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Global assessment of impacts on Energy

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Global assessment of impacts on Energy

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Executive Summary:

This Deliverable addresses impacts of climate change on energy demand due to changes in residential heating and cooling needs.

The Deliverable is organised in two Parts. Part I describes use of TIAM-UCL model to assess energy demand in Africa, while Part II reports on implementation of POLES-JRC model for global assessment of implications of global warming on residential energy demand.

Climate impacts in the energy system: TIAM-UCL

Heat stress is the inability of a person to cool sufficiently to maintain a healthy body temperature. High temperature and water vapour pressure reduces the efficacy of sweating and can lead to a dangerous build-up of body heat. We use two metrics, Apparent Temperature and Humidex to calculate heat stress in both present and future climates and calculate heat stress from the ensemble of CORDEX-Africa simulations for a control period and at two specific warming levels, +2°C and +4°C above pre-industrial. The increase in temperatures and changes to the precipitation distribution under climate change are projected to increase the intensity of heat stress events in Sahel and introduce new heat stress events in Northern and Central Africa. As the intensity of heat stress as well as economic performances increase in Africa it is expected that the use cooling technology will increase. The energy system therefore will need to be able to supply more energy to power fans or air conditioning units to prevent heat stress. The cooling requirement to turn a heat stress event into a non-heat stress event is computed to prevent heat stress across the continent. We find the least cost future energy system that meets the projected increase in demand and derive the increase in energy system costs. Using the same physical climate change drivers (extracted from the representative concentration pathway RCP8.5) we investigate the effect of the increase in energy demand from cooling under two socioeconomic pathways in line with the possible climate scenario SSP3 and SSP5. The total increase in energy costs to prevent heat stress in Africa is found to be \$51bn / \$46bn by 2035 and \$487bn / \$1.040bn by 2075 under the SSP3 / SSP5 respectively. However stronger economic development under lower population growth in SSP5 makes the relative costs to Africa’s GDP lower than in the SSP3 case. Higher economic development per capita could increases the aptitude to adapt to higher temperature in Africa.

Climate impacts in the energy system: POLES-JRC

Based on HELIX results of nine scenarios produced by two global climate models (see Deliverable D4.5), this report studies the impacts of climate change on the energy system with the global energy model POLES-JRC. The daily average temperatures are transformed into heating and cooling degree-days, which are used to assess heating and cooling needs evolution in time and for given Specific Warming Levels (SWL) of 1.5, 2 and 4 degrees Celsius. POLES-JRC also accounts for the impacts of

income, energy prices, insulation efforts and improvements in technology efficiency. The time-step is annual, so short-term extreme events are not assessed.

Results show that the increase in global average temperatures leads to a decrease of heating needs of around 50% at world level. On the other hand, demand for residential air cooling increases over time, due partly to the higher summer temperatures and partly to the higher equipment rate (allowed by a higher economic development). Residential cooling needs by the end of the century reach the current level of total final energy needs for residential heating. The resulting sum of global heating and cooling needs increases by around 50% by 2100.

A scenario without climate change was also tested, based on today’s temperatures. Even then, the AC equipment rate of hot countries will increase due to growing income, leading to some increase of electricity consumption to satisfy cooling needs; heating needs decrease due to improved efficiency, but to a lower extent than with a changing climate. The total energy consumed for heating and cooling at world level also increases by around 50% by 2100.

The global climate change impacts are the sum of diverse regional situations:

- The relatively colder Europe sees a decrease of the sum of heating and cooling needs (-42% by the end of the century).
- China sees a 20% increase of the sum of heating and cooling. By then, the (increasing) cooling needs will have reached the (decreasing) heating needs.
- India increases its cooling consumption dramatically, far more than its current and expected level of heating demand.

Finally, it is worth noting a dramatic increase of cooling needs is expected in Asia and other hot and developing regions like sub-Saharan Africa, the two regions that will concentrate most of world’s population. Therefore there is a strong case for improving the energy efficiency of new devices, developing the local power infrastructure necessary to cope with such a rise and anticipating and trying to mitigate possible peaking needs in particular.

Contents

Part I: Climate impacts in the energy system: TIAM-UCL

1 Introduction

Heat stress is the inability of a body to cool sufficiently to maintain a stable internal temperature. Methods of mitigating heat stress include evaporative cooling, seeking shade, modifying work-schedules or utilising additional space cooling. Heat stress level is affected by the ambient conditions and personal sensibility to heat. There are several different heat stress metrics (Buzan et al, 2015), which are dependent on a number of variables including temperature, relative humidity, wind speed and radiation. Tropical regions with high temperatures and humidity are more vulnerable to heat stress than other regions; moreover coastal cities are particularly susceptible to changes in heat stress as evaporation from the sea increases the water vapour pressure which is a key component of heat stress.

Increases in heat stress will require more cooling for comfort and healthy working conditions and more refrigeration for food security. The economic costs of climate change impacts have been investigated in Burke et al (2015) and almost every country in Africa is shown to be vulnerable to increasing temperatures causing a reduction in GDP. The urban fraction of the total populations is predicted to increase into the 21st century. The urban heat island effect is expected to exacerbate the issues of increasing temperatures increasing the frequency of heat stress. The primary response to heat stress is the use of space cooling devices such as fans and air conditioning units. Both are reliant on electricity power and therefore with an increase in heat stress there is likely to be an increase in demand for electricity. While reductions in heating energy demand could partially balance out the increases in cooling energy demand, especially at the global scale, the two are not directly equivalent in the energy system, as heating services are largely provided by secondary fuels and cooling by electricity. The increased demands in electricity could necessitate increases in generation and transmission capacity, mitigating heat stress with increased space cooling could thus have significant impacts on the optimal least-cost technology mix of regional energy systems, investment requirements, operating costs, energy prices and thus the wider economy and welfare. Previous studies have examined the impacts of climate change on heating and cooling demands using changes in degree-days number with set threshold temperatures and project significant impacts at the regional scale (Isaac and van Vuuren, 2009; Labriet et al, 2015). This study presents the costs of mitigating heat stress specifically with a focus on Africa under high-end climate change scenarios.

2 Data and Model

The inputs for the climate analysis are the bias corrected versions of data produced as part of the CORDEX Africa project (Nikulin et al, 2012). The CORDEX simulations were developed by driving regional climate models (RCMs) with data from general circulation models (GCMs) used during the CMIP5 project (Taylor et al, 2011). The bias correction was performed as part of the HELIX project, the method of bias correction used was multisegment statistical bias correction (Grillakis et al, 2013; Papadimitriou et al, 2015).

The input data used were eleven simulations from CORDEX Africa with a daily temporal resolution. In line with the HELIX focus on high-end climate change scenarios, for a model to be used in the analysis it was required that the GCM reach a global average temperature change of +4°C for thirty years; six of the climate models which were used to drive four regional models over Africa met this criteria. Table 1 shows the combinations of GCMs and RCMs used in this study. The historic data was taken as the final 20 years before the start of the future projections of the CMIP5 project, corresponding to 1986-2005. By requiring the temperatures reach +4°C the future simulations were all from RCP8.5 which is a high emissions scenario. The mean of the ensemble of future climates reaches +2°C and +4°C during the 30 year periods centred on 2035 and 2076 respectively. A table showing the time slices for the GCM results used for analysis is shown in Table 2.

Table 1: CORDEX Africa GCMs and RCMs combination (*X* indicates the results were used in this study)

	RCA4	CCLM4.8.17	RACMO22T	HIRHAM5
CanESM2	*X*			
CM5A-MR	*X*			
CSIRO-Mk3.6.0	*X*			
HadGEM2-ES	*X*	*X*	*X*	
ICHEC-EC-EARTH	*X*		*X*	*X*
MPI-ESM-LR	*X*	*X*		

Table 2: Time slices from the GCM simulations used for +2°C and +4°C analysis

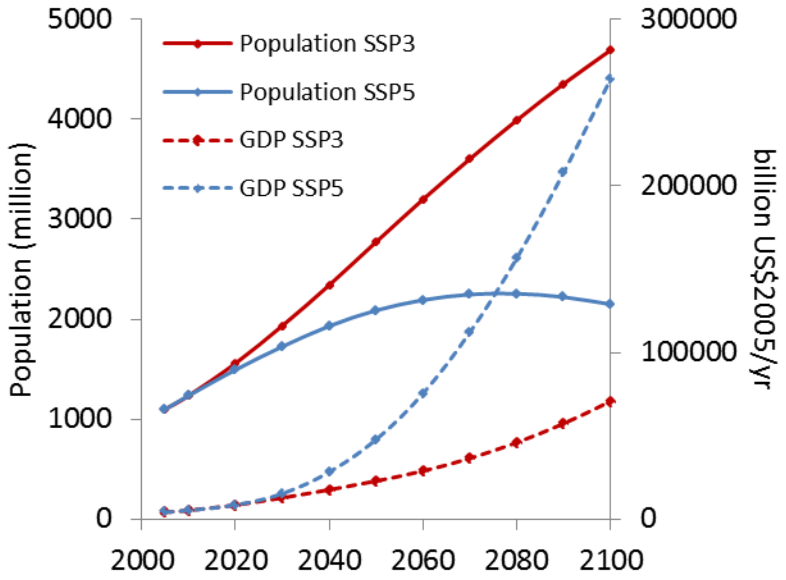
Model	+2°C	+4°C
CanESM2	2012-2041	2053-2082
CM5A-MR	2015-2044	2052-2081
CSIRO-Mk3.6.0	2030-2059	2067-2096
HadGEM2-ES	2021-2050	2057-2086
ICHEC-EC-EARTH	2021-2050	2068-2097
MPI-ESM-LR	2020-2049	2066-2095
GCM weighted mean	**2020-2049**	**2061-2090**
RCM weighted mean	**2020-2049**	**2062-2091**

The Shared Socioeconomic Pathways SSP3 and SSP5 have been selected for the socioeconomic part of the analysis (O'Neill et al, 2017). A main difference between these two SSPs is the representation of trade in the scenarios: SSP5 represents a free market world compare to a more regional fragmentation for SSP3, which is why we choose to apply firstly our analysis to SSP3 and conduct a sensitivity study with SSP5 as the regional energy system could be seen as more insulated from international exchanges in the SSP3. The two scenarios present also very contrasting GDP and population changes over the XXI^{rst} century (figure 1).

The SSP3 scenario corresponds to a world where the focus is on regional rather than global trade and competition, policies allow the use of high emission energy sources and there is little technological development in the energy sector. SSP3 is the socioeconomic scenario that relates the closest to the realisation of the representative concentration pathway RCP8.5 used for the physical climate data from CMIP5. The population data from SSP3 were gridded by Murakami and Yamagata (2016) and the outputs were used as part of this work. From the scenario database, population data was used to estimate the number of people affected by heat stress in the historic and future periods.

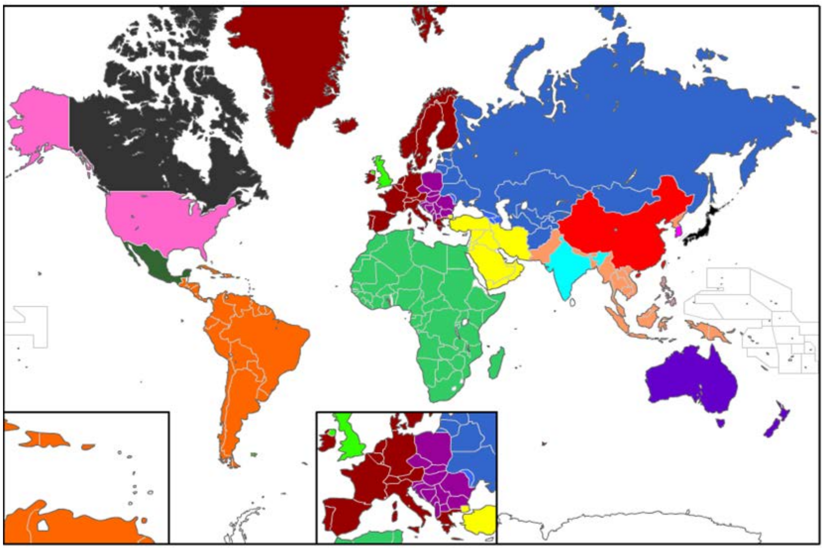
As sensitivity study we apply the same climate change drivers as presented above to a representation of SSP5 within TIAM-UCL. In fact population and GDP data are used as a driver for the calculation of the energy demands for the future periods within the energy system model (as described in the method section below). The SSP5 is an extreme socioeconomic scenario marking the upper end of the scenario literature in fossil fuel use, food demand, energy use and greenhouse gas emissions. The population growth is lower in SSP5 however the global economic development is higher driving a higher level of standard of living in Africa. In 2100 the mean per capita GDP under SSP5 is almost 10 times higher than the SSP3.

Figure 1: SPP3 (red) and SSP5 (blue) GDP (left axis, dote line) and population (right axis, solid line) for Africa.



TIAM-UCL is a technology-rich global optimisation model, which derives the least-cost future energy system within given technological, economic and pol-icy constraints. It models the flows of energy carriers from primary resources to final service demands via stages of extraction, transformation and transportation. With perfect foresight over the chosen time period, the model selects energy technologies based on their investment and running costs and operational parameters, so as to meet service demands while minimising the total cost of the system. The world is represented as 16 regions (figure 2), one of which is Africa (Anandarajah et al, 2011).

Figure 2: TIAM-UCL regional representation.



3 Methodology

3.1 Heat Stress calculation

There are multiple heat stress metrics available for analysis (Buzan et al, 2015), two of which have been selected for further analysis: Apparent Temperature (AT) and Humidex (HD). Both indices are dependent on temperature and vapour pressure, which in turn is dependent on surface pressure and specific humidity. The derivation of the vapour pressure and the two indices are shown in Table 3. The heat stress indices are calculated on each grid cell (0.44◦ × 0.44◦) with a temporal resolution of 1 day.

Table 3: Heat stress formula for Apparent Temperature (AT) and Humidex (HD) calculations with reference. (T is temperature and VP water vapour)

AT:	$AT = 0.92T + 0.228VP$	Steadman (1984)
HD:	$HD = T + 0.555VP$	Buzan et al (2015)

Each of the heat stress indices has different ranges for slight, moderate, strong and extreme stress; these values are specified in Zhao et al (2015) and are shown in Table 4. HD is a comfort index which is used for both indoors and outdoors conditions. The AT indoor version is used in this work and the ranges of values span from just above indoor comfort (slight) to the point at which heat stroke can occur (extreme). For each GCM-RCM combination the number of days with heat stress in each level were calculated and then averaged to produce the ensemble mean.

Table 4: Heat stress levels and the values which correspond to severity of stress.

Variable	Slight	Moderate	Strong	Extreme
AT	28-32	32-35	35-40	>40
HD	35-40	40-45	45-54	>54

A reduction in ambient temperature reduces the value of the heat stress indices for a given water vapour pressure and it is therefore possible with sufficient cooling to prevent a heat stress event. It is possible to calculate the difference in temperature between a heat stress day and a no stress day by rearranging the equations from Table 3. The difference between the observed temperature and the maximum temperature for no heat stress is assumed to be the cooling requirement. The cooling requirement is a measure of both temperature change and time and is calculated in cooling degree days (CDDs).

3.2 Energy Demand calculation

In TIAM-UCL, the energy service demands are an exogenous input to the model, and are calculated for each modelled time slice (t) based on socio-economic drivers and elasticity constants, which represent how closely the demands are coupled to the drivers and vary over the modelled time horizon. The energy demands for residential cooling (RC) and commercial cooling (CC) are calculated with Equations 1 and 2, where NumHou is the number of households, GDPPHOU is the gross domestic product per household and PSER is the service industry activity (in trillion USD).

$$RCDemandt = RCDemandt{-}1 \times NumHou \times GDPPHOU^{Elasticity} \qquad (1)$$

$$CCDemandt = CCDemandt{-}1 \times PSER^{Elasticity} \qquad (2)$$

For this analysis, it is assumed that all space cooling services in the model are used to mitigate heat stress and so the total cooling requirement is the sum of the cooling required, calculated in CDDs, to mitigate each heat stress level (HSL). As described by Brown et al (2016), the relationship between temperature and cooling energy demand may be represented by different functions depending on factors including building properties, diffusion of cooling technologies and cultural preferences. Following the method of Labriet et al (2015), this study assumes that the usage of cooling appliances changes but the diffusion of appliances does not change due to climate change. Based on this, the cooling energy demands are assumed to scale proportionally with the change in cooling degree days.

Given these assumptions to simulate the impact of heat stress mitigation on energy demand, the CDDs required to mitigate each HSL are calculated by summing the population-weighted apparent temperature heat stress results over Africa and scaling each portion of the unadjusted cooling energy demands by the ratio of CDDs in the future period relative to the historic period (equation 3). In this study the costs of adjusting the energy system to mitigate all levels of heat stress together are calculated.

$$A = CDDfuture \,/\, CDDhistoric \qquad (3)$$

The TIAM-UCL model is run for the period 2005-2100, the extended time horizon reflecting the fact that policy-makers and industry agents make decisions to prepare for, and which affect, the years and decades to come. In TIAM-UCL, the Africa region is split into rural (1) and urban (2) sub-regions for which the residential demand drivers and elasticities are defined separately. This represents the significant differences in access to energy supply and service technologies between the urban and rural populations. The commercial demand is not split into urban and rural regions. The model is run with two energy demand scenarios: the "base" case without climate change impact on cooling requirement and the "climate change" case where the cooling energy demand has been scaled to take into consideration the requirement to avoid the additional heating stress from climate change. From the energy system model we will focus on the SSP3 socio-economic pathways results, with a further sensitivity analysis of the effects of the same physical climate change drivers under the different socioeconomic development of SSP5.

4 Results

4.1 Heat stress calculation results

Figure 3 presents the apparent temperature (AT) heat stress results over Africa for the historical timeslice (the humidex results are not presented). Heat stress levels are split between slight and moderate level, with high occurrence in central tropical Africa and coastal area and lesser occurrence in other regions. Very few strong or extreme events are calculated during the historical period.

Figure 3: Number of AT heat stress day number for historical timeslices: slight (top left), moderate (top right), strong (bottom left) and extreme (bottom right) levels.

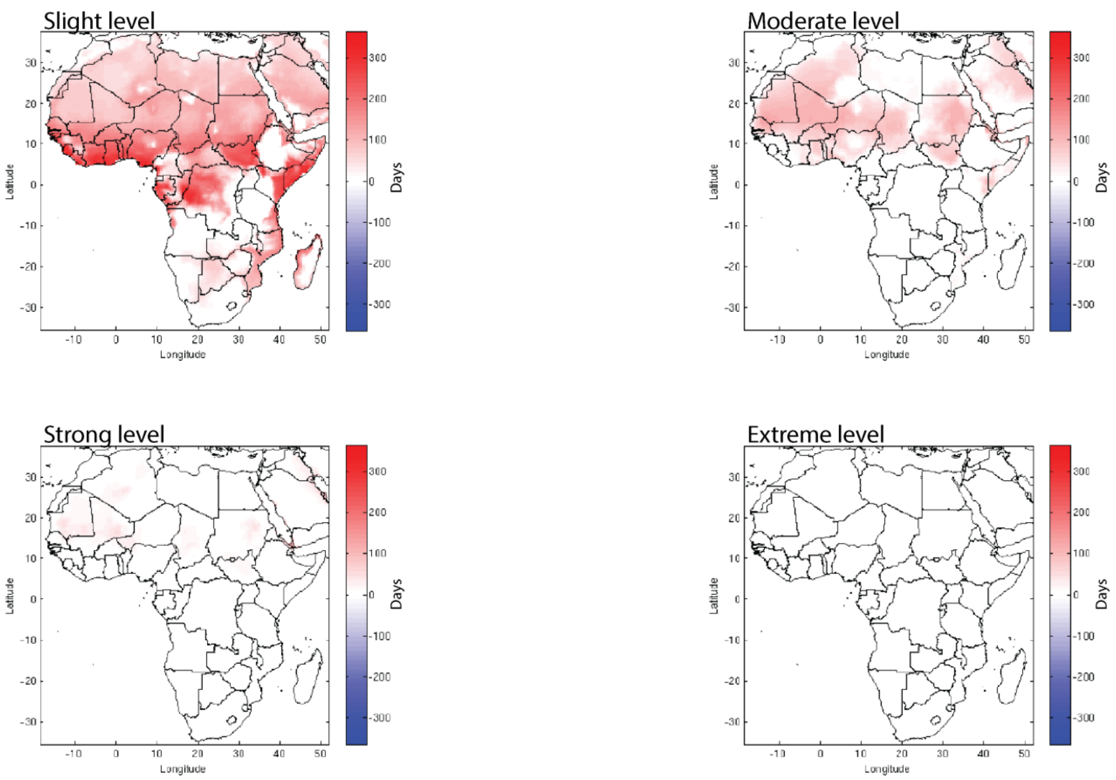
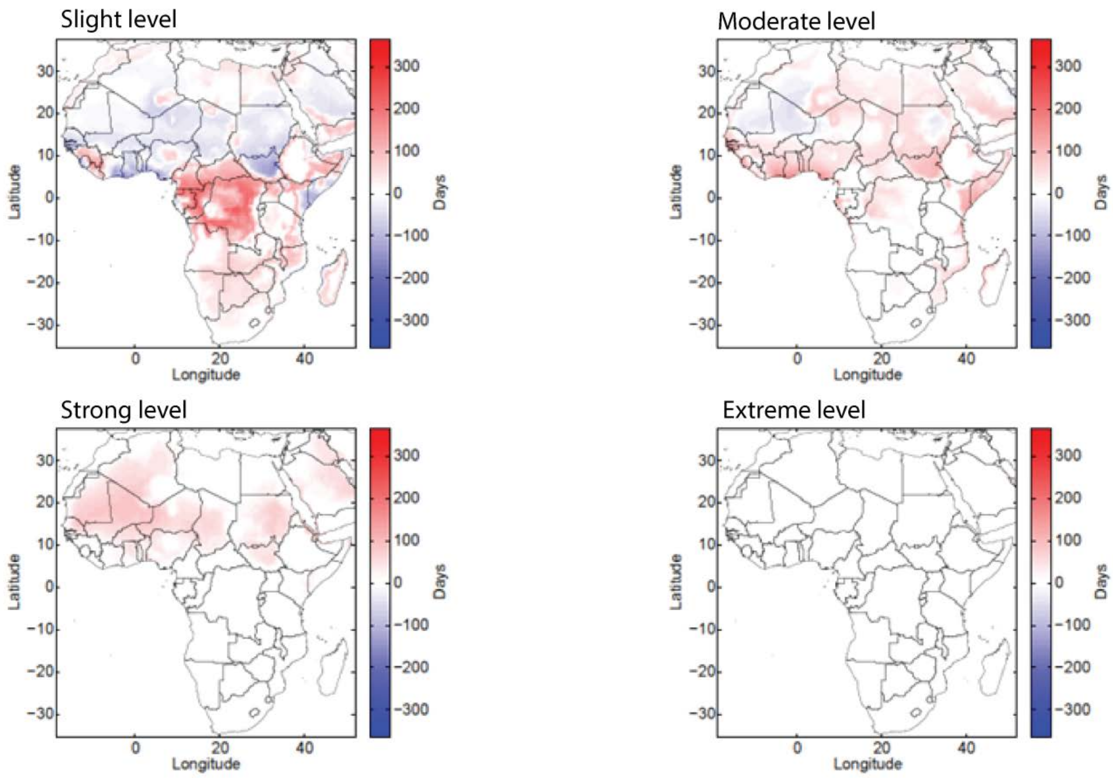


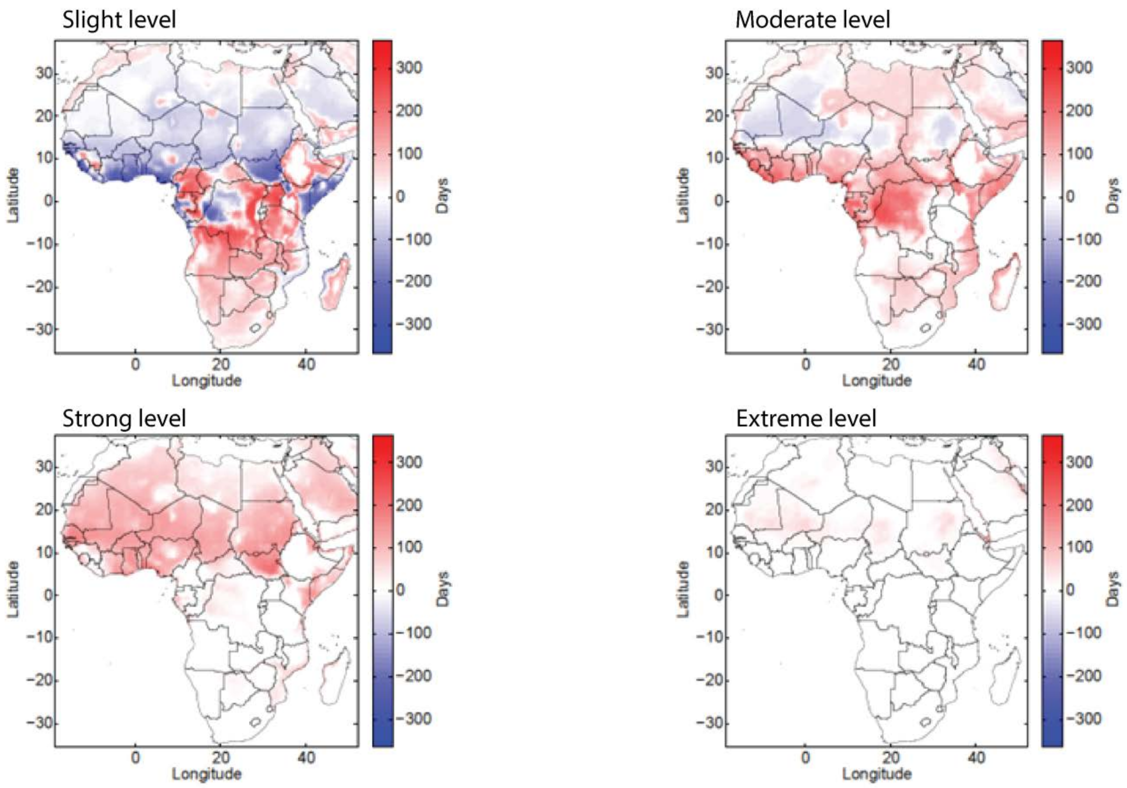
Figure 4 shows the impact of a 2°C warming on apparent temperature heat stress frequencies across Africa. For both indices the same pattern emerges: either the number of slight heat stress events increases, indicating the regions previously unaffected will become vulnerable, or where the number of slight events decreases the number of moderate, and in the case of apparent temperature strong, heat stress events increases. When global temperatures are 4°C above the preindustrial level (Figures 5) the heat stress geographical distribution changes are similar to a 2°C change but with a higher intensity. This higher intensity is also accompanied by an increase in the number of strong heat stress events using the humidex index (not presented).

Figure 4: Difference in AT heat stress day number between the 2°C and historical timeslices: slight (top left), moderate (top right), strong (bottom left) and extreme (bottom right) levels.



The main result of note is that in almost all regions where we find a reduction in slight heat stress events we find an increase in moderate events. Where we find a reduction in the number of moderate events there is an increase in the number of strong heat stress events. In general the distribution of heat stress events increases in severity with climate change. The increase in moderate and stronger events affects highly populated coastlines and West African Sahel nations. The same response is found in central Africa over much of the Central African Republic and the Democratic Republic of the Congo. The equatorial and tropical regions show higher instances of heat stress with changes in strong heat stress events almost exclusively in the northern hemisphere. The highly populated West African region experiences the largest changes in moderate and strong heat stress events.

Figure 5: same as Figure 4 for 4°C.



4.2 Increase in cooling demand

The difference in the cooling degrees day requirement to prevent heat stress between the historic and future simulations are shown in Figures 6 for the +2°C and +4°C thresholds. The cooling energy demands are calculated for the time slices at +2°C and +4°C and are linearly interpolated and extrapolated to define the demand pathways. Figure 7 shows the cooling energy demands for the “base” and “climate change (*ClCh*)” cases, where CC is the commercial cooling energy demand, RC1 is the rural residential cooling energy demand and RC2 is the urban residential cooling energy demand. In 2005, space cooling accounts for 0.4% of the total final energy demand in Africa. In the base case this drops to 0.2% by 2100 but in the heat stress case space cooling rises to account for 1.2% of the total final energy demand by 2100.

Figure 6: Additional cooling degree days required to prevent all AT heat stress under 2°C (left) and 4°C (right) compare to present day situation.

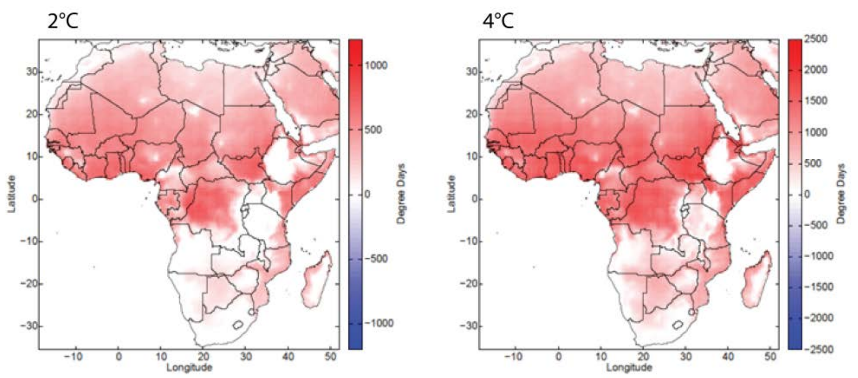
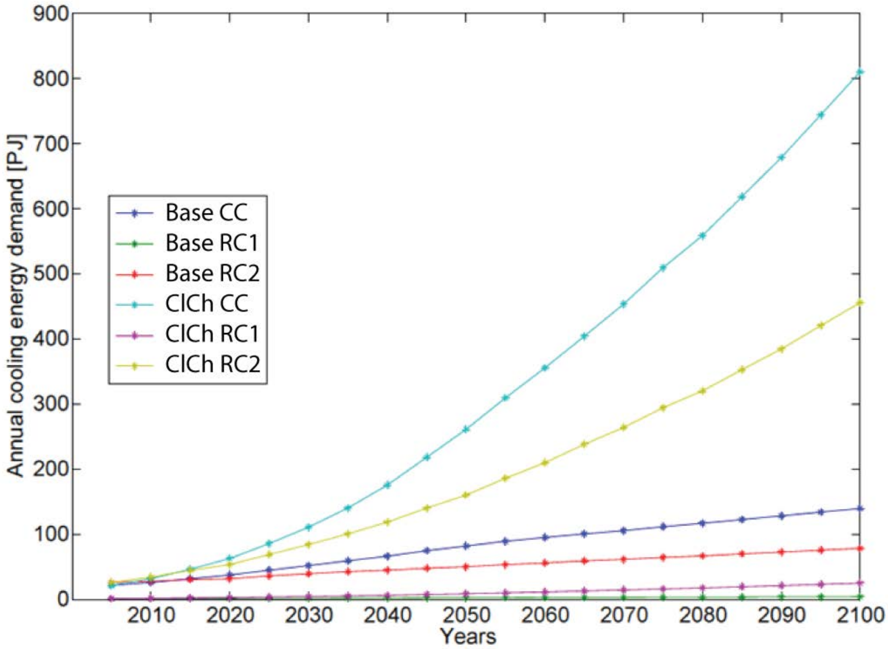


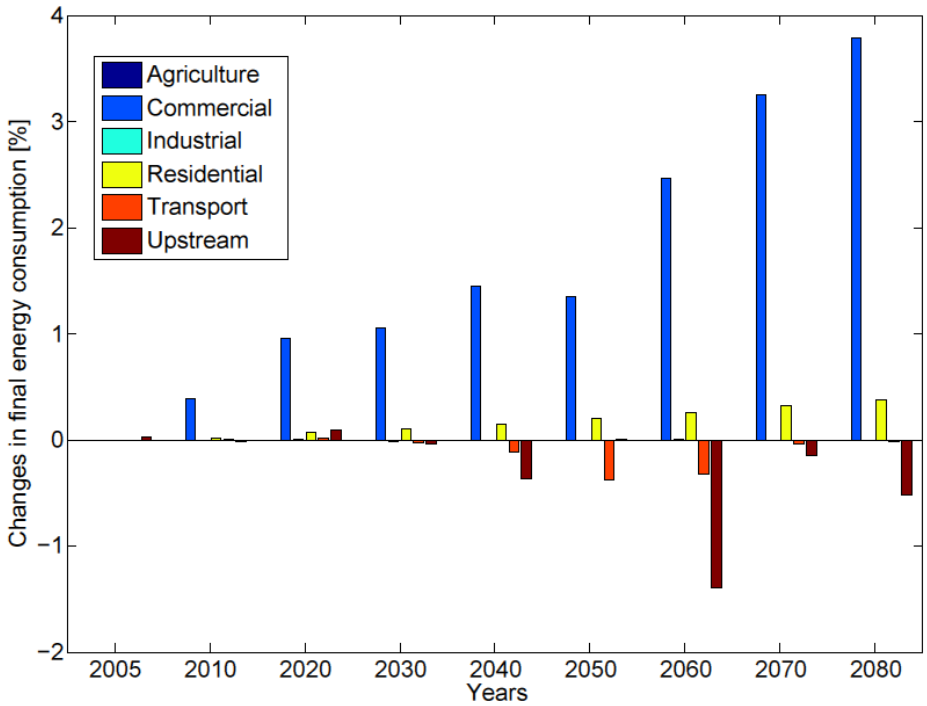
Figure 7: Commercial (CC) and residential cooling (RC) demand in the base (Base: no climate change impact) and the climate change (ClCh: effect on cooling requirement resulting from heat stress avoidance) cases – SSP3 scenario.



4.3 Impact of increased cooling energy demand

TIAM-UCL results for the "base" case and the "climate change" case (with cooling energy demand increased by the requirement of avoiding heat stress) are compared. Figure 8 shows the impact of the increased residential and commercial cooling energy demand on the final energy consumption of all the economic sectors. The changes in the residential and commercial sectors induce changes in the generation technology and fuel mix in other sectors: for example, final energy consumption in the transport sector decreases slightly in the middle of the century because gas is partially replaced with electricity, and energy consumption in the upstream sector (extraction of fossil fuel) decreases around 2060 and 2080 as the use of electricity and heat respectively are reduced. The total energy consumption of the Africa region is increased by 0.1% in 2035 and 0.3% in 2076 due to the additional cooling to mitigate heat stress.

Figure 8: Changes in sectoral energy consumption under heat stress relative to the base case (no heat stress reduction impact) for Africa – SSP3 scenario.



The increased cooling energy demands in the "climate change" case do not affect the technologies selected by TIAM to fulfil these end demands. From 2020 onwards in both scenarios, commercial cooling is entirely provided by rooftop chiller units and residential cooling is entirely provided by room air conditioning units.

Figure 9 shows the mix of electricity generation technologies in the "base" case. The share of renewable energy sources - solar PV and hydroelectricity - grows rapidly from the middle of the century. To provide the additional electricity required in the heat stress case, approximately 3% additional generation is required from 2040 onwards. Of this additional generation, solar PV provides an increasing share rising from 5% in 2045 to 15% in 2070. This mainly replaces coal in the technology mix, while the share of natural gas remains approximately constant around 3%.

The total annual cost of the regional energy system is composed of expenditures (such as capital required for building and decommissioning technologies, operations and maintenance, commodity imports, commodity delivery and taxes) and revenues (from commodity exports, subsidies and the salvage values of decommissioned technologies). As several of these finance streams occur earlier or later than the energy generation which they facilitate, TIAM includes mechanisms to annualise them over the period of generation (Loulou et al, 2004). As the energy supply in a given year is made possible by the construction and operation of supply technologies in previous years, the energy system cost (Cost (ES)) relevant for this analysis is defined as the sum of the annual investment and operations costs from the model base year up to the year in question. All costs are reported in year 2005 US $ and are undiscounted.

Figure 9: Electricity generation sources in the “base” case for Africa – SSP3 scenario.

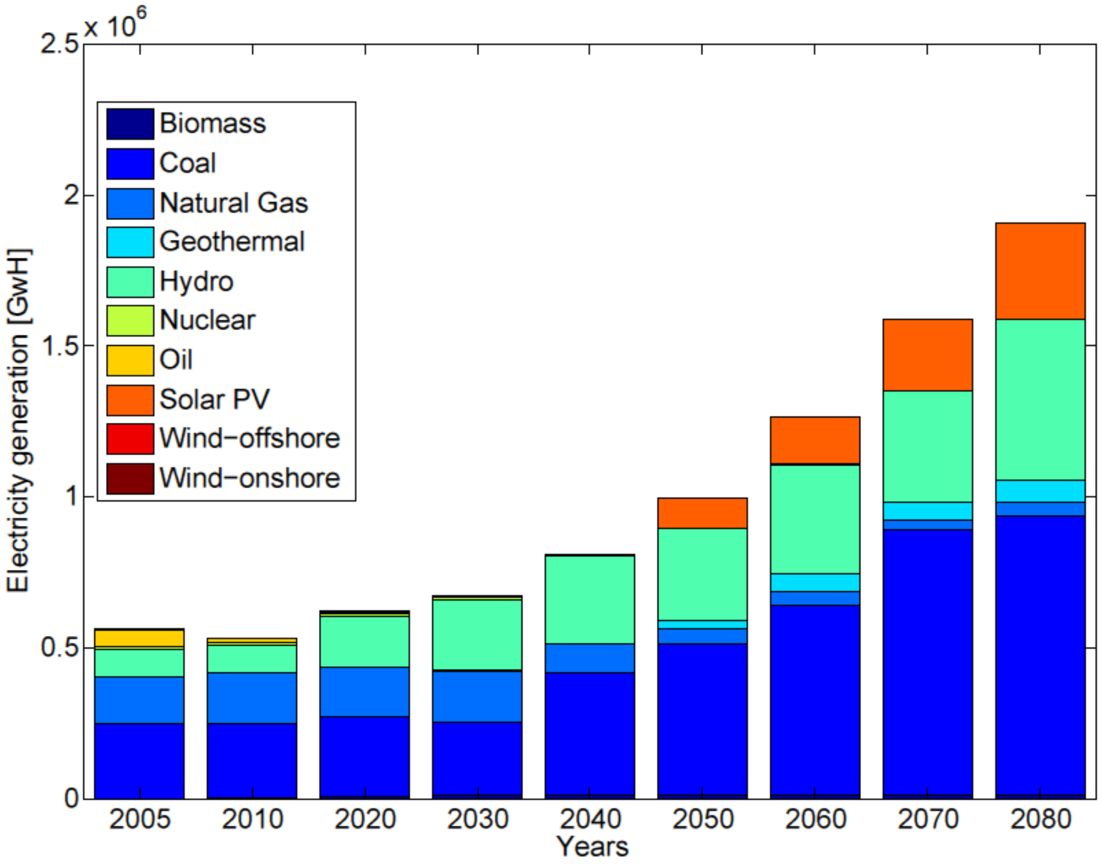


Table 5 shows the Africa energy system costs for the base case and heat stress case under SSP3 shared socio-economic pathway. Due to the increased cooling energy demand required to mitigate heat stress resulting from the 2°C global average temperature rise, the energy system cost up to 2035 increases by 0.26%, which is equivalent to approximately $51.3 billion. Due to the heat stress resulting from the 4°C global average temperature rise, the energy system cost up to 2076 increases by 0.60%, which is equivalent to approximately $486.5 billion.

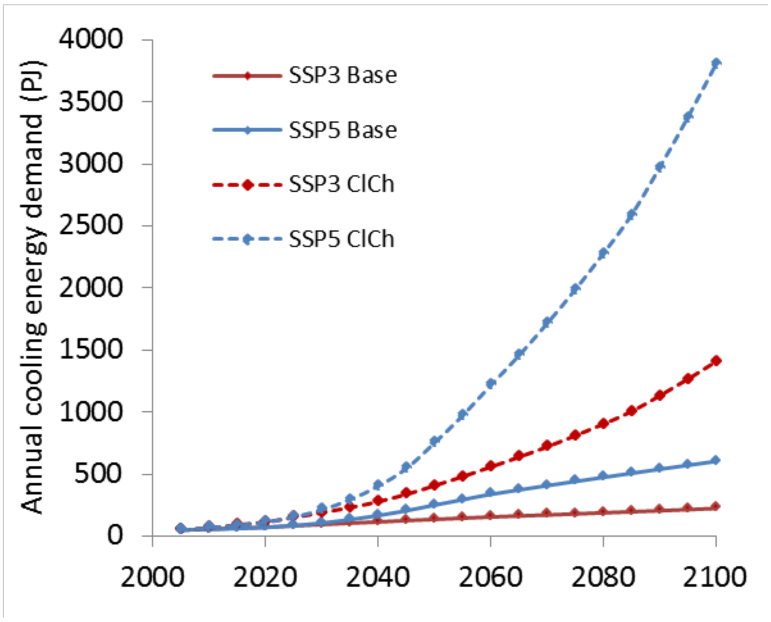
Table 5: Costs (investment and operating) of the energy system in Africa under “base” and “climate change” case (in million 2005US Dollars) under SSP3.

	Base case		Climate Change case	
Period from 2005 to year=	**2035**	**2076**	**2035**	**2076**
Temperature increase	**-**	**-**	**+2°C**	**+4°C**
Cost (ES)	**20,089,746**	**81,201,095**	**20,141,073**	**81,687,621**
Cost rise over base case	**-**	**-**	**+0.26%**	**+0.60%**
Cost rise as fraction of GDP	**-**	**-**	**0.03%**	**0.06%**

5 Sensitivity to the socio-economic pathway

As seen in figure 2 SSP3 and SSP5 show strong socioeconomic differences. In comparison to SSP3, the population is lower in SSP5, however the global economic growth is higher driving the cooling energy demand in Africa to a higher level for the reference case (figure 10). In 2100 the base case cooling energy demand (adding the domestic and commercial sectors as one variable) under SSP5 is 3 times higher than the SSP3 showing a larger constrain from the economic development (SSP5) than from the population growth (SSP3) as described in the storylines of the SSPs in O'Neill et al (2017). The same physical climate change is then applied on to the cooling energy demand to study its impact under a different economic development.

Figure 10: SPP3 (red) and SSP5 (blue) cooling energy demand in the base (Base: no climate change impact; solid line) and the climate change (ClCh: effect on cooling requirement resulting from heat stress avoidance; dotted line) for Africa.



The results of the SSP5 pathways are presented for the "base" case and the "climate change" case in table 6. In comparison to the SSP3 results, the demand for SSP5 in 2035 (the 2°C threshold period) is not as such largely different, however even if the demand is slightly higher in SSP5 the costs resulting in the base and heat-stress reduction case are lower due to a larger utilisation of cheaper fuel and technologies in the interconnected and wealthier world represented in SSP5 (table 6). The case is slightly different later in the century as GDP difference is driving larger demand in energy production. At this stage of development in the SSP5 scenario the fossil fuel and nuclear production of electricity needs to be supplemented by alternative generation such as wind and solar to fulfil the demand. This increases the absolute cost by 50% of the energy system for Africa in 2076; in the parallel however the total GDP in 2100 for Africa has trebled (figure 2). As consequence the impact of avoiding heat-stress under climate change in Africa under the SSP5 scenario represents only 0.04% rise of the energy system as fraction of the GDP over the period (table 6).

Table 6: Costs (investment and operating) of the energy system in Africa under "base and "climate change" case (in million 2005US Dollars) under SSP5.

	Base case		Climate Change case	
Period from 2005 to year=	**2035**	**2076**	**2035**	**2076**
Temperature increase	**-**	**-**	**+2°C**	**+4°C**
Cost (ES)	**18,778,354**	**122,435,170**	**18,825,299**	**123,475,868**
Cost rise over base case	**-**	**-**	**+0.25%**	**+0.85%**
Cost rise as fraction of GDP	**-**	**-**	**0.02%**	**0.04%**

6 Discussion and Conclusion

The impacts of climate change on heat stress in Africa are explored using two heat stress indices, apparent temperature and humidex. The description of the derivation and limits for the indices are described in detail by Zhao et al (2015). To calculate the values for the heat stress indices data from the CORDEX-Africa project were used. Six GCMs were combined with four RCMs and eleven GCM-RCM pairings were completed. The majority of Africa experiences an increase in the number of heat stress events, with noticeable increase in the number of strong and extreme heat stress days. The increase in overall intensity of heat stress happens in highly populated regions such as the Nigerian coast, the Great Lakes and along several major rivers including the Nile, Volta, Niger and Zambezi. The apparent temperature heat stress results were used to scale the cooling service energy demand for the Africa region in the TIAM-UCL model under two specific shared socio-economic pathways.. Meeting the additional energy demand had the effect of increasing the energy system cost over the 2005-2076 period by 0.6% and 0.85% under SSP3 and SSP5 respectively. However the GDP development of Africa shows different behaviours under the two socio-economic scenarios. The results are compiled in table 7 showing an absolute higher costs in the "climate change" case under SSP5 in 2100 but a lower impact on the GDP . The change in the energy system cost to supress the heat-stress corresponds to 0.06% of the cumulative GDP for Africa over the same period in SSP3 but only 0.04% under SSP5. The additional yearly cost increases with time (as global warming increases).

Table 7: Physical climate change driver applied to cooling energy demand to avoid heat stress (RCP8.8) and effects on the costs of the energy system over Africa under the two socioeconomic pathways SSP3 and SSP5.

		Base		*Climate Change*	
	Period to the year=	*2035*	*2075*	*2035*	*2075*
RCP8.5	*Temperature*	-	-	+2°C	+4°C
	Demand Factor Increase	-	-	**2.2**	**6.3**
SSP3	*Cost (ES) (2005 US$)*	20,089,746	81,201,095	20,141,073	81,687,621
	% GDP	-	-	**0.03%**	**0.06%**
SSP5	*Cost (ES) (2005 US$)*	18,178,354	122,435,170	18,825,299	123,475,868
	% GDP	-	-	**0.02%**	**0.04%**

With the signing of the Paris accord (United Nations, 2015) the global community agreed to work to prevent catastrophic climate changes that are projected in RCP8.5. However continued commitment to reducing carbon dioxide emissions is necessary to reach the agreed goals. With the long lead time of energy systems, often measured in decades, decision makers will be faced with choosing between increasing capacities to prevent potential heat stress or being unable to provide energy when the need is critical.

In this study, the climate change effect of heat stress is applied to the Africa region and cooling energy demand only. Clearly, climate change will also affect other geographical regions and elements of the energy system, such as heating demand and renewable resources, whose combined impacts could affect the technology choices made by TIAM-UCL in individual regions, commodity trading between regions and thus the regional and global mitigation costs. However this study highlights that the wellbeing under climate change as well as the climate change cost on the energy system depends on the wealth development of the region affected. Population and society has a better ability to cope and adapt to higher temperature under higher economic development for the Africa region.

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Part II: Climate impacts in the energy system: POLES-JRC

1 Introduction

The HELIX project brings together different types of models in order to analyse the impacts of climate change in different parts of the world. We focus in this report on the impacts on the energy sector. These impacts range from changes in the availability of water, which can cause decreased thermal production efficiency or changes in hydro production, to risks for the infrastructure, for example implied by (infra-annual) extreme events, or changes of demand patterns. Studying these impacts is crucial for evaluating and designing the adequate mitigation and adaptation policies in order to minimize the negative impacts of climate change. Ciscar and Dowling (2012) looked at how impact assessment models represent these impacts and show that more work is needed in this area. The modelling tool used in HELIX (POLES-JRC model, see Annex A and (Keramidas, 2017)) allows evaluating impacts on yearly energy demand. Indeed, it deals with the impacts of temperature changes on the energy demand for residential heating and cooling. Other impacts are not studied here since the available data and modelling capabilities are not adequate.

Several studies focused on the energy impacts of climate change. One of the few global studies is Isaac and van Vuuren (2009). They used Heating Degree Days (HDD) and Cooling Degree Days (CDD) indicators[1] to represent the impact of climate change on heating and cooling residential needs in the world. Mima et al. (2011) and Mima and Criqui (2015) looked at the impacts at a European scale within the FP7 ClimateCost project[2], country by country. They carried out an evaluation of the increase of cooling needs and decrease of heating needs. They also looked at the variations of water resource for hydropower and the decreased thermal production because of constrained water resource. Dowling (2013) studied the impact of several climate change scenarios from different global climate models (GCM[3]), as part of the PESETA2 project, at the European scale. The interest was on residential and service energy needs for heating and cooling, as well as the efficiency of thermal power plants and the changes in renewable production (hydro, wind, solar). The main conclusion is that the heating needs will decrease as average temperatures increase, and this energy gains largely outbalance the increase in cooling needs.

The global climate models provide updated scenarios of average (bias-adjusted) daily temperatures for the world, which are converted to HDD and CDD. This sectoral study then provides an assessment of the impact on the energy needs for future cooling and heating demand in the residential sector. We report here the world total, the European total, China and India, which are considered crucial regions regarding cooling and heating needs[4].

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[1] HDD and CDD are indicators based on the measured external temperature and a reference temperature. They reflect the energy needed to heat (HDD) or cool (CDD) a building.
[2] http://www.climatecost.cc/
[3] Global Climate Model, e.g.: HadGEM3 GC2 (see Williams et al. 2015)
[4] Although POLES-JRC allows computing the country-by-country effects, the inputs from the climate models may be less relevant for small countries.

2 Data and model

2.1 Climate data management

Input temperature data are from the latest HELIX climate scenario datasets (as of end 2016 / 2017). Seven scenarios come from the climate model ECEARTH3HR and two scenarios from HadGEM3. Each scenario describes the average daily temperature in a grid cell, covering the entire globe. Table 1 describes the scenarios studied.

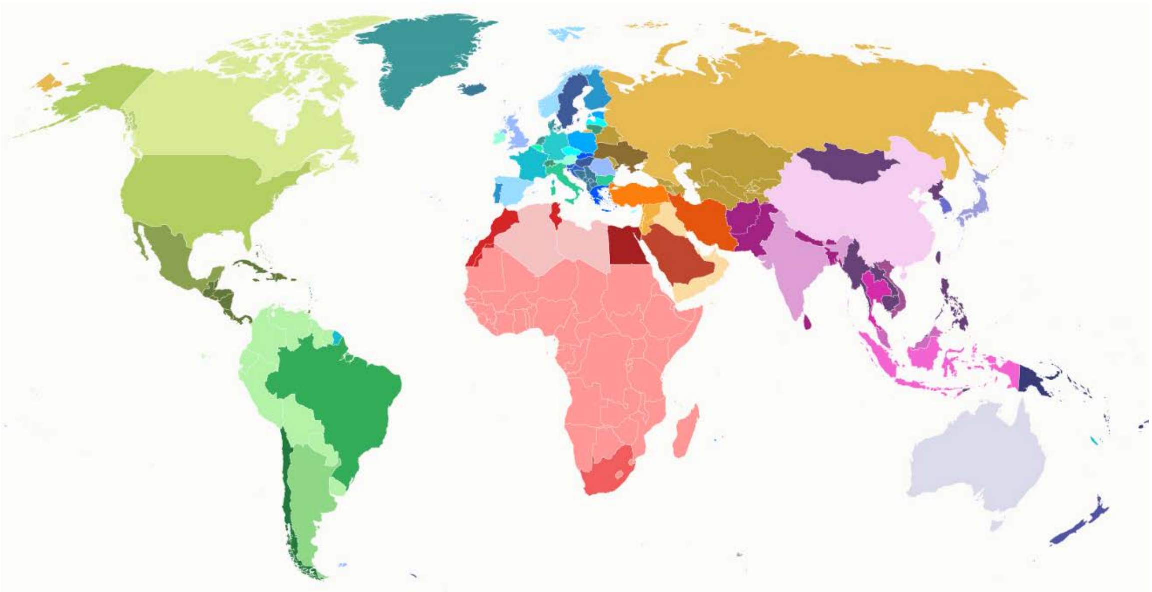
Table 1. HELIX task 4.4 scenarios tested

Hi Res Model	SST
ECEARTH - R1	IPSL-CM5A-LR
ECEARTH - R2	GFDL-ESM2M
ECEARTH - R3	HadGEM2-ES
ECEARTH - R4	EC-EARTH
ECEARTH - R5	GISS-E2-H
ECEARTH - R6	IPSL-CM5A-MR
ECEARTH - R7	HadCM3LC
HADGEM-R1	IPSL-CM5A-LR
HADGEM-R3	HadGEM2-ES

2.2 POLES-JRC model

The model used is the global energy model POLES-JRC (Prospective Outlook on Long-term Energy Systems), described in (Keramidas 2017). POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables, etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (see Annex A). The world is described by 66 countries or groups of countries, as shown in Figure 11.

Figure 11: Regions described in POLES



In this report we focus on the energy demand from heating and cooling residential demand, described in the section below. We analyse the climate scenarios with the POLES-JRC model research version (2015) developed for the LAMP[5]/CLIMACAP[6] project, which has a detailed modelling of heating and cooling demand in the residential sector.

3 Methodology

3.1 Climate heating and cooling indicators

Grid-cell temperatures were converted in Heating Degree Days (HDD) and Cooling Degree Days (CDD) by difference with the set point temperature of 18°C:

$$HDD_{year} = \sum\nolimits_{days} \max(0, (18 - T_c))$$

$$CDD_{year} = \sum\nolimits_{days} \max(0, (T_c - 18))$$

with Tc: the average daily temperature expressed in °C

After the data on average daily temperature by geographical cell has been transformed into HDD and CDD by cell, values at country or region level are then calculated through a weighting by population density (regional distribution as of 2000). This allows capturing requirements for heating and cooling services at country / region level while coping with potentially heterogeneous distribution of population.

[5] http://www.cgd.ucar.edu/iam/projects/lamp.html
[6] http://climacap.websitebuilderpro.com/home/4576315425

$$HDDi = \frac{\sum_j HDD_{i,j} P_{i,j}}{\sum_j P_{i,j}}$$

$$CDDi = \frac{\sum_j CDD_{i,j} P_{i,j}}{\sum_j P_{i,j}}$$

with:

i: country

j: geographical cell

Pi,j: population of cell j belonging to country i

HDDi,j / CDDi,j: HDD and CDD of cell j belonging to country i

The population migrations within a country are not accounted and can lead to an over- or underestimate of the future weighted HDD and CDD.

The POLES-JRC model was then run for each of the nine climate scenarios using as input the moving average over 30 years of CDD and HDD, so as to be consistent with the analysis specifications of task 4.4 of the HELIX project. Modelling results are compared to a case without no climate change ("noCC").

3.2 Modelling energy demand in residential buildings

Residential buildings are represented by a building stock module that captures the need for new dwellings as a function of population, income, renewal of scrapped buildings and renovation of existing buildings. The time-step is annual (no infra-annual phenomenon, such as extreme events, are accounted for). The module also describes the evolution of surfaces per dwelling, as a function of income.

3.2.1 Space heating

The model simulates the evolution of heating demand derived from the building module. Key drivers are:

- development of insulation (which diffusion follows a logistic function dependent on the return on investment, compared to both heating and cooling expenses),
- energy prices,
- residential surfaces (which includes a wealth effect),
- and the evolution of HDD over time, captured through an elasticity coefficient.

3.2.2 Space cooling

The representation of energy needs for cooling purposes in the residential sector is derived from work by Mc Neil (2007), Isaac (2009), Mima (2009) and Daioglou (2012).

Energy demand for space cooling in the residential sector (AC_{RES}) in any country is currently described as a function of air conditioning (AC) unit electricity consumption (UEC) multiplied by the number of dwelling equipped with cooling systems (Dwl_{AC}):

$$AC_{RES} = UEC * Dwl_{AC}$$

The first factor is the unit electricity consumption; it depends on:

- per-capita revenues (adapted from Isaac 2009 and Daioglou 2012),
- CDD (adapted from Isaac 2009 and Daioglou 2012),
- the efficiency of the air conditioner,
- the insulation of the building.

The equation describing the unit electricity consumption is:

$$UEC = UECth * TechnicalImprovementFactor * InsulationFactor$$

Where UEC_{th}, the theoretical unit electricity consumption, is evaluated as (adapted from Isaac 2009 and Daioglou 2012):

$$UEC_{th} = 5.13 * \text{Income per capita} + 0.0621 * \text{CDD} * \text{Income per capita} - 1658$$

The technical improvement factor is based on an improving trend, modulated by the budgetary coefficient related to cooling, and a floor value derived from the historical best performance.

The insulation factor follows the return on investment of insulation (which combines heating and cooling expenses).

The second important factor determining the AC consumption is the number of dwellings equipped; it is the product of the number of dwellings (Dwl) by the share of dwellings equipped (ShDwlAC):

$$DwlAC = Dwl * ShDwlAC$$

The share of dwellings equipped depends on:

- a diffusion rate: DiffAC, that depends on income per capita
- a maximum penetration rate: DwlACMax (expressed in % of total dwellings), that depends on CDD so as to capture the climate characteristics of the country/ region:

$$ShDwlAC = DiffAC * DwlACMax$$

with DwlACMax being fitted on US data (McNeil 2007):

$$DwlACMax = 1 - 0.949 * \exp(-0.00187 * CDD)$$

and DiffAC fitted on international data (Isaac 2009):

$$\text{DiffAC} = \frac{1}{1 + \exp(4.152 - 0.237 * \text{Income per capita})}$$

3.2.3 Caveats

The modelling of residential heating and cooling needs is based on a limited amount of data points, which makes it difficult to separate the impacts of HDD and CDD from the socio-economic drivers (population, size of households, income per capita and other drivers), particularly for cooling.

In this latter case the data availability is scarce, corresponds to a limited set of climate situations and usually covers only a short time frame (2000-2010). In addition, the effect of humidity on cooling needs is not considered in this study.

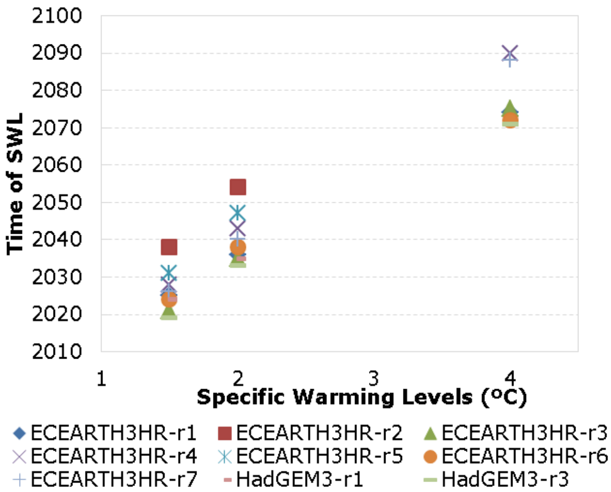
Finally, the modelling does not capture explicitly the way the evolution of technical progress and lifestyle change may influence energy uses over such a long-term time frame.

4 Results

The results in this report are shown in two different forms:

- first, the evolution in time of the input (HDD, CDD) and output data (heating demand, cooling demand);
- then, the level of these indicators for Specific Warming Levels (SWL) of 1.5, 2 and 4°C above pre-industrial temperatures – shown in Figure 12 for each scenario and each SWL.

Figure 12: Time at which Specific Warming Levels are reached for each studied scenario.



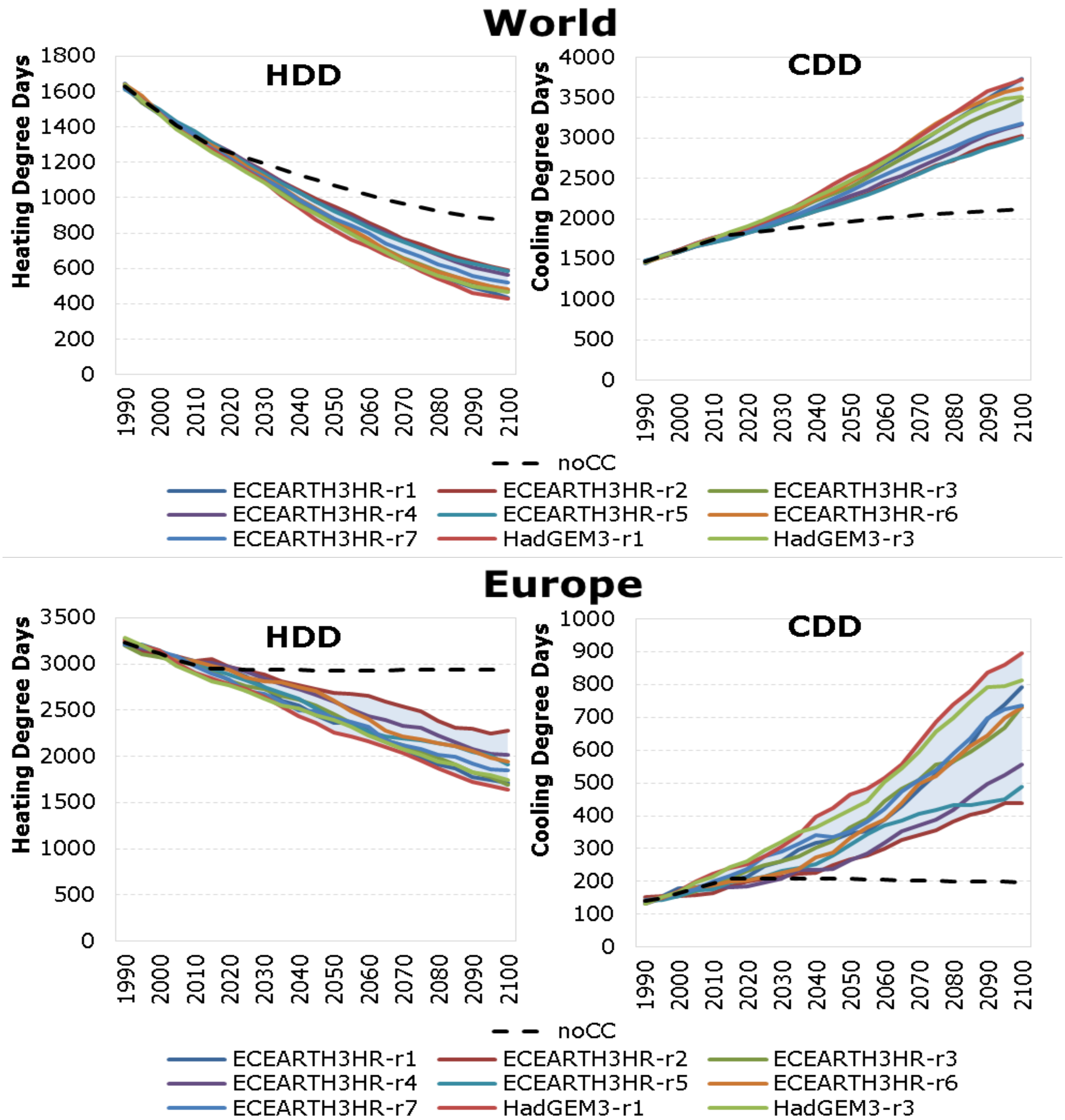
	RCP85		
Model	SWL:1.5	SWL:2	SWL:4
ECEARTH - R1	2025	2036	2074
ECEARTH - R2	2038	2054	n.a.
ECEARTH - R3	2021	2035	2075
ECEARTH - R4	2028	2043	2090
ECEARTH - R5	2031	2047	n.a.
ECEARTH - R6	2024	2038	2072
ECEARTH - R7	2026	2040	2088
HADGEM-R1	2024	2035	2071
HADGEM-R3	2019	2033	2071

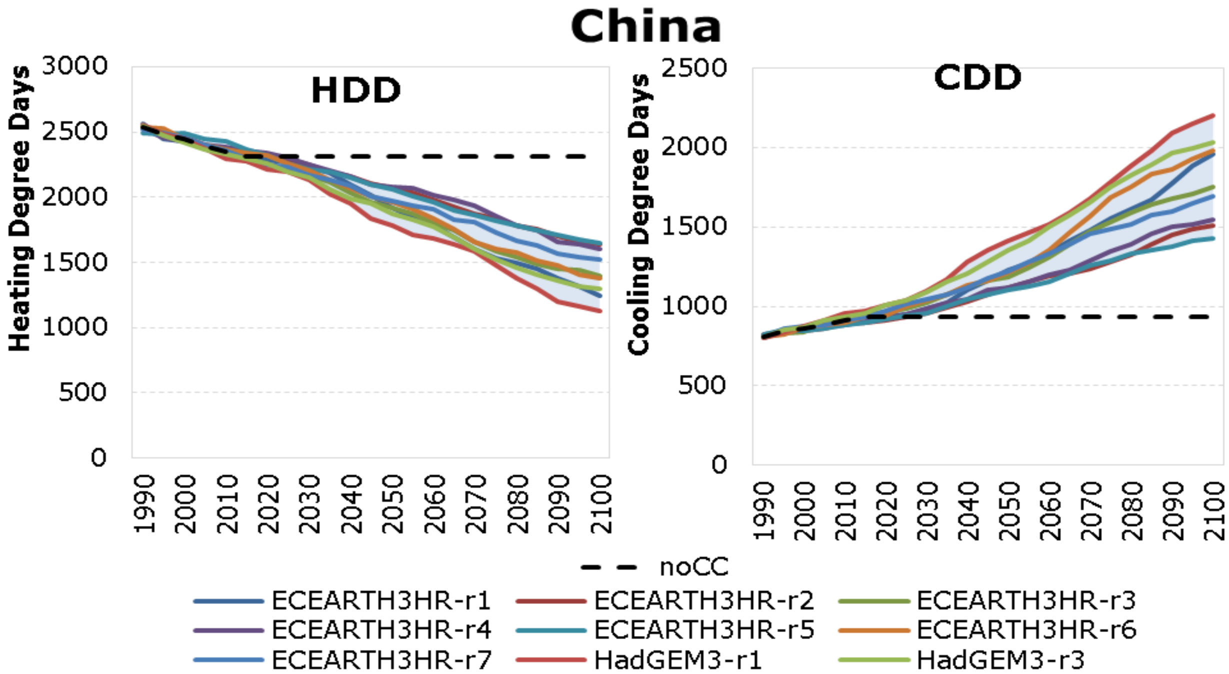
We choose to show results for the world as a whole, EU28, China and India.

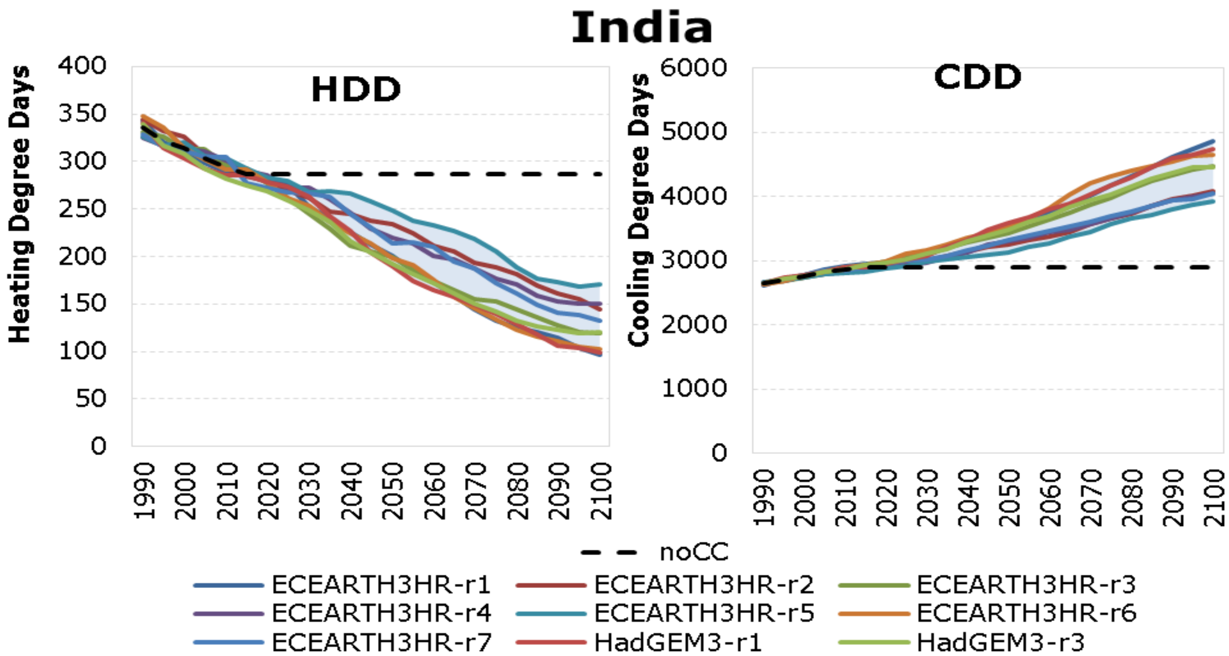
4.1 Processed climate data

Figure 13 below shows the evolution of the degree-days in all nine climate scenarios as used in POLES-JRC inputs, averaged over 30 years. The "no climate change" scenario is defined by temperatures fixed at the level of 2010 and is used as a point of comparison.

Figure 13: Evolution in time of HDD and CDD for the world, Europe, China and India. "noCC" stands for "no climate change".







We observe that all studied regions are warming throughout the century. They all see a decrease of cold days (HDD decrease by around 700 by 2100) and increase of hot days (CDD increase by around 1500 in the century).

However, even without climate change, the distribution of the population across countries implies that the global population will see on average higher temperatures (warmer countries see population increase, colder countries see population stagnation or decrease): the global population is expected to “naturally” (without climate change) see around 300 less HDD and 1200 more CDD by 2100.

India and China are among the most populated countries globally, and have high CDD (particularly India), which are expected to increase further. The focus on these countries will therefore allow to study the development of cooling needs in countries with fast developing economies.

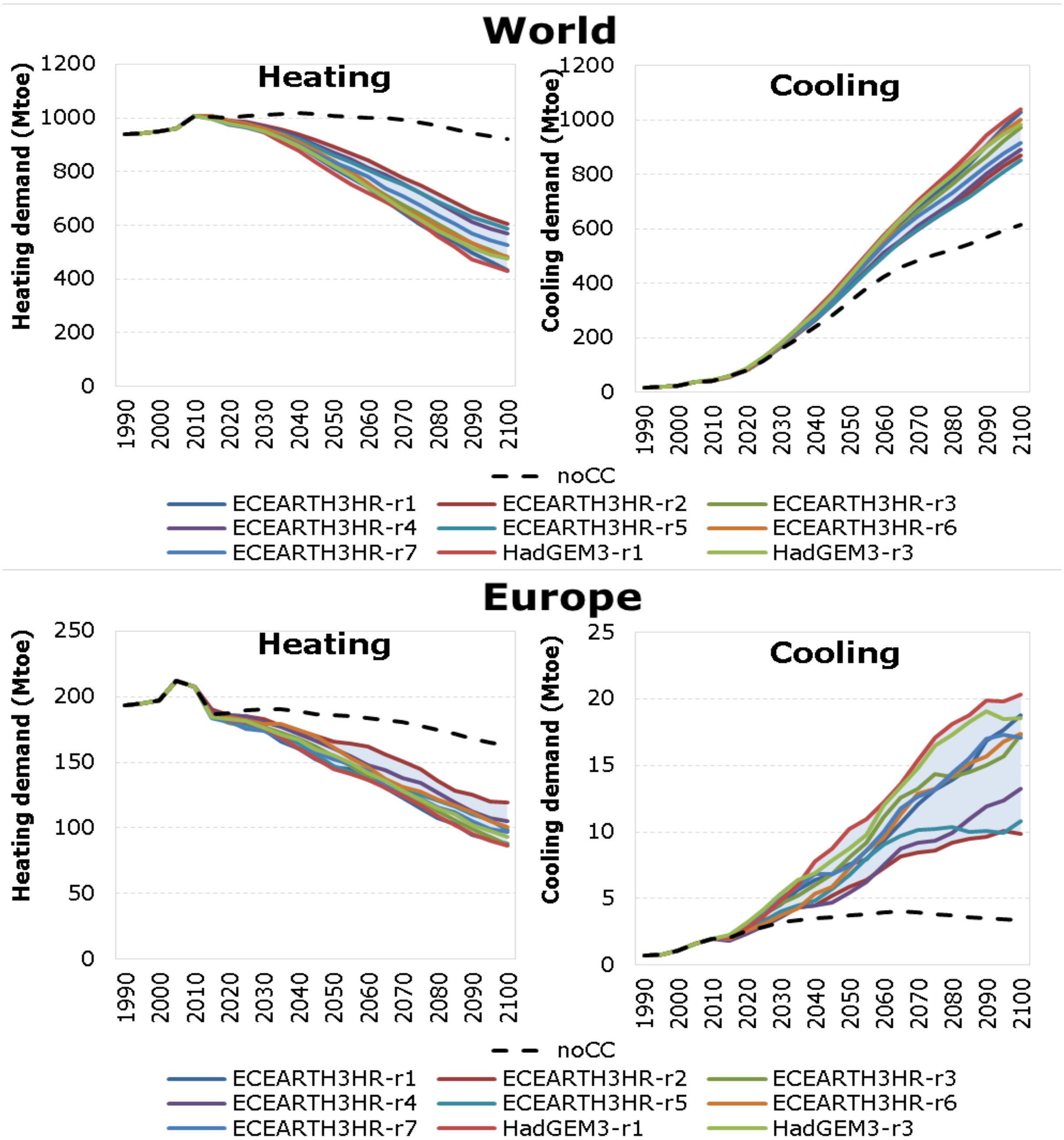
4.2 Climate impacts on energy

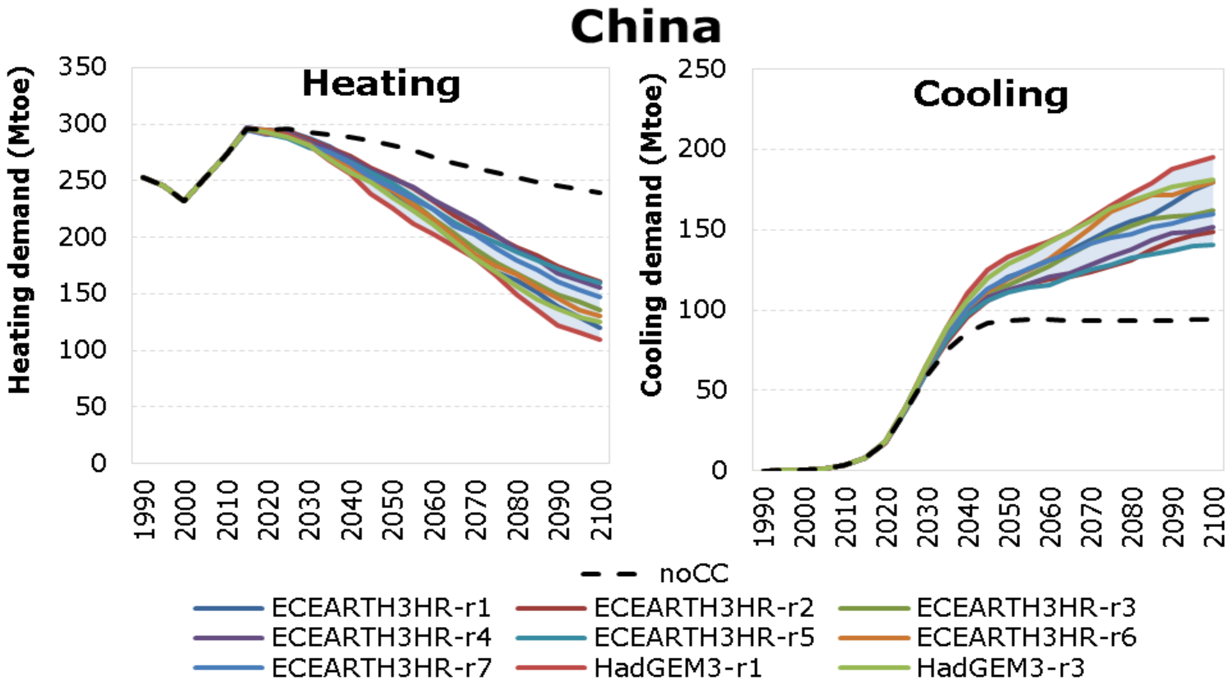
The results of the POLES-JRC scenario are presented below. First we show the evolution in time of heating and cooling needs for each region. Then we show the consumption for given Specific Warming Levels (SWL).

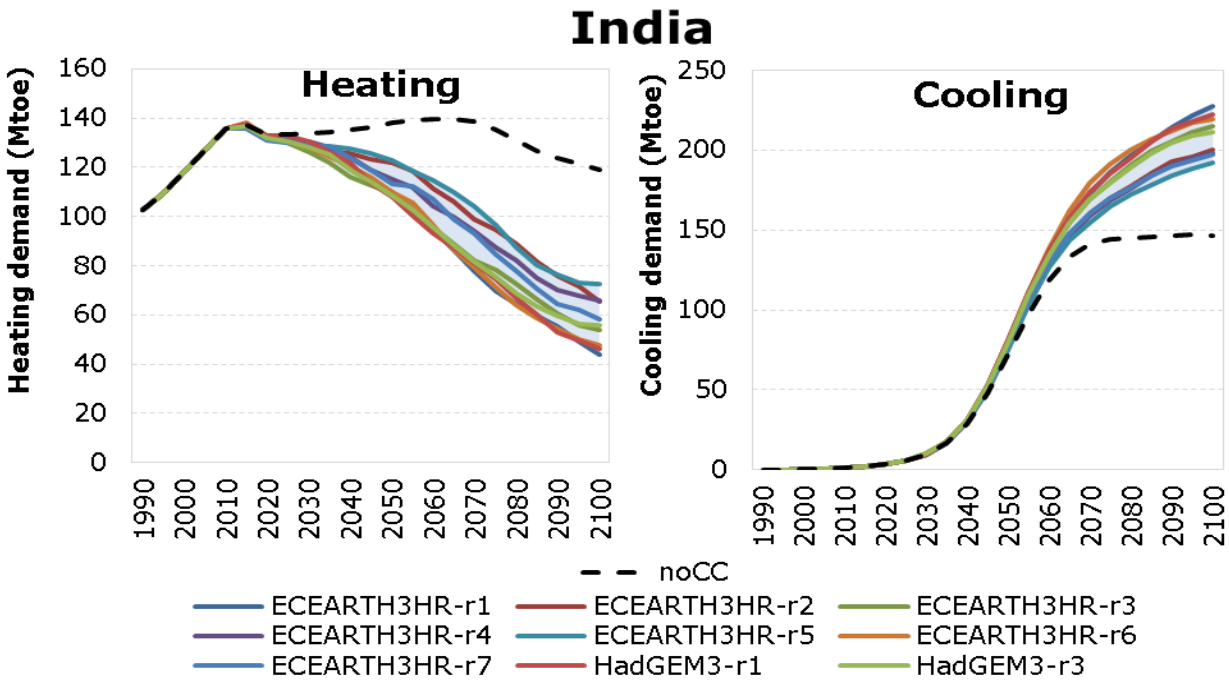
4.2.1 Energy consumption over time

The associated evolution of residential heating and cooling needs is shown in Figure 14.

Figure 14: Evolution in time of heating and cooling needs for the world, Europe, China and India. "noCC" stands for "no climate change".







The results show a decrease of residential heating needs by almost half by the end of the century, for the four cases studied (at the world and European level, in China and in India). The "no climate change" scenario shows a slight decrease because of a change in population distribution and the development of insulation.

The increase of energy demand for residential cooling is dramatic. At the global level, it will consume in 2100 roughly the same amount of final energy as residential heating today. Around 2070, the increasing residential cooling is expected to overcome the decreasing energy needs for residential heating. In Europe, cooling will remain much smaller than heating, but in China they are expected to be of same importance by the end of the century. India could represent more than a fifth of the global cooling needs by the end of the century. When comparing scenarios with and without climate change, we see that the increase of cooling energy demand is also expected to happen, although to a lesser extent. Indeed, the bulk of the expected increase in already hot countries can be attributed to two factors: an increase of population and an increase of income per capita. India or sub-Saharan Africa are good examples. Indeed, the scenarios show that most of the energy demand for cooling by 2040 would take place even without any climate change. The impact of increasing temperatures only becomes a driver in the 2nd half of the century.

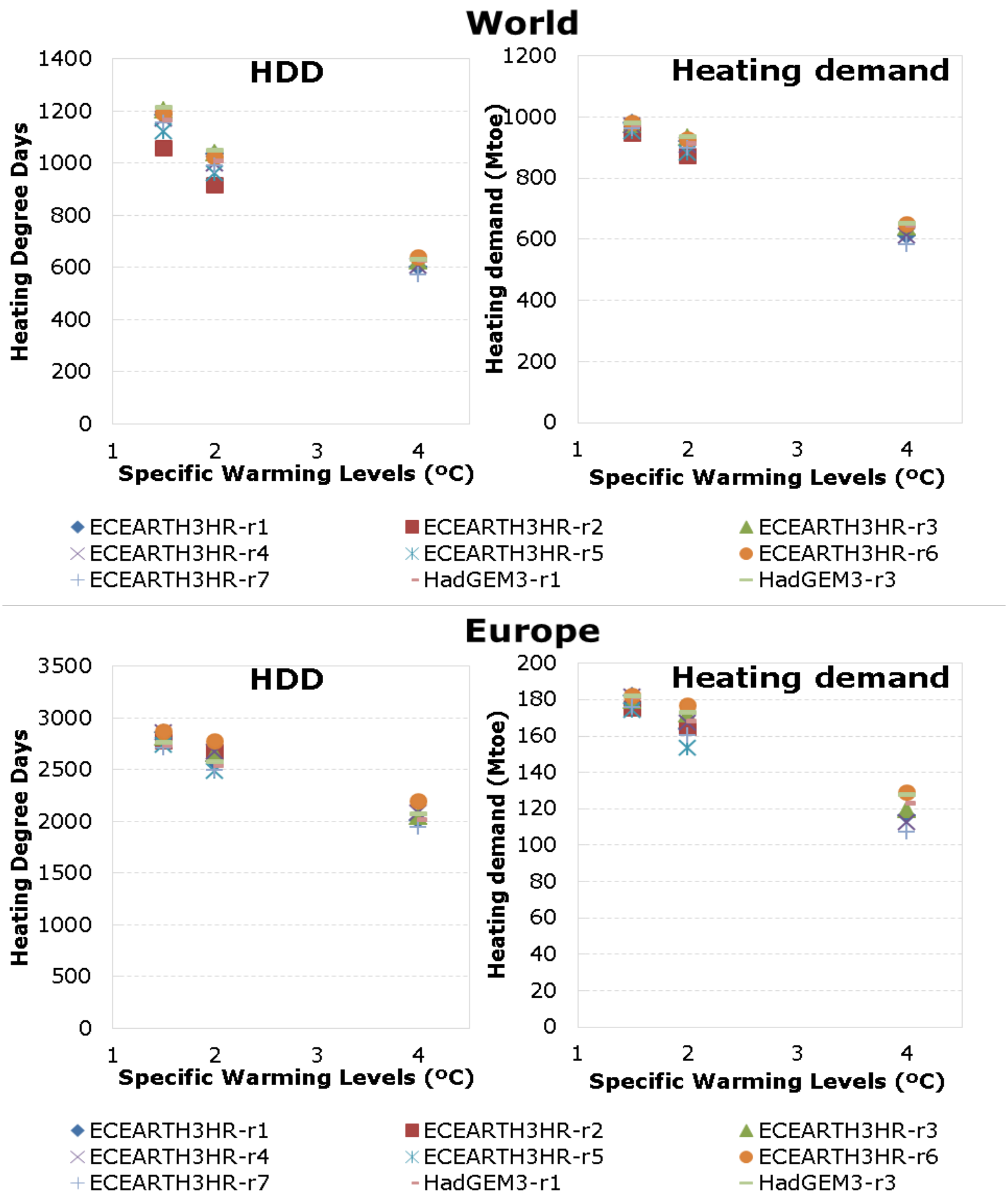
The combination of residential heating and residential cooling needs increases by around 50% in a century. This finding remains valid in the scenario with no climate change, although the share of cooling decreases from around two-thirds to around two-fifths.

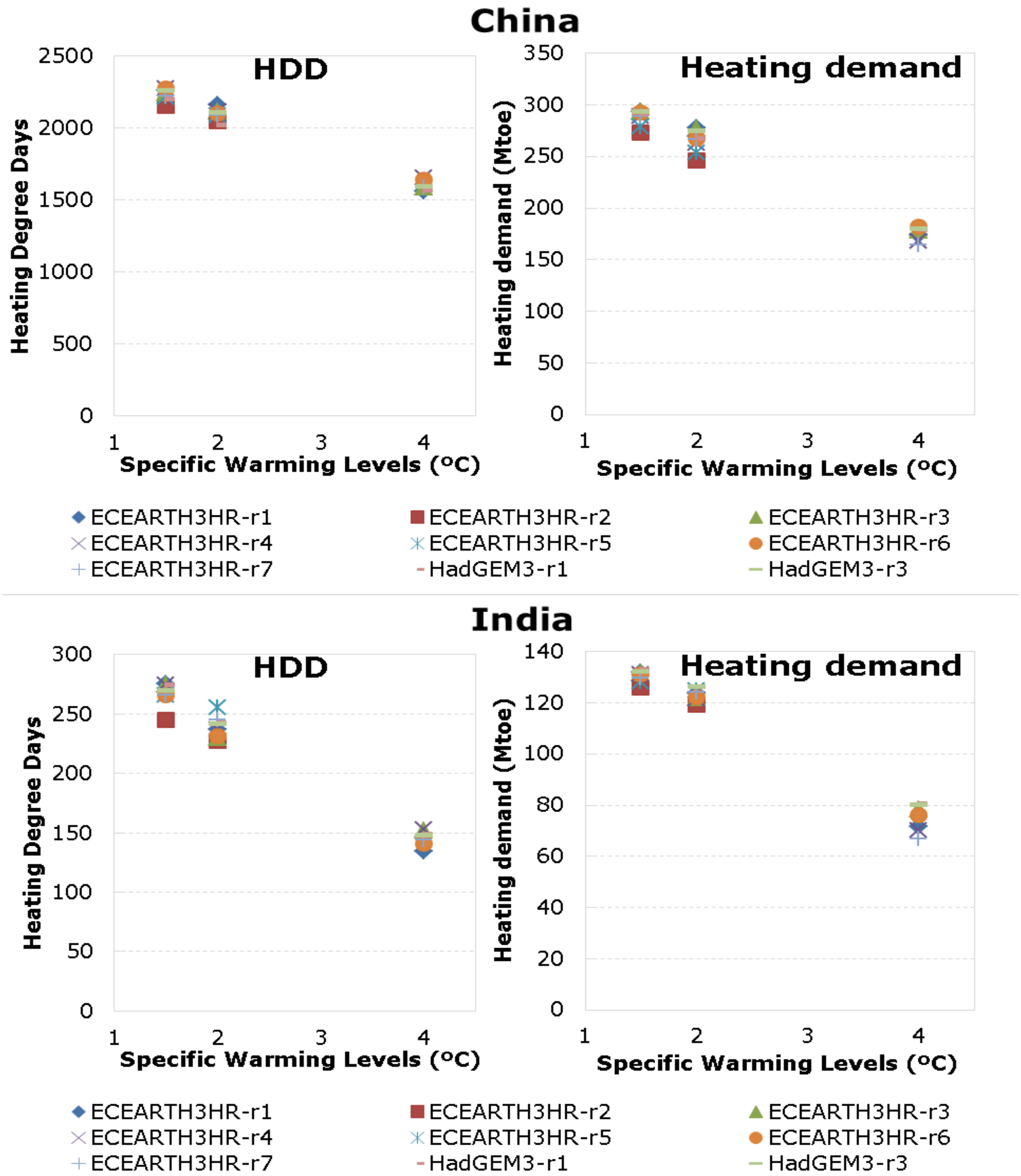
4.2.2 Energy consumption per SWL

4.2.2.1 *Heating*

First we show a comparison of the HDD and energy for residential heating in Figure 15.

Figure 15: HDD and heating needs at 1.5, 2 and 4°C SWL for the world, Europe, China and India.



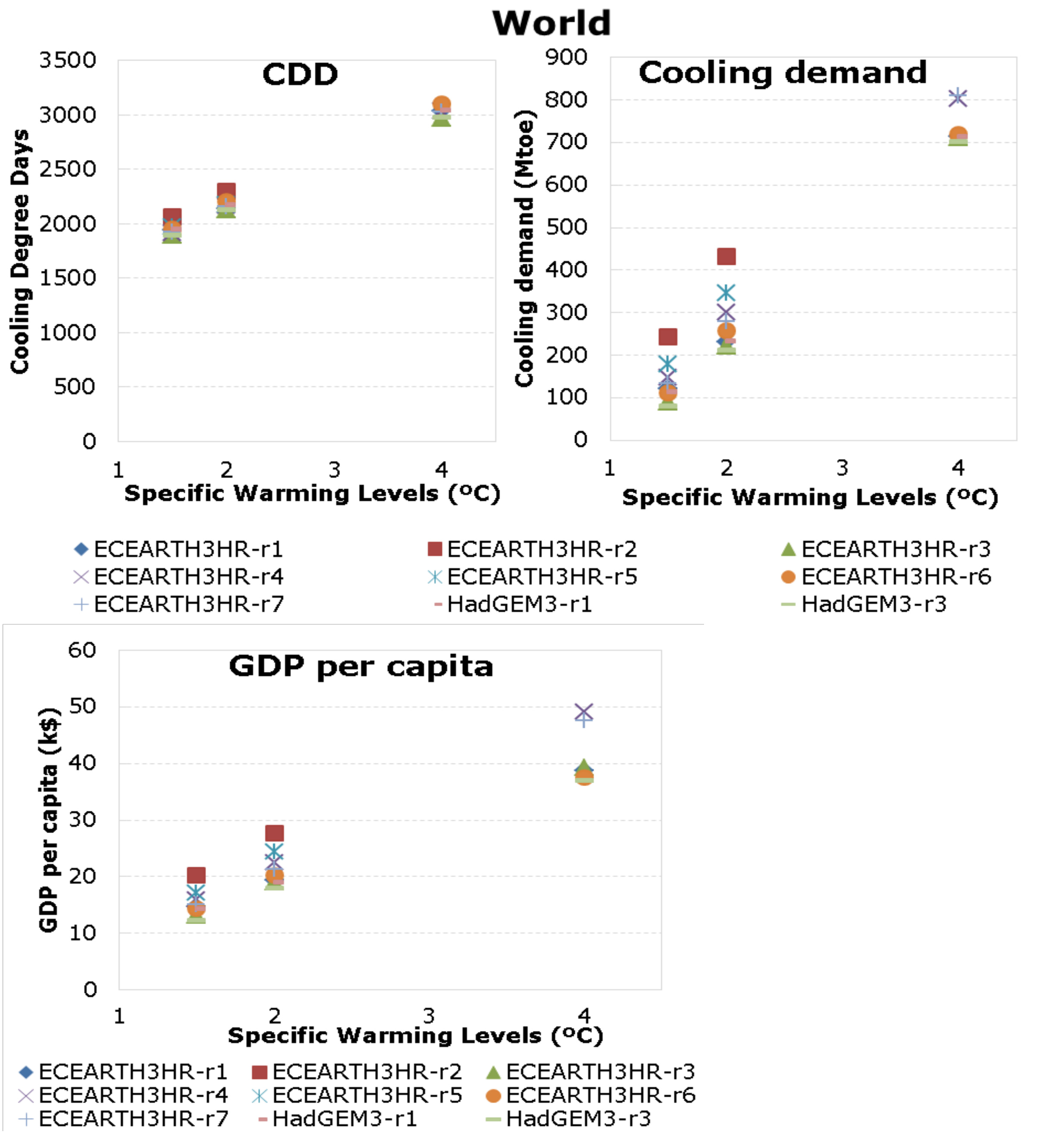


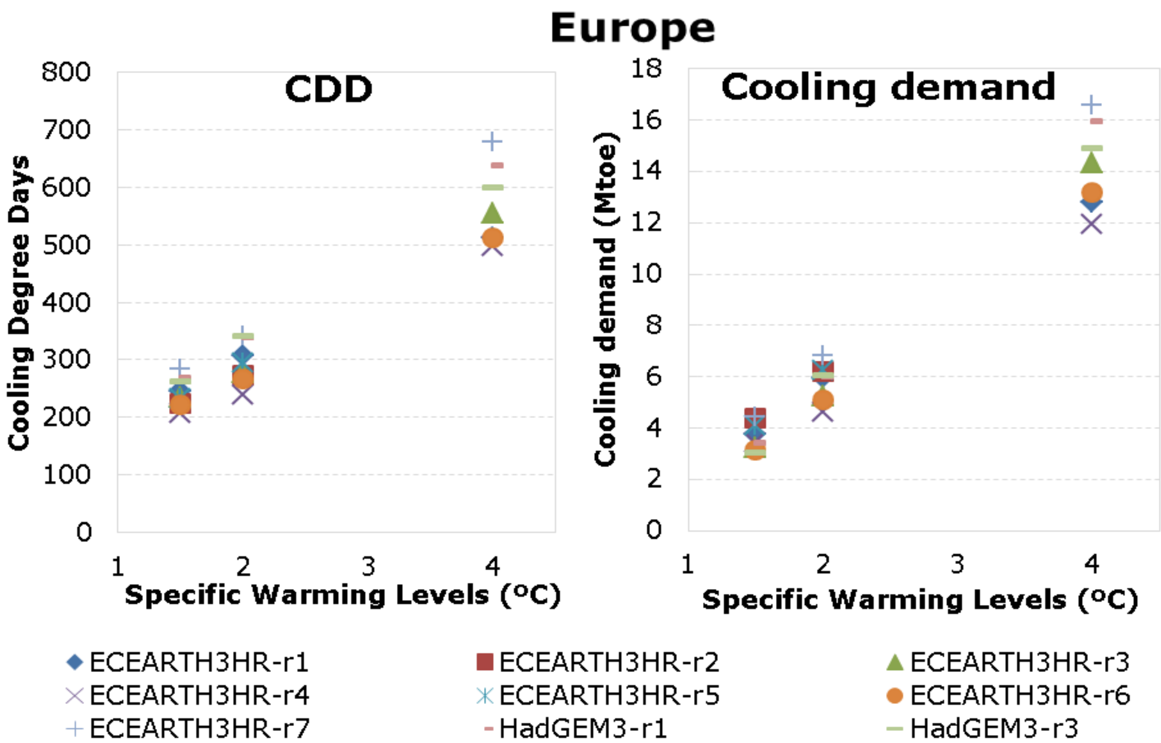
Just like in the previous section, Figure 15 shows a consistent and direct link between HDD and heating needs. For example, the Indian HDD decrease of 39% between SWL 2°C and SWL 4°C also corresponds to a decrease of heating demand of 39%. On a global level, HDD decrease by 38% between the SWL 2°C and the SWL 4°C, while heating needs decrease by 31%.

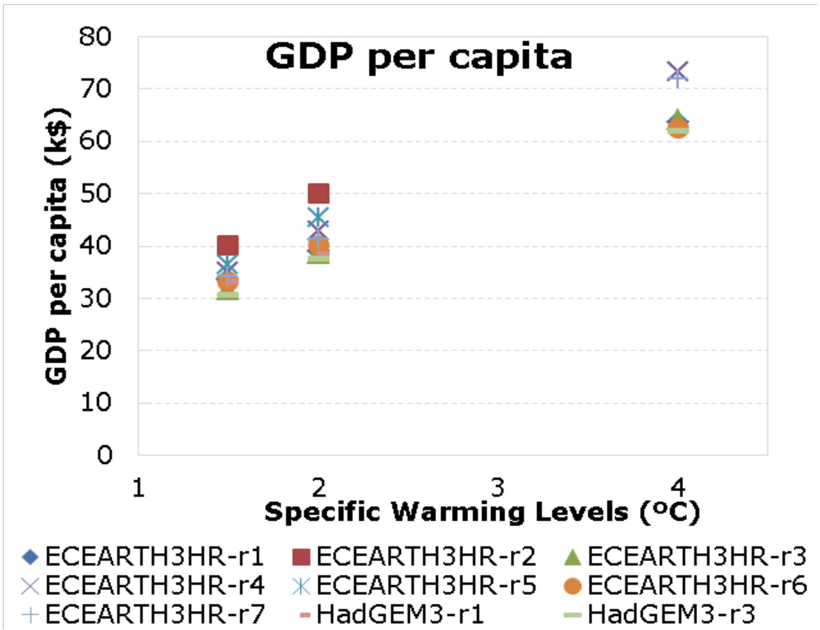
4.2.2.2 *Cooling*

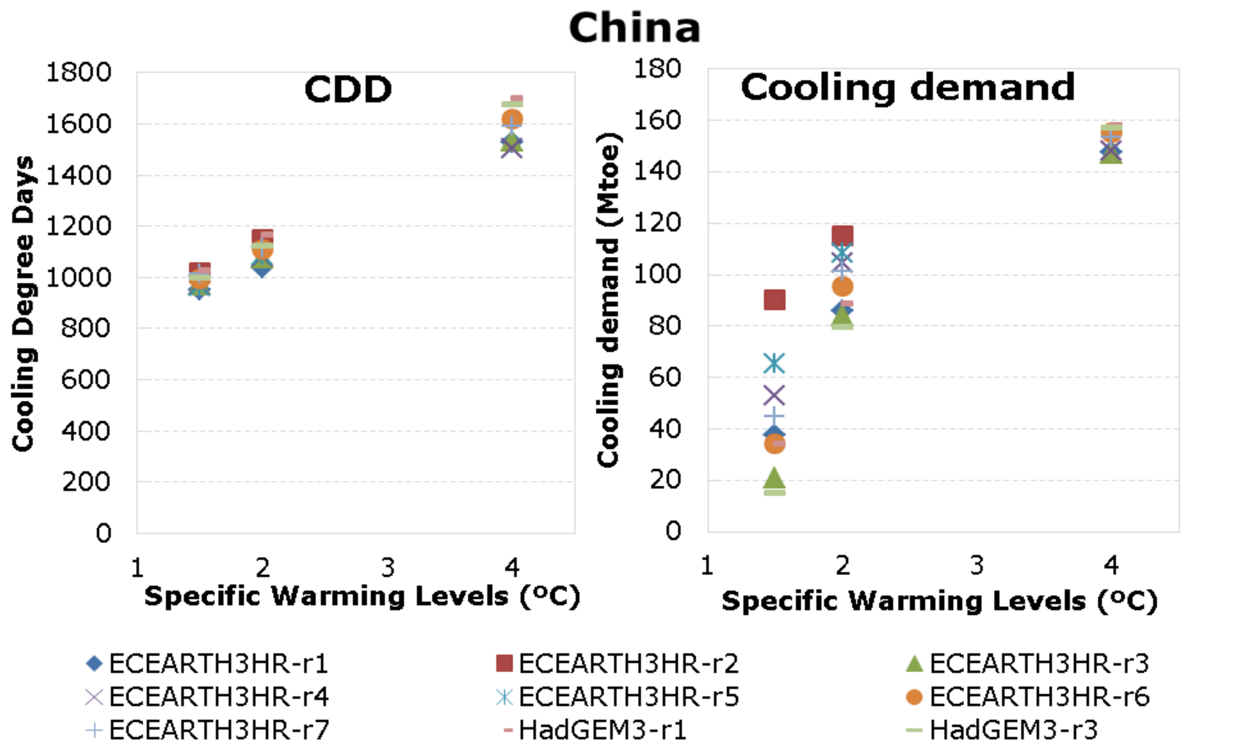
The link between CDD and cooling demand also exists. However, and unlike heating demand which concerns mostly developed countries that are already equipped, cooling will take place primarily in countries that are currently warm but poorly equipped: another important driver of AC equipment rate and future cooling demand in developing regions is income, also shown in Figure 16.

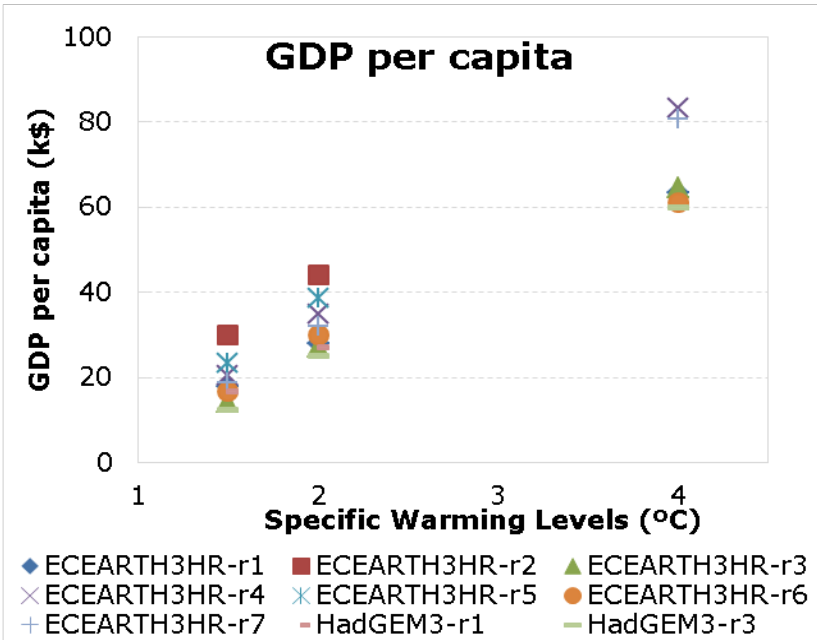
Figure 16: CDD, cooling needs and GDP per capita at 1.5, 2 and 4°C SWL for the world, Europe, China and India.

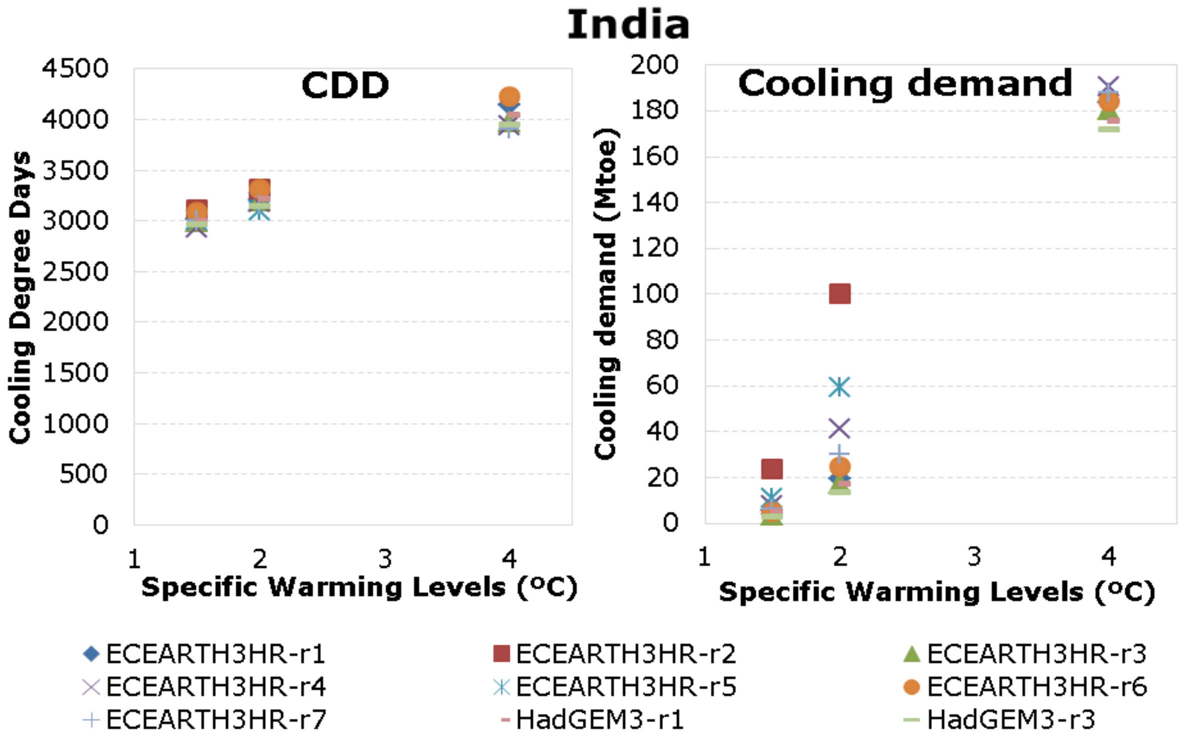


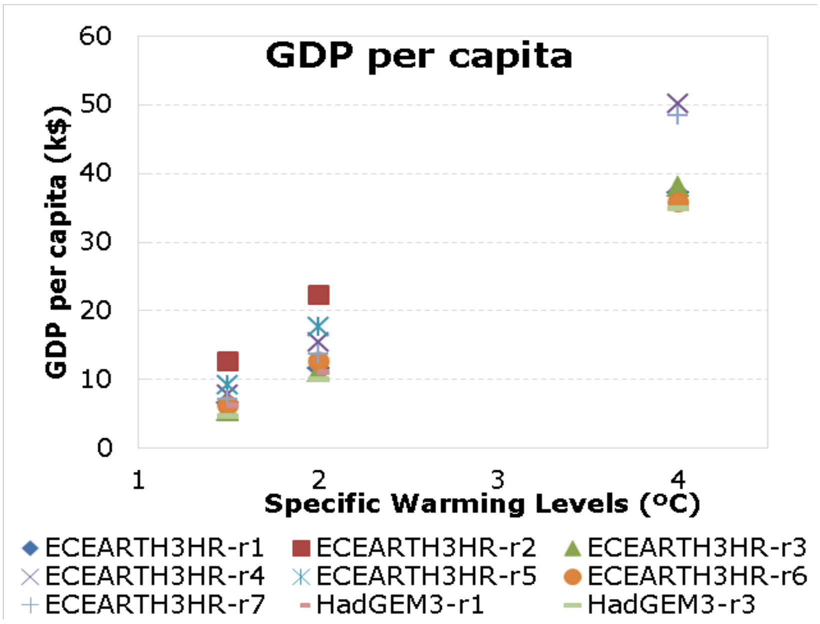

Europe
CDD
Cooling Degree Days
Specific Warming Levels (°C)
Cooling demand
Cooling demand (Mtoe)
Specific Warming Levels (°C)
ECEARTH3HR-r1
ECEARTH3HR-r2
ECEARTH3HR-r3
ECEARTH3HR-r4
ECEARTH3HR-r5
ECEARTH3HR-r6
ECEARTH3HR-r7
HadGEM3-r1
HadGEM3-r3


GDP per capita
GDP per capita (k$)
Specific Warming Levels (°C)
ECEARTH3HR-r1
ECEARTH3HR-r2
ECEARTH3HR-r3
ECEARTH3HR-r4
ECEARTH3HR-r5
ECEARTH3HR-r6
ECEARTH3HR-r7
HadGEM3-r1
HadGEM3-r3


China
CDD
Cooling Degree Days
0
200
400
600
800
1000
1200
1400
1600
1800
1
2
3
4
Specific Warming Levels (°C)
Cooling demand
Cooling demand (Mtoe)
0
20
40
60
80
100
120
140
160
180
1
2
3
4
Specific Warming Levels (°C)
ECEARTH3HR-r1
ECEARTH3HR-r2
ECEARTH3HR-r3
ECEARTH3HR-r4
ECEARTH3HR-r5
ECEARTH3HR-r6
ECEARTH3HR-r7
HadGEM3-r1
HadGEM3-r3


GDP per capita
GDP per capita (k$)
0
20
40
60
80
100
1
2
3
4
Specific Warming Levels (°C)
ECEARTH3HR-r1
ECEARTH3HR-r2
ECEARTH3HR-r3
ECEARTH3HR-r4
ECEARTH3HR-r5
ECEARTH3HR-r6
ECEARTH3HR-r7
HadGEM3-r1
HadGEM3-r3

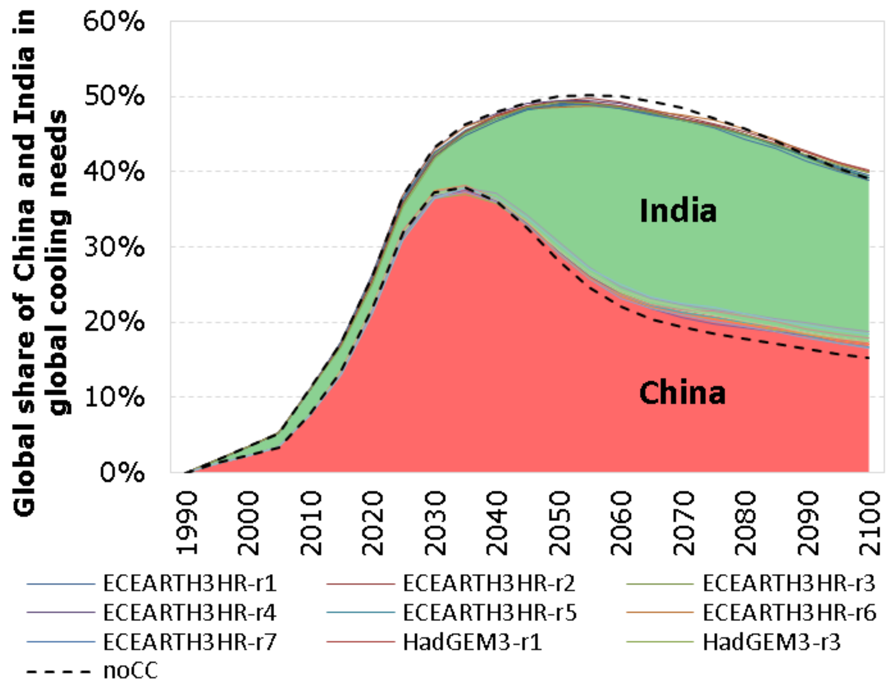




The connection between CDD and cooling demand is harder to see on the graphs compared to HDD and heating demand, since the evolution of incomes, and therefore, AC equipment rate, also plays a predominant role.

China and India show dispersed cooling demand associated with the SWL considered. In particular, China cooling demand is spread between 15 and 90 Mtoe in the 1.5°C SWL, and India is spread between 17 and 100 Mtoe in the 2°C SWL. This can be understood when looking at the year of SWL (Figure 12) and the evolution of cooling demand (Figure 14): the 2019-2038 period (1.5°C SWL) is a period of very strong development of cooling demand in China, and the 2033-2054 period (2°C SWL) sees strong development in India. This evolution is rather independent from CDD and has more to do with an increase of GDP per capita above 10-20 k$ (see Figure 16), meaning that many people come out of poverty and manage to acquire and use new AC equipment. Besides, the world total reflects the Indian and Chinese cooling developments, which make up around 50% of the global cooling by 2050 (40% by 2100), as shown in Figure 17. These factors explain that the global cooling needs in SWL of 1.5 and 2°C are quite dispersed.

Figure 17: Share of China and India in the total world cooling demand.



5 Conclusion

The study of the impacts of climate change on the energy sector with POLES-JRC shows a strong influence of temperatures on both heating and cooling needs. Heating needs are expected to decrease by a factor of two during the century, while energy for cooling needs will represent by 2100 as much (final) energy as today's energy consumption for heating needs.

Residential cooling is driven by both increased temperatures and increased revenues, which implies a higher AC equipment rate. China and India both face high temperatures, but they also see a strong economic development, respectively in the 2020's and the 2040's, which is the main explaining factor for the increasing cooling demand in the first part of the century. The impact of climate change is stronger in the second half of the century.

These findings emphasize the expected strong development of residential cooling in the century, which more than offsets the decrease of heating needs. The sum of heating and cooling is expected to increase by around 50% over the period. The hot developing countries like India will undergo dramatic evolutions of the electricity consumption for cooling needs. In order to mitigate the impact of expected rise in cooling energy demand, efforts should be focused on further improving the efficiency of cooling devices. Besides, the management of the electricity load will be impacted by the cooling demand, with potential extreme peak load. In a context with a large scale deployment of renewable energy sources, the correlation between cooling demand load and solar availability could be used to mitigate the impact of the cooling load.

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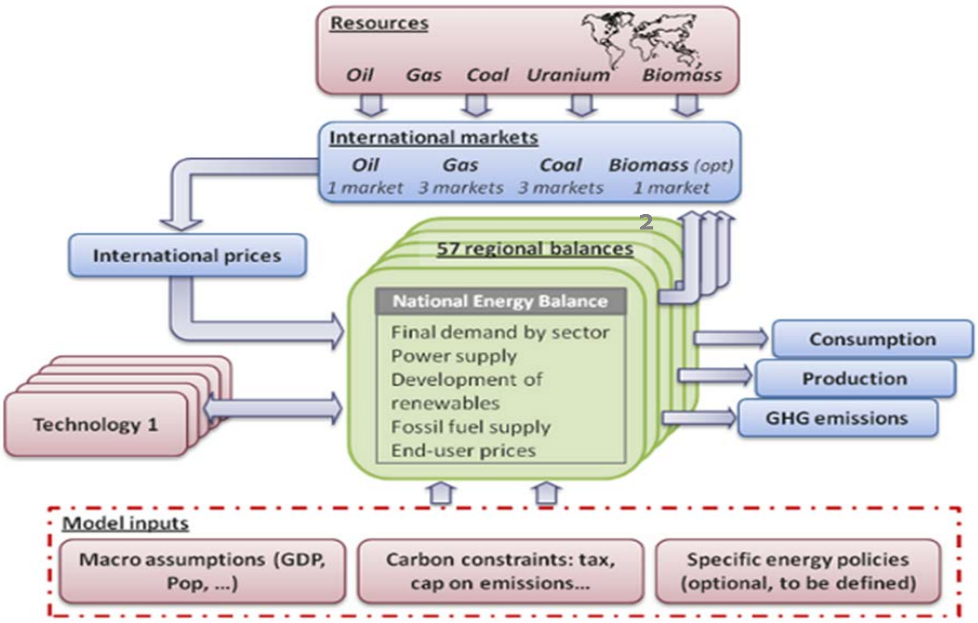
Annex A. POLES-JRC description

POLES (Prospective Outlook on Long-term Energy Systems) is a global energy model covering the entire energy system, from primary supply (fossil fuels, renewables, ..) to transformation (power, biofuels, hydrogen) and final sectoral demand. International market and prices of energy fuels are simulated endogenously. Its high level of regional detail (57 countries / regions) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES usually operates on a yearly basis up to 2050 (2100 in this exercise) and is updated yearly with recent information (2012 data for most series).

The JRC POLES-ADVANCE version[7] (as developed in 2015) has been used for this exercise, it includes a module on climate impact on energy demand in residential buildings. Differences with other exercises done with the POLES model by JRC in other projects, or by other entities (namely the University of Grenoble and Enerdata) can come from different i/ model version, ii/ historical data sets, iii/ parameterisation, iv/ policies considered.

Figure 18. POLES model general scheme



Source: Enerdata

Final demand

The final demand evolves with activity drivers, energy prices and technological progress. The following sectors are represented:

- industry: chemistry (energy uses and non-energy uses are differentiated), non-metallic minerals, steel, other industry;

[7] See http://themasites.pbl.nl/models/advance/index.php/ADVANCE_wiki

- buildings: residential, services (specific electricity uses are differentiated, different types of buildings are considered);

- transport (goods and passengers are differentiated): road (motorcycles, cars, light and heavy trucks – different engine types are considered), rail, inland water, international maritime, air domestic and international;

- agriculture.

Complementary information on the impact of climate on residential buildings is given in the section "Methodology" above.

Power system

The power system describes capacity planning of new plants and operation of existing plants for 40 technologies.

The planning considers the existing structure of the power mix (vintage per technology type), the expected evolution of the load demand, the production cost of new technologies, and resource potential for renewables.

The operation matches electricity demand considering the installed capacities, the variable production costs per technology type, the resource availability for renewables.

The electricity demand curve is built from the sectoral distribution over 2 typical days: one for summer and one for winter, each decomposed into twelve 2h blocks.

Electricity price by sector depend on the evolution of the power mix, of the load curve and of the energy taxes (by default kept constant).

Other sectors

The model also describes other energy transformations sectors: liquid biofuel (BTL), coal-to-liquid (CTL), gas-to-liquid (GTL), hydrogen (H2).

Oil supply

Oil discoveries, reserves and production are simulated in 80 individual countries and for 6 types of fuel: conventional crude & NGLs (inland and shallow water), tar sands, extra heavy oil, oil shale (kerogen), deepwater and arctic oil.

The market is structured along the market power of the different countries:

- non-OPEC production produces depending on remaining reserves, oil price and production cost;

- OPEC production adjusts to the evolution of demand and non-OPEC production;

- Gulf production can develop a spare capacity to adjust for short term variations, it adjusts to the evolution of demand and non-Gulf production.

International oil price depend on the evolution of spare capacity in the Gulf (short term: 1 year), global Reserve / Production ratio (long-term) and marginal production cost of non-conventional oil. Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Gas supply

Gas discoveries, reserves and production are simulated in 80 individual countries or regions for 4 types of gas: conventional gas (inland and shallow water), shale gas, deepwater and arctic gas. They supply 15 regional markets, made up of the national gas demand of the 57 countries and regions. 37 of the producers are considered as key producers with a capacity to export on international markets through trading routes. Gas transport is done through inland pipeline, offshore pipelines or LNG.

Gas price is simulated for 3 regional markets: Europe, America, Asia. It depends on the transport cost, the regional R/P ratio (long-term trend), the evolution of oil price and the development of LNG (integration of the different regional markets). Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Coal supply

Coal production is simulated in 74 individual countries or regions. Some countries (USA, Australia, China, India) have two or more production regions to better represent transportation costs which can represent a significant share of the coal delivery cost. They supply 15 regional markets, made up of the national coal demand of the 57 countries and regions. 26 of the producers are considered as key producers with a capacity to export on international markets through trading routes.

Coal delivery price for each route depends on the transport cost (international and inland), the mining cost, and other operation costs. An average delivery price is calculated for each of the 15 consuming markets. The model also calculates an average international price for 3 "continental" markets: Europe, Asia, America. Price to consumer considers the evolution of taxation, including the impact of a carbon value.

Biomass supply

The model differentiates 3 types of primary biomass: energy crops, short rotation crop (cellulosic) and wood (cellulosic). They are described for each of the 57 country through a potential and a production cost curve – in the case of SRC and wood this is derived from look-up tables provided by the specialist model GLOBIOM-G4M (Global Biosphere Management *Model)*.

Biomass can be traded, either in solid form or as transformed liquid biofuel.

Wind, solar and other renewables

These renewables are associated to potentials per country, which can be more detailed (in the case of wind and solar, where supply curves are used) or less (hydro, geothermal, ocean where only a potential figure is used).

GHG emissions

CO_2 emissions from fossil fuel combustion are derived directly from the energy balance, that is influenced by mitigation policies (carbon value, support policies to technologies, energy efficiency targets).

Other GHGs from energy and industry are simulated using activity drivers identified in the model (sectoral value added, mobility per type of vehicles, fuel production,..) and abatement cost curves.

GHG from agriculture and LULUCF are derived from GLOBIOM-G4M lookup tables.

Regional coverage

Table 2: POLES-JRC regional coverage (57 countries and regions, incl. 28 EU Member States)

Europe	CIS	North America	Latin America	Africa	Middle East	Asia
Detailed EU28	Russia	USA	Mexico	Egypt	Gulf	Japan
Switzerland	Ukraine	Canada	Rest Central America	Morocco & Tunisia	Mediterranean Middle East	Korea, Rep.
Norway	Other CIS					China
Iceland			Brazil	Algeria & Libya		Indonesia
Former Yugoslavia (excl. Croatia)			Rest South America	South Africa		India
Turkey				Rest Sub-Saharan Africa		Oceania (inc. Australia & New-Zealand)
						Rest South-East Asia
						Rest South-Asia