Meded. Zitt. K. Acad. Overzeese Wet.
Bull. Séanc. Acad. R. Sci. Outre-Mer
65 (2019 – 2): 227-239
DOI:

Impact Modelling of Climate Change from the Global to the Local Scale*

by

Piet TERMONIA** & Daniel GELLENS***

KEYWORDS. — Global Climate Change; Regional Climate Impact; Climate Models.
SUMMARY. — The societal impact of weather and climate phenomena is mainly felt through the occurrence of extreme events (storms, extreme precipitation, floods, heat waves, hail). Processes on short time scales (ranging from a few hours to a few days) play an important role in the impact assessment of climate change on long time scales (next century). The Royal Meteorological Institute (RMI) provides both operational weather forecasts and climate advice. To do so, numerical computer models are used. It is shown here how scientific advances in numerical weather prediction can lead to better climate information.

TREFWOORDEN. — Globale klimaatverandering; Regionale klimaatimpact; Klimaatmodellen.
SAMENVATTING. — *Impactmodellering van klimaatverandering van de globale naar de regionale schaal.* — De maatschappelijke impact van weer- en klimaatfenomenen laat zich voornamelijk voelen in het voorkomen van extreme weersituaties (stormen, hevige neerslag, overstromingen, hittegolven en hagel). Processen die zich voordoen op korte tijdschalen (gaande van een paar uur tot een paar dagen) spelen een belangrijke rol voor het inschatten van klimaatimpact op de lange tijdschalen (komende eeuw). Het Koninklijk Meteorologisch Instituut (KMI) levert zowel operationele weersvoorspellingen als klimaatadvies. Daarvoor worden numerieke modellen gebruikt. In dit artikel tonen we aan hoe wetenschappelijke vooruitgang in het domein van de numerieke weersvoorspellingen kan leiden tot betere klimaatinformatie.

MOTS-CLÉS. — Changement climatique mondial; Impact climatique régional; Modèles climatiques.
RÉSUMÉ. — *Modélisation de l'impact du changement climatique de l'échelle mondiale à l'échelle locale.* — L'impact sociétal des phénomènes météorologiques et climatiques se fait principalement sentir par l'apparition d'événements extrêmes (tempêtes, fortes précipitations, inondations, vagues de chaleur, grêle). Les processus à court terme (allant de quelques heures à quelques jours) jouent un rôle important pour estimer l'impact du changement climatique à long terme (siècle prochain). L'Institut royal météorologique (IRM) fournit à la fois des pré-

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* Paper presented at the meeting of the Section of Technical Sciences held on 28 February 2019. Text received on 29 May 2020 and submitted to peer review. Final version, approved by the reviewers, received on 13 October 2020.
** Member of the Academy; Royal Meteorological Institute, av. Circulaire 3, B-1180 Brussels (Belgium).
*** Member of the Academy; Director-General *a.i* Royal Meteorological Institute, av. Circulaire 3, B-1180 Brussels (Belgium).

visions météorologiques opérationnelles et des avis sur le climat. Pour ce faire, des modèles numériques sont utilisés. Nous montrons ici comment les progrès scientifiques dans le domaine des prévisions météo numériques peuvent conduire à de meilleures informations climatiques.

Introduction

Weather events represent some of the most severe natural risks. For instance, the floods that occurred in Belgium from 12 November to 15 November 2010 led to one hundred and eighty million euros of damage claims. Another example is the so-called Pentecost storm in 2014, for which the damage claims amounted to about six hundred and fifty million euros. During the 2003 European heat wave, eight consecutive days went by with temperatures higher than 40° C in several places in Europe. The death toll of that heat wave exceeded seventy thousand in Europe (Robine *et al.* 2008).

The mission of the Royal Meteorological Institute (RMI), as the Belgian National Meteorological Service (NMS), is to provide permanent services to ensure Belgian national security, to provide meteorological information to the population and to support the political authorities (Royal Decree of 31 December 1986). The weather office of the RMI issues warnings in case of extreme weather events and monitors the meteorological situation on a 24/7 basis.

Extreme weather events do not only have an important societal impact today. It is expected that under a changing climate, some of those events will become more extreme or will occur more frequently. Climate change has been quantified in the latest Assessment Report Nr. 5 (AR5) of the Intergovernmental Panel on Climate Change (IPCC) according to so-called Representative Concentration Pathways (RCPs) that express climate change as a function of the radiative forcing of the scenarios ranging from 2.6 to 8.5 W/m^2 at the end of the century (van Vuuren *et al.* 2011). According to the AR5 (IPCC 2013), under the most severe RCP8.5 scenario, one expects a global warming of about 3.7 °C (with an uncertainty ranging from 2.6 °C to 4.8 °C) by the year 2100.

However, the impact of that change will be manifested through extreme natural events (fig. 1, IPCC 2014). This figure shows the change of the key risks for Europe, in the current climate, for the mid-century and by the end of the 21st century. It includes the major natural risks related to heat and cold spells and extreme precipitation (or lack thereof) that the NMSs are forecasting and monitoring today.

Extreme events take place on a smaller spatial scale than the global scale. So, in order to increase our scientific knowledge about them, it is necessary to rely on the same modeling tools that are used for Numerical Weather Prediction (NWP).

Here we give a brief overview of the history and challenges of NWP and we will then explain how the RMI expertise on NWP has been used to compute high-resolution climate change scenarios for Belgium. The same model is also used for overseas applications as will be shown below.

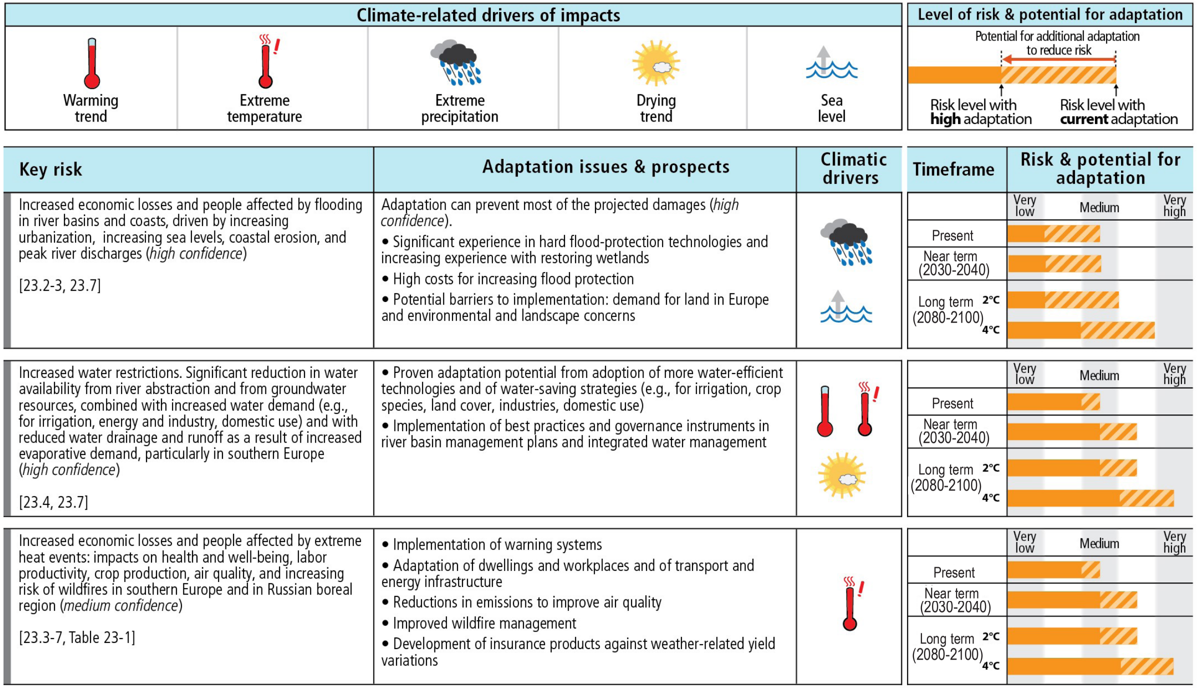

Fig. 1. — Key risks from climate change in Europe and the potential for reducing risk through mitigation and adaptation. Risk levels are presented in three time frames: the present, near term (2030-2040), and long term (2080-2100). For each time frame, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but since the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions. Key risks were identified based on assessment of the literature and expert judgment. Table taken from the WGII report of the AR5 (IPCC 2014).

Numerical Weather Prediction

Numerical weather prediction consists of computer models that numerically solve the dynamical equations of the atmosphere (Bauer *et al.* 2015). The planet is covered with a three-dimensional grid and the spatial derivatives are approximated by using the information in the neighbouring grid boxes. By carefully discretizing the time derivatives, the state of the atmosphere can be computed a time step ahead into the future. Phenomena smaller than the size of the grid boxes are "parameterized" by empirical relations. For models running at resolutions of about 10 km, this is done for the following processes: turbulence, deep convection, radiation, phase transitions of water and interactions with the topography.

The discretized equations are then reduced to a set of numerical operations that can be carried out on a computer. The bigger the computing power, the more grid boxes can be computed and the higher the resolution of the model can be. By increasing the resolution more phenomena get explicitly solved by the model equations and one can expect that the model becomes more precise. Historically the science of NWP has followed the progress in computing science and this has led to a substantial improvement in the forecast skill of today's NWP models.

Figure 2 shows the progress of the global model of the European Centre for Medium-range Weather Forecasts (ECMWF). It depicts the so-called anomaly correlation — the anomaly is the difference with the mean value — between the predicted 500 hPa geopotential height — this is the height where the pressure is 500 hPa — by the model and the one obtained from the observations. It can be seen from this figure that at three days' lead time the model was reaching an accuracy of 90 % around 1990, whereas the same 90 % have been reached for five days' lead time since 2010. One can roughly state that a decade of research and development on climate modelling has increased the forecast skill of one-day lead time further into the future.

The atmosphere is a non-linear system (Lorenz 1963). Small errors in the initial conditions will grow in time until the forecast becomes unreliable. The corresponding uncertainties are estimated by Ensemble Prediction Systems (EPSs). EPSs compute a numerical forecast, then perturb the model and its initial state a number of times to introduce artificial errors and run it again with these perturbations. This delivers for each model output variable a probability distribution of the predicted variables. The spread of this distribution is an indicator of the uncertainty of the forecast. For instance, the ECMWF provides twice a day an EPS with one unperturbed and fifty perturbed model runs.

The resolution of the ECMWF model is currently 8 km. This is not enough to properly solve deep convection systems which are responsible for thunderstorms. To go to higher resolution one relies on specialized models that run on limited geographical areas, the so-called Limited-Area Models (LAMs). By limiting the domain one reduces the necessary computing resources, and one can spend the computing power on computing more details with higher resolution.

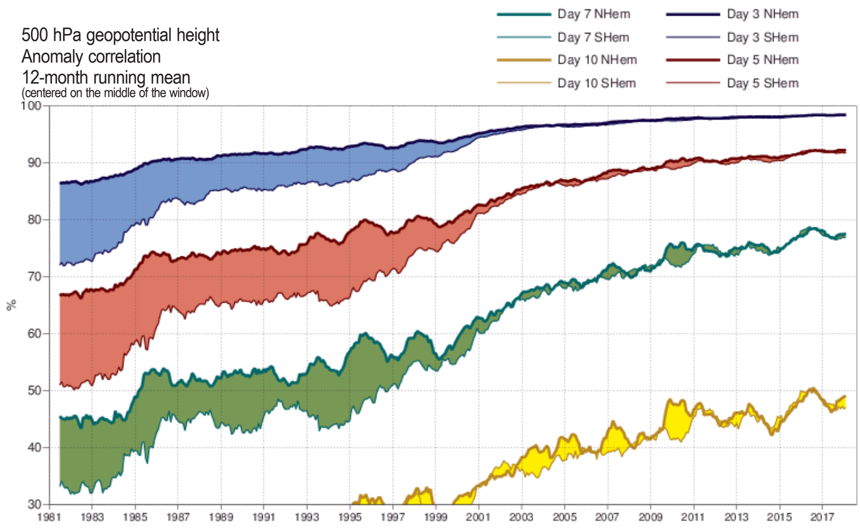

Fig. 2. — Anomaly correlation between the 500 hPa geopotential height (*i.e.*, the height where the pressure is 500 hPa) predicted by the global model of the ECMWF and the observations. The thick lines represent the anomaly correlation for the northern hemisphere, whereas the thin lines represent the one for the southern hemisphere. One notices a progressive improvement in the forecast skills in the southern hemisphere, which is slowly converging to the performance in the northern hemisphere.

The RMI is a member of the ALADIN Limited-Area Model consortium (Termonia *et al*. 2018a). This is an international consortium of sixteen NMSs that develops and maintains a state-of-the-art LAM NWP system, called ALADIN System. The consortium includes thirteen European and three North-African countries. The ALADIN System is operationally used in each of the countries to provide high-resolution NWP forecasts to meet their national needs. The operational model configuration runs at resolutions of the order of 1 km, which allows to improve the realism of extreme precipitation events. The RMI runs the ALADIN System on its own HPC infrastructure. The model outputs are used by the forecasters. The output is post-processed and disseminated, for instance on the RMI website (see figure 3 for an illustration on this).

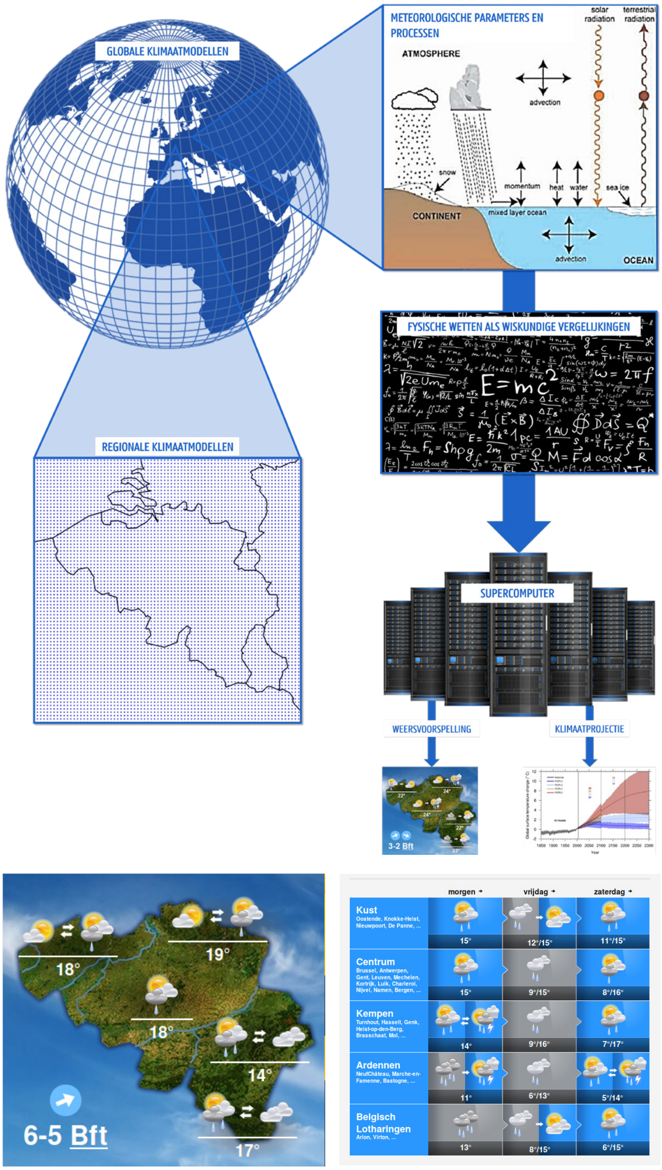

Fig. 3. — Limited-Area Models solve the atmospheric equations to provide operational weather forecasts. By limiting the geographical area one can run the model with higher resolution, as shown on the left. The model output is used by weather forecasters to provide daily forecast. These forecasts are disseminated to the public, for instance on the RMI website (see right-hand side).

Climate Change Simulations

The same type of models is used for climate simulations. The main specificity of climate models is the radiative forcing which follows the prescribed pathways as put forth by the IPCC. Climate simulations cover more than a century; so, given the limitations in computing power, they can only run with resolutions of about 100 km. This means that Belgium is covered with only a few grid boxes, which is too coarse to simulate the extreme weather phenomena mentioned above.

By using the ALADIN System, the RMI has developed a regional climate model that can be run with spatial resolution of a few kilometers. The parameterizations are adapted to give a better representation of the deep convective systems, thus providing details at the so-called convection permitting scales, which are the scales at which the processes for extreme precipitation occur. This model called ALARO-0 (De Troch *et al.* 2013, Giot *et al.* 2016) has also been used to analyse the urban heat island effects and to downscale the coarser scale climate model outputs. In a recent Belgian project, COmbining Regional climate Downscaling EXpertise in Belgium (CORDEX.be), this model was used together with three other regional climate models run by the universities of Leuven, Louvain and Liège. The CORDEX.be project was funded by the Belgian Science Policy Office (Belspo) and provided a set of high-resolution climate scenarios for Belgium. The project also performed a number of impact studies (Termonia *et al.* 2018b).

The four climate models of the CORDEX.be project have been validated with respect to the observations from the climatological observation network of the RMI. To this end the models were run for the past period 1980-2010. Figure 4 shows some of the validation maps. Although the models slightly differ in the precise quantities, they reproduce the observed spatial pattern over Belgium in a qualitatively satisfactory manner. Subsequently, the models were run for one hundred years in the future, until the end of the 21st century. The data were archived and various climate change signals were computed. Figure 5 shows an example of increase of winter precipitation by the end of the century.

Within the CORDEX.be project, scenarios were used to compute climate impact with Local Impact Models (LIMs) for heat waves (Hamdi *et al.* 2016), urban-heat island effects (Lauwaet *et al.* 2015), impacts on crop growth (Gobin 2012), impacts on isoprene emissions (Bauwens *et al.* 2018) and on storm surges and wave heights for the North Sea (see the project's website, http://www.euro-cordex.be/, for more detailed information). By focusing on the end of the 21st century using a scenario with the largest greenhouse gas emissions (RCP8.W5), the most prominent impacts of climate change for Belgium were identified. They include: (*i*) a strong increase in the number of tropical days and heat wave days (*e.g.*, an increase of a factor 3 to 4 in the number of heat waves in the Brussels urban environment); (*ii*) an increase in winter precipitation and long extremely wet periods; (*iii*) an intensification of summer precipitation extremes, especially in urbanized areas (*e.g.*, the precipitation intensity with hourly time scale and ten-year return period may increase up to 100 %); (*iv*) an increased variability for biomass production and yields; and (*v*) severely reduced winter snow height maxima.

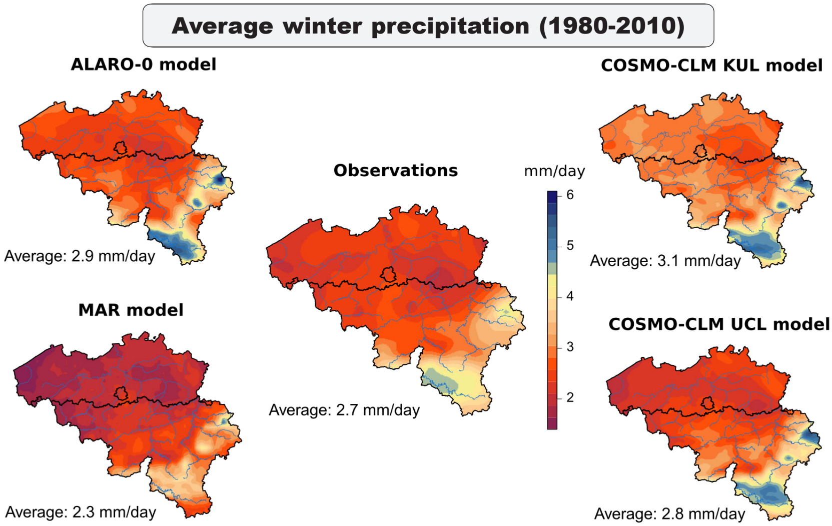

Fig. 4. — Validation of winter precipitation for the four regional climate models used in the CORDEX.be project as described by Termonia *et al.* (2018b) compared to the climatology from the RMI observation network.

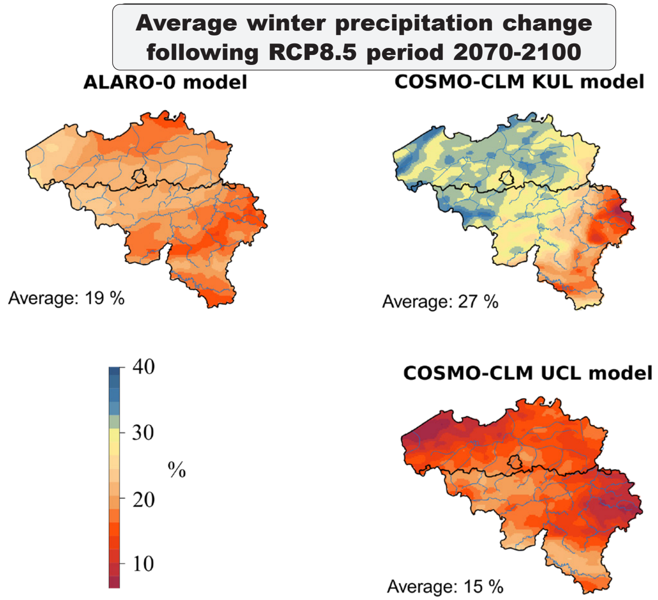

Fig. 5. — Climate change of winter precipitation in Belgium according to three of the CORDEX.be climate models. All three models give climate change signals of the same order of magnitude.

The atmospheric dynamics is a complex system. Explaining the scientific basis of climate change, including the related scientific uncertainties, is often a challenge. By relying on ensembles of climate model runs provided by climate research centres worldwide, one can quantify the uncertainties. Based on those uncertainty estimates, climate change signal can be separated from the noise. Such a quantification was done for Belgium within the CORDEX.be project by KU Leuven (see table in Termonia *et al.* 2018b). A similar study was performed in northwest Ethiopa by Van Vooren *et al*. (2019) in a collaboration between the RMI and UGent and has shown how parameterization of the orography can impact the simulated precipitation.

The second challenge of science communication is to properly explain what the impact numbers mean in practice. Since climate change impact is felt through similar extreme weather events as forecasted today, the CORDEX.be project has disseminated its results on the climate change impacts on heat waves in a format that is similar to the one used for weather forecasts. Figure 6 shows one of the future heat waves simulated by the ALARO-0 model under the RCP8.5 scenario, presented in the format of a weather forecast as it would be communicated on the RMI website. The heat wave takes place in 2063 and lasts for thirteen days. However, a word of caution should be given here: the forecasted event will not happen literally on 6 July 2063. In climate simulations the model output does not correspond to the real weather at the exact place and time, but the long-term climate runs reproduce the climate, including the amplitudes and the occurrence frequencies of weather phenomena. Nevertheless, this kind of presentation demonstrates climate change in a more tangible way than the climate change impact statistics do.

The ALARO-0 model of the RMI has been used recently over Central Asia. For instance, Cai *et al.* (2019) used this model to study the circulation within the Mountain-Oasis-Desert System (MODS) in the region. During the thirty-one summers (1986-2016), two simulations were performed: (*i*) a control simulation (CTL) where the land use/cover presents the current situation of the oasis areas in the study region, and (*ii*) a simulation where the oasis areas were replaced by the surrounding desert (NO_OASIS). The difference of the two runs is used to detect the potential effect of oasis expansion on summer precipitation. The result is shown in figure 7 indicating that the presence of the oasis is responsible for an increase of the total summer precipitation with quantities up to about 40 mm.

Currently, the ALARO-0 model is being used in the H2020 AFTER project (Kotova *et al.* 2018) to study climate change impact over Central Asia. This project has similar goals and structure as the Belgian CORDEX.be project. First, a limited number of climate runs are being performed over the region of interest in Central Asia, following the IPCC AR5 prescribed RCP scenarios. The models used are the REMO model of the HZG-GERICS climate centre of Germany and the ALARO-0 model of the RMI, the latter being exactly the same model as the one used for the CORDEX.be project. The guidelines of the CORDEX project are followed. Considerable attention will be paid to model validation and bias correction. Subsequently, the outputs of these models will be used to run LIMs for biomass production, similarly as done for Belgium in the CORDEX.be project. The project will also include a stakeholder dialogue. Since the CORDEX-Central Asia domain covers the Xinjiang region, these scenarios will be used later to study the MODS effect under a changing future climate.

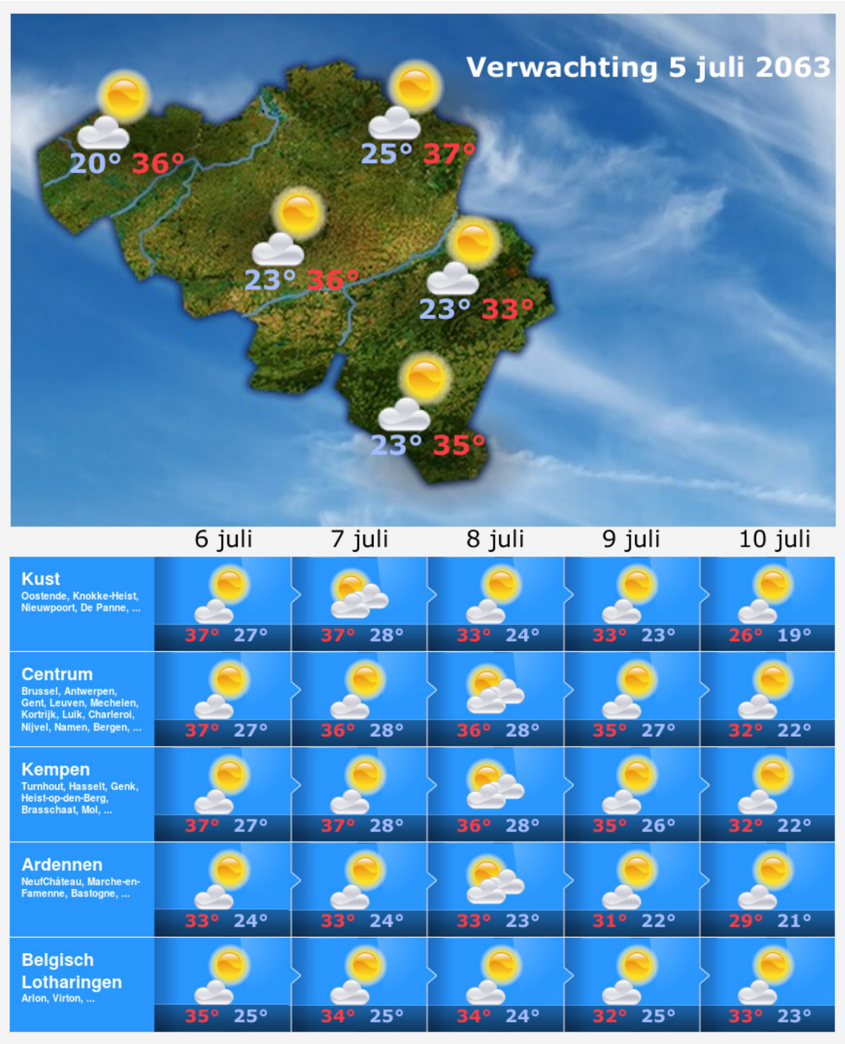

Fig. 6. — One of the future heat waves found within the ALARO-0 RCP8.5 simulation, presented here in the format of a weather forecast as it could be communicated on the RMI website.

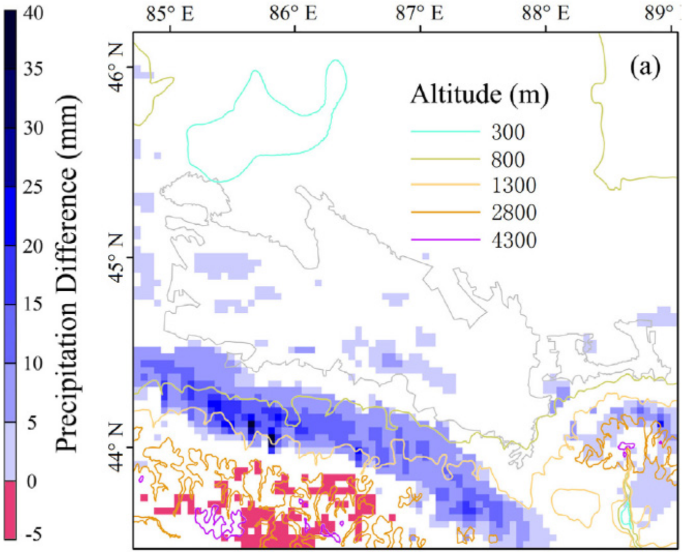

Fig. 7. — Total averaged summer precipitation during the period 1981-2016 computed from the difference between the model simulation with oasis and the model simulation without oasis. The oasis considerably increases the total precipitation with up to about 40 mm. The oasis area is indicated by the grey line. The coloured lines indicate the height contour of the mountains.

Conclusion

In 2009, the World Meteorological Organization (WMO) held the third World Climate Conference (WCC-3) to set up a global network for climate services. Climate services are services that allow to disseminate climate information to the public and to specific socioeconomic users. This requires a strong partnership between the providers of climate services and the stakeholders. Climate services are needed for policy making and sustainable development by providing reliable climate projections and climate information. WCC-3 led to the creation of several climate centres worldwide. In Belgium such a climate centre does not exist yet. Instead, the Royal Meteorological Institute has started to develop its own climate services in strong partnership with universities.

This paper illustrates how longstanding advances in weather forecast by means of numerical weather prediction models have helped the RMI to build climate change scenarios for Belgium. This work was done in close collaboration with climate modelling groups at universities. Climate data are now archived and may serve to develop further climate services.

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