INCA – an operational nowcasting system for hydrology and other applications

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The high-resolution analysis and nowcasting system INCA (Integrated Nowcasting through Comprehensive Analysis) provides 3-D hourly fields of temperature, humidity, and wind, and 2-D fields of cloudiness, precipitation rate, and precipitation type at an update frequency of 15 min. The system operates on a horizontal resolution of 1 km and a vertical resolution of 100-200 m. It combines surface station data, remote sensing data (radar, satellite), forecast fields of numerical weather prediction models, and high-resolution topographic data. In the alpine area, the system provides meteorological input for operational high-resolution flood forecasting and winter road maintenance. INCA employs a new radar/raingauge combination algorithm and includes elevation effects on precipitation using an intensity-dependent parameterization. In temperature analysis and nowcasting the pooling of cold air is parameterized as a function of terrain parameters. Verification results showing the skill of the nowcast compared to a numerical weather prediction model (ALADIN) are presented.

1. INTRODUCTION

Most existing observation-based forecasting systems focus on the prediction of precipitation and convective activity (BROWNING & COLLIER, 1989; LI et al., 1995; HAND, 1996; GOLDING, 1998; PIERCE et al., 2000; SEED, 2003). During the World Weather Research Program (WWRP) Forecast Demonstration Project of the 2000 Sydney Olympics several of these methods were tested and compared (PIERCE et al., 2004). In the same project, one wind analysis and nowcasting system was tested and evaluated (CROOK & SUN, 2004). However, research has generally focused not so much on forecasting the wind field as such but its effect on the initiation and development of deep convection (WILSON & SCHREIBER, 1986; WILSON et al., 2004). Similarly, analysis and nowcasting of near-surface temperature (SUN & CROOK, 2001) and humidity has traditionally been regarded as a means for predicting convective developments and not so much as a value in itself.

At the same time there is an increasing demand in public and private sectors for high-quality very-short-range forecasts of temperature, wind, global radiation, cloudiness, and precipitation. Real-time flood-warning systems are implemented based on hydrological models that require meteorological input at small scales and short lead times. Transportation planning is increasingly dependent on meteorological forecasting. Weather services face the challenge of issuing weather warnings at a high update frequency and with more precise geographical specification.

In order to satisfy these requirements the INCA system was developed. The most important operational application of the system is flood forecasting. It should be emphasized that INCA is a relatively young system still undergoing scientific and technical development. While individual components and concepts have been developed earlier (HAIDEN, 1997; 1998; 2001) actual work on the operational system has started in spring 2004. The general strategy was to start with a working baseline version to which further improvements and refinements could be added in a step-by-step process. This approach has the advantage that (a) forecasters and applications using the baseline version can provide valuable feedback at an early stage, and (b) the baseline version can be used as a benchmark against which the significance of further improvements can be measured.

The following description gives an overview of the general characteristics and data sources (Sections 2 and 3) used in INCA. The analysis and nowcasting components are described in Section 4, and verification results are presented in Section 5.

2. GENERAL CHARACTERISTICS

The INCA system provides frequently updated forecasts in the nowcasting range (up to +6 h) and improves numerical weather prediction (NWP) forecasts for up to +48 h through downscaling and bias correction. The analyses generated by INCA are not used as initial conditions for NWP model integrations and therefore not constrained by NWP model dynamics or physics. Highly structured fields are produced both in space and time without causing noise-related adverse effects in subsequent forecasts. The methods used for spatial interpolation are simple, such as distance-weighting in geometrical and physical (e.g. θ-) space. The idea behind this choice is, apart from its straightforward implementation, that the system should be as transparent as possible and the number of 'climatological' assumptions kept at a minimum. It also makes further developments and improvements easier and allows easier interpretation of results. The meteorological fields analyzed in INCA are

- Temperature (3-d)
- Humidity (3-d)
- Wind (3-d)
- Gust speed (2-d)
- Precipitation (2-d)
- Precipitation type (2-d)
- Cloudiness (2-d)
- Global radiation (2-d)

There is limited inter-dependency between fields. For example, in the nowcasting of temperature the cloudiness analysis and nowcast is taken into account. The cooling effect of thunderstorm cells due to evaporation of precipitation is considered in the analysis and nowcasting of 2m temperature. The temperature, humidity, and wind analysis will be used to assess the initiation and evolution of convective cells (STEINHEIMER & HAIDEN, 2007).
In addition to the quantities listed above, derived fields are computed. These fields are mostly convective parameters such as lifted condensation level (LCL), convective available potential energy (CAPE), or equivalent potential temperature. Other derived fields are snowfall line and surface temperature needed for precipitation type (snow, rain, snow/rain mix, freezing rain), as well as icing potential, which is however still in the experimental stage. Using snowfall line, forecasts of snowfall accumulation (water equivalent) are generated.
The high resolution of 1 km is a fundamental characteristic of INCA. It enables the system to take most station observations at 'face value', since at this resolution the actual elevation and exposition of a station coincide reasonably well with those on the numerical grid. A wind observation at a mountain pass, for example, will not be representative of conditions a few km away because of acceleration of the flow through the pass. If this observation is used to create a high-resolution 3-d wind field analysis it is important that the analysis system is able to simulate the characteristics of the location. Only then can a kinematic or dynamic downscaling procedure make proper use of the local wind observation.
From topographic maps it can be seen that a resolution of 1 km is required to resolve major alpine valleys in a way that the modelled valley floor is close to the actual valley floor height. It is a sufficient resolution to approximately reproduce slope inclinations on the sidewalls of major valleys. Side-valleys, however, are already smoothed, even at 1 km resolution. It will be part of further studies with INCA to determine the potential benefit of having even higher resolution. Another reason for using the 1 km grid is that it corresponds to the resolution of the radar data used. One of the main conceptual differences between INCA and another Austrian analysis system VERA (STEINACKER et al., 2006) is that INCA analyses use NWP model information for interpolation between observations, whereas VERA uses climatological information through a fingerprint method.
The discretization in the vertical uses a *z*-system, where *z* is the height above the 'valley floor surface' shown schematically in Figure 1. In mountainous or hilly terrain, the valley floors of

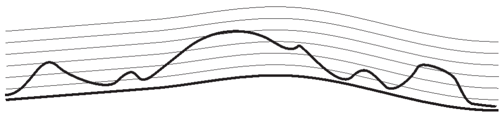

Fig. 1: Schematic depiction of INCA coordinate surfaces. The vertical coordinate is the height above the valley floor surface, which forms the base of the topography. Vertical resolution is 200 m.

adjacent valleys are generally found at comparable heights. Thus one may define a hypothetical surface that is smooth compared to the actual topography and connects major valley floors (HAIDEN, 1998). In this way the topography is conceptually separated into a base topography and a relative topography. This separation is, of course, not unique, and depends on what is considered a major valley. In practical applications, the valley floor surface is computed objectively by identifying for every gridpoint the minimum elevation within a given radius, and arithmetically smoothing the resulting field over a circle of the same radius. For alpine topography, a radius of 10 km was found appropriate. Over completely flat terrain, topography and valley floor surface coincide. The vertical resolution of INCA is currently equidistant at Δz = 200 m. The system has 21 levels (including the surface), thus it covers the lowest 4000 m above the local valley floor surface. For the wind analysis, the valley floor surface is set to zero, i.e. a true *z*-coordinate with horizontal levels is used. The vertical increment in the case of wind has been set to Δz = 125 m

3. DATA SOURCES

In the case of the 3-d INCA analyses of temperature, humidity, and wind, NWP forecasts provide the first guess on which corrections based on observations are superimposed. For this purpose the output of the limited area model ALADIN running operationally at ZAMG is used. The NWP fields are 1-hourly, at a resolution of 9.6 km, with 60 levels in the vertical (WANG et al., 2006). The INCA analysis and nowcasting methods do not depend critically on the horizontal resolution of the NWP fields and can be based on other NWP models. The Swiss version INCA-CH, for example, uses COSMO fields as a first guess.

The single most important data source for the INCA system are surface meteorological stations. ZAMG operates a network of ~250 automated stations (Teilautomatisches Wetterstationsnetz, TAWES) across the country. In the vertical, this network spans most of the topographic range in Austria, with highest stations Brunnenkogel (3440 m), and Sonnblick (3105 m). Although the distribution of stations is biased towards valley locations there is a sufficient number of mountain stations to construct three-dimensional correction fields to the NWP model output, based on observations. The station density versus elevation roughly corresponds to the area-height distribution of the topography up to about 1500 m. At higher elevations, the station density is lower than it ideally should be according to the area-height distribution.

In addition to the meteorological stations the hydrological service of Austria operates a network of real-time hydrometeorological stations, of which ~100 have already been integrated into the operational analysis system. This gives a roughly two-fold increase in station density in those areas (Fig. 2). For the hourly temperature and humidity analysis, SYNOP stations from neighbouring countries are used as well.

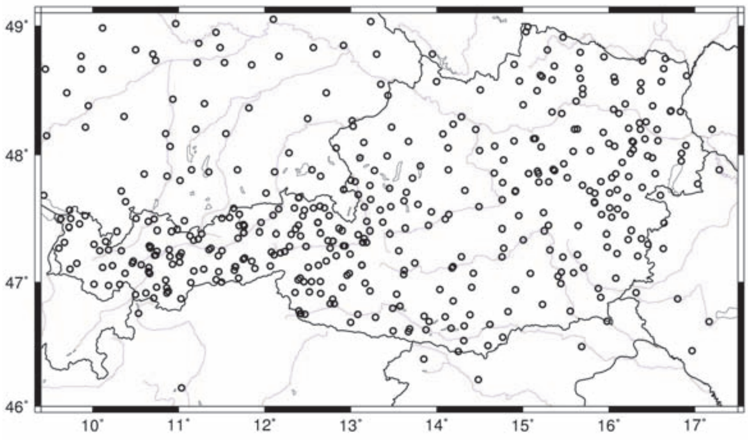

Fig. 2: Stations used operationally in the INCA temperature and humidity analysis (TAWES stations + SYNOP stations + hydrological stations).

The Austrian radar network is operated by the civil aviation administration (Austrocontrol). It consists of five radar stations located at the Vienna airport, near the city of Salzburg, near the city of Innsbruck (on Patscherkofel mountain), in northeastern Carinthia (on Zirbitzkogel mountain) and in western Austria (on Valluga mountain). ZAMG operationally obtains 2-d radar data synthesized from these 5 locations, containing column maximum values in 14 intensity categories, at a time resolution of 5 minutes. Ground clutter has already been removed from the data. However, due to the mountainous character of the country, radar data is of limited use in many areas in western Austria, especially during wintertime, when precipitation may originate from rather shallow cloud systems.
The Meteosat 2nd Generation (MSG) satellite products used in INCA are 'Cloud Type', which consists of 17 categories, and the VIS image. Cloud type differentiates mainly between different degrees of opaqueness. It also diagnoses whether clouds are more likely convective or stratiform in character. The VIS image is used to downscale the infrared-based (and thus coarser resolution) cloud types during the day.
The 1-km topography used in INCA is obtained through bilinear interpolation from the global 3'' elevation dataset provided by NASA (SRTM) (Fig. 3). For the extrapolation of 3-d ALADIN forecast fields into valleys, a 'valley floor surface' is derived from the elevation dataset. It represents the mesoscale average height of valley floors and is computed by assigning to every gridpoint the minimum elevation found within a radius of 10 km. The resulting field is smoothed with a running average 20km×20km window.

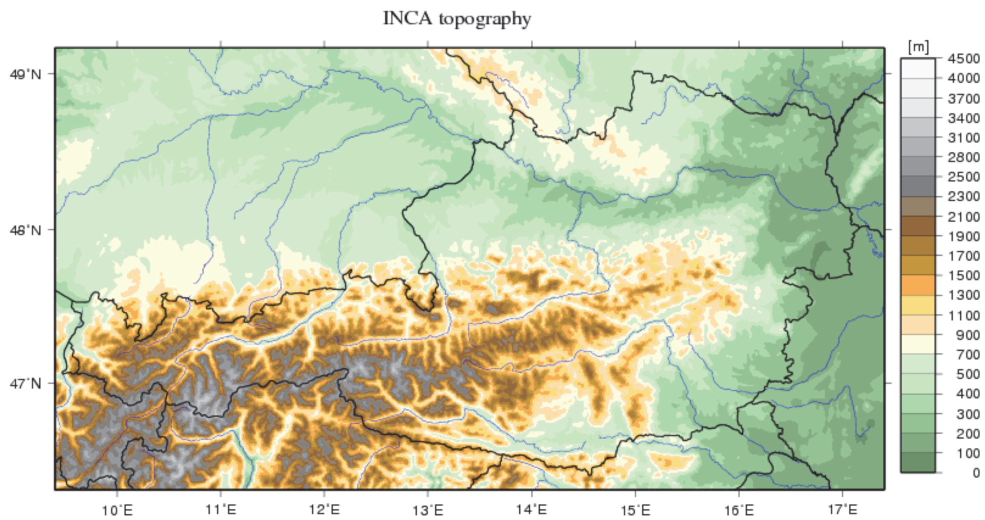

Fig. 3: INCA topography

4. ANALYSIS AND NOWCASTING

A full description of the INCA analysis and nowcasting scheme is given in HAIDEN et al. (2011). Here, a brief overview describing the methods used is presented. Those fields which are analyzed three-dimensionally (temperature, humidity, wind), are generated as follows.
First guess: The NWP fields are interpolated tri-linearly to the INCA grid (horizontal resolution 1 km, vertical resolution 200 m for temperature and humidity, 125 m for wind). Within valleys that are not represented by the NWP model, a downward shifting of the first guess to the valley-floor surface is performed.
Observation correction: Differences between station observations and first guess are interpolated three-dimensionally. The interpolation uses a distance-squared weighting method. In the horizontal, geometrical distance weighting is used, while in the vertical the distance weighting is performed in potential temperature space. The three-dimensional squared 'distance' between INCA gridpoint (i,j,m) and the k-th station is given by

$$r_{ijmk}^2 = (x_k - x_i)^2 + (y_k - y_j)^2 + c^2(\theta_k^{NWP} - \theta_{ijm}^{NWP})^2 \ ,$$

where the parameter c has the dimension of an inverse temperature gradient. Based on cross-validation its optimum value for both temperature and humidity was found to be close to $3{\cdot}10^4$ m/K. It means that a distance of 1 K in potential temperature space is equivalent to a horizontal distance of 30 km. The resulting difference field is added to the first guess, giving the final analysis (Fig. 4). In the case of wind, a relaxation algorithm is applied to ensure mass-consistency of the wind field with the INCA topography. Wind vectors at the station locations are kept at their observed values during the relaxation.

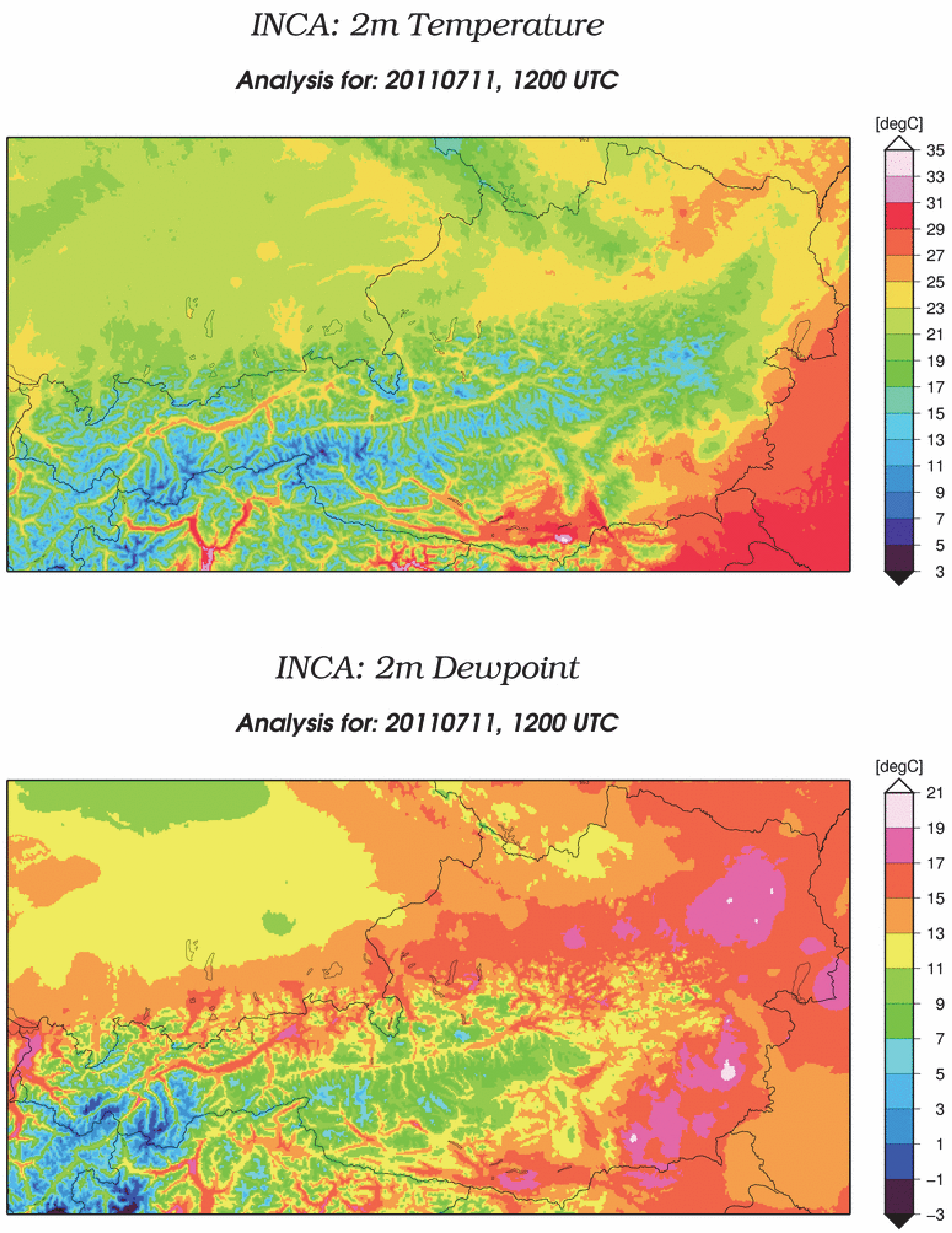

Fig. 4: Example of an INCA 2-m Temperature and Dewpoint Analysis (11/07/2011, 12Z)

Nowcast: The difference field created by interpolating the observation increments is not just added to the first guess at analysis time (+0 h) but also to the NWP forecast at subsequent times (+1 h, +2h, ..). In other words, the trend of the NWP forecast is superimposed on the most recent analysis. At lead times beyond +6 h, the INCA nowcast asymptotically merges into the bias-corrected NWP forecast. In the case of temperature, the effect of errors in the NWP cloud forecast is taken into account in the nowcast. This is especially important when low cloudiness (stratus, inversion fog), which strongly reduces the amplitude of the diurnal temperature cycle in the boundary-layer, is not well captured.

Those fields, which are analyzed two-dimensionally (precipitation, cloudiness, global radiation), are computed as follows.

Analysis: Surface station data are algorithmically combined with remote sensing data (radar in the case of precipitation, satellite in the case of cloudiness). In this way the higher quantitative accuracy of the station data, and the better spatial coverage of the remote sensing data, can be utilized. No NWP model first guess is used in the analysis of 2-d fields. The resulting analysis reproduces the observed values at the station locations. In between it contains the spatial structure given by the remote sensing data. In the case of precipitation, an intensity-dependent parameterization of elevation effects is used (HAIDEN & PISTOTNIK, 2009) in addition to the station/radar combination. Figure 5 illustrates the individual steps of the precipitation analysis procedure.

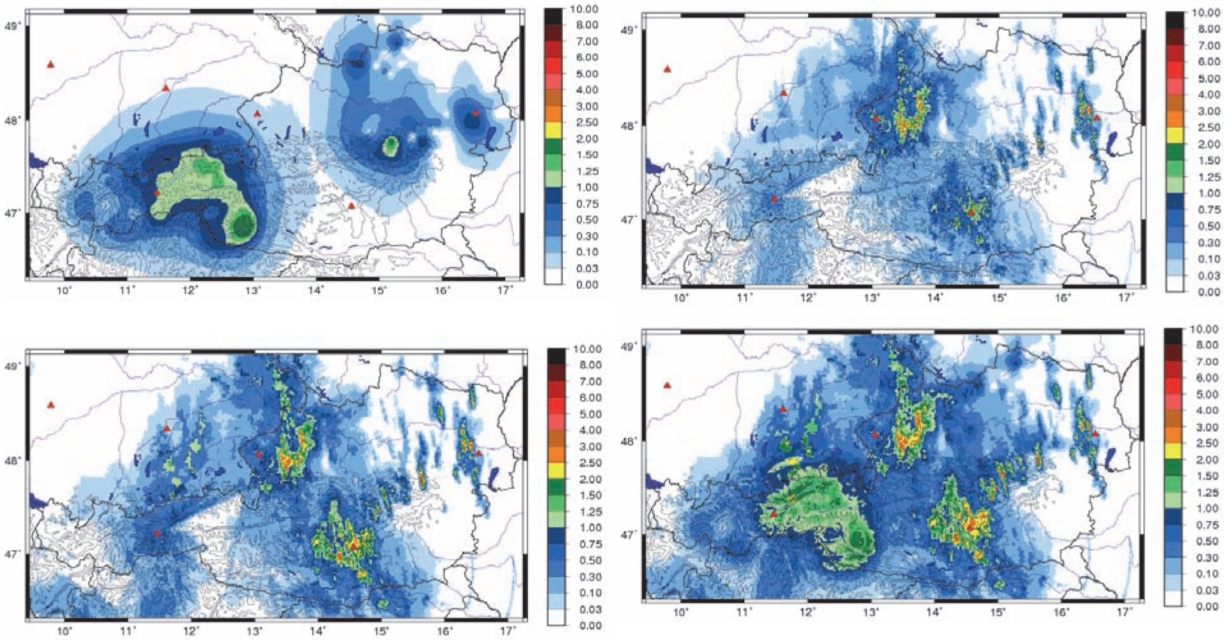

Fig. 5: Example of a 15-min INCA precipitation analysis based on the combination of station and radar data. Upper left panel (a): pure station interpolation, upper right panel (b): uncorrected radar field (Max-CAPPI), bottom left panel (c): corrected radar field, bottom right panel (d): final INCA precipitation analysis.

Nowcast: From consecutive analyses, motion vectors are computed using a correlation method. The resulting vectors are filtered statistically by setting a threshold for the correlation and meteorologically by comparing it with the NWP wind at 850 and 700 hPa. Using these vectors, the nowcast of cloudiness and precipitation is computed. Between +2 h and +6 h, the nowcast is merged with the NWP forecast with a linearly decreasing weight, so that from +6 h onwards the pure NWP forecast is used. The most important application of the INCA precipitation forecast is operational flood prediction (KOMMA et al., 2007). For improved nowcasting of convective cells (STEINHEIMER & HAIDEN, 2007) a number of additional 2-d fields (e.g. CAPE, CIN, LCL, moisture convergence) are computed.

5. VERIFICATION

Cross-validation shows that the skill of the precipitation analysis, which combines radar data, surface station data, and a parameterized elevation dependence, exceeds that of the pure radar data, and is also significantly better than pure station interpolation (Tab. 1).

Period /Type	Validation Area	Number of Analyses	Number of Stations	Relative MAE station interpolation	Relative MAE INCA analysis	Relative improvement
21.11.2008 00-12Z stratiform	Eastern Lower Austria (lowlands)	48	39	45.5%	42.3%	7%
21.11.2008 00-12Z stratiform	Salzburg (mountainous)	48	27	51.2%	46.3%	10%
28.07.2008 15-19Z convective	Salzburg (mountainous)	16	23	104.0%	55.6%	47%
03.06.2008 16-22Z convective	Tyrol (mountainous)	24	29	78.1%	64.6%	17%
04.06.2008 00-24Z strat+conv	Austria	96	260	101.5%	64.5%	36%

Tab. 1: Cross-validation of the INCA 15-min precipitation analysis for different regions and different types of precipitation events.

As can be seen from Table 1, the improvement of INCA compared to station interpolation is most pronounced in convective cases. In stratiform cases, the improvement is smaller because (a) the stations already capture a larger portion of the spatial variance of the precipitation field, and (b) spurious structures in the radar field caused by beam shielding and attenuation, bright band effects, etc. limit analysis quality.
Cross validation of the temperature analysis for a month typical of fall/winter stability conditions (Nov 2007) shows an MAE near 1 K, and an RMSE near 1.5 K. During the course of that month, the MAE averaged over all stations varied between 0.7 K (well-mixed conditions) and 1.9 K (inversion conditions, partly with Foehn effects). The difference of MAE between stations is even larger, ranging from values near 0.3 K in lowland areas with high station density, to values above 2 K in some deep alpine valleys (Tab. 2). The main reasons for large analysis errors are insufficient information about inversion heights and about patterns of Foehn-induced mixing in mountain areas.

Station	Elevation (m)	Topographic setting	BIAS (K)	MAE (K)	RMSE (K)
11035 Vienna	198	Lowland	0.0	0.3	0.4
11053 Ried	431	Lowland	-0.4	0.7	0.9
11136 Krimml	1009	Alpine valley	0.3	1.8	2.4
11127 Obergurgl	1938	Alpine valley	0.8	2.0	2.6
11126 Patscherkofel	2247	Mountain top	0.4	1.0	1.3
11343 Sonnblick	3105	Mountain top	0.9	1.5	2.1

Tab. 2: Cross-validation of the INCA 1-h temperature analysis for the whole month of Nov 2007, for stations in different topographic settings.

Averaged over all stations and seasons, the nowcast of temperature is significantly better than that of the NWP model during the first 6 hours of the forecast (Fig. 6). Beyond +6 h there is a small but non-negligible benefit from the downscaling procedure. In the classical nowcasting range the INCA forecast by roughly one-half. The bias is reduced to very small values.

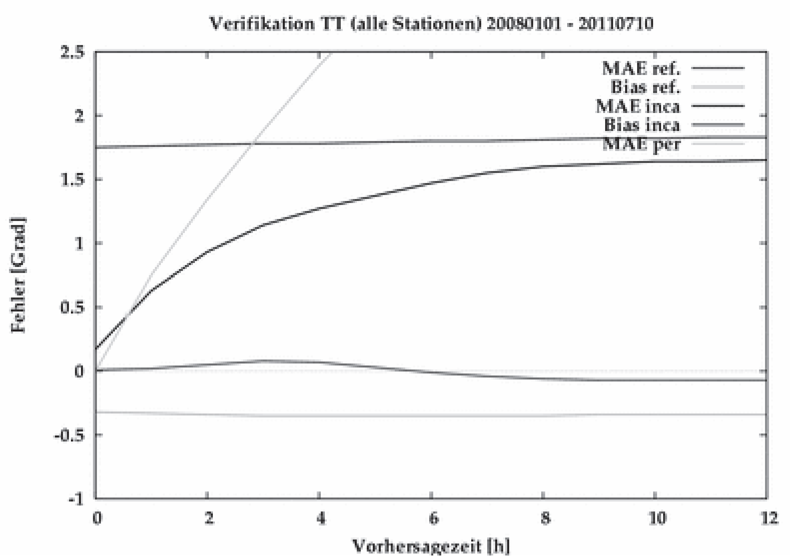

Fig. 6: 2m temperature forecast error as a function of forecast time, averaged over all stations, for the 18 month period Jan 2008 – June 2009. Red and green curves show MAE and BIAS of the reference forecast (ALADIN model). Dark blue and magenta curves show MAE and BIAS of the INCA forecast. Light blue curve indicates persistence forecast.

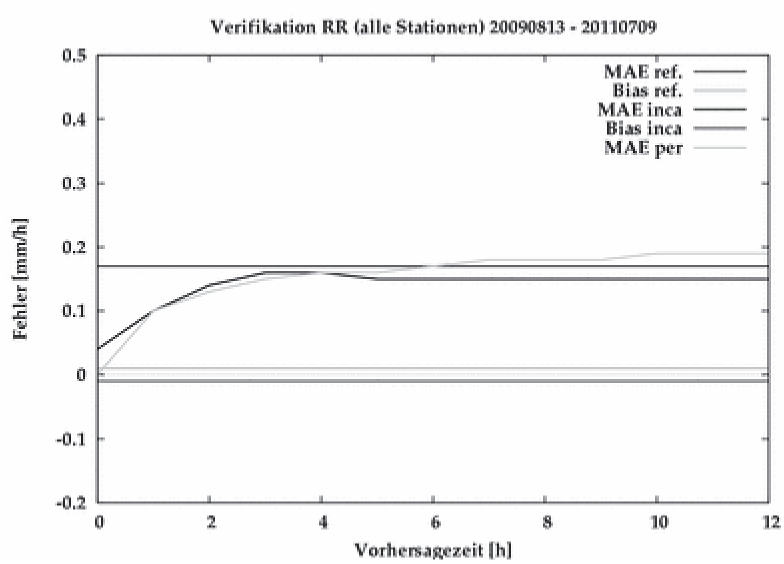

Fig. 7: 2m temperature forecast error as a function of forecast time, averaged over all stations, for the 18 month period Jan 2008 – June 2009. Red and green curves show MAE and BIAS of the reference forecast (ALADIN model). Dark blue and magenta curves show MAE and BIAS of the INCA forecast. Light blue curve indicates persistence forecast.

Verification of the precipitation nowcast shows a similar result, with significant improvements relative to the NWP forecast in the nowcasting range. However, as expected the benefit of the nowcasting vanishes earlier (at 2-3 h) (Fig. 7).

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