Nowcasting nocturnal cloudiness with an ultra-dense road weather measurement network

by
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Abstract

Ice and snow are important risks in winter precipitation. In this study we show several events of slipperiness in Switzerland, mainly caused by rain or snow falling on a frozen surface. Other reasons for slippery conditions are frost or freezing dew in clear nights and nocturnal clearing after precipitation, which goes along with radiative cooling. All these risks are connected with the existence or absence of clouds. Forecasting the cloud amount on a scale of 1-3 hours therefore is of special interest for road weather.

Cloud amount and the difference between air and surface temperature are important parameters of the radiation balance. In this contribution, we show the relationship between them, proved at several stations all over Switzerland. We found a quadratic correlation coefficient of 80% and improved it considering other meteorological parameters like wind speed. We conclude that temperature difference is a signature for nocturnal cloudiness.

We investigated nocturnal cloudiness for a case from winter 2001/02 in northern Switzerland. There, an ultra-dense combination of two networks with 70 stations in total is operated, measuring air and surface temperature, wind and other parameters. With the aid of our equations, these measurements where converted into cloud maps, including also precipitation seen by radar. We identified a frontal precipitation area, postfrontal clearing, freezing, and the first clouds of a following frontal passage.

These findings will improve the observation of clouds and cloud movement as well as the prediction of road surface state and the risk of slippery conditions.

1. Introduction

Road weather forecasting is one of the key topics in today's meteorology. Worst cases in road weather are those who lead to unexpected slipperiness, caused by snowfall, rain falling on supercooled ground or freezing rain water after (postfrontal) clearing. Especially in clear nights, hoarfrost or freezing drew are other important risks. The aim of this work is to find a better way to forecast these risks, depending most of all on near-surface temperatures.

A key parameter is the cloud amount. A change from overcast to cloudy or clear sky and back – due to radiation reasons or advection – can cause big variations in surface temperature. We intend to investigate the relationship between cloud amount and near-surface temperatures, and to quantify the influence of clouds on ground measurements. Because most critical cases occur at night, and due to the cease of solar radiation as a complicating factor, we decided to concentrate on nocturnal events.

Slipperiness occurs preferably in certain meteorological circumstances. A main factor is that surface temperatures should be around freezing point. At lower temperatures, there would be no rain, and the probably falling dry snow can be handled much better. With warmer temperatures, there is no reason why surface temperature should reach the freezing point, even if there is a strong radiative cooling in clear nights. Because meteorological situations often are not changing too fast, there are just a few dangerous time periods every winter.

For the time period from November 2001 to April 2002, ice and snow detected on the roads of the canton of Lucerne in central Switzerland are shown in Fig 1. There are only three critical time periods in the whole winter, two around December 15 and 25, and another one in the second half of February. All three periods lasted for several days, and the road weather maintenance had to pay great attention. Some case studies of this winter are already published by Grimbacher and Schmid (2002).

In the rest of the winter, the risk of icing or other reasons for slipperiness is fairly small. Nevertheless temperature, cloudiness and precipitation should be regarded very well to handle even these small risks.

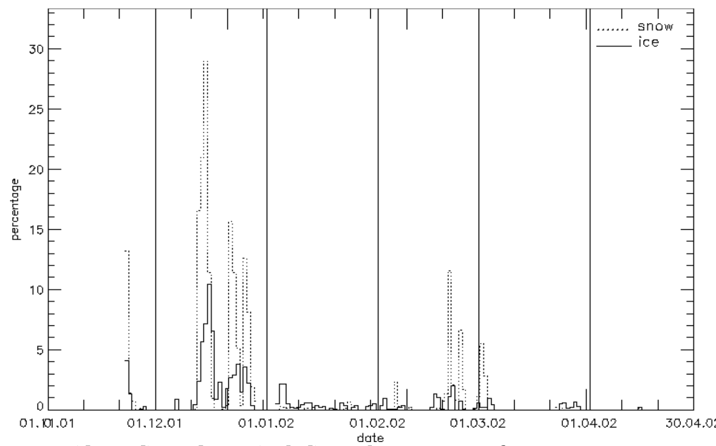

Fig 1: Occurrence of snow (dotted) and ice (solid) in the canton of Lucerne. Percentage of all measurements at 52 road weather stations in winter 2001/02.

In the next section, we will introduce the data networks included in our study. We will summarise our methods to analyse these data and show an equation for cloud amount calculations. After applying our method at single stations of different types, we will concentrate to a case in November 2001 with postfrontal clearing and slipperiness due to freezing rain water in the canton of Lucerne and the surrounding areas in northern Switzerland. Finally, we summarise the main results of the study and give an outlook on further and ongoing work.

2. Procedure

2.1 Data

2.1.1 Road weather station network in the Lucerne area

To study small-scale phenomena like clouds, one needs a measurement network as dense as possible. In central Switzerland a road weather network with 52 stations within an area of about 40×40 km^2 has been installed by the road inspection office of the canton of Lucerne. Placed on the side of cantonal routes, every station measures every quarter of an hour the most important road weather parameters like air and surface temperature (temperature in 2m above ground and in 0.05m above ground), humidity, visibility, rain rate, wind speed and direction, ground temperature (temperature in 7cm below the surface) and road surface conditions (Mathis, 2000).

2.1.2 Automatic Network (ANETZ)

Another measuring system called ANETZ is operated by MeteoSwiss. This network covers 72 meteorological stations all over Switzerland. At each station almost all parameters of interest, such as air and surface temperature, pressure, rain rate, humidity, wind direction and speed, and ground temperature are measured in a temporal resolution of 10 minutes. Additionally, every three hours six of these stations do have direct observations by eye, including the total amount, type and height of the clouds. The observers estimate cloudiness in Octa, assigning clear sky with zero Octa, overcast sky with eight Octa and fog with nine Octa of clouds (SMA, 1982).

2.1.3 Precipitation seen by radar

All over Switzerland, there are three C-band weather radars owned by MeteoSwiss. Every five minutes a full volume scan is taken, and a composite image of whole Switzerland is created. The measured values are classified in 16 levels of reflectivity, connected to 16 levels of precipitation intensity. The spatial range of this composite data set is 2×2 km^2 (Mecklenburg et al., 2000). Although there are several well-known measurement problems like clutter, attenuation or the underestimation of snow amount (Schmid and Mathis, 2004), the radar image gives a good overview on precipitation.

2.2 Methods

2.2.1 Clouds and radiation

The search for a relation between cloudiness and near-surface temperatures leads to a flashlight onto radiation equation theory. Several authors (e.g. Bogren et al., 2001 or Best, 1998) claim that the short-wave and long-wave radiation balance has the greatest influence on air and surface temperature (T_{air} and $T_{surface}$) and especially on the temperature difference

(1) $T_{diff} = T_{air} - T_{surface}$.

Since short-wave radiation is zero in nocturnal cases, radiation balance depends on long-wave radiation. At overcast conditions and with low clouds, the long-wave emission of the ground and the irradiation of clouds are of the same range. Therefore, $T_{surface}$ or T_{diff} remain relatively unaffected by radiation. The fewer clouds we observe and the higher (colder) they are, the more long-wave emission of the ground cannot be compensated by irradiation (Czeplak and Kasten, 1987). Energy is taken from ground or from the air near ground, and T_{diff} increases.

Empirically we found an equation to correct the height-dependency of the cloud influence. We define a New Cloud Parameter (Ncp) with

(2) $Ncp = \exp(-h / h_{max}) \cdot N$,

where N is the observed cloud amount, h is the mean height of the cloud base and h_{max} =10000m is the maximum cloud height near the tropopause. We want to point out, that according to equation (2) there are two reasons for a change in *Ncp*. The *Ncp* increases due to a larger amount of clouds or due to a reduction in cloud height, and vice versa.

The other parts of the energy balance, such as the turbulent fluxes of latent and sensible heat, heat of fusion and the heat flux to soil, are normally considered to be small. Especially the turbulent fluxes depend on wind speed. Heat of fusion is connected to humidity and to precipitation events. However, these contributions should be kept in mind.

2.2.2 Connection between cloud amount and temperatures

We assume that near-surface temperatures are influenced by clouds. Because we focus on critical winter road weather, we concentrate on the nights from November to April. As already mentioned, there are nocturnal observations of cloud amount and corresponding measurements of temperatures at six ANETZ stations and for several winters. One of these stations is located in Payerne. There, we tested the relationship between cloud amount *Ncp* and temperature difference T_{diff} for well defined conditions: wind speed between 0 and 2m/s, air temperature between -5°C and +5°C. Out of several function types, the exponential function type

(3) $Ncp = c + \exp(b \cdot T_{diff} + a)$

leads to the highest correlation coefficient of 0.90 (Grimbacher and Schmid, 2003).

There are several other measurements related to cloudiness. E.g., the difference between surface and ground temperature is connected to *Ncp* in an exponential equation with a correlation coefficient of 0.79, or the difference between the mean air temperature of the last hour and the mean air temperature of the hour before is coupled to *Ncp* through a third order polynomial with a correlation coefficient of 0.63. Further we will concentrate on the exponential relation between *Ncp* and T_{diff}.

2.2.3 Equation parameters under certain circumstances (wind, temperature ranges)

With increasing wind speed the influence of turbulence increases. Best (1998) suggested a wind speed up to 3m/s not to influence radiative cooling too much. For the measurements in Payerne, we found this value quite realistic. There, for wind speeds between 0m/s and 1m/s the correlation coefficient is 0.9, for wind speeds from 3m/s to 4m/s it's 0.82 and for stronger winds it's getting insignificant very soon (Grimbacher and Schmid, 2003).

Concerning the temperature range, we found a similar tendency. The warmer it is, the lower the correlation coefficients are. With air temperatures below freezing point we gained a correlation coefficient of 0.9, for the temperatures above 10°C it's only 0.83.

We decided to use a specific equation parameter set for five wind speed and four temperature classes.

Ncp / Octa	0 to 5	5 to 6	6 to 7	7 to 8	fog	Total
wind speed up to 2m/s	0	0	14	58	20	92
wind speed over 2m/s	0	3	38	83	1	125
Total	0	3	52	141	21	217
Percentage	0	1.4	24.0	65.0	9.7	

Table 1: Precipitation measurements and cloud observations in Payerne.

2.2.4 Cloudiness and precipitation

The intensity of precipitation is measured at all ANETZ and road weather stations used in this study. We want to consider it as an additional indicator of cloudiness. Another source of precipitation information is weather radar, detecting precipitation not only at a single point but over a spatial area.

Precipitation mostly indicates overcast conditions. A few weather situations are imaginable, where convective precipitation comes along with less then eight Octa up to nearly clear sky. For Payerne, the statistic is shown in Table 1. In 75% of all precipitating cases the *Ncp* is larger then seven Octa, and in only 1.4% it is lower than six Octa. While considering wind speeds lower than 2m/s the connection is very good. With stronger winds it's still acceptable. Note, that only 5.9% of all measured data sets are connected with precipitation.

According to these results we define the *Ncp* to be 7.5 Octa for all times with precipitation observation.

2.2.5 Sources of error

There are several sources of error related to our calculations and their verifications. The two most important ones should be mentioned here:

Cloud observation by eye isn't easy. Especially in dark nights without moonlight it is often difficult to decide whether there are clouds or there are none, and in which height the clouds occur (Feijt and de Valk, 2001). These uncertainties in both, height and amount of clouds, have effects on the calculation of the observed *Ncp* with equation (2) and to the quality of the following comparisons.

Road weather stations are located on roads normally consisting of black tarmac. Especially on sunny days in spring or late in winter the tarmac heats up and therefore surface temperature rises. After twilight the energy has to be emitted through radiation or through turbulence (Bogren et al., 2001). Ground and surface temperatures, starting at a high level, are dying out in the first part of the night. Because the air temperature is not affected and normally smaller than the surface temperature, our method calculates eight Octa for these periods. So, we decided not to calculate an *Ncp* at the beginning of the night as long as the surface temperature is monotonically decreasing. About 15% of all data from road weather stations are affected by this problem. Because the ANETZ stations are normally situated on grassland where the heating effect is small, they are not affected.

3. Results

3.1 Comparison of observed and calculated cloud amount at one station

3.1.1 Result in Payerne

We investigated our method with the measurements in Payerne in winters 1996 to 2002. All temperature ranges and all wind speeds are taken, and the Ncp is calculated with the particular relation parameters. 80% of the nights are used to retrieve the relation parameters, the other independent 20% are used to check the quality.

As a result the comparison between calculated and observed Ncp is shown in Fig 2. Most points are concentrated near the diagonal. The correlation coefficient is 0.91, and the root mean square error (RMS) is 1.34 Octa.

3.1.2 Results at other ANETZ-Stations

We implemented the equations retrieved in Payerne at three other ANETZ stations with cloud observations, located in Wynau, Vaduz and Kloten. The results are listed in Table 2. For Wynau and Kloten, they are nearly as good as for Payerne. The results for Vaduz are bit worse. Vaduz is located in the Rhine valley and the surrounding mountains may influence the radiation balance and the near-surface temperatures.

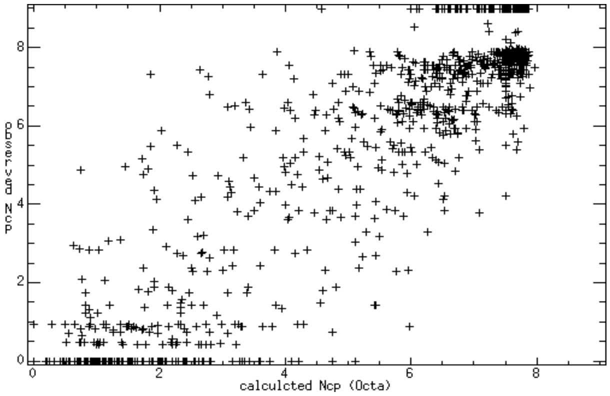

Fig 2: Observed and calculated New Cloud Parameter (Ncp) in Payerne. 1152 points of independent data are used.

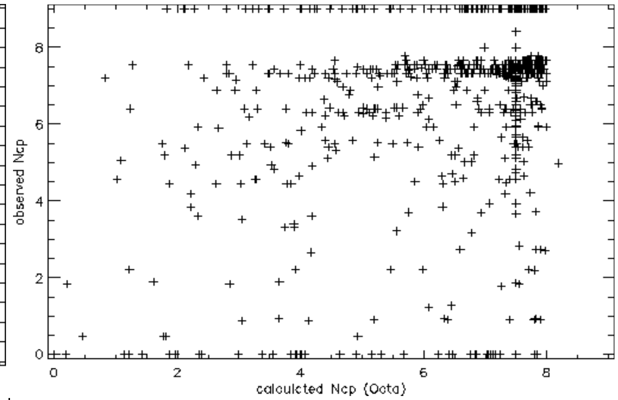

Fig 3: Comparison of cloud observations in Wynau (ANETZ) and calculated Ncp in Roggliswil (road weather station), 8 km away.

Station	Number of measurements [#]	RMS [Octa]	Correlation coefficient [1]
Payerne	1152	1.34	0.91
Wynau	1154	1.56	0.84
Vaduz	1087	2.36	0.71
Kloten	1155	1.33	0.88

Table 2: Proofing our method at several ANETZ stations by calculating an Ncp with the relation parameters of Payerne and comparing the results to the observed cloudiness. Results for independent data.

Wind speed	Number of measurements [#]	RMS [Octa]
All	995	2.00
> 1 m/s	589	1.68
> 4 m/s	130	1.53

Table 3: Proofing our method at the road weather station in Roggliswil by calculating an Ncp out of their data with the relation parameters of Payerne and comparing the results to the observations of Wynau.

3.1.3 Comparing ANETZ-Station Wynau with road weather station Roggliswil

Located in the canton of Berne, Wynau is the ANETZ station next to the road weather network in the canton of Lucerne. The nearest station to Wynau is Roggliswil in a distance of 7.98km. This is not too far away to make a comparison impossible, but it's not close enough to compare without any problems. The cloudiness observed in winters 2000 to 2002 in Wynau and the related calculations for Roggliswil are shown in Fig 3. As in Payerne, most points are concentrated near the diagonal, but some errors are visible especially with clear sky observation and overcast calculation or with overcast conditions at one station and broken sky at the other. In both cases fog and high fog at only one of the stations may influence the observed scatter in Fig 3.

Table 3 shows the RMS of a comparison between Wynau and Roggliswil. It is of the same order as at a single ANETZ station (Table 2). In disadvantage to our results in Payerne, the RMS of this comparison decreases with increasing wind speed. Without wind, the two stations can behave decoupled and due to their own environment. This is especially true for the foundation of fog. The stronger the wind blows the more homogenously clouds are distributed over a wider area. Now, the measurements in Wynau and Roggliswil are influenced by almost the same type and amount of clouds.

Considering the spatial differences we conclude that our method works very well, even at stations of other type.

3.2 Case study: November 27 to 28, 2001

3.2.1 Synoptic situation

On November 27, the synoptic situation of Europe is dominated by two lows near Iceland and a high slide east of the Azores. Several fronts pass through central Europe driven by the west wind regime. In the afternoon a cold front streaks Switzerland from north-west. In Lucerne precipitation starts at 14UTC, and it is raining all the afternoon. The precipitation area crosses through northern Switzerland until the early evening. The frontal passage is followed by a short period of high pressure influence, but an occlusion reaches Switzerland in the course of November 28.

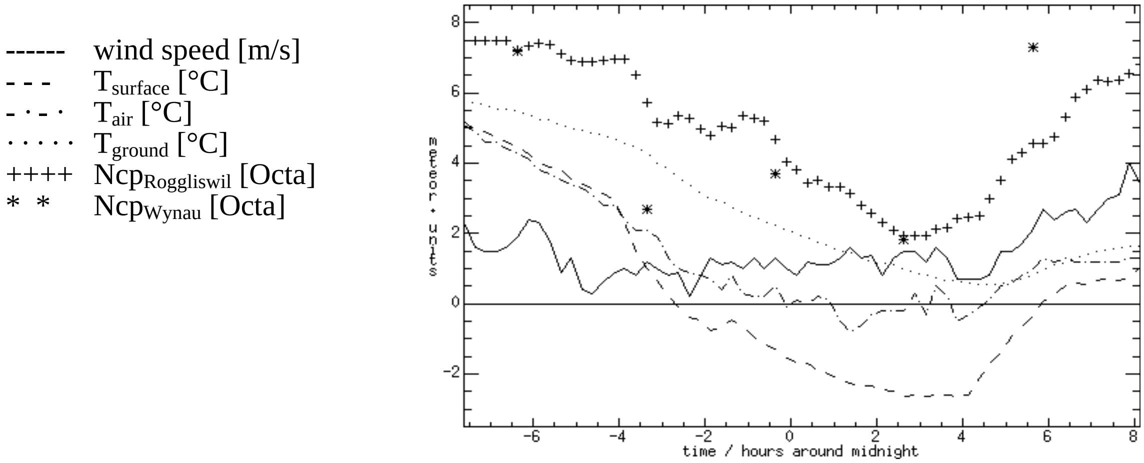

Fig 4: Some meteorological parameters in the night from November 27 to 28, 2001 in Roggliswil. Solid: wind speed, dashed: surface temperature, dash-dotted: air temperature, dotted: ground temperature, crosses: calculated Ncp, asterisks: observed Ncp (Wynau).

3.2.2 Meteorological parameters

Fig 4 shows the most important meteorological parameters, measured at the road weather station of Roggliswil. Additionally, the observed cloud amount of Wynau is marked.

All temperatures are falling, starting at about 5°C. The near-surface air cools down the fastest and drops below freezing level 2½ hours before midnight. Air temperature reaches the 0°-level after midnight but remains warmer than surface temperature all through the night. Some of the changes in air temperature are clearly related to increases and decreases in wind speed. The ground temperature reacts more slowly but also significantly.

Both the cloud amount calculated out of these data and the observed Ncp in Wynau, 8km away from the calculation, show a related behaviour. Starting with overcast conditions (and a few rain measurements) there's a rapid postfrontal clearing leading to the lowered surface temperature. The cloud conditions change between broken and nearly clear throughout the night, and in the early morning just before sunrise cloud amount increases back to six to eight Octa as a first sign of the approaching occlusion.

3.2.3 Cloud and precipitation map

For the night from November 27 to 28, 2001, all data of both networks are calculated every 15 minutes. The resulting Ncp at approximately 70 stations are interpolated, and precipitation seen by radar is overlaid. In Fig 5 some cloud and precipitation maps of our study area in northern Switzerland are displayed. Each station and its calculated cloud value is marked with a circle. By considering the cloud conditions at consecutive time steps one can clearly identify the movement of precipitation, clouds and clearing tendency.

The first half of the night is dominated by the cold front already mentioned. At 18UTC it is still raining or snowing in large parts of the study area. Other parts are overcast, and only in the very north-western regions of Switzerland clouds are broken. Later on, cloudiness decreases in the northern part of the map, but in the south-easterly part it's still overcast or precipitating.

In the second half of the night it gets clear almost everywhere. At 02UTC, most of the stations of both networks detect no or only few clouds. Exceptions are some stations at the lake of Lucerne and in the very south-east. Two hours later, it is clear there, too. But in the north-westerly part there are new clouds and some precipitation is visible. This is the first sign of an occlusion, reaching and crossing Switzerland in the following hours.

There's a radar echo marked as precipitation in all four maps at about Swiss coordinates 610 / 230. This is clearly due to clutter effects of the Jura. Other clutter echoes of the alpine mountains can be identified in addition.

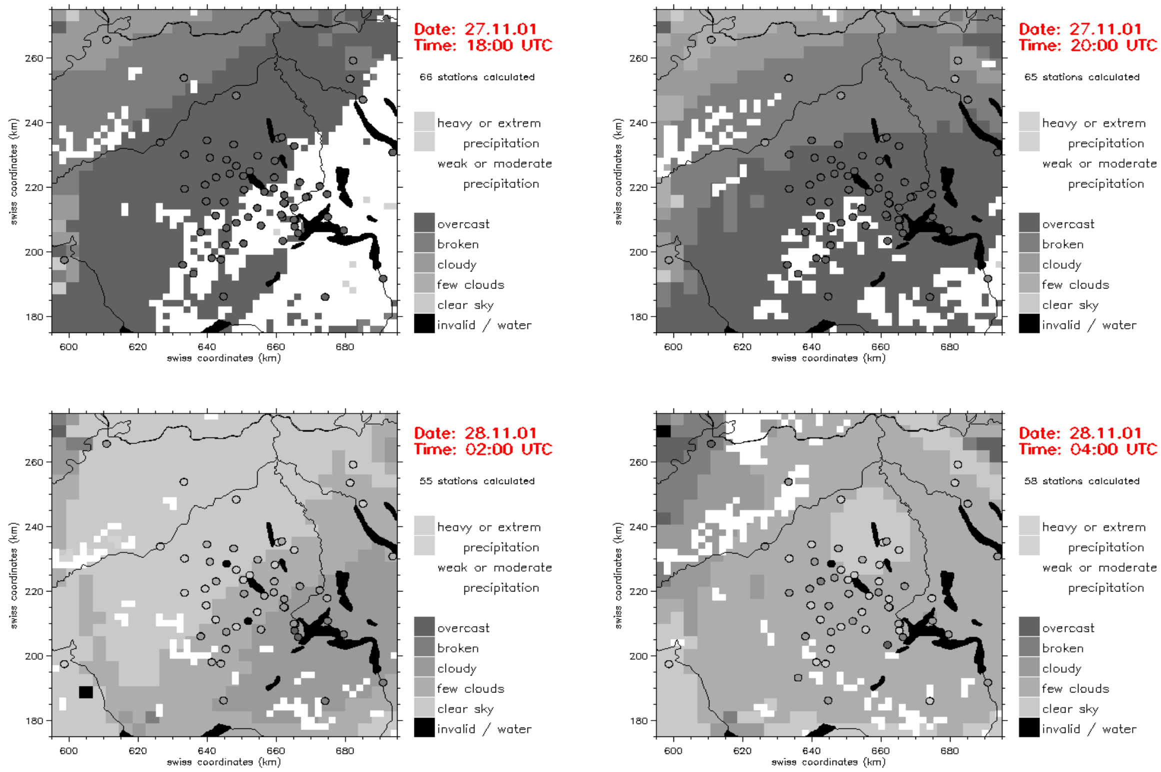

Fig 5: Interpolated cloudiness and radar precipitation in parts of northern Switzerland. The calculated cloud amount at each station is given, too.

The 52 stations of the road weather measurement network are located in the centre of the maps. Even in this dense network, neighboured stations often show a different calculated cloud amount. E.g. at 2UTC, most of the stations identify clear sky, but also few and more clouds are detected. Clouds can be small scale phenomena, but at the same time calculations can fail or stations can react differently to our method, because they are influenced from different surroundings. Another possibility for a small temperature difference may be an evaporative effect after rain or snow. On the other hand it is still possible that there is a local variation in cloudiness, or locally limited fog or high fog. This shows to us the uncertainty in single point measurements and therefore the importance of having a network as dense as possible.

3.2.4 Influences on surface state

The area of postfrontal clearing reaches the road weather measurement network in the canton of Lucerne around and after midnight. In consequence, surface temperature decreased and reached the freezing level at nearly all stations. Surface states changed from wet to frozen or iced. Freezing rain water was detected at several stations in the canton of Lucerne, and road maintenance had to use de-icing chemicals. In Fig 1, this event is connected to a clear peak in the second half of November, indicating ice or snow in up to 15% of all surface state measurements. Some more information of this event, including maps of surface state, are already published by Grimbacher and Schmid (2003). In the early morning new clouds were advected and another precipitation area arrives.

4. Conclusions

The way to describe the radiative and advective interaction between cloudiness and near-surface temperatures seems to be a good direction to learn more about the predictability of surface state. On the other hand, cloudiness and surface state are highly critical parameters in the domains of road weather, and their forecast is not easy. Surface state is closely linked to precipitation, remaining rainwater and the near-surface temperatures, and its change often is related to advection. Either cold air is advected, or the postfrontal clearing, caused by advective motion of possibly precipitating clouds, leads to radiative cooling.

We found that there are general connections between cloudiness, temperature difference and precipitation. First of all we developed an equation to correct the height dependency of observed cloud amounts. The resulting cloudiness is named Ncp. With precipitation, the sky is almost always overcast, otherwise the relation between Ncp and temperature difference is of exponential type and has to be adapted to different conditions of wind speed and temperature. Once we got the parameters of the relationship in Payerne, we could use them at all other stations. We achieved RMS between 1.3 and 2.4 Octa, depending on the particular location of the stations.

In a case study, we showed the cloud conditions in northern Switzerland during a critical winter night. We detected the advective motion of a nearly cloud free area after a cold frontal passage and the arrival of a following occlusion. The clearing was coupled with radiative cooling and followed by a decrease in surface temperature and a change in surface state from wet to frozen. Some stations of the ultra-dense network in the canton of Lucerne rested at a rather higher value of calculated cloud amount, probably due to their special surrounding, to evaporation effects or fog. We conclude that one should use a measurement network as dense as possible to calculate two-dimensional cloud maps, because only several neighboured stations give a good impression of the real cloud situation of a region.

In the created maps we can identify both the motion of precipitating areas and the advection, foundation and dissipation of cloud fields. We calculated spatial cloudiness with a time resolution of 15 minutes. Precipitation measured by radar already can be nowcasted with tracking algorithms like COTREC (Mecklenburg et al., 2000). As ongoing work, we will try to track radar precipitation together with cloud information gathered in this study. Using this information, we intend to create high resolution forecasts of near-surface temperature and road surface state.

Acknowledgments

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