	C5 (high-resolution precipitation observations)
	Could be used with	U4 (flood risk assessment)

Presentation		*Style*	*Colour*	*Range*
	Map	P1	R11	R11 (adjusted)

Motivation	To evaluate any spatial dependencies in precipitation extremes, caused by e.g. topography or urbanization.
Experience user	
References	Frei C, R Schöll, S Fukutome, J Schmidli, PL Vidale 2006: Future change of precipitation extremes in Europe: Intercomparison of scenarios from regional climate models, J. Geophys. Res., 111, D06105, doi:10.1029/2005JD005965.

Short-duration extreme precipitation intensity/duration

Sector	Infrastructure
ID	intdurfreq, arearedfac
Description	Statistical characterization of extreme short-duration precipitation
End users	water services, city planners and consultants dealing with design and management of infrastructure sensitive to pluvial flooding.

Calculation method

Id	Title	Period	Statistical processing	Unit	Threshold	Comment
intdurfreq	Intensity-Duration-Frequency (IDF) curve	Selected accumulation periods (AP) from 15 min to 24 h	For each AP, find the threshold that is exceeded (e.g.) 30 times in the 5-year period, fit a Generalized Pareto (GP) distribution to the 30 extremes, estimate intensities for return periods between (e.g.) 1 and 10 years → IDF-curves	mm AP^{-1}		
arearedfac	Areal Reduction Factors (ARFs)	Selected accumulation periods (AP) from 15 min to 24 h	As intdurfreq above but for spatial averages between 9 km^2 (3×3 grid cells) and (e.g.) 2500 km^2 (50×50 grid cells), then take the ratio between corresponding IDF-values → ARFs	-		

Calculation caveats	*It needs to be confirmed that the GP distribution is generally applicable.*

Interpretation caveats

Spatial representation	S4
Other caveats	
Could be compared to	C5, C6
Could be used with	U4 (flood models)

Presentation

	Style	*Id*	*Colour*
Distribution curve	P9	ntdurfreq	
Distribution curve	P10	arearedfac	

Motivation	*These indices represent the type of information on short-duration rainfall extremes used in urban hydrological analysis and design.*
Experience user	
References	Maidment DR (Ed.) 1993: Handbook of hydrology. New York, McGraw-Hill.

Soil Temperature

Sector	Agriculture, green infrastructure
ID	*Soiltemp*
Description	Soil temperature is the average temperature of urban soils at 10 cm depth. This is important for urban vegetation activity and soil microbial activity which controls soil carbon respiration (Kaye et al. 2005, Crawford et al. 2011).
End users	Urban planners, landscape architects, agricultural sector, gardeners

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
soiltemp	Soil temperature	Monthly	Average monthly soil temperature	°C		

Calculation caveats	Soil temperature is dependent on soil thermal properties, moisture, and soil composition (Dudhia 1996).

Interpretation caveats

Spatial representation	S1, S4
Other caveats	
Could be compared to	
Could be used with	

Presentation

	Style	*Colour*
Map	P1	R1/2
Time Series	P2,P3	

Motivation	This is an important variable for plant and agricultural growth and health as well as carbon cycling processes by vegetation and soils (Kaye 2005, Crawford 2011).
Experience user	

References

Crawford B, CSB Grimmond, A Christen 2011: Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area. Atmospheric Environment 45:4, 896-905.

Dudhia J 1996: A multi-layer soil temperature model for MM5. Preprints, The Sixth PSU/NCAR mesoscale model users' workshop.

Kaye JP, RL McCulley, IC Burke 2005: Carbon fluxes, nitrogen cycling, and soil microbial communities in adjacent urban, native and agricultural ecosystems. Global Change Biology 11:4, 575-587.

Solar insolation

Sector	Agriculture, green infrastructure, energy
ID	*shortwave*
Description	Solar insolation (*shortwave*) is the amount of energy received at the surface from sunlight (W m^{-2}) from both direct and diffuse shortwave radiation on a flat, horizontal surface at mean roof level.
End users	Building engineers, architects, urban planners, solar energy sector

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
shortwave	Shortwave solar insolation	Average monthly values for modelling period	Average monthly total energy	MJ m^{-2} $month^{-1}$		

Calculation caveats

Interpretation caveats

Spatial representation	S1, S4
Other caveats	
Could be compared to	
Could be used with	U5

Presentation

	Style	*Colour*
Map		
Time Series	P2	

Motivation	Important variable for plant and agricultural health and performance and building energy applications (e.g. solar energy resource potential, influencing energy demand for buildings).
Experience user	

References

Lindberg F et al. 2015: Solar energy on building envelopes–3D modelling in a 2D environment. Solar Energy 115, 369-378.

Loutzenhiser PG et al. 2007: Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. Solar Energy 81:2, 254-267.

Surface runoff

Sector	Infrastructure
ID	*monthmaxsrunoff, monthminsrunoff*
Description	Monthly maximum and minimum surface runoff, which refers to the fraction of the total runoff generated as overland flow, e.g. on impervious surfaces.
End user	Consultants, city water management

Calculation method

ID	*Title*	*Period*	*Statistical Processing*	*Unit*	*Threshold*	*Comment*
monthmaxsrunoff	Maximum surface runoff in each month (annual cycle)	Monthly	Maximum surface runoff per month	mm h^{-1}	-	
monthminsrunoff	Minimum surface runoff in each month (annual cycle)	Monthly	Minimum surface runoff per month	mm h^{-1}		

Calculation caveats

Interpretation caveats

Spatial representation:	S6
Could be compared to:	
Could be used with:	U4

Presentation

	Style	*Colour*	*Range*
Map	P1, P3	R11	0 to range based on analysis of data
Time Series	P2		

Motivation	Fundamental indicator for flood risk and water resource management. This has been measured in tailored measurement campaigns using specialized sensors but is not measured on a regular basis.
Experience user	Of use for many additional applications
References	

Snow cover indicators

Sector	Non-specific, transport, infrastructure, energy
ID	*ndayswithsnow, maxsnowcover*
Description	Snow cover
End users	E.g. road authorities and persons working with building construction

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
ndayswithsnow	Number of days (per year) with a snow cover > 1 cm	yearly	Calculating number of days per year meeting the criterion, averaging	-	1 cm	
maxsnowcover	Mean annual maximum snow cover depth	yearly	Finding each annual maximum, averaging	cm		

Calculation caveats

Interpretation caveats

Spatial representation	S2
Other caveats	
Could be compared to	
Could be used with	

Presentation

	Style	*Colour*
Map	P1	R11
Time Series	P3, P2	0 to range based on analysis of data

Motivation	Presence of snow has large consequences for many parts of society, the most direct maybe being maintenance of roads, runways etc. It is also a fundamental component of the hydrological cycle and affects runoff, river discharge, ground water formation etc.
Experience user	Of use for many additional applications
References	

Thom discomfort index

Sector	Health, human comfort
ID	*thomindex*
Description	Thom discomfort index is a physiological thermal stress indicator for people based on dry-bulb and wet-bulb temperature (Thom 1957, Epstein and Moran 2006).
End users	General public, Bologna
Calculation method	TDI = $0.5T_W + 0.5Ta$, where T_w is wet-bulb temperature and T_a is air temperature (Eq. 4, Epstein and Moran 2006). T_w can be calculated from air temperature and moisture information according to Stull (2011): $T_w = T\ \mathrm{atan}[0.151977(RH\% + 8.313659)^{1/2}] + \mathrm{atan}(T + RH\%) - \mathrm{atan}(RH\% - 1.676331) + 0.00391838(RH\%)^{3/2}\ \mathrm{atan}(0.023101RH\%) - 4.686035$ The highest hourly TDI value for each day is used to sum the number of days per year with TDI above 24 and 28, respectively.

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
thomindex	Thom discomfort index	Yearly	Number of days exceeding the defined thresholds (24 and 28 Thom index)	days		

Calculation caveats	O4
Interpretation caveats	*Spatial representation* S1 *Other caveats* O4 *Could be compared to* *Could be used with*

Presentation

	Style	*Colour*
Map	P1	R1
Time Series	P2, P6	

Motivation	Assessing thermal stress is important for worker health and safety, industrial productivity, and athletic performance. This heat stress index incorporates relevant meteorological variables related to physiological thermal stress into a single value. Many thermal stress indices have been developed since the early 1900s (see review and comparison by Epstein and Moran 2006). For example, the wet bulb globe temperature index (WBGT) developed by the U.S. Navy in 1957 has been used widely and adopted as an ISO standard (ISO 7243). The Thom index is selected for this work because it is highly correlated with the WBGT index and has the advantage of being technically easier to implement.
Experience user	See other metrics provided to compare underlying assumptiobs
References	Epstein Y, DS Moran 2006: Thermal comfort and the heat stress indices. Industrial health 44.3: 388-398.

Stull R 2011: Wet-bulb temperature from relative humitidy and air temperature. J Appl. Meteorology and climatoloy, 50, 2267-2269.
Thom EC 1959: The discomfort index. Weatherwise 12.2: 57-61.

Tropical nights

Sector	Heat stress and human comfort
ID	*tropicalnights*
Description	Tropical nights are nights when minimum 2 m air temperature remains greater than 20° C (e.g. Fischer and Schär 2010).
End users	General public
Calculation method	*Id* / *Title* / *Period* / *Statistical processing* / *Unit* / *Threshold* / *Comment* tropicalnights / Tropical nights / Yearly / Number of days with daily minimum temperature greater than 20°C. / nights / 20°C /
Calculation caveats	
Interpretation caveats	*Spatial representation* S1 *Other caveats* *Could be compared to* *Could be used with*
Presentation	*Style* / *Colour* / *Default range* *Map*: P1 / R5 / 0-30 *Time Series*: -
Motivation	This indicator has been shown, in combination with hot days (indicator id: *hotdays*), to explain temporal and spatial variance of excess mortality during recent European heatwaves (e.g. Fischer and Schär 2010). The temperature threshold used to identify a tropical night that is used follows EEA (2009). The indicator "Tropical nights" is meant as an intuitive way to present high temperatures occurrences for the public.
Experience user	
References	EEA Report No 5/2009. Ensuring quality of life in Europe's cities and towns – tackling the environmental challenges driven by European and global change. ISSN 1725-9177 Fischer EM, C Schär 2010: Consistent geographical patterns of changes in high-impact European heatwaves. Nature Geoscience 3.6: 398-403.

Universal Thermal Climate Index

Sector	Health, human comfort
ID	*utcindex*
Description	The UTCI is a thermal comfort indicator based on human heat balance models and designed to be applicable in all seasons and climates and for all spatial and temporal scales (Bröde et al. 2012). There are 10 UTCI thermal stress categories defined as follows: above +46: extreme heat stress; +38 to +46: very strong heat stress; +32 to +38: strong heat stress; +26 to +32: moderate heat stress; +9 to +26: no thermal stress; +9 to 0: slight cold stress; 0 to -13: moderate cold stress; -13 to -27: strong cold stress; -27 to -40: very strong cold stress; below -40: extreme cold stress.
End users	General public, health authorities Bologna
Calculation caveats	UTCI is calculated in the Town Energy Balance (TEB) model used during the downscaling of regional climate data in this project (Masson 2000).

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
UTCIsun	Universal Thermal Climate Index	hourly	hourly	°C		UTCI for a person in the sun
UTCIsun	Universal Thermal Climate Index	hourly	hourly	°C		UTCI for a person in the shadow

Interpretation caveats	*Spatial representation*	S1
	Other caveats	
	Could be compared to	
	Could be used with	

Presentation		*Style*	*Colour*
	Map	P1	R1
	Time Series	P2, P6	

Motivation	The UTCI is selected for this work (in addition to the Thom Discomfort Index) because it uses a human energy balance approach to account for heat exchange between humans and the surrounding atmosphere. This physiologically-based method is also incorporated and used in operational urban climate canopy models such as TEB (Masson, 2000).
Experience	

user	
References	Bröde P et al. 2012: Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). International journal of biometeorology 56:3, 481-494. Masson V 2000: A physically-based scheme for the urban energy budget in atmospheric models. Boundary-layer meteorology 94:3, 357-397.

Zero crossings

Sector	Infrastructure and transport
ID	*zerocrossings*
Description	Number of days with 2 m air temperatures on both sides of 0 °C.
End users	Nordic road administrations

Calculation method

Id	*Title*	*Period*	*Statistical processing*	*Unit*	*Threshold*	*Comment*
zerocrossings	Number of days on both sides of 0 °C	yearly	Days with temperatures on both side of zero (requires daily max and daily min temp).	days		Only evaluated during winter months.

Calculation caveats

Interpretation caveats

Spatial representation	S1
Other caveats	
Could be compared to	
Could be used with	

Presentation

	Style	*Colour*
Map	P1	R7
Time Series	-	

Motivation	When temperature often changes around 0 °C, it has consequences for winter road maintenance. Examples are thaw/freezing cycles affecting the road icing conditions, increasing the deterioration of road surfaces.
Experience user	
References	

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