The Economics of Weather and Climate Risks Working Paper Series
Working Paper No. 1/2016

ISSN 2074-9317

European snow under 2 degree global warming

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Abstract

In this paper we used snow water equivalent (SWE) output from the hydrological model VIC and an ensemble of regional climate models from the CORDEX project to assess the change in pan-European snow conditions for a climate 2 degrees warmer than pre-industrial time. The ensemble was constructed using different 30-year periods, corresponding to when each driving global climate model reach +2 degrees relative to pre-industrial. A validation against different SWE datasets is also presented, indicating that for the Alps there is a positive bias in the hydrological model run, increasing with higher altitude. The bias is smaller for the climate model driven ensemble than for the run driven with meteorological observations.

1. Introduction

It has been politically agreed to limit the global warming to 2 degrees compared to pre-industrial levels. The IMPACT2C project aims to quantify the regional effects of this warming in different sectors. This article focusses on the snow conditions for the impact on winter tourism. For a warming of 2 degrees globally, Vautard et al. (2014) showed that the warming in Europe will be greater than 2 degrees, and that the winter season in particular may warm up to 4 degrees.

Pre-industrial levels were derived from the period 1881-1910. Since not all regional climate model (RCM) runs went that far back in time a reference period 1971-2000 was used, while the average global temperature increase from the pre-industrial period to this reference period was determined from three different re-analysis datasets to be on average 0.46 degrees (Vautard et al. 2014). The future 30-year period centred on when we are expected to reach the remaining 1.54 degrees warming relative to 1971-2000 is here referred to as the *2-degree period*. Data from each global climate model/general circulation model (GCM) gave different results, and by creating an ensemble of model results based on these periods (different for each driving GCM) rather than a fixed time window of 2031-2060, small reductions in the inter-model spread of seasonal precipitation was observed in addition to of course larger reductions in the temperature spread (Vautard et al. 2014). Time periods for 1.5, 2 and 3 degrees for the models used are presented in Table 1.

Simulations

In the IMPACT2C project, five hydrological models were run using the same forcing, temperature and precipitation from 11 RCM runs, shown in Table 1. The RCM data was bias-adjusted with E-OBS (version 5) as reference. An intercomparison of five hydrological models using the same forcing data is available in Greuell et al. (2015). Out of the five models, VIC, Variable Infiltration Capacity model (Liang et al. 1994), was selected as it allows for subgrid output on different elevation bands (each representing a certain fraction of the area of the grid cell), which is usable for mountainous regions of interest to the skiing industry. VIC has also been used for similar purposes in other studies, e.g. Scott et al. (2008). The data used in this article was also the basis for the analysis of the economic impact on the European alpine skiing industry in Damm et al. (2016).

RCM	Driving GCM and scenario	1.5°C period	2°C period	3°C period
CSC_REMO2009	MPI-ESM-LR:			
	RCP 2.6	2035-2064	-	-
	RCP 4.5	2020-2049	2050-2079	-
	RCP 8.5	2014-2043	2030-2059	2053-2082
IPSL_WRF33	CM5A: RCP 4.5	2009-2038	2028-2057	-
KNMI_RACMO22E	EC-EARTH:			
	RCP 4.5	2018-2047	2042-2071	-
	RCP 8.5	2012-2041	2028-2057	2052-2081
SMHI_RCA4	EC-EARTH:			
	RCP 2.6	2028-2057	-	-
	RCP 4.5	2019-2048	2042-2071	-
	RCP 8.5	2012-2041	2027-2056	2052-2081
	HadGEM2_ES:			
	RCP 4.5	2007-2036	2023-2052	2055-2084
	RCP 8.5	2004-2033	2016-2045	2037-2066

Table 1: Regional climate model runs used in this study. The time periods correspond to when the driving GCM hits 1.5, 2 and 3 degrees global warming relative to the pre-industrial period 1881-1910. For more details see Vautard et al. (2014).

Observations

A gridded 1-km dataset (from here on **SLF dataset**) with daily data for 1998-2014 covering Switzerland was retrieved from SLF, Switzerland. The dataset was produced using observations from 298 snow monitoring sites located with close to even altitude distribution from 200 to 3000 m ASL. The data assimilation and model is described in Magnusson et al. (2014).

A **regulation dataset** used by the Norwegian hydropower industry was obtained from the Norwegian Water and Energy directorate. The dataset contains over 40000 high-quality measurements for Norway from 1914 onwards (36171 in the period 1958-2009). The measurements mainly cover the start of the spring melt.

Morin et al. (2012) presented an 18-year long (1993-2011) snow and meteorological dataset from the site **Col de Porte** (CDP) in the Chartreuse range in France. The data is freely available and is here used as a case study.

SSM/I (Special Sensor Microwave Imager) and **MODIS** (Moderate-Resolution Imaging Spectroradiometer) are two satellite instruments, from which a dataset with 25 km resolution containing snow cover and snow water equivalent was developed by Brodzik et al. (2007). The dataset was downloaded from http://nsidc.org/api/metadata?id=nsidc-0321

Choice of index

According to Amelung & Moreno (2009), the economic impact of climate change on the ski industry can be estimated from the change in length of the skiing season (days with more than 30 cm of snow). Abegg (1996) argued that a ski resort can be considered snow-reliable if 7 out of 10 winters has more than 30 cm of snow for at least 100 days between 1 Dec and 15 Apr. Töglhofer et al. (2011) studied overnight stays in Austrian ski resorts from a short-term climate variability perspective and confirmed that snow is much more significant than temperature.

We therefore settled on "number of days with more than 30 cm of snow" as our main index of interest. Comparing snow depth and snow water equivalent introduces uncertainty related to variable snow density. While the density is low in the beginning of the season and increases as the snow packs more densely throughout the season, the snow in ski slopes tends to be packed much faster, and the exact implications may need further study beyond the scope of this article. For this study, we used a fixed density of 400 kg/m3 (as also used in e.g. Scott et al. 2008), making 30 cm snow equal to 120 mm snow water equivalent.

2. Method

Hydrological model run

VIC was forced by precipitation, temperature, humidity and the incoming fluxes of shortwave and longwave radiation. Based on Schwarb (2000) a vertical gradient in precipitation of 30 percent per kilometer was introduced, in such a way that the mean precipitation over the grid cell was conserved.

VIC runs were performed using the 11 bias-adjusted RCM runs as well as a separate run using only E-OBS (version 9) as forcing data to be used as a reference. Note that this VIC E-OBS run is also using the variables listed above, and does not assimilate any snow measurements. For all runs, the model was setup with a spatial resolution of 0.5 degrees, covering 1970-2010 for the E-OBS forcing while the climate model runs start between 1951 and 1971 and end between 2095 and 2100.

In four locations, the model produced an unrealistic accumulating snow water equivalent from year to year, which could not be found in the measurements, giving up to 50 m SWE by the end of 2010. These points were removed before further analysis took place.

Evaluation

In order to assess the quality of the snow simulation, the model runs were compared to available snow water equivalent data from observations. Although measurements of snow depth are more common and have been used to compare modelled SWE output we chose here to only use SWE observations directly to reduce the uncertainty and complexity associated with using a density parameterisation of density such as in Jonas et al. (2009). Since models, point observations and satellite observations are different in their representation of snow we have chosen to compare the model output to the different datasets using different methods:

- The 1x1 km grid cells of the SLF dataset was aggregated to the VIC grid (longitude, latitude, elevation band).

- For comparison with the point measurements of the NVE dataset the VIC data was interpolated from the eight closest values for each location (2 lon * 2 lat * 2 elev).

- For the MODIS-SSM/I dataset, the VIC data was averaged to match the time resolution of 8 days and the satellite data was interpolated to the VIC grid. Due to the fact that satellite instruments cannot measure deep into the snowpack two exceedance thresholds were chosen, 10 mm and 100 mm SWE, and the hit rate (fraction of correctly modelled events) was analysed.

- The location of measurement station Col-de-Porte is close to the center of one of the model grid cells in the VIC run, so this cell was used without horizontal interpolation.

Future outlook

The 1.5 and 2 degree periods for each model run (Table 1) was compared to the reference period.

3. Results

SLF gridded observations over the alps

The multi-year monthly mean SWE values in the SLF dataset was subtracted from the corresponding values in the VIC E-OBS to give the bias of SWE climatology, shown in figure 1.

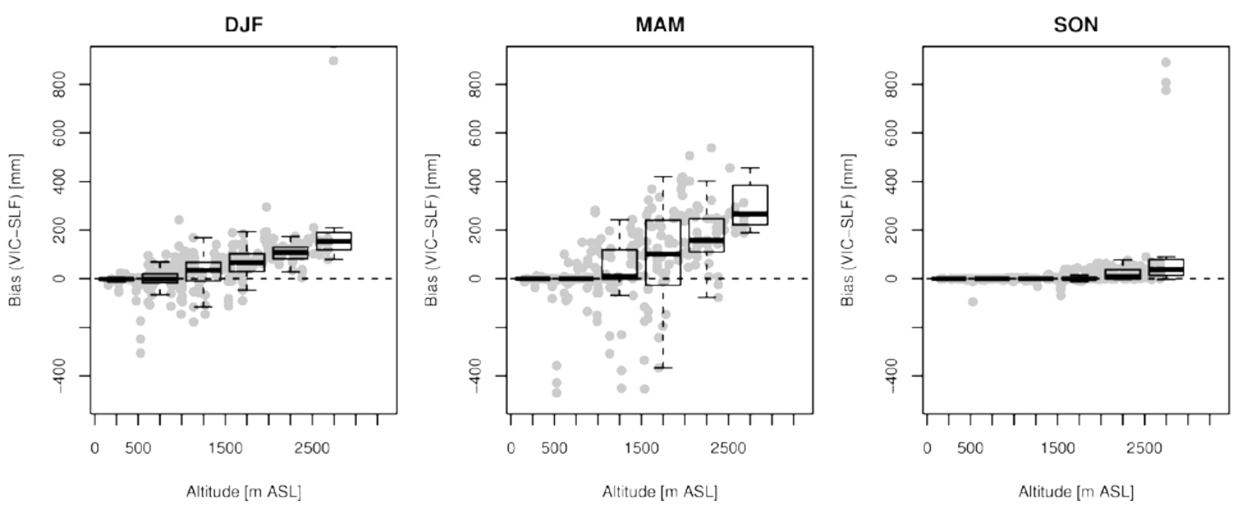

Fig. 1: Bias of SWE climatology over Switzerland (multi-year monthly mean values, VIC E-OBS simulation minus SLF reference dataset) presented separated by season and altitude. The boxplots show, for each 500 m altitude interval, the quartile (25%, median, 75%) positions for

data from each location in their respective elevation interval. The underlying data is shown as grey dots (one for each longitude, latitude, elevation band).

The DJF mean SWE for the SLF and VIC runs are shown in Fig. 2.

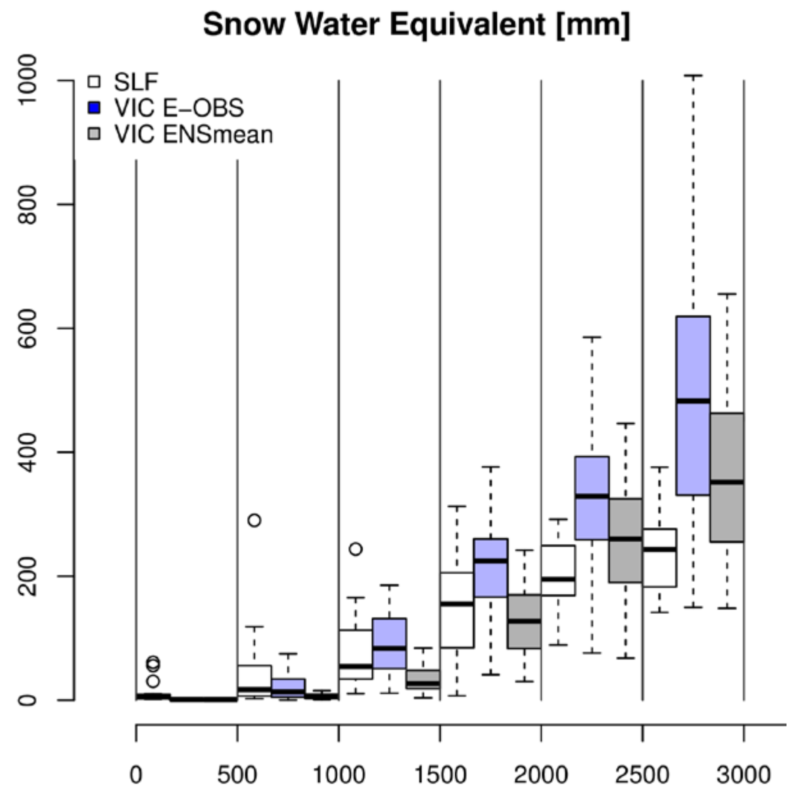

Fig. 2: December-February mean SWE 1998-2010 for SLF (white), VIC E-OBS (blue) and the ensemble mean of the VIC RCM runs (grey).

NVE regulation dataset

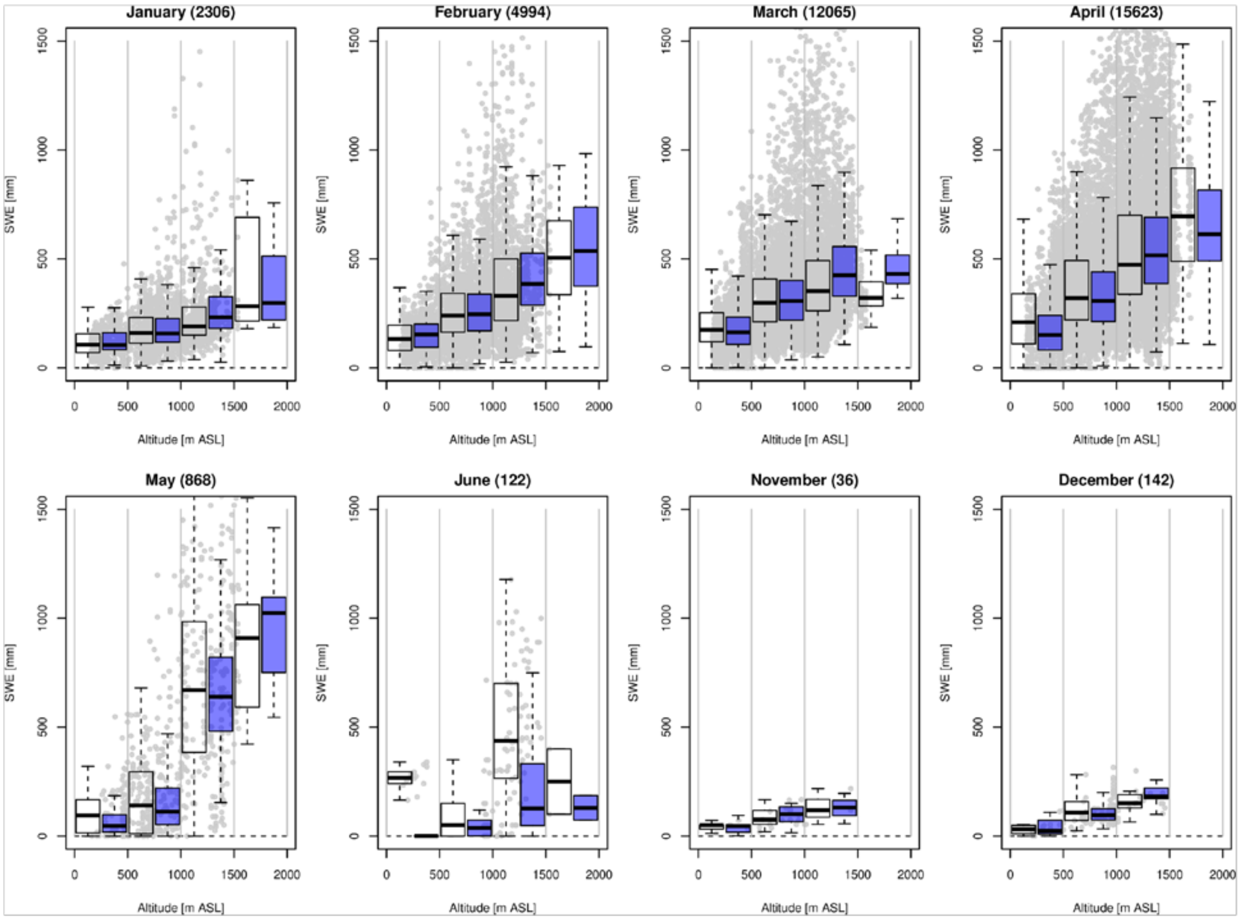

Fig. 3: Snow water equivalent statistics for the NVE dataset over Norway compared to point interpolation from the VIC E-OBS simulation 1970-2010, with one panel for each month (Jul-Oct are not shown since they contain less than 10 points each). Boxplots show for each 500-meter altitude interval the distribution of values for the NVE dataset (white) and VIC E-OBS simulation (blue). The grey points show the underlying NVE dataset, with numbers in parentheses above each panel indicating number of measurement points in each month.

Col de Porte: Time series from both manual snow pit measurements and ground-based cosmic ray counter (NRC) instruments are compared with the VIC E-OBS dataset in Figure 4.

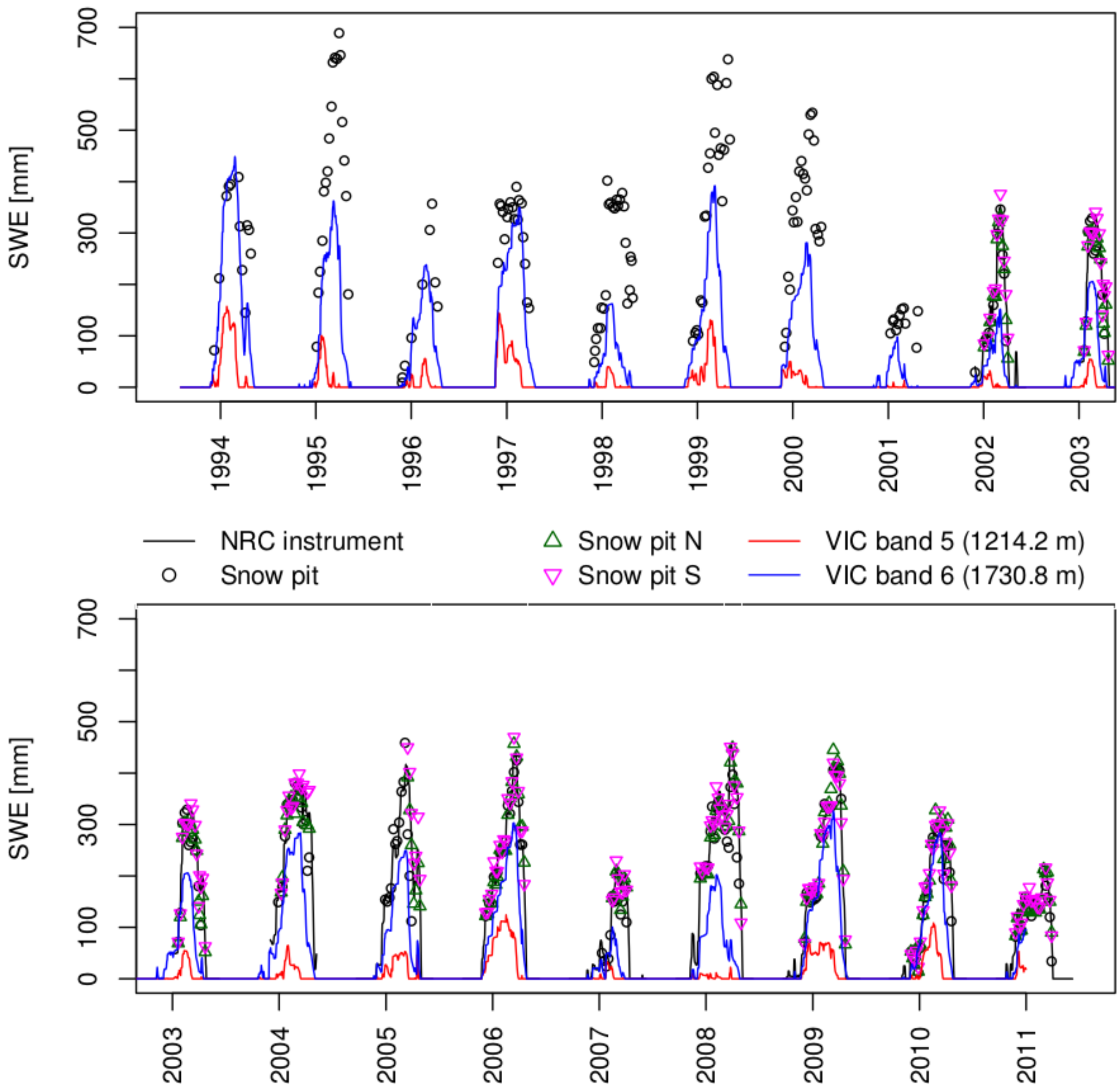

Fig 4: Snow water equivalent from the Col de Porte site. The NRC instrument series is drawn as a black line while the three manual snow pit measurements are shown as symbols. The station is located at 1325 m above sea level. The two nearest elevation bands are shown as lines; band 5 (at 1214.2 m, red line) and band 6 (at 1730.8 m, blue line).

Satellite: The fraction of successful representations of snow or no snow for two thresholds and two temporal resolutions is shown in Fig. 5.

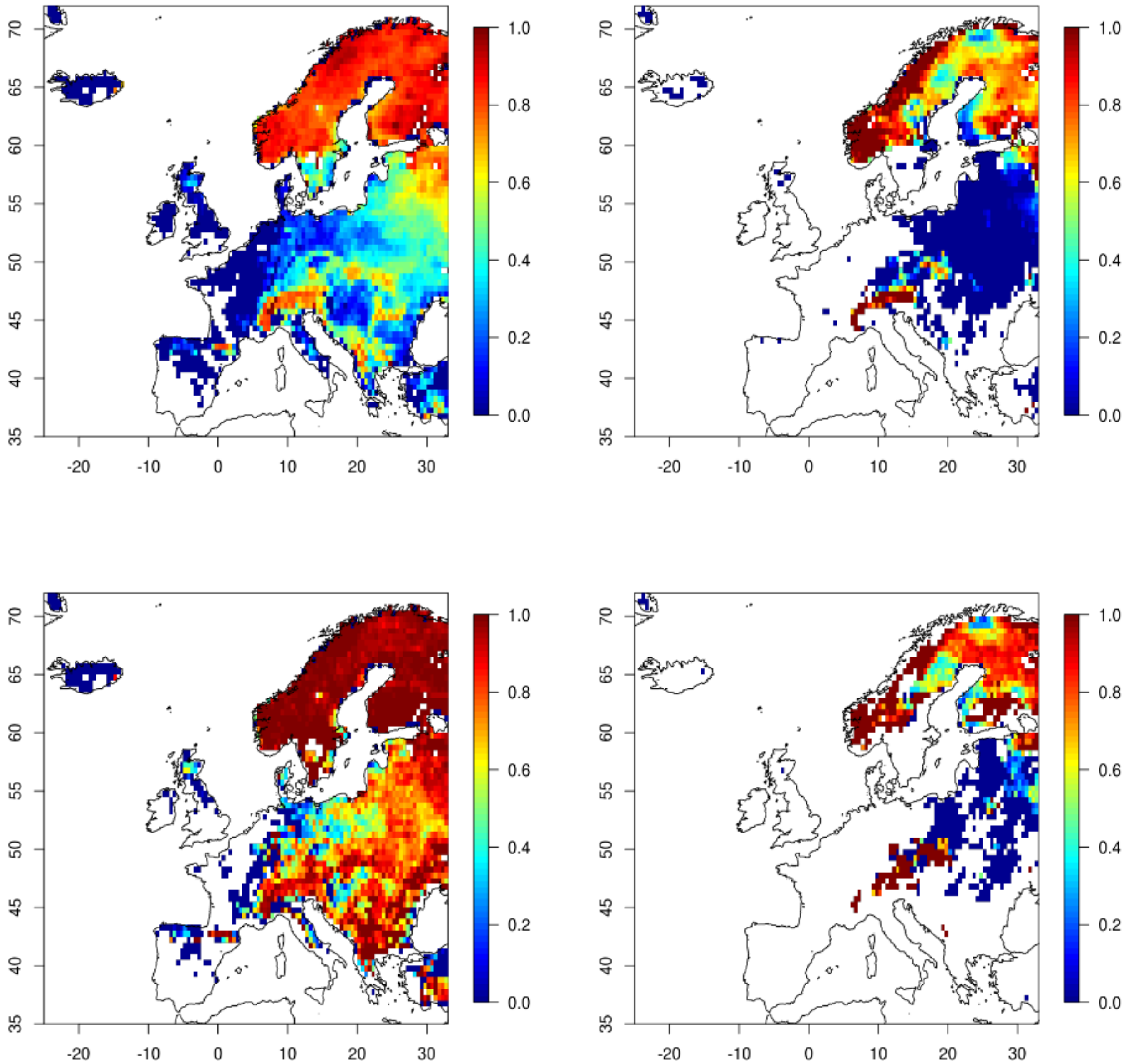

Fig. 5: Agreement between VIC E-OBS and SSM/I for thresholds of 10 mm (left) and 100 mm (right). Calculated as number of times when VIC and SSM/I agree on being above threshold, divided by number of times the SSM/I dataset is above threshold. An agreement of 1 means that all occasions have been correctly reproduced by VIC. The top panels show 8-day mean values (original dataset time resolution, which gives 355 time steps for the period Mar 2000 - Feb 2008) while the bottom panels show monthly mean values (95 time steps for the same period).

Impact:

Validation of days above the 120 mm SWE threshold are shown for the area covered by the SLF dataset in Fig. 6. The impact of the different temperature increases on the number of days above 120 mm SWE is shown in Fig. 7 for the two regions Scandinavia and the Alps at different elevation intervals, and for all of Europe in Fig. 8.

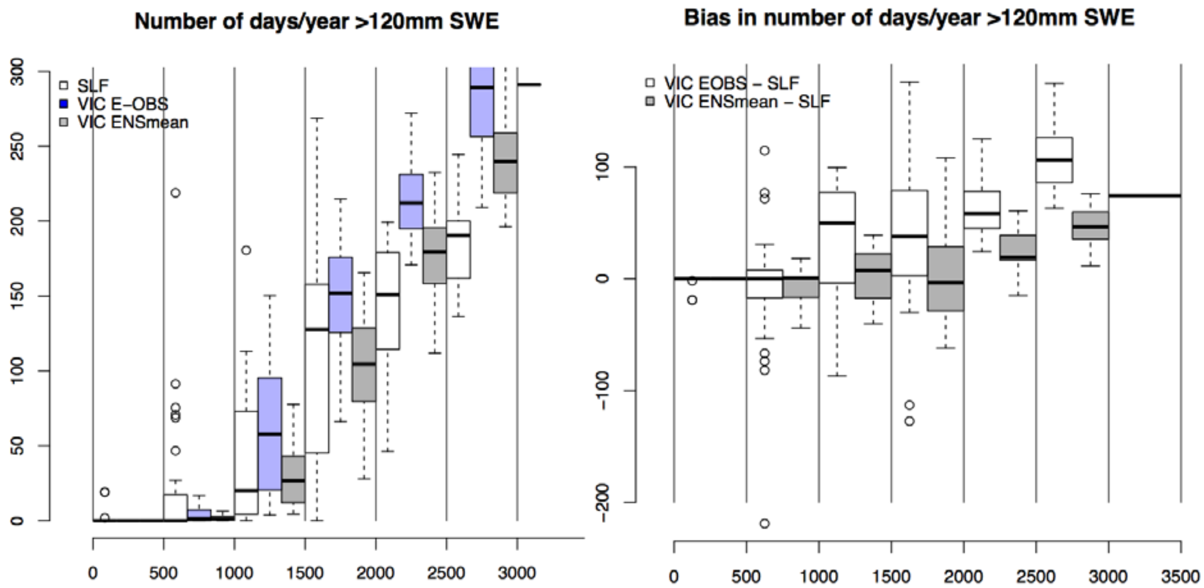

Fig. 6: Comparison of the annual mean number of days above 120 mm SWE in the SLF dataset, the VIC E-OBS simulation and the ensemble mean of the VIC RCM ensemble. Analysis is performed on the VIC grid over the Swiss alps.

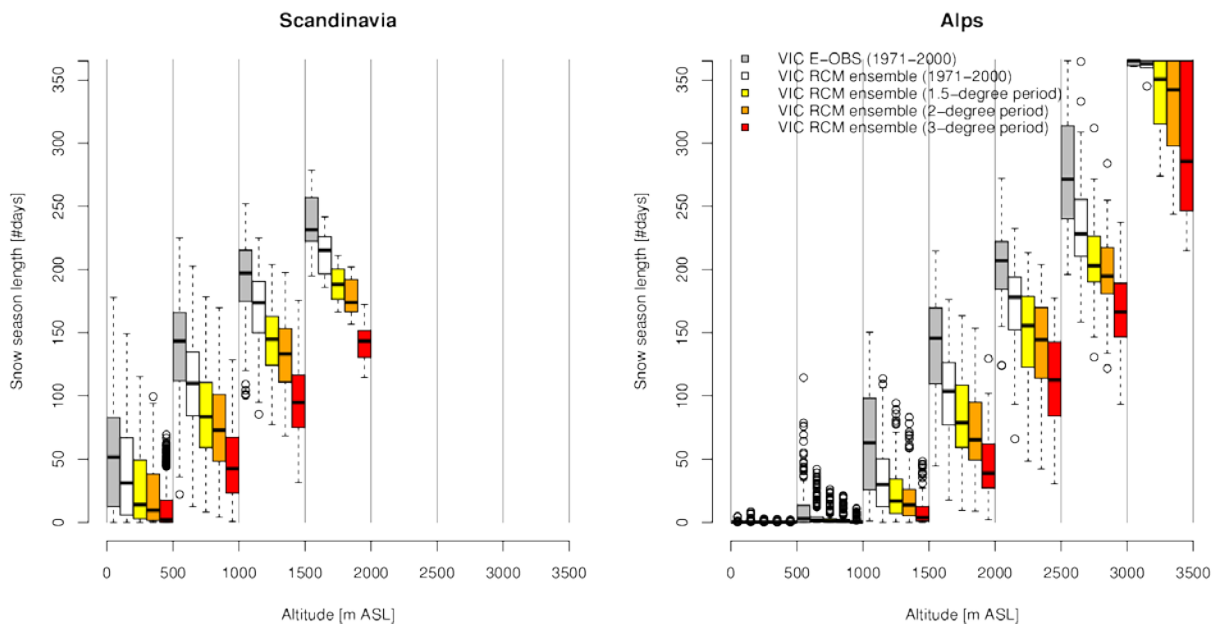

Fig. 7: Annual number of days with more than 120 mm snow water equivalent for the two regions Scandinavia (left) and the Alps (right). The histograms show distributions in 500-meter elevation bins for each of the datasets. For the reference period 1971-2000 the VIC E-OBS simulation is shown in grey and the 11 selected VIC RCM simulations are shown in white. For the 1.5-degree (11 members), 2-degree (9 members) and 3-degree (5 members) periods the VIC RCM simulations are shown in yellow, orange and red, respectively.

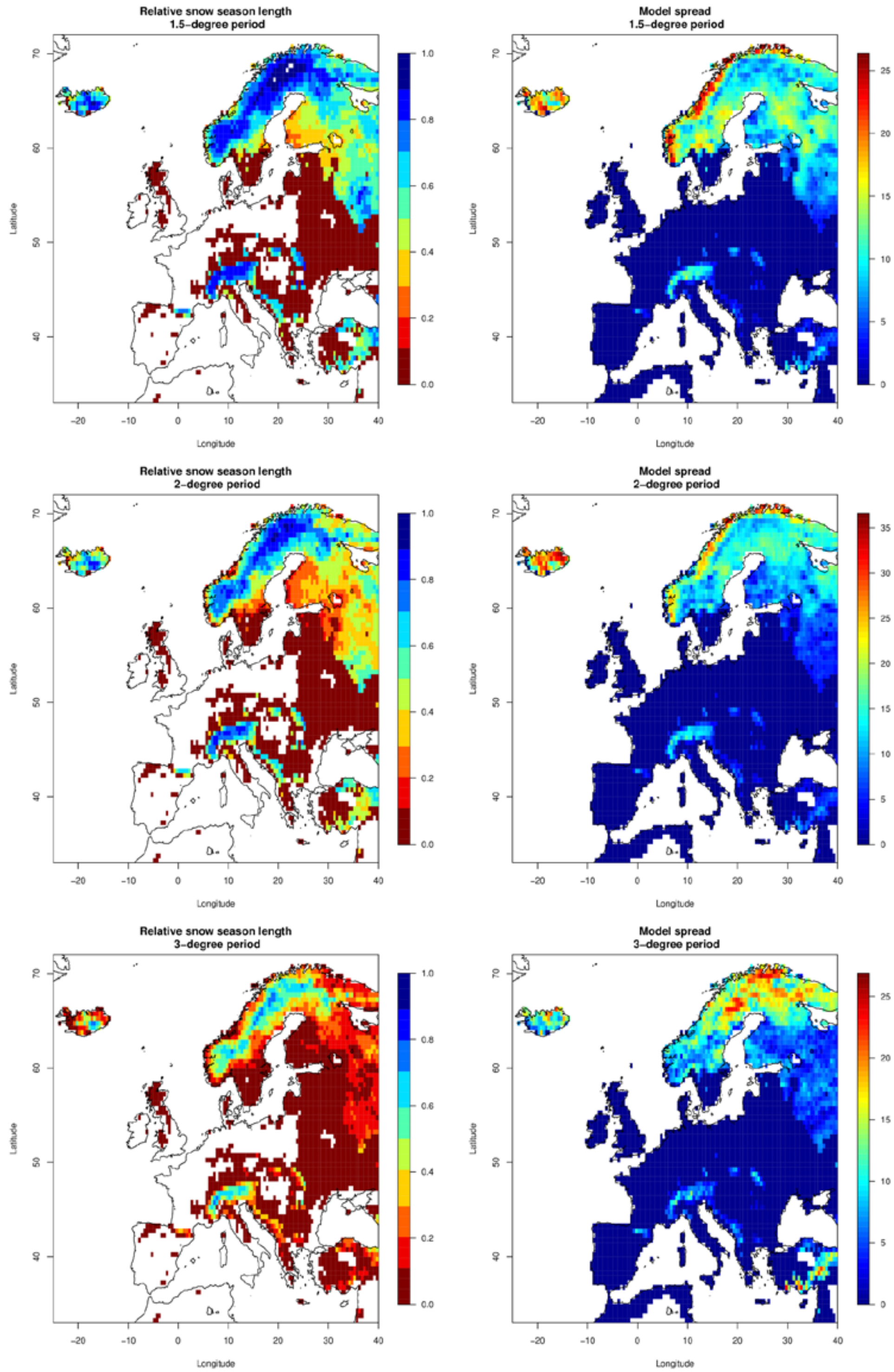

Fig. 8: Number of days >120 mm SWE for the 1.5, 2 and 3-degree periods (left top, middle and bottom respectively) relative to 1971-2000. The panels on the right show the ensemble spread (standard deviation of the reduction in number of days for the VIC RCM runs). Lower numbers indicate less spread (more agreement within the ensemble).

4. Discussion

Figure 1 shows that the VIC E-OBS simulation has a positive bias which increases by altitude. In relative terms, this corresponds to about 2-3 times the observed values for altitudes above 1000 m ASL (not shown). The VIC RCM ensemble however shows much smaller bias, as can be seen in Fig. 2. The positive bias for high altitudes in the VIC E-OBS run is also confirmed by the NVE regulation dataset, Fig. 3.

Reasons for the different biases may include:

- Reduction in physical consistency between temperature and precipitation due to bias-correction of the RCM ensemble being performed separately for each variable.
- Biases in the GCM-RCM chain that may not have been adjusted with the quantile mapping method used.
- Use of constant elevation gradients in the VIC model (for temperature run was set to constant (–0.0098 K/m), which may be too large. However, the temperature lapse rate can compensate for lack of gradients in radiative fluxes (which e.g. for incoming solar radiation is negative due to increased cloud cover with elevation). In the current model setup it may therefore be regarded as a tunable parameter.
- Possible biases in the E-OBS dataset. This may particularly be an issue in high-elevation areas, where there are few observations. Haylock et al. (2008) details the methods used for the E-OBS dataset.

The fact that the ensemble mean has smaller bias than the VIC E-OBS run is rather interesting, considering that E-OBS was used in the bias correction procedure. However, the bias-adjustment was performed with E-OBS version 5 while the VIC run was run with version 9, so it is possible that some of the differences may come from that. (This will be investigated further before final submission.)

The model run has a negative bias for the Col-de-Porte site (Fig. 4). While the station is located at 1325 m altitude, not even the modelled SWE at 1730.8 m has enough snow. However, in the VIC simulations this grid point has a mean elevation of 870 meters. The assumed gradients, as discussed above, are then applied onto the forcing data and may therefore have a relatively large effect at this large elevation difference. Comparing the temporal structure of the simulation to the observed time series, the model seems to perform better for the start of the snow season than the end, with a too early onset of the spring melting most years at this location.

The comparison with satellite data (Fig. 5) shows good agreement for most areas with much snow, including the Scandinavian mountains, the Alps, the Pyrenees as well as the Carpathian and Balkan mountains, but that there is a mismatch for lower-lying areas.

As was already shown in Fig. 2, the bias in the VIC RCM ensemble is much smaller than in the VIC E-OBS run, leading to similar biases when applying the 120 mm threshold (Fig. 6).

For the reference period 1971-2000, Figure 7 shows that the annual number of days above 120 mm SWE in the VIC RCM ensemble is lower than in the VIC E-OBS simulation (except for the highest elevations close to being above 120 mm all year around). As discussed above this is possibly due to a positive bias in the VIC E-OBS run. The number of days decrease by approximately the same amount (typically 50 days) for Alpine locations above 1500 m, naturally constituting a larger fraction of the season being lost at lower altitudes. For Scandinavia the pattern is similar to alpine locations of one kilometer higher altitude.

Fig. 8 shows that many areas will no longer have any days with more than 120 mm SWE in the future periods, and even mountainous regions may have their number of days reduced by 40-60 percent. The largest model spread is found along the Norwegian coast for the 1.5 and 2-degree periods, while for the 3-degree periods it is in the northern parts of Fennoscandia. The model runs however are not exactly the same for the different periods (see Table 1), with the number of runs decreasing from 11 in the reference and 1.5-degree periods to 9 and 5 in the 2 and 3-degree periods respectively.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7 / 2007-2013 under grant agreement no 282746; IMPACT2C: Quantifying projected impacts under 2°C warming.

The authors would like to thank Tobias Jonas at the WSL Institute for Snow and Avalanche Research (SLF) for access to a pre-release version of the gridded SWE dataset for Switzerland and Tuomo Saloranta at the Norwegian Water and Energy directorate for providing the Norwegian dataset.

We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://www.ecad.eu).

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