Enabling Climate Information Services for Europe

DELIVERABLE 6.17

Report on high resolution estimates of 2030-2060 summer temperatures

Activity:	*WP6 – Energy*
Activity number:	*Task 6.8 – Future energy demand in Italy*
Deliverable:	*Report on high resolution estimates of 2030-2060 summer temperatures*
Deliverable number:	*6.17*
Authors:	*Michele BRUNETTI – ISAC-CNR* *Maurizio MAUGERI – University of Milan* *Simone SCAPIN – ISAC-CNR, University of Milan, RSE S.p.A.* *Francesco APADULA – RSE S.p.A.*

The work leading to this publication has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 265240.

Summary

This report describes the activities performed by ISAC-CNR to produce Deliverable 6.17 of the ECLISE Project – High-resolution estimates of 2030-2060 summer temperatures. These activities were performed within task 6.6 - Future energy demand in Italy that also allowed producing deliverable 6.16 – High-resolution gridded temperature dataset over Italy for the past 5 decades. Deliverable 6.17 was produced in order to fulfil RSE (Ricerca sul Sistema Energetico, one of the users of the ECLISE Project) needing. The estimated high-resolution future temperatures were used as input data of a model, developed in cooperation with RSE, in order to assess the impact of temperature on Italian electricity demand. The application of the model to scenario data allowed investigating the sensibility of the present-day electricity demand to climate variability and change.

1. Introduction

A number of recent papers have shown that temperature has a strong impact on electricity demand in many areas of the world (see e.g. Feinberg and Genethliou, 2005 and Apadula et al. 2012).

A common strategy to measure this impact consists in using degree-days: they are proportional to the amount of heat that has to be pumped out form buildings (cooling) - or added to buildings (heating) - in order to maintain an indoor comfortable temperature. Degree-days are defined for cooling (*CDD*) as $max\{T - T_{S_1}, 0\}$ and for heating (*HDD*) as $max\{T_{S_2} - T, 0\}$, where T is daily mean temperature and T_{S_1} and T_{S_2} are threshold values, which are usually different. There is no general agreement about threshold temperatures to be used, so they are optimized case by case.

In this context, a linear model linking the Italian daily aggregate electricity demand in the 1990-2013 period to minimum and maximum temperatures and solar radiation was developed. The model is based on the superimposition of deterministic components related to the weekly cyclical demand pattern and to long-term demand changes and on weather sensitive components. The weather sensitive components are related to cooling degree-days (*CDD*), heating degree-days (*HDD*) and solar radiation, the latter being estimated using daily temperature range as a proxy (Hunt et al., 1998). The model and the results we obtained applying it to the Italian electricity demand in the 1990-2013 period are described in Scapin et al. (2014). The novelty of the results presented in that paper relies on the explicit estimation of the time evolution of the impact of these weather sensitive components on Italian daily aggregate electricity demand.

In this report, after a brief presentation of the model, we focus on the construction of *CDD*, *HDD* and solar radiation records representative of the entire Italian territory. These records were first estimated for the latest decades. Then projections for the XXIth century were obtained using 4 different RCM-GCM combinations and considering the A1B scenario. Finally, considering the present-day relations among meteorological variables and electricity demand, we use the *CDD*, *HDD* and solar radiation future projections to investigate the sensibility of the present-day electricity demand to climate variability and change.

2. Temperature dependence of the Italian electricity demand

The model we use in order to study the temperature dependence of the Italian daily electricity demand (*D(t)*), assumes that it can be described by means of the following relation:

$$D(t) = \sum_{i=0}^{3} \alpha_i t^i + \sum_{j=1}^{4} \beta_j I_j(t) + \sum_{k=1}^{3} \gamma_k V_k(t) + \varepsilon(t) \qquad (1)$$

where:

- The first term consists of a third order polynomial which aims to evaluate the temporal evolution of electricity demand caused by the economic conjuncture and by long-term changes in consumption habits. We found that higher order polynomials do not increase the predictive ability of the model.
- The second term consists of dummy variables $I_j(t)$, introduced in order to account for the strong weekly pattern of electricity demand. In particular $I_1(t)$ is set to 1 on Monday and 0 otherwise; in analogy, $I_2(t)$, $I_3(t)$ and $I_4(t)$ are used to model the behaviour of Friday, Saturday and Sunday. No dummy variables are used for central weekdays (Tuesday, Wednesday, Thursday) which can be

grouped together since they exhibit similar behaviour. In this way, the dummy variable term accounts for the differences between central weekdays and the rest of the week.

- The third term consists of a summation over three exogenous variables (V_k), describing the influence of weather factors over the Italian electricity demand. In particular these variables are cooling degree-days (*CDD*), heating degree-days (*HDD*) and solar radiation (*S*), obtained according to a procedure explained in the next paragraph.
- The last term represents the error of the model (i.e. the difference between the actual and the estimated demand).

The coefficients α_i , β_i and γ_i of relation *(1)* are obtained by means of least squares regression.

We applied the model to the Italian aggregated National electricity demand of ordinary days considering twelve two-year periods, starting from 1990-1991 and ending in 2012-2013 (Scapin et al., 2014). This allowed us to get both the evolution of the electricity demand characteristics and, at the same time, to acquire a statistically significant number of points for the regressions.

3. Italy National *CDD, HDD* and solar radiation records

3.1 Construction of the model exogenous variables

The *CDD*, *HDD* and solar radiation records considered in relation *(1)* were obtained with a bottom-up approach: first, local *CCD*, *HDD* and solar radiation records were estimated for all Italian points of a 30-arc-second-resolution digital elevation model (GTOPO30, USGS, 1996) that are urbanised according to GLC2000 land cover (European Commission, Join Research Center, 2003), then an average was computed over them. The number of GTOPO30 Italian urban grid-points is 13110 (see figure 1).

The construction of the grid-point *CCD*, *HDD* and solar radiation records will be described in the next paragraphs.

3.2 Construction of grid-point temperature records

The first step to evaluate daily *CDD*, *HDD* and solar radiation records for each Italian urbanised grid-point consisted in estimating the corresponding T_n and T_x temperature records (we define daily mean temperature (T_m) as $(T_n+T_x)/2$). For this purpose we used the technique discussed by Brunetti et al. (2009; 2012), which was extensively applied over the Italian territory in order to reconstruct past evolution of temperature at high spatial resolution (see deliverable 6.16). The underpinning idea of the method is that the spatio-temporal structure of temperature (*T*) on a given Julian day *j* can be described by the superimposition of a climatological field (given by local averages for day *j* over a reference period) and a time-dependent anomaly field (*A*).

$$T(\lambda,\theta,t)=\overline{T_j(\lambda,\theta)}+A(\lambda,\theta,t) \tag{2}$$

where λ and θ are the geographical coordinates and *t* is time, which is here considered at daily resolution.

The climatological field of a given Julian day depends on the geographical properties of the territory (elevation, latitude, longitude, etc.) and shows considerable spatial gradients, especially in presence of complex orography such as in the Italian case. On the contrary, the anomaly field usually exhibits strong spatial coherence; its short-term variability is associated with weather conditions, while its long-term evolution is linked to climate change.

In order to estimate the temperature anomaly records (T_n, T_m and T_x) corresponding to each Italian urbanised grid-point $A(\lambda_g,\theta_g,\ t)$), we considered a network of 92 daily minimum and maximum temperature series homogenized and completed in the frame of the ECLISE Project. First we transformed the data into anomalies ($A_j(\lambda_j,\theta_j,t)$), taking the period 1961-1990 as a reference for the computation of daily climate normals. Then we projected the station anomalies onto the grid-point by means of the following method:

$$A(\lambda_g,\theta_g,t)=\sum_j w_j(\lambda_g,\theta_g,t)A_j(\lambda_j,\theta_j,t) \tag{3}$$

$$w_j(\lambda,\theta,t)=\alpha\ exp\left(-\frac{d_j(\lambda,\theta)^2}{\tau_d{}^2/\ln(2)}\right)\ exp\left(-\frac{\Delta z_j(\lambda,\theta)^2}{\tau_z{}^2/\ln(2)}\right) \tag{4}$$

where $d_j(\lambda,\theta)$ and $\Delta z_j(\lambda,\theta)$ are, respectively, the distance and the elevation difference between the position (λ_g,θ_g) of the grid-point under analysis and the j-th station and τ_d and τ_z, - here assumed respectively equal to 80 km and 400 m - describe the extent to which a single observation is weighted with respect to distance and elevation: exponentials decrease by half when distance reaches τ_d and, in analogy, when elevation difference equals τ_z. The coefficient $\alpha = 1/\sum_i w_i(\lambda,\theta,t)$ is a normalization term.

Once the daily temperature anomaly records (T_n, T_m and T_x) were available for all urbanised grid-points, the corresponding absolute value records were obtained by simply superimposing daily climate normals to the anomaly records. These grid-point normals were obtained fitting the monthly grid-point normals computed as described in Brunetti et al. (2014) (see deliverable 6.16), by means of the first two harmonics of a Fourier series.

3.3 Use of the effective temperature

Once we estimated daily temperature records for all Italian urbanised grid-points, we considered that the request for heating and cooling also depends on past temperature as local buildings have significant thermal inertia. To account for this effect we used the following effective temperature T^*, a delayed signal obtained through exponential smoothing of the temperature series:

$$T^*(t) = \beta T^*(t-1) + (1-\beta)T(t) \qquad (5)$$

with time (t) expressed in days.

The extent of smoothing is tuned by β. We set it equal to 0.5, in accordance with Taylor and Buizza (2003). The effective temperature index was computed for daily mean temperature only.

3.4 Construction of grid-point *CDD* and *HDD* records

In order to capture the non-linear response of electricity demand to temperature, we considered piecewise linear functions, namely degree-days.

Cooling degree-days are defined as:

$$CDD(t) = max\{T(t) - T_{S_1}, 0\}$$

where T is the grid-point daily mean temperature.

In analogy, heating degree-days are defined as:

$$HDD(t) = max\{T_{S_2} - T(t), 0\}$$

The thresholds values T_{S_1} and T_{S_2} are arbitrary, and there is no general agreement on their optimal choice. In this study we determined them by minimizing model errors, finding $T_{S_1} = 20°C$ and $T_{S_2} = 15°C$.

3.5 Construction of district solar radiation records

The grid-point daily extreme temperature records (T_n and T_x) were used to estimate grid-point global solar radiation records (H) by means of the following formula (Hunt et al., 1998):

$$H(t) = a_0 H_0 \Delta T(t)^{0.5} + a_1 \qquad (6)$$

where a_0 and a_1 are site-dependent empirical coefficients, ΔT is the daily temperature range (T_x-T_n) and H_0 is the exo-atmospheric radiation on the horizontal plane, i.e. the daily integral of solar irradiance that would be observed on a horizontally oriented surface placed at the top of the atmosphere. H_0 can be easily determined by standard computation (see e.g. Iqbal (1983), whereas a_0 and a_1 can be recovered from previous studies. We used for the entire Italian territory the values proposed by Abraha and Savage (2008) ($a_0=0.190\ K^{-0.5}$, $a_1=-2.041 MJ\ m^{-2}$) for Padua (northern Italy).

In order to relate the influence of solar radiation on electricity demand we introduced the following piece-wise linear function:

$$S(t) = max\{H_S - H(t), 0\}$$

The threshold value $H_S=17\ MJ\ m^{-2}$ was selected by minimizing the model errors. Beyond this threshold the effect of an increase of solar radiation does not produce any decrease of the electricity demand.

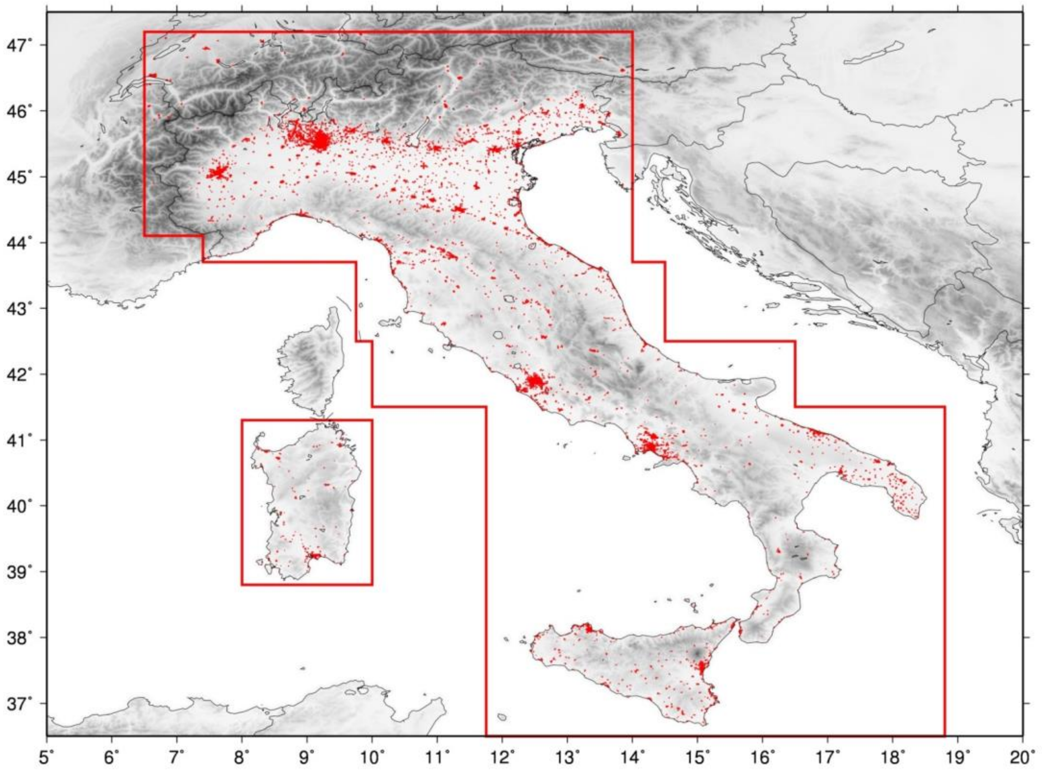

Figure 1 – Grid-points corresponding to urbanised areas according to GTOPO30.

4. *Impact of CDD, HDD* and solar radiation on the Italian electricity demand

Within the ECLISE project, in collaboration with RSE, we studied the impact of *CDD*, *HDD* and solar radiation on the Italian electricity demand. The results of these investigations are discussed in Scapin et al. (2014). They show that relation *(1)* explains from 97.7% (2008-2009) to 99.4% (1996-1997) of the variance of the Italian daily demand record (ordinary days only), with a mean absolute percentage error (MAPE) included in the 0.78% – 1.18% interval for all periods excluded 2008-2009 (MAPE=1.44%), which has a break in the demand record, due to the global economic crisis, which was not easy to account for using this model. Moreover, they show that relation *(1)* establishes a strong contribution of cooling degree-days to the Italian electricity demand, with values peaking in summer months of the latest periods up to more than 200 GWh day^{-1} (i.e. about 23% of the corresponding average Italian electricity demand). This contribution shows a strong positive trend in the 1990-2013 period: the coefficient of the cooling degree-days term in the regression model increases from the first two-year period (1990-1991) to the last one (2012-2013) by a factor 3.5, which is much greater than the increase of the Italian total electricity demand (figure 2). On the contrary, the HDD and solar radiation contributions have trends comparable to that of the electricity demand. The data of the last 3 two-year periods allow quantifying the present-day dependence of the Italian electricity demand of an ordinary day on *CDD* in 24.6 GWh day^{-1} °C^{-1}. For HDD and solar radiation we prefer quantifying this dependence considering the average values over the latest 6 two-year-period coefficients. The values are, respectively, 6.6 GWh day^{-1} °C^{-1} and 2.9 GWh day^{-1} MJ^{-1} m^{2}.

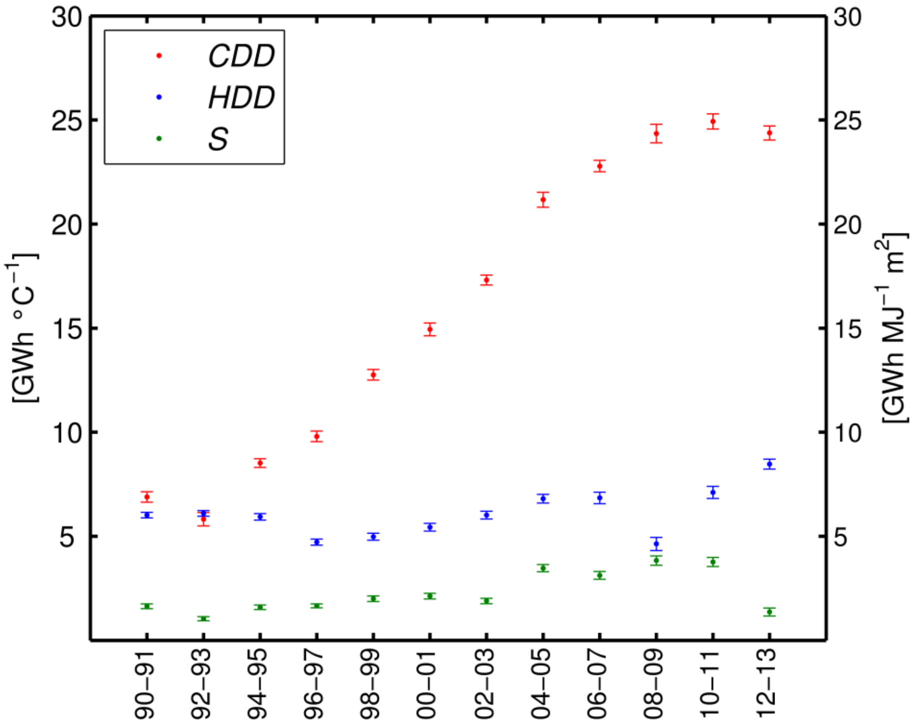

Figure 2 - Coefficients of the CDD, HDD and solar radiation terms of relation (1) in the 12 two-year periods of the 1990-2013 interval.

5. Scenarios for the XXIth century

5.1 Regional Climate Models

Thanks to the robust high-resolution past reconstruction of temperature for Italy (see section 3 and Deliverable 6.16), it was possible to evaluate the ability of 4 RCM–GCM combinations in reproducing temperature variability and change in this area. Specifically, four RCM-GCM combinations were taken into account from the ENSEMBLES project: KNMI-ECHAM5, SMHI-ECHAM5, SMHI-BCM and SMHI-Had. We considered the historical run of the models forced by GCM and their future projections under the A1B scenario.

We first transformed the model data into anomalies with respect to the 1961-1990 normals and used these anomalies to get urbanised grid-points anomaly records by means of the procedure outlined in section 3. Then we detrended these records and compared day-to-day variability with the day-to-day variability of the corresponding observational detrended grid-point anomaly records. The comparison was performed considering the different months of the year and analysing all Italian urbanised grid-points. It allowed calculating the ratios between the standard deviations of the projected and the observational detrended records. These ratios depend on both the month of the year and the position of the grid-point.

The seasonal behaviour is shown in figure 3, that gives evidence of the distributions of the grid-point ratios by means of box-plots: the central boxes correspond to the first, second and third quartiles, whereas the vertical lines indicate the absolute range covered by the ratios. The most evident result concerns spring months that show a general tendency to have a reduced variability in the model data with respect to observational data. An opposite behaviour is generally present in autumn and winter.

The spatial pattern of the ratios is shown in figure 4 for March, June, September and December. The most evident result concerns some coastal areas showing a reduced variability in the model data with respect to observational data.

The ratios shown in figures 3 and 4 were used to get the multiplicative correcting factors to adjust the scenario anomalies: they are simply the inverse of these ratios. After the correction, the monthly detrending curves were added to the records in order to obtain adjusted projected grid-point anomaly records. The anomalies were then converted into absolute values as outlined in section 3 (i.e. by means of the superimposition of the anomaly and climatology fields).

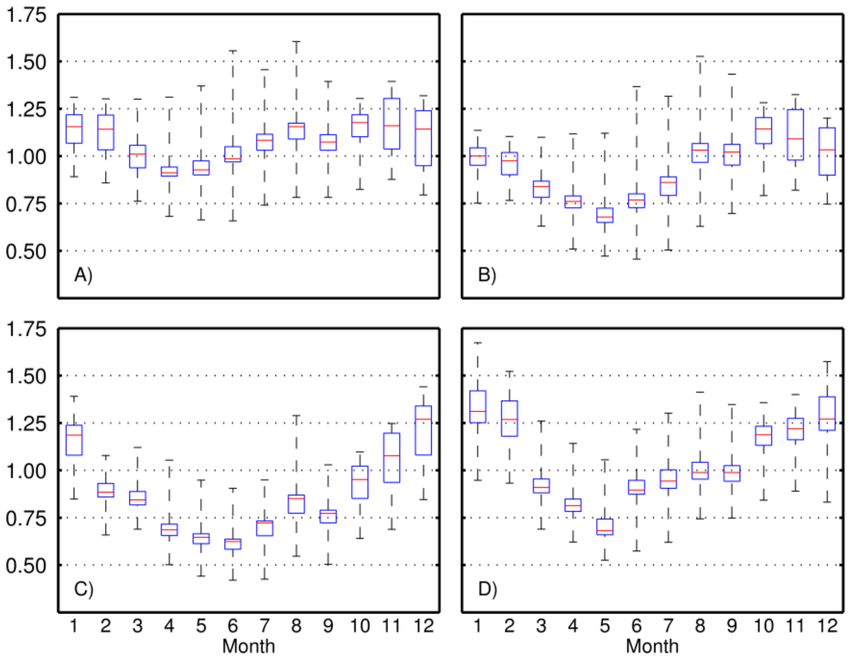

Figure 3 – Ratios between the standard deviations of the observational and projected detrended daily anomaly records. A) KNMI-ECHAM5; B) SMHI-ECHAM5; C) SMHI-BCM; D) SMHI-Had.

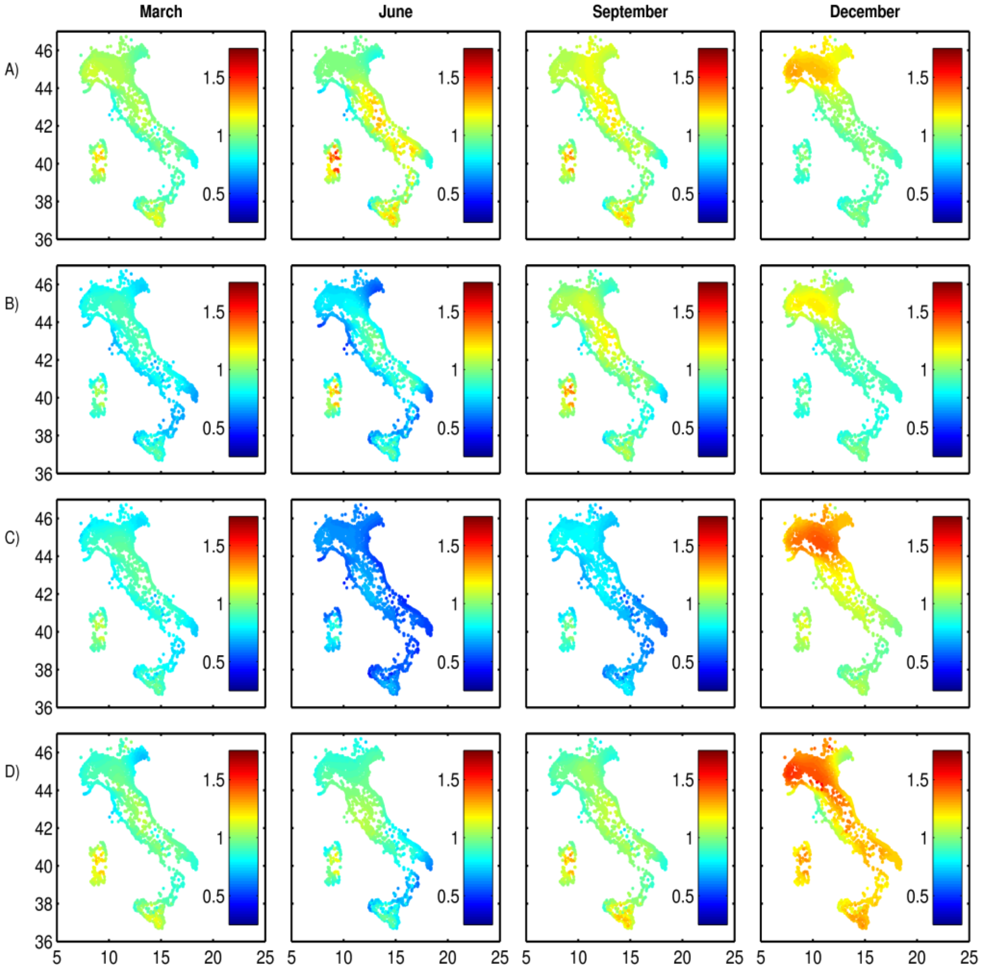

Figure 4 – Spatial distribution of the ratios between the standard deviations of the observational and projected detrended daily records for March, June, September and December. A) KNMI-ECHAM5; B) SMHI-ECHAM5; C) SMHI-BCM; D) SMHI-Had.

6. Temporal evolution of the *CDD*, *HDD* and solar radiation records

The adjusted model outputs were used to calculate national *CDD*, *HDD* and solar radiation urbanised grid-point records for the 2001-2100 period, according to the procedure outlined in section 3.

We show the temporal evolution of these records in figure 5. In particular, for each 10-year interval of the 2001-2100 period we show the daily average value of the *CDD* record in the period May-October, the average value of the *HDD* record in the period November-April and the average value of the solar radiation record over the whole year. The figure also displays the curves obtained by averaging the values corresponding to the 4 RCM-GCM combinations. *CDD* and *HDD* show a clear trend, whereas solar radiation does not show a clear temporal evolution. Using least square linear interpolation and considering the average of the 4 models, the *CDD* trend turns out to be 0.29±0.01 °C/decade, whereas the *HDD* trend turns out to be -0.27±0.02 °C.

Beside to CDD and HDD trends, it is also interesting to study the evolution of their yearly cycles. At this purpose, we considered three 30-year periods of the 2011-2100 interval and investigated the monthly distributions of these variables calculated from the 4 RCM-GCM combinations. The results are shown in figure 6 by means of box-plots as the ones shown in figure 3. The distributions were obtained considering all model results together.

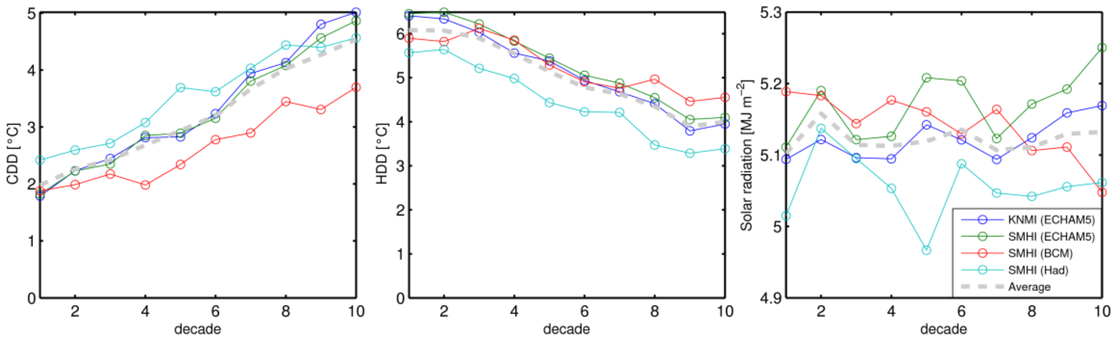

Figure 5 – 10-year average CDD (May-October), HDD (November-April) and solar radiation (January-December) for the 4 RCM-GCM combinations. The figure also shows the average among the 4 model curves.

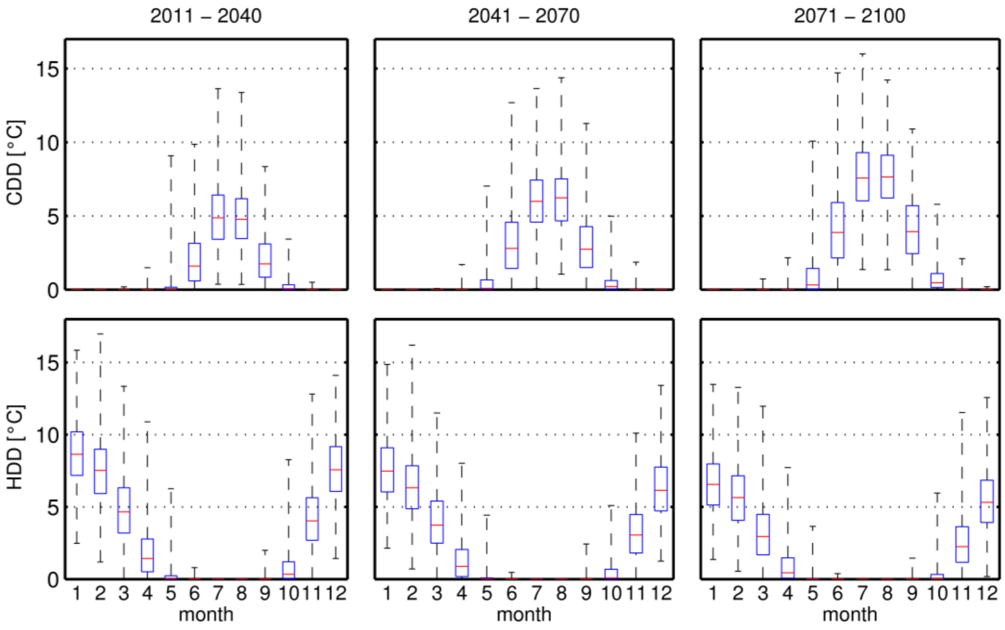

Figure 6 – CDD and HDD distributions over the months of the year, according to the RCM-GCM considered combinations, in three 30-year periods in the 2011-2100 interval.

The present-day relations among meteorological variables and electricity demand we presented in section 4 and the records presented in section 6 can be used to investigate the sensibility of the present-day electricity demand to climate variability and change. At this purpose, we simply run the model for the 2001-2100 period with the *CDD* coefficient we obtained for the 2012-2013 period and with average values of the *HDD* and solar radiation coefficients we get over the twelve 2-year periods of the 1990-2013 interval (these coefficients do not show significant trends in this period). The results are shown in figure 7, which displays the average contribution to the Italian electricity demand of all meteorological terms of relation (1) in 10 consecutive 10-year periods of the 2001-2100 interval.

This analysis has naturally not to be considered as a future electricity demand scenario, as beside to changes in the meteorological variables, we will certainly have considerable changes in many other drivers of the electricity demand.

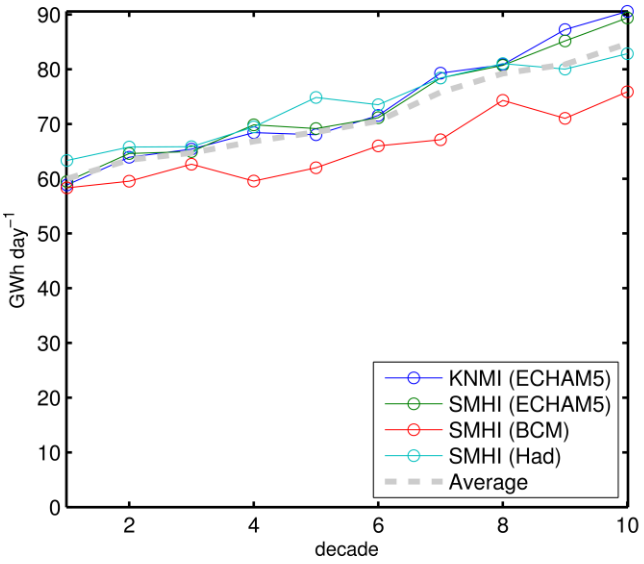

Figure 7 –Average contribution of the meteorological terms of relation (1) to the Italian electricity demand in 10 consecutive 10-year periods of the 2001-2100 interval obtained using meteorological data from the 4 RCM-GCM combinations and considering the present-day links among meteorological variables and electricity demand. Of course, this should not be considered as an energy scenario, as electricity sensitivity to weather variables will certainly change in the future.

7. Conclusions

We set up a methodology to estimate cooling degree-day, heating degree-day and solar radiation records that are representative of the urbanised areas of the Italian territory. These records were used within a model linking meteorological variables to the Italian aggregated electricity demand: it allowed estimating the present-day dependence of the Italian electricity demand on cooling degree-days, heating degree-days and solar radiation.

Four RCM-GCM combinations were used to get the evolution of cooling degree days, heating degree days and solar radiation under A1B climate change scenario. The results give evidence of an increase of cooling degree-days of about 130% and a decreasing of heating degree days of about 35% across the XXIth century. The global effect, considering the present-day relationship between demand and meteorological variables, is a positive forcing of the electricity demand due both to the stronger increase of *CDD* with respect to *HDD* decrease and to the much higher impact of *CDD* on the electricity demand.

References

1. Abraha, M.G, Savage, M.J., 2008. Comparison of estimates of daily solar radiation from air temperature range for application in crop simulations, Agricultural and Forest Meteorology 148, 401-416.

2. Apadula, F., Bassini, A., Elli, A. Scapin, S., 2012. Relationships between meteorological variables and monthly electricity demand, Applied Energy 98, 346-356.

3. Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Simolo, C., Spinoni, J., 2009. Estimating local records for Northern and Central Italy from a sparse secular temperature network and from 1961-1990 climatologies. Adv. Sci. Res., 3, 63-71.

4. Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Simolo, C., Spinoni, J., 2012. Projecting North Eastern Italy temperature and precipitation secular records onto a high resolution grid. Physics and Chemistry of the Earth, 40-41, 9-22.

5. Brunetti, M., Maugeri, M., Nanni, T., Simolo, C., and Spinoni, J., 2014. High-resolution temperature climatology for Italy: interpolation method intercomparison. International Journal of Climatology, 34, 1278–1296

6. Feinberg EA, Genethliou D., 2005. Load forecasting. In: Chow JH, Wu FF, Momoh JJ, et al., editors. Applied mathematics for restructured electric power systems: optimization, control, and computational intelligence. New York: Springer; p. 269–285.

7. Hunt, L.A., Kuchar, L., Swanton C.J., 1998. Estimation of solar radiation for use in crop modelling. Agricultural and Forest Meteorology, Volume 91, Issues 3–4, pp. 293–300.

8. Iqbal, M., 1983. An introduction to solar radiation, Academic Press.

9. Scapin. S., Apadula, F., Brunetti, M., Maugeri, M., 2014. Response of electricity demand to temperature and solar radiation in Italy, Weather, Climate and Society. (submitted)

10. Taylor, J. W., Buizza, R., 2003. Using weather ensemble predictions in electricity demand forecasting, International journal of forecasting 19, 57-70.

11. USGS (United States Geological Survey). 1996. GTOPO30 Documentation. Available at http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

12. European Commission, Joint Research Centre. 2003. Global Land Cover 2000 database. Available at http://bioval.jrc.ec.europa.eu/products/glc2000/data_access.php

Links to concrete results:

http://www.eclise-project.eu/

http://www.isac.cnr.it/climstor/ECLISE-project.html

Results about this deliverable were presented in a paper published on the *International Journal of Climatology* and in a manuscript submitted for a scientific publication to *Weather, Climate and Society* peer reviewed journal:

M. Brunetti, M. Maugeri, T. Nanni, C. Simolo, J. Spinoni; 2014. High-resolution temperature climatology for Italy: interpolation method intercomparison. International Journal of Climatology, 34, 1278–1296.

Scapin. S., Apadula, F., Brunetti, M., Maugeri, M., 2014. Response of electricity demand to temperature and solar radiation in Italy, Weather, Climate and Society. (submitted)

References to activity meetings:

The objectives this deliverable have been presented at the ECLISE Kick-off meeting (De Bilt - 09 March 2011).

The methods and partial results have been presented at the First ECLISE meeting (Norrkhoping - 6-7 March 2012) and at the second ECLISE meeting (23-26 April 2013, Crete, GR).

The results will be presented to the second SISC (Società Italiana per le Scienze del Clima) conference (Venice – 29-30 September 2014). Submitted extended abstract: Scapin S., Apadula F., Brunetti M., and Maugeri M. “A preliminary approach to estimate the impact of climate change on electricity demand in Italy”.