Nat Hazards (2008) 44:329–339
DOI 10.1007/s11069-007-9130-5

ORIGINAL PAPER

Development of a model-based high-resolution extreme surface wind climatology for Switzerland

Stéphane Goyette

Received: 31 March 2006 / Accepted: 18 January 2007 / Published online: 18 August 2007

Abstract An innovative methodology aimed at establishing a numerical model-based high-resolution climatology of extreme winds over Switzerland is described, that makes use of the Canadian Regional Climate Model where a new windgust parameterization has been implemented. Self-nesting procedures allow windstorms to be studied at resolution as high as 2-km. The analysis of ten major windstorms concludes that the average spatial pattern and magnitude of the simulated windspeeds are well captured, and the areas that experienced extreme winds correspond well with observations and to the location where forest damage was reported following the last two of these storms. This climatology would eventually serve to form risk assessment maps based on the exceedance of windspeed thresholds. There is, however, a need for further investigations to encompass the full range of potential extreme wind cases. The ultimate goal of this methodology is to assess the change in the behaviour of extreme winds for a climate forced by enhanced greenhouse gas concentrations, and the impact of future windstorms over the Alpine region at high resolution.

Keywords Windstorm · Wind damage · Storm damage · RCM · Wind gust · Winterstorm

1 Introduction

Several high-resolution gridded climate parameters, including temperature and precipitation, are available for Switzerland in the second half of the twentieth century (e.g. Gyalistras 2003). These regional datasets are generated by a variety of statistical and empirical methods to interpolate station data onto specific grids, i.e. the spatialization (e.g.

S. Goyette (✉)
Climatic Change and Climate Impacts, University of Geneva,
7 route de Drize, Geneva, Switzerland
e-mail: stephane.goyette@unifr.ch

Tveito and Schöner 2002). However, no such climatology exists for winds; the major difficulty being related in part to the spatialization of wind speeds and wind directions. Maximum wind and gust velocities are of key importance because of the impacts that they are capable of generating in both lowland and mountain regions (Beniston 2003).

The development of a high resolution extreme wind climatology is made possible nowadays by self-nesting model techniques capable of reproducing spatially this highly variable field influenced by small-scale features of the underlying terrain. This technique may thus be considered as a sophisticated interpolation technique, not only used for winds but also for a whole set of relevant climate parameters that are simulated in a physically-consistent manner.

Over the North Atlantic Ocean a number of subpolar low-pressure systems travel with the westerlies. Cyclonic activity is particularly strong during winters when frequent storms bring adverse conditions in western European countries (Nilsson et al. 2006; Schüepp et al. 1994; Beniston and Innes 1998; Dorland et al. 1999; Dobbertin 2002]. In Switzerland, the number of station recordings with hourly maximum wind speeds exceeding 30 m s^{-1} (i.e. Beaufort 10 force capable of exerting substantial damage) during the last 28 years (1978–2005) is highly variable, ranging from 60 in 2003 to more than 2160 in 1999; 368 of these cases are related to the storms that afflicted the Alps from December 25–28, 1999, and include the famous "Lothar" storm; these numbers are based on the Swiss automated network ANETZ datasets (Bantle 1989). The number of hourly wind maximum events seems to increase, accompanied by a slight but positive tendency for these violent windstorms to extend over a larger area of Switzerland during this period. The spatial distribution of strong winds and that of the gusts during stormy events in Switzerland is complicated by the complex topography of the Alps to the South and to the presence of the Jura Mountains to the North, in addition to the impact of storms that varies from one storm to another. If these strong and widespread storms were to become more intense or more frequent in the future, damage to the environment and to infrastructures would increase in response to the amount of kinetic energy induced by these winds. Damage from windstorms is caused by strong sustained winds and gusts where damage varies approximately exponentially with the speed of wind gusts (Dorland et al. 1999). A regional climatology of the extreme winds is therefore of interest. A spatial characterization of these extreme winds is difficult to establish in the complex terrain of Switzerland on the basis of measurements alone since the density of station observations is too "coarse" to compute an accurate spatial distribution of wind speed, and the characteristics of wind velocity over mountains are related to their topographic, rather than to their altitudinal, effects (e.g. Barry 1992).

Although computer power has greatly increased in the last decade, the horizontal resolution of Regional Climate Models (RCMs) nested within General Circulation Models (GCM) remain nonetheless too coarse to supply extreme wind climate data of the quality required by the insurance, engineering, foresters, as well as by many industrial sectors. Although computationally resource intensive, multiple nesting techniques driven by reanalysis data has shown genuine skill in resolving a number of specific strong wind events over the Alps such as the Feb 27, 1990 Vivian, and the Dec. 26, 1999 Lothar storms (Goyette et al. 2001; Goyette et al. 2003). A recent study using a similar methodology showed that the CRCM produced realistic wind field simulations compared to station observations over Southern Sweden during the windstorm Anatol in early December 1999 (Nilsson et al. 2006). The simulated winds were in congruence with inland observations. Most of the damaged forest stands were located on south-westerly slopes in the areas of simulated maximum wind speed greater than 30 m s^{-1}. This methodology is also appropriate for investigating windstorms with carefully selected General Circulation Model (GCM) outputs. Over complex terrain, non-linear behaviour of the flow precludes the use of statistical or other empirical downscaling techniques to generate reliable wind information at high spatial resolution; however, the multiple-nesting method has demonstrated genuine skill simulating strong winds events (Benoit et al. 1997; Goyette et al. 2003). The use of GCM outputs to drive a RCM can be further justified by the fact that this study is the first phase of a larger comparison project where the change of the extreme wind climatology following the IPCC A2 greenhouse-gas warming-scenario over the period 2071–2100 is envisaged. The prerequisite of simulating adequately the spatial distribution and the magnitude of the winds during a collection of storms in Switzerland represents yet a "minimal" requirement to validate the approach suggested in this paper; this is achieved by comparing model results with station data.

This paper describes the self-nesting methodology used to downscale a series of windstorms with the Canadian RCM and discuss about the requirements for the development of a useful numerical high-resolution extreme wind climatology for Switzerland. As a preliminary analysis for the validation, the simulated mean sea-level pressure associated with the strongest windstorms is compared to reanalysis data for comparable situations. The simulated wind maxima on the 2-km grid are also compared with the ones from the Swiss climate observation network during these storms.

2 Model and data

The model used in this study is the Canadian RCM whose principal characteristics is an efficient semi-Lagrangian, and semi-implicit marching scheme (Tanguay et al. 1990; Laprise et al. 1997), applicable to a wide range of atmospheric motions, coupled with the physical parameterizations of the second generation GCM of the Canadian Centre for Climate modelling and analysis (GCMII; McFarlane et al. 1992). This combination is applicable to both short-and long-term simulations (Caya and Laprise 1999; Laprise et al. 1998). The model has an option allowing nudging the large-scale flow over the computational domain as described in Biner et al. (2000). In this approach, the model is forced towards a particular solution because we impose on it a known solution coming either from observations (e.g. reanalysis data) or from a previously simulated run with a numerical model (e.g. GCM outputs). This model uses the multiple self-nesting methodology on a number of collocated grids that capture accurately the wind speed and direction (Goyette et al. 2001; Benoit et al. 1997). Recently, the implementation of a physically-based parameterization using computations of wind gusts has been performed with the CRCM at high resolution (Goyette et al. 2003). The parametric scheme captures the essential features of wind gusts on a very fine grid mesh, and has thus been applied to the case of an extreme wind climatology for Switzerland at high resolution (here with a 2-km grid spacing).

Lateral and upper boundary conditions are provided by simulations with the UK HADLEY Centre HadAM3H global model (Pope et al. 2000), whose results are available for the 1961–1990 control period in the context of the EU 5th Framework Program "PRUDENCE" project (Christensen et al. 2002). This high-resolution GCM (~150 km) has been used to drive a number of RCMs in the PRUDENCE project; this GCM compares well with observed surface pressure, temperature and other flow fields (Beniston et al. 2006) but according to Hanson et al. (2004), it accurately identifies the North Atlantic storm tracks but underestimates the level of cyclone activity within this region.

In order to overcome problems of computing resources required for climate simulations at high resolution, the development of high-resolution extreme wind climatology using the CRCM nesting methodology based on the "N" most extreme windstorms is currently being developed for Switzerland. To identify the most severe and widespread windstorms during the 1961–1990 period, daily outputs of wind maximum simulated with the 50-km HIRHAM4 RCM of the Danish Meteorological Institute (Christensen et al. 1998) driven by the HadAM3H GCM outputs, also available to us in the Framework of PRUDENCE project, are averaged over Switzerland (21 grid points in total); these averages are then classified in descending order of intensity to provide results for the strongest storms that have affected Switzerland. The HIRHAM4 simulated outputs are used as analogues for identifying a plausible set of storms, which are subsequently downscaled with the CRCM and its self-nesting procedure. This rather selective approach is intended to avoid marginal storms, i.e. those covering only a fraction of the Swiss territory. These analogues are preferred to the HadAM3H simulated wind outputs because of the better "storm" signatures as a consequence of the higher spatial resolution of this RCM.

Each of these situations are first downscaled to 160 km with the CRCM for a nine-day period, following which the 160 km atmospheric outputs serve as driving nesting conditions for the subsequent 60 km run with same model. These outputs then drive the 20 km integration, whose results serve as driving conditions for the 5 km, which in turn drives the ultimate 2-km integration for a one-day simulation over Switzerland; at this resolution the new windgust parameterization is applied as shown in Fig. 1. For additional technical details regarding the multiple self-nesting procedure as well as of the model configuration, the reader is referred to the paper of Goyette et al. (2003). It should be noted that the

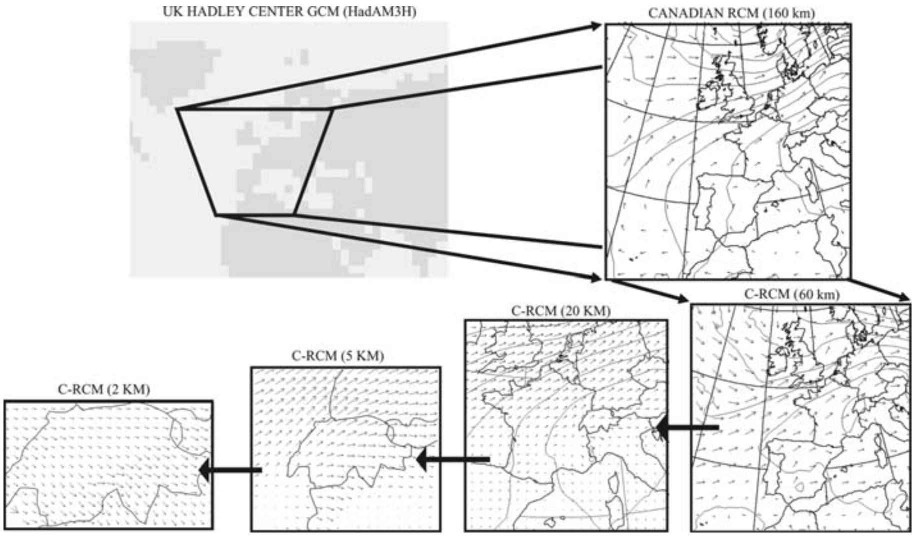


Fig. 1 Self-nesting technique involves a number of model simulations: input data comes from Hadley Centre's GCM HadAM3H, 41 × 33 grid centered over Western Europe. These are downscaled with the Canadian RCM at 160-, 60-, 20-, 5- and finally to 2 km resolution. The 160-km CRCM has 30 × 30 grid points in the horizontal. The 60-, 20- and 5-km CRCMs have nearly the same number of grid points in the horizontal, i.e. ~100 × 100; the number of vertical levels ranges from 20 for the 60-km CRCM to 30 for the 5-km CRCM. The 2-km CRCM has a 180 × 120 grid in the horizontal and 50 vertical levels

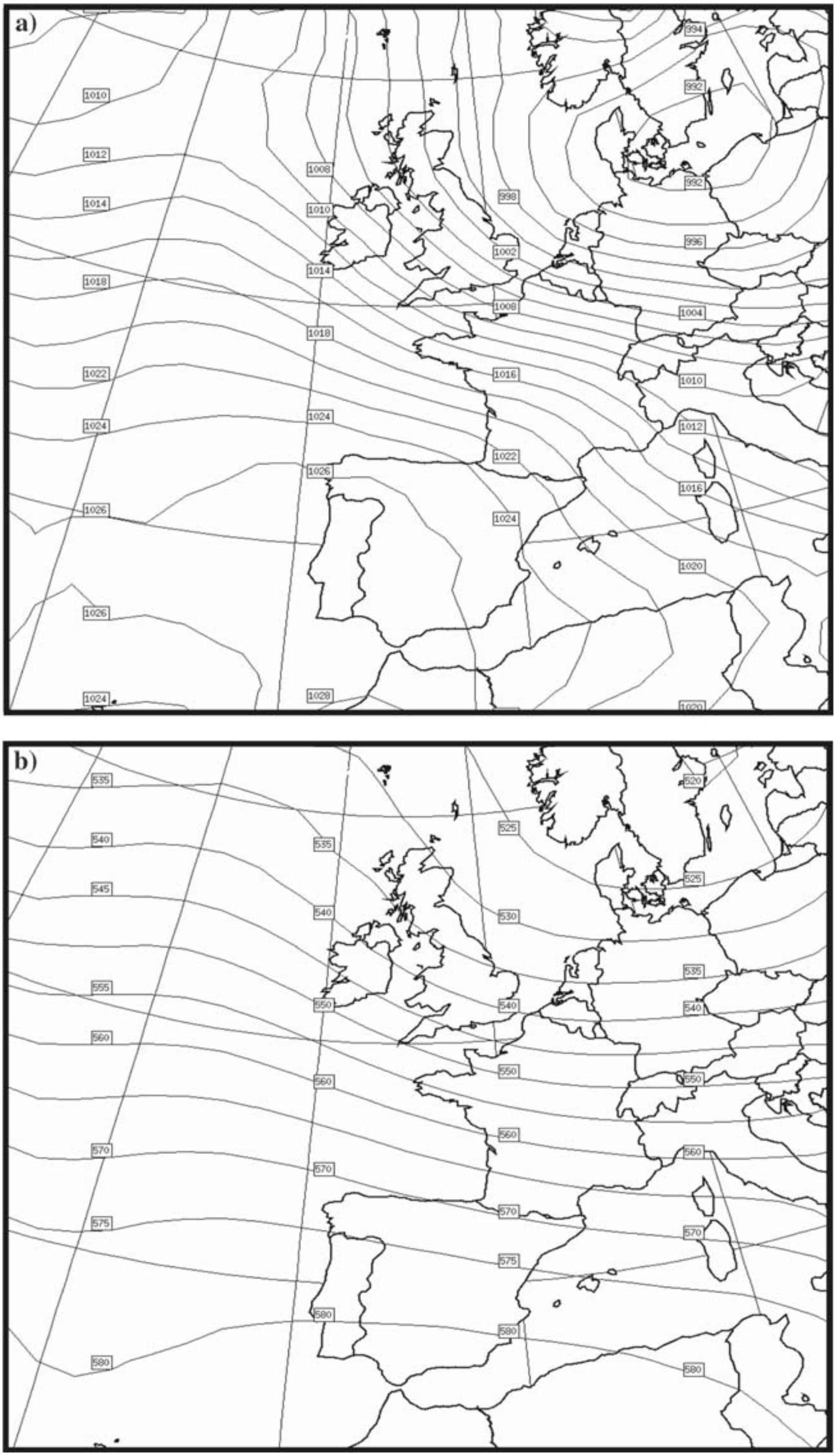
simulated surface pressure and winds with the 50-km HIRHAM-4 RCM compares qualitatively well with the 60-km simulated ones with the CRCM; this intermediate step is meant to verify that the CRCM is effectively downscaling the same extreme events that were identified previously.

A number of windstorms have been refined with this methodology on the 2-km grid over Switzerland and this paper illustrates the 10 strongest. The maximum windspeeds are compared with observed hourly maximum winds of the Swiss automated station network ANETZ, averaged over a comparable number of observed storms. The data are not homogenized by MeteoSwiss but different tests of plausibility are applied and values corrected where necessary (see Jungo et al. 2002, p 489). To identify the most severe windstorms in the observational datasets, the hourly wind maxima are averaged over all stations and the averages are then sorted out in descending order of magnitude in order to select ten strong wind events. In order to enrich the comparison, the corresponding 10 windstorms mean sea-level pressure fields from the NCEP–NCAR reanalysis data (Kalnay et al. 1996) are compiled and compared with the first ten simulated average on the 160-km CRCM grid mesh.

3 Results

To illustrate concisely the atmospheric circulations that generated the simulated windstorms, the synoptic averages mean sea-level pressure and the 1000–500 hPa thickness fields are shown in Fig. 2. These windstorms are generated by westerlies induced by deep cyclones travelling in the North Atlantic and deepening in the Baltic Sea during the November to March months. The mean sea-level pressure pattern averaged during the simulated storms with the 160-km CRCM corresponds well with the NCEP-NCAR mean sea-level pressure (not shown) averaged over the 10 strongest wind storms recorded in Switzerland since 1978. The mean low-pressure centre is located over Southern Scandinavia-Baltic Sea and the high is located over the Azores; this configuration produces a strong pressure gradient with isobars tilted in a northwest-southeast direction resulting in strong westerly flow components over Switzerland. The local pressure gradient of 6 hPa 290 km^{-1} (1012 hPa to the South and 1006 hPa to the North) across Switzerland is also found in the NCEP-NCAR mean sea-level pressure averaged over these storms. The deeper cyclones (four of them) producing the strongest winds over Switzerland may be considered as explosives according to the criterion of Sanders and Gyakum (1980) which states that they are so when the central pressure geostrophically adjusted to 60°N decays at least 24 hPa in 24 h. The rate of deepening of the other cyclones ranges from -12 to -10 hPa 24 h^{-1}. These cyclones deepened south of the mean low-pressure centre from the Baltic Sea to the northeast of Switzerland. The mean 1000–500 hPa thickness (Fig. 2b), conducive to storm systems, shows a zonal pattern stretching far in the North Atlantic ocean inducing a steep N–S gradient around 40–50°N, which is indicative of strong flow from the North Atlantic directly towards the UK, France, Switzerland and Germany.

As an illustration of the relevance of the application of the multiple self-nesting methodology, a summary of the simulated strong winds in Switzerland with the 2 km CRCM is provided. The gust speeds for the ten-strongest storms show that the average of simulated hourly mean–maximum wind speed distribution, averaged at all the ANETZ stations using bi-linear interpolation on the mesh, $\overline{V}_{max}^{CRCM} = 28.8\ \mathrm{m\ s}^{-1}$, differs from the observed hourly mean maximum winds by $-1.4\ \mathrm{m\ s}^{-1}$, and the standard deviation of this quantity, $\sigma_{vmax} = 8.2\ \mathrm{m\ s}^{-1}$, differs from the observations by $-1.2\ \mathrm{m\ s}^{-1}$. The spatial


a)
1010
1012
1014
1018
1022
1024
1026
1026
1024
1008
1010
1014
1018
1024
1026
1028
998
1002
1008
1016
1022
1024
994
992
992
996
1004
1010
1012
1016
1020
1020
b)
535
540
545
555
560
570
575
580
535
540
550
560
570
580
525
530
540
550
560
570
575
580
520
525
535
540
550
560
570
580

◀ **Fig. 2** Mean sea-level pressure in hPa (**a**) and 1000–500 hPa thickness in dam (**b**) simulated with the 160-km CRCM averaged over the ten strongest windstorms. Isobars are contoured every 2 hPa and thicknesses every 5 dam

distribution of mean daily maximum wind speed simulated at 2 km includes a number of details as shown in Fig. 3. In general during these events maximum winds are usually found at elevated alpine stations on the average (e.g. Santis = 32 m s^{-1}, Grand St Bernard 29 m s^{-1}, Jungfraujoch = 66 m s^{-1}) but winds are underestimated somewhat in the Jura (e.g. Chasseral = 28 m s^{-1}, La Dôle = 25 m s^{-1}). Strong winds are also at low elevation stations in the Swiss Mitteland (Payerne = 25 m s^{-1}, Zurich = 26 m s^{-1}), in western (Davos 28 m s^{-1}) and southern Switzerland (Locarno 30 m s^{-1}).

The observed relative low wind velocities in the southern and western part of Switzerland tend to be somewhat overestimated by this parameterization and because of spin down problems; the simulations duration is only one day as a consequence of the limited computer power resources.

A remarkable finding is concerning the source of the gusty nature of the winds at the surface: the mean vertical profiles of virtual potential temperature and windspeed simulated with the 2-km CRCM reveals a stable boundary layer above the surface, and that the vertical profile of wind speed shows the presence of the low-level jet flowing at more than 30 m s^{-1} in the 1000–1200 m layer (Fig 4b). Wind shear generated turbulence is thus expected to produce short bursts at the surface as wind gusts. These profiles are supported by observations recorded at station Payerne at 0000 UTC made during one of the strongest widespread storms in Switzerland. Individual simulated storms indicate similar behaviour near the surface where the windgust parameterization is often operative during such events (Goyette et al. 2003).

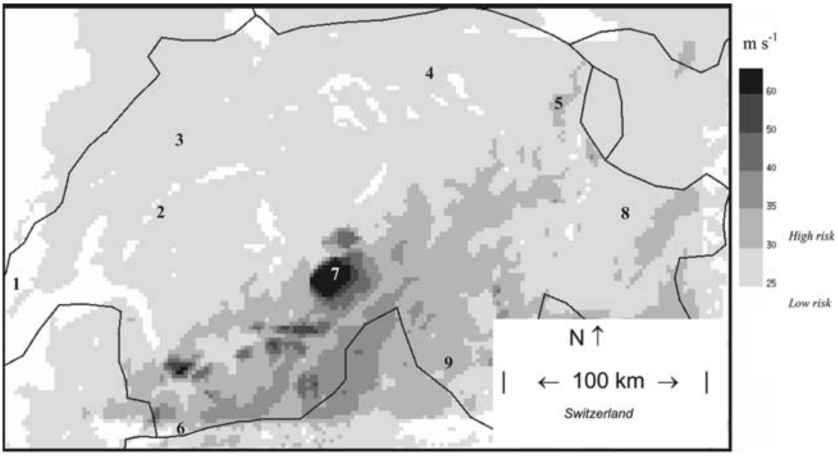


Fig. 3 Spatial distribution of maximum wind speed (m s^{-1}) averaged over the 10 strongest windstorms as simulated by the CRCM at 2 km grid spacing; grey tones refer to wind speeds, scale is shown on the right. Numbers refer to ANETZ station locations: (1) La Dôle [1314/1670], (2) Payerne [520/489], (3) Chasseral [1212/1599], (4) Zürich [535/556], (5) Säntis [1848/2490], (6) Grand St Bernard [2407/2472], (7) Jungfraujoch [3330/3580], (8) Davos [1826/1590], and (9) Locarno [236/366] where CRCM and station observation altitudes (m) are indicated in brackets. The empirical risk is based on the Beaufort scale

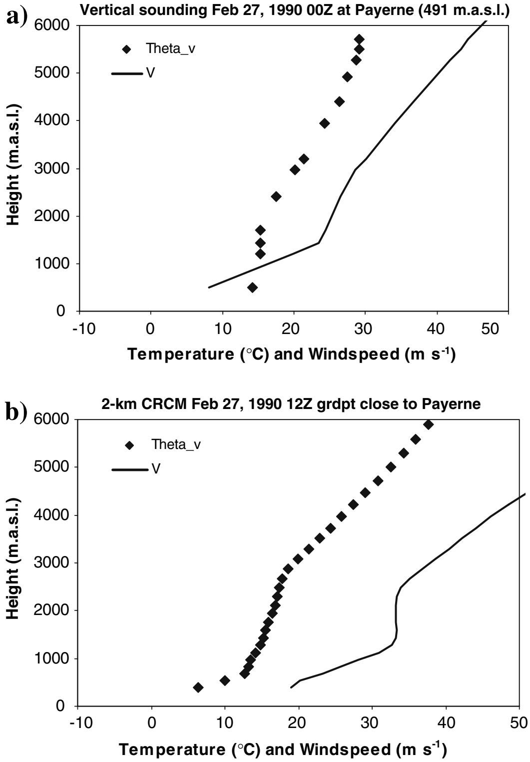


Fig. 4 Observed (**a**) and simulated (**b**) vertical profiles of virtual potential temperature (°C) and windspeed (m s^{-1}) at Payerne. Note that the observed profile is done at 0000 UTC whereas the simulated profiles are valid at 1200 UTC, to avoid model spinup problems

4 Discussion

Despite the recent developments in computing technology in terms of power and memory space, numerical climate simulations (i.e. at least 30 years) using RCM self-nesting approach to reach very high resolution cannot be achieved within reasonable time limits: on the fastest single processor computer available today, a one-day simulation with the 2-km CRCM takes more than real time. Alternatively, the proposed methodology allows for computationally affordable simulations of individual storms selected for their intensity and their impacts over a region of interest.

In this methodology, the coarser model simulations are used to refine the weather patterns provided by the HadAM3H GCM, whereas the finer model simulations in combination with high-resolution topography are used to capture the small-scale features, in the horizontal as well as in the vertical, leading to the complex wind fields simulated during the severe storms. The wind velocity fields simulated during the ten strongest storms over Switzerland result mainly from the combined effects of the strong synoptic-scale forcings and the significant topographic controls of the local terrain.

On the basis of HadAM3H GCM flow fields as input data, the averaged windspeed simulated with the 2-km CRCM using the self-nesting technique agree with observations within 10–15%. The temporal and spatial variabilities of the simulated winds are somewhat underestimated as a consequence of the similarity of the selected storms. Analysis is difficult because of the relative rarity of extreme winds events in a limited area; but due to the high damaging potential of such storms it is of interest to study them in their details. On average during these storms, the fastest windspeed (>30 m s^{-1}) is remarkably well correlated with observed damage areas (see Schüepp et al. 1994; Fig. 2b). Differences between observed and simulated wind are also due to the finite dimension of the grid cells; there are a large amount of variations in the wind speed and direction within a 2×2 km^2 surface particularly over the complex terrain of Switzerland. Nevertheless, the spatial details provided by this method produce useful information that may be used to infer the potential wind damages to forests and infrastructure following major cyclone development in the North Atlantic Ocean.

Observations also show that damage may be caused by other types of flow, e.g. southerly and north-easterly flows. Therefore, in order to establish a useful climatology of extreme winds, a wider collection of storms is required.

5 Conclusions

The development of a methodology to establish a model-based high-resolution extreme wind climatology for Switzerland has been outlined. This method allows to dynamically downscale (i.e. refining spatial details) each storm separately, then compiling the average maximum wind speeds and directions at high resolution without undertaking multi-year simulations and considering the most severe storms *a posteriori* using simulated long time series. The analysis of ten windstorms is very encouraging; most of these storms are generated by westerly flows induced by cyclones deepening near the Baltic Sea and the potential areas, which experienced violent winds in Switzerland agree reasonably well with observations. Most of the simulated storms occurred from December to March: observation also shows that westerly flow is the dominant one during the winter season. It can therefore be concluded that this methodology, involving the multiple self-nesting of a RCM driven by GCM outputs, is suitable to achieve the primary goal of this research. The methodology is also applicable to other regions of interests since the RCM can be applied to other regions of the globe.

However, some of these high winds may be generated by purely southerly flow, South Foehn (Hoinka 1985) or by northerly to north easterly flow, the “Bise” (Wanner and Furger 1990), which may cause damage over regions of Switzerland. These preliminary results thus prompt the need for further storm investigation. The end product of this compilation is expected to form a basis for the development of a realistic and useful high-resolution extreme wind climatology where many other wind storms are needed to complete this dataset.

The same methodology may be applied over other countries and regions and this may lead to a different position of the averaged cyclones responsible for strong winds; a particular example is given by the Anatol storm that struck southern Scandinavia in early December 1999 (Nilsson et al. 2006).

This study is the first phase of a larger project: a comparison with the future climate wind gusts is subsequently envisaged where the ultimate goal is to assess the change of the extreme wind climatology following the IPCC A2 greenhouse-gas warming-scenario over the period 2071–2100.

Acknowledgments This study has been partially funded by NCCR-Climate program of the Swiss National Science Foundation (grant No. FN-7449). The author would like to thank Prof. M. Beniston for his constructive comments to this manuscript as well as to the two reviewers for help to improve and clarify the text.

References

Bantle H (1989) Program documentation for the Swiss climate data base at the computing center of ETH-Zürich. MeteoSuisse publication, Zürich, Switzerland (in German)

Barry RG (1992) Mountain weather & climate. 2nd edn. Chapman and Hall, Inc, Routledge, 402 pp

Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K (2006) Future extreme events in European climate: an exploration of regional climate model projections. Climatic Change (in press)

Beniston M (2003) Climatic change in mountainous regions: a review of possible impacts. Climatic Change 59:5–31

Beniston M, Innes J (eds) (1998) The impacts of climate variability on forests. Springer-Verlag, Heidelberg/New York, 329 pp

Benoit R, Desgagné M, Pellerin P, Pellerin S, Chartier Y (1997) The Canadian MC2: A semi-Lagrangian, semi-implicit wideband atmospheric model suited for finescale process studies and simulation. Mon Weather Rev 125:2382–2415

Biner S, Caya D, Laprise R, Spacek L (2000) Nesting of RCMs by imposing large scales. 7.3–7.4. In: Research activities in atmospheric and oceanic modelling, WMO/TD–No. 987, Report No. 30

Caya D, Laprise R (1999) A semi-implicit semi Lagrangian regional climate model: the canadian RCM. Mon Weather Rev 127:341–362

Christensen JH, Carter TR, Giorgi F (2002) PRUDENCE employs new methods to assess European climate change. EOS 83:147

Christensen OB, Christensen JH, Machenhauer B, Botzet M (1998) Very high-resolution regional climate simulations over Scandinavia—Present climate. J Clim 11:3204–3229

Dobbertin M (2002) Influence of stand structure and site factors on wind damage comparing the storms Vivian and Lothar. Forest Snow and Landscape Research 77:187–205

Dorland C, Tol RSJ, Palutikov JP (1999) Vulnerability of the Netherlands and Northwest Europe to storm damage under climate change. Climatic Change 43:513–535

Goyette S, Brasseur O, Beniston M (2003) Application of a new wind gust parameterisation. Multi-scale case studies performed with the Canadian RCM. J Geophys Res 108:4374–4390

Goyette S, Beniston M, Caya D, Laprise JPR, Jungo P (2001) Numerical investigation of an extreme storm with the Canadian Regional Climate Model: the case study of windstorm VIVIAN, Switzerland, February 27, (1990). Clim Dyn 18:145–178

Gyalistras D (2003) Development and validation of a high resolution monthly gridded temperature and precipitation data set for Switzerland (1951–2000). Clim Res 25:55–83

Hanson CE, Holt T, Palutikof JP (2004) An integrated assessment of the potential for change in storm activity over Europe: implication for insurance and forestry in the UK. Tech. Rep. 12, Tyndall centre for Climate Change Research, Univ. East Anglia, UK, 98 pp

Hoinka KP (1985) Observation of the airflow over the Alps during a foehn event. Quart J R Met Soc 111:199–224

Jungo P, Goyette S, Beniston M (2002) Daily wind gust speed probabilities over Switzerland according to three types of synoptic circulation. Int J Climatol 22:485–499

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-years Reanalysis project. Bull Amer Meteor Soc 77:437–471

Laprise R, Caya D, Bergeron G, Giguère M (1997) The formulation of the André Robert MC2 (mesoscale compressible community) model. Atmos Ocean 35:195–220

Laprise R, Caya D, Giguere M, Bergeron G, Côté H, Blanchet J-P, Boer GJ, McFarlane NA (1998) Climate and climate change in Western Canada as simulated by the Canadian regional climate model. Atmos Ocean 36:119–167

McFarlane NA, Boer GJ, Blanchet J-P, Lazare M (1992) The Canadian climate centre second generation general circulation model and its equilibrium climate. J Climate 5:1013–1044

Nilsson C, Goyette S, Bärring L (2006) Relating forest damage data to the wind field from high resolution RCM simulations: case study of Anatol striking Sweden in December 1999. Global Planet Change (in press)

Pope DV, Gallani M, Rowntree R, Stratton A (2000) The impact of new physical parameterizations in the Hadley Centre climate model HadAM3. Clim Dyn 16:123–146

Sanders F, Gyakum JR (1980) Synoptic climatology of the “bomb”. Mon Weather Rev 108:1589–1605

Schüepp M, Schiesser HH, Huntrieser H, Scherrer HU, Schmidtke H (1994) The winterstorm “VIVIAN” of 27 February 1990: about the meteorological development, wind forces and damage situation in the forests of Switzerland. Theor Appl Climatol 49:183–200

Tanguay M, Robert A, Laprise R (1990) A semi-implicit semi-Lagrangian fully compressible regional forecast model. Mon Weather Rev 118:1970–1980

Tveito OE, Schöner W (eds) (2002) Applications of spatial interpolation of climatological and meteorological elements by the use of geographical information systems (GIS). Cost 719, Rep. 28/02. Norweg. Met. Inst, Blindern, Oslo, Norway, 44 pp

Wanner H, Furger M (1990) The Bise—Climatology of a regional wind north of the Alps. Meteorol Atmos Phys 43:105–115