# Advanced Weather Forecasting for the Road Management and Transportation

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## ABSTRACT

Weather conditions have a major impact on the safety and operation of roads. They affect driver behaviour, vehicle performance, pavement friction, roadway infrastructure and maintenance, risk management and prevention. Weather events and their impacts on roads can be predictable, non-recurring incidents that affect safety, mobility and productivity. This work shows a multi-model high-resolution forecast system which is tailored to transportation weather-related problems and, particularly, to roads. It is based on leading diagnostic and prognostic weather research capabilities which are being developed at the Epson Meteo Centre (CEM). The system is a research and development effort, but some algorithms are now operationally used at CEM. Two relevant winter case study are presented, showing the capability of the system to forecast situations with a potential high-impact on road transportation and safety.

**Keywords:** numerical models, precipitation type forecast, case studies, road management, prototype.

## 1. INTRODUCTION

Weather acts through visibility impairments, precipitation (snow or rain), high winds, and temperature extremes to affect driver capabilities, vehicle performance, pavement friction, roadway infrastructure, and crash risk. Millions of vehicles crashes every year and part of them (10-15% but more than 20% in some countries) were weather-related. Weather-related crashes are defined as those crashes that occur in adverse weather or on slick pavement. The tab. 1 summarizes the impacts of various weather events on roadways, traffic flow, and operational decisions.

In this framework, weather forecast have a huge impacts on roads, traffic and operational decisions. Where the complexity of the land characteristics are the peculiar element, such as in Italy, a system for road management may be very useful to provide weather forecast and road conditions in a country where road transportation is a fundamental element of the economy and car travels are very common for everybody.

After the developing and implementation of a number of tools related to our multi-modelling system, such as precipitation-type algorithms, snow height level, surface temperature evolution and others, at Epson Meteo Centre (Centro Epson Meteo, CEM, in Italian) all these tools have been integrated to give high resolution forecast for transportation (train, roads, airports).

The CEM WeST-MS (CEM Weather Surface Transportation Management System) is designed to be a functional prototype tool which can be used, for instance, by road and highway management. In general, the system is designed to provide timely weather and surface (roads) condition forecasts and in the future it might be coupled with other tools, such as road treatment planning ones, for example. It integrates data from various numerical weather prediction models (see sect. 2), surface observation information and climatology to produce weather forecasts at a number of forecast points. These forecast points may be at surface observation stations as well as at any desired point. The weather forecasts at each forecast location can be used as input other diagnostic tools, such as a pavement heat balance model, which can predict the road surface temperature and the snow depth at each forecast lead-time. These forecasted road conditions could be also used to generate, for instance, treatment plans at each site. The system was designed to be modular so a single component could be utilized without needing all the components. At the moment, the CEM WeST-MS is a research and development effort. As such, overall reliability of the system has not been exhaustively evaluated, even if some of the diagnostic tools, such as the forecast precipitation type and snow depth algorithms have been tested on numerous winter cases and are now operationally used. Examples of application in two winter case studies will be shown in the section 3.

| Road Weather Variables | Roadway Impacts | Traffic Flow Impacts | Operational Impacts |
|---|---|---|---|
| Air temperature and humidity | • Pavement friction | • Traffic speed<br>• Accident Risk | • Road treatment strategy |
| Wind speed | • Visibility distance (due to blowing snow, dust)<br>• Lane obstruction (due to wind-blown snow, debris, no large vehicles circulation) | • Traffic speed<br>• Travel time delay<br>• Accident risk | • Vehicle stability<br>• Access control (e.g., restrict vehicle type, close road)<br>• Evacuation decision support |
| Precipitation (type, rate, start/end times, distribution) | • Visibility distance<br>• Pavement friction<br>• Lane obstruction | • Roadway capacity<br>• Traffic speed<br>• Travel time delay<br>• Accident risk | • Vehicle traction<br>• Driver capabilities/behaviour<br>• Road treatment strategy<br>• Traffic signal timing<br>• Speed limit control<br>• Evacuation decision support<br>• Institutional coordination |
| Fog | • Visibility distance | • Traffic speed<br>• Speed variance<br>• Travel time delay<br>• Accident risk | • Driver capabilities/behaviour<br>• Road treatment strategy<br>• Access control<br>• Speed limit control |
| Pavement temperature | • Infrastructure damage | • Roadway capacity<br>• Traffic speed<br>• Travel time delay<br>• Accident risk | • Road treatment strategy |
| Pavement condition | • Pavement friction<br>• Infrastructure damage | • Roadway capacity<br>• Traffic speed<br>• Travel time delay<br>• Accident risk | • Vehicle performance<br>• Driver capabilities/behaviour (e.g., route choice)<br>• Road treatment strategy<br>• Traffic signal timing<br>• Speed limit control |
| Water level | • Lane submersion (e.g. in case of floods) | • Traffic speed<br>• Travel time delay<br>• Accident risk | • Access control<br>• Evacuation decision support<br>• Institutional coordination |

Table 1. Weather Impacts on Roads, Traffic and Operational Decisions (adapted from FHWA)

Several types of input data are required by the system. These data are all internally generated and disseminated from CEM High-Performance Computer Facility. Various types of numerical prediction model data (gridded or statistical) are used in creating the forecasts, and observation data are required for creating empirical relationships with the forecasts. These data are fundamental for the system to be able to make ‘tuned’ weather and road condition forecasts.
The meteorological and forecast data used by the system are listed below:

- CEM-MSM model, 00, 06, 12, 18 UTC runs;
- WRF model, 00, 06, 12, 18 UTC runs;
- MesoNH model 00, 06, 12, 18Z runs;
- observations;
- ensemble data;
- statistical and diagnostic model outputs.

The CEM WeST-MS creates the weather forecast time series data required to drive the prototype module which ingests reformatted meteorological data (observations, models, statistical data, climate data, etc.), produces meteorological forecasts at user-defined forecast sites and forecast lead times. The forecast variables (time series data) can be used, for example, to calculate the pavement surface temperature. In order to achieve this goal, independent forecasts from each of the data sources are used to produce the overall forecast.

## 2. MODELLING SYSTEM

Atmospheric models require heavy computer resources. The concurrent possibility to distribute the computation over a cluster of computer has been one of the basic ideas of the implementation of atmospheric modelling at CEM, with the load distribution handled by a cluster management system, which gives opportunities to make efficient use of systems. The research group of CEM has developed a parallel computation for weather forecasting both for global and regional domains, with a mesh grid size (the distance among computational points) up to a few km. Now, with the developing of our algorithms, a cluster of computer with different characteristics will be used to make high performance computations on atmospheric physics from global to local scale, both for weather forecasting and our researches. The whole system has been designed for high scalability and maximum flexibility, in order to satisfy the requirement of operational uses together with the research developments. This also means that some computations can be daily made together with others performed in some cases with defined conditions (area, time period, and weather situation).

Computations are renewed every 6 hours and up to 384h forecast, depending on domain and model resolution. For the applications related to roads management and transportation, high-resolution models are run up to 144h and at a resolution operationally ranging from 10 to 20 km, even if more detailed resolutions (a few km) are used for research and off-line testing. Particularly, three model constitutes the prediction system suitable for this task and they will be described below. Furthermore, diagnostic algorithms are added to better specify more parameters such as the height of snowfall and precipitation type.

### 2.1 Cem-MSM

The Cem-MSM is a scalable and flexible model suitable for a wide range of atmospheric scales. A brief summary of the nonhydrostatic (NHY) formulation of the model is given [11]. An hydrostatic-pressure vertical coordinate is used for HY and NHY primitive equations. The fully-compressible NHY system can be written as:

$$\frac{dU}{dt} = fV - K\frac{\partial S}{\partial x} - RT\frac{\partial q}{\partial x} - \frac{T}{\overline{T}}\frac{\partial q}{\partial(\ln\sigma)}\frac{\partial\overline{\Phi}}{\partial x} + F_U \tag{2.1}$$

$$\frac{dV}{dt} = -fU - K\frac{\partial S}{\partial y} - RT\frac{\partial q}{\partial y} - \frac{T}{\overline{\overline{T}}}\frac{\partial q}{\partial(\ln\sigma)}\frac{\partial\overline{\Phi}}{\partial y} + F_V \tag{2.2}$$

$$\delta\frac{dW}{dt} = -g + g\frac{T}{\overline{\overline{T}}}\frac{\partial q}{\partial(\ln\sigma)} + F_W \tag{2.3}$$

$$\frac{C_v}{C_P}\frac{dq}{dt} = -S\left(\frac{\partial U}{\partial X} + \frac{\partial V}{\partial y} + \frac{\sigma}{R\overline{\overline{T}}}\frac{\partial U}{\partial\sigma}\frac{\partial\overline{\Phi}}{\partial x} + \frac{\sigma}{R\overline{\overline{T}}}\frac{\partial V}{\partial\sigma}\frac{\partial\overline{\Phi}}{\partial y}\right) + \frac{g\sigma}{R\overline{\overline{T}}}\frac{\partial w}{\partial\sigma} + \frac{F_T}{T} \tag{2.4}$$

$$\frac{dT}{dt} = \frac{R}{C_p}T\frac{dq}{dt} + F_T \tag{2.5}$$

$$\frac{dQ}{dt} = F_Q \tag{2.6}$$

where q = ln(p), δ is one for NHY runs and zero for the HY ones, S is the square of the map scale factor, m, and K is

$$K = \frac{1}{2}\left(U^2 + V^2\right). \tag{2.7}$$

The total derivative

$$\frac{d}{dt} = \frac{\partial}{\partial t} + S\left(U\frac{\partial}{\partial x} + V\frac{\partial}{\partial y}\right) + \sigma'\frac{\partial}{\partial\sigma} \tag{2.8}$$

is expressed in terms of the horizontal wind images,

$$\begin{pmatrix} U \\ V \end{pmatrix} = \frac{1}{m}\begin{pmatrix} -\sin\lambda & -\cos\lambda \\ \cos\lambda & -\sin\lambda \end{pmatrix}\begin{pmatrix} u \\ v \end{pmatrix} \tag{2.9}$$

Conservation of total energy is assured since the continuity equation is strictly retained. The time integration is semi-implicit and semi-Lagrangian. Lateral boundary relaxation is considered; it may be either explicit or implicit, time-splitting. A lateral boundary blending may be also considered and 4th order horizontal diffusion is applied. Since non-zero boundary conditions may cause serious difficulties with semi-implicit time schemes, perturbation method is applied for the resolution of the equation in the model, because zero lateral boundary condition can be satisfied and diffusion can be applied to perturbation only [3]. The model uses a type of dynamical initialization which can be considered whenever there is a doubt about the balance state of the initial conditions or when a field such as vertical motion is not given in the initial analysis. But the inizialization on the finer meshes is omitted when these are driven by coarser runs. Flux computation in the surface layer follows the Monin-Obukhov similarity profile [1] with a multi-layer soil model in which different classes of vegetation and soil types are considered. Vertical turbulent eddy diffusion of momentum, heat and vapour is computed in this study via a non-local approach in the boundary layer where in the free atmosphere the formulation is based on scale parameters obtained from observation (other option available in the model is a Mellor-Yamada improved TKE scheme [6]). Deep convection is treated with a relaxed Arakawa-Schubert scheme [7]-[8]; Kain-Fritsch (K-F) parameterization is also available [4]. The microphysics treatment employs five prognostic species including water vapour, cloud water, cloud ice, snow and rain [10].

### 2.2 MesoNH

MesoNH is a mesoscale non-hydrostatic model developed by the Centre National de Recherches Meterologiques (Meteo-France) and the Laboratoire d'Aerologie (CNRS). Meso-NH is a numerical model able to simulate atmospheric motions at different scales, from the large meso-alpha scale down to the micro-scale. It is a grid point model and makes use of an Arakawa C-grid both for the horizontal and the vertical grid. The model makes use of the anelastic approximation in the resolution of the equations of motion. In this approximation the fluid is virtually uncompressible or pseudo-uncompressible. The time scheme is explicit; lateral boundary conditions are variable: cyclic, or rigid wall, or open or a combination of these different types of conditions can be chosen.

MesoNH allows grid-nesting and two or more models can be run at the same time, with the possibility of a two-way interaction between the coarse and the fine mesh model at every time step. It is operationally nested in CEM-ESM, the European-scale version of the Epson Meteo Centre model. Physiographic data (topography, soil-vegetation characteristics, etc.) can be given by the user, or data files are already present with a global domain and a resolution of 1 km for orography and surface cover type, and of 10 km for clay or sand fraction. For the microphysical scheme up to eight water species can be chosen (vapour water, cloud water, rain, ice, snow, graupel, hail and pristine ice), or a combination of these species [9], and several cloud schemes can be used (usually the Kessler scheme is chosen for warm clouds). For deep convection K-F scheme is used [4].

Turbulence can be treated one-dimensionally where only the vertical turbulent fluxes are taken in account or three dimensionally where all the fluxes are computed [2]. The turbulent mixing length can be calculated with different approaches selected by the user. To not cause major restrictions for the time step, because of the use of an explicit time scheme, for the vertical diffusion term a semi-implicit or fully implicit time scheme can be chosen. Also several options for the radiation scheme can be chosen, but for a complete treatment of radiation the ECMWF radiation scheme is implemented.

### 2.3 WRF

The WRF model is a flexible, state-of-the-art, atmospheric model usable in a massively parallel computing environment [13]. It offers numerous physics options, thus tapping into the experience of the broad modelling community. It is suitable for use in a broad spectrum of applications across scales ranging from meters to thousands of km. Such applications include research and operational numerical weather prediction, data assimilation and parameterized-physics research, downscaling climate simulations, driving air quality models, atmosphere-ocean coupling, and idealized simulations (e.g. boundary-layer eddies, convection, baroclinic waves). It is a fully-compressible, Euler nonhydrostatic model with a run-time hydrostatic option available and it is conservative for scalar variables. Terrain-following hydrostatic-pressure, with vertical grid stretching permitted, is used as vertical coordinate [5]. Time integration is split-explicit using a 3rd order Runge-Kutta scheme with smaller time step for acoustic and gravity-wave modes. Second to sixth order advection options in horizontal and vertical are available. Sub-grid scale turbulence formulation in both coordinate and physical space. Divergence damping, external-mode filtering, vertically implicit acoustic step off-centring are considered. Explicit filter option are also available. Initial conditions may come from three dimensional real-data. One-way, two-way, and moving nesting are provided. Microphysics uses bulk schemes ranging from simplified physics suitable for mesoscale modelling to sophisticated mixed-phase physics suitable for cloud-resolving modelling. Cumulus parameterizations are based on adjustment and mass-flux schemes for mesoscale modelling [4]. Surface physics uses multi-layer land surface models ranging from a simple thermal model to full vegetation and soil moisture models (4 layers), including snow cover and sea ice. Turbulence scheme is based on turbulent kinetic energy prediction [6] or non-local K schemes. Atmospheric radiation physics adopt longwave and short-wave schemes with multiple spectral bands; a simple shortwave scheme with cloud effects and surface fluxes is included. The domain is automatically decomposed for a multiprocessor run.

## 3. CASE STUDIES

To outline the functionality of the system, two case study are presented: the first one is the 31st of December 2005, and the second is the 26-27th of January 2006. These two cases are characterized by snow precipitation in the northern Italy; the January case is particularly interesting due to the amplitude and the amount of snowfall, which produced the major snow event in the last 20 years.

### 3.1 December 31st, 2005

This case was characterized by a cold air mass coming from the northern Europe with very low temperature the night before this day, between -10°C and -15°C in the Po valley. Partially sunny during the day, with maximum temperature around 0°C at midday. In the evening, a frontal system from the Atlantic ocean hit the northern and western Italy, with freezing rain and snow which gave many problems in the main roads and highways. For example, in Milan and in the evening, drizzle, snow grains and snow were recorded, while in Bergamo and Brescia snow were recorded after 7 p.m., but in the western part of Piedmont, for instance, no precipitation occurred (fig. 1). The figs. 2 and 3 show the three-hours sequence of precipitation type forecasted by model at 18 and 21 UTC, Dec. 31st and 00 and 03 UTC, Jan. 1st, using a diagnostic module adapted from NCEP precipitation-type algorithm [12].

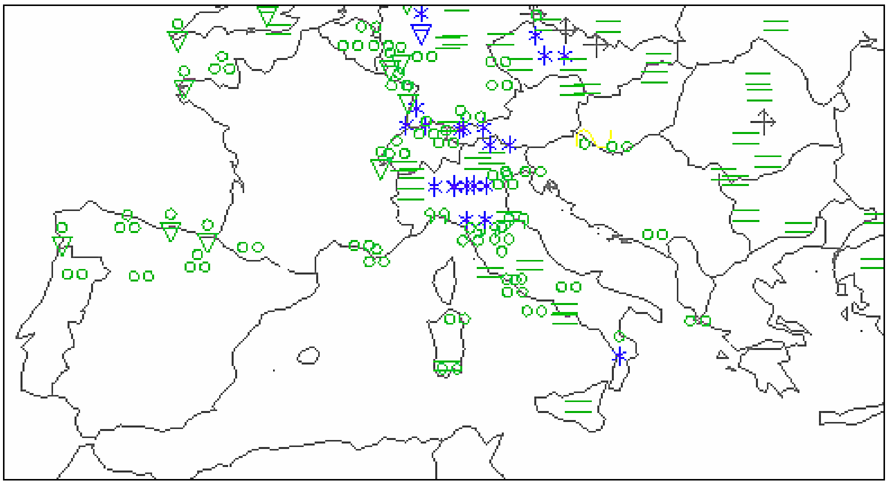

Fig. 1. Map of weather at 00 UTC, January 1st, 2006. Snow, represented by a * is reported in the Po valley from Lombardia to Veneto.

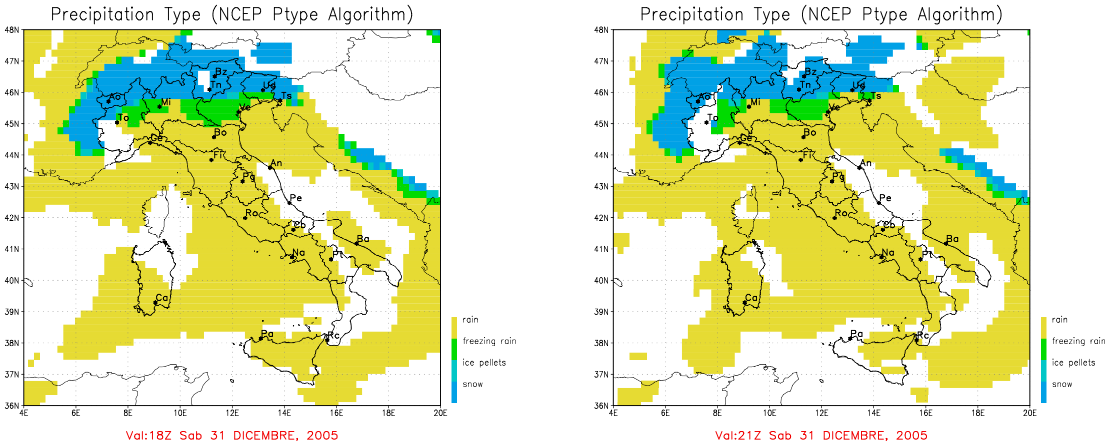

Fig. 2. Evolution of the precipitation type (December 31st, 2006), as forecasted by prediction system. Yellow areas are referred to rain, green areas are for freezing rain and blue and light-blue areas are for snow and ice pallets.

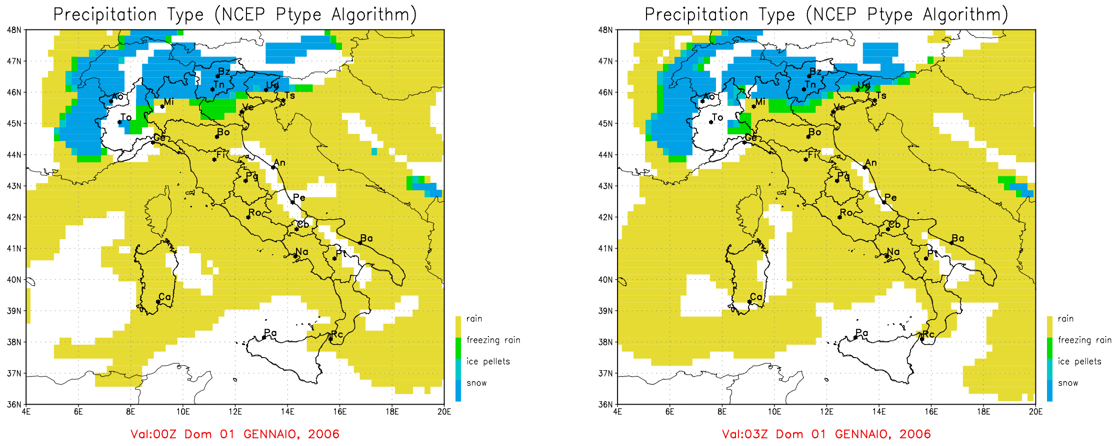

Fig. 3. Same as fig. 2 for the night of Dec. 31st-Jan. 1st.

The type of precipitation is quite well reproduced compared to the observations recorded in that day. Fig. 4 represents the level where the precipitation type will be solid, considering an algorithm developed at Epson Meteo Centre. The map at 18 UTC is presented concerning the height level at which the precipitation is forecasted as snow.

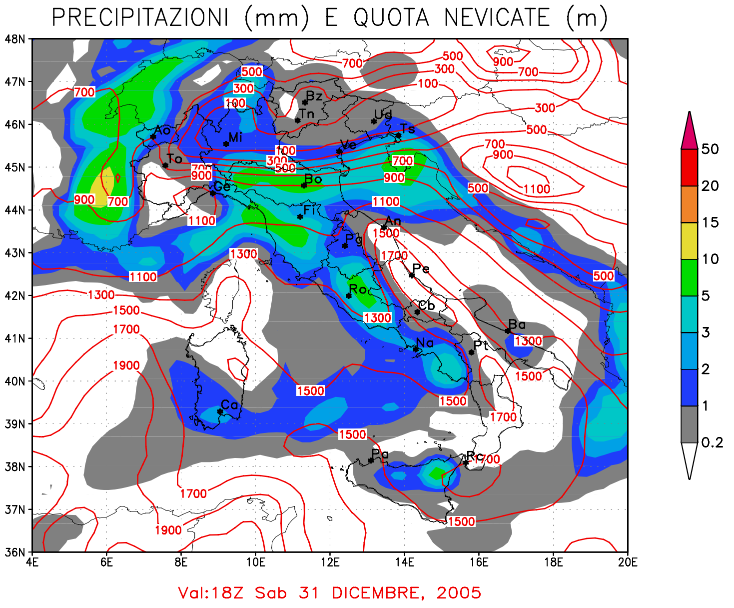

Fig. 4. Forecast of height of snowfall (a.s.l.) and precipitation amount at 18 UTC, Dec. 31st, 2005.

### 3.2 January 26-27th, 2006

A cold air mass was present over northern Italy due to an high pressure on the eastern Europe. A low pressure on western Mediterranean Sea produced south and southeast wind toward the Alps, with humid air blocked by the mountains in the south alpine region. In the morning of the 26th of January, snow started to fall. Then, for about 48 hours, snow occurred in the Po valley and generally in Piedmont, Lombardia, Liguria, Emilia, Trentino. This has been the major snow event (fig. 5) in the last 20 years for northern Italy, both for the extension and the amount of precipitation: 65 cm in Sondrio, 60 in Genoa, 55 in Como and Ovada, 50 in Novara, 45 in Lodi and Vercelli, 43 in Bergamo, 40 in Milan and Pavia, 35 in Alessandria, 30 in Biella and Brescia, 15 in Reggio Emilia.

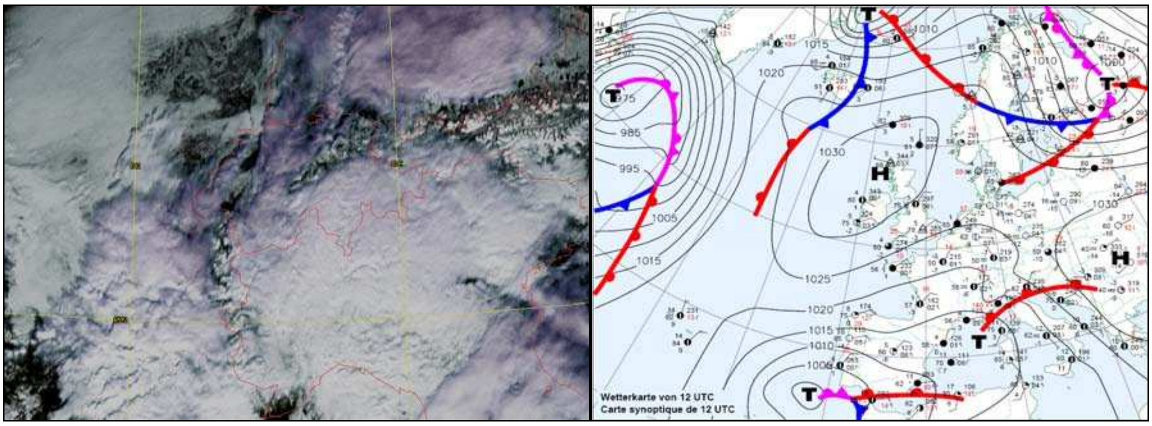

Fig. 5. Satellite image and the synoptic chart at 12 UTC of January 27th, 2006 (from MeteoSwiss).

The fig. 6 shows two maps of precipitation type and height of snowfall at 12 UTC of January 27th, 2006. The area in light blue at the left represents the snow precipitation as computed by NCEP precipitation-type algorithm. The area extent is confirmed by the level of snowfall, represented by a red line on the right map. The total amount of snowfall computed by the model was close to those observed by measurements.

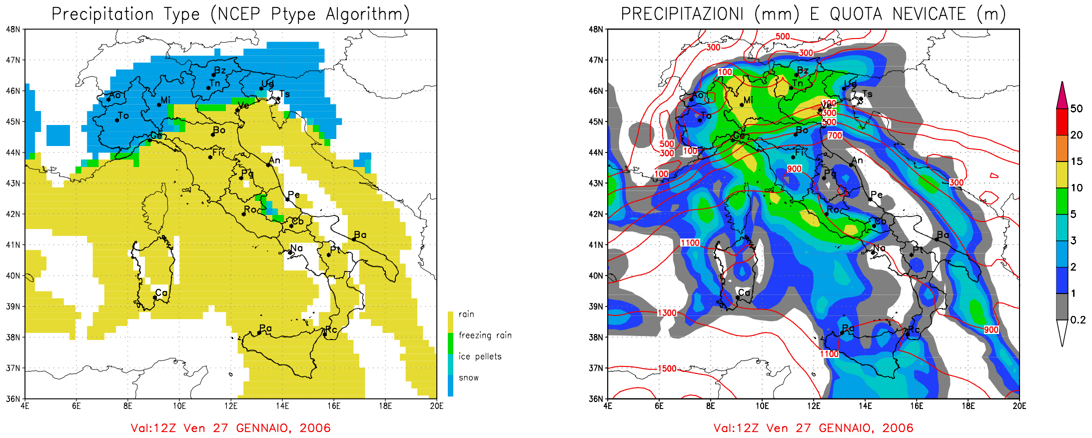

Fig. 6. Precipitation type, height of snowfall and precipitation amount at 12 UTC of January 27th, 2006

## 4. CONCLUSIONS

The CEM-WRMS is a research and development effort, designed to provide timely weather and road condition forecasts, integrating data from various numerical weather prediction models, surface observation information and climatology to produce weather forecasts at a number of forecast points. The weather forecasts at each forecast location can be used as input other diagnostic tools, such as the pavement heat balance model, that predicts the road surface and subsurface temperature profiles and the snow depth at each forecast lead-time. Even if the overall reliability of the system code has not been exhaustively evaluated the forecast precipitation type and snow depth algorithms have been tested on numerous winter cases and are operationally used at Epson Meteo Centre.

Two case studies have been presented: the first is at the end of 2005, with snow and freezing rain and the second is the 26-27 January, 2006, the major snow event in northern Italy in the last 20 years. Applications of precipitation type algorithm and snowfall height and amount have been briefly shown. Results have been close to observation, both from a qualitative and quantitative point of view, with amounts comparable to measurements and the location of snow precipitation in the area where they really occurred.

Many other winter cases, not outlined here, have shown results comparable to observations, so that CEM WeST-MS may be a prototype of a reliable system to produce advanced weather forecasts for road and surface transportation management

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