VERIFICATION OF STATISTICAL AVALANCHE FORECASTING BASED ON NUMERICAL WEATHER PREDICTION INPUTS

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ABSTRACT: Electronic meteorological stations are increasingly being used to supplement manual weather measurements in avalanche mitigation programs. The British Columbia Ministry of Transportation Avalanche and Weather program has spent over 18 years developing a province wide sensor network and database system to capture and manage these data. Presently, the challenge is to use the real-time and historical data to better support the decisions of avalanche technicians.

Avalanche prediction software based on a nearest neighbour algorithm has been developed and applied at several avalanche areas in BC. Predictions of avalanche activity in the 12 hours following the forecast time update hourly in step with electronic sensor outputs.

In order to extend the avalanche prediction further into the future, weather sensor inputs can be replaced with output from numerical weather forecast models. Preliminary results for avalanche predictions based on UBC (winter 07-08) and Environment Canada (winter 06-07) weather forecasts are presented and compared with predictions from sensor data.

These are the first steps toward an integrated weather and avalanche information service that can be used to support experienced avalanche technicians and speed the training of new personnel.

KEYWORDS: Avalanche, numerical weather forecasting, nearest neighbours.

1. INTRODUCTION

Throughout British Columbia, highly experienced avalanche technicians ensure the safe operation of mountain highways through constant monitoring of weather and snow conditions, application of explosive avalanche control measures, and road closures. The British Columbia Ministry of Transportation's Weather and Avalanche Program (MoT) operates a province wide network of automated weather stations that provide real time weather data from weather plots and remote mountain stations, in addition to the traditional manual weather, snowpack, and avalanche observations. The Snow Avalanche and Weather System database (SAWS) was created to manage these data and enable technicians to store and access them in a timely and meaningful manner. In order to make better use of the historical information contained in SAWS, a pilot statistical avalanche forecasting system (AFS) based on a nearest neighbour model was developed and tested for use in five avalanche prone highways corridors.

The pilot AFS also ingests numerical weather prediction (NWP) data from UBC Weather Forecast Research Team (UBC), as well as Environment Canada's Canadian Meteorological Centre (EC), and these forecasts are fed to the AFS models in each area in order to extend avalanche predictions 12 to 36 hours into the future.

This paper contains preliminary weather forecast verification results, as well as verification of avalanche forecasts that are produced by combining the AFS with NWP data.

1.1 *Statistical avalanche prediction*

The nearest neighbour algorithm (Buser 1983, Purves 2003, McClung and Tweedy 1994) can aid the avalanche forecaster by recalling weather and avalanche information for several days in the historic record that are similar in terms of weather. Previous efforts were based on twice daily manual observations (Floyer and McClung 2003, Purves 2003, McClung and Tweedy 1994), though Roeger et al. (2001) showed that avalanche forecasts up

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Table 1
Climatic and operational characteristics of Kootenay Pass, Bear Pass, Cayoosh Summit (Duffy Lake) and 3 Valley Gap. (Haegli 2004, Floyer and McClung 2003, McClung and Schaerer 2006, Weick, personal communication 2008)

	Kootenay Pass	Bear Pass	Duffey Lake	3 Valley
Snow climate	Transitional	Maritime	Maritime	Transitional
Average annual snowfall (Nov-Apr)	1011 cm/yr	917 cm/yr	733 cm/yr	672 cm/yr
Average % of days per season with avalanches	12.7%	16.7%	7.5%	8.1%
Maximum avalanche path height	600 m	1900 m	1000 m	1000 m
Roadside weather plot elevation	1780 m	370 m	1350 m	610 m
Avalanche control methods/ vehicles currently used	Gaz-Ex, Helicopter, Hand and Case Charges, Preventative Closures	Howitzer, Helicopter, Hand and Case Charges, Preventative Closures	Helicopter, Hand and Case Charges, Helicopter, Gaz-ex., Preventative Closures	Helicopter, Preventative Closures
Length of electronic data record	1996 – 2008	2001–2008	1997 – 2008	1999 – 2008

to 24 hours in advance could be usefully achieved by incorporating numerical weather prediction inputs at Kootenay Pass. In contrast with these previous works, current research focuses on coupling the AFS, hourly electronic weather sensor data, and NWP to provide automated weather and avalanche prediction services that can aid technicians in maintaining safe road operation and train the coming tide of new avalanche technicians.

It is critical that electronic data are incorporated into statistical avalanche prediction since regular manual observations are no longer taken in some areas, and automated weather stations now provide information for areas that are inaccessible during storms.

2. DESCRIPTION OF LOCATIONS

The AFS was applied to five widely separated and climatically distinct British Columbia transportation corridors: Kootenay Pass on Highway #3 Salmo, Bear Pass on Highway #37A near Stewart, the Duffey Lake road on Highway #99 north of Pemberton, Three Valley Gap on Highway #1 west of Revelstoke (hereafter: Kootenay, Bear, Duffey, 3Valley).

Kootenay and Bear passes have been described in detail (Floyer and McClung 2003, Roeger et al. 2003) and Kootenay Pass was the site of the first operational numerical avalanche prediction model in Canada (McClung and Tweedy 1994). Avalanches in Kootenay Pass are frequently initiated by explosives in order to clear out snow deposits and unstable layers, thus reducing the size of avalanche deposits on the road and shortening road closures. The 21 Gaz-Ex exploders can be fired remotely in any weather, at any time, during dry and moist avalanche periods. By contrast, most avalanches in Bear Pass occur naturally though, when possible, helicopter bombing and a Howitzer cannon are used. The Duffey and 3Valley are controlled by helicopter bombing and a small number of fixed avalanche control devices. Table 1 summarizes some important climatological, geographic, and operational features of these areas. For more thorough descriptions of these sites refer to McClung and Tweedy (1994), Floyer and McClung (2003), and Roeger et al. (2003), Haegli (2004).

3. WEATHER AND AVALANCHE OBSERVATION DATA

Electronic precipitation, snow depth data, and air temperature at various stations within these avalanche areas are measured using a liquid precipitation gauge, a sonic ranging snow height sensor, and a digital thermometer placed on a tripod in the weather plot at road elevation. Wind data are taken by anemometers on nearby ridges in Kootenay Pass and the Duffey Lake road, and at road elevation for the other areas. The data are collected and reported hourly by SAWS. Data were filtered to exclude observations with missing data, periods in which one or more sensors were not properly functioning, and periods for which avalanche observations or NWP data are not available. All avalanche information was observed by MoT technicians and stored in SAWS.

4 METHODS

4.1 Nearest neighbours

When generating a prediction, the nearest neighbours algorithm chooses *k* rows of weather data from the historical database that are most similar to the current or forecast weather (Buser et al. 1983). The nearest neighbour (NN) ratio is the number of neighbours that are associated with avalanches, divided by *k*. If the NN ratio exceeds the chosen threshold value (hereafter: *threshold k*), then the model predicts that avalanches will occur.

The NN ratio represents a relative estimate of the probability of avalanches given recent weather. These probability estimates are relative in the sense that larger numbers indicate a greater chance that avalanches will occur. Previous studies (McClung and Tweedy, 1994, and Floyer and McClung, 2003), found that the Kootenay (Bear) Pass nearest neighbour model NN ratio of 6/30 (7/30) produces optimal model accuracy. In the remaining areas the NN ratio of 6/30 was also used. No effort was made to convert these ratios into conventional probabilities; instead, the AFS reports the raw NN ratio and lets the human forecaster interpret the meaning of this value.

Nearest neighbours distances in this study are computed in the Euclidian distance metric (Buser et al. 1983) with some transformation (McClung and Tweedy 1994, Floyer and McClung 2003) that removes positive skewness from the precipitation data. All variables are then standardized by subtracting the overall mean and dividing the result by the standard deviation.

When nearest neighbours are chosen during generation of predictions, only one observation from any given day is used. Also, during prediction validation, observations that are within 1000 hours of the test datum are excluded to avoid boosting retroactive prediction accuracy artificially.

4.2 *Numerical weather prediction*

Two different numerical weather prediction sources were used in this study: UBC and the EC. The EC uses a short-range regional forecast model named the Global Environmental Multiscale (GEM) model (CMC 2008). It is based on a non-uniform horizontal grid with 15 km resolution and 58 vertical levels. 48 hour forecast are produced twice daily (00 UTC and 12 UTC), since May 18, 2004. These forecasts are available for free on the internet, but must be downloaded in large geographical domains and there were no resources available to develop a system for ingesting and processing this data in real time. Bilinear interpolation of archived forecasts was used to produce retroactive forecasts of weather conditions at each electronic meteorological station location in this study for the 2006-7 winter season.

UBC weather forecast data is not archived, so only data from the 2007-8 winter season was used. UBC forecasts are produced by a 4-model NWP ensemble that has been run daily for a year as part of a project to improve short term, mesoscale, forecast skill over the complex (steep mountain, coastal) terrain of western N. America. The four models used in this study include NMS (Nonhydrostatic Modeling System from the University of Wisconsin), MM5 (Mesoscale Model version 5 from NCAR and Penn State), MC2 (Mesoscale Compressible Community model from RPN Canada), and WRF (Weather Research and Forecast model from NCAR and NCEP). All the models are run for the same set of nested domains of 108, 36, 12, and 4 km horizontal grid spacing. All initializations are from the 00 UTC Eta analysis, from NCEP. Real-time forecasts and verification statistics may be viewed at http://weather.eos.ubc.ca/wxfcst/.

Table 2
Variables used in the analysis at Bear Pass and all other sites. Values indicate the number of hours over which memory variables are computed.

	Bear	Bear NWP	All others	Others NWP
Present temp	✓	✓	✓	✓
Max temp (hours)	-	-	24	24
Hourly precip	✓	✓	✓	✓
Cumulative precip (hours)	30	-	24	-
Cumulative snowfall (hours)	30	-	24	-
Wind speed	Max of past 18 hours	Max of past 18 hours	Average over 1 hour	Average over 1 hour

No interpolation was necessary, as UBC produces Kalman-Filtered (Stull et al. 2004) forecasts for the electronic weather stations used in this study. Kalman filtering is a process that uses the error of recent forecasts at a particular remote weather station to correct the current forecast for that location.

4.3 Automated data manipulation

Cordy et al. 2006 describes in greater detail the methodology used in generating datasets upon which nearest neighbour predictions are made. In brief, each hourly datum includes raw and memory variables such as the present temperature, the maximum temperature in the previous 24 hours, the total liquid equivalent of precipitation during the past 36 hours, or the difference in

Table 3
Contingency table (total number of cases N = a + b + c + d)

		Observation	
		Event	No event
Prediction	Event	a: true positive	b: false positive
	No Event	c: false negative	d: true negative

Table 4
Fitness metrics, ranges, and perfect score values

Fitness metric	Equation	Range	Perfect score
Proportion correct (PC)	$\frac{a+d}{N}$	0 – 1	1
Un-weighted average accuracy (UAA)	$0.5\left(\frac{a}{a+c}+\frac{d}{b+d}\right)$	0 – 1	1
Peirce's skill score (PSS)	$\frac{a}{a+c}-\frac{b}{b+d}$	-1 – 1	1
Bias	$\frac{a+b}{a+c}$	0 – ∞	1

snowpack heights over the past 20 hours. All of these variables can be changed, and the optimal variables were obtained by trial and error for Kootenay and Bear Passes. For the other areas, the avalanche technicians selected the variables that they determined to be optimal for the SAWS based avalanche predictions. In the case of NWP based avalanche predictions it was not always possible to obtain forecast data for all stations that the technicians deemed valuable, so NWP and SAWS data corresponding to the nearest station was used. Also, there are no NWP forecasts for the height of new snow or the overall snow height, so those variables were excluded from the NWP models. Descriptions of the variables that are used for each area are shown in Table 2.

The same data processing procedures are used to generate datasets as when formatting real time (or retroactive) SAWS and NWP input data. Each hourly observation is associated with the avalanches that occurred within 12 hours of that datum, and these are recalled for the user in the summary of nearest neighbour information.

4.4 Fitness metrics

Fitness metrics are used to evaluate and compare the accuracy and performance of models. There are three fitness metrics used in this study: proportion correct (PC), bias, and the Peirce skill score (PSS). The equations that define these fitness metrics are shown in Tables 3 and 4 (Jolliffe and Stephenson 2003).

The proportion correct (PC) is an intuitively appealing measure of the overall success of the model; it is the proportion of the whole sample that is a correct forecast of either event. It is included here because it is commonly used in numerical avalanche forecasting research.

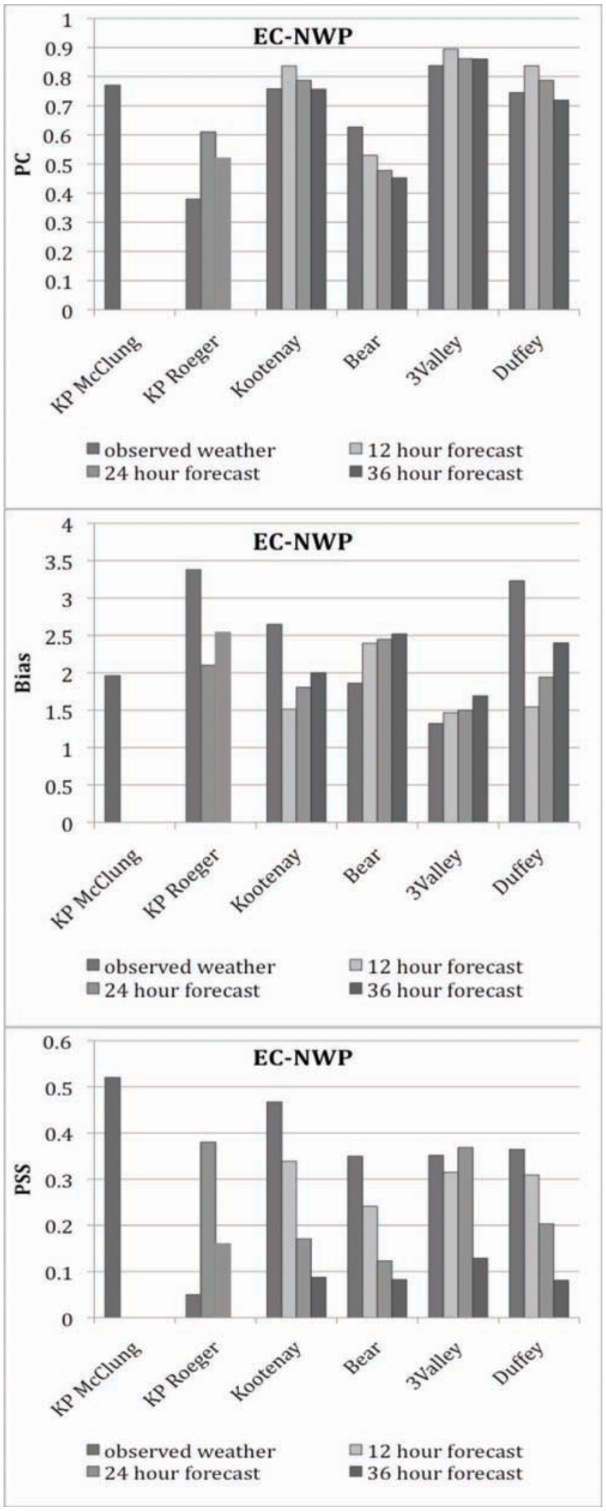
Peirce's skill score, also known as the Hanssen-Kuipers discriminant in Purves et al. (2003) and true skill score (Roeger et al. 2003), measures skill relative to an unbiased random reference forecast, and therefore is the most important performance metric in this study. A score of 0 indicates that the model has the same forecast skill as a random forecast or a constant prediction of event or non-event. A perfect forecast would have a PSS of 1 (Jolliffe and Stephenson 2003).

Bias values greater than (less than) one indicate that the event was forecast more than (less than) it was observed. This is known as overforecasting (underforecasting) (Roeger et al. 2003).

5 RESULTS

In figures 1-6 it is apparent that for Kootenay and Bear Passes this model performs with similar success to previous efforts that used manual weather observations and UBC-NWP (McClung and Tweedy 1994, Roeger et al., 2003). It must be noted that the original McClung and Tweedy (1994) model did not use NWP inputs, and the more accurate of the two 24 hour forecasts from Roeger et al. (2003) was made using the MC2 model on its own, while the other used an ensemble of MC2 and NMS models. PC can be a deceiving statistic when events are more rare, as shown by the excellent scores of the Duffey and 3Valley models. It is clear from the PSS values that these models show no skill. In these areas, avalanche days are more rare events, and so the PC is apparently boosted because it is easier to predict non-avalanche days when they overwhelmingly dominate the dataset.

All models presented here perform better than a constant or random forecast, but the Kootenay Pass models based on weather observations are far more skillful, as expected. The bias indicates that all models overforecast avalanches. However, this is consistent with



Figures 1-3: PC, Bias, and PSS of Environment Canada NWP based models, winter 06-07. KP refers to previous works in Kootenay Pass (McClung and Tweedy (1994) and Roeger and McClung (2003), Roeger only made 24 hour forecasts using two different NWP models.

the higher consequences of having forecasted a non-event when an avalanche occurs.

Similar, though poorer, results were obtained for predictions made with UBC-NWP (see charts at the end of this paper).

6 DISCUSSION

Previous models also included new snow density or penetration information. These variables proved to be highly statistically significant in all previous studies (McClung and Tweedy 1994, Floyer and McClung 2003, Purves 2003). Roeger et al. (2003) used a temperature-based proxy function to replace density variables used in the McClung and Tweedy (1994) model, but this function did not improve accuracy in the model presented here.

Despite the fact that electronic sensors do not take the full range of measurements used in previous studies, and the fact that NWP forecasts include no snow height information at all, the results of this preliminary study are promising. It is clear that the AFS accuracy produced using NWP inputs declines at a rapid rate as forecasts extend farther into the future.

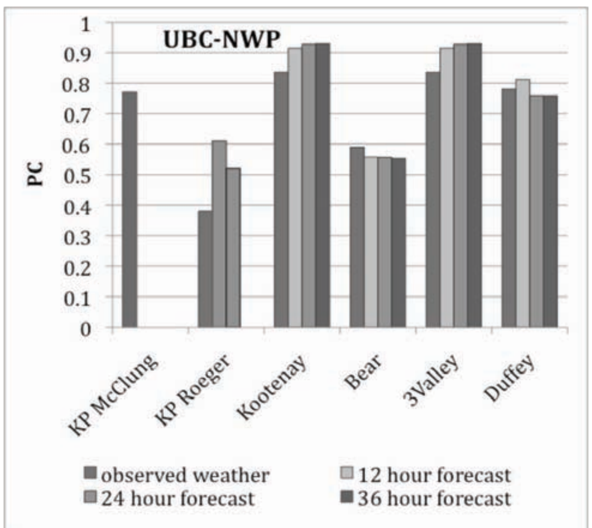
The AFS NWP verification tools enable the MoT to assess the efficacy of numerical weather and avalanche prediction systems. The AFS has now been applied operationally for two seasons, and in the second season, 12 to 36 hour avalanche forecasts based on UBC NWP were used by technicians in three areas.

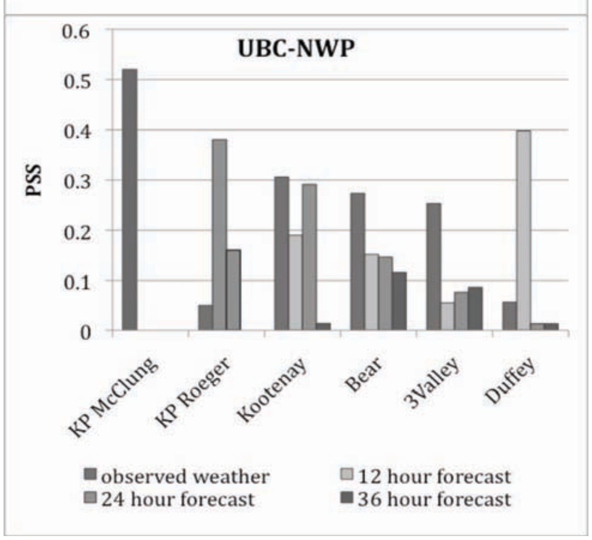
The Avalanche Forecast System created for the MoT has the potential to be a useful addition to the suite of tools provided to the avalanche technicians. During operations, technicians at Kootenay Pass refer to the predictions of the AFS to support their inductive reasoning regarding the state of instability of the snow cover (K. J. Malone, personal communication 2007). They use the nearest neighbour distances to judge the degree of uncertainty of the numerical predictions and they review the avalanche occurrences listed in the nearest neighbour report to confirm and improve their intuition regarding patterns of weather and avalanche occurrences.

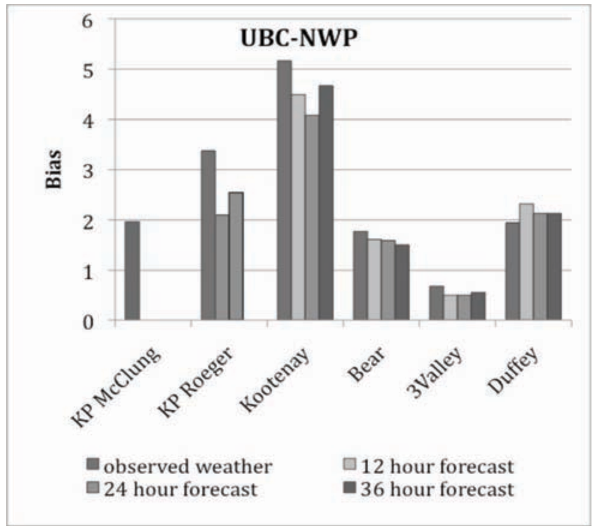
8 CONCLUSIONS

The Avalanche Forecasting System presented here predicts avalanches in the coming 12 hours using hourly interval electronic weather sensor inputs to a nearest neighbour model, and as far as 36 hours into the future when NWP inputs are used. The accuracy and skill of the NWP based forecasts compare favourably in relation to previous studies. The Kootenay Pass models (using both weather observations and forecasts) were most accurate, and while the Duffey and 3Valley models seemed accurate, they lacked skill. The Bear Pass models also failed to shine in terms of accuracy. However, Cordy (2006) showed that NN models for Bear Pass can be more accurate when using weather observations than this paper demonstrates. It is important to keep in mind that only one season of data for each NWP source was evaluated in this study, and more thorough investigation continues.

The results show that there is promise for the use of electronic weather sensor information for avalanche prediction in different climatic regions across British Columbia, and for the application of NWP for generating true avalanche forecasts. The AFS can help to increase the accuracy of human perception with regards to instability, and to plan staffing of avalanche technicians and road crew personnel. The AFS could be especially useful for MoT avalanche technicians in training.







Figures 4-6: PC, Bias, and PSS of UBC NWP based models, winter 07-08. *KP refers to previous works in Kootenay Pass (McClung and Tweedy (1994) and Roeger and McClung (2003). Roeger only made 24 hour forecasts using two different NWP models.*

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