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Road Surface Condition Forecasting in France

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ABSTRACT

A numerical model designed to simulate the evolution of a snow layer on a road surface was forced by meteorological forecasts so as to assess its potential for use within an operational suite for road management in winter. The suite is intended for use throughout France, even in areas where no observations of surface conditions are available. It relies on short-term meteorological forecasts and long-term simulations of surface conditions using spatialized meteorological data to provide the initial conditions. The prediction of road surface conditions (road surface temperature and presence of snow on the road) was tested at an experimental site using data from a comprehensive experimental field campaign. The results were satisfactory, with detection of the majority of snow and negative road surface temperature events. The model was then extended to all of France with an 8-km grid resolution, using forcing data from a real-time meteorological analysis system. Many events with snow on the roads were simulated for the 2004/05 winter. Results for road surface temperature were checked against road station data from several highways, and results for the presence of snow on the road were checked against measurements from the Météo-France weather station network.

1. Introduction

A winter road maintenance strategy depends on a number of factors, including climatic and demographic conditions as well as the road network density and traffic. Most countries use road-weather forecasting systems to predict road conditions, organize maintenance, and reduce the risk of accidents.

Numerical models are used to predict road surface conditions based on local predictions at road weather station locations and interpolation between these sites using thermal mapping surveys. Thermal mapping is performed using a vehicle-mounted infrared thermometer (Paumier and Arnal 1998; Shao 2000; Chapman et al. 2001). The prediction corresponding to a road weather station is made using numerical models. Many models exist. The main models are described in the literature (Thornes 1984; Rayer 1987; Shao 1990; Sass 1992; Jacobs and Raatz 1996; Crevier and Delage 2001; Yahia 2006). In recent years, attempts to improve prediction accuracy have been undertaken. They consist of adding complementary information as input to the road-condition prediction models. For example, in Finland, satellite and real-time camera data are used within an operational prediction tool (Iivanainen and Pettersson 2004). The large amount of input data improves the results but increases costs, leading to use of operational prediction systems only for the main road network. In this study, another approach is considered to build a less expensive system usable over the entire road network. This paper describes a system that uses only numerical weather forecasts as input to predict road surface conditions for the entire French road network. The initial road temperature and moisture profiles are provided by a long-term simulation of road

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conditions. The meteorological data are obtained through meteorological analysis that combines observations and weather models.

In winter, ice and snow are major dangers for road users. Ice formation on the road remains a difficult problem to model because of the many different phenomena involved—for example, freezing rain, hoar frost, freezing surface water, or freezing fog. Given the many physical processes that must be considered to treat all of these types of road icing, it would appear to be difficult to represent all of them in a single numerical model. The processes considered by currently available numerical models are usually simple (e.g., the freezing of water present on the surface of the road) and are represented using a bucket-type reservoir system of liquid and solid water. Some recent models describe ice formation in detail. In the specific context of bridges, Knollhoff et al. (2003) and Greenfield and Takle (2006) have developed a predictive model that calculates frost/snow depth and determines several types of surface states, based on the computation of surface fluxes. In particular, they consider the latent heat process resulting from phase changes of water on the top of the bridge, taking into account the vapor flux that plays an important role during frost formation on the surface (Jansson et al. 2006). Given that a model for all types of ice or snow presence on the road is currently not available, a method to reduce risk, in the absence of a prediction, is to detect it as soon as possible using sensors. For example, a sensor can be used specifically to detect freezing rain and freezing fog, with a recent algorithm that makes it possible to evaluate quantitative information on ice accumulation (Ryerson and Ramsay 2007). The prediction system described in this paper focuses on one type of winter road condition, the presence of snow on the road, and takes into account the thermal fluxes during snow deposition and the snow–road interface properties (snow grain type, wet or dry snow, etc.).

Note that road surface conditions depend on external processes such as road traffic and the quantity of deicers (salt) present on the road. For example, Chapman and Thornes (2005) showed the importance of traffic on road surface temperature. Using thermal mapping, they observed that the temperature difference in a lateral road section might reach 1.5°C between the highest and lowest traffic densities. The research project described in this paper does not take these phenomena into account, though they should be considered in further research because they are not negligible.

The first section of this paper is a brief description of the Interactions between Soil, Biosphere, and Atmosphere (ISBA)-Route/''Crocus'' coupled model used in this study. This model and its validation on the Col de Porte experimental site using observed meteorological variables near the surface were presented in detail in a recent paper (Bouilloud and Martin 2006). The focus of the current paper is to evaluate the predictive skill of the ISBA-Route/Crocus model and check it against observations. After a short description of the models and the prediction conditions, we will concentrate on the experimental site for which precise observations of road surface temperature and snow cover are available. Then we will focus on winter 2004/05 in France. The very cold winter made it possible to assess both surface temperatures and occurrence of snow on the road under conditions as close as possible to future operational conditions.

2. Brief description of the model and its validation

The ISBA-Route/Crocus coupled model was described in detail in Bouilloud and Martin (2006). It consists of the coupling of two one-dimensional models, that is, a soil model (ISBA; Noilhan and Planton 1989; Noilhan and Mahfouf 1996) and a snow model (Crocus; Brun et al. 1989, 1992). ISBA is used here in its multilayer version (''ISBA-DF''; Boone et al. 2000). Crocus is a detailed snow model originally used for avalanche forecasting in France (Durand et al. 1999). Both models were adapted to account for road processes. The main modifications were the introduction of road thermal and hydric properties for ISBA, treatment of capillary rise of water in Crocus (Coléou and Lesaffre 1998; Coléou et al. 1999), and a precise description of the thermal properties of the road–snow interface. The validation of the coupled model was done using data from a comprehensive experimental field campaign during three winters at the Météo-France Col de Porte experimental site (1320 m, Chartreuse mountain range, French Alps). In addition to continuous automatic recording of atmospheric and snowpack conditions, a total of 60 snowfall events were documented using manual measurements over the experimental road. The model evaluation consisted of the comparison of simulated and measured road surface temperatures, temperatures at a depth of 0.6 m, and snow depth and road–snow interface conditions (e.g., the occurrence of a water-saturated layer at the bottom of the snowpack). The model was validated using a pavement type corresponding to a highway structure, for which the surface layer is made of semigrainy bituminous concrete. This type of road composition was used for the simulations for all of France (section 5). The physical and thermal properties of the pavement are listed in Table 1. The surface properties used were an

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TABLE 1. Physical and thermal properties of the road structure and the underlying soil: Δz is the total layer thickness, ρ is the dry density, k_{dry} is the dry thermal conductivity, and W_{sat} is the volume porosity.

Material	Δz (m)	ρ (kg m^{-3})	k_{dry} (W m^{-1} K^{-1})	W_{sat} (%)
Semigrainy bituminous concrete	0.005	2000	2.1	6.35
Semigrainy bituminous concrete	0.077	2000	2.1	2.35
Sand gravel cement mix	0.512	2400	2.0	7.2
Unbound gravel	0.174	2200	2.0	8.8
Natural soil	8.5	1700	3.0	42.5

albedo of 0.07, an emissivity of 0.96, and a roughness length of 5×10^{-4} m.

The ISBA-Route/Crocus coupled model accurately simulated the road surface temperature and the occurrence of snow on the road. However, some discrepancies in terms of the simulated snow depth occurred. The simulation errors were mainly caused by uncertainties in the precipitation phase, difficulties in predicting the snow density, or phenomena not accounted for by the model (e.g., snow transport by wind). In addition, snowmelt was a bit too slow. This was due to the fact that the model did not take into account the heterogeneity of the snow and lateral transfers that accelerated melting. More details about the experiments, the model, and the local validation can be found in Bouilloud and Martin (2006).

3. Prediction conditions

To evaluate the predictive capacity of the model, the primary goal of this work, we used operational forecasts from Météo-France for tests at both the experimental site and throughout France. To obtain the initial conditions for the prediction, we forced ISBA-Route/Crocus with analyzed meteorological data provided by the Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige (SAFRAN; translated as Analysis System Providing Atmospheric Information to Snow; Durand et al. 1993). The same system was also used to spatially and temporally disaggregate the forecasts. For application throughout France, we used the 8 km $\times$ 8 km grid already used by Météo-France for road surface temperature predictions, which were based on the SAFRAN–ISBA-Route (SIR) system. Figure 1 shows a simplified diagram of the prediction system. In this study, we followed the same principles for both the experimental site and the nationwide validations. In this section, we will describe the SAFRAN system, the principle of the prediction by SIR, and the adopted definition for a ''presence of snow on the road'' event.

a. The SAFRAN model

SAFRAN (Durand et al. 1993) is the model that provided the meteorological forcing data. The SAFRAN model was first developed for mountainous regions (Durand et al. 1999) and was later applied throughout France (Quintana-Seguí et al. 2008). The objective of the ''analysis'' mode is to produce the most accurate estimation of the atmospheric variables and downward fluxes needed to force the ISBA-Route/Crocus model. In this section, only the main characteristics of the SAFRAN model are presented. SAFRAN uses an optimal interpolation method to analyze most of the parameters (Gandin 1963). The analysis is done over climatically homogeneous zones, which are areas of irregular shapes in which the horizontal climatic gradients are weak. SAFRAN estimates one value of each

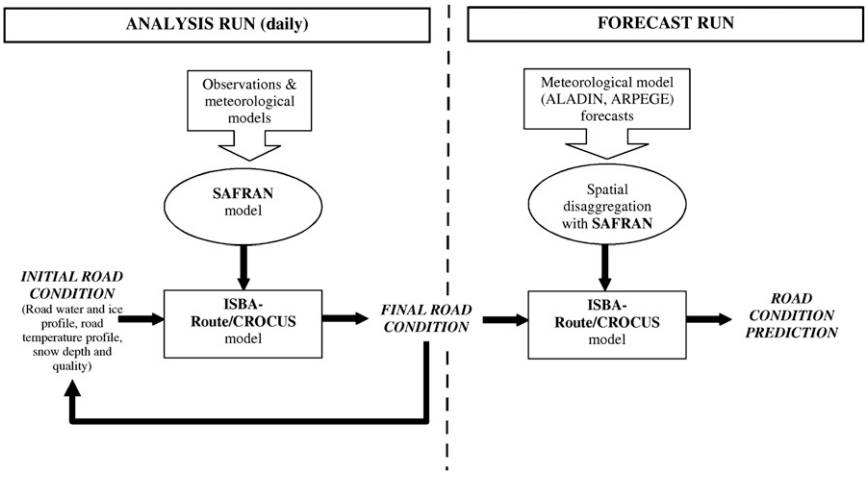


FIG. 1. Simplified diagram of the road condition prediction system.

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parameter for each zone at several altitudes. Within the zone, analyzed parameters depend only on elevation and aspect. The zones are not isolated; that is, observations from neighboring zones can be used. For the nationwide version of SAFRAN, the zones were determined using the expertise of local forecasters in each French department. The result was 612 zones as homogeneous as possible from a meteorological point of view. For the needs of hydrological forecasting or road condition prediction, the SAFRAN analysis is interpolated on an 8 km $\times$ 8 km regular grid. Prior to the analysis, SAFRAN runs a quality-control check on the observations, based on a comparison between observed and analyzed quantities at the observation locations. The meteorological variables analyzed are air temperature, wind speed, humidity, downwelling shortwave and longwave radiation fluxes, cloudiness, rainfall, and snowfall. SAFRAN uses observations from the Météo-France observational network as input. It combines these observations with preliminary estimates derived from the numerical weather prediction model Action de Recherche Petite Echelle Grande Echelle (ARPEGE; Courtier and Geleyn 1988) or Aire Limitée Adaptation Dynamique Développement International (ALADIN; Bubnová et al. 1993). The analysis is performed in two stages. The free atmosphere profiles are first calculated with a vertical step of 300 m every 6 h. Then SAFRAN determines the surface parameters, using a cruder method. The precipitation analysis is done once per day to take into account data from the climatological network (available at a daily time step, at 0600 UTC). Last, all of the variables are interpolated at an hourly time step:

1) All altitude profiles (temperature, humidity, and cloudiness) and surface wind are linearly interpolated.
2) Solar and longwave radiation are calculated using a radiative transfer scheme based on the vertical profiles of the temperature, humidity, and cloudiness determined previously.
3) The 2-m temperature at 1200 UTC is corrected using the maximum temperature observation and is then adjusted hourly using the solar radiation value and a relaxation to an equilibrium temperature.
4) The hourly precipitation value is based on determination of the zero isotherm, determination of the hourly snow–rain transition altitude based on the previous step and observations, estimation of the daily rain/snow ratio based on the ratio at each observation site, and then computation of the hourly precipitation (and phase) using the relative humidity and the daily ratio.

The ''forecast'' mode was a simplified version of the analysis mode in which only data from the numerical prediction models are used. In this mode, SAFRAN produced only a downscaling and a temporal interpolation of the numerical weather prediction model outputs.

b. The SIR application principle

In the SIR application, an analysis system is run to produce the initial condition (temperature, water, and ice content) of the road every day at 0600 UTC. Results of the long-term analysis simulation were used to initialize the predicted road condition variables (i.e., the temperature profile, soil water, and ice content for each layer of the soil). In this mode, the outputs of the SAFRAN analysis are used to force the ISBA-Route model. Then a 24-h prediction run is made in which ISBA-Route is forced by SAFRAN forecast data. The principle is the same as presented in Fig. 1, except that snow is not considered.

c. The definition of presence-of-snow-on-the-road events

The ISBA-Route/Crocus coupled model simulates snow on the surface of the road and predicted its evolution with respect to meteorological conditions. However, in reality snow is frequently removed by maintenance services, and in the current study this could not be accounted for. This point was crucial and prevented the direct use of the output model. It was therefore decided not to focus on the exact time of the beginning of the snow cover or the duration of the snow cover, but rather on determination of an event defined as either the presence of snow on the road or ''no snow.'' Each of the 24-h prediction periods was initialized without snow on the road. Then the event referred to as presence of snow on the road was considered to occur if snow was continuously present for 6 h, or 2 h if it occurred at the end of the period. No depth criteria were introduced in the definition because the roads are cleared as soon as snow accumulates. This definition avoided having to consider a brief occurrence of snow as a snow event and allowed us to focus on major events. Of course, the event definition used here can be adjusted in the future to match the needs and constraints of the road maintenance services.

4. Col de Porte experimental site

The predictive capacity of the model was first assessed at the Col de Porte experimental site. The predictions were compared with the observed presence-of-snow-on-the-road events during three winters (1997/98–1999/2000). At the experimental site, snow was removed by the operators or it melted naturally. In some cases, snow remained for several days on the experimental road. Such cases had no practical interest and were excluded

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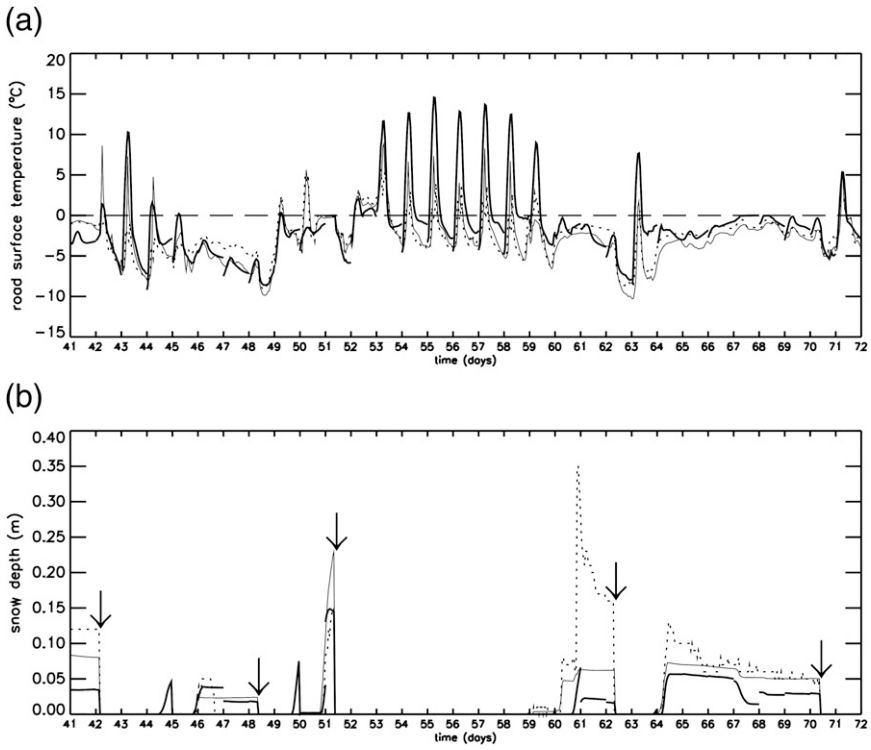


FIG. 2. (a) December 1998 comparison of the road surface temperature measured (dashed line), simulated using the observed forcing data (thin line), and simulated using the forecast forcing data (thick line). (b) As in (a), but for the snow depth (with manual snow removals indicated by ↓).

from the test. Only days without snow on the road at the beginning of the prediction were retained. However, in contrast to most highway stations that provide only road surface temperature measurements, the experimental site equipment allowed an accurate determination of snow presence (using video and snow-depth sensors) on the road. Hence, in this section, particular attention was paid to the snow occurrence events.

a. Example of results for December 1998

Figure 2 compares predicted road temperature and snow depth with the values simulated using the observed meteorological data and with the measured values. The curves corresponding to the predicted variables were discontinuous because the runs were initialized every day at 0600 UTC using the analysis mode described in section 3b. The quality of the simulations using forecast forcing data was lower than that of the simulations using observed forcing data. In the run with forecast data, shading due to trees and mountains near the site was not taken into account, leading to large errors during the day. However, the model predicted the observed negative temperatures during this month with higher accuracy. This gave an estimation of the error expected for application throughout France and was not considered to be crucial because the focus was on the minimum temperature and temperatures below 0°C.

In Fig. 2, there are three cases of good predictions of the presence-of-snow-on-the-road event and three poor predictions. The three good cases occurred on 5–6 December (days 45–46), 10–11 December (days 50–51), and 24–25 December (days 64–65). The three poor predictions occurred on 4–5 December (days 44–45), 9–10 December (days 49–50), and 19–20 December (days 59–60). The first two cases correspond to false predictions of snow presence on the road. They are due to snowfall that was predicted but not observed. In the third poor case, snowfall was predicted, but the snow remained on the road for less than 2 h at the end of the period.

b. Statistical results for the three winters of the field campaign

A contingency table was established to summarize the results obtained during the three campaign winters (Table 2) for presence-of-snow-on-the-road events. From these results, several statistical scores were calculated. The scores used to characterize the efficiency of the

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TABLE 2. Contingency tables for the presence-of-snow-on-the-road events for the simulations using observed meteorological forcing, analyzed meteorological forcing, and forecast forcing data.

Simulation		Measurement: Snow on road	Measurement: No snow on road
Observed meteorological forcing	Snow on road	42	2
	No snow on road	2	218
Analyzed meteorological forcing	Snow on road	40	7
	No snow on road	4	213
Forecast forcing	Snow on road	30	12
	No snow on road	14	208

prediction were the probability of detection, the false-alarm ratio, and the miss ratio. These scores are well suited to the context of predicting a rare event in a sample, because the correct prediction of a nonevent was not taken into account. To characterize the prediction of nonevents, the correct-prediction-of-nonoccurrences ratio was also calculated. Table 3 gives the different scores for simulations with observed, analyzed, and forecast forcing data. For the calculation of the road surface temperature score, only days without predicted and observed snow on the road were used. Table 4 provides the mean error and the root-mean-square error for the road surface temperature for the three simulations. Curves of relative operating characteristics (ROC; Mason and Graham 1999) were plotted for the presence-of-snow-on-the-road event predictions. These curves made it possible to evaluate the sensitivity of model capacity to key parameters.

c. *Result analysis*

1) SIMULATION WITH OBSERVED FORCING DATA

As expected, the road surface temperature simulated with the observed forcing was the most accurate among the three simulations, with a root-mean-square error (RMSE) of 2.84°C. This result has already been discussed in a previous publication (Bouilloud and Martin 2006). In this work, special emphasis was placed on the simulation of the presence-of-snow-on-the-road events. The majority of such events are reproduced using the observed forcing data. The probability of detection was 95.5% (Table 3).

2) SIMULATION WITH ANALYZED FORCING DATA

The road surface temperature simulated with analyzed forcing data was less accurate (RMSE of 4.10°C) than that simulated using the observed forcing data. The majority of presence-of-snow-on-the-road events were simulated very well, again with good statistical scores. Eleven cases of incorrect simulation of a presence-of-snow-on-the-road event were detected. Two of them were cases close to the limit of the adopted definition, and nine of them were due to an incorrect precipitation phase in the meteorological forcing (observed snow and analyzed rain or vice versa).

TABLE 3. Comparison of statistical scores for the daily presence-of-snow-on-the-road event simulation using observed forcing, analyzed forcing, and forecast forcing data, for the 1997/98, 1998/99, and 1999/2000 winter database (264 days). POD, FAR, MR, and CFNO represent, respectively, the probability of detection, the false-alarm ratio, the miss rate, and the correct forecasts of nonoccurrence.

Simulation type	POD	FAR	MR	CFNO
Observed forcing	95.5%	4.5%	4.5%	99.1%
Analyzed forcing	90.9%	14.9%	9.1%	96.8%
Forecast forcing	68.2%	28.6%	31.8%	94.5%

3) SIMULATION WITH FORECAST FORCING DATA

The RMSE for this case was 4.85°C, higher than in the two other cases. This relatively high value is partly linked to very local effects. Among them, the shading effect due to trees immediately south of the experimental field is probably the most important. In forecast mode, we did not take into account solar masking so as to remain as close as possible to operational conditions. This primarily affected daytime scores. The prediction of the negative minimum temperatures, relevant for frost risk, was more satisfactory. In fact, for all the days without snow during the 3 yr, the probability of detection was 74.2%, whereas the percentage of false alarms was approximately 8.2%. The prediction of the presence-of-snow-on-the-road event resulted in a 68.2% probability of detection and a false-alarm percentage of 28.6%. Among the 26 poor predictions, 8 were cases close to the limit of the adopted definition (as explained previously) and 18 were due to incorrect precipitation type in the forcing data.

4) ROC CURVES FOR THE PRESENCE OF SNOW ON THE ROAD

Using the definition of the presence-of-snow-on-the-road event described in section 3c, the ROC curve

TABLE 4. Comparison of the hourly global mean error (MEg) and the global root-mean-square error (RMSEg) for road surface temperature for the snow-free cases (186 days in the 1997/98, 1998/99, and 1999/2000 winter database).

Simulation type	MEg (°C)	RMSEg (°C)
Observed forcing	0.50	2.84
Analyzed forcing	1.80	4.10
Forecast forcing	2.44	4.85

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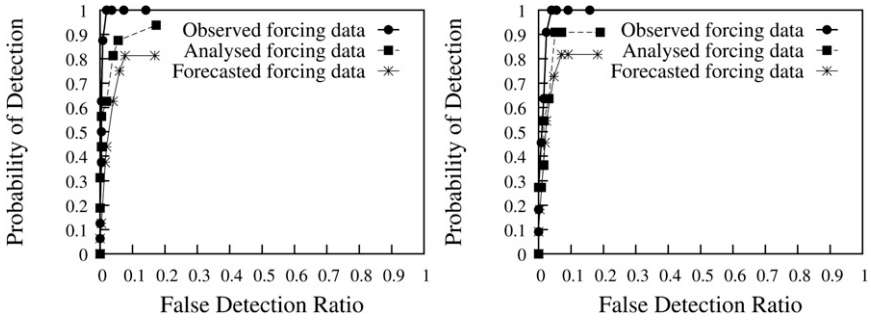


FIG. 3. Daily ROC curve analysis for the detection of presence of snow on the road in the 1997/98, 1998/99, and 1999/2000 winter database (264 days) for the simulations with observed forcing, analyzed forcing, and forecast forcing data. Plotted symbols correspond to thresholds varying from 0.3 to 0 m, with a 0.02-m step. (left) A snow-depth observation threshold of 0.05 m; (right) a snow-depth observation threshold of 0.1 m.

representing the probability of detection as a function of the false-detection ratio was plotted, taking into account different time thresholds. The duration of the continuous period used in the definition varied from 2 to 10 h, with a time step of 1 h. The ROC curve (not shown here) confirmed the very accurate simulation of the events with the observed or analyzed forcing data, with an ROC curve close to the upper-left-hand corner. The results are not too dependent on the time period, an interval of 4–8 h being the best.

In that the predicted snow depth can be considered an indicator of the maintenance operations needed, the predictive capacity for snow depth was assessed. We slightly modified the presence-of-snow-on-the-road event, using a duration of snow cover above 0.05 or 0.1 m instead of the original 0.0-m threshold. For each definition, ROC curves were plotted with thresholds varying from 0.3 to 0 m (with 0.02-m depth intervals) in the forecasts. Results are shown in Fig. 3 for the three types of forcing data. As expected, the curves showed decreased performance when going from observed to analyzed and then to forecast forcing data. In that all curves are located in the lower-left-hand corner, the good predictive capacity of the model was confirmed for this parameter. Integration of the area under the data points is usually used to measure the accuracy of the prediction (Swets 1988; Takle 1990). At this time, an area value of greater than 0.7 is considered to indicate that the prediction system potentially has practical value. For the three types of simulation, the area under the curve is approximately the same for the two snow-depth thresholds considered (0.05 or 0.1 m). For example, for the 0.05-m threshold, the area is respectively 0.99, 0.94, and 0.87 for the simulations with observed, analyzed, and forecast forcing data. These results confirmed the good predictive capacity of the model. However, the best results were obtained for predicted thresholds of 0.04–0.06 m for both observed thresholds. This result raises the issue of an underestimation of the predicted snow depth by the system.

5. Prediction for all of France

a. Extension of the model and experimental conditions

In this section, the ISBA-Route/Crocus coupled model was applied and validated for all of France. This study benefited from the operational environment of the SIR suite described in section 3b. The 2004/05 winter was simulated with the ISBA-Route/Crocus coupled model to evaluate the simulated road surface temperature with data that were not available in real time and to assess the quality of the prediction of the snow events. This winter was of particular interest because of the frequent snowfalls in the plains, leading to extensive traffic difficulties. At first, we focused on the road surface temperature and, in particular, on minimum temperatures. Then the predictive capacity for snow events was assessed using data from the snow climatological network for validation in the absence of adequate data for roads.

b. The road surface temperature validation database

The highway temperature database used for the validation process is detailed in Table 5. The spatial distribution of the stations is shown in Fig. 4. Note that the road surface sensors are subjected to traffic and the presence of salt.

c. Results for road surface temperature

Figure 5 shows results for the Viry station (A40 highway). Model results for this station were among the best. The mean error and the root-mean-square error for the predictions were respectively −0.6° and 2.9°C. The scores were better for nighttime and minimum

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TABLE 5. The main characteristics of the selected stations for the validation of the surface temperature.

Highway	Location in France	Alt (m)	No. of stations	Measurement period
A4	East	190–274	5	2 Feb–30 Apr 2005
A10	Paris area	90	1	1 Nov 2004–30 Apr 2005
A20	Southwest	288–424	7	1 Jan–30 Apr 2005
A40	Southeast	450–550	7	1 Jan–15 Feb 2005

temperatures because of the absence of shading factors in the simulation. In most cases, the maximum predicted road surface temperature was higher than the measurement. This problem is not essential for road maintenance services, which are mainly interested in road ice. The nocturnal cooling was well simulated, except in a few cases such as the 14–17 January period (days 13–16). The simulation with the analyzed forcing did not result in improved simulation of this period; a very local valley fog (not analyzed and not forecast) was the main reason for this discrepancy. Owing to the presence of one of the authors at this site, the significant snow event predicted by the model during the night from 14 to 15 February (days 44–45) was observed. In the same manner, another snowfall event with less snow was observed the next day. The measured road surface temperature that fluctuated around 0°C during the snowfalls confirmed this result.

Table 6 shows the mean error and root-mean-square error for the entire sample of stations in analysis and forecast modes. The distribution among the stations of the global mean error and the root-mean-square error is given in Fig. 6 (only for the forecast mode).

On average, the results were better than those obtained at the Col de Porte experimental site because of the lower influence of site effects (shading, wind, etc.) in plains or large valleys [see section 3c(3) for discussion of the Col de Porte case]. The distribution of the predicted road surface temperature among the stations (Fig. 6) showed that for the majority of stations the mean errors were within the [−0.5°, 1.5°C] range and the root-mean-square errors were within the [3°, 4°C] range. Two stations (one station along the A40 highway and one station along the A10 highway) showed very poor results. The A40 highway station had a mean error of 4.3°C and a root-mean-square error of 6.1°C. These poor scores were probably due to local effects such as wind, shadowing, or temperature inversion due to a pronounced valley effect on this Alpine highway. Because of measurement-quality technical concerns at the A10 station, it was decided to exclude it from further tests.

d. Results for the minimum road surface temperature

Figure 7 shows the results for the minimum road surface temperature simulated (with analyzed or forecast meteorological forcing data) for two stations, Viry (A40) and Laugerie (A20). The Viry station was the coldest with mostly negative temperatures. The model presented a slight cold bias at Viry and a slight warm bias at the more temperate Laugerie station.

For a more comprehensive assessment of model performance, several statistical scores using the minimum surface temperature and the prediction of negative temperatures were calculated for the A20 stations (Table 7). The other stations were not used because of suspicious data (A10), an excessively short measurement period (A4) due to frequent sensor breakdowns, or excessively cold temperatures (A40) leading artificially to very high scores due to a quasi totality of negative nocturnal temperatures. As expected, the RMSE was lower in analysis mode (although the bias was higher at some stations). For forecast mode, the probability of detection was greater than 81% and the false-alarm ratio was lower than 30% for all stations. An ROC analysis was performed using several temperature thresholds to predict the ''observed negative minimum road surface temperature'' event. The considered

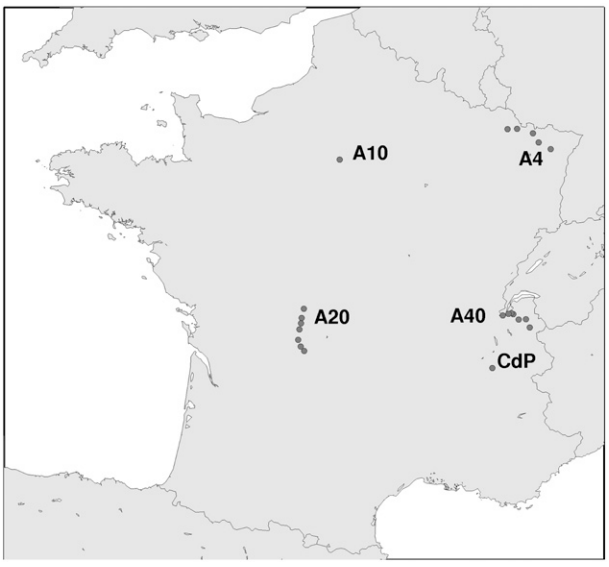


FIG. 4. Geographical distribution of the road weather stations used for the validation. The location of the Col de Porte (CdP) experimental site is also indicated.

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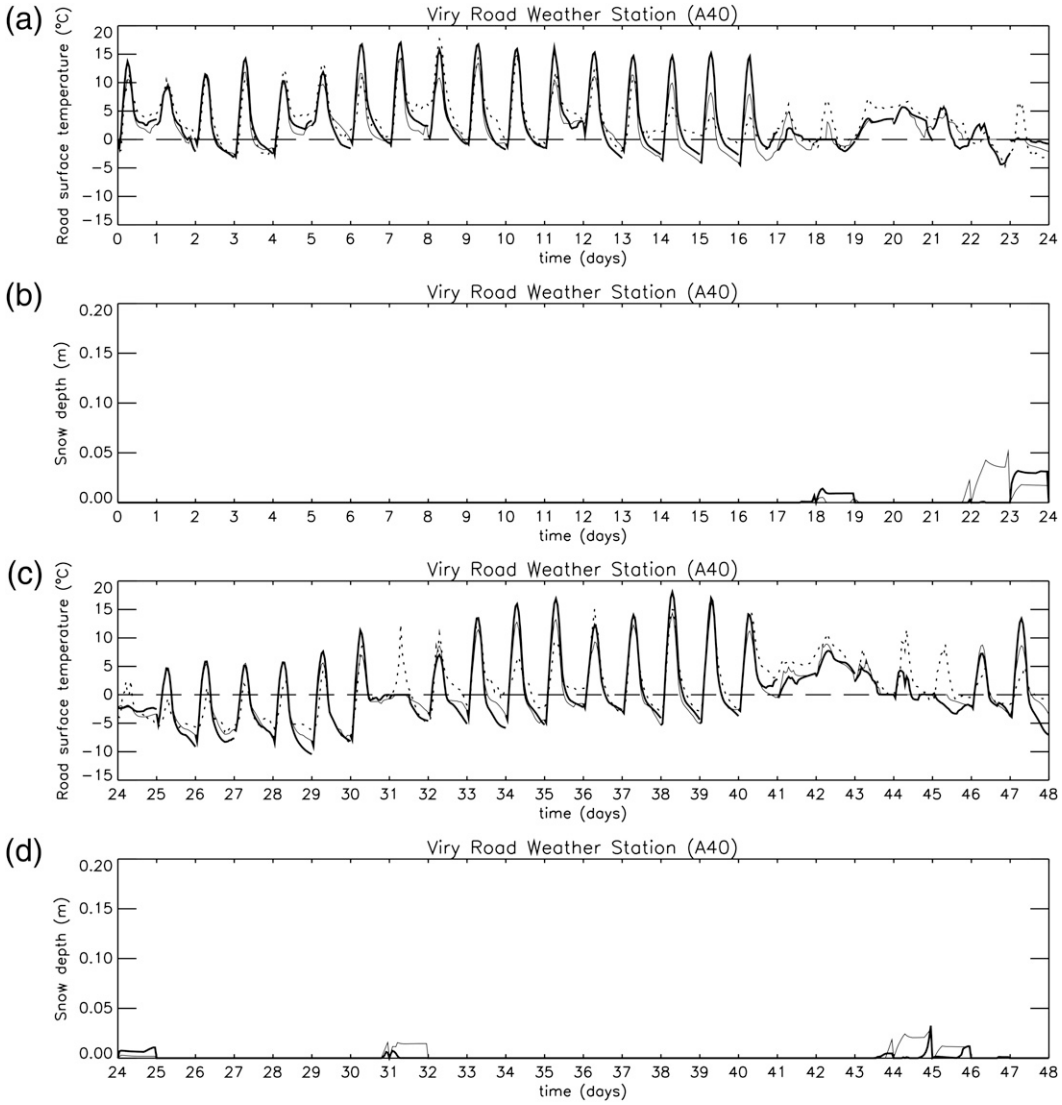


FIG. 5. (a),(c) Viry road weather station comparison of the measured road surface temperature (dashed line) with the simulation using analyzed forcing data (thin solid line) and with the simulation using forecast forcing data (thick solid line). (b),(d) As in (a) and (c), but for the snow depth.

thresholds varied from 5° to −5°C, with a 1°C step. Results were similar for all of the stations. Graphical results for only three stations (including the stations with the worst and best results) are given in Fig. 8. As for the detection of snow [section 4c(4)], the area under the data points was computed for each station (Table 7). The area under the curve exceeds 0.9 for each station, and therefore the prediction system has potentially major practical value. Although all of these ROC curves can be considered to be satisfactory, significant differences could be observed, with the best results for Magnac-Bourg and the worst for Laugerie station. The RMSE calculated for the daily minimum road surface temperature confirmed the previous results. The best RMSE was for Magnac-Bourg station (1.9°C), and the worst was for Laugerie station (2.5°C). On the ROC curves, the best results were obtained for the 0° and −1°C detection thresholds, showing that the model was either unbiased or affected by a small negative bias, depending on the station.

TABLE 6. Comparison of the hourly MEg and RMSEg of the road surface temperature for all road weather stations of the validation database (listed in Table 5).

Analyzed forcing		Forecast forcing	
MEg (°C)	RMSEg (°C)	MEg (°C)	RMSEg (°C)
0.3	2.9	0.6	3.7

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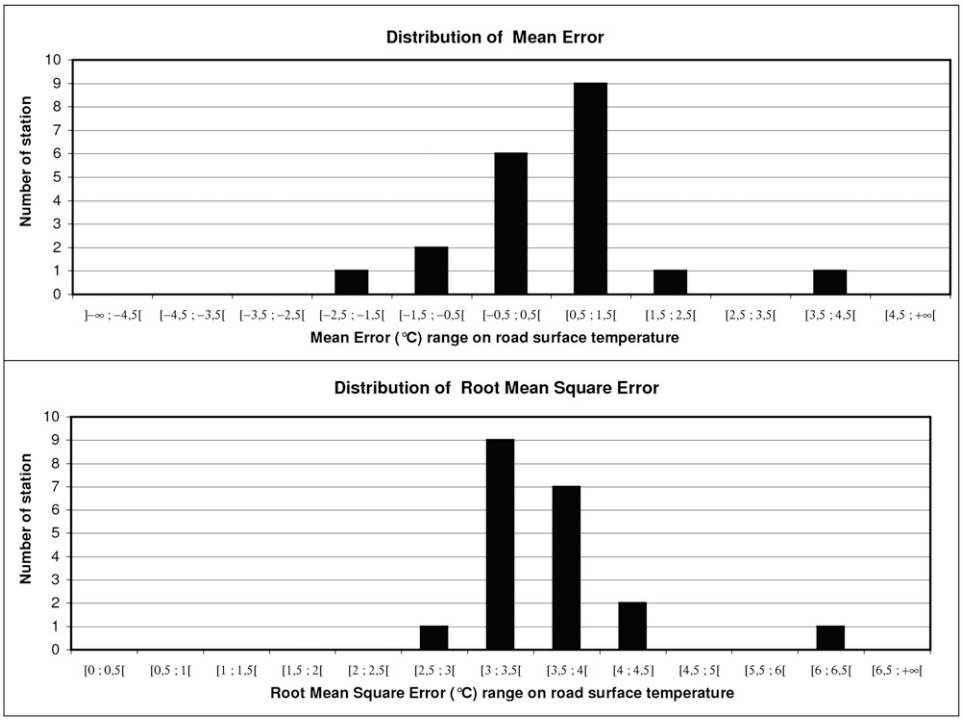


FIG. 6. Distribution of the hourly (top) mean error and (bottom) RMSE of the road surface temperature for all stations in the database (listed in Table 5).

e. Perspectives for presence-of-snow-on-the-road prediction for all of France

During the 2004/05 winter, many snowfall events occurred in France. Because of a lack of validation data from road weather stations, the information from the Météo-France observation network was used to assess the performance of the model. This network includes 5556 observation stations. Most of them were automatic or climatological stations, but about a hundred were staffed stations. The daily snowfall occurrence observations and the daily observations of snow on the ground were used in this study. Of course, the data did not compare directly to the quantities simulated by the model (presence of snow on the road), but they were used to account for the spatial distribution and detection of the snow event. Human observations were also included in the dataset. These sites are located within main French towns (i.e., they are more representative of urban areas than of roads). For all of these reasons, the validation presents some limitations and must be considered to be a preliminary step. Figure 9a shows the results of the simulation (in analysis and forecast modes) for the event occurring from 0600 UTC 28 December to 0600 UTC 29 December 2004. Figure 9b shows a comparison between the simulated snow presence on the road and the observed snowfall occurrence observations, for grid points containing a measurement station (or the nearest observation site if several stations are present in the same grid point). Figure 9c compares the simulated snow presence on the road with the observed snow presence on natural surfaces for the stations with staffed observations. In this figure, the size of the plotted points was increased for better legibility.

According to French newspaper archives, traffic was hindered by snow in the southeast quarter of the country. Both analysis and forecast runs simulated snowfall and snow on the road in this region. Other traffic disturbances were observed in the northeast. The predicted presence of snow on the road seems to be representative of the event, even though it may be too vast geographically (especially to the east of Paris).

For the grid points with staffed observations, the predicted presence of snow on the road was compared with the observed presence of snow on the natural surface. The relatively high probability of detection (69%) and the relatively low false-alarm ratio (11.5%) confirmed the good prediction of this event. Statistical scores for all of the events of the winter are given in Fig. 10 (the event described in detail above is event 2). These results varied significantly for the different events. They can be considered to be promising, but, because of differences between observed and simulated snow variables, a detailed analysis is virtually impossible. This

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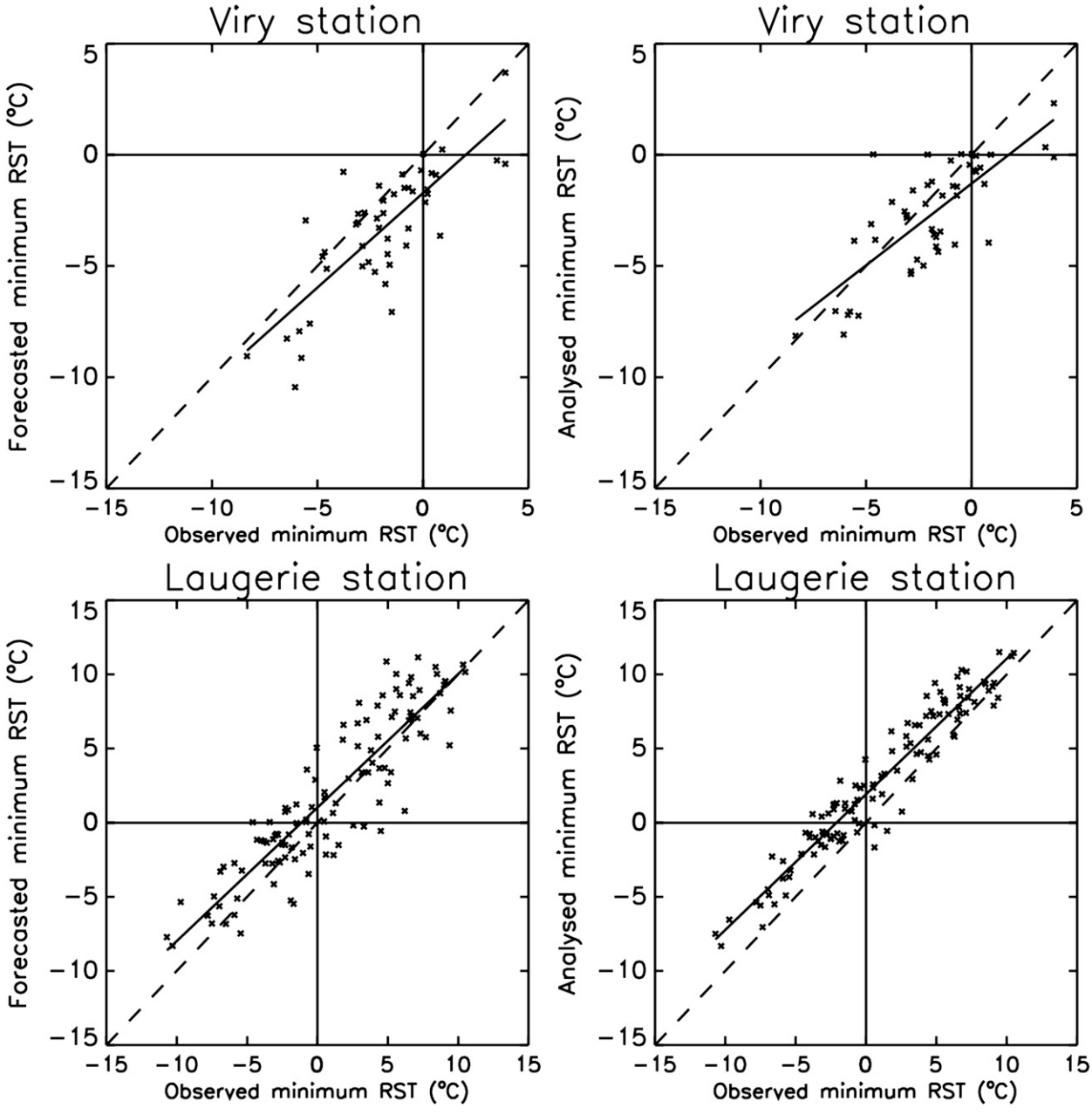


FIG. 7. Comparison of the predicted and measured daily minimum surface temperature [in (right) analysis and (left) forecast modes] for (top) Viry (A40; 46 days from 1 Jan to 15 Feb 2005) and (bottom) Laugerie (A20; 120 days from 1 Jan to 30 Apr 2005) road weather stations. A linear fit is superimposed on the data.

work shows that there is now an urgent need to gather appropriate data for further validation of this model.

6. Conclusions and discussion

The ISBA-Route/Crocus coupled model was developed with the primary goal of predicting the road surface conditions in winter. The model was able to simulate accurately the behavior of a snow layer deposited on a road by using observed meteorological data. The evaluation was done using data from a comprehensive experimental field located at Col de Porte, which consisted of 60 ''snow on road'' events (from the 1997/98 winter to the 1999/2000 winter) under natural conditions (without traffic or deicers). This comprehensive database was used to evaluate the model in a forecast mode, with meteorological forecasts as input. The model was able to predict the presence-of-snow-on-the-road

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TABLE 7. Statistical daily results for the comparison of the minimum road surface temperature in forecast or analysis mode, for the 1 Jan–30 Apr 2005 period (here ME is mean error, R^2 is the variance explained by the linear regression; and A is the area under the ROC curve).

Station/simulation	ME (°C)	RMSE (°C)	R^2	POD	FAR	MR	CFNO	A
A20 La Coulerouze								
Forecast	0.1	2.3	0.8	87%	16%	13%	72%	0.95
Analysis	0.9	2.1	0.86	67%	13%	33%	83%	0.95
A20 La Garde								
Forecast	−0.7	2.1	0.87	92%	29%	8%	63%	0.95
Analysis	0.1	1.6	0.91	79%	21%	21%	79%	0.96
A20 Laugerie								
Forecast	0.9	2.5	0.8	81%	17%	19%	71%	0.93
Analysis	1.8	2.3	0.92	61%	10%	39%	88%	0.96
A20 Le Mazataud								
Forecast	−0.4	2.0	0.86	92%	30%	8%	56%	0.95
Analysis	0.2	1.6	0.92	92%	23%	8%	70%	0.96
A20 Magnac-Bourg								
Forecast	0.3	1.9	0.86	90%	21%	10%	63%	0.97
Analysis	0.9	1.6	0.93	83%	11%	17%	84%	0.98
A20 Népoulas								
Forecast	−1.1	2.5	0.85	100%	30%	0%	60%	0.96
Analysis	−0.6	1.7	0.93	96%	27%	4%	68%	0.97
A20 Pierre-Buffière								
Forecast	0.1	2.2	0.82	89%	25%	11%	62%	0.96
Analysis	0.9	1.7	0.92	67%	14%	33%	86%	0.97

events with detection and false-alarm rates that were respectively on the order of 70% and 30%. The false predictions were mainly related to errors in the meteorological forecast. The poor scores for the road surface temperature predictions can be attributed to very local effects not taken into account by the model in forecast mode (solar masking by high trees in the immediate vicinity of the field).

The model was extended to all of France with an 8-km spatial resolution. The validation of the road surface temperatures was done using measurements from highway road weather stations. Predictions were relatively homogeneous for all stations, with a root-mean-square error of approximately 3°–4°C (slightly better than for the experimental site). This level of error might be considered to be too high for maintenance services. Results from operational road surface temperature models linked with road weather stations give better results, with a root-mean-square error of 1°–2°C. However, it must be noted that the type of approach tested here does not require any equipment. It can be used as a large-scale tool to delineate areas at risk or can be used routinely for roads without equipment.

In addition, this model can be improved in several ways. The first involves the physics of the model, that is, parameterization of traffic and partial integration of deicers. The second would be to improve the prediction by coupling it with fine-resolution numerical weather forecast models. The third would be to use local data to account for microscale meteorological effects, where available. The development of roadside weather stations will allow an improvement of the results, by using the data in the initialization of the road model, by downscaling of the meteorological forecasts to very particular sites, or by using the data to calibrate statistical correction methods of the outputs. The combined use of our approach and road weather stations is a promising

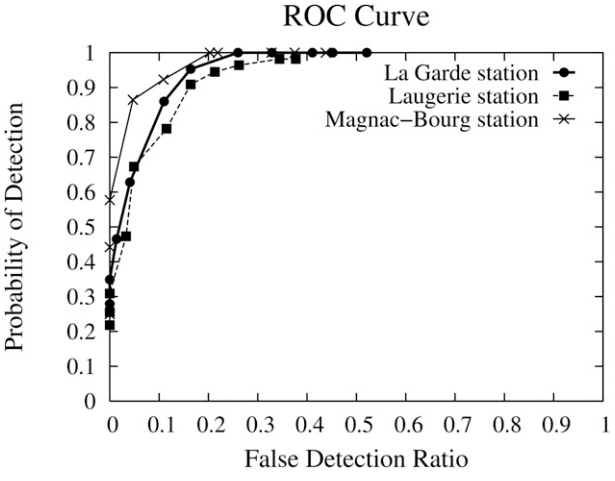


FIG. 8. ROC curve analysis for the prediction of daily ''negative minimum road surface temperature'' for three stations on the A20 highway (120 days from 1 Jan to 30 Apr 2005). The symbols on the curves correspond to minimum road surface temperatures varying from 5° to −5°C with a 1°C step.

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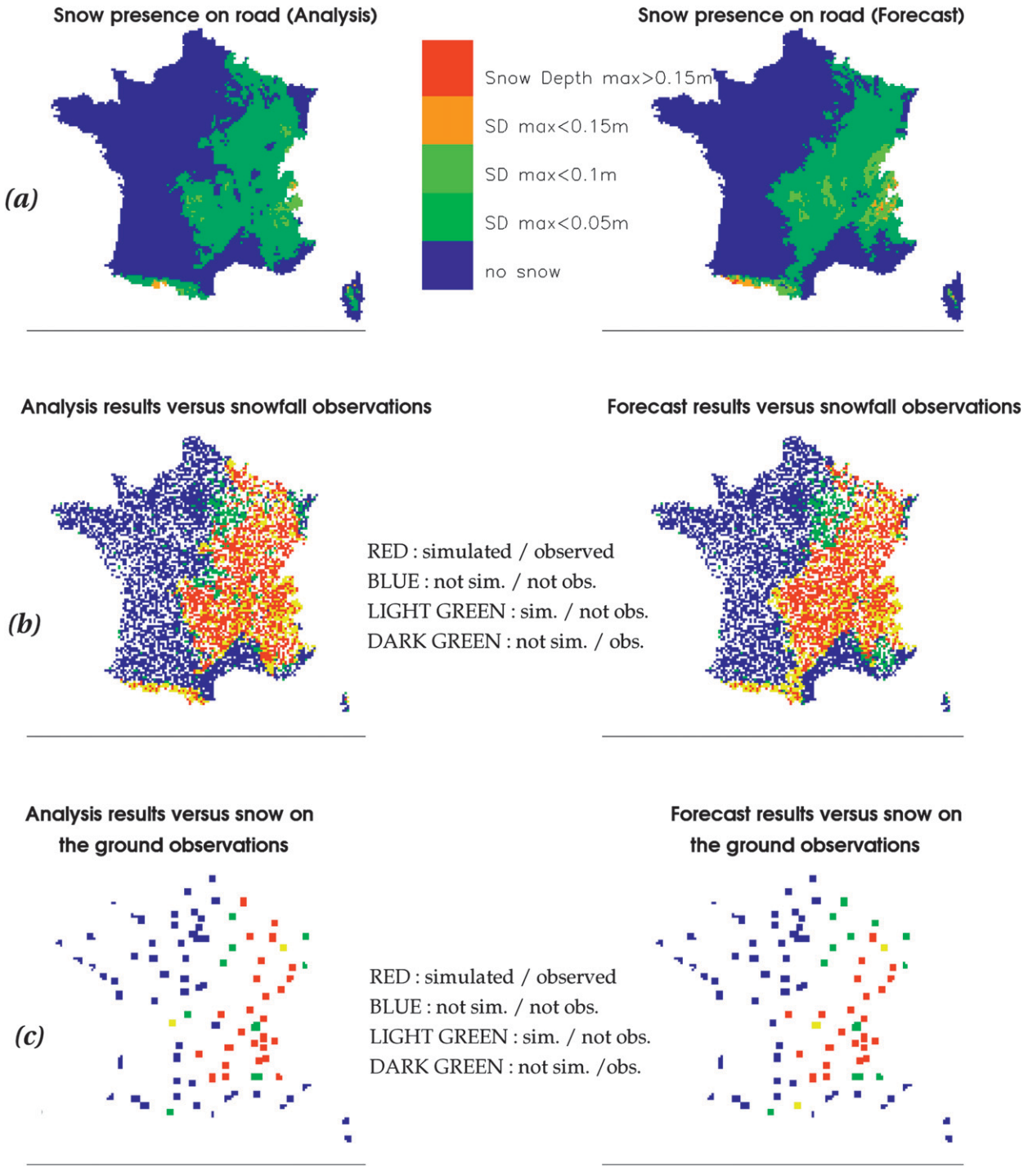


FIG. 9. (a) Results of the simulations (with analyzed forcing and forecast forcing data) of snow presence on the road for the 28–29 Dec 2004 event, and a comparison of these results with observation of (b) snowfall occurrence and (c) snow presence on natural ground.

way to propose a consistent product over all of France, with improved performance at critical points of the networks.

At present, the model enables monitoring of road conditions throughout France and constitutes a relatively inexpensive way to predict road surface conditions. The preliminary results for all of France are encouraging, but a comprehensive validation still remains to be done. In fact, the road weather stations are rarely equipped with snow-depth sensors, and, moreover, when

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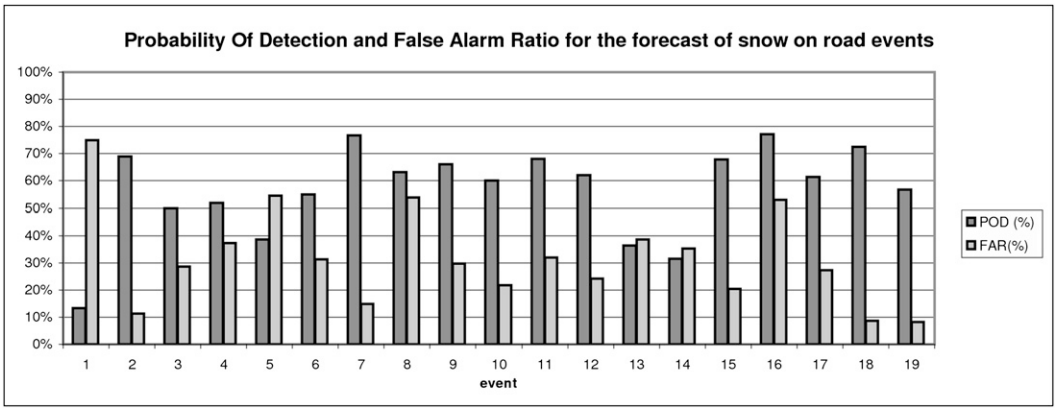


FIG. 10. Statistical results of the prediction of "snow on the road" for the 19 events of the 2004/05 winter.

this is the case, the reliability of the measurements is questionable (because of technical problems and errors caused by the presence of salt brine). The use of archived data from operational centers may improve the validation, but these data are not easily accessible. The evaluation of this model will be continued over coming years, subject to the availability of the data. Another evaluation method would be to use the model in real time on a well-instrumented site. For this purpose, a further operational test of the model is being considered at the Paris-Roissy airport.

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