TOWARDS A HIGH-RESOLUTION OPERATIONAL FORECASTING TOOL FOR THE SOUTHERN ALPS – NEW ZEALAND

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ABSTRACT: The Southern Alps of New Zealand are located in an extreme maritime climate with high precipitation amounts and strong winds causing heavy winter storms with exceptional deposition. In addition, frequent rain-on-snow events can cause widespread avalanching making avalanche warning a challenging task. This study aims to provide decision support for avalanche forecasters by coupling a snow cover model (SNOWPACK) with a numerical weather prediction model (NWP). The open-source Advanced Regional Prediction System (ARPS) is well suited for small-scale (sub-kilometer) weather dynamics and was used in this study. As a proof of concept ARPS simulations were performed with a horizontal resolution of 3 km as well as 1 km for a period of 10 days between July 4 and July 13, 2013 for the Craigieburn Range area. During this period about 50 cm of new snow were observed at Porters Ski Area, whereas the vast amount (~38 cm) was related to a single storm on July 6, 2013. Results show that at least a 1 km horizontal resolution was required to simulate this particular event and the resulting precipitation amounts. By forcing the Swiss snow cover model SNOWPACK with the ARPS forecasted data – on a 1 km grid – we were able to simulate the 24-hour new snow amounts during this period with fair accuracy while using fixed densities for new snow between 50 kg m^{-3} and 75 kg m^{-3}. Although more investigation and simulations for a longer period are required we believe that this initial study, proposing a coupling between ARPS and SNOWPACK, shows promising potential to become an operational forecasting tool for New Zealand's warnings services.

KEYWORDS: Southern Alps, ARPS, SNOWPACK, snow cover simulation, decision making

1. INTRODUCTION

Avalanche warning requires a) knowledge of the state of the snow cover and b) an accurate weather forecast. However, performing snow profiles or stability tests is time consuming and often not possible. Therefore, snow cover modeling especially when coupled to numerical weather prediction models become a valuable source of information for avalanche warning services (Durand et al., 1999; Schirmer et al., 2010; Bellaire et. al, 2011; 2013; Bellaire and Jamieson, 2013a, 2013b).

The Advanced Regional Prediction System (ARPS) was used to carry out the weather simulations in this study. ARPS is developed by the Center for Analysis and Prediction of Storms at the University of Oklahoma (Xue et al., 2001). ARPS is a non-hydrostatic compressible flow solver of the Navier-Stokes equations, using a terrain-following coordinate system, applied to a land-atmosphere interaction system and used operationally for weather forecasting.

ARPS has been validated in numerous studies for real case scenarios in complex terrain (Chow et al., 2006; Weigel et al., 2006) and compared and verified with a variety of other models under different atmospheric stability regimes (Fedorovich et al., 2004; Beare et al., 2006). The model was also applied successfully at the spatial resolution of the micro-scale (less than 100 m) to investigate turbulence structures over forested hills (Dupont et al., 2008; Fesquet et al., 2009), cold-air pooling dynamics (Colette et al., 2003; Kiefer and Zhong, 2011; Katurji and Zhong, 2012) and long-range

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transport of turbulence and flow interaction with topography (Katurji et al., 2011).

Snow cover models have been developed for various applications, such as avalanche forecasting, hydrology or climate modeling. Therefore, a variety of snow cover models exist with different degrees of complexity (Etchevers et al., 2004). The two most advanced snow cover models are the Swiss snow cover model SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, 2002b) and the French model CROCUS (Brun et al., 1989, 1992). Both models treat snow as a three-component material consisting of ice, water and air. Changes of the snow cover, i.e. mass, momentum and energy exchange are calculated using a Lagrangian Finite Element method (SNOWPACK) or finite difference method (CROCUS).

The snow cover model SNOWPACK was developed to simulate the snow cover at locations of automated weather stations (AWS) and is the choice of this study. If the meteorological input is provided by AWS, only a now-cast is possible (Lehning et al., 1999), while a forecast becomes possible when the meteorological fields are derived from a NWP model such as ARPS.

Since snow cover models are forced by meteorological data from various sources, the simulations can only be as good as the input data. An accurate modeling of the snow cover, especially the formation of critical weak layers and snow melt, requires small scale modeling of wind, turbulent fluxes and radiation (Fierz et al., 2003; Feick et al., 2007). We present initial results as well as challenges towards a potential operational forecasting tool, i.e. an open-source coupled numerical weather prediction (ARPS) and snow cover model (SNOWPACK).

2. DATA

2.1 *Region & Study Site*

The mountain range of the Southern Alps extends much of the length of New Zealand's South Island. The Craigieburn Range is located approximately at the latitude of Christchurch marked by the white circle in Figure 1, the location of the automated weather station (AWS) and a study plot of the Porters Ski Area are indicated by a white open circle.

Standard meteorological parameters such as air temperature, relative humidity or wind speed and direction are measured by the AWS as well as snow height and 24-hour new snow amounts (HN24). The station is located at an elevation of 1905 m a.s.l. Skilled observers on a regular basis performed bi-weekly snow profiles and were used for verification of the snow cover model SNOWPACK.

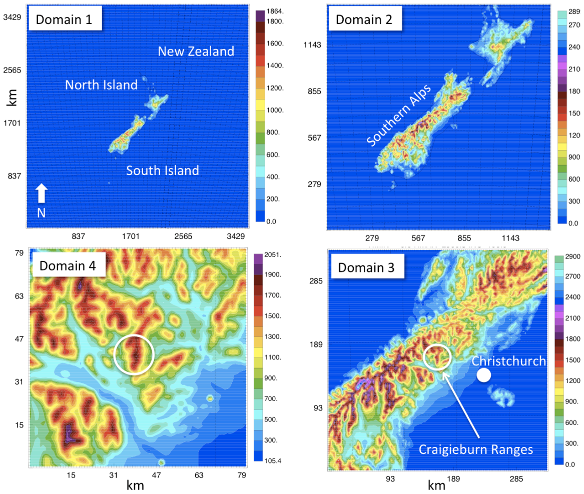

Figure 1: Level plots (elevation in m) of the four model domains (D1-D4).

2.2 *Synoptic weather system*

The synoptic meteorological system that was responsible for the snowstorm was caused by a high-latitude low-pressure center situated south west of the South Island (Figure 2). This low-pressure center was advancing from west to east and bounded to the north with a sub-tropical anti-cyclonic belt. The synoptic pressure distribution allowed for establishing a strong west to east pressure gradient across the South Island, which was exacerbated by the Southern Alps topography.

As a result, wind gusts on the eastern side of the main divide measured by a weather station in Christchurch city airport reached 100 km h^{-1}. Most of the snow precipitation fell on the western side of the Southern Alps were the high elevation blocked the moist and cold flow associated with the cold front. The high elevation points of the eastern side of the divide also experienced snow precipitation, but most of the low elevation and eastern coast was snow free.

3. METHODS

In the following section we would like to briefly summarize the setup of the two models ARPS and SNOWPACK.

3.1 ARPS

In this study we have chosen to setup ARPS in a telescoping grid nesting method by which a mother domain of coarse resolution is used to produce initial and boundary conditions for a daughter nested domain of finer resolution. This method allows for improving the time efficiency of the model runs when limited computational resources are available.

Four domains were used (D1 to D4, see Table 1), the D1 simulation was initialized with three-dimensional meteorological fields derived from the National Center for Environmental Prediction (NCEP) global reanalysis datasets (FNL; Saha et al., 2006). D1 is nudged at the boundary zone with the global datasets every 6 hours to maintain the realistic evolution of the synoptic weather systems. D2 to D4 are then assimilated at the boundaries with data from their mother domains every 3 hours.

The geographic database for topography, land-surface cover, soil and vegetation types was derived from the global dataset at around 1 km spatial resolution developed by the United States Geological Survey (USGS).

For better model performance the simulations (3 km, D3) were run over periods of 4-day blocks covering the overall period between July 4 to 13, 2013. The 1 km resolution simulation (D4) was run for a 22 hour period starting on July 6 00:00 LST. D4 simulation was introduced to test the hypothesis that a higher resolution simulation is required to simulate spill over precipitation to the eastern side of the Southern Alps.

Because the land and sea surface temperatures are initialized from the FNL global model, not accounting for a re-initialization every 4 days introduces a regional bias in the pressure distribution due to inaccurate sea surface temperature representations. Each block of simulations is allowed to run for 12-hours spin up time to establish the equilibrium between the input meteorological fields and the model resolved fields. The spin up time is consequently not included in the analysis.

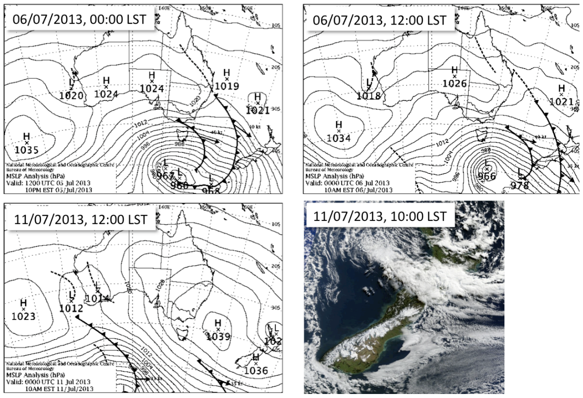

Figure 2: Mean sea level pressure maps for July 6, 2013 snow storm. A snap shot from MODIS for the post storm period shows the extent of snow cover on the ground.

3.2 SNOWPACK

The snow cover model SNOWPACK was forced with hourly forecasted data from ARPS as described in the previous section with 3 km and 1 km resolution, respectively. For this study we used the total precipitation amounts, air temperature and relative humidity, wind speed and direction as well as forecasted incoming short-wave and long-wave radiation.

ARPS data of the closest grid point (Euclidean distance) was used to generate 1-hourly time series extending a period of 10 days for the 3 km run and 22 hours for the 1 km run. SNOWPACK was then forced with this data assuming bare soil on the ground.

Note that we chose default setting for SNOWPACK for this initial study (e.g. neutral conditions, threshold for rain/snow + 1.2 °C, larger being rain). A wet adiabatic lapse rate of 0.65 °C per 100 m was applied to the ARPS forecasted air temperature to account for elevation difference between grid point and station elevation.

4. RESULTS

4.1 Verification of ARPS setup

Several sensitivity tests were performed with the convective, micro-physics and soil model schemes with the aim in simulating the closest to observed freezing temperatures. In addition, the domain size setup (number of grid points and spatial resolution) was optimized to account for the synoptic and meso-scale formation zones of low-pressure systems that are essential for the cold front propagation over New Zealand's South Island. The best combination of options is shown in Table 1.

4.2 Forecasting the July 6 storm with ARPS

24-hour precipitation sums for the 3 km and 1km runs are shown in Figure 3. With the 3 km run precipitation does not reach the station (cross) and almost all precipitation fell an the east side (upslope) of the Southern Alps, i.e. the spill-over from east to the west, which is often observed during such weather patterns did not occur as strong in the 3 km run as observed. By increasing the horizontal resolution to 1 km precipitation was modeled successfully on the high elevation points of the east side of the divide (Figure 3 bottom panel). During the 22-hour period ARPS produced a total amount of 33 mm liquid water for the closest grid point to the study plot, where on that day 38 cm of new snow (HN24) were observed.

4.3 Snowpack simulations for July 6 storm

SNOWAPCK was forced with forecasted data from both model runs, i.e. 10 days (3 km) and 22-hours (1 km), respectively. As stated above little precipitation (< 1 mm) was modeled at the closest grid point of the 3 km run, hence no new snow was simulated by SNOWPACK at that resolution.

At the study side of the Porters Ski Area ~ 38 cm of new snow (HN24) were observed on July 6, 2013. While forcing SNOWPACK with data of the closest grid point from the 1 km ARPS run (i.e. 33 mm of liquid water over 24 hours) only 13 cm of new snow were simulated. Due to very high wind speeds (> 30 m/s) the implemented new snow density parameterization (Schmucki et al., 2014), seems to estimate too high new snow densities. Therefore, simulations were performed with fixed densities of 50 kg m^{-3}, 75 kg m^{-3} and 100 kg m^{-3} producing 41 cm, 33 cm and 25 cm of new snow (HN24), respectively.

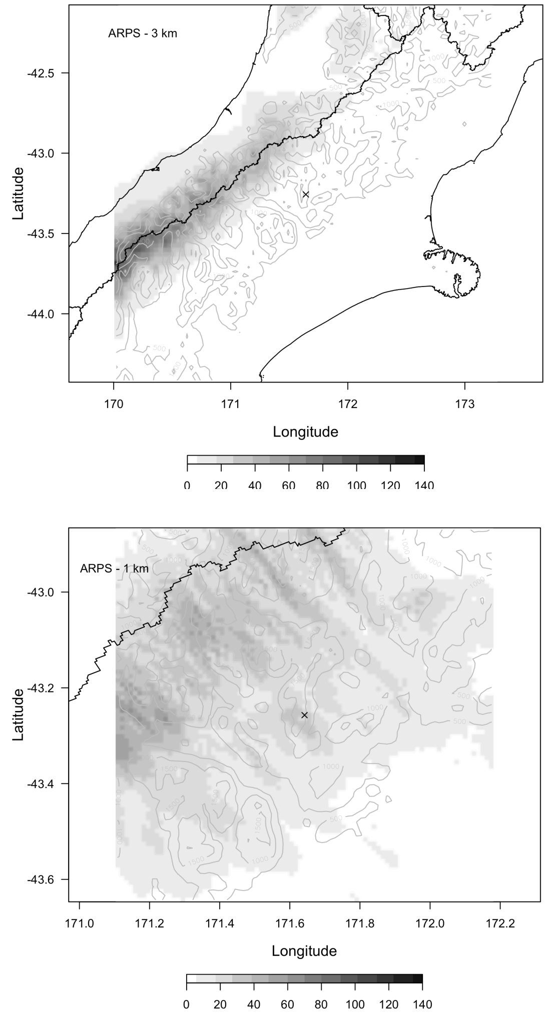

Figure 3: 24-hour (22-hour for 1 km) cumulative precipitation in mm for July 6, 2013 for ARPS simulations on a 3 km grid (top) and 1 km grid (bottom). The cross shows the location of the automated weather station and study plot centered in the corresponding model domain.

5. DISCUSSION

Weather forecasting and especially forecasting snow precipitation for complex alpine terrain is a challenging task. We showed that at least for the particular event on July 6, 2013 a high-resolution, i.e. 1 km horizontal resolution, simulation was required in order to reproduce this event. Indeed so-called convection permitting models (i.e., operational models with a resolution on the order of 1 km) show considerably improved skill scores when compared to their coarse-resolution counterparts (e.g. Weusthoff et al., 2010).

Due to the somewhat unique snow climate of the Southern Alps – maritime with strong winds – it is not surprising that SNOWPACK, which was calibrated in the Swiss Alps, needs to be adjusted for New Zealand. We showed that the currently implemented parameterization for new snow density produces too high new snow densities due to the high wind speeds during the storm.

Hence, a new parameterization for new snow density is required, which takes into account high wind speeds. Furthermore, ARPS forecasted parame-

Domain	**dx, dy, dz, dz$_{min}$** **km**	**Nx, Ny, Nz** **-**	**Convection**	**Soil Model**	**Microphysics**
D1	27, 27, 0.3, 0.1	137, 137, 35	Kain-Fritsch, Kain (2004)	NCEP-OSU multilayer scheme, Chen 1996, Ek & Mahrt 1992	MYSM, Milbrandt & Yau (2005)
D2	9, 9, 0.3, 0.05	157,157, 35	Kain-Fritsch, Kain (2004)	NCEP-OSU multilayer scheme, Chen 1996, Ek & Mahrt 1992	MYSM, Milbrandt & Yau (2005)
D3	3, 3, 0.3, 0.05	115, 115, 35	Resolved	NCEP-OSU multilayer scheme, Chen 1996, Ek & Mahrt 1992	MYSM, Milbrandt & Yau (2005)
D4	1, 1, 0.3, 0.05	115, 115, 35	Resolved	NCEP-OSU multilayer scheme, Chen 1996, Ek & Mahrt 1992	MYSM, Milbrandt & Yau (2005)

Table 1: Summary table of the used setup for each of the three model domains (D1-D4). Given for each doamin are the horizontal resolution dx (West-East) and dy (South-North) and the minimal vertical resolution dz$_{min}$ in kilometers as well as the number of grid points and vertical levels (N). The columns Convection, Soil Model and Microphysics indicate which scheme was used for the corresponding domain.

ters were taken from the first atmospheric level at 25 m above ground. Interpolation of near surface fields, e.g. 2 m above ground, using e.g. a logarithmic profile might help to overcome this issue.

If SNOWPACK settings currently used in Japan – also a maritime climate – would improve the snow cover modeling for the Southern Alps of New Zealand remains to be tested.

6. CONSLUSIONS & OUTLOOK

ARPS was setup and tested for the Craigieburn range a mountain range of the Southern Alps. ARPS simulations were carried out with 3 km and 1 km horizontal resolution. For the single storm event on July 6, 2013 a 1 km horizontal resolution was found to be a prerequisite for an accurate modeling of cold-season precipitation in terms of localization as well as amounts.

Observed new snow amounts (HN24) were simulated with fair accuracy in terms of amount, timing and localization if a fixed new snow density was assumed.

Future work will include enhancing the spatial resolution of the NWP-model to sub-kilometer resolutions to investigate more detailed and challenging case studies as well as improvements of SNOWAPCK for maritime climate.

This initial study serves as a precursor towards a fully operational coupled SNOWPACK-ARPS tool for the New Zealand avalanche warning service, which could be easily adapted to other regions worldwide.

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