Local effects of climate change over the Alpine region: A study with a high resolution regional climate model with a surrogate climate change scenario

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1. Introduction

Mountainous regions are likely to be among the most affected by global warming [Intergovernmental Panel on Climate Change (IPCC), 2007]. In fact, surface elevation itself has been identified as a key factor in modulating the temperature and precipitation change signal [e.g., Giorgi et al., 1997; Fyfe and Flato, 1999; Leung and Ghan, 1999; Gao et al., 2006]. In order to capture such signal, high model horizontal resolution is necessary and therefore regional climate models (RCMs) can be especially suitable tools to study climate change processes over mountainous areas.

To date, numerous RCM simulations have been conducted over domains covering the Alps region or some of its sub-areas, with horizontal grid spacing varying from about 70 km to less than 10 km [e.g., Marinucci and Giorgi, 1992; Giorgi et al., 1990, 2004; Grell et al., 2000; Jones et al., 1997; Gao et al., 2006; Jacob et al., 2007; Déqué et al., 2007; Suklitsch et al., 2008]. In particular, Im et al. [2010, hereafter I10] developed a 15 km grid spacing RCM over the central Mediterranean region (including the Alps) with a sub-grid scale land surface parameterization [Giorgi et al., 2003] reaching a local grid box size of 3 km. The purpose of their model development effort was to provide high resolution climate information for the study of climate change effects on Alpine catchment basin hydrology. I10 applied the model to a present day simulation and validated it against different observational datasets, showing that the model produced relatively accurate climatological statistics.

Extending the work of I10, and before a full climate change simulation is carried out, here we use I10’s modeling system in the so called “surrogate” climate change (SCC) scenario configuration [Schär et al., 1996], by which a given warming level is imposed on the fields used to drive the RCM (see below). The purpose of our surrogate scenario, in which the external dynamical forcing is not altered, is to assess how internal thermodynamical and hydrological processes (especially the surface ones) respond to the imposed warming and how this response might modulate the surface climate change signal. In other words, in this work we use the SCC approach to assess the importance of local controls of regional climate change over the Alps. Note that the SCC approach has been used by Schär et al. [1996], Frei et al. [1998] and Seneviratne et al. [2002], but only for month-long or multi-month long simulations, while here it is applied to a full continuous 10-year simulation. It is also important to stress that the SCC approach does not allow to simulate the effects of changes in large scale circulations, and therefore it does not provide a full picture of climate change for the region of application.

2. Model and Experiment Design

We use the latest version of the ICTP regional climate model RegCM3 described by Pal et al. [2007]. Details about the model configuration are given by I10. As given by I10, the model includes the land surface scheme BATS of Dickinson et al. [1993] and the mosaic-type parameterization of Seth et al. [1994] (hereafter referred to as Sub-BATS) as implemented within the RegCM3 by Giorgi et al. [2003]. In Sub-BATS, each grid cell of the dynamical model is divided into N regularly spaced sub-grid cells of equal area, each with its own specification of topographical elevation, vegetation class, and soil type. Sub-BATS requires as input solar and infrared downward radiation, precipitation, near-surface air temperature, water vapor,
wind speed, pressure, and density. These variables are disaggregated from the model to the sub-grid as described by I10. In particular, temperature is disaggregated based on topographical information and assuming a constant lapse rate of -6.5 K/km, and humidity is disaggregated assuming a constant relative humidity. After the calculations of land surface processes are completed, Sub-BATS returns to the atmospheric model values for albedo, surface upward infrared flux, momentum flux, sensible heat flux, and latent heat flux. These variables are re-aggregated from the sub-grid to the coarse grid via a simple averaging procedure. The reader is referred to Giorgi et al. [2003] and I10 for more detail on the sub-grid scheme.

The SCC approach follows Schär et al. [1996]. It consists of adding a temperature anomaly to the initial and lateral meteorological boundary conditions while keeping the relative humidity constant, which results in an increase of specific humidity. The sea surface temperature within the interior domain is also increased by the same anomaly. In our experiment the amount of greenhouse gases is not changed, since this effect is secondary for small domains as used here [Seneviratne et al., 2002]. Schär et al. [1996] show that this procedure does not affect the dynamical structure of the circulations entering the model from the lateral boundaries. For the present experiments we use an illustrative constant temperature anomaly warming of 3 K, a value in the mid of the IPCC [2007] range for the end of the 21st century.

The model domain is the same as I10’s, and it encompasses the Alpine region, the Italian Peninsula and adjacent central Mediterranean regions. The coarse grid cell size is 15 X 15 km on a Lambert Conformal projection while the sub-grid cell size is 3 X 3 km, therefore, each coarse grid cell is divided into 25 subgrid cells. Topography and landuse distributions for these grids are shown by I10. Two experiments are here intercompared, each covering the period of 1 September 1982 through 31 December 1992 (where the first four months of the simulations are not included in the analysis to allow for model spin-up), with the model being driven at the lateral boundaries by 6-hourly NCEP-DOE Reanalysis II data [Kanamitsu et al., 2002] and over the ocean areas by weekly SSTs from the NOAA Optimum Interpolation (OI) SST dataset. One simulation is the same as I10’s with Sub-BATS scheme (REF) while the other includes the surrogate climate change perturbations (SCC). We also conducted similar experiments without use of the Sub-BATS scheme, however the basic conclusions where similar to those found for the Sub-BATS simulations, therefore those experiments are not discussed here.

We do not present a validation of the simulations, since this is already extensively reported by I10, who show that the model has a generally good performance in reproducing various climate statistics over the region and that the Sub-BATS scheme leads to a general improvement of the surface climatology in particular snow and runoff over the mountainous areas of the domain. For example, biases for seasonal mean temperature and precipitation were mostly less than 1K and 20% and both the spatial and temporal patterns over the Alps were well reproduced. Also note that here we focus our analysis only over the Alpine region, which lies in the center of the full domain (see I10), therefore results are presented only for this Alpine sub-domain.

3. Results

Figure 1 shows changes (SCC minus REF averaged over the full ten years of simulations) in temperature, precipitation, snow, runoff, root zone soil moisture, and evapotranspiration over the Alpine region, both for December-January-February (DJF) and June-July-August (JJA). Also shown is the mean monthly evolution of the same variables in the REF and SCC simulations averaged over the Alps (boxed area of Figure 1 (top left)).

As expected, the entire domain shows a warming induced by the SCC (top panels) close to the imposed 3 K. The warming is slightly larger in winter, when advective processes are most important, but it is essentially retained throughout the year. A clear topographical modulation of the warming signal is found both in winter and summer, with the warming increasing with elevation by up to 1 K. This result is in line with previous work [Giorgi et al., 1997; Fye and Flato, 1999; Leung and Ghan, 1999]. In winter, when substantial fine scale spatial variability of the warming signal is found, it is primarily associated with a reduction in snow cover (third row panels), and the associated local snow-albedo feedback mechanism.

Figure 2 shows the elevation dependency of the temperature, precipitation, snow and runoff change over the Alpine region for the four seasons. The relation between warming and snow change is evident. The magnitude of both quantities increases with topographical elevation until a maximum is reached around 1700 m in winter (DJF) and 2000 m in spring (MAM), and then it decreases for higher elevations. At these high elevations the increased snow melt due to the warming is counterbalanced by increased precipitation (see Figure 1). This increase in winter precipitation is expected in view of the increased atmospheric water content in SCC conditions and it is therefore associated with a reduction in snow cover (third row panels), and the associated local snow-albedo feedback mechanism.

Figure 2 shows that also the winter (and spring) precipitation enhancement depends on elevation due to the orographic forcing of the Alpine chain. The winter increase in precipitation is widespread throughout the analysis region (Figure 1), and this induces an increase in soil water content, evaporation and runoff. Figure 1 also shows that the peak runoff month occurs earlier in the year in the SCC run (April) compared to the REF simulation (May) because of the earlier peak snow-melt season. Changes in runoff as a function of elevation show different seasonal behavior in response to the elevation dependency of the snow-melt and precipitation changes.

The summer results exhibit quite different features. The warming signal still shows an elevation magnification effect (although smoother than in winter), however this is not associated with a decrease of snow cover, which is generally small in summer. Rather, it is tied to a decrease in precipitation over the higher Alpine areas in the SCC run. This decrease in precipitation occurs despite the greater water vapor content in SCC conditions and it is therefore associated with a local feedback mechanism. To explore this mechanism we first analyzed changes in convective vs. non-
Figure 1. Spatial distribution of difference between the SCC and REF simulations in surface air temperature (K), precipitation (mm/day), snow water equivalent (mm), surface runoff (mm/day), root layer soil moisture (mm), and evapotranspiration (mm/day) for the (left) winter (DJF) and (middle) summer (JJA). (right) Monthly variations of the same variables for the REF and SCC simulations averaged over (top left) Alps box (6.3-16E, 45.8-48N and 5.5-8E, 43.8-45.8N). All averages are taken over the entire 10-year simulations.
convective precipitation and found that while the convective rain remained on average essentially unchanged, most of the decrease shown in Figure 1 was due to reduced non-convective precipitation.

Insights into the decrease of non-convective precipitation require an analysis of the temporal evolution of snow cover, relative humidity and precipitation from the spring to the summer months (Figure 3). We find that relative humidity, which essentially regulates the occurrence of non-convective precipitation, decreases over the Alps in the SCC run during the summer months. This decrease of summer relative humidity is due to reduced soil water contents at the beginning of summer (see Figure 1) induced by reduced snow accumulation and earlier snowmelt. The reduction of relative humidity, and thus cloudiness is confirmed by an increase in net infrared surface energy flux over the Alpine peaks (Figure S1). Reduced snow accumulation and cloud cover also increase solar absorption due to a decrease in surface and top of the atmosphere albedo, resulting in a positive net absorbed solar energy flux under SCC warming conditions (Figure S1). As the soil water decreases, evapotranspiration still increases due to the higher surface temperatures (and thus higher potential evapotranspiration), but this increase is limited by the reduced soil water contents and therefore the relative humidity is kept at reduced values under the SCC warming.

This feedback mechanism is depicted in Figure 4. It is entirely due to internal local processes involving the surface hydrologic and energy cycles and the modified cycle of snowpack formation and melting. Although we presented here results only for the Alpine region, we found the same process over other mountainous regions within the domain, such as the Apennines and the Balkan mountains, with shifts in the peak reduced precipitation month determined by the different seasonal cycles of snow accumulation and melting. We conclude that this process can possibly be generalized to other mid-latitude mountainous regions.

4. Concluding Remarks

In this paper we analyze a surrogate climate change (SCC) simulation with a high resolution RCM over the Alpine region using a sub-grid surface process scheme (Sub-BATS). Extending previous applications of the SCC approach, we performed continuous multi-year simulations (10-year). The Alpine region undergoes a warming throughout the year in line with the imposed SCC warming and shows a marked elevation dependency generally consistent with previous studies. The simulated precipitation response to the SCC forcing is different for the summer and winter seasons. In winter, precipitation increases over the Alpine region due to the higher water vapor amounts imposed by the SCC approach, and this response shows a marked elevation dependency. In summer, although the atmosphere contains more water vapor and the large scale circulations...
are not affected by the SCC forcing, precipitation actually decreases over the Alpine peaks. This is due to a local feedback process involving reduced snow cover and soil water content at the beginning of summer (see Figure 4). [17] A number of global and regional model studies investigated the projected changes in summer precipitation over the Alpine region due to greenhouse gas forcing [e.g., Jones et al., 1997; Déqué et al., 2007; Gao et al., 2006; Giorgi and Coppola, 2007; Giorgi and Lionello, 2008; Faggian and Giorgi, 2009]. They consistently found a decrease of summer precipitation over the Alps. This was confirmed by more recent simulations completed as part of the ENSEMBLES project (e.g., see Figure S2). This projected precipitation decrease is consistent with that found in our SCC experiment, however in these previous studies changes in large scale circulations, and most noticeably a northward shift of the mid-latitude storm track, were also responsible for this result [Giorgi and Coppola, 2007]. It is difficult to unambiguously separate the contributions of storm track shift and local feedbacks to the Alpine summer precipitation decrease, but our results suggest that the latter provides a significant contribution. Our proposed mechanism is also consistent with the results of previous studies that investigated the interplay of snow cover, soil moisture and precipitation change in mid-continental regions [e.g., Wetherald and Manabe, 1995; Gregory et al., 1997; Hayhoe et al., 2007; Rowell and Jones, 2006; Rowell, 2009]. For example, Rowell and Jones [2006] assessed the important role of anomalous soil moisture reduction during spring leading to future summer drying over continental Europe in a series of idealized experiments. Although we discussed only results for the Alpine area, the same type of behavior was found over other mountainous regions of the domain (the Apennines and the Balkans), which indicates that this conclusion might be more general, at least for mid-latitude mountain areas. Our study provides strong indications that local feedbacks associated with the surface hydrologic cycle are important in determining the local response to global warming over mountainous regions. These local feedbacks interact with the dynamical and thermodynamical forcing provided by changes in the large scale structure of the atmosphere to provide the full local response to global warming.

Figure 3. Spatial distribution of monthly snow amount in the (a) REF and (b) SCC simulations and differences in (c) relative humidity at 925hPa and (d) precipitation from March to August.

Figure 4. Schematic diagram of local feedback leading to the summer precipitation decrease in the SCC simulation.
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References


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