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Swiss Model Simulations for Extreme Rainfall Events on the South Side of the Alps

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Executive Summary

The project RAPHAEL successfully demonstrated the potential of a coupled system of meteorological and hydrological models for flood forecasting. The use of direct model output from a meteorological model enables a hydrological model to predict the runoff of a watershed. A potential use of such a system would be an automated flood warning system.

The Institute for Atmospheric and Climate Science of the ETH Zürich (formerly Institute for Climate Science) showed that, based on direct model output of the Swiss Model of MeteoSwiss, its hydrological model WaSiM-ETH was able to forecast the runoff of the Ticino river into the Lago Maggiore with reasonable accuracy during the years 1996 to 1999. The flood events were well captured by this combined system.

Thanks to project RAPHAEL, MeteoSwiss was able to run a series of sensitivity experiments with the Swiss Model that gave valuable insights into the effects of different precipitation and surface parameterizations, advection schemes, and increased vertical resolution. In addition, the Swiss Model was used to provide a high resolution analysis data of the precipitation events. The results obtained with the Swiss Model are still partially valid with the new Local Model and at least provide hints of the sensitivity that could be expected from the Local Model.

A unique data set containing meteorological observations and particularly rainfall amounts with hourly resolution of several institutions in Germany, Italy, and Switzerland has become available through RAPHAEL and is a valuable basis for the verification of heavy precipitation events on the south slope of the Alps.

The results of the RAPHAEL project are available on CD-ROM. The deliverables of the project to the EU are public and include German, Italian, and Swiss meteorological observations and model simulation results in the form of charts and ASCII data files (RAPHAEL format, see Appendix) for further use.

Abstract

MeteoSwiss participated in the project RAPHAEL by providing simulations of its limited-area numerical weather-prediction model, the Swiss Model. The Swiss Model data was used as input by hydrological models to simulate the runoff from a mountainous watershed. Two target watersheds were defined, one on each side of the alpine ridge: The Ticino watershed south of the Alps, and the Ammer watershed north of the Alps. Four events with heavy precipitation were defined for each of the two watersheds. Each event consisted of a few days with heavy precipitation and following high water levels in the target area.

The results of the various Swiss Model simulations for the Ticino watershed were compared to hourly rainfall data available for the events. The observations were collected for the RAPHAEL project from several institutions in Germany, Italy, and Switzerland. The task of collecting the observational data and bringing it into a standardized format required a substantial amount of the project resources.

The Swiss Model was run in the operational configuration and, for the purpose of a sensitivity analysis, in a series of special configurations to study the effects of the following changes: Analyses as driving lateral boundary conditions from the governing model instead of forecasts, enhanced precipitation scheme, increased vertical resolution, feedback of the evapotranspiration from a hydrological model. Some changes were first applied in conjunction because of existing model configurations, but it soon became clear that they had to be applied in turn, so that the effect could be studied for each change separately, independent of the other changes. The simulated precipitation was verified graphically against the observations.

The operational SM configuration proved to be well tuned and less prone to overestimate heavy precipitation than those SM configurations with higher vertical resolution. In contrast to the expectation, the use of analysis boundary fields instead of forecast fields did not always improve the quality of the rain fields. The forecast boundary fields were available hourly, whereas the analyses of the driving model were only available at 6-hour intervals. The advantage of hourly updates of the boundary fields proved at least in some cases to yield better simulations than the analysis fields despite the better accuracy of the latter. The changes resulting from modifying the advection scheme, the precipitation scheme and the surface parameterization were more difficult to assess due to the large variability in the model results.

These sensitivity results were based on the now phased-out SM. However, the new non-hydrostatic Local Model (LM) shares some features such as the physical parameterizations with the SM. Many of the findings are probably to a high degree still valid for the LM.

In addition to these model specific results of the sensitivity study, there are other achievements of the RAPHAEL project which are valuable for future use. The strategy for coupled simulations of episodes can be applied in similar projects. Not only the accumulated data themselves but also the definition of a standard format for observations and model output (RAPHAEL format, see Appendix) proved very useful and will be used in future studies.

The results of the run-off simulations by the Institute for Atmospheric and Climate Science ETH (IACETH) or other RAPHAEL participants are not presented in this report. Only one particularly interesting application of the IACETH is mentioned here: They used a 3.5-year continuous dataset gained from concatenating SM forecast of the years 1996 – 1999 for hydrological modeling. It shows that an operational flood forecasting based on direct Swiss Model output is feasible and could be a helpful tool for flood management.

1 Introduction

Severe flooding is a high risk in the Alps and often leads to great property damage and sometimes to the death of people. A flood forecasting system could provide warning ahead of time and allow for timely precautions. To tackle the problem of flood forecasting in the mountains, a group of eleven institutes from Europe and Canada started the project RAPHAEL. The EU-funded project RAPHAEL (Runoff and Atmospheric Processes For Flood Hazard Forecasting And Control) was planned in the framework of the Mesoscale Alpine Programme (MAP), a multi-year, international initiative to advance the knowledge in mountain meteorology. This report summarizes the contribution of MeteoSwiss (participating under it's former name Swiss Meteorological Institute) to the project RAPHAEL.

The basic objective of the RAPHAEL project according to the RAPHAEL Final Report (Bacchi and Ranzi 2000) was:

1) "to develop, implement and demonstrate the use of coupled meteorological and hydrological models at the regional scale in order to improve flood forecasting and management in complex mountain watersheds."

With this guideline, further specific objectives were (Bacchi and Ranzi 2000):

2) "to apply coupled atmospheric-hydrological models and carry out a multi-scenario modeling experiment to show the potential use of advanced flood forecasts in view of the control of hazardous flood events;
3) to investigate the benefits achievable in atmospheric models by introducing hydrological feedback with detailed land-surface schemes, including snow and ice dynamics;
4) to validate meteorological data generated by numerical weather prediction models and meteorological observations by means of runoff measurements and distributed hydrologic water balance calculations;
5) to investigate the benefits of remotely-sensed land surface parameters, state variables and fluxes (e.g., land cover, soil moisture, snow cover, evapotranspiration) as related to sub-grid parameterization of both meteorological and hydrological models;

6) to improve techniques and tools for scale-adaptation of observed and simulated variables, with particular reference to the areal distribution of rainfall, snow cover, and land-surface-atmosphere fluxes."

Comparing simulated and observed discharge from a watershed, the coupled system offered a new approach to validate the precipitation predicted by the numerical weather prediction model. Figure 1 shows an example of such a comparison for an episode of heavy precipitation in fall 1993. The three bar charts at the top represent three different precipitation data sources for the hydrological model, in blue the observed precipitation, in red the precipitation as simulated by the MC2 meteorological model, and in yellow the precipitation from the Swiss Model (SM). With each one of these data sets, the Institute for Atmospheric and Climate Science of the ETH (IACETH) simulated with it's hydrological model the runoff from the combined upper Ticino, Verzasca and Maggia watersheds into Lake Maggiore (Jasper et al. 1999). The line chart in the bottom half shows this simulated runoff in the respective colors plus the observed runoff in black. This type of figure provides information about the accuracy of a coupled system for flood forecasting. In addition, the different meteorological models can be verified in an integrative way not only against the measured rainfall but also against the independent runoff observation. This validation is described in the paper of Jasper and Kaufmann, 2002.

The results of these validations and the hydrological modeling are not part of this report. Only the work done at MeteoSwiss within the framework of the RAPAHEL project is documented here. More information about other meteorological models and the hydrological modeling can be found in the final Report of the RAPAHEL project (Bacchi and Ranzi, 2000).

Because of the focus of the RAPHAEL project on flood forecasting, eight episodes of heavy precipitation between 1993 and 1999 have been chosen. The events and the simulation strategy for each event are defined in Section 2. MeteoSwiss contributed to RAPHAEL by providing simulations of the Swiss Model (SM), which was the operational NWP model at the time of the project. The hydrological models were run for two target areas. The target areas and the SM standard mode simulations are described in Section 3. Several different experimental modes of the SM have also been tested and evaluated in RAPHAEL. The results of these sensitivity experiments are found in Section 4.

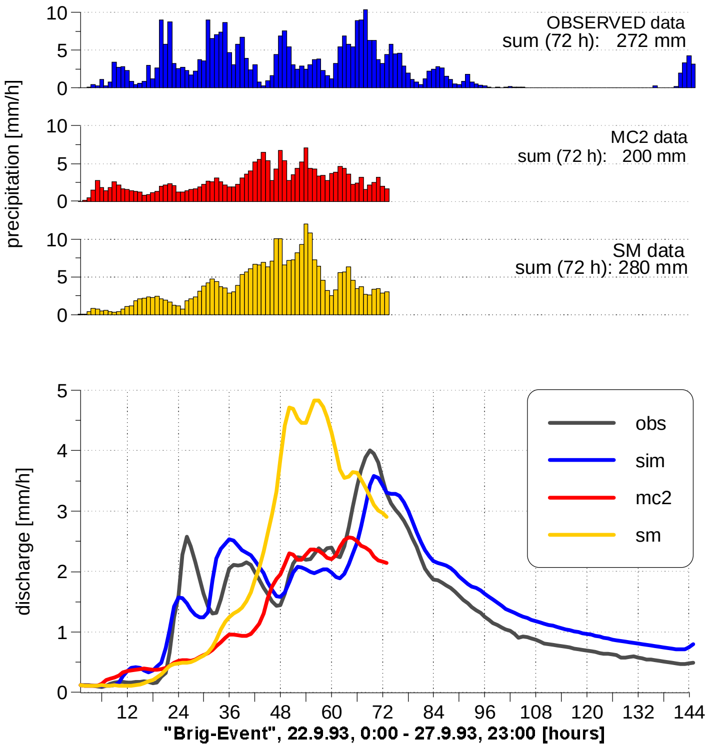


Figure 1 Precipitation as observed (blue bar chart) and simulated by the two meteorological models MC2 (red) and SM (yellow). The line chart shows the observed runoff (black) and the runoff simulated the by the hydrological model in the colors respective to the used input data: Observed rainfall (blue), MC2 model output (red), and SM model output (yellow). (Figure by K. Jasper, IACETH).

2 Simulation strategy for the RAPHAEL events

Seven events of heavy precipitation were chosen to be the test cases for RAPHAEL. Table 1 summarizes the simulations for the RAPHAEL Task 2.2 (standard mode simulations) with the initial times of the individual meteorological model runs from which the data for the hydrological models were generated. Four events were chosen for the target area south of the Alps (the Ticino-Toce area, see large black box in Figure 4), three events for the target area north of the alps (the Ammer area, see small box in Figure 4). One more event for the Ammer area was added as optional during the project (see Table 4).

Table 1 List of all events required for RAPHAEL Task 2.2

Event (event names are Underlined)	**Initial times**	**Simulation range**
Ticino-Toce 1: TT1 September 1993, "Brig" case	1993-09-21 12:00z 1993-09-22 12:00z 1993-09-23 12:00z	36 h 36 h 36 h
Ticino-Toce 2: TT2 October 1993, "Locarno" case	1993-10-11 12:00z 1993-10-13 00:00z	48 h 48 h
Ticino-Toce 3: TT3 November 1994, "Piemonte" case	1994-11-03 00:00z 1994-11-04 00:00z 1994-11-05 00:00z	36 h 36 h 36 h
Ticino-Toce 4: TT4 June 1997, "Snowmelt" case	1997-06-26 12:00z 1997-06-28 00:00z	48 h 48 h
Ammer 1: AM1 July 1993	1993-07-16 12:00z 1993-07-17 12:00z 1993-07-18 12:00z	36 h 36 h 48 h
Ammer 2: AM2 August 1995	1995-08-27 12:00z 1995-08-28 12:00z 1995-08-29 12:00z 1995-08-30 12:00z	36 h 36 h 36 h 36 h
Ammer 3: AM3 July 1997	1997-07-17 00:00z 1997-07-18 12:00z	48 h 48 h

The simulation strategy outlined in Table 1 was adopted by trying to satisfy at best the following guidelines:

(1) Overlap of model runs is 12 hours. The precipitation of the first 12 hours is ignored because of spin-up effects in the meteorological models.
(2) SM runs initialized at 00:00 UTC are better for afternoon convection. Thus runs starting at 00:00 UTC would be preferable in general.
(3) For events before 25 September 1995 12:00 UTC, the SM can only be run out to 36 hours in the forecast mode.

Figure 2 and Figure 3 provide detailed graphs of hourly average rainfall for all the events over the Ticino-Toce and the Ammer watersheds. The time strategy for simulating the entire events is indicated by the bold horizontal segments on the two Figures.

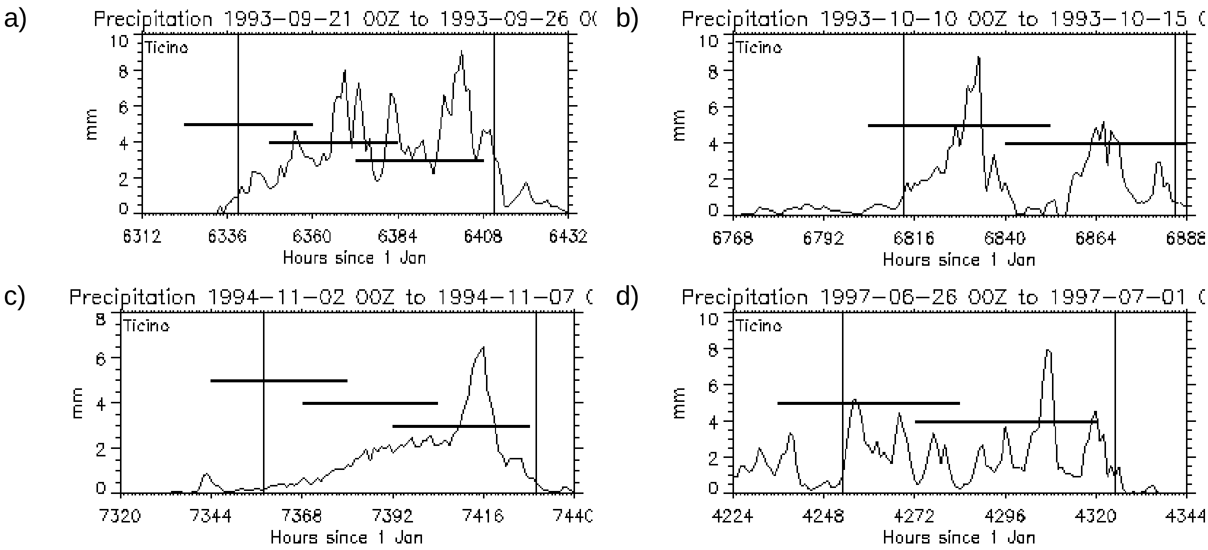


Figure 2 Area-average precipitation (derived from 51 stations) and periods for the meteorological simulations (bold lines) for Ticino-Toce events a) TT1 to d) TT4. Numbered major tick marks on x-axis indicate 00:00 UTC, each minor tick mark is one hour. The vertical lines mark the beginning and end of the events. (Precipitation data prepared by IACETH).

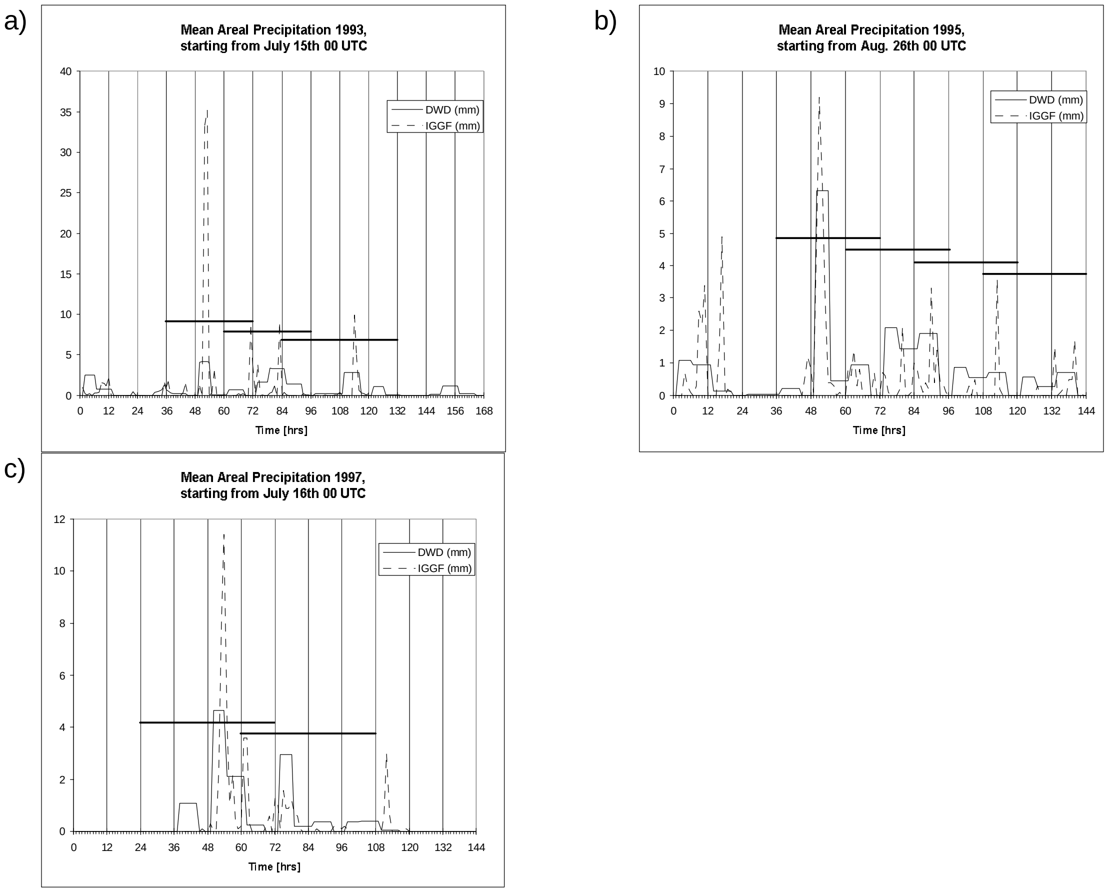


Figure 3 Area-averaged precipitation and meteorological simulations (bold lines) for Ammer episodes a) AM1 , b) AM2, and c) AM3. Numbered major tick marks on x-axis mark 00:00z and 12:00z, each minor tick is one hour. (Precipitation data source: IGGF).

3 Swiss Model standard mode simulations

The Swiss Model (SM) was the operational model from 1994 until 2001 for short range weather prediction at MeteoSwiss. Forecasts up to 48 hours were calculated twice a day, starting at 00:00 UTC and at 12:00 UTC. The SM was a hydrostatic limited-area model with 145 x 145 grid points horizontally and 20 vertical layers. It used a rotated longitude/latitude grid with a resolution of 0.125 degrees (ca. 14 km). The 20 vertical layers were in hybrid coordinates (pressure levels – terrain following). The full domain of the Swiss Model is shown in Figure 4.

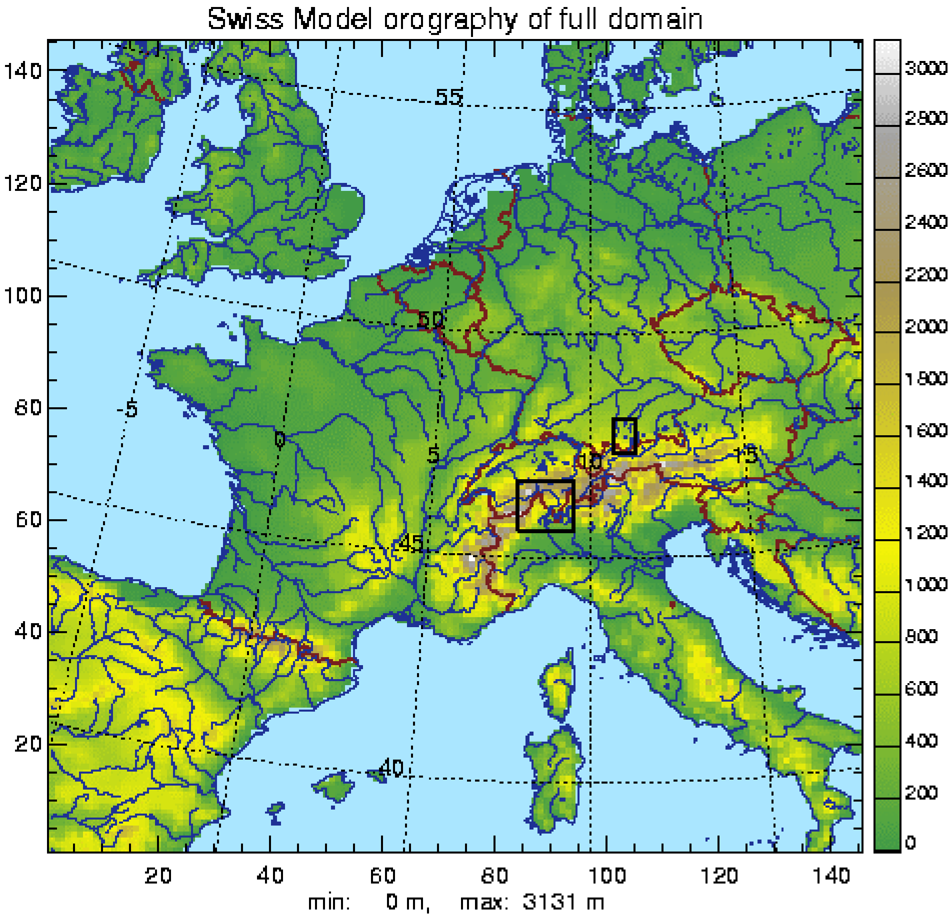


Figure 4 Swiss Model topography with Ticino-Toce area (black rectangle in the center) and Ammer area (smaller rectangle to the upper left side).

The source code of the SM was the same as the code of the Europa-Modell (EM) and the Deutschland-Modell (DM) of the German Weather Service (DWD) (Majewski 1991). The EM and DM were phased out by 15 December 1999. Before that, the EM provided the initial conditions and boundary values for the Swiss Model. For some surface fields (most importantly snow cover), the DM analysis was used for a more detailed definition of the initial conditions.

The SM had five prognostic variables. With these five variables, a forecast was calculated from prognostic equations. All other output values were derived diagnostically from these variables at specified intervals. The five prognostic variables were:

- Surface pressure
- Total heat
- Total water content
- 2 components of horizontal wind

For the RAPHAEL project, two sub-domains within the SM grid were defined (black boxes in Figure 4). The SM output within these two areas was provided to the hydrological models. The rectangular box of the Ticino-Toce area contained 11 x 10 grid cells. The total area was 150 km x 140 km = 21000 km^2. The coordinates of the four corner grid cells are shown in Table 2.

Table 2 Coordinates of the Ticino-Toce area: Center coordinates of the four SM grid cells at the upper left, upper right, lower left, lower right corner of the Ticino-Toce subdomain.

SM grid	84 / 67		SM grid	94 / 67
GG	7.671 E / 46.72 N	. . .	GG	9.462 E / 46.75 N
UTM	398425 m / 5175245 m (Zone 32)		UTM	535315 m / 5177422 m (Zone 32)
	. . .			. . .
SM grid	84 / 58		SM grid	94 / 58
GG	7.727 E / 45.60 N	. . .	GG	9.475 E / 45.62 N
UTM	400710 m / 5050246 m (Zone 32)		UTM	537053 m / 5052428 m (Zone 32)

Table 3 Coordinates of the Ammer area: Center coordinates of the four SM grid cells at the upper left, upper right, lower left, lower right corner of the Ammer subdomain.

SM grid	101 / 78		SM grid	105 / 78
GG	10.74 E / 48.12 N	. . .	GG	11.48 E / 48.11 N
UTM	629421 m / 5331458 m (Zone 32)		UTM	684433 m / 5332058 m (Zone 32)
	. . .			. . .
SM grid	101 / 72		SM grid	105 / 72
GG	7.727 E / 45.60 N	. . .	GG	11.45 E / 47.36 N
UTM	630372 m / 5248087 m (Zone 32)		UTM	685259 m / 5248670 m (Zone 32)

The SM output domain for the Ammer area contained 5 x 7 grid points and covered 69 km x 97 km = 6693 km^2. The coordinates of the four corner grid cells are shown in Table 3.

All Ticino-Toce and Ammer events of the RAPHAEL project were simulated with the SM. The standard simulations were made in two modes, the forecast and the analysis mode. The sensitivity mode simulations of the SM are described later in Section 4.

The analysis and forecast mode differ in the driving lateral boundary values, which are provided by the EM. In the forecast mode (Figure 5 a), which is the operational mode of the SM, the boundary conditions are provided hourly by the operational EM forecast. MeteoSwiss has an archive of EM boundary conditions and can reproduce forecasts after 1992. Forecasts until 25 September 1995 00:00 UTC can only be run up to a forecast range of 36 hours due to the lack of EM fields after hour 36.

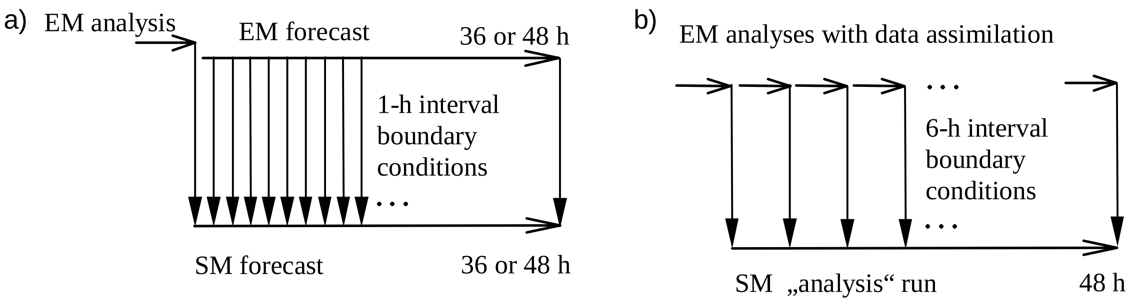


Figure 5 SM forecast driven by a) hourly EM forecast b) six-hourly EM analyses.

In the so-called analysis mode of the SM (Figure 5 b), the boundary conditions for the simulation are all provided in six-hourly intervals by the EM analysis cycle. The SM itself does not assimilate any observations. MeteoSwiss only archives the 00:00 UTC and 12:00 UTC analyses. The additional data for the analysis runs were kindly provided by the DWD.

Table 4 lists all standard mode Swiss Model simulations for RAPHAEL Task 2.2, showing the initial times of the individual METEO simulations for which model output was provided to the HYDRO models. MeteoSwiss provided a total of 59 simulations, 21 more than to the 38 required by the simulation strategy. These additional runs are printed in green in Table 4.

Due to the unavailability of the EM boundary conditions, the SM forecasts prior to 25 September 1995 where limited to a forecast range of 36 hours. In three cases, the 36 hours were less than what was asked for by the simulation strategy. These cases are printed in red in Table 4.

Table 4 List of Swiss Model standard simulations for Task 2.2. **Green**: *Additional forecast runs not required by the simulation strategy.* Red: *Reduced forecast range of 36 h instead of the 48 h required by the simulation strategy.*

Event (names underlined)	**Initial times**	**Forecast mode Simulation range**	**Analysis mode Simulation range**
Ticino-Toce 1: TT1 September 1993, “Brig”	***1993-09-20 12:00z***	***36 h***	
	1993-09-21 12:00z	36 h	48 h
	1993-09-22 12:00z	36 h	48 h
	1993-09-23 12:00z	36 h	48 h
	1993-09-24 12:00z	***36 h***	
Ticino-Toce 2: TT2 October 1993, “Locarno”	***1993-10-10 00:00z***	***36 h***	
	1993-10-11 00:00z	***36 h***	
	1993-10-11 12:00z	*36 h*	48 h
	1993-10-13 00:00z	*36 h*	48 h
	1993-10-14 00:00z	***36 h***	
Ticino-Toce 3: TT3 November 1994, “Piemonte”	***1994-11-02 00:00z***	***36 h***	
	1994-11-03 00:00z	36 h	48 h
	1994-11-04 00:00z	36 h	48 h
	1994-11-05 00:00z	36 h	48 h
	1994-11-06 00:00z	***36 h***	
Ticino-Toce 4: TT4 June 1997, “Snowmelt”	***1997-06-25 00:00z***	***48 h***	
	1997-06-26 00:00z	***48 h***	
	1997-06-26 12:00z	48 h	48 h
	1997-06-27 00:00z	***48 h***	
	1997-06-28 00:00z	48 h	48 h
	1997-06-29 00:00z	***48 h***	

Event (names underlined)	Initial times	Forecast mode Simulation range	Analysis mode Simulation range
Ammer 1: AM1	***1993-07-14 12:00z***	***36 h***	
July 1993	***1993-07-15 12:00z***	***36 h***	
	1993-07-16 12:00z	36 h	48 h
	1993-07-17 12:00z	36 h	48 h
	1993-07-18 12:00z	*36 h*	48 h
	1993-07-19 12:00z	***36 h***	
Ammer 2: AM2	***1995-08-25 12:00z***	***36 h***	
August 1995	***1995-08-26 12:00z***	***36 h***	
	1995-08-27 12:00z	36 h	48 h
	1995-08-28 12:00z	36 h	48 h
	1995-08-29 12:00z	36 h	48 h
	1995-08-30 12:00z	36 h	48 h
Ammer 3: AM3	1997-07-17 00:00z	48 h	48 h
July 1997	1997-07-18 12:00z	48 h	48 h
	1997-07-20 00:00z	***48 h***	
Ammer 4: AM4	***1999-05-19 00:00z***	***48 h***	
May 1999	***1999-05-20 00:00z***	***48 h***	
	1999-05-21 00:00z	***48 h***	
	1999-05-22 00:00z	***48 h***	

The RAPHAEL model output format (see Appendix) contained a field named “Experiment” in the header. For SM, this was a three letter symbol. The labels for the standard simulations are listed in Table 5. A complete list including the labels for the sensitivity studies follows later in Table 7.

Table 5 Experiment labels of the SM standard simulations. The “Levels” column shows the number of vertical levels, the column “Advection Scheme” the name of the numerical advection scheme used, and “Code Version” is the Swiss Model version.

Exp.	Description	Levels	Advection Scheme	Code Version
K2p	Operational forecast configuration 1998, SM forecast	20	Semi-Lagrange	2.25
B2s	Operational forecast May 1999 (AM4), SM forecast	20	Semi-Lagrange	2.25
ana	Simulation driven by EM analyses, SM analysis	20	Semi-Lagrange	2.25

In forecast and analysis mode, the SM was running with 20 vertical levels and a Semi-Lagrangian advection scheme with a 240 seconds time step. The upper boundary was a rigid lid (no radiative upper boundary condition) and the uppermost levels were nested into the driving EM fields. The source code version of the model was 2.25.

3.1 Ticino-Toce episodes

Figure 6 shows the area of the Ticino-Toce area as defined for the SM. The large colored check pattern shows the digital elevation model (DEM) used in the SM in the Ticino-Toce subdomain. The combined watershed of the three rivers Ticino (at Bellinzona), Maggia, and Verzasca before the inlet into Lago Maggiore is outlined in red and the high resolution DEM of the hydrological model WaSiM is drawn within it.

The two standard simulation modes of the SM were compared. The result of the two modes compared to each other for the Ticino-Toce area are presented as catchment-averaged hourly precipitation in Figure 7. For the calculation of the average precipitation it was assumed that the rain falls uniformly within each SM grid cell with an area of approximately 196 km^2. No interpolation of the rainfall was done. The average rainfall for the Ticino at Miorina catchment (outermost red and black boundary in Figure 6, area 6599 km^2) was calculated by weighting each grid cell by the fraction of the grid cell being within the watershed boundary. The exact values of this weighting are given in the Appendix.

Each episode consists of 2 – 3 model runs according to Table 4. The runs overlap 12 hours in time. The idea was to discard the first 12 hours for hydrological simulation because of model spin-up effects of the standard mode (first 6 hours) and of an eventually nested higher resolution run (another 6 hours). The additional SM forecasts that were not required by the simulation strategy are not shown.

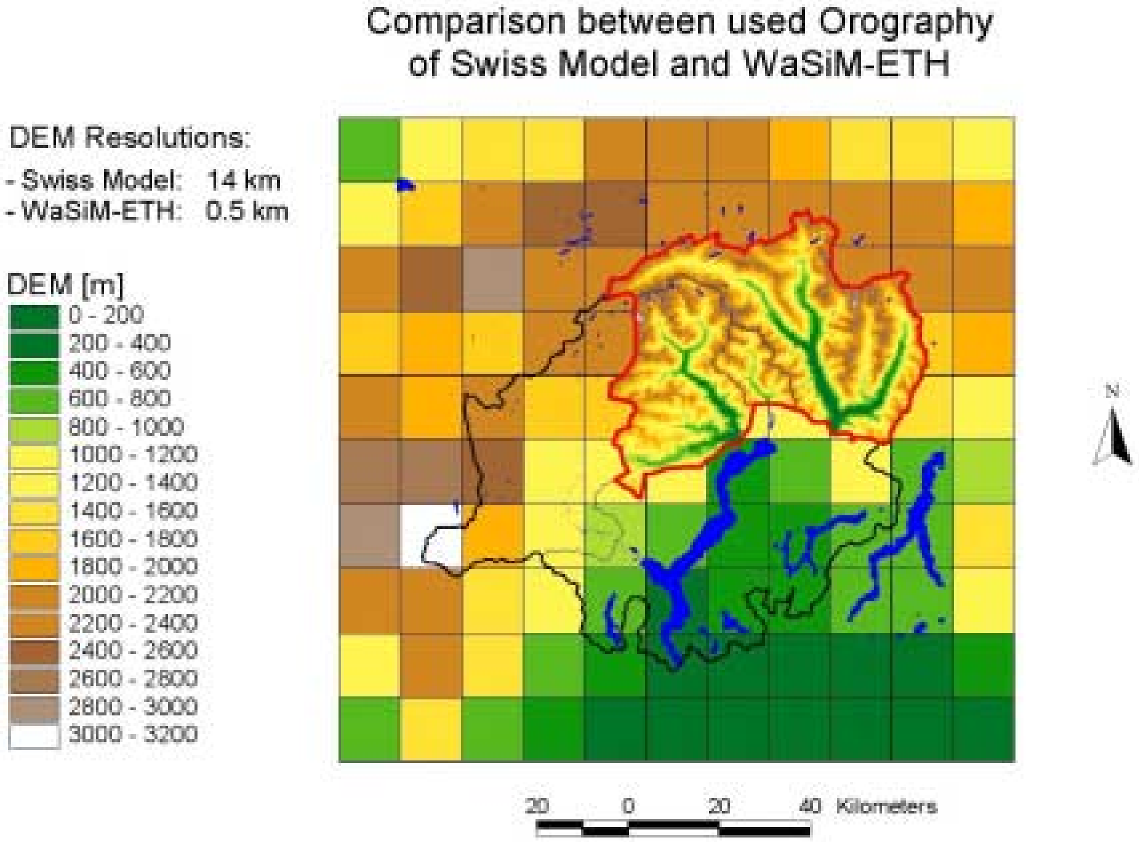


Figure 6 *Digital elevation models (DEM) of the Ticino-Toce domain of the SM and WaSiM. The areas outlined in red are the Maggia, the Verzasca, and the Ticino catchment areas (from left to right). The outer boundary in red and black is the complete Ticino at Miorina watershed. Figure prepared by K. Jasper, IACETH.*

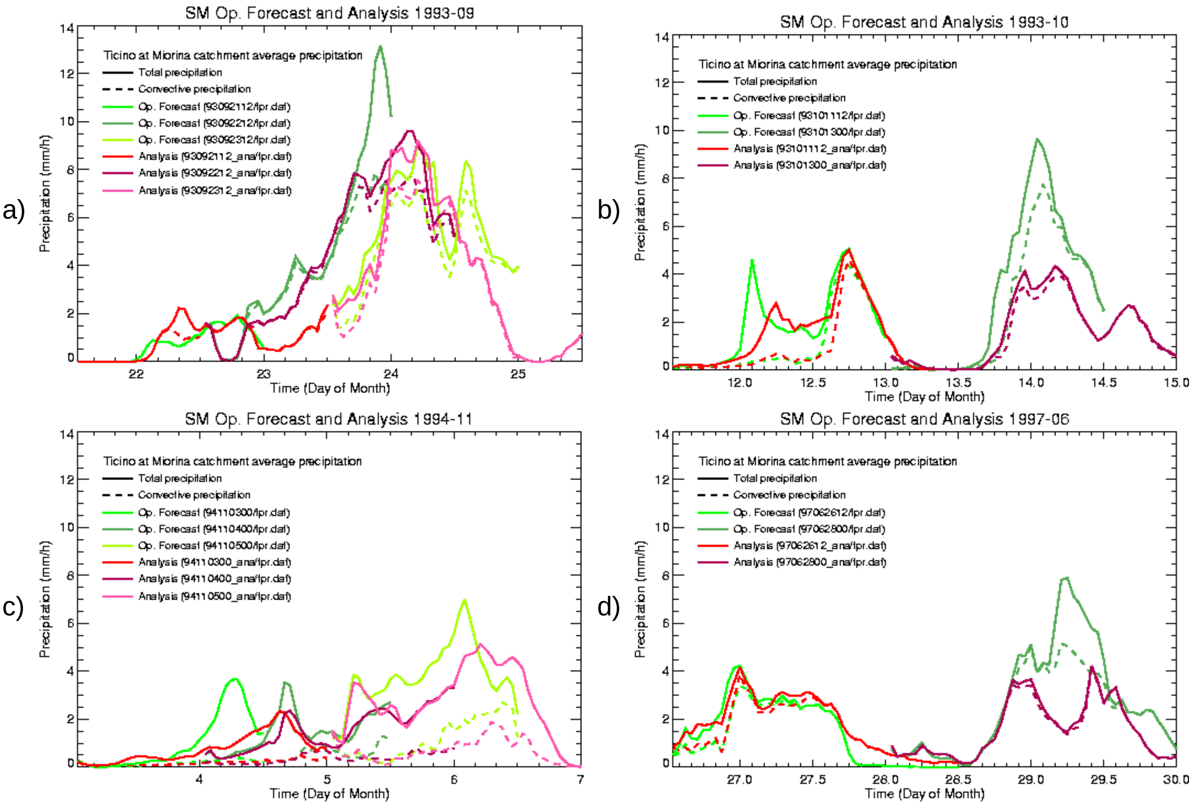


Figure 7 Average precipitation over the Ticino at Miorina watershed for the SM forecast (shades of green) and analysis mode (shades of red), for the four Ticino-Toce episodes. The solid lines show total precipitation, the dashed lines the convective fraction.

3.1.1 Ticino-Toce 1 (“Brig”)

Figure 7 a shows the hourly average of the Ticino-Toce episode 1, the so-called “Brig” case. The two SM modes agree well up to 23 September 1993 12:00 UTC. This event is dominated by convective rainfall. Figure 8 shows the spatial pattern of the two SM modes at that time. It is very similar and fits well with the observations (Figure 8 a, b). At 22:00 UTC, the forecast shows an excessive grid scale precipitation peak. The most intense precipitation occurs 2 hours earlier SW of the Toce area, outside the Ticino at Miorina watershed (Figure 8 c). It then moves towards NE into the watershed, thus the peak for the catchment average is two hours later. When compared to the observations, the forecast is clearly overpredicting this event. The corresponding analysis driven simulation (Figure 8d) is still too high but much closer to the actual precipitation. This kind of rainfall overestimation in just a few grid cells is often referred to as “grid point storm”.

The forecast has again excessive precipitation towards the end of the episode (Figure 9 c), but this time in the convective fraction (see Figure 7a). The analysis mode (Figure 9 b, d, f) has initially a better positioning of the rainfall than the forecast (Figure 9 a, c, e) but then the rainfall in the analysis mode moves too quickly towards the east (Figure 9 d, f).

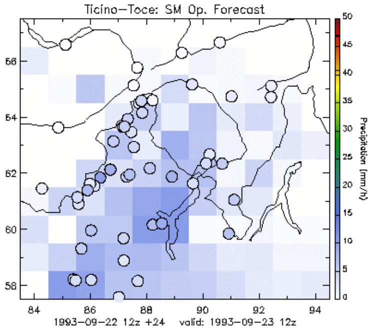
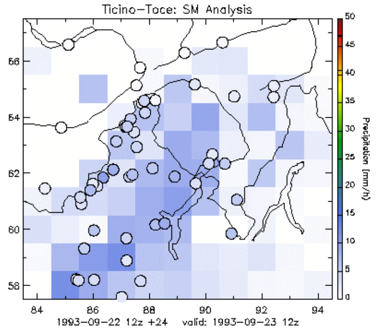
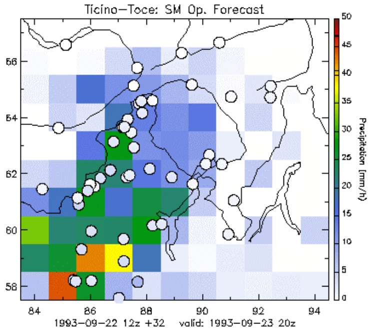
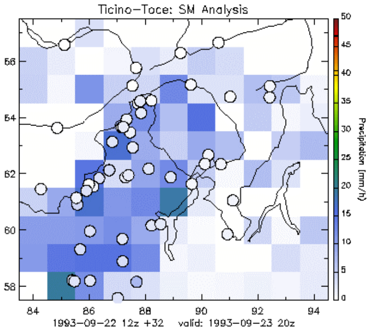
Time (UTC)		Forecast		Analysis mode
12:00	a)		b)	
20:00	c)		d)	

Figure 8 Spatial distribution of 1-h precipitation at 23 Sep 1993 12:00 and 20:00 UTC. Left panels: SM forecast mode, right panels: SM analysis mode. Filled circles: 1-h observations.

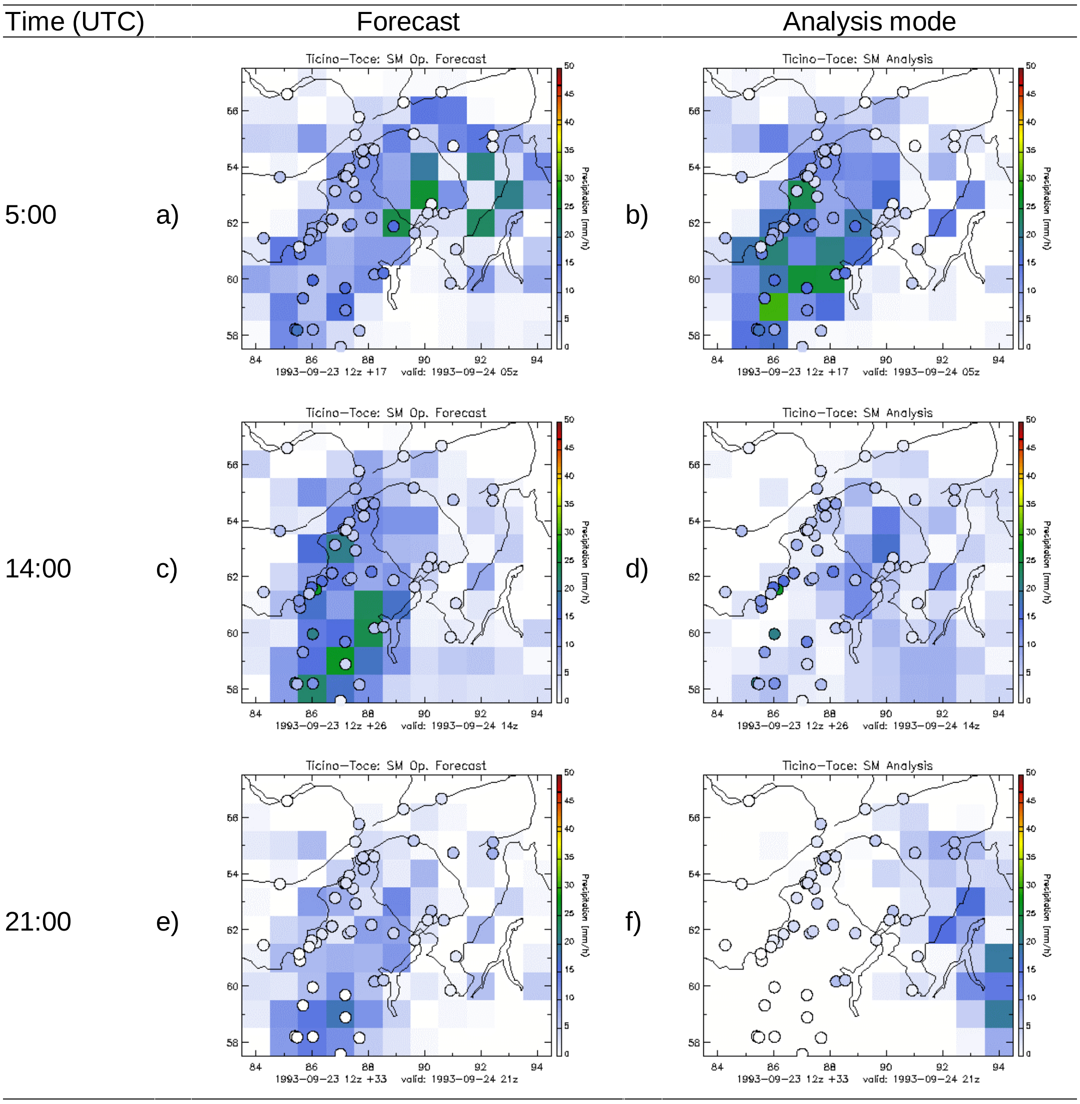


Figure 9 Spatial distribution of 1-h precipitation at 24 September 1993 5:00, 14:00, and 21:00 UTC. Left panels: SM forecast, right panels: SM analysis mode. Filled circles: 1-h observations.

3.1.2 Ticino-Toce 2 (“Locarno”)

In the Ticino-Toce 2 episode (Figure 7 b), there is a first peak at 12 October 1993 2:00 UTC in the forecast mode. The observations do not support this increased rainfall (Figure 10 a, b). There is a pronounced peak in the forecast at 14 October 01:00 UTC. The values are unrealistically high (Figure 10 c). The peak rainfall in the analysis occurs at the same time, but the amount fits better with the observations although the precipitation is a bit too far to the east (Figure 10 d).

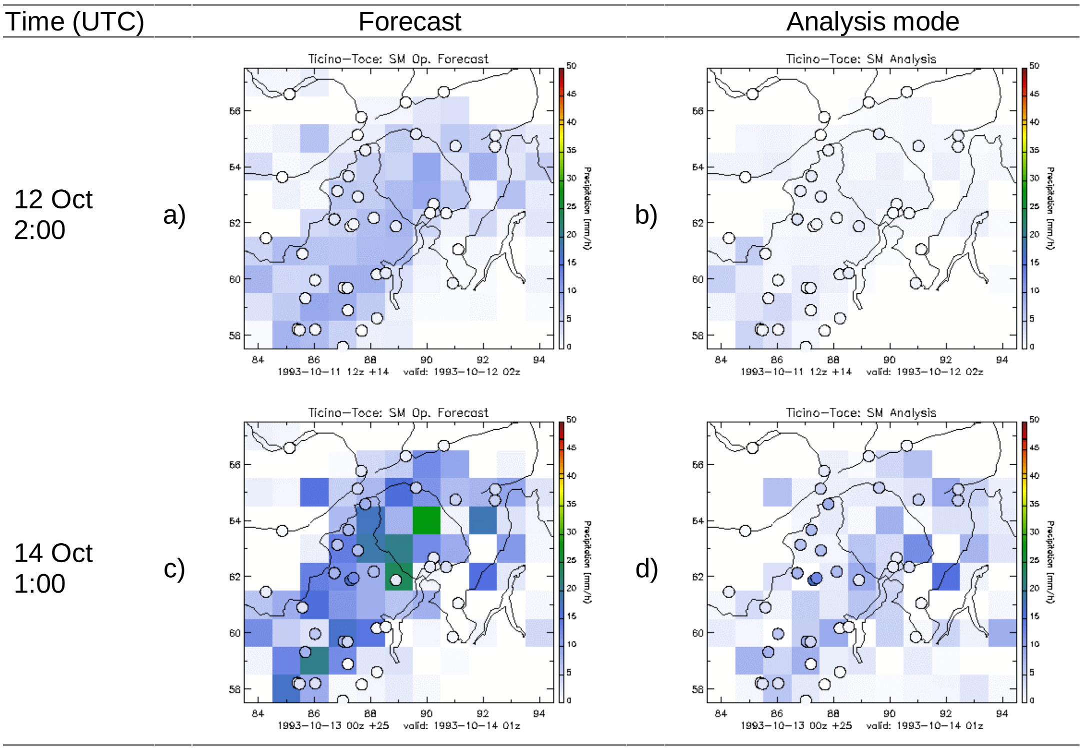


Figure 10 Spatial distribution of 1-h precipitation at 12 October 1993 2:00 and 14 October 1:00 UTC. Left panels: SM forecast; right panels: SM analysis mode. Filled circles: 1-h observations.

3.1.3 Ticino-Toce 3 ("Piemonte")

The Ticino-Toce 3 episode (Figure 7c) is dominated by grid scale precipitation, unlike the other Ticino-Toce episodes which are all dominated by convective precipitation. The forecast has a first peak, mostly from grid scale precipitation, at 4 November 1994 7:00 UTC. The forecast overestimates the precipitation at that time, whereas the analysis fits well with the observations (Figure 11a, b). The same is true for the next peak at 16:00 UTC (Figure 11c, d). From 5 November 10:00 to 6 November 3:00 UTC the forecast has constantly more grid scale precipitation than the analysis. The amount of rain is clearly too high in the forecast (Figure 12a) and it moves too quickly to northwest (Figure 12c, e). The analysis mode has much better amounts and better positioning (Figure 12 b, d, f).

In Figure 12 it is suspicious that three of the Italian sites (Passa del Moro, Piano Dei Camosci/Formazza, Vivaio Forestale Crosa/Varallo, red arrows in Figure 12 e) do not measure any amount of rainfall. These three sites continuously report zero precipitation after 5 November 9:00 UTC despite the heavy precipitation at this day and the following, and despite the nearby and distant stations that all do measure large amounts of rain. It is very likely that these measurements are wrong. This example demonstrates that observations should be interpreted with care.

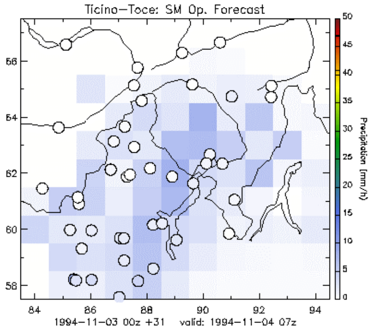
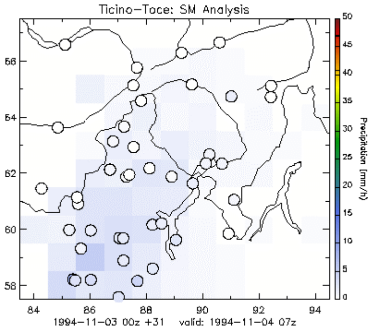
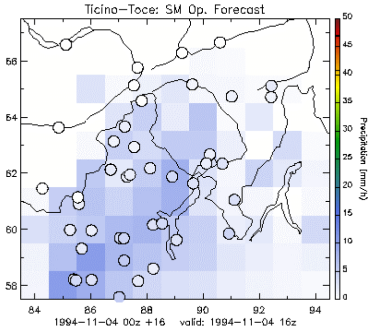
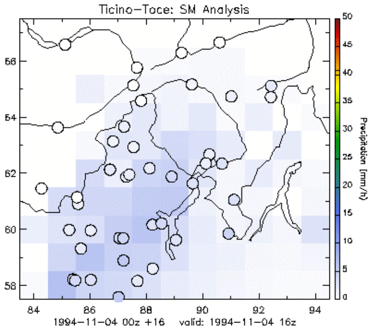
Time (UTC)		Forecast		Analysis mode
7:00	a)		b)	
16:00	c)		d)	

Figure 11 Spatial distribution of 1-h precipitation at 4 November 1994 7:00 (top) and 16:00 UTC (bottom). Left panels: SM forecast, right panels: SM analysis mode. Filled circles: 1-h observations.

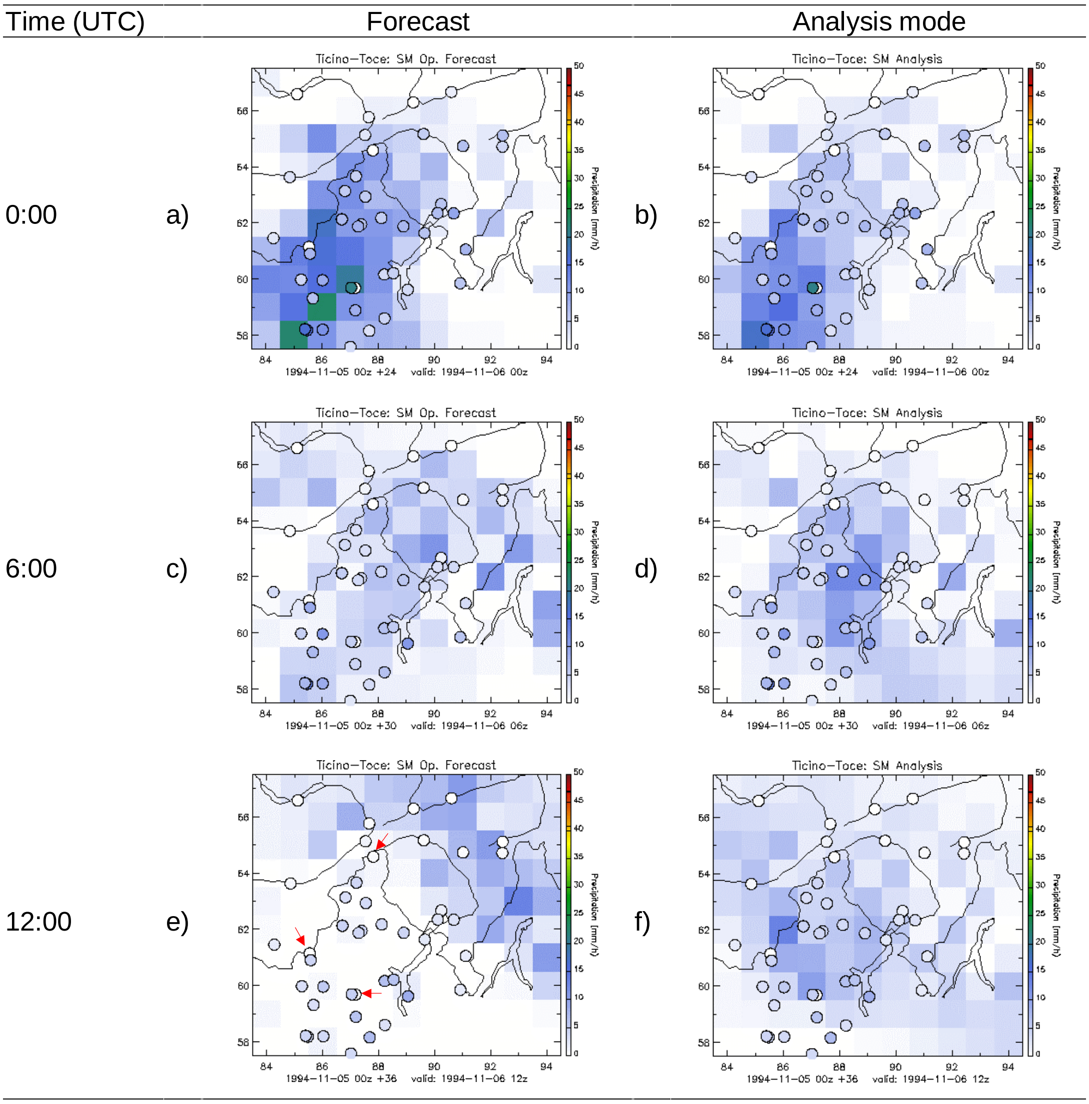


Figure 12 Spatial distribution of 1-h precipitation at 6 November 1994 0:00, 6:00, and 12:00 UTC. Left panels: SM forecast, right panels: SM analysis mode. Filled circles: 1-h observations. The red arrows in panel e) point to three stations with suspiciously constant zero measurements.

3.1.4 Ticino-Toce 4 ("Snowmelt")

During the Ticino-Toce 4 episode (Figure 7d), the forecast and analysis show very good agreement up to 28 June 1997 21:00 UTC except for a few hours after 27 June 18:00 UTC. The observations show at this same time isolated thunderstorms (Figure 13 a – c). The analysis captures this as convective precipitation, but the amount cannot be compared with observations due to the erratic nature of the observed rainfall. Later, the onset of the next peak compares for both modes well with the observations (Figure 14 a, b). The forecast shows an extreme peak at 29 June 6:00 UTC (Figure 7 d), whereas the analysis at the same time dives down. The forecast pattern is not only too strong, but shifted towards the northeast by about 60 km (Figure 14 c). The location of the precipitation in the analysis is about right, but the amount is too small (Figure 14 d).

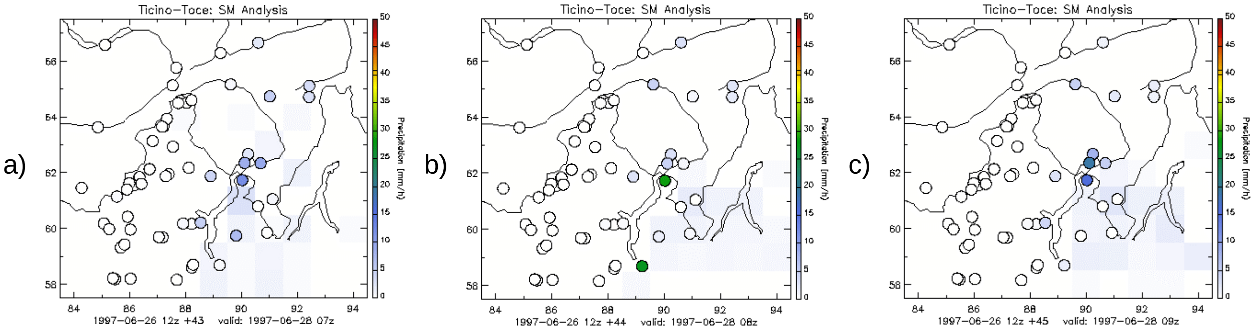


Figure 13 Spatial distribution of 1-h precipitation from 7:00 to 9:00 UTC at 28 June 1997. SM analysis. Filled circles: 1-h observations. a) 7:00, b) 8:00, c) 9:00 UTC.

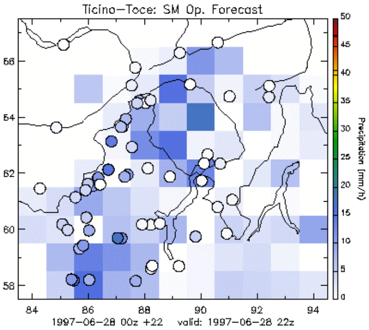
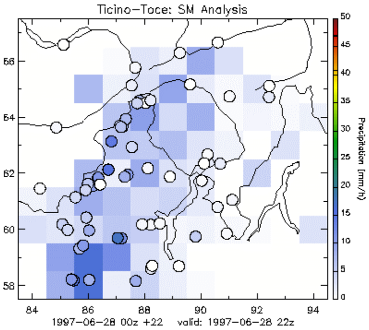
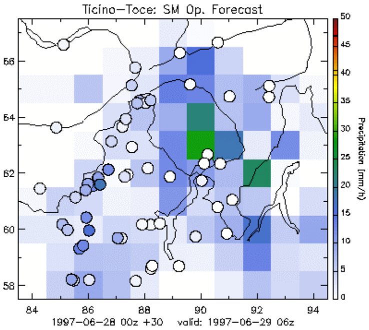
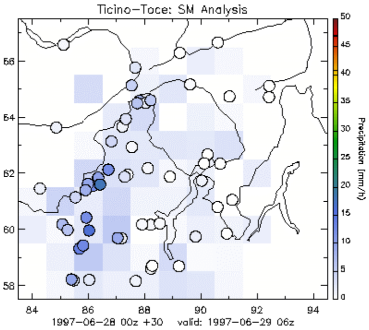
Time (UTC)		Forecast		Analysis mode
28 June 22:00	a)		b)	
29 June 6:00	c)		d)	

Figure 14 Spatial distribution of 1-h precipitation at 28 June 1997 22:00 (top) and 29 June 6:00 UTC (bottom). Left panels: SM forecast, right panels: SM analysis mode. Filled circles: 1-h observations.

3.1.5 SM time series for the Ticino-Toce area

The operational forecast of the SM is archived since August 1996. This gave us the opportunity to construct long term time series from the archived forecasts. For these time series, only the forecasts starting at 00:00 UTC were used. Hours 7 to 30 were taken from each 00:00 UTC forecast and concatenated into one file per year. This way, if 6:00 UTC to 6:00 UTC sums e.g. of precipitation were built, all data of one 24 hour sum are from the same SM run. An application of these time series with the hydrological model WaSiM (Schulla et al. 2001) of the IACETH is described in the RAPHAEL project report, Section 2.4 (Bacchi and Ranzi, 2000). It demonstrated that a coupled system of SM and WaSiM could be used to predict flood events.

3.2 *Ammer episodes*

The same procedure as for the Ticino-Toce episodes was used to calculate the average precipitation of the Ammer watershed. Figure 15 shows the catchment-average hourly precipitation for the four Ammer episodes. At MeteoSwiss, these data have not been compared to observations. Therefore, only a few remarks will be made here.

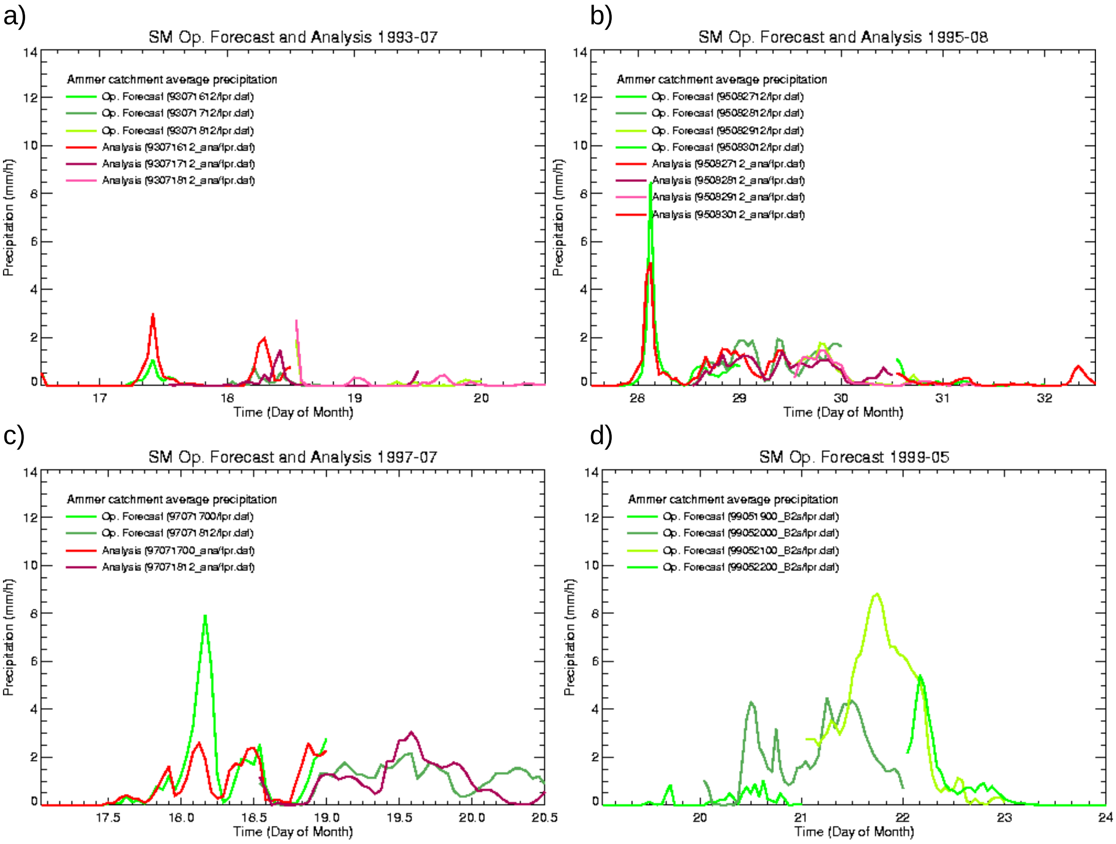


Figure 15 Comparison of average precipitation over the Ammer watershed for the SM forecast and analysis modes, for the four Ammer episodes.

In the Ammer 1 episode (Figure 15 a), the catchment-average rainfall of the analysis mode has a higher peak than the forecast. This is the opposite behavior of what we found for all other RAPHAEL episodes, but the precipitation amounts are fairly small in this episode so this result may not be significant.

In the Ammer 2 episode (Figure 15 b), both modes clearly show a peak in the precipitation at 28 August 1995 3:00 UTC, but the forecast is 35% higher than the analysis. The forecast for the Ammer 3 episode (Figure 15 c) shows an three-fold increase relative to the analysis.

The Ammer 4 episode (Figure 15 d) has been added late in the project, as more recent event with major flooding. No SM analysis is available for this episode. A peak rainfall at 21 May 1999 17:00 UTC was forecast by the SM initialized at 21 May 00:00 UTC (light green in Figure 15 d). The forecast initialized 24 hours earlier did not show such an extreme peak (dark green in Figure 15 d).

The Ammer watershed is small and includes only a few SM grid points. The simulated rain of the SM varies a lot from grid cell to grid cell. Therefore the average rainfall of the Ammer catchment area is very sensitive to the positioning of the rain in the model.

3.3 Conclusions for the standard mode simulations

The precipitation in both the operational forecast and analysis versions of the SM are in general quite good at the scale of the Ticino at Miorina watershed. However, there is a clear tendency of the operational forecast to overestimate the rainfall amount, especially with heavy precipitation peaks. This overestimation is produced by the grid scale fraction of the precipitation, not by the convection scheme. The SM develops unrealistic rainstorms at one or a few grid points where it overreacts to the condition of the atmosphere. The analysis on the other hand sometimes slightly underestimates the precipitation amount.

The location of the rainfall depends on the wind field, which in turn is heavily influenced by the boundary values of the driving model EM. There are a few cases where the positioning of the forecast mode is more accurate, as at the end of the Ticino-Toce 1 episode. This could be due to the 1-hour interval in the forecast mode as opposed to the 6-hour interval in the boundary values in the analysis mode. This shows that the frequency of the update of the boundary values is important.

Due to the large variations in the rainfall between adjacent grid cells, the catchment average precipitation is sensitive to the location of the rainfall. This is already visible in the case of the relatively large Ticino at Miorina watershed. The error in average precipitation due to positioning errors grows with decreasing size of the catchment.

The Ammer area is very small compared to the grid size of the SM. A relatively small spatial shift in the precipitation field can lead to large deviations in the average precipitation. The Ammer watershed is at the lower end of the scale of watershed sizes, for which meteorological model forecast with a resolution of 14 km can be sensibly used.

4 Swiss Model sensitivity analysis

Sensitivity analyses of the participating models were a major objective of project RAPHAEL. Two sensitivity studies were conducted with the SM (Table 6). The first study was related to the precipitation parameterization and the vertical resolution of the model. The second study was related to surface parameterization, in regard to an eventual feedback of the hydrological models to the SM. In order to obtain more detailed information about the effects of each change in the model, a couple of additional sensitivity experiments were made (Table 6). The sensitivity experiments have been made with all four of the Ticino-Toce episodes as defined in Table 1.

The SM is, unlike the other meteorological models in RAPHAEL, a hydrostatic model. Therefore it would not be sensible to attempt sensitivity studies with a higher horizontal resolution than the standard mode with 14 km. Due to the coarse resolution of the SM grid relative to the size of the Ammer watershed, the Ammer episodes were not used for sensitivity experiments.

Table 6 summarizes all SM simulations for RAPHAEL Task 2.5 (sensitivity studies of meteorological models). Each configuration of the SM has a unique experiment label that appears in the “Experiment” field of the RAPHAEL file header (see Appendix). All experiment labels used for RAPHAEL are described in Table 7.

Table 6 List of Swiss Model simulations in sensitivity mode for RAPHAEL Task 2.5.

Event	SM initial time	Sensitivity experiments		Additional experiments					Archive
Ticino-Toce 1, “Brig”	1993-09-21 12:00z	Q2p	x02	R2p	e20	x01		B32	A25
Sep 1993	1993-09-22 12:00z	Q2p	x02	R2p	e20	x01		B32	H10
	1993-09-23 12:00z	Q2p	x02	R2p	e20	x01		B32	A1a
Ticino-Toce 2, “Locarno”	1993-10-11 12:00z	Q2p	x02	R2p	e20				
Oct 1993	1993-10-13 00:00z	Q2p	x02	R2p	e20				
Ticino-Toce 3, “Piemonte”	1994-11-03 00:00z	Q2p	x02	R2p	e20	x01	nda		C2f
Nov 1994	1994-11-04 00:00z	Q2p	x02	R2p	e20	x01	nda		C2f
	1994-11-05 00:00z	Q2p	x02	R2p	e20	x01	nda		C2f
Ticino-Toce 4, “Snowmelt”	1997-06-26 12:00z	Q2p	x02	R2p	e20		nda		
Jun 1997	1997-06-28 00:00z	Q2p	x02	R2p	e20		nda		

Table 7 Experiment labels for the SM simulations. The column “Levels” shows the number of vertical levels, “advection scheme” the name of the numerical advection scheme, and “code version” the Swiss Model source code version.

Exp.	Description	Levels	Advection Scheme	Code Version
K2p	Operational forecast configuration 1998, SM standard simulation in forecast mode	20	Semi-Lagrange	2.25
B2s	Operational forecast May 1999 (AM4), SM standard simulation in forecast mode	20	Semi-Lagrange	2.25
ana	Simulation driven by EM analyses, SM standard simulation in analysis mode	20	Semi-Lagrange	2.25
Q2p	Ice-phase scheme, 40 levels, Eulerian advection scheme	40	Euler	2.25
x02	Evapotranspiration off in Ticino-Toce area (rectangular box of 11 x 10 gridpoints)	20	Semi-Lagrange	3.018
R2p	40 levels, Eulerian advection scheme	40	Euler	2.25
e20	Eulerian advection scheme	20	Euler	2.25
x01	Evapotranspiration off for full domain	20	Semi-Lagrange	3.018
nda	No initialization with DM analysis	20	Semi-Lagrange	2.25
B32	Operational forecast configuration July 1999	20	Semi-Lagrange	3.018

Exp.	Description	Levels	Advection Scheme	Code Version
A25	Archived forecast, recalculated 1994	20	Semi-Lagrange	2.05
A1a	Archived forecast, oper. Sep. – Dec. 1993	20	Semi-Lagrange	1.10
H10	Archived forecast, same as A1a	20	Semi-Lagrange	1.10
C2f	Archived forecast, oper. Sep. 1994 – Feb. 1995	20	Semi-Lagrange	2.15

4.1 Ice-phase scheme and vertical resolution

The first SM sensitivity experiment was related to precipitation parameterization and vertical resolution. The main change was to introduce an additional prognostic variable. In the two standard simulation modes, there are five prognostic variables as described in Section 3. The water content of the air is stored as a total and does not distinguish between solid, liquid, and vapor phase. The differentiation into the separate phases is done diagnostically every time step in order to calculate the precipitation. In the so-called ice-phase scheme version of the SM, an additional prognostic variable is introduced, describing the solid state water or ice-phase. This variable retains the cloud ice as frozen water content from one time step to the next. A consequence of this treatment of the cloud ice is that the ice particles are advected horizontally.

The operational forecast mode uses 20 vertical levels and a Semi-Lagrangian advection scheme. This advection scheme is less accurate than the Eulerian advection scheme, but allows a larger time step (240 s instead of 90 s) and thus saves computing time, a critical issue for an operational model. In addition, the Eulerian advection scheme allows to apply a radiating upper boundary condition (Herzog 1995) as opposed to the reflective upper boundary of the operational forecast mode. This allows vertically propagating waves to leave the model domain and thus avoids spurious noise caused by reflection. In consequence the vertical nesting of the upper levels in the operational Semi-Lagrangian mode is no longer needed in the Eulerian version.

A version of the SM with 40 levels vertical resolution, an Eulerian advection scheme, and the above described ice-phase scheme, further named “E40L ice-phase” has been tested against the operational forecast. The average precipitation was obtained the same way as in the standard mode simulations. In Figure 16, pronounced departures from the operational forecast are visible in the catchment-average hourly precipitation.

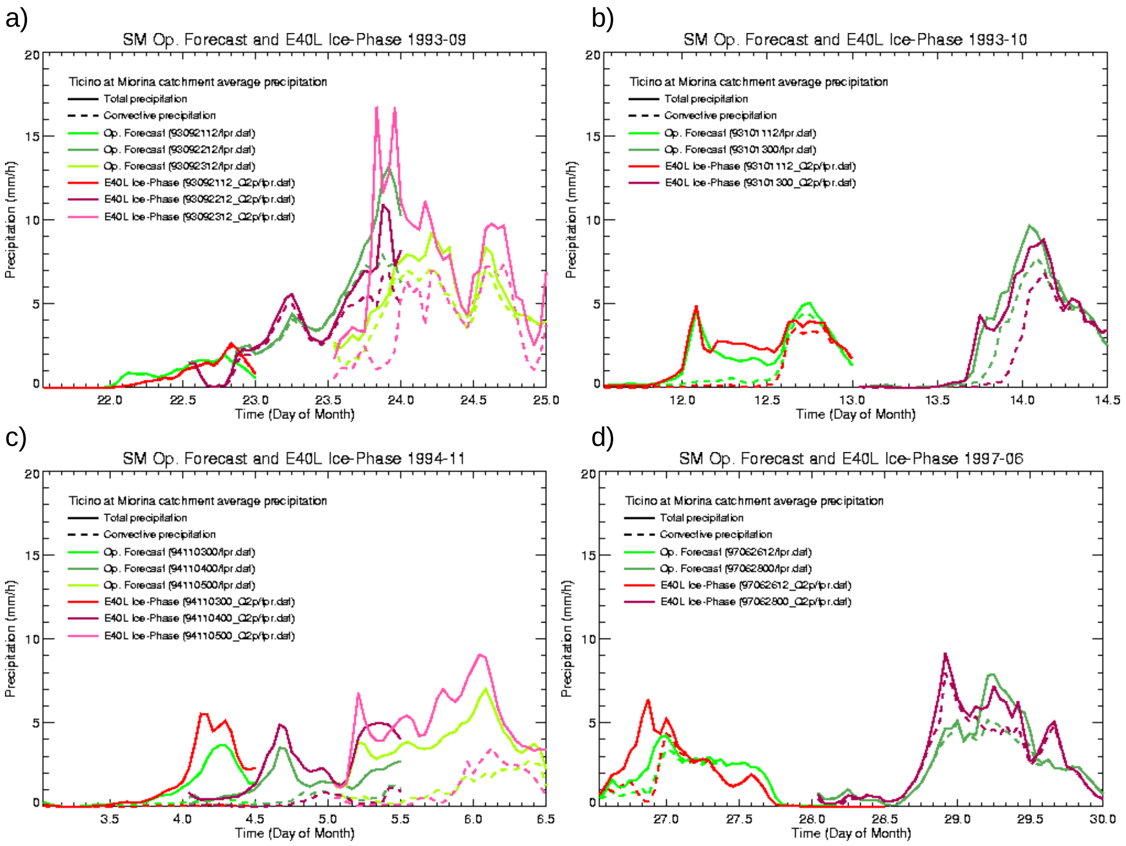


Figure 16 Average precipitation simulated by operational forecast and E40L ice-phase version, for the four Ticino-Toce episodes.

However, there were several changes to the model involved and the change in precipitation could not be attributed directly to the cloud-ice scheme. In order to determine which of the several model changes from the operational forecast to the E40L ice-phase version accounts for the changes in precipitation, the E40L ice-phase version has been compared to an otherwise identical version but without ice-phase scheme, named “E40L reference” (experiment label R2p). To investigate if the vertical resolution is the cause for the observed changes, an SM version with 20 levels like the operational forecast but Eulerian advection scheme (E20L, experiment label e20) was used.

Figure 17 shows the catchment-average hourly precipitation of the mode with (E40L ice-phase) and without (E40L reference) ice-phase scheme. From this figure, it can be seen that the difference in hourly precipitation rate exceeds 1.5 mm h^{-1} only during one short period within the Ticino-Toce 1 episode (Figure 17 a). At all other times, the two model versions are very close to each other (Figure 17 b - d).

Comparing Figure 17 to Figure 16, it is clear that the big changes between the operational forecast and the E40L ice-phase version is not due to the ice-phase scheme. In order to test if it is the vertical resolution that caused the observed changes, an SM version with 20 levels like the operational forecast but Eulerian advection scheme (E20L) was used as intermediate step. The result for each episode will be discussed separately in the following.

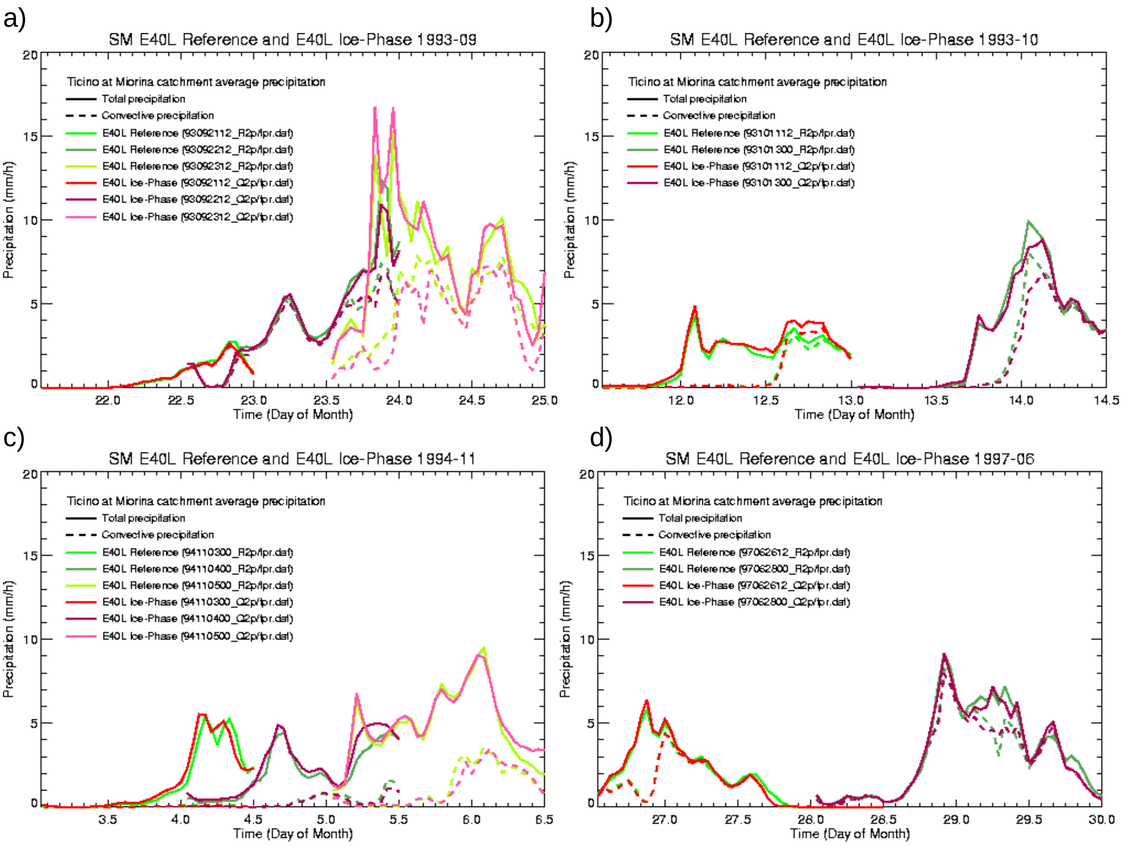


Figure 17 Average precipitation simulated with (E40L ice-phase) and without (E40L reference) ice-phase scheme, for the four Ticino-Toce episodes.

4.1.1 Ticino-Toce 1

The Ticino-Toce episode 1 is where the SM shows the biggest response to the model changes. The peak at 23 September 1993 22:00 UTC of the E40L ice-phase mode is less pronounced than in the operational forecast (Figure 16 a) and occurs two hours earlier. At the beginning of the third run, the E40L ice-phase version produces two extreme peaks that were not at all present in the operational forecast. These peaks consist of grid scale precipitation. The convective fraction of the precipitation is in contrast much lower in the E40L ice-phase version than in the operational forecast.

In the first half of 23 September, the E20L version is a bit closer to the E40L reference than to the operational forecast but otherwise closely follows the operational forecast (Figure 18). The E20L version has a higher peak at 24 September 8:00 UTC than all other versions.

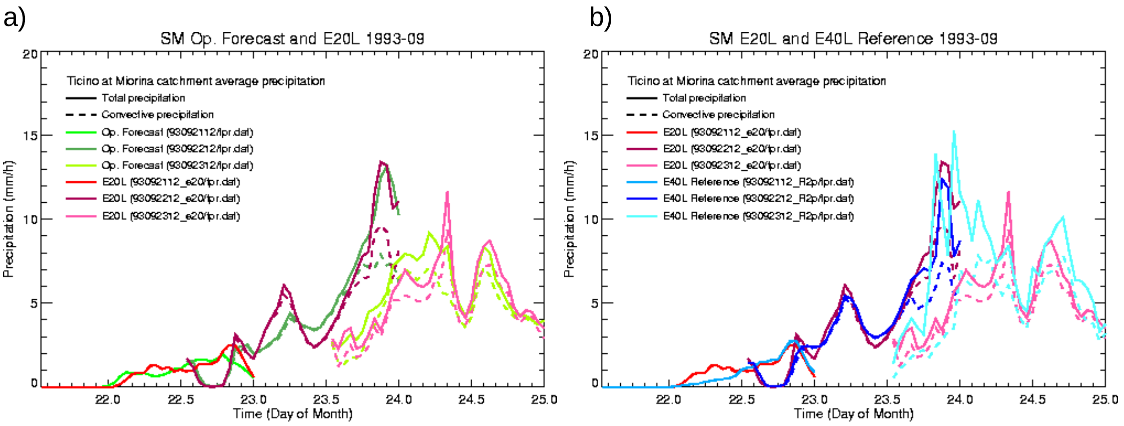


Figure 18 a) average precipitation of operational forecast and E20L model version. b) E20L and E40L model versions.

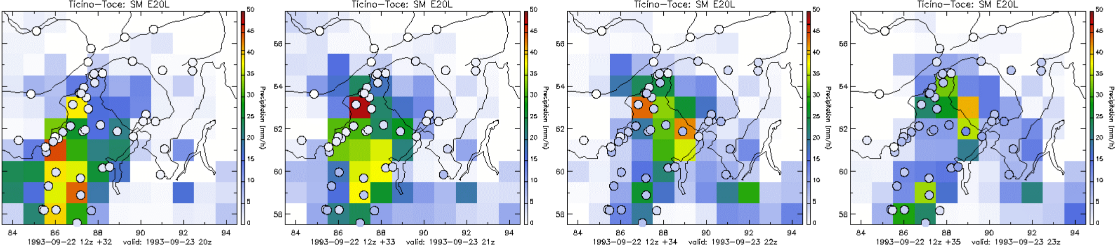
Figure 19 a – c shows the movement of the precipitation field for four hours on 22 September and for three different versions of the SM. The spatial distribution of the E40L versions for the same verification time but from the third model run are shown in Figure 19 d and e. They also show excessive precipitation peaks at this time.

When the modified SM version results are compared to the observations at the time of the extreme peak at 23 September 20:00 – 23:00 UTC (Figure 19), it is obvious that the amount of precipitation is far too high for all forecast versions. The exact occurrence in time and space of the peak differs little from version to version. Specifically, the cloud-ice scheme does not damp the peaks at isolated grid points, it rather seems to enhance them. It seems that the meteorological conditions around that time are such that all model versions (except the analysis, see Figure 7 in section 3.1.1) produce a heavily overestimated rainfall peak.

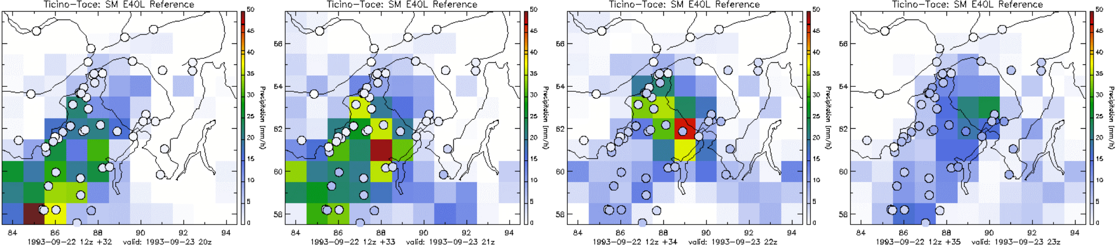
4.1.2 Ticino-Toce 2

During the Ticino-Toce episode 2, there is good agreement of the total precipitation between all model versions. The convective fraction however is considerably smaller in the E40L ice-phase version than in the operational forecast (Figure 16 b), and it is still a little smaller than in E40L reference (Figure 17 b). The grid scale fraction compensated for this.

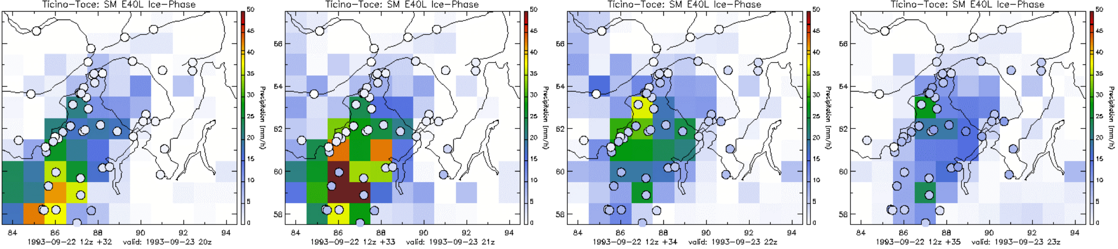
a) E20L



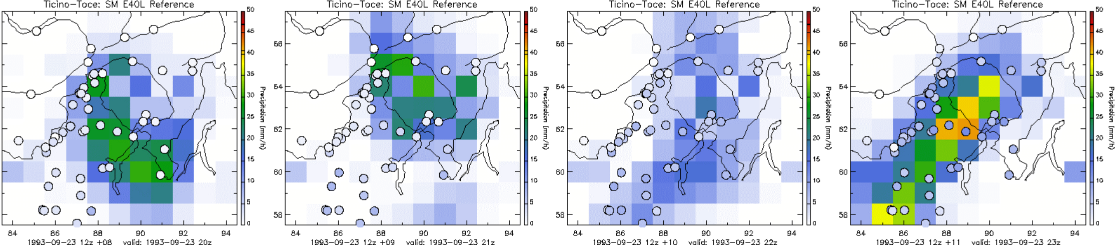
b) E40L reference



c) E40L ice-phase



d) E40L reference, initialized 24 h later



e) E40L ice-phase, initialized 24 h later

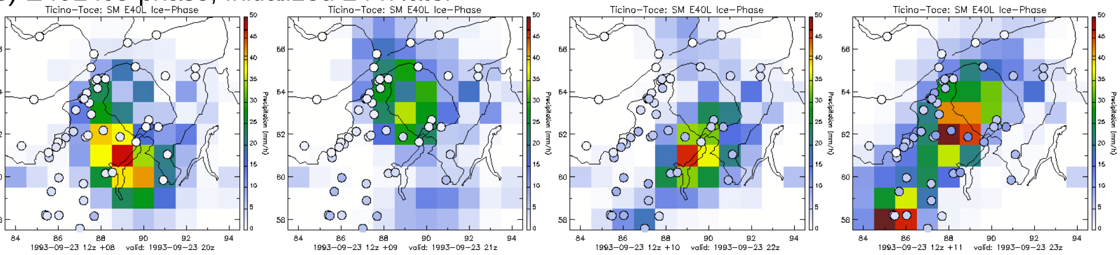


Figure 19 Sequence of spatial 1-h precipitation patterns from 20:00 UTC to 23:00 UTC at 22 September 1993. Forecast a) Eulerian 20 levels b) Eulerian 40 levels c) Eulerian 40 levels plus ice-phase scheme d) Eulerian 40 levels, initialized 24 h later e) Eulerian 40 levels plus ice-phase scheme, initialized 24 h later. The dots show the observed rainfall in the same color scale.

4.1.3 Ticino-Toce 3

In the Ticino-Toce episode 3, the E40L ice-phase has more precipitation than the operational forecast (Figure 16 c). The major part of the increase occurs when changing the number of levels from the E20L to the E40L Reference version (Figure 20 b). The difference between operational forecast and E20L is usually small and of varying sign (Figure 20 a).

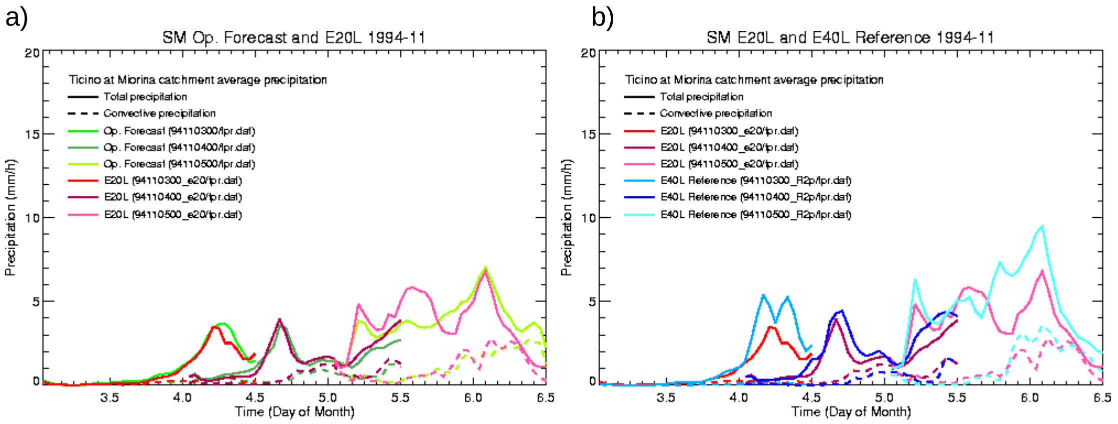


Figure 20 Left column: Catchment average precipitation of operational forecast and E20L model version. Right column: E20L and E40L Reference model versions.

Figure 21 shows the spatial precipitation pattern of three different SM versions at the same verification time. Both 40-level versions increase the catchment averaged rainfall compared to the operational forecast, but the increase is not uniform in space. The region with very strong precipitation extends more to the northeast in the 40-level versions (Figure 21 b and c) than in the operational forecast (Figure 21 a).

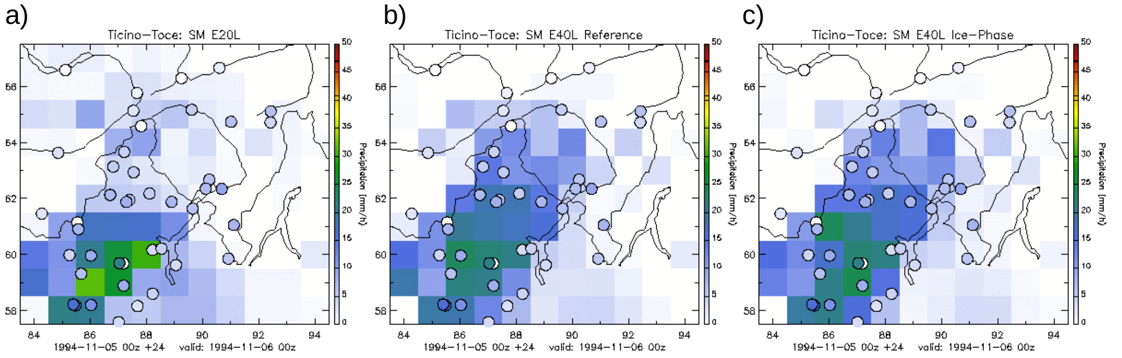


Figure 21 Spatial 1-h precipitation patterns at 5 November 1994 6:00 UTC of a) operational forecast, b) E40L reference, c) E40L ice-phase.

4.1.4 Ticino-Toce 4

Similar results as for the previous episodes are obtained for the Ticino-Toce episode 4. The E40L ice-phase and E40L reference versions agree well but have considerable more precipitation than the operational forecast and the E20L version. A comparison to observations shows that the rainfall peak is grossly overestimated in the two versions with 40 levels (Figure 22 b, c) although the precipitation pattern is more coherent and better positioned than in the Eulerian 20 level version (Figure 22 a), regardless of the advection scheme (Semi-Lagrangian operational forecast not shown).

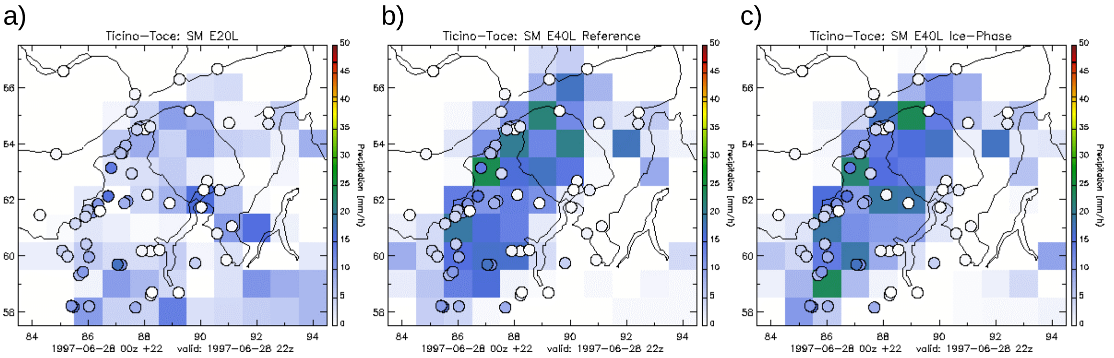


Figure 22 Spatial 1-h precipitation patterns at 28 June 1997 22:00 UTC of a) E20L, b) E40L reference, c) E40L ice-phase.

4.1.5 Conclusions for the ice-phase scheme and vertical resolution

The E40L ice-phase version of the SM in general predicts considerably more precipitation than the operational forecast. However, this increase is not due to the ice-phase scheme. The precipitation parameterization does not much affect the heavy precipitation in the Ticino-Toce episodes. Whereas some enhancements of the peak rainfall are observed relative to the E40L reference version, the overall difference between the two 40-level versions is only small. The grid size of the SM is possibly too large for the advection of cloud ice to have a significant effect.

Both 40-level versions predict too much rainfall during heavy precipitation events. Interestingly, the convective precipitation has the opposite tendency than the total precipitation. It is reduced in the 40-level versions, and more so in the E40L ice-phase than in the E40L reference. The major difference in rainfall however is observed when changing the vertical resolution of the model from 20 levels to 40 levels. This is presumably due to the narrower vertical grid spacing in the 40 level versions. The saturation of a grid element is reached earlier with smaller grid cells.

The changes in the model code between the operational forecast, the E20L and the E40L reference version of the SM only affect numerical aspects, there is no change in the model physics involved. This demonstrates that there can be relatively large variation of the results due to purely numerical changes in the model. Care must be taken to separate the effects of changed model physics from the effects of changed numerics such as increased vertical resolution.

4.2 Evapotranspiration

The second SM sensitivity experiment was related to the surface parameterization. As a test for the potential effect of feeding the evapotranspiration (ET) from the hydrological model back into the meteorological model, the ET was set to zero within the Ticino-Toce area bounding box (11 x 10 grid points or 21000 km^2). This area is three times bigger than Ticino at Miorina watershed and eight times bigger than the combined Ticino-Maggia-Verzasca catchment areas. The corresponding SM simulations are in the following named “No ET in TT”. The change in the surface flux of latent heat is quite dramatic compared to an actual coupling experiment. There, the ET of the hydrological model would be approximately in the same range as the ET of the meteorological model, not constantly zero. In addition, the ET of the hydrological model would only have been provided for the eight times smaller Ticino-Maggia-Verzasca watershed. Thus the effect in an actual coupling experiment would be considerably smaller.

4.2.1 Evapotranspiration turned off in the Ticino-Toce area

Figure 23 shows the catchment-average precipitation for the operational forecast and the “No ET in TT” version. The difference in the average precipitation are very small, especially in view of the dramatic change in surface parameterization.

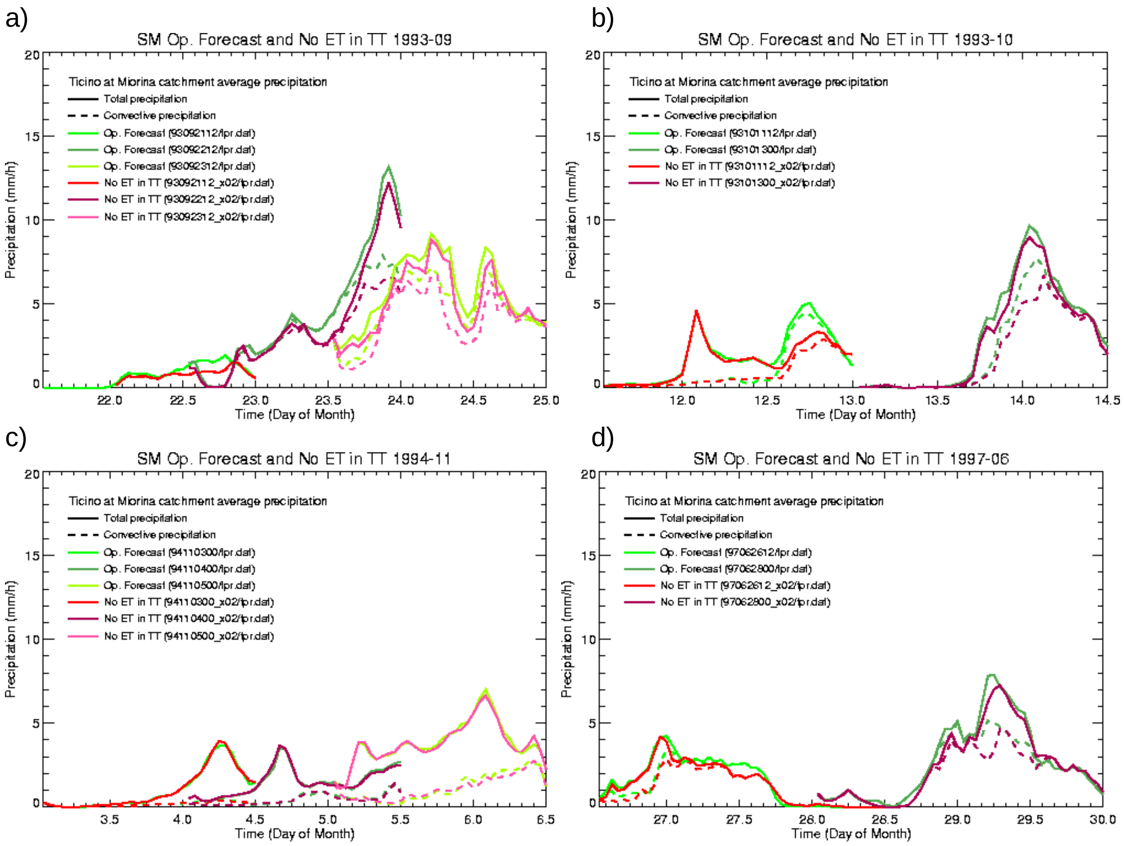


Figure 23 Comparison of the average precipitation of the operational forecast to the precipitation calculated with evapotranspiration turned off in the Ticino-Toce area, for the four Ticino-Toce episodes.

The total precipitation in the Ticino-Toce 1 episode is reduced by at most 2 mm h^{-1} or 40 % (Figure 23 a). This reduction occurs only in the convective fraction, the grid scale precipitation is not changed.

The Ticino-Toce 2 episode contains the largest difference between the operational forecast and the "No ET in TT" version. It occurs at 1993-10-12 18 UTC, after 30 hours of simulation. The spatial distribution of the rainfall at this time is similar (Figure 24), but the precipitation is reduced in the "No ET in TT" version, and more so in the central region.

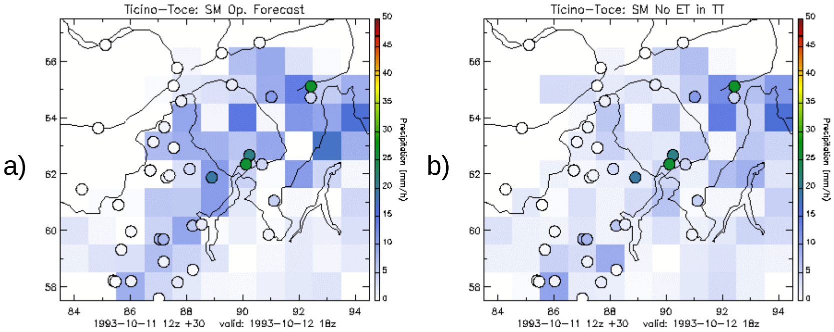


Figure 24 Spatial 1-h precipitation patterns at 12 October 1993 18:00 UTC of a) operational forecast, b) forecast with ET set zero within Ticino-Toce bounding box.

Like in the previous episode, the reduction in the "No ET in TT" version only occurs in the convective precipitation (Figure 23 b). The grid scale precipitation does not change in the first model run. In the second run, it even partially compensates for the reduction of the convective fraction. This behavior is consistent with the expectation that the convective parameterization scheme is less triggered with reduced low-level moisture.

In the Ticino-Toce 3 episode, the operational forecast and the “No ET in TT” version have nearly identical results in total precipitation (Figure 23 c).

The total precipitation is also in good agreement during the Ticino-Toce 4 episode. There is a dip in the convective precipitation at 1997-06-29 05 UTC (Figure 23 d) in the “No ET in TT” version. This reduction occurs only at this hour and is partially compensated for by grid scale precipitation.

4.2.2 Evapotranspiration turned off in the whole model domain

In order to further investigate the influence of the ET on precipitation, the Ticino-Toce episodes 1 and 3 have been simulated with a version of the SM in which the ET was set to zero everywhere in the model domain. The result is presented in Figure 25. Still, the change in the average rainfall is quite small in the Ticino-Toce 1 episode (Figure 25 a). The reduction takes place in the convective fraction of the precipitation only. During the Ticino-Toce 3 episode, the only episode where the convective fraction is very small, there is almost no difference at all in the rainfall (Figure 25 b).

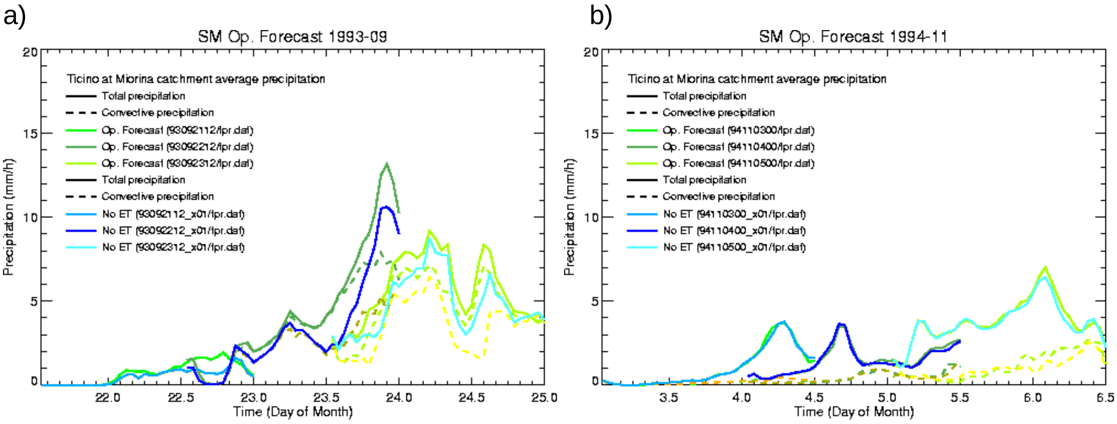


Figure 25 Comparison of the average precipitation of the operational forecast to the precipitation calculated with evapotranspiration turned off in the full SM domain, for a) the Ticino-Toce 1 and b) the Ticino-Toce 3 episodes.

4.2.3 Conclusions for Evapotranspiration

The amount of local ET is of minor importance for the heavy rainfall rates during the Ticino-Toce episodes. It seems that the advection provides a constant humidity supply, not only for the grid scale precipitation, but also for the convective precipitation. Even the experiments with ET set to zero in the full SM domain show only a small reduction of convective precipitation relative to the operational forecast. Thus for the advection of humidity into the Ticino-Toce area, the ET is not important. It seems that the humidity already in the air at the beginning of the model simulation is dominating the rainfall amount produced later on.

An experiment with the ET from hydrological model fed back into the meteorological model would probably not result in any significant change in the rainfall. In consequence, this two-way coupling of the meteorological and the hydrological model has not been attempted within the RAPHAEL project. It should be reconsidered for future studies with greater time and space scales and less extreme precipitation events.

4.3 Additional SM experiments

A few more experiments with the SM have been made during the RAPHAEL project. These are in the following described very briefly.

4.3.1 DM analysis for SM initialization

For the operational forecast, the initialization of the model was done with the help of the Deutschland Modell (DM) analysis. The DM analyses have been available starting 1994-09-09 12 UTC until 1999-12-15 00 UTC. Only a few DM surface fields were used, the most important being the snow coverage. A benefit could be expected because of the higher resolution of the DM relative to the EM. For the Ticino-Toce episodes, no difference was found in the rainfall amount, whether or not the DM analysis was used for initialization.

4.3.2 Optimized model code

In 1999, an optimized source code version (SM version 3.018) became available. No differences in the rainfall during the Ticino-Toce events where observed.

4.3.3 Archived SM forecasts

The archived data from the model version that was operational at the time of the episodes shows a slightly lower precipitation than the version used for RAPHAEL, but the differences are small. The following catchment averages have been calculated the same way as for all previous experiments.

- Ticino-Toce 1: The archived 3-h sums had up to 4.9 mm (or 1.6 mm per hour) less precipitation than the RAPHAEL standard mode forecast.
- Ticino-Toce 2: The archived 6-h sums had up to 5 mm (or 0.8 mm per hour) less precipitation than the RAPHAEL standard mode forecast.

5 Conclusions

The following conclusions summarize the findings of the previous chapters and are naturally restricted to events that are similar to those examined here, namely heavy precipitation events on the slopes of the Alps with strong advection of humidity from the south towards the Alps.

The Swiss Model provides adequate precipitation forecasts for flood prediction and warning purposes for watersheds larger than approximately 2000 km^2. For smaller areas, the precipitation within the catchment area is too sensitive to positioning errors of the model precipitation.

The Swiss Model overestimates the orographic effect over the south-facing slopes of the Alps. The overestimation happens in the grid scale part of the precipitation, not in the convection. Interestingly, the analysis mode in general tends to underestimate the precipitation amount, especially at the times where boundary values are available.

A frequent update of boundary values as in the operational forecast has a positive effect on the accuracy of the forecast, especially on the positioning of the rain. The low frequency of the six-hour interval of boundary-value updates in the analysis mode has a negative impact. Positioning errors in the rainfall occurs due to the linear interpolation of the field between the times of the boundary value updates. Non-linear features such as fronts are not well enough represented between the updates.

The introduction of a prognostic variable for the cloud ice, the so-called ice-phase scheme, does not give a considerable effect and is barely visible in the results. Possibly, the spacing of the Swiss Model is too coarse for the ice-phase scheme to have a significant influence. The advection of cloud ice is assumed to be more important with smaller horizontal grid spacing.

The vertical resolution of the Swiss Model has a very large effect on the precipitation forecast. An increase in vertical resolution produces a strong increase in the already overestimated precipitation amounts during heavy precipitation. This detrimental effect on rainfall rates has to be kept in mind when increasing the vertical resolution.

It is not possible to decide whether the Eulerian or the Semi-Lagrangian version of the model is more accurate. The Eulerian version gives more consistent precipitation patterns. The overall differences between the two advection schemes is small and does not point consistently in one direction.

The evapotranspiration is not an important factor for the studied heavy precipitation events. This is due to the advection of large humidity amounts from the Mediterranean sea towards the south slope of the Alps. Hence the RAPHAEL episodes are not well suited to measure the influence of surface parameterization.

In view of the hydrological simulations (not described in this report) that were made with the SM and other meteorological models, it can be said that despite the limitations of numerical weather prediction, a system consisting of a meteorological model and a hydrological model is well suited to produce flood warnings ahead of time. In section 2.4 of the RAPHAEL final report (Bacchi and Ranzi, 2000), this is documented for the RAPHAEL events as well as for the 3.5 year continuous period.

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Appendix

A.1 The RAPHAEL data format

The formats for meteorological data files were defined in project RAPHAEL according to the following guidelines. They are of general nature and recommended for use in other projects as well:

- ASCII files, text in English.
- Use of ISO8601 international standard date and time notation (for a summary on ISO8601 see http://www.cl.cam.ac.uk/~mgk25/iso-time.html).
- Explicit time zone (+00 marks UTC, +01 stands for Central European time, +02 for Central European daylight saving time).
- Comments in the header are marked by a hash mark ("#") as first character on the line.
- Each data column has exactly one label just above the first data line. A label starts with a letter and must not contain whitespace or special characters.
- Column width is free, columns must be separated by minimum one whitespace (i.e. space or tab).
- Data row labels use date and time in same sequence as ISO8601, but separated by blanks, for easy use with spreadsheets, statistics, and graphics programs.
- Exactly one line per time.
- Exactly one column per site, grid point, or parameter, i.e. the file has as many data columns as sites, grid points or parameters, respectively.
- One file per parameter, or alternatively one file per station. Multiple parameters and multiple sites in the same file are not allowed.
- Remove comments with {} in examples.
- Parameter name according to Table A1.

Table A1 List of abbreviations for parameters. (Note: abbreviations are similar but not always equal to ECMWF code table 2 version 128)

Abbrev.	**Description**
YYYY	Year (model data: verification time)
MM	Month (model data: verification time)
DD	Day (model data: verification time)
HH	Hour (model data: verification time)
TZ	Time zone
FC	Forecast range (model data only)
ALB	Albedo
CPR	Convective precipitation
DR10M	Wind direction 10 m
ITOT	Surface short wave total incoming radiation ("Global radiation")
LFR	Land fraction
PS	Surface pressure
RH2M	Relative Humidity 2 m
RSR	Reflected shortwave radiation
SD	Snow depth
SDUR	Sunshine duration
SF	Snow fall (water equivalent)
SLHF	Surface latent heat flux
SLRB	Surface longwave radiation balance
SP10M	Wind speed 10 m
SPLL	Wind speed on lowest model level
SSHF	Surface sensible heat flux
SSRB	Surface shortwave radiation balance
STY	Soil type
T2M	Temperature 2 m
TCC	Total cloud cover
TD2M	Dewpoint temperature 2 m
TPR	Total precipitation
VIS	Visibility

Two file formats for meteorological data are defined below. The first and preferred format is for the storage of one parameter (e.g. temperature) from a multitude of stations in one file. The second format defines the storage of all parameters of the same station in one file. These two formats are exclusive alternatives and should not be mixed. A third format is defined for model output. This format mainly differs in the header fields.

A.1.1 Observational surface data, several stations and one parameter

This format allows one parameter of several stations to be collected into one file. It is the preferred format for observational surface data. The comments in curly brackets {} are not part of the format and should not appear in actual files.

Example:

```
Area: Ticino watershed
Observations start: 1997-01-01 01 +01          {ISO8601 date and time format, +01 is time zone CET}
Observations end: 1997-01-01 24 +01
#
# Free comments marked with # as first character on line
# Useful to provide additional data documentation.
# This file is example data, no real data.
#
# YYYY year
# MM month
# DD day
# HH hour
# TZ time zone
#
# ID, Name, abbreviation, altitude [m MSL], Long., Lat., data begin, data stop
# 9130, San Bernardino, SanBer, 1639, 9.18, 46.46, 1997-01-01, 1997-12-31
# 9397, Cimetta, Cimett, 1672, 8.8, 46.2, 1997-01-01, 1997-12-31
# 60, Disentis, Disent, 1190, 8.85, 46.7, 1997-01-01, 1997-12-31
#
Parameter: T2M
Description: Temperature at 2 m AGL (1h-mean values from HH-0:20 to HH+0:40)
Unit: 0.1 degree Celsius
Missing value code: -999
Number of stations: 3
YYYY MM DD HH TZ     1639    1672    1190      {... all heights on 1 line}
YYYY MM DD HH TZ   513823  484569  488532      {... all eastings on 1 line}
YYYY MM DD HH TZ  5145272 5116386 5171937      {... all northings on 1 line}
YYYY MM DD HH TZ   SanBer  Cimett  Disent      {... all column labels on 1 line}
1997  1  1  2 01      -87     -84     -65      {... all values for this time on same line}
1997  1  1  3 01      -91     -76     -58
1997  1  1  4 01      -90     -71     -50
```

A.1.2 Observational surface data, one station and several parameters

This format allows several parameters of one site per file. Although this is easier to produce from station records, it is less suitable for interpolation or modeling purposes where spatial data is required.

Example:

```
Name: Locarno Piazza Grande
ID: 1234
Altitude:  222  m MSL                          {meters above mean sea level}
Longitude: 7.89 decimal degrees
Latitude: 45.6  decimal degrees
UTM-E:  413429 m                               {easting}
UTM-N: 5050300 m                               {northing}
Observations start: 1998-08-24 06 +01          {ISO8601 date and time format, +01 is time zone CET}
Observations end: 1998-08-24 09 +01
#
```

```
# Free comments marked with # as first character on line
#
# This is a non-existing fantasy station
#
Number of parameters: 2
Parameter: T2M                                {one of T2M, TPR, ... see list}
Description: Temperature at 2 m AGL
Unit: 0.1 degree Celsius
Missing value code: 999
Parameter: TPR                                {repeated block for each parameter}
Description: 1 h precipitation sum            {repeated block for each parameter}
Unit: 1 kg/m2                                 {repeated block for each parameter}
Missing value code: 999
YYYY MM DD HH TZ  T2M    TPR                  {... all column-labels on same line}
1998 08 24 06 00   56      0                  {... all values for this time on same line}
1998 08 24 07 00   67      1                  {... all values for this time on same line}
1998 08 24 08 00  999     20                  {... all values for this time on same line}
1998 08 24 09 00   70     13                  {... all values for this time on same line}
```

A.1.3 Data format for model output

The model output of all meteorological models participating in RAPHAEL was provided in this format. A similar format was used for the hydrological model output.

Example:

```
Driving model: EM analysis                         {or EM forecast, ECMWF analysis, ECMWF forecast}
Driving model initial time: 1998-08-24 00 +00      {ISO 8601 date and time format, +00 is time zone UTC}
Model: SM                                          {NH, MC2, BOLAM3}
Initial time: 1998-08-24 06 +00                    {ISO 8601 date and time format, +00 is time zone UTC}
Range: 36 hours
Simulation type: Analysis                          {Analysis or Forecast mode}
Experiment: K2p                                    {Any string for version of model setup}
Mesh: 0.125 degree rotated long/lat
#
# Free comments marked with a # as first
# character on the line
#
# This is example model output, not real data
#
Parameter: T2M                                     {see list of abbreviations}
Description: Temperature at 2 m AGL
Unit: 1 degree Celsius
Dimension of field: 14, 12                         {dimension in W->E, S->N direction}
YYYY MM DD HH TZ FC     222     444                {... all heights on 1 line}
YYYY MM DD HH TZ FC  413429  423339                {... all eastings on 1 line}
YYYY MM DD HH TZ FC 5050300 5051000                {... all northings on 1 line}
YYYY MM DD HH TZ FC i01_j01 i02_j01                {... all column labels on 1 line}
1998 08 24 06 00 00     4.5     1.2                {... all values for same time on 1 line}
1998 08 24 07 00 01     5.6     2.3
1998 08 24 08 00 02     6.7     3.4
1998 08 24 09 00 03     7.8     4.5
```

A.2 Ticino-Toce catchment areas

Tables A2 and A3 give the fraction of each SM grid cell which lies within the Ticino at Miorina watershed (at the outlet of Lago Maggiore) and the combined Ticino-Maggia-Verzasca watershed (above the Lago Maggiore inlet), respectively. The grid cells are those of the Ticino-Toce subdomain as defined in Section 3.

Table A2 Fraction of SM grid cells within the Ticino at Miorina watershed (Ticino-Toce catchment area).

SM grid	84	85	86	87	88	89	90	91	92	93	94
67	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0.1	0.1	0.35	0.05	0	0
65	0	0	0	0	0.45	1	1	1	0.45	0.15	0
64	0	0	0	0.3	1	1	1	1	1	0.45	0
63	0	0	0.6	1	1	1	1	1	1	0.25	0
62	0	0	0.7	1	1	1	1	1	0.75	0	0
61	0	0.3	0.85	0.9	1	1	1	1	0.6	0	0
60	0	0	0	0.15	0.8	1	0.9	0.6	0	0	0
59	0	0	0	0	0.25	0.5	0.3	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0

Table A3 Fraction of SM grid cells within the combined Ticino, Maggia and Verzasca watershed (area simulated by the hydrological model WaSiM).

SM grid	84	85	86	87	88	89	90	91	92	93	94
67	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0.1	0.1	0.35	0.05	0	0
65	0	0	0	0	0.25	1	1	1	0.45	0.15	0
64	0	0	0	0	0.15	1	1	1	1	0.45	0
63	0	0	0	0	0.35	1	0.85	0.65	1	0.25	0
62	0	0	0	0	0.3	0.5	0.1	0	0.05	0	0
61	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0