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Relating forest damage data to the wind field from high-resolution RCM simulations: Case study of Anatol striking Sweden in December 1999

C. Nilsson [a,*], S. Goyette [b], L. Bärring [a,c]

[a] *Department of Physical Geography and Ecosystems Analysis, Geobiosphere Science Centre, Lund University, Sölvegatan 12, S-223 62 Lund, Sweden*
[b] *Department of Geosciences, University of Fribourg, Pérolles, Fribourg CH-1700, Switzerland*
[c] *Rossby Centre, Swedish Meteorological and Hydrological Institute, S-601 76 Norrköping, Sweden*

Abstract

Forestry is of major economical importance in Europe, and recent devastating windstorms have pinpointed the vulnerability of this economic sector to windstorms. Forest damage is an important economic issue at a country level and may become even of larger concern under future conditions following global warming. An underlying question is to what extent the storm damage is due to changes in the wind climate compared to the effect of changes in forest management practices? In this paper, the first part of this rather complex problem is tackled.

By using the Canadian Regional Climate Model, CRCM, including a physically based gust parameterisation scheme, NCEP–NCAR reanalysis wind fields for the windstorm Anatol, on December 3–4, 1999, were downscaled, into a nested set-up, to 2 km resolution. The aim is to relate the simulated storm wind field to the observed distribution of storm damaged forests in Scania in southern Sweden, as a first methodological step towards analysing the effect of future windstorms in Swedish forests at the highest spatial resolution one can afford nowadays.

Our results show that the CRCM produced realistic wind field simulations, compared to station observations, of the windstorm event in 1999. The simulated winds were underestimated at the coasts, but in congruence with inland observations. Most of the damaged forest stands were located on south-westerly (SW) slopes, which indicated a south-westerly wind during the wind throw process. This SW wind direction was evident in the early phase of the simulated storm, but then changed into a westerly flow, at an earlier stage than the true observations specified. Further, most damage occurred in the areas of simulated maximum wind speed greater than 30 m s^{-1}.

To conclude, the CRCM has proven to be a useful tool to realistically simulate a forest damaging storm event. Hence, the model could be used for further study cases, preferably driven by a GCM, in order to reveal a greater understanding about recent storms, which in turn helps us evaluate future climate change driven storm conditions.

Keywords: forest; windstorm; wind throw; wind damage; storm damage; RCM; wind gust; winter storm

1. Introduction

In the North Atlantic Ocean, the general circulation of the atmosphere gives rise to numerous subpolar low-

* Corresponding author. Fax: +46 46 222 4011.
E-mail address: Carin.Nilsson@nateko.lu.se (C. Nilsson).

pressure systems that travel with the westerlies. Cyclonic activity over this region is particularly strong during autumn and winter when frequent storms are potentially damaging to ecosystems and infrastructures in western European countries (Schüepp et al., 1994; Beniston and Innes, 1998; Dorland et al., 1999; Dobbertin, 2002). Despite the fact that nature as well as human infrastructure and property to a large extent has adapted to this windy climate, windstorm-induced damage is considered as one of the major threats by forest owners (Blennow and Sallnäs, 2002) and by the reinsurance industry (Berz, 2005). In a survey of northern European forest damage during the period 1950–2000, Schelhaas et al. (2003) found that storms were responsible for 53% of the annual average of 35 million m^3 wood damaged by disturbances.

During December 1999 several devastating windstorms hit Europe. The first was the storm that struck southern Scandinavia on 3–4 December, nicknamed Anatol by the German weather services (Ulbrich et al., 2001). Later during 26–28 December two storms nicknamed Lothar and Martin, swept across France, Germany and Switzerland. Together they caused 170 deaths, vast damage to forests and infrastructure, and further impacted upon society at a total cost over 18 billion Euro; foresters reported that these two storms in three days blew down 165 million m^3 of timber, the equivalent of six months of timber harvest (Munich Re., 2002). Anatol caused substantial damage to the forests in Denmark, where more than one year's worth of timber production was lost (Munich Re., 2002). Likewise, forests in Scania, the southernmost province of Sweden, were uprooted and totally destroyed. In total, 5 million m^3 of timber were damaged in southern Sweden (Nilsson et al., 2004), even with a substantial part of the landscape being open agricultural land. Observations of maximum wind speed at Falsterbo, a coastal station at the south-western tip of Scania, rated Anatol the most violent storm over southern Sweden since 1967 (Vedin and Alexandersson, 1999). The recent windstorm of 8 January 2005, nicknamed "Gudrun", was of similar magnitude but passed over Sweden along a more northerly path over largely forested regions (SMHI, 2005), thus triggering devastating forest damage (Schlyter et al., 2006).

Strong sustained winds and gusts are the main cause of forest damage. However, there are several factors influencing the susceptibility of a single tree to rupture or uprooting by wind force. Forest management is a key factor, as synthesized by Persson (1975), Peltola et al. (1999a), Venäläinen et al. (2004) and Zeng et al. (2004) amongst others, in that it regulates the chosen tree species, tree height and stand density by management practices such as plantation, thinning and clearing. The management practices, in turn affect the root depth and width, determining the anchorage of the trees, together with the general wind stress in the stand (Coutts et al., 1999; Peltola et al., 1999b; Danjon et al., 2005). Further, while the location in the terrain determines the general wind exposure of a forest stand, soil properties, soil chemistry, and the acclimatization of the trees influences their ability to cope with strong winds. The spatial variation of wind-induced forest damage depends the position of a stand in the landscape. Earlier studies show that wind exposure, elevation, aspect and mosaic of land cover types are the most influential factors affecting where in the landscape damage occurs (Foster and Boose, 1992; Lindemann and Baker, 2002).

To link the distribution of wind-induced forest damage to the wind field a method is needed for estimating storm intensity and strong winds at both the regional and local scale. Since the characteristics of wind velocity are strongly related to local topographic features, measurements from a typically sparse network of meteorological stations are of limited utility. One approach, for solving this problem, is to use high-resolution numerical modelling for obtaining a physically consistent picture of the local and fine scale structure of the wind field. To increase the resolution of global climate models or reanalysis datasets, dynamical downscaling by means of regional climate models or numerical weather prediction (NWP) models without data assimilation have so far mainly been used to analyse the wind and wave climate over oceanic and coastal areas (for example, Lowe et al., 2001; Weisse et al., 2005), and for assessment of wind climate and wind power resources over land (for example, Heimann, 2001; Žagar et al., 2006). Few studies have used this kind of high-resolution limited-area models (LAM) without assimilating local observations from within the model domain for studying the impact of windstorms over land.

Regional climate models (RCMs) using multiple nesting techniques driven by reanalysis data has shown genuine skill to downscale windstorms over complex terrain such as the February 27, 1990 "Vivian", and the December 26, 1999 "Lothar" storms over Switzerland as well as over the smoother terrain of Belgium (Goyette et al., 2001; Goyette et al., 2003). The modelling approach uses a self-nesting methodology to downscale from the coarse input resolution to the high-resolution output that captures the wind speed and direction (Benoit et al., 1997; Goyette et al., 2001). Recently, a physically-based parameterisation for diagnostic "on-line" computation of wind gusts have been implemented in the Canadian RCM, CRCM hereinafter (Goyette et al., 2003). This parameterisation was recently found to give a good general representation of the wind speed distribution over land (Rockel, 2005; Rockel and Woth, 2007). While sophisticated data assimilation schemes (see for example Huang et al., 2002, who uses the Anatol windstorm as a test case) use observations within the model domain for improving the numerical solution, this approach is clearly not possible in the context of analysing future climate projections. It is therefore relevant to investigate the performance of regional climate models that are forced at the boundaries only by large-scale gridded input data.

The aim of this study is to relate the pattern of the recorded distribution of storm damaged forest to simulated wind fields, using outputs generated by a high-resolution regional climate model, which uses a multiple nesting technique, as a first step towards analysing the effect of windstorms in Swedish forests. We aim at using a methodology that can be employed to analyse the impact of windstorms in projections of future climate conditions. For this purpose, models that employ data assimilation of local observations cannot be used. We emphasize the advantage of having a realistic gust wind parameterisation and the capability for high spatial resolution simulations available in the Canadian Regional Climate Model (CRCM) to allow a good comparison with high-resolution, spatially resolved, quantitative forest damage reports for a specific windstorm.

2. Data and methods

2.1. Description of study area

The area of wind field simulation includes the southernmost provinces of Sweden, Scania and Blekinge (Fig. 1a) and our analyses are based on data covering almost all of Scania, the rectangle in Fig. 1a. The landscape within the provinces varies from low-lying plains (Fig. 1b) rich in clay, with predominantly agricultural activity in the southwest, along the west coast and in the north east coastal part of Scania, to a small-scale moraine landscape in the centre of Scania, with beech forests and mixed forests (Erlström et al., 1999) on gently rolling ridges streaking in a NW/SE direction. Further north and north east of Scania and in Blekinge in a hilly landscape, needle-leaf forests are found, dominated by Scots pine and Norway spruce. The forest cover has doubled since the early 19th century, and now 31% of Scania, and 64% of Blekinge, is covered with forest (Fig. 1c, and Anonymous, 2004). The climate conditions in Scania can be described as a mild coastal climate, with mean temperatures ranging from −2 °C in January to 17 °C in July and a yearly precipitation mean of 661 mm (Blennow et al., 1999).

2.2. Description of the Anatol windstorm

The December 3–4, 1999 severe windstorm nicknamed Anatol is an example of strong westerly flow over Northern Europe during the winter season induced by an intense cyclonic activity. The event has been thoroughly described by Nielsen (2000), Rosenørn (2000), Voldborg (2000) and Ulbrich et al. (2001). Here we summarise the evolution of this severe weather system.

The low-pressure system developed west of Ireland on December 2 between 12 UTC and 18 UTC, with a maximum deepening rate of 13 hPa during 6 h when the low-pressure centre crossed northern Scotland and further deepened over the North Sea during the night and morning of December 3. Further, the low-pressure centre travelled over southern Scandinavia during the evening and night December 3–4. A surface pressure of 952 hPa (Voldborg, 2000) was recorded over Jylland, Denmark at 19 UTC, before beginning to fill over the Baltic during the morning of December 4. The track of the centre low is displayed in Figs. 2 and 3; in Fig. 2 the mean sea-level pressure, computed on the basis of the NCEP–NCAR reanalyses (Kalnay et al., 1996), show that the centre of the low-pressure system developed west of Ireland on December 2 between 12 and 18 UTC, passed Scotland with a core value of 985 hPa, and then moved over southern Norway and deepened further.

On the Danish island of Rømø on the west coast, gust speeds were recorded at close to 50 m s^{-1} (Voldborg, 2000), far beyond the Beaufort scale maximum (12 Bft, i.e. over 33 m s^{-1}). Local observations in Denmark show that wind speeds associated with the storm were the strongest on record at several synoptic stations (Nielsen, 2000).

The storm winds aloft were associated with a very powerful Atlantic jet stream that extended across the eastern North Atlantic and into Western Europe, where wind speed ranging from 60 to 72 m s^{-1} were found over southern Scandinavia, northern Germany and Poland on December 3, at 12 UTC. This enhanced jet stream was associated with a large-scale pattern of below-average heights over the eastern North Atlantic and above-average heights over the central North Atlantic.

The atmospheric sounding (Fig. 4) recorded at Copenhagen on December 4, 1999 at 00 UTC shows that the virtual potential temperature was strongly increasing from the 900 hPa to the 500 hPa level above the surface indicating a stable boundary layer, and that the wind speed vertical profile shows the presence of the low-level jet flowing at more than 45 m s^{-1} in the 800–700 hPa layer (in this situation about 1500–2500 m). Wind shear generated turbulence is thus expected to produce short bursts at the surface as wind gusts.

2.3. Observation data of wind speed and storm damage

Hourly maximum wind gusts from 5 stations in the Swedish Meteorological and Hydrological Institute (SMHI) automatic station network were used as a reference for the simulated wind fields (Fig. 5). Station locations are displayed in Fig. 1a. At these stations the maxima of the 10-minute averages, recorded every hour, ranged from 15 m s^{-1} to near 30 m s^{-1} on late December 3, whereas the hourly maximum gust winds reached 30 m s^{-1} to 43 m s^{-1} (Fig. 5).

The Regional Forestry Board in Kristianstad, managing the province of Scania and Blekinge in southern Sweden, collected storm damage data after the event. The geo-coded data give information on those forest stand areas with damage somewhere within the stand (Fig. 1b). The forest stands with damage are concentrated around, and on top of the largely forested ridges (see Fig. 1b). Further, there are scattered damage in the more extensive forests in the north of Scania and Blekinge.

2.4. Data and methods describing forest damage in the landscape

A digital elevation model (DEM) over Scania (Fig. 1b), having 50 × 50 m resolution, from Lantmäteriet

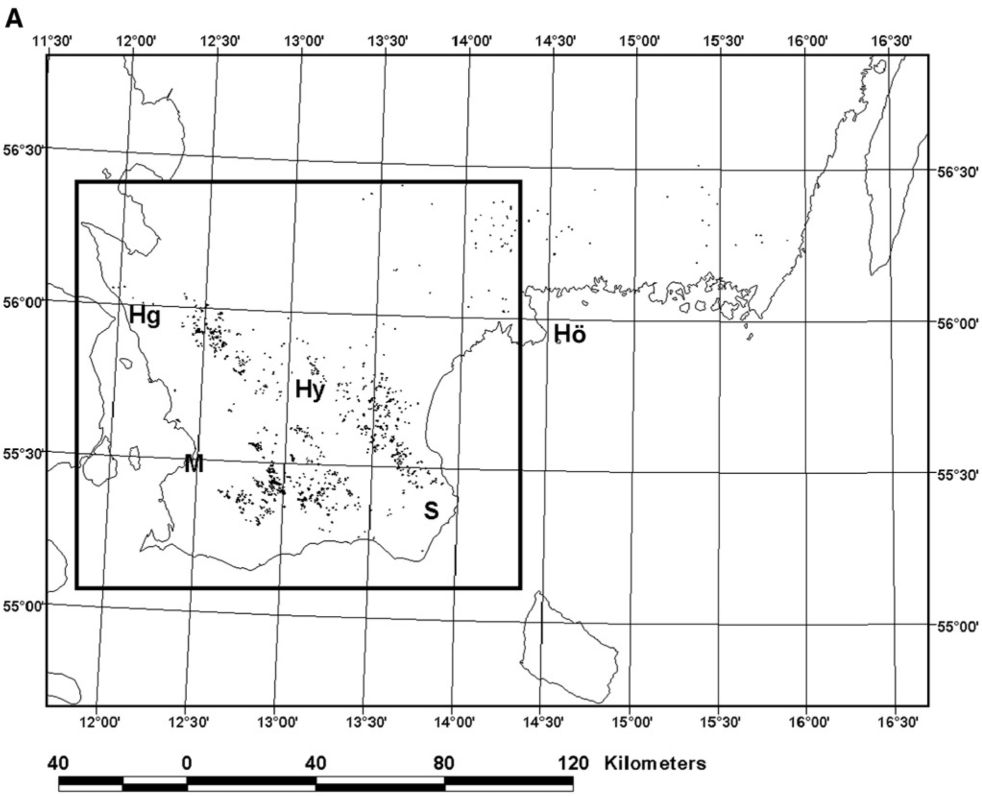

Fig. 1. a) Study area in southern Sweden, with storm damaged forest areas, from the storm in December 1999, in black. Our area of analysis is defined by the inner rectangle, covering most of the province of Scania. The location of the meteorological stations at Helsingborg (Hg), Hörby (Hy), Malmö (M), Skillinge (S), and Hanö (Hö) are shown. b) Map showing the topography of Scania as a shaded relief. The altitude ranges from sea-level to 225 m above sea-level. Source: The Swedish National Land Survey (Lantmäteriet). The red areas are the reported forest stands with storm damage, from the Regional Board of Forestry in Kristianstad, Sweden. c) Forest cover (green) in the study area derived from the land use categories in ECOCLIMAP (Masson et al., 2003), in comparison with the land use map (lower right inset) of Scania from the Swedish National Atlas (forests are green, open land is yellow, urban areas are red).

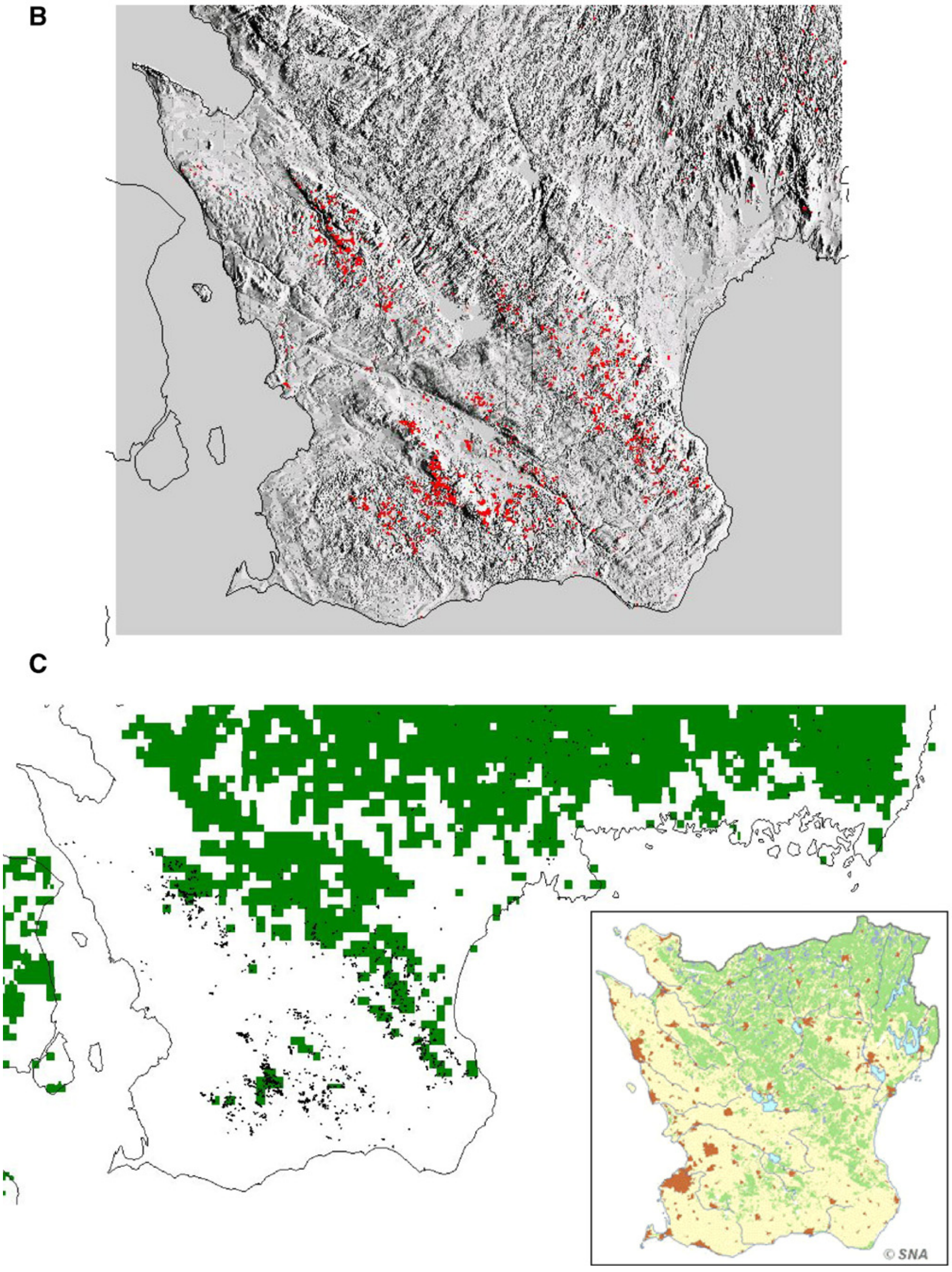

Fig. 1 (*continued*).

(The Swedish Land Survey) was used to produce information on aspect and slope, using the ESRI ArcView 3.2 GIS software and Spatial Analyst extension. The aspect information was smoothed by averaging over a 3×3 pixel window, and a 5×5 pixel window. For each damaged forest stand, the average of aspect and slope was calculated, as well as the range of aspects within the forest stands. The distributions of damaged forest stands versus aspect were similar, using either the 3×3 or the 5×5 pixel window smoothing. The majority of damaged stands were found on slopes with aspects from 150 to 240°, that is slopes facing about SSE to WSW.

Forest stands with a range of aspects less than 90° were selected for further analysis, and a comparison was made between no smoothing, and using the 3×3 or the

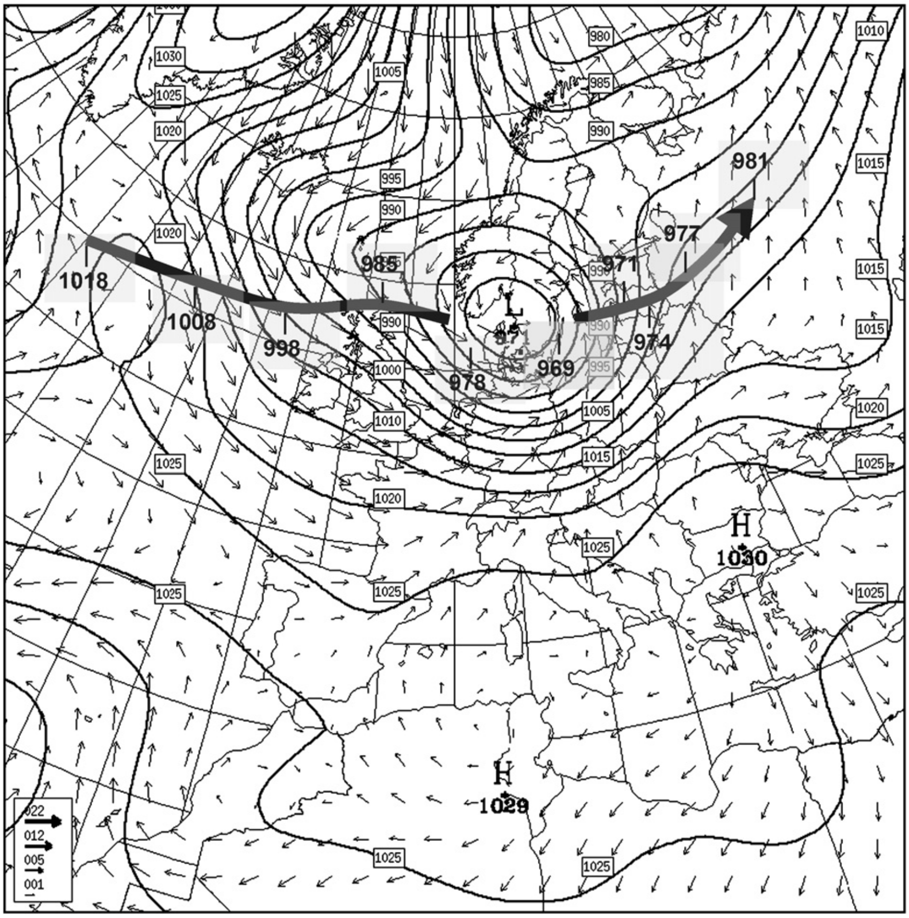

Fig. 2. Mean sea-level pressure field and 1000-hPa wind vectors of December 3, 1999 at 18 UTC computed on the basis of NCEP–NCAR reanalyses. Units are hPa and isobars are drawn every 5 hPa and wind speed vectors are shown in inlet in m s^{-1}. Superimposed on this field is the track of the low-pressure system that produced the storm Anatol from December 2, 12 UTC to December 5, 12 UTC with pressures in hPa indicated every 6 h.

5 × 5 pixel window smoothing to find the most suitable smoothing window. The 5 × 5 pixel window was chosen for our study, since the general wind exposure in the low-relief landscape with gently undulating hills (maximum elevation of about 230 m) accentuates a large-scale exposure to wind directions, rather than a small-scale topography-induced wind field. Further, most damage occurred in very gentle slopes, from 0 to 3°.

With no smoothing, or minor smoothing, forest stands showed a diverse range in aspect, despite the landscape being fairly flat. For stands with a range of aspect greater than 90° it would be impossible, with the given damage data, to distinguish a representative aspect where the wind throw had occurred.

In southern Sweden, it can be safely assumed that all forests are managed in some way. The forest cover information (Fig. 1c) was produced by combining the forest type classes in the two land use categories in ECOCLIMAP (Masson et al., 2003). A comparison of this classification with the land use map from the Swedish National Atlas of Scania shows that, although the resolution is coarse, the spatial distribution of the forest cover is well represented.

3. Numerical modelling

The chosen model for this investigation, the Canadian RCM, (CRCM) includes a state-of-the-art physically-based parameterisation used for diagnostic “on-line” computations of wind gusts (Goyette et al., 2003).

Since the CRCM is a limited-area model (LAM), boundary conditions covering the study period are required. The lateral and uppermost nesting consists of driving the embedded CRCM with a time series of reanalysis data provided by National Center for Environmental Prediction–National Center for

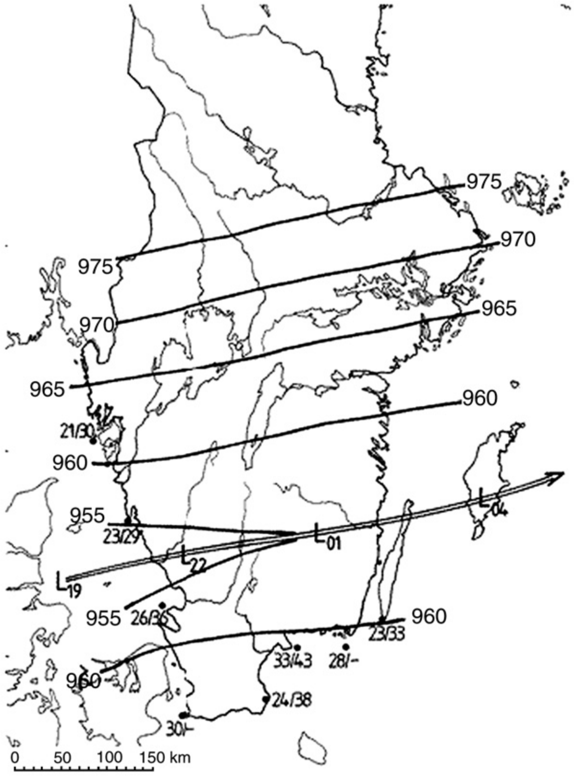

Fig. 3. Map showing the track of the low-pressure centre across southern Sweden on December, 3–4 1999. The lines show the lowest pressure during the passage, and the L_{tt} shows the low-pressure centre at time tt. Source: Vedin and Alexandersson (1999).

Atmospheric Research (NCEP–NCAR) described in Kalnay et al. (1996). The time series were extracted from NOAA–CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>. Data were transformed at a spectral T32/L12 resolution, extending from 1000 hPa to 10 hPa, with an archival period of 6 h. Denis et al. (2003) have shown that this spatial and temporal resolution of the flow fields is adequate for driving the model, and for realistic small-scale simulated features of the fields to further develop.

The modelling approach used to downscale the windstorms is designed as operating in “one-way”, and the CRCM uses the multiple self-nesting methodology on a number of collocated grids, accurately capturing the wind speed and direction in an optimal fashion (Benoit et al., 1997; Goyette et al., 2001). The December windstorm was simulated on four embedded computational grids at 60, 20, 5, and 2 km grid spacing referred to as domain A, B, C, and D respectively (Fig. 6). More details on the grid configuration and on the different vertical-level distributions are found in Goyette et al. (2001).

The CRCM has an option allowing nudging of 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 large-scale atmospheric states coming either from observations (e.g. reanalysis data) or from outputs generated from a previous run with the same model. This procedure may be considered as an indirect data assimilation technique (von Storch et al., 2000) warranting, to a certain extent, that the model is not deviating much from the driving conditions. The spectral nudging technique was used to downscale the NCEP–NCAR flow fields at 60 km on domain A for the December 1–6 period inclusively with outputs saved 6-hourly. The next step consisted of nesting the 20-km simulation on domain B, driven by the 60-km flow field

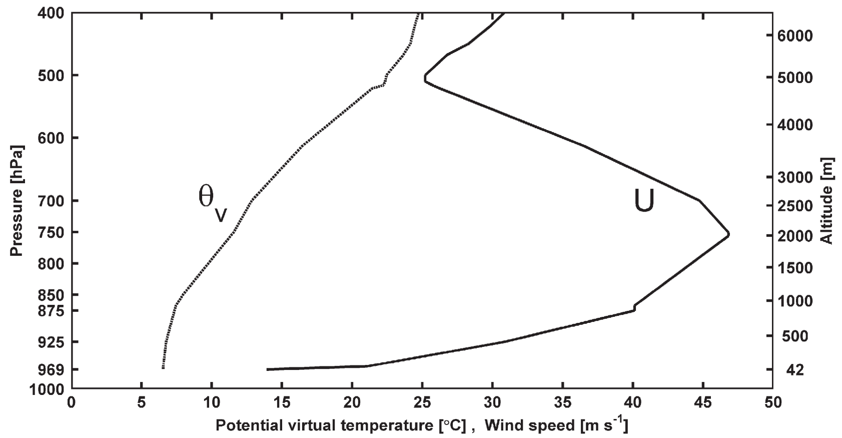

Fig. 4. Virtual potential temperature (°C) and wind speed profiles (m s^{-1}) at Copenhagen on December 4, 1999 at 00 UTC. Data from <www.weather.uwyo.edu/upperair/sounding.html>.

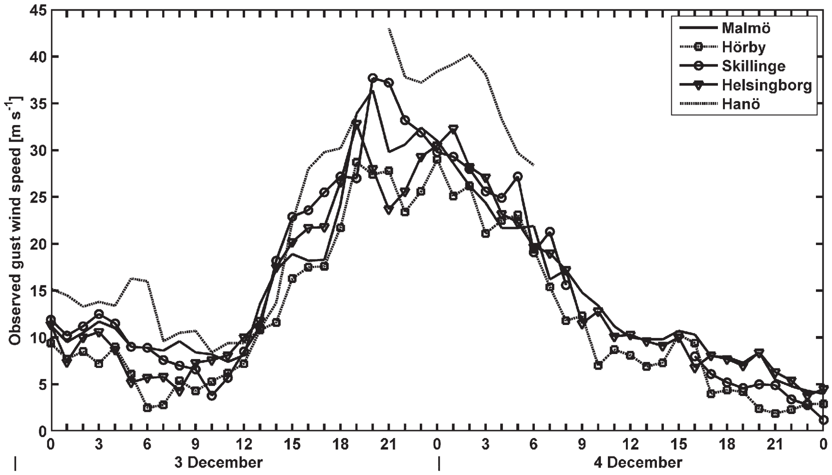

Fig. 5. Gust wind speed measured at SMHI automatic stations during the period December 3 from 00 UTC to December 5 00 UTC. Stations refer to the locations in Fig. 1a. For Hanö and Skillinge some measurements are missing because of temporary instrument or data transfer failure.

for the December 1–5 period, with outputs saved 3-hourly. Then the 5-km simulation was nested in domain C, which was driven by the 20-km simulated outputs for the December 1–5 period, with outputs saved at hourly intervals. Finally the 2-km simulation was performed on domain D, driven by the 5-km simulated flow fields for the December 3–4 period, with outputs saved at hourly intervals (Fig. 6). For the last two nesting steps, the model was forced by previous model atmospheric outputs only at the lateral boundaries, and no spectral nudging was used. Nevertheless, the large-scale features of the 5- and 2-km CRCM runs are generally well reproduced ensuring, to a certain extent, that the 2-km simulation is the result of the downscaling of the NCEP–NCAR conditions for the considered period. Consequently only the smaller scales feature of the wind field near the surface is analysed and presented in this analysis and further compared with observational features.

Lower boundary conditions involved specifying the topography height, the land use, soil and vegetation characteristics, and the evolving lake and sea surface temperature. On domain A, many of the land characteristics have been derived on the basis of Wilson and Henderson-Sellers' (1985) database and projected on the computational grid. The SST is derived from AMIP II sea surface temperature, and sea–ice concentration boundary conditions (Taylor et al., 2000) were taken from their website <www-pcmdi.llnl.gov/> and projected on the computational grid. These monthly mean values were used subsequently in the 20, 5, and 2-km CRCM run. For the 20, 5, and 2-km CRCM simulations, the ECOCLIMAP database (Masson et al., 2003) served to prepare the fixed lower boundary conditions over the surface (vegetation and soil types and other properties). The topography height was derived from the USGS (DEM) database (distributed by the Land Processes Distributed Active Archive Center (LP DAAC), available from their website, and projected on the computational grids.

4. Results

4.1. The simulated storm wind field

The simulated results presented in this section are provided by the application of the 2-km CRCM, in computational domain D for the period of December 3–4, 1999 over southern Scandinavia as shown in Fig. 6. The multiple scale analysis is out of the scope of this study, so only overall results are presented prior to the small-scale analysis.

The spatial distribution of the 920 hPa wind vectors and intensity fields during the period of December 3–5, 1999, is shown in Fig. 7. The simulated wind fields describe the evolution of the storm event. During the onset the simulated wind direction was south-westerly (at 12 UTC December 3), and then gradually the wind speed increased concomitant with a turning towards generally westerly winds (from 15 UTC to 18 UTC), which eventually increased in wind speed to storm intensity (at 21 UTC December 3 to 03 UTC December 4) with winds from WNW. Generally the simulated wind fields in Fig. 7 reach above storm (25 m s^{-1}) in Scania except near the northern boundary. Even though the simulated winds are not in exact phase with the

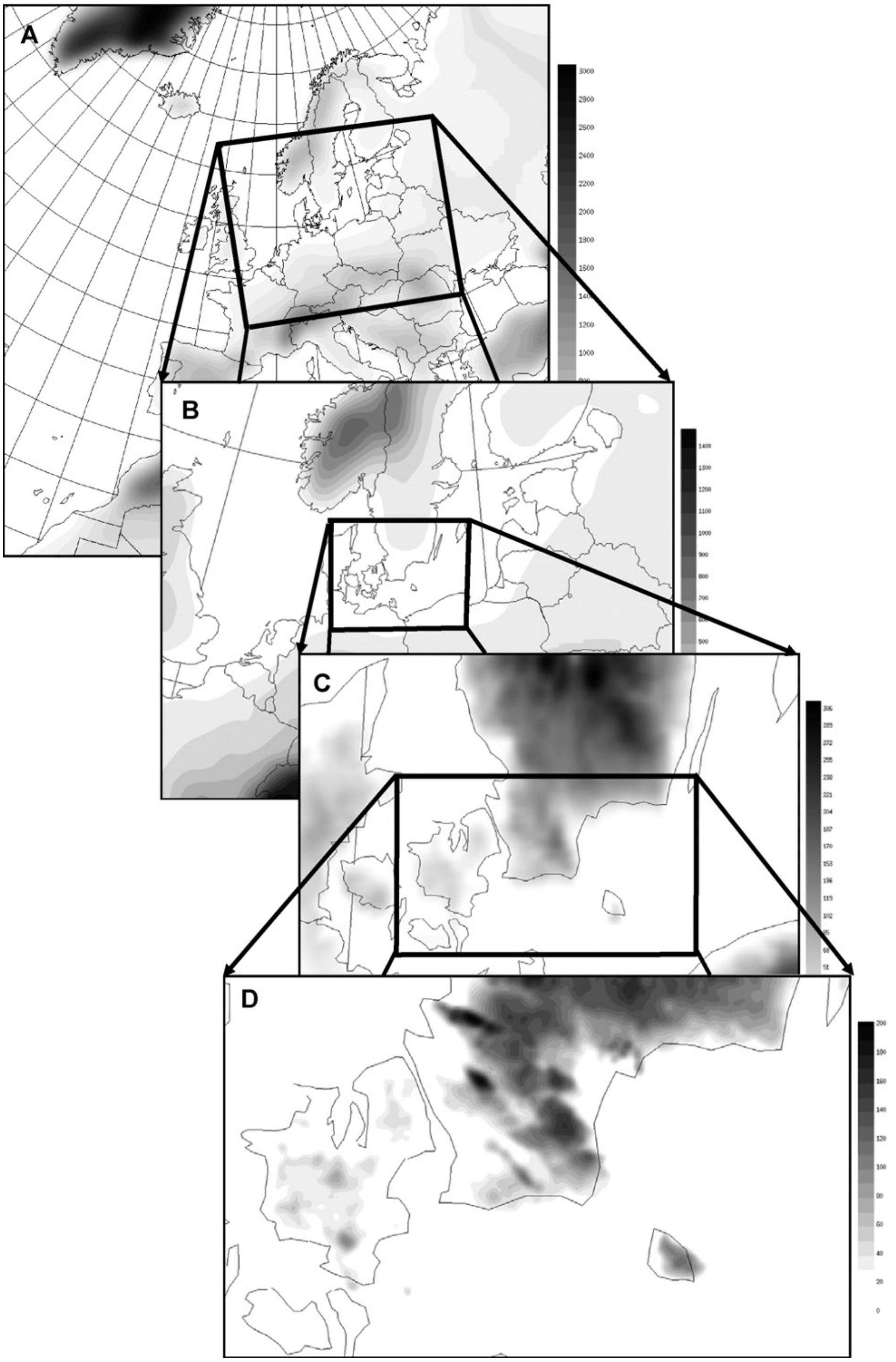

Fig. 6. CRCM multiple self-nesting strategy, surface height above mean sea-level (m) used at 60 km (domain A), 20 km (B), 5 km (C) and 2 km (D) grid spacing.

observed ones (few hours ahead of the observed average), the simulated winds capture observations in a realistic manner for the period of December 3–5, 00 UTC. This is seen in the central of Scania, and along the west coast, (see stations Hörby, Helsingborg and Malmö in Fig. 1a), although the peak wind in

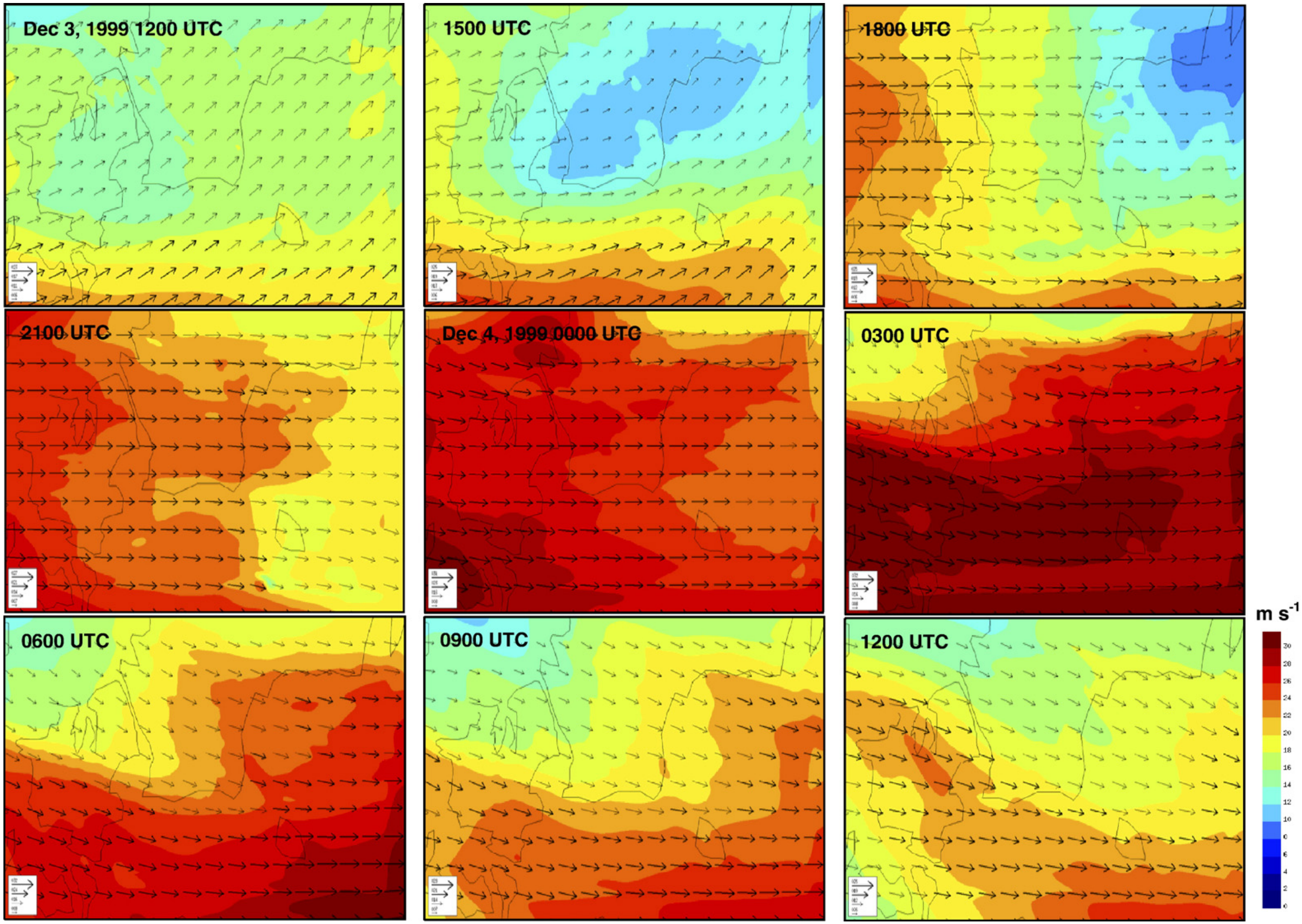

Fig. 7. A time sequence of the 920 hPa wind vectors and intensity fields simulated with the 2 km CRCM over southern Sweden during the Anatol storm on December, 3–4 1999. Vector intensities (the instantaneous horizontal winds) are shown in insets and intensity in m s^{-1} by the colour scale (right).

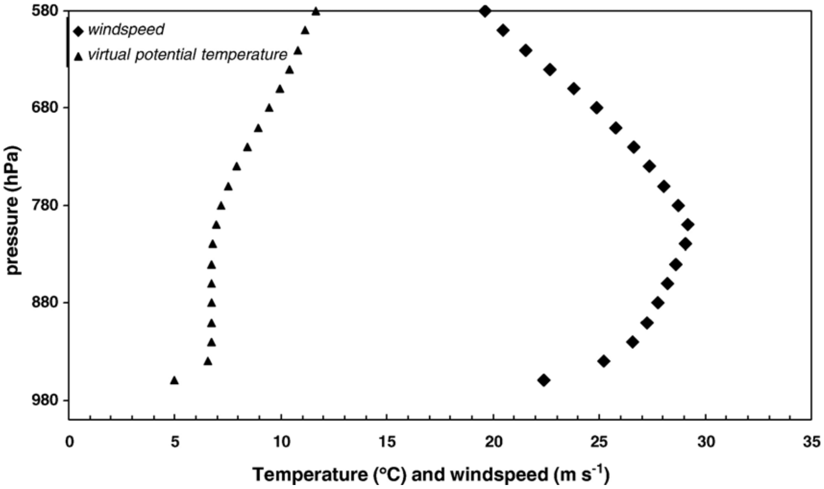

Fig. 8. Vertical profiles of wind speed (m s^{-1}) and virtual potential temperature (°C) simulated with the 2-km CRCM in the lower atmosphere for a gridpoint located between stations Helsingborg and Hörby on December 4, 1999 00 UTC where forest damages have been recorded (cf. Fig. 1a).

observations (Fig. 5) is underestimated by up to about 5 m s^{-1}. At the eastern coastline, however, the underestimation in the simulated wind is larger — up to 13 m s^{-1} (Hanö station).

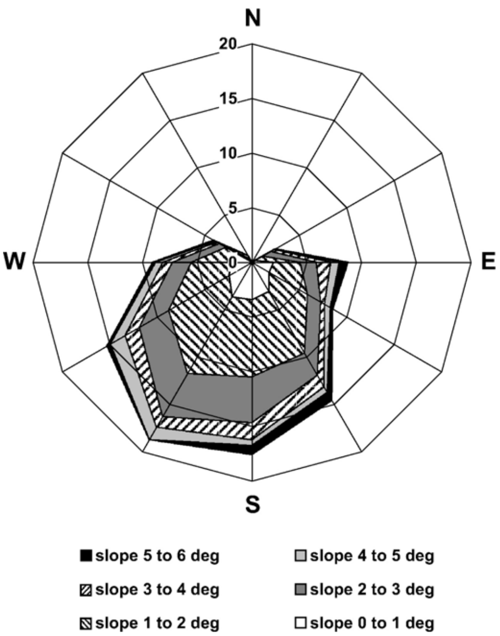

Fig. 9. The cumulative distribution of forest areas with storm damage (%), in relation to mean aspect of the forest stand (with aspect based on smoothing by a 5×5 pixel window of a DEM with 50×50 m resolution) and slope angle (50 m×50 m). Included in the figure are those areas with forest damage, which are small enough to only cover an aspect range of maximum 90°. Slope angles increase from 0–1° (inner circle, white), to 5–6° slope angle (outer circle, black).

The relatively strong winds in the southern part of the domain on Dec 3, 12 UTC, are due in part to a problem induced by the spin-off of the driving atmospheric fields. Actually, it takes a few hours for the 2-km CRCM wind fields to adjust to the resolution when initialised with the coarser driving conditions. One way to circumvent this problem is to run the model for a longer period but this 2-day simulation presented here is rather expensive in terms of CPU time and in disk space, a longer run just could not be afforded.

As can be seen in Fig. 8, a low-level jet is simulated at 780 hPa (approximately 2035 m) in western Scania between Helsingborg and Hörby stations where the vertical profile of the virtual potential temperature displays a stable atmospheric layer. Similar features are also seen in the observed profiles made at

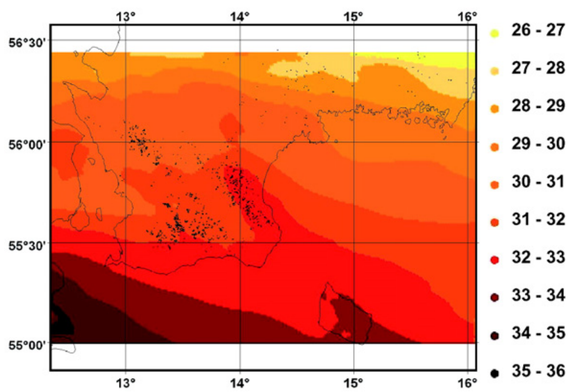

Fig. 10. Simulated maximum wind speed at 10 m height over the period of December, 3–4 1999. Dark areas are wind damaged forests. Legend shows wind speeds from 26 to 36 m s^{-1}.

Table 1
Proportion of damaged forest, within the analysed area (see rectangle in Fig. 1a) at different maximum wind speeds simulated by CRCM from December 3, 12 UTC until December 4, 12 UTC

Maximum wind speed (m s^{-1})	Damaged forest (%)
26–27	0.0
27–28	0.9
28–29	1.1
29–30	0.4
30–31	21.7
31–32	52.9
32–33	23.0

Copenhagen station, located roughly 50 km south of this point (see Fig. 4). The violent westerly winds simulated at the surface are induced by the low-level jet peaking at more 30 m s^{-1} where the large wind shear is producing turbulent eddies strong enough to overcome the buoyancy force created by the temperature inversion. At the same moment, that is on December 4 00 UTC, the simulated wind is gusting at 29.3 m s^{-1} where the hourly mean wind speed reached barely 15 m s^{-1} at the anemometer-level indicating that the windgust parameterisation is operative at this time. Moreover, the simulated strong winds are of similar magnitude as the observations made at the stations Helsingborg and Hörby (see Fig. 5).

4.2. Forest storm damage in relation to the landscape and the wind field

The forest damage data obtained from the Regional Forestry Board show that in total close to 5000 ha (4959 ha) of damaged forest were reported in the two provinces Scania and Blekinge, where Scania had 94% of the damage. The average size of a reported forest stand with damage was 2.5 ha. The median of the forest stand size was 1.4 ha, and the maximum size reached 66 ha.

The forest area with reported damage, with an aspect range of less than 90°, accounts for 2769 ha (59%) of the damaged area in the study region (the rectangle in Fig. 1a), or 1572 of the 1866 reported forest stands (84%) in Scania. Of the remaining 41% of damaged forest areas, growing in a more heterogeneous topography, 28% (1314 ha) were located on a surface with an aspect range of 90 to 180°, 11% (494 ha) were growing on a surface with an aspect range of 180 to 270°, and finally 2 large forest stands, covering 96.5 ha (2%), had an aspect range of 280 to 290°.

Most of the wind damage in the study area, 54%, occurred within areas categorised as forested in the ECOCLIMAP data base. Most storm damaged forest stands were on average facing S to SW areas (5 × 5 pixel window smoothing of aspect), and were located on hillsides with gentle slope angles, from 0 to 3° (Fig. 9). It can also be seen that damage has occurred in stands with aspects in almost all compass directions, except to the north.

Almost all forest damage, nearly 98%, occurred in areas where the simulated maximum wind speeds is above 30 m s^{-1} (Fig. 10, Table 1). In the south-eastern part, the simulated maximum winds peak at 32 m s^{-1} approximately where the station Skillinge (S) is located (Fig. 1a).

5. Discussion

This paper presented an analysis of the impacts of one major windstorm, Anatol, that struck south Scandinavian regions on December 3–4, 1999, using a numerical regional climate model driven by data provided by the NCEP–NCAR reanalysis. The aim was to relate recorded forest damage to high-resolution simulated wind field, as an initial move towards analysing storm effects in Swedish forests. The model set-up comprised a self-nesting technique allowing surface characteristics to be represented ultimately with 2 km grid spacing. This configuration, when used in conjunction with a gust parameterisation, captured the essential features of the atmospheric circulation at fine scales, as well as of the maximum surface wind field, during the study period. The 1000 hPa wind fields in the NCEP–NCAR reanalysis dataset (Fig. 2) show that the strongest wind speeds, above 20 m s^{-1}, were found over the North Sea and on the coasts of Germany and Denmark between December 3, 18 UTC and December 4, 00 UTC. Thus, solely on the basis of reanalysis data, the severe impact of Anatol over southern Sweden could not be projected because these winds, while strong, are not considered devastating (i.e. 8 Bft).

In contrast, the downscaled wind fields for December 3–4 show that the CRCM are able to represent the local structure of the intense winds across Scania (Fig. 7). However, as mentioned in the Results section, station observations at Hanö, Skillinge, Malmö and Helsingborg (Fig. 5), all located on the eastern and western coast, show a higher maximum wind speed than the simulated wind speeds during the storm event (Fig. 10). The simulations, in comparison with the wind observations, seem to capture the surroundings of Hörby, in central Scania, more realistically.

Although wind is the forcing agent for wind damage in forests, there is a wide variation in critical wind speed within and between forest stands, due to management, and site-specific conditions (Persson, 1975; Peltola et al., 1999a,b; Venäläinen et al., 2004; Zeng et al., 2004). In this study we have described the forest damage in relation to its exposure in the landscape, by using aspect and slope, together with forest cover. The expected result would be that forest damage occur mainly on the windward side of slopes (Foster and Boose, 1992), and the most susceptible forest stands to wind throw are those which are newly thinned, or standing close to recently cleared areas, as summarised by Zeng et al. (2004) and Venäläinen et al. (2004), amongst others. Information on management practices for each forest stand was not available for the stands with reported damage, which makes it impossible to take this factor into account. However, the aspect and slope information derived from the DEM, imply that most damage occurred in forest stands facing S to SW (Fig. 9). This in turn implies, if not the main wind direction during the storm event, so at least the general direction of the gusts that most likely damaged a majority of the trees.

The simulated evolution of the storm (Fig. 7) describes the storm as initially a south-westerly flow in the early afternoon December 3, then turning into a full storm with westerly winds during mid-afternoon and evening on the same day. Wind observations over Denmark and Sweden (Fig. 2a–d in Voldborg, 2000) show a similar development, but with a longer time period of wind from the southwest, until 18 UTC on December 3, before a more westerly flow developed at 21 UTC on December 3. Hence, the forest damage distribution could partly be explained by the south-westerly winds in the early stage of the storm event, which were picked up reasonably well by the simulations.

The relation between forest damage and forest cover distribution in Scania, with 46% of the damage occurring outside forested areas (Table 1), according to the classification in the ECOCLIMAP database. This is an effect of the typical features of the landscape in Scania — i.e. being mainly a flat agricultural area with scattered forest parcels.

Most damage in forests seems to have occurred within areas, which in the simulation reached high maximum wind speed, see Fig. 10 and Table 1. A further reference could be made to the station observations in Fig. 5, where the maximum gust winds peak between 18 UTC and 21 UTC, which coincide with the time when the wind direction is turning, according to Voldborg (2000). However, the storm damage in the forests does not need to be related directly to the maximum wind speeds, since the critical wind speed can be lower and thus occur during an earlier stage of the storm. Mean wind speeds of 11–15 m s^{-1}, with gusts of 24 m s^{-1}, have been found enough to uproot trees in Finland (Peltola et al., 1999a) under unfrozen conditions. Contributing factors are a high stand density, together with a low ratio between tree diameter and tree height (Peltola et al., 1999a). In our case, it is highly likely that at least some of the stands have been damaged already in the early stages of the storm, at lower wind speeds, and then the damage has increased during the storm due to the suddenly new open spaces within the forests, or the destruction of the edge trees, which used to protect the trees further inside the stand.

Another aspect on the storm damage distribution is the earlier history of strong winds or storms. Just a few days prior to Anatol, on November 29 and December 1, southern Sweden experienced strong westerly winds (Vedin and Alexandersson, 1999), which might have caused damage to the root systems and decreased the anchoring of the trees, thus facilitating the wind throws on December 3.

Modelling studies have shown that as global climate is warming, the cyclone track in the north Atlantic may undergo a shift in position and an increased density of deep cyclones (e.g. Leckebusch and Ulbrich, 2004; Fischer-Bruns et al., 2005; Weisse et al., 2005; Leckebusch et al., 2006). Thus, it is of interest to study the impact of the most severe windstorms for current climate as well as for the global warming conditions in order to better locate the impacts of these storms on the forest environment. Further, if winter storms similar to the Anatol storm become more frequent, these storms are likely to have more severe impacts on forests than progressive changes in means especially if recurrencey time between damaging storms becomes shorter than the recovery period of the forest. Annual frost time becomes shorter due to the warming trend and this further increases the wind throw risk. Effects of windstorms on forests have both short and long term impacts for the standing biomass, forest health and its composition (Ulanova, 2000).

The linkage between windstorms, as climate changes, is, however, delicate to establish, because these events are by definition relatively rare, and the specific combination of the synoptic conditions and forest stand characteristics makes it complicated to compare different events. In this respect, each event is unique and a modelling approach is a promising way to better understand the underlying processes and the relative importance of different contributing factors.

As a final remark, “medium” resolution RCM operating at spatial resolutions of about 50 km, used for climate simulations, cannot be used directly to infer the impact of windstorms at very fine scales. The multiple self-nesting technique to scale specific events down to 1–2 km appears as a reasonable one, yielding realistic results so far, since the fine grid can accommodate a good topographic and physiographic representation of the terrain thus allowing fine scale atmospheric details to be simulated consequently matching the requirements of impact assessments. With high-resolution initial and boundary data one or two of the nesting steps can be omitted whereby improving the efficacy of the methodology. However, since stand-related factors, such as soils conditions, tree height, stand density, and roughness variations were not possible to resolve with the field data presently available, one major step in improving the spatial resolution would be to resolve the individual forests stands, both in terms of wind field simulations, and available field data. For Scandinavian conditions, however, this would require a horizontal resolution of the order of 100 m or even better. In terms of physically based dynamical downscaling, such a high resolution would clearly require a different model formulation, which currently is out of scope in the context of climate scenario simulations.

One way to get around the problems stated above – the link between climate change and storm effects on forests, and the requirements of high resolution – is to use a technique similar to the one described in this paper, but with driving conditions from a GCM. Such results will give valuable insights on the impact of windstorms on the natural environment at fine spatial scales for global warming expected in the 21st century. Such a simulation of the January 2005 hurricane-force windstorm “Gudrun”, that passed over a forested part of the country and destroyed 75 million m^3 of timber, will enable us to analyse the relationship between maximum winds and wind throw in greater detail, because the largely forested region provides a much larger damage field data set.

6. Conclusion

This study has showed that by using the Canadian RCM with physically based gust parameterisation, and downscaled NCEP–NCAR reanalysis data to 2 km resolution, using the self-nesting capacities, it is possible to get a realistic, detailed picture of a forest-damaging storm. However, each storm is unique in its features, and our case study of Anatol’s advance over Scania in December 3, 1999, did produce results indicating the reliability of the CRCM, despite the flat features of the landscape with mostly agricultural land and the resolution and scarce information about damage within forest stands.

What we found were: The CRCM produced a realistic simulation of wind field, compared to observation data. Most damage occurred in forests facing S to SW, indicating that this wind direction was prevalent during the peak of the wind throw process. The turn of the wind direction in the simulation, from SW to W, had been picked up, but with a slight time difference. Most damage had occurred in the areas of simulated maximum wind speed greater than 31 m s^{-1}. The CRCM is a tool, which can be used for further study cases, preferably driven by a GCM, in order to reveal a greater understanding about recent storms, which in turn helps us evaluate future climate change driven storm conditions.

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