JOINT WMO TECHNICAL PROGRESS REPORT ON THE GLOBAL DATA PROCESSING AND FORECASTING SYSTEM AND NUMERICAL WEATHER PREDICTION RESEARCH ACTIVITIES FOR 2016

MeteoSwiss - Switzerland

1. Summary of highlights

"[Major changes in the data processing and forecasting system during the last year]"

2. Equipment in use

3. Data and Products from GTS in use

[Author: Marc Musa]

At present nearly all observational data from GTS are used. Further in use are GRIB data from Bracknell, Washington and Offenbach as well as T4-charts from Bracknell and Washington. Additionally most of MOTNE and OPMET data are used as well.

The migration from traditional ASCII Codes to BUFR messages, which has to be done country by country due to different quality of the BUFR messages, has been completed to 40 % for SYNOP and to 30% for TEMP messages from European countries.

An increase can be reported for SYNOP, TEMP and METAR, while the number of DRIFTER and AIREP/AMDAR has decreased. BUFR data amount has doubled since the last reporting.

Typical figures on message input for 24 hours are:

SYNOP	: 48552
TEMP A + B	: 4500
PILOT A + B	: 885
METAR	: 394255
TAF FT + FC	: 63311
AIREP, AMDAR	: 20609
GRIB	: 10156
BUFR	: 64972
BATHY/TESAC	: 1
DRIFTER	: 3834

4. Forecasting system

4.1 System run schedule and forecast ranges

[Authors: Philippe Steiner / André Walser / Daniel Leuenberger / Andreas Pauling / Pirmin Kaufmann]

In the operational forecasting service of MeteoSwiss several numerical models are used, depending on the forecasting range. For the very short range COSMO-1 is the primary model running every 3 hours with a forecast range of +33h (03 UTC forecast +45h). For the short to early medium range, the deterministic model COSMO-7 and the ensemble prediction system COSMO-E are available. COSMO-7 runs 4 times a day with a forecast range of +72h, while COSMO-E runs twice a day with a forecast range of +120h.

For the medium range forecasts and in part also for the short range the IFS of ECMWF with the high resolution model HRES and the ensemble prediction system ENS are mainly used. Additionally the HRES results are compared with the US model GFS.

Furthermore the forecasters have access to post processed data such as Kalman Filter and Model Output Statistics (MOSMIX by DWD) and INCA by ZAMG.

For the interpretation by the forecasters the model data are presented with the visualization system Ninjo (developed by a consortium of several meteorological services). In addition the COSMO fields can be visualized with a browser tool, and the ECMWF fields with ecCharts (an ECMWF webtool).

In the case of a nuclear incident, the forecasters have the possibility to start trajectory and diffusion calculations for the support of the emergency response authorities. For trajectories, the Lagranto model provides calculations with input data of COSMO-1, COSMO-7 and ECMWF HRES. For diffusion calculations, the FLEXPART model is used based likewise on COSMO-1, COSMO-7 and ECMWF HRES input data. Additionally NOAA HYSPLIT calculations are used as supplement and backup.

Short range

Medium and extended range forecasting are based on external NWP sources, but MeteoSwiss runs their own short- to early medium-range forecasting systems. The core of this system is the non-hydrostatic model COSMO (of the Consortium for Small-Scale Modelling).

At MeteoSwiss, the model is running operationally at three spatial scales: The local models COSMO-1 with a horizontal grid-spacing of 1.1 km (0.01 degrees) and COSMO-E with a horizontal grid-spacing of 2.2 km (0.02 degrees), as well as the regional model COSMO-7 with a horizontal grid-spacing of about 6.6.km (0.06 degrees). COSMO-1, COSMO-7 and COSMO-E are driven by the ECMWF global model HRES and ENS, respectively. The nesting procedure and model domains of COSMO-1 and COSMO-E is illustrated in Figure 1.

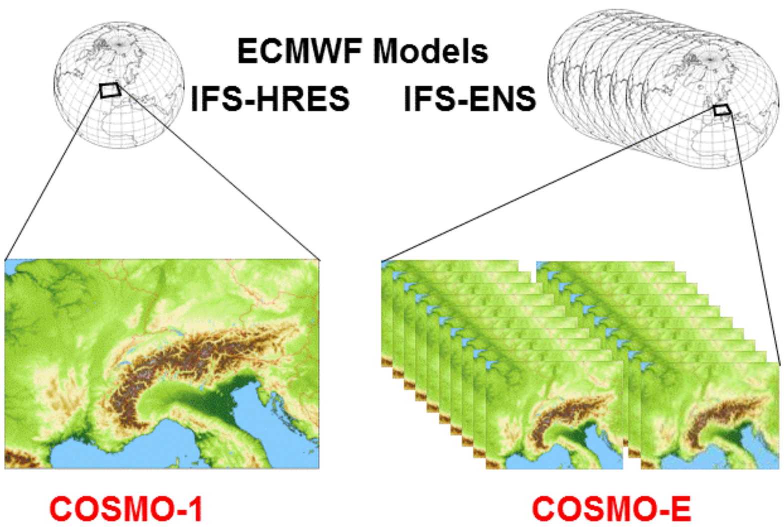

Figure 1. Main NWP system of MeteoSwiss and their nesting in HRES and ENS, respectively.

Both COSMO-1 and COSMO-7 have their own nudging assimilation cycle, which is updated in intervals of 3 hours and 6 hours, respectively. COSMO-E is initialized by a kilometric ensemble data assimilation system (KENDA). The cut-off time for all cycles is 45 minutes.

A sophisticated set of scripts controls the whole operational suite, and allows for a very high reliability of the system, with less than 2% of the forecasts requiring manual intervention. This same environment is also used to run parallel suites, to validate proposed modifications to the system, and to facilitate experimentation by the modelling group.

The computing resources and expertise are provided by the Swiss National Supercomputing Centre (CSCS, see www.cscs.ch). COSMO-1, COSMO-7 and COSMO-E are calculated on a two cabinets Cray CS-Storm equipped with NVIDIA Tesla K80 GPUs and Intel Haswell 12-cores CPUs. The two cabinets hosts identical and independent systems called escha (production) and kesch (R&D and failover). COSMO-1 runs on 9 nodes using 144 GPUs and 18 CPUs and requires 35 minutes for a 33h forecast-. Pre- and post-processing run on 5 service nodes with Intel Haswell CPUs of the system. A large multi-terabytes long term storage is used for archiving purposes and a 1 GBit/s link connects the MeteoSwiss main building with the CSCS (Swiss Center for Scientific Computing, located in Lugano, on the southern side of the Alps).

4.2 Medium range forecasting system (4-10 days)

-/-

4.2.1 Data assimilation, objective analysis and initialization

4.2.1.1 In operation

"[information on Data assimilation, objective analysis and initialization]"

-/-

4.2.1.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

4.2.2 Model

-/-

4.2.2.1 In operation

"[Model in operational use, *(resolution, number of levels, time range, hydrostatic?, physics used)*] "

-/-

4.2.2.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

4.2.3 Operationally available Numerical Weather Prediction Products

"[brief description of variables which are outputs from the model integration]"

-/-

4.2.4 Operational techniques for application of NWP products *(MOS, PPM, KF, Expert Systems, etc..)*

-/-

4.2.4.1 In operation
"[brief description of automated (formalized) procedures in use for interpretation of NWP ouput]"

-/-

4.2.4.2 Research performed in this field
"[Summary of research and development efforts in the area]"

-/-

4.2.5 Ensemble Prediction System (EPS)

4.2.5.1 In operation
"[Number of runs, initial state perturbation method, perturbation of physics?]" *(Describe also: time range, number of members and number of models used: their resolution, number of levels, main physics used, perturbation of physics, post-processing: calculation of indices, clustering)*

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4.2.5.2 Research performed in this field
"[Summary of research and development efforts in the area]"

-/-

4.2.5.3 Operationally available EPS Products

A neural classification scheme is in application based on ECMWF/IFS-ENS to provide forecasters with guidance related to medium range forecasts up to 240 hours.

4.3 Short-range forecasting system (0-72 hrs)

[Authors: Philippe Steiner / André Walser / Daniel Leuenberger / Andreas Pauling / Pirmin Kaufmann / Xavier Lapillonne / Stephanie Westerhuis / Jean-Marie Bettems / Daniel Cattani / Jonas Bhend / Christoph Spirig / Mark Liniger]

4.3.1 Data assimilation, objective analysis and initialization

4.3.1.1 In operation
Data assimilation of COSMO-1 and COSMO-7 is based on the nudging or Newtonian relaxation method, where the atmospheric fields are forced towards direct observations at the observation time. Balance terms are also included: (1) hydrostatic temperature increments balancing near-surface pressure analysis increments, (2) geostrophic wind increments balancing near-surface pressure analysis increments, (3) upper-air pressure increments balancing total analysis increments hydrostatically. A simple quality control using observation increments thresholds is in action.
For the initialization of the COSMO-E ensemble system, a Local Ensemble Transform Kalman Filter (LETKF) based data assimilation system using 40 ensemble members is employed, similar to that described in Schraff et al. (2016).
The following conventional observations are currently assimilated in the COSMO assimilation systems: synop/ship/buoys (surface pressure, 2m humidity (nudging only), 10m wind for stations below 100 m above msl), temp/pilot (wind, temperature and humidity profiles), airep/amdar (wind, temperature) and wind profiler data. COSMO-1 and KENDA additionally assimilate radar data, using the 2-dimensional latent heat nudging scheme. An empirical quality function for radar

quantitative precipitation estimates is in operation, which is based on the frequency of signal occurrence of a particular radar pixel (Leuenberger et al (2010) and references therein).
MeteoSwiss uses its own snow analysis which is derived from MSG satellites combined with dense observations. A multi-layer soil model with 8 layers for energy and 6 for moisture is used. Finally, the vegetation and ozone fields are based on climatic values.
The MeteoSwiss Data Warehouse (DWH) is the operational data base for conventional observations. Data from DWH is retrieved at CSCS in BUFR format, and converted to the NetCDF format with the bufrx2netcdf software of DWD. The number of assimilated conventional observations is monitored.

4.3.1.2 Research performed in this field

KENDA currently provides the initial data for COSMO-E. It is planned to use the deterministic analysis of the LETKF for COSMO-1 by downscaling the assimilation increments to the COSMO-1 mesh. To account for systematic model errors in KENDA, additive perturbations will be developed based on past model forecast differences as a proxy for parts of the model error. It is also planned to extend the KENDA system by additional observations such as 2m temperature and humidity from SYNOP, humidity and temperature profiles from Raman Lidar in Payerne as well as radar volume reflectivity and radial winds and satellite observations.

4.3.2 Model

4.3.2.1 In operation

A thorough description of the COSMO Model itself can be found on the COSMO web site. It is a primitive equation model, non-hydrostatic, fully compressible, with no scale approximations. The prognostic variables both for all operational variants of COSMO are the pressure perturbation, the Cartesian wind components, the temperature, the specific humidity, the liquid water content, cloud ice, rain, snow and turbulent kinetic energy. COSMO-1 and COSMO-E furthermore use a prognostic graupel (ice pellets) hydrometeor class in the microphysical parameterization. COSMO-7 uses the Tiedtke scheme to parameterize convection, whereas in COSMO-1 and COSMO-E convection is parameterized by a shallow convection scheme, and the deep convection is explicitly computed.

The model equations are formulated on a rotated latitude/longitude Arakawa C-grid, with generalized terrain-following height coordinate and Lorenz vertical staggering. Spatial discretization is done using finite differences of at least second-order; time integration is based on a third-order Runge-Kutta split-explicit scheme. Advection of dynamic variables is performed using a fifth-order upstream discretization. Fourth-order linear horizontal diffusion with an orographic limiter is active for wind in COSMO-7 only. Rayleigh-damping is applied in the upper layers. For the advection of the humidity constituents, a symmetric, Strang-splitted positive-definite advection scheme after Bott is used is used at each time step.

COSMO-7 is calculated on a 393 x 338 mesh with a 3/50° mesh size (about 6.6 km), on a domain covering most of Western Europe. 60 layers are implemented in the vertical, whereas the vertical resolution in the lowest 2 km of the atmosphere increases from about 10 m up to 250 m. The main time step is 60 seconds. Table 1 summarizes the specifications of the newly introduced COSMO-1 and COSMO-E configuration.

	COSMO-1	COSMO-E (21 members)
Number of grid points and levels	1158 x 774, 80L	582 x 390, 60L
Horizontal mesh size	1/100° ~ 1.1km	1/50° ~ 2.2km
Time step	10s	20s
Data Assimilation	Conv. Observations + Radar	Conv. Observations + Radar

Table 1 Specification of COSMO-1 and COSMO-E

MeteoSwiss provides pollen forecasts which are based on the numerical pollen dispersion model COSMO-ART of the Karlsruhe Institute of Technology (KIT) (Vogel et al, 2009, and Vogel et al, 2008). Simulated species include birch (since 2011), grass (since 2012), Ambrosia (since 2014) and alder (since 2016/17). COSMO-ART is activated in both the COSMO-7 and the COSMO-1 configuration. COSMO-1 gets the pollen boundaries from COSMO-7.

The GPU version of COSMO
Compiler directives and a domain-specific embedded language (DSEL) named STELLA, made it possible to create a GPU version of COSMO. This version is now operationally used for weather forecasting and climate research on a hybrid system named Piz Kesch (Cray CS Storm). This GPU-version of the code brings significant benefits both in terms of time-to-solution as well as in energy-impact for typical use-cases of the COSMO model.

4.3.2.2 Research performed in this field
Within the framework of a dissertation we are investigating possibilities to improve fog and low stratus forecasts. The current focus lies on better representation of the microphysics and soil processes.

Some further work has been carried out to increase performance portability, i.e. achieving optimal performance on different architectures using a single source code. A new domain specific library GridTools, more general, is being developed and will replace STELLA, in addition a complementary source to source translation tool, CLAW, is being developed to automatized code transformation for a given architecture.

4.3.3 Operationally available NWP products
"[brief description of variables which are outputs from the model integration]"
-/-

4.3.4 Operational techniques for application of NWP products
MeteoSwiss has developed and maintains "fieldextra", a tool aimed at producing and delivering complex packages of numerical weather forecasts. An official COSMO software, fieldextra is used both as a pre- and post-processing instrument on the MeteoSwiss NWP production suite.

Designed as a toolbox, robustly written and thoroughly tested, fieldextra supports the manipulation of NWP model data, especially COSMO model data, and gridded observations. Input data is read once by the execution of the software, as many products as desired can be delivered. In between, a set of operators that can be combined in any meaningful way allows the construction of the aforementioned products. The program is controlled by a collection of Fortran namelists, stored in a control data file. Checks are performed on user defined parameters, with a diagnostic report delivered by the end of each execution. Simple data operations, as well as demanding processing is supported. As for example, selection of data satisfying convoluted constraints, the comparison and/or merging of multiple fields, horizontal and vertical re-gridding, computation of regional conditions, stability indices or EPS derived quantities are easily performed. Both point values and gridded fields can be generated. GRIB 1, GRIB 2, NetCDF and a rich set of ASCII formats are offered. Last but not the least, a major effort is continuously devoted to the optimization of both the memory footprint and the execution time. Fieldextra is increasingly used as a standard software among the COSMO community.

4.3.4.1 In operation: Man-machine NWP-processing technique
Since end of 2014, a new system is operationally providing localized hourly values to >5000 sites covering Switzerland, from actual time to seven days ahead. This system, called “data4WEB”, combines high resolution meteorological model fields (COSMO-1, COSMO-E, INCA and the

ECMWF's IFS model), observations, and the expertise of human forecasters in order to provide high quality and very localized forecasts.
The algorithms developed for data4WEB use different adaptation techniques to adapt raw NWP fields to the input given by forecasters on a regional scale. Each predicted variable is treated in a specific way in order to take into account its physical properties and the complex topography of Switzerland. This "man-machine" system allows forecasters to influence NWP fields at a regional scale to modify, whenever necessary, errors or case specific biases of the model. An update cycle of the whole procedure is performed every 30 minutes to ensure that the forecasts provided to the end-users are refreshed shortly after every forecaster's intervention and after each new NWP input. This efficiency guarantees a fast reaction time, for instance in the case of mismatches between model forecasts and observations.

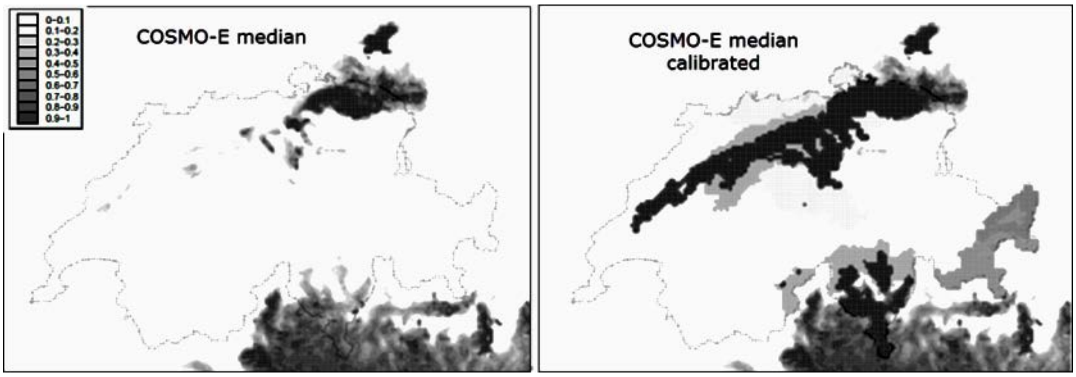

Figure 2. Adjusting high-resolution NWP (COSMO-E median) with regionally aggregated estimate by forecaster. On the left the original NWP cloud field, on the right same field after integrating forecaster's input.

4.3.4.2 Research performed in this field
"[Summary of research and development efforts in the area]"

4.3.5 Ensemble Prediction System

4.3.5.1 In operation
COSMO-E is a 21 member ensemble with an unperturbed control run and 20 perturbed runs, and started the operational production in May 2016. All member use the non-hydrostatic COSMO model, operated at a 2.2 km grid on the broad Alpine area and with a forecast range of 120 hours. Initial condition perturbations are taken from the ensemble data assimilation system KENDA, lateral boundary conditions perturbations from the ECMWF ENS, and model perturbations are based on stochastic perturbations of physical tendencies (SPPT).

4.3.5.2 Research performed in this field
As other limited-area ensemble prediction system, COSMO-E is generally underdispersive in the short-range and near surface. Another issue is a lack of convection triggering over flat terrain. Therefore, the current research focuses on the spread-skill relationship and additional perturbation in the boundary layer.
Moreover, we examined different methods to select initial and lateral boundary conditions for COSMO-E. Currently, the first 20 members of KENDA and IFS-ENS are used to initialize and drive COSMO-E. This represents a random selection. We could show that the forecasts could be improved by using a cluster analysis based on temperature, humidity and wind fields to select the driving IFS-ENS members. The effect from different the initial condition selections was negligible, also in the short-range. However, there may be potential to improve the very short-range forecasts by a targeted selection of initial conditions.

4.3.5.3 Operationally available EPS Products

"[brief description of variables which are outputs from the EPS"

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4.4 Nowcasting and Very Short-range Forecasting Systems (0-12 hrs)

4.4.1 Nowcasting system

4.4.1.1 In operation

"[information on processes in operational use, as appropriate related to 4.4]"

(Note: please also complete the CBS/PWS questionnaire on Nowcasting Systems and Services, 2014)

Tracking and characterization of convective cells by radar (system TRT)

MeteoSwiss runs operationally the real-time object-oriented nowcasting tool TRT (Thunderstorms Radar Tracking), as a part of its severe thunderstorms nowcasting, warning and information system. TRT is a multiple-radars nowcasting system that uses heuristic and centroid-based methods for the automatic detection, tracking and characterisation of intense convective cells.

During the summer season, based on the TRT, MeteoSwiss starts the diffusion, by local and national radio stations, of heavy thunderstorms warnings in whole Switzerland for the general public as well as to civil protection authorities, with simple flash-news, with a lead time of 30-120 min (Hering et al., 2005).

TRT is based on a dynamic thresholding scheme applied on the reflectivity data of multiple-radar composites (Hering et al., 2004). The dynamic scheme is able to identify each storm object at individual thresholds, depending on the stage of its life cycle. A detected storm cell is tracked in successive images using the method of the geographical overlapping of cells. It is then possible to create the time history of cell displacement, and tracks are created from a sequence of radar images. Since TRT is tuned to identify individual cells rather than storm systems, the evolution of cell-based characteristics is available to the forecasters. Complex cases with several cells, splits and merges are also taken into account.

As input the TRT uses the reflectivity data of the Swiss composite image of 4 volumetric, dual-polarization, C-Band Doppler radars with a time resolution of 5 minutes. A 20-elevation volume scan between -0.2° and 40° is performed operationally. For the cell detection we use the vertical maximum projection between 1 and 18 km.

In order to explore the capability of the tool to assess the severe weather potential of thunderstorms, TRT fully exploits 3D-radar data and has been expanded to a multiple-sensors system including cloud-to-ground lightning data with both polarities (Hering et al., 2006). Cell characteristics describing the 3D storm structure and properties as well as the accompanying time series, are computed from the volumetric radar data. These parameters include grid- and cell-based 15/45 dBZ echo tops, VIL (Vertically Integrated Liquid), as well as the altitude of the maximum storm reflectivity. To compute the multiple-radar severe storms detection products TRT uses the 3D Cartesian composite image of the Swiss radar network.

TRT also runs a heuristic cell severity ranking algorithm (Hering et al. 2008). This algorithm integrates the most significant radar-based severity attributes from the 3D storm structure into a single numerical parameter, in order to assess the potential danger posed by the individual cells. The severity rank is computed by integrating the cell-based attributes VIL, the EchoTop 45dBZ altitude, the maximum cell reflectivity, and the area above 55 dBZ with a fuzzy-logic-like scheme.

For a detailed description see:

Hering, A. M., C. Morel, G. Galli, S. Sénési, P. Ambrosetti, and M. Boscacci, 2004: Nowcasting thunderstorms in the alpine region using a radar based adaptive thresholding scheme. Proceedings, Third ERAD Conference, Visby, Sweden, 206-211. www.copernicus.org/erad/2004/online/ERAD04_P_206.pdf

Hering, A. M., S. Sénési, P. Ambrosetti, and I. Bernard-Bouissières, 2005: Nowcasting thunderstorms in complex cases using radar data. Proceedings, World Weather Research

Programme's Symposium on Nowcasting and Very Short Range Forecasting (WSN05), Toulouse, France, September 5-9, 7 pp. www.meteo.fr/cic/wsn05/resumes_longs/2.14-73.pdf

Hering, A. M., U. Germann, M. Boscacci, and S. Sénési, 2006: Operational nowcasting of thunderstorms in the Alpine region using 3D-radar severe weather parameters. Proceedings, Fourth ERAD Conference, Barcelona, Spain, 453-456. www.grahi.upc.edu/ERAD2006/proceedingsMask/00122.pdf

Hering, A. M., U. Germann, M. Boscacci, and S. Sénési, 2008: Operational nowcasting of thunderstorms in the Alps during MAP D-PHASE. In Proceedings of 5th European Conference on Radar in Meteorology and Hydrology (ERAD), 30 June–4 July 2008, Helsinki, Finland. pp. 5. Copernicus: Goettingen, Germany.

Quantitative precipitation estimation by radar (product RAIN)

The quantitative precipitation estimate (QPE) Nowcasting radar product RAIN was developed to meet both the meteorologist's and the hydrologist's requirements. It is the best radar estimation of precipitation amount on the ground in Switzerland. The RAIN product is the result of sophisticated correction algorithms for radar operation in the Alps. Data processing includes automatic hardware calibration, adjustment with gauge measurements, 8-step dynamic elimination of ground echoes, frequency-based residual ground echo removal, and correction for beam shielding and vertical reflectivity profile (Germann et al. 2006).

For a detailed description see:

Germann, U., G. Galli, M. Boscacci, and M. Bolliger, 2006: Radar precipitation measurement in a mountainous region. Q. J. R. Meteorol. Soc., 132, 1669-1692.

Real-time radar-raingauge merging (CombiPrecip)

CombiPrecip aims to produce accurate precipitation estimation maps by combining raingauges and radar data in real-time. The underlying technology is geostatistical in nature, where both spatial and temporal information has been taken into account in a so called co-kriging with external drift modelling scheme. The technique is coupled with innovative engineering to mitigate artifacts in the extrapolation regime and in the presence of strong convective cells where lack of sufficient representativeness of raingauge data typically causes problems. CombiPrecip is running operationally at MeteoSwiss and shows a significant improvement over radar-only rainfall maps especially in terms of bias.

For a detailed description see:

Sideris I.V., M. Gabella, R. Erdin and U. Germann, 2014. Real-time radar-raingauge merging using spatiotemporal co-kriging with external drift in the alpine terrain of Switzerland, Q. J. Roy. Meteor. Soc. 140: 1097-1111.

Context and Scale Oriented Thunderstorm Satellite Predictors Development (COALITION)

Through a 3-year fellowship funded by EUMETSAT MeteoSwiss has developped a nowcasting applications into an entity-oriented model, which merges severe convection predictors retrieved from different sources (MSG, Weather Radars, NWP, lightning climatology and orographic gradients) with evolving thunderstorm properties. The heuristic model calculates probabilistic information about time, space and intensity evolution of severe convection for use by decision makers. Focus is given to early detection of severe storms over the European Alpine region. The project was terminated in 2012 and at MeteoSwiss the system runs now in real-time, in an operational mode.

For a detailed description see:

L. Nisi, P. Ambrosetti and L. Clementi, 2014. Nowcasting severe convection in the Alpine region: the COALITION approach. Q. J. R. Meteorol. Soc. 140: 1684–1699. DOI: 10.1002/qj.2249.

Automatic precipitation alerts: NowPAL

MeteoSwiss recently introduced NowPAL (NOWcasting of Precipitation AccumuLations), a novel operational nowcasting system specifically designed to issue heavy rainfall alerts over pre-defined geographical regions in Switzerland.

Since the impact of heavy precipitation strongly depends on the immediate past rainfall, the tool combines the past observed precipitation accumulation with the forecast rainfall field. The total rainfall is then evaluated within pre-defined geographical regions and compared with threshold values in order to issue the alerts. The thresholds used for the alerts are the rainfall values corresponding to specific return periods. Since it is fully configurable, the system is appropriate to issue automatic alerts for different customers and applications, ranging from the general alerts for the 159 Swiss official warning regions to more specific alerts for small urban areas or alpine catchments.

For a detailed description see:

Panziera L., Gabella M., Zanini S., Hering A., Germann U., and Berne A., 2016: A radar-based regional extreme rainfall analysis to derive the thresholds for a novel automatic alert system in Switzerland. Hydrol. Earth Syst. Sci., 20, 2317–2332.

Automatic heavy thunderstorm alerts: Flash-O-matic

In case of severe thunderstorms MeteoSwiss alerts authorities and the population by means of flash-news warnings with a lead-time of some tens of minutes. These short-term warnings are based mainly on the operational, multi-sensor nowcasting system TRT (see Chap. 4.4.1.1). Although the current nowcasting systems run automatically, the final decision for the warning and its release are taken by the forecaster on duty. To speed up the whole warning process and to allow the final users (such as emergency services, authorities, and the general public) to save several minutes to take action, MeteoSwiss recently introduced the short-term, small-scale fully automated operational thunderstorm warning system Flash-O-matic. The full warning chain is completely automatized, including decision making and warning issuing by SMS. The tool allows a user to receive thunderstorm information for a given specific location directly and automatically on his phone whenever the system detects an approaching cell.

The new Flash-O-matic algorithm integrates the cell severity ranking product and the latest cell motion vectors from the TRT system to extrapolate cell position; it also accounts for the forecast uncertainty. Alerts are characterized by four intensity levels. They are computed every 5 minutes for the next 30 minutes and are issued for every ZIP code (mean size of about 10 km^2 in populated areas).

For a detailed description see:

Hering A., Nisi L, Della Bruna G., Gaia M., Nerini D., Ambrosetti P., Hamann U., Trefalt S., and Germann U., 2015: Fully automated thunderstorm warnings and operational nowcasting at MeteoSwiss. Proceedings European Conference on Severe Storms (ECSS), 14–18 September 2015, Wiener Neustadt, Austria, ECSS2015-80-1.

4.4.1.2 Research performed in this field

"[Summary of research and development efforts in the area]"

Ensemble technique for radar precipitation fields (technique REAL)

As part of the WMO-WWRP forecast demonstration project MAP D-PHASE and the European concerted research action COST-731 MeteoSwiss developed an ensemble technique to characterize the residual errors in radar precipitation fields. Each member of the radar ensemble is a possible realization of the unknown true precipitation field given the observed radar field and knowledge of the space-time error structure of radar precipitation estimates. Feeding the alternative realizations into a hydrological model yields a distribution of response values, the spread of which represents the sensitivity of runoff to uncertainties in the input radar precipitation field. The presented ensemble generator is based on singular value decomposition of the error covariance matrix, stochastic simulation using the LU decomposition algorithm, and autoregressive filtering. The real-time implementation of the radar ensemble generator coupled with a semi-distributed hydrological model in the framework of MAP DPHASE is one of the first experiments of this type worldwide.

For a detailed description see:

Germann, U., Berenguer M., Sempere-Torres, D. and Zappa M., 2009: REAL – Ensemble radar precipitation estimation for hydrology in a mountainous region. Q. J. R. Meteorol. Soc., 135, 445-456.

Nowcasting heavy orographic precipitation using Doppler radar and radiosounding (project COST-731)

MeteoSwiss developed as part of COST-731 a novel heuristic system for nowcasting heavy precipitation in the Alps. The system uses as input estimates of the mesoscale wind field as derived from real-time Doppler radar measurements and information on air mass stability from radio-soundings and ground stations. Both mesoscale flow and upstream air mass stability are predictors of the amounts and geographic distribution of heavy orographic precipitation, and can therefore be exploited for nowcasting. Since 2012 the system runs at MeteoSwiss in real-time, in a pre-operational mode.

For a detailed description see:

Panziera L, Germann U. 2010. The relation between airflow and orographic precipitation on the south-ern side of the Alps as revealed by weather radar. Q. J. R. Meteorol. Soc. 136: 222–238. DOI:10.1002/qj.544

Improving Preparedness and Risk Management for Flash Floods and Debris Flow Events (project IMPRINTS)

Over complex terrain such as the Alps current nowcasting systems based on Lagrangian persistence of radar precipitation fields fail to produce useful forecasts, because the orography interferes with the evolution of precipitation, in particular by means of blocking and enhancement. As part of the FP7 research project IMPRINTS (2009-2012), MeteoSwiss investigates orographic forcing of precipitation and incorporate the findings into current Lagrangian persistence nowcasting systems. If successful, the resulting radar nowcasting system will be implemented in the Swiss radar data processing chain and will be extended by ensemble techniques and an algorithm for blending radar nowcasts with NWP model output.

For a detailed description see:

Panziera, L., U. Germann, M. Gabella and P. V. Mandapaka, 2011. NORA–Nowcasting of Orographic Rainfall by means of Analogues. Q. J. R. Meteorol. Soc. 137: 2106–2123

Mandapaka, P.V., U. Germann, L. Panziera and A. Hering, 2011. Can Lagrangian Extrapolation of Radar Fields Be Used for Precipitation Nowcasting over Complex Alpine Orography?, Weather and Forecasting, 27: 28-49

Mandapaka, P.V., U. Germann, L. Panziera, 2013. Diurnal cycle of precipitation over complex Alpine orography: inferences from high resolution radar observations. Quarterly Journal Royal Met. Soc. 139: 1025-1046. DOI: 10.1002/qj.2013.

Panziera, L., C. N. James and U. Germann, 2015. Mesoscale organization and structure of orographic precipitation producing flash floods in the Lago Maggiore region. Q. J. R. Meteorol. Soc., 141: 224-248. DOI: 10.1002/qj.2351.

4.4.2 Models for Very Short-range Forecasting Systems

4.4.2.1 In operation

"[information on models in operational use, as appropriate related to 4.4]"

Integrated Nowcasting through Comprehensive Analysis (INCA)

The nowcasting analysis and forecasting system INCA, developed by the Austrian NWS ZAMG is run operationally at MeteoSwiss. This novel approach produces meteorological fields, with high resolution in time and space (gridded values) for several parameters, incorporating available information like numerical models and diverse kinds of observation (both in-situ and remote sensed), as well as high resolution orography. Several customer oriented products have been developed und made operational, particularly for the rain and snow forecast of in the Nowcasting range (both internally and externally).

4.4.2.2 Research performed in this field

"[Summary of research and development efforts in the area]"

Integrated Nowcasting through Comprehensive Analysis (INCA)

The interpolation algorithm between NWP model and INCA 3D-grid has been further optimized for use with very high resolution NWP models data (horizontal grid size 1-2 km). The vertical interpolation weights for temperature and humidity corrections have been modified. The overall performance for temperature and humidity has been improved. The update frequency has been increased to 10 min for all the parameters.

4.5 Specialized numerical predictions

[Specialized NP on sea waves, storm surge, sea ice, marine pollution transport and weathering, tropical cyclones, air pollution transport and dispersion, solar ultraviolet (UV) radiation, air quality forecasting, smoke, sand and dust, etc.]

-/-

4.5.1 Assimilation of specific data, analysis and initialization (where applicable)

4.5.1.1 In operation

"[information on the major data processing steps, where applicable]"

-/-

4.5.1.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

4.5.2 Specific Models (as appropriate related to 4.5)

[Authors: Pirmin Kaufmann / Andreas Pauling / Dominique Ruffieux / Alexander Haefele / Laurent Vuilleumier]

4.5.2.1 In operation

The pollen module of the numerical dispersion model COSMO-ART (Vogel et al. 2008) was developed by the Karlsruhe Institute of Technology (KIT) in collaboration with MeteoSwiss. Daily runs with COSMO-ART performed by MeteoSwiss provide high-resolution pollen forecasts. Pollen concentrations are calculated by both the COSMO-7 and the COSMO-1 setups as described in chapter 4.3.2.1. COSMO-1 (domain greater Alpine area) makes use of pollen boundaries provided by COSMO-7 (domain central and southern Europe). This ensures the presence of pollen in COSMO-1 that were transported over large distances. Modelled pollen species include alder, birch, grasses and Ambrosia. Modelled pollen concentrations were provided to various European pollen information services on a daily basis.

CN-MET is an integrated analysis and forecasting system consisting of a high resolution numerical weather prediction model and a dense surface and upper air observation network. Upper air observations are performed with three radar wind profilers and 3 microwave radiometers for temperature and humidity profiling. CN-MET provides meteorological information for dispersion calculations in the case of an accident in a nuclear power plant.

The dispersion of airborne radioactive nuclides is modelled using the FLEXPART model. FLEXPART is a freely available Lagrange particle dispersion model that has been adapted for use with the COSMO model input by the Swiss institute EMPA. The dispersion calculations are based on the two operational resolutions of the COSMO model at MeteoSwiss and the ECMWF HRES and are run in both routine and on-demand mode.

The LAGRANTO tool of the Federal Institute of Technology (ETH) is used to calculate trajectories for the determination of air mass origin, for ballooning predictions, and for fast estimates of the dispersion path of airborne pollutants for emergency response.

4.5.2.2 Research performed in this field

A) The teams of numerical weather prediction (NWP) and ground-based remote sensing are working together on the assimilation of newly available remote-sensing data.

Based on O-B analyses (see previous report) we expect that humidity data from Raman lidar could be particularly beneficial for NWP for runs when no radiosonde is available. Humidity from the lidar is most efficiently assimilated in the COSMO model together with temperature such that the existing observation type TEMP can be used. This required a significant improvement of the temperature profiles derived from the lidar data which could be achieved only in Summer 2017. A 2-day test data set consisting of temperature and dew point profiles every 30 min (i.e. 96 profiles) has been prepared (see Figure 3). First assimilation tests with COSMO-7/nudging using 6 h assimilation windows were successful insofar as that the lidar data have been accepted by the model and that the model reacted to it. The imminent next step is to do case studies with COSMO-E (2 km ensemble version of COSMO) and to quantify the impact using several quality scores.

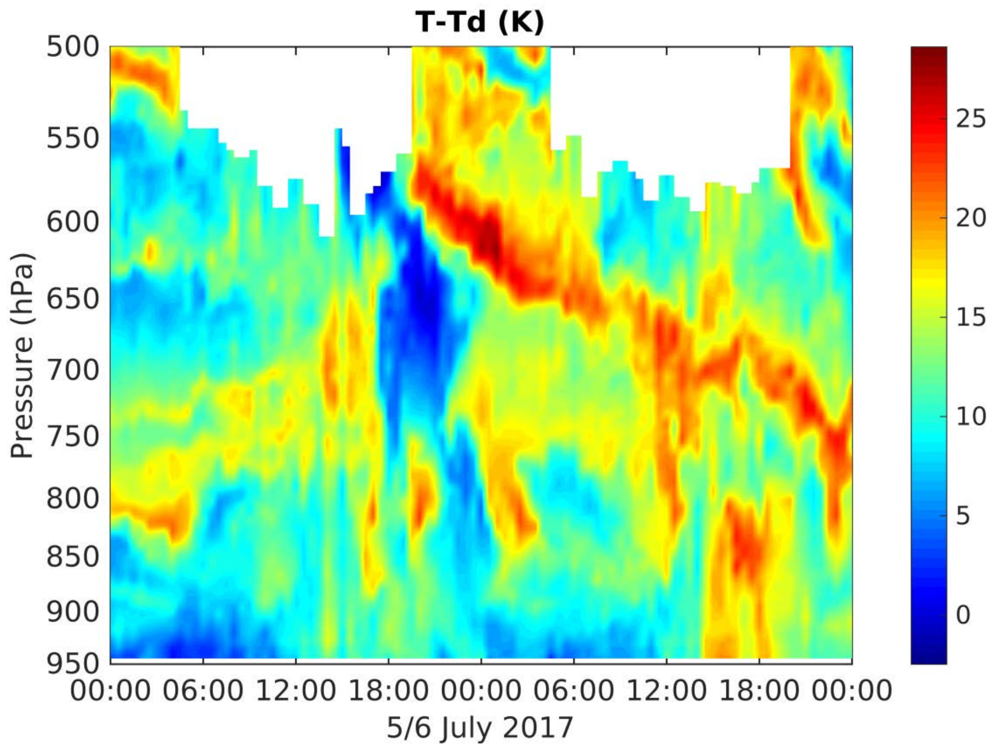

Figure 3. Difference between temperature (T) and dew point (Td) as measured by the Raman lidar at Payerne.

B) The SimUVEx simulation tool allowing deducing realistic human skin UV exposure from real UV irradiance data has been improved to allow 1) a quicker processing of high resolution UV data, typically allowing treating 1-min resolution data for multi-year datasets; 2) using parameterization for a wider set of UV irradiance data as input such as global UV irradiance instead of the previously necessary separation in direct, diffuse and reflected irradiance; 3) introducing shading objects such as head caps or umbrellas (see Figure 4 for type caps used and face regions considered).

1. Baseball-style Cap ***2. Helmet*** ***3. Middle-brimmed hat*** ***4. Wide-brimmed hat***

Figure 4. Head morphologies with hat (brim size): 1. a baseball-style cap (10 cm frontal), 2. a helmet (7 cm frontal, 4 cm lateral), 3. a middle - brimmed hat (6 cm) or 4. a wide-brimmed hat (17 cm).

As mentioned in the 2015 reports, MeteoSwiss work focused in 2015-2016 on implementing an estimation of UV broadband erythemally-weighted radiation on a large spatial and temporal scale using information from the Meteosat Second Generation satellite. This would allow reaching a ~1km spatial and 15 minutes temporal resolution. The large regional coverage (potentially most of Europe) and the unprecedented temporal and spatial resolution for UV satellite estimates should enable meaningful epidemiological research relating UV exposure and skin cancer. Currently, a dataset focusing on Switzerland and on years 2013-2016 is being prepared. First retrievals for specific pixels were ground measurements are available, typically the BSRN station at Payerne, have been performed, and the estimates have been compared to data for clear-sky cases for year 2015 (see Figure 5).

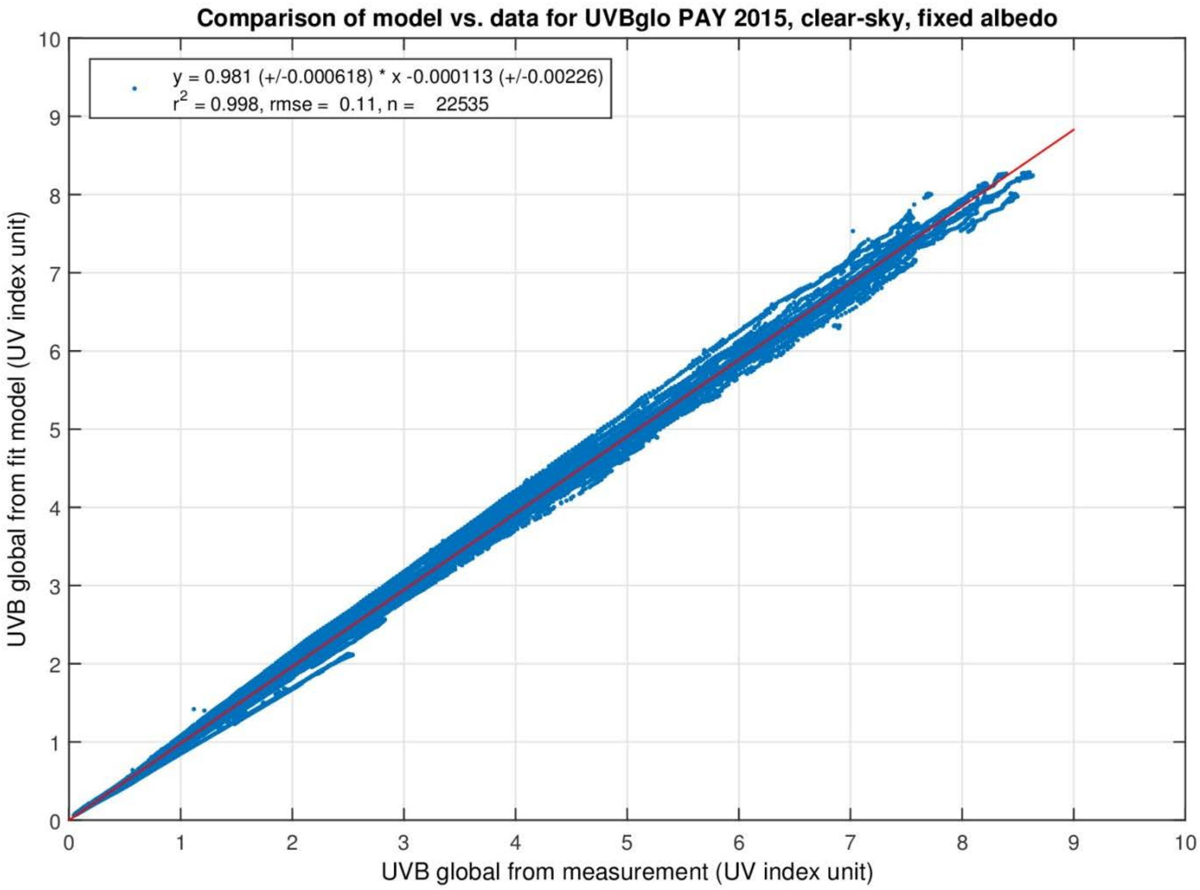

Figure 5. Comparison of model estimate based on satellite information with ground measurements at the Payerne BSRN station for clear-sky cases for year 2015 (Ohmura et al. 1998).

C) MeteoSwiss is involved in a number of research activities within the frame of continuous development of COSMO-ART, focused on the modelling of pollen emission. As species react differently to meteorological conditions, the parameterization of the pollen season is required for each species. the main effort in this direction was carried out in the course of a project funded by the Swiss National Science foundation. It is entitled "Identification of key factors governing Ambrosia POLlen EMIssion by field experiments and their implementation in the numerical pollen dispersion model COSMO-ART (POLEMIC)" and runs over 2014-2017. The basic idea was to collect pollen concentrations data very close to the source along with meteorological data to establish their relationship. The location of the measurement site was a small village in Serbia where the Serbian partner performed all the measurements. Once this project is finished, the results will be used operationally in COSMO-ART.

In addition to emission, precise prediction of the start and the end of the pollen season, as well as knowledge about the seasonal course is a prerequisite for correct pollen forecasts. The reduced pollen production with increasing altitude is taken into account as well. Knowledge on the detailed plant distribution is equally important. Pauling et al. (2012) developed a set of methods that can provide such inputs to COSMO-ART. They depend on the GLOBCOVER dataset and pollen data as well as inventory data in the case of Ambrosia.

4.5.3 Specific products operationally available

Daily maps of mean pollen concentrations for Switzerland were available on the Website of MeteoSwiss. Similar maps were available for France and Italy on the Website of the aerobiological network of France (RNSA) and Italy (AIA) respectively.

The FLEXPART model results are delivered to the authorities for emergency response as geographical representations of affected area, time-integrated concentration, averaged concentration, and deposition on the ground.

4.5.4 Operational techniques for application of specialized numerical prediction products (MOS, PPM, KF, Expert Systems, etc..) (as appropriate related to 4.5)

4.5.4.1 In operation

Weather services with customer-tailored products for aviation (Clear Air Turbulence), energy management (photovoltaic, hydro-electricity) and decisional tools for surface transportation (road gridding: snow, icing), or even genetic algorithms for gale warning started their operation in 2015.

4.5.4.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

4.5.5 Probabilistic predictions (where applicable)

4.5.5.1 In operation

"[Number of runs, initial state perturbation method etc.]" *(Describe also: time range, number of members and number of models used: their resolution, main physics used etc.)*

-/-

4.5.5.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

4.5.5.3 Operationally available probabilistic prediction products

"[brief description of variables which are outputs from probabilistic prediction techniques]"

-/-

4.6 Extended range forecasts (ERF) *(10 days to 30 days)*

[Authors: Daniel Cattani / Jonas Bhend / Christoph Spirig / Mark Liniger]

4.6.1 Models

4.6.1.1 In operation

For about 10 years now, MeteoSwiss is processing monthly forecasts. The forecasts are based on forecast data from the ECMWF extended range prediction system. The system was deployed in autumn 2008 and has become fully operational since then.

4.6.1.2 Research performed in this field

In the framework of the Horizon 2020 project Heat-Shield (an initiative aiming to increase the thermal resilience of European workers in the context of global warming, https://www.heat-shield.eu/), MeteoSwiss is currently setting up an early warning system for heat stress based on ECMWF's monthly forecasts. As part of these developments, verification of the extended range ensembles against observations at 1800 European surface sites has been carried out. This extensive surface observation data set was obtained by combining the data sets ECA&D (European Climate Assessment & Dataset, http://www.ecad.eu), GSOD (Global Surface Summary of the Day, https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod), and selected records of SMN (SwissMetNet, the national monitoring network of MeteoSwiss). At these locations, the performance of the 20 years hindcasts of cycle 41r2 initialized between begin of May and end of July has been analysed. The focus of the verification was on temperature and humidity as these are the dominating variables affecting physiological heat stress, which can be expressed by indices such as the wet bulb globe temperature. Daily model output of temperature and dewpoint temperature has been bias-corrected with a quantile mapping approach (Rajczak et al., 2016), by using the hindcasts and corresponding observations in leave-one-out mode. WBGT hindcasts were then computed from these bias-corrected hindcasts of temperature and dewpoint temperatures. Figure 6 shows the resulting ensemble mean correlations for temperature, dewpoint, and WBGT at a lead time of 15 days. On average, WBGT correlations remained marginally positive up to lead times of 30 days, skill in terms of the continuous ranked probability skill score (CRPSS) against climatology remained positive up to lead times of 20 days.

Figure 6. Ensemble mean correlation of WBGT at a lead time of 15 days for 1996-2015 hindcasts initialized between May and July.

4.6.2 Operationally available NWP model and EPS ERF **products**

Operational products based on the ECMWF ensemble forecast system include maps of weekly categorical probability forecasts of surface temperature, precipitation and geopotential height over various regions. A monthly outlook for Switzerland is publicly available on the MeteoSwiss website. The prototype forecast developed within the HeatShield project mentioned above issues forecasts of heat stress risks in the upcoming four weeks in the form maps as shown in Figure 7 and is made available on http://heatshield.biometeo.it/en .

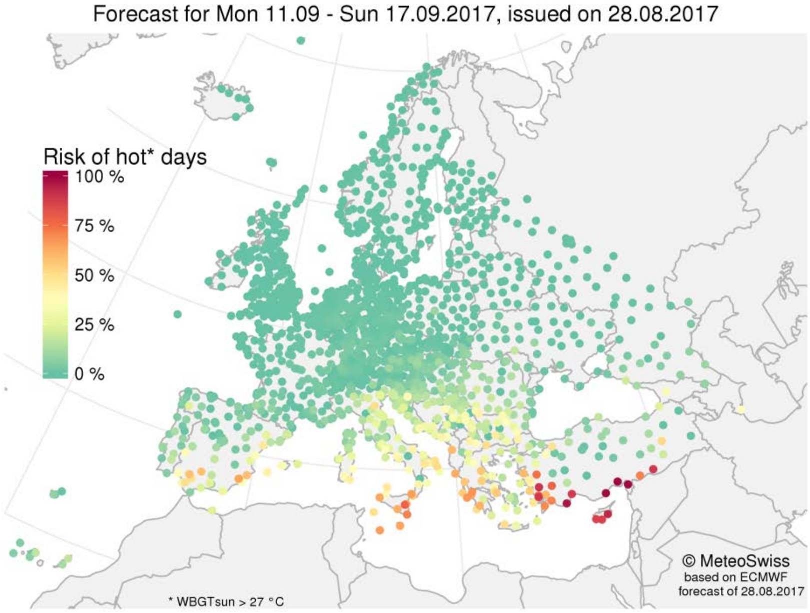

Figure 7. Product of the HeatShield forecast prototype: Weekly average risk of hot days at 1800 locations in Europe.

4.7 Long range forecasts (LRF) *(30 days up to two years)*

4.7.1 In operation

MeteoSwiss issues long range forecasts (up to 7 months) on the basis of the ECMWF seasonal forecast model system (currently System 4). Data from the forecasting system is post-processed using the climate-conserving recalibration technique (CCR, Weigel *et al.,* 2009) developed by MeteoSwiss.

4.7.2 Research performed in this field

As part of the FP7 project EUPORIAS, MeteoSwiss has compiled a comprehensive verification of the ECMWF System 4. Monthly and 3-monthly mean near-surface temperature and precipitation forecasts have been verified against ERA Interim using a range of scores and measures to quantify various aspects of forecast quality. As part of this project, a public web platform https://meteoswiss-climate.shinyapps.io/skill_metrics has been set up that allows users to browse the verification results (Wehrli et al, 2017). The web platform allows users to zoom in regionally and to investigate the evolution of forecast quality for specific times of the year that are of relevance to the user's application (Figure 8).

Also, MeteoSwiss is involved in the Copernicus Climate Change Service (C3S) activity on evaluation and quality control of the C3S seasonal forecasts (https://climate.copernicus.eu/quality-assurance-multi-model-seasonal-forecast-products). As part of this activity, MeteoSwiss analyses and documents the forecast quality of all C3S forecasting systems (currently ECMWF System 4, Météo France System 5, and Met Office GloSea 5). Furthermore, MeteoSwiss is engaged in developing metadata standards for seasonal forecast products and verification metrics, and in developing an evaluation and quality control prototype application to be delivered as part of the climate change service.

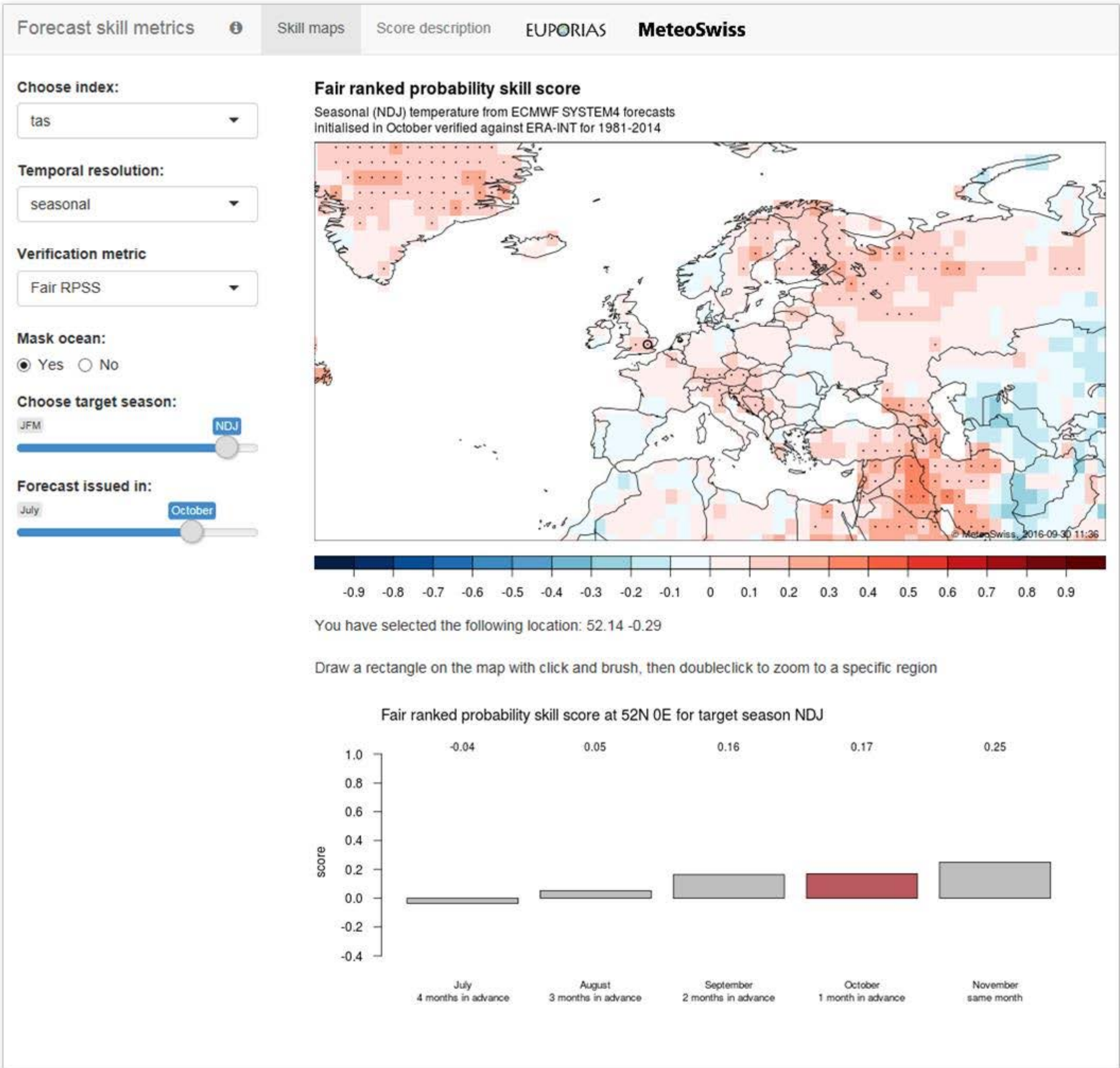

Figure 8. Screenshot of the web platform visualizing forecast quality measures for the ECMWF System4 seasonal forecasts. In the main panel, a map of ranked probability skill scores (RPSS) for November to January (NDJ) mean temperature from forecasts initialized

4.7.2 Operationally available EPS LRF products

"[brief description of variables which are outputs from the model integration]"

-/-

5. Verification of prognostic products

[Authors: Daniel Cattani / Jonas Bhend / Christoph Spirig / Mark Liniger]

5.1 Annual verification using a global score

Verification based on global score COMFORT (Continuous MeteoSwiss FORecast quality) is used currently to derive forecast quality on different time periods (annual, trimestral or daily). COMFORT scores permit a good monitoring of the forecast quality with respect to the fixed goals for each forecasts' lead times (see Figure 9). Moreover detailed analyses, of the quality of particular parameters, over a given region, and selected weather types, enable to identify the potential of improvements either on the processing side or on the forecasters methods.

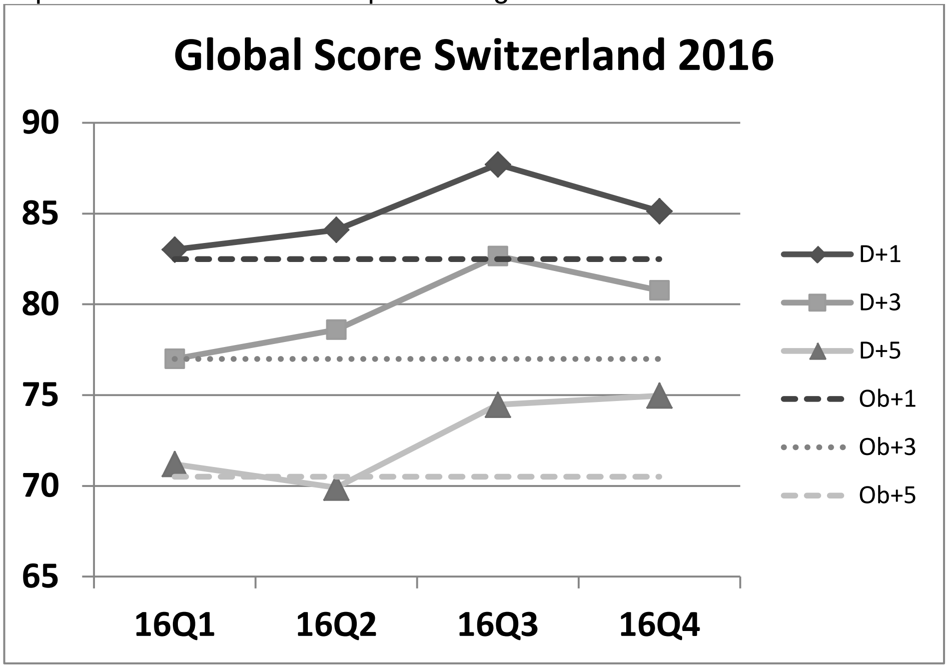

Figure 9. Annual verification using COMFORT global score for 3 different lead times (Day +1, day +3 and day+5), and expected quality at the same lead times.

5.2 Verification browser

A verification browser is now available to forecasters (Figure 10). It is designed as tool to provide individual or collective scores of weather forecasts in order to point out the individual or team's strengths and weaknesses. The forecaster uses this platform to access, after each of his or her shifts, a summary of his/her performance with a comparison to the "initial proposition" from the models. The added value by the forecaster can be easily shown.

Recommendations addressed to forecasters can be elaborated using the browser by analyzing the forecast's quality stratified by situations (examples Figure 11, Figure 12 and Figure 13).

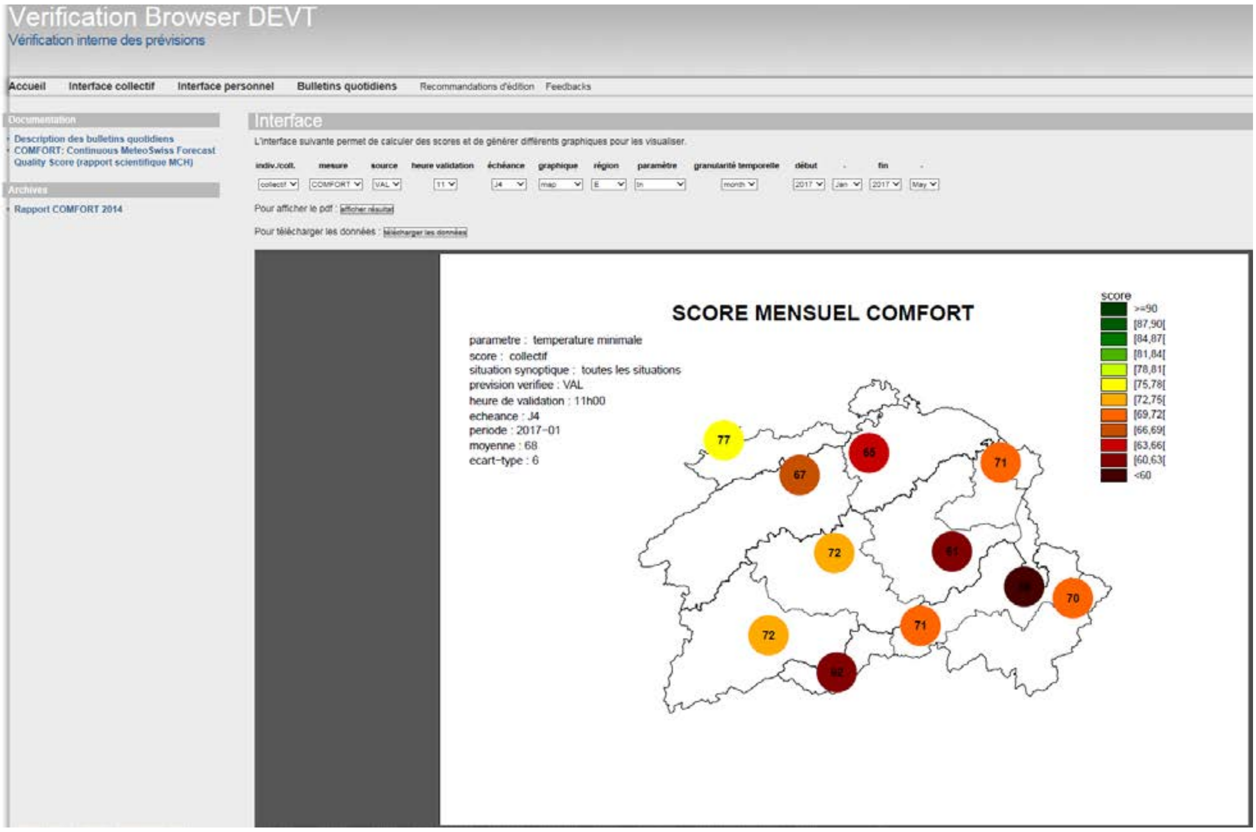

Figure 10. Screenshot of the verification browser developed by MeteoSwiss.

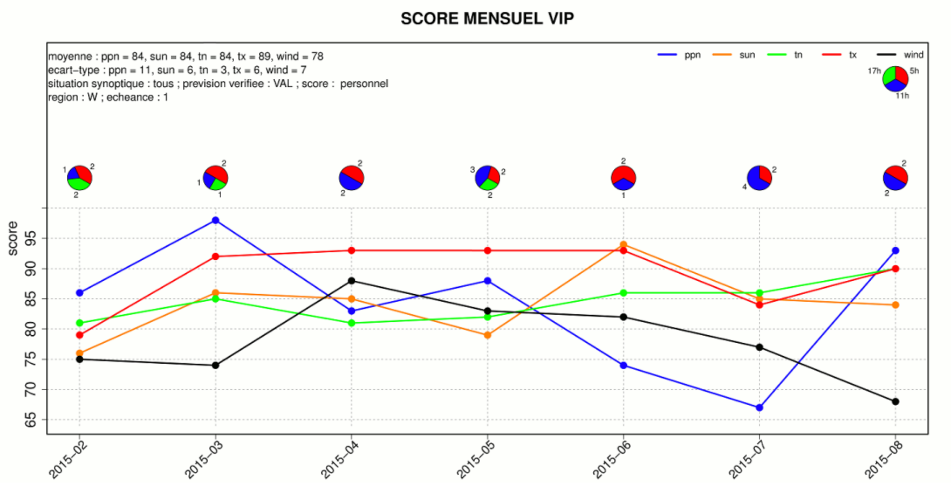

Figure 11. Time series of monthly scores for a specific forecaster. The colored lines represent the score per parameter. The pie chart above indicates the number of specific shifts during the month (green for afternoon, red for night and blue for morning).

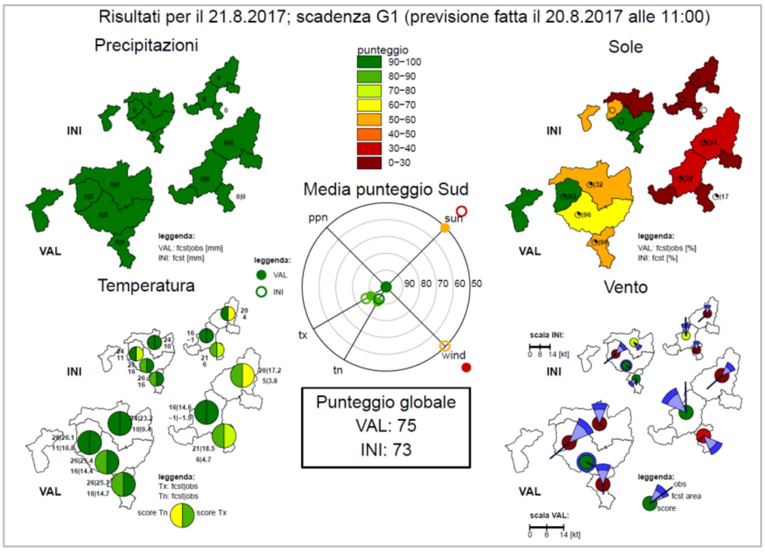

Figure 12. Example of a feedback panel addressed to an individual forecaster for its day+1 forecast. It displays the daily analyses with the scores for precipitation, relative sunshine duration, temperature minimum and maximum and wind. On the charts scores are indicated for each subregions. On the smaller charts the initialization quality (INI), on the larger the forecarster's (VAL). In the center the aggregated scores of each parameter, and underneath the global scores resuming in one number the forecast quality.

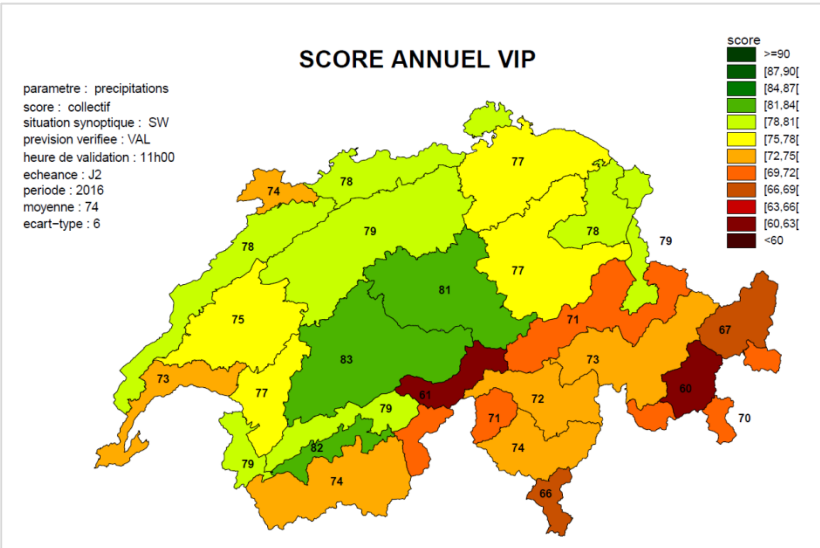

Figure 13. Annual score for 2016 of precipitations by southerly flow, day+2 over all Switzerland.

5.2 Research performed in this field

"[Summary of research and development efforts in the area]"

-/-

6. Plans for the future *(next 4 years)*

6.1 Development of the GDPFS

-/-

6.1.1 "[major changes in the Operational DPFS which are expected in the next year]"

6.1.2 "[major changes in the Operational DPFS which are envisaged within the next 4 years]"

6.2 Planned research Activities in NWP, Nowcasting, Long-range Forecasting and Specialized Numerical Predictions

"[Summary of planned research and development efforts in NWP, Nowcasting, LRF and Specialized Numerical Predictions for the next 4 years]"

6.2.1 Planned Research Activities in NWP

6.2.2 Planned Research Activities in Nowcasting

We have several developments in nowcasting and VSRF: improvement of existing algorithms and introducing new ones, integrating new data sources and types, operationalisation of mature systems with special attention to end user needs. Some keywords:

- Improvement of hail, rain, and snow nowcasting by using radar dual-polarisation information
- Estimation of convective wing gusts (downdraft)
- Improving early detection of heavy thunderstorms
- Introducing uncertainty estimation by ensemble techniques/probability for relevant variables.
- Merging object and gridded precipitation nowcasting
- INCA: Improvement of the ground temperature analysis and evaluation of possibilities for improvements of wind analysis. Introduction of non Euclidean distances for temperature and humidity corrections Introduction of a new interpolation routine included in the software fieldextra.
- Expanding seamless forecast for most relevant variables from nowcasting- VSRF to SRF
- Automatic hail warning.

6.2.3 Planned Research Activities in Long-range Forecasting

Development and provision of user oriented long term forecasts will continue to be a focus in the upcoming years. We thereby rely on dynamical models and will continue to optimize our post-processing techniques.

6.2.4 Planned Research Activities in Specialized Numerical Predictions

7. Consortium

[Authors: COSMO Consortium members]

7.1 System and/or Model

The *COSMO Model* (http://cosmo-model.org/content/model/general/default.htm) is a nonhydrostatic limited-area atmospheric prediction model. It has been designed for both operational numerical weather prediction (NWP) and various scientific applications on the meso-β and meso-γ scale. The COSMO Model is based on the primitive thermo-hydrodynamical equations describing compressible flow in a moist atmosphere. The model equations are formulated in rotated geographical coordinates and a generalized terrain following height coordinate. A variety of physical processes are taken into account by parameterization schemes.

Besides the forecast model itself, a number of additional components such as data assimilation, interpolation of boundary conditions from a driving model, and postprocessing utilities are required to run the model in NWP mode, climate mode or for case studies.

7.1.1 In operation

Regional numerical weather prediction at Deutscher Wetterdienst is based on the COSMO Model. COSMO-EU (see sections 4.3.1 and 4.3.2) covers Europe with 665x657 grid points/layer at a grid spacing of 7 km and 40 layers, and the convection-resolving model COSMO-DE, covers Germany and its surroundings with a grid spacing of 2.8 km, 421x461 grid points/layer and 50 layers. Based on COSMO-DE, a probabilistic ensemble prediction system on the convective scale, called COSMO-DE-EPS, became operational with 20 EPS members on 22 May 2012. It is based on COSMO-DE with a grid spacing of 2.8 km, 421x461 grid points/layer and 50 layers. See also section 7.3 for COSMO members.

On behalf of COSMO, ARPA-SIMC operates the regional ensemble prediction system **COSMO-LEPS** (http://www.cosmo-model.org/content/tasks/operational/leps/default.htm) at the European Centre for Medium Range Weather Forecasts (ECMWF) in the "Framework for Member-State time-critical applications". COSMO-LEPS is the Limited Area Ensemble Prediction System developed within the COSMO consortium in order to improve the short-to-medium range forecast of extreme and localized weather events. It is made up of 16 integrations of the COSMO model, which is nested in selected members of ECMWF EPS.

COSMO-LEPS covers Central and Southern Europe with 511x415 grid points/layer at a grid spacing of 7 km and 40 layers. The system runs twice a day, starting at 00 and 12UTC with a forecast range of 132 hours.

7.1.2 Research performed in this field

The joint research and development is mainly undertaken within the framework of eight working groups (http://cosmo-model.org/content/consortium/structure.htm) and through a number of priority projects (PP) and priority tasks (PT). There are several PPs and PTs being implemented, and several follow-up PPs and PTs that extend the completed projects and tasks. These are listed below.

PP "Km-Scale Ensemble-Based Data Assimilation for High-Resolution Observations" (KENDA-O), see section 7.4.1.

PP "COSMO-EULAG Operationalization" (CELO) is aimed at integrating the EULAG dynamical core within COSMO framework, consolidating and optimising the setup of the anelastic EULAG dycore for the high-resolution NWP, optimizing and tuning the COSMO physical parameterizations, and testing and exploiting forecasting capabilities of the integrated model. Two follow-up PPs are proposed, EX-CELO and CEL-ACELL.

PP "Comparison of the Dynamical Cores of ICON and COSMO" (CDIC) tests the performance of the new ICON dynamical core for regional applications, and compares it to the COSMO dynamical core,

PP "Testing and Tuning of Revised Cloud Radiation Coupling" ($T^2(RC)^2$) is aimed at improving the cloud-radiation coupling in the COSMO model. tests and optimizes The representation of radiation interactions with cloud and aerosol are comprehensively tested and optimized. The extension of project over two years is proposed. The work towards improving the representation of cloud-radiation interactions in the ICON is planned.

PP "Calibration of COSMO Model" (CALMO) which aims at development of automatic, multivariate and objective calibration of parameterizations of physical processes for the model. PP CALMO is completed, and the follow-up project "Calibration of Model-Methodology Applied on Extremes"

(CALMO-MAX) has been initiated. The aim of CALMO-MAX is to consolidate and extend the findings of the previous project, and to provide ng a permanent COSMO framework for objective model calibration.

PP "Intercomparison of Spatial Verification Methods for COSMO Terrain" (INSPECT) aims at evaluation of spatial verification methods for convection-permitting deterministic and ensemble products.

PP "Performance On Massively Parallel Architectures" (POMPA) is aimed at preparing the COSMO model code for future massively parallel high performance computing systems and novel architectures including GPU systems.

PP "Studying Perturbations for the Representation of Modelling Uncertainties in Ensemble Development" (SPRED) deals with the development of convection-permitting ensembles and especially methodologies for near-surface model perturbations.

PT on "Implementation of the Bechtold Convection scheme In the model: deterministic And ensemble-mode tests" (CIAO) is aimed at assessing the sensitivity of the COSMO forecast skills to the use of recently imp implemented ECMWF IFS (Bechtold) cumulus convection scheme, where the focus is on both deterministic and ensemble forecasts.

PT "Consolidation of Surface to Atmosphere Transfer" (ConSAT) continues with the improvements of the turbulence scheme and atmosphere-surface interactions.

PT "Evaluation of the Dynamical Core Parallel Phase" (EDP2) deals with the C++/STEALLA and FORTRAN dynamical cores. During so-called parallel phase these dycores co-exist and should be carefully maintained, synchronized, and evaluated. EDP2 provides recommendations to the COSMO Steering Committee which actions should be taken at the end of the parallel phase.

PT "TERRA Nova" is aimed at comprehensive testing the new version of the soil parameterization scheme TERRA (including novel features used within ICON but not yet utilized within COSMO).

PT "Analysis and Evaluation of TERRA_URB Scheme" (AEVUS) deals with evaluation and verification of the performance of the urban module TERRA_URB within COSMO, and calibration of the scheme disposable parameters,

A permanent PP "Working Group6's Support Activities" (WG6-SPRT) takes care of maintenance of the COSMO model code, model documentation, model releases, training, and assistance in operational COSMO applications.

Environmental prediction aspects of the model involving chemistry, aerosol effects and transport (COSMO ART) are developed in close cooperation with the Karlsruhe Institute for Technology (KIT) in Germany.

7.2 System run schedule and forecast ranges

See section 4.1

7.3 List of countries participating in the Consortium

COSMO stands for **CO**nsortium for **S**mall-scale **MO**delling. The general goal of COSMO is to develop, improve and maintain a non-hydrostatic limited-area atmospheric model, the COSMO model, which is used both for operational and research applications by the members of the consortium. The consortium was formed in **October 1998** at the regular annual DWD (Germany) and MeteoSwiss (Switzerland) meeting.

A Memorandum of Understanding (MoU) on the scientific collaboration in the field of non-hydrostatic modeling was signed by the Directors of DWD (Germany), MeteoSwiss (Switzerland), USAM (Italy, then named UGM) and HNMS (Greece) in March/April 1999. The MoU has been replaced by an official COSMO Agreement, which was signed by the Directors of these four national meteorological services on 3 October 2001. Recently a new COSMO Agreement aiming at future challenges in high resolution regional numerical weather prediction as well as climate and environmental applications was accepted by the Directors of the COSMO members and was signed on 7 August 2014.

In 2002, the national weather service of Poland (IMGW) joined the Consortium in effect from 4 July. The National Institute of Meteorology and Hydrology (NMA) of Romania and the Federal Service for Hydrometeorology and Environmental Monitoring of the Russian Federation joined the Consortium in effect from 21 September 2009. The Israel Meteorological Service (IMS) successfully passed two-year application in September 2016 and recently joined the Consortium in effect from 1st January 2017.

Currently, the following national meteorological services are COSMO members:

Germany	DWD	Deutscher Wetterdienst
Switzerland	MCH	MeteoSchweiz
Italy	ReMet	Aeronautica Militare-Reparto per la Meteorologia
Greece	HNMS	Hellenic National Meteorological Service
Poland	IMGW	Institute of Meteorology and Water Management
Romania	NMA	National Meteorological Administration
Russia	RHM	Federal Service for Hydrometeorology and Environmental Monitoring
Israel	IMS	Israel Meteorological Service

The following regional and military services within the member states are also participating:

Germany	AGeoBw	Amt für GeoInformationswesen der Bundeswehr
Italy	CIRA	Centro Italiano Ricerche Aerospaziali
Italy	ARPAE-SIMC	ARPAE Emilia Romagna
Italy	ARPA Piemonte	Agenzia Regionale per la Protezione Ambientale Piemonte

Seven national meteorological services, namely Botswana Department of Meteorological Services, INMET (Brazil), DHN (Brazil), Namibia Meteorological Service, DGMAN (Oman) and NCMS (United Arab Emirates) and Turkmenistan Administration of Hydrometeorology use the COSMO model in the framework of an operational licence agreement including a license fee.

National meteorological services in developing countries (e.g. Egypt, Equador, Indonesia, Kenya, Magadascar, Malawi, Mozambique, Nigeria, Philippines, Rwanda, Tanzania, Ukraine, Vietnam, and Zimbabwe) are entitled to operate the COSMO model free of charge.

7.4 Data assimilation, objective analysis and initialization

7.4.1 In operation

The data assimilation system for the COSMO model is based on the observation nudging technique. The variables nudged are the horizontal wind, temperature, and humidity at all model layers, and pressure at the lowest model level. The other model variables are adapted indirectly through the inclusion of the model dynamics and physics in the assimilation process during the relaxation. At present, radiosonde, aircraft, wind profiler, surface synoptic, ship, and buoy data are used operationally. For model configurations at the convection-permitting scale, radar-derived precipitation rates are included additionally via the latent heat nudging method. If nudging is used for data assimilation, an extra initialization is not required. Separate two-dimensional analysis schemes based on the successive correction technique are deployed for the depth of the snow cover and the sea surface temperature, and a variational scheme for the soil moisture.

Gradually, the default data assimilation system based on nudging technique is being replaced with Local Ensemble Transform Kalman Filter (LETKF, see section 7.4.2).

As for COSMO-LEPS, the following initialization is performed: the upper-level initial conditions of the individual members are interpolated from the ECMWF EPS elements providing the boundaries. On the other hand, the initialization at the lower boundary is performed by taking the surface fields of COSMO-EU, including soil temperature and humidity, and blending them with those provided by ECMWF.

On January 20 2017 the global numerical weather prediction system ICON run at DWD introduced hybrid combination (En-Var) of an Ensemble-Kalman Filter (EnKF) with the variational 3D-Var scheme, which allows for using the Ensemble-based information of flow-dependent error covariance matrices in the deterministic analysis. In the result ICON model forecasts used as an initial and boundary conditions for several COSMO model operational setups has substantially improved.

7.4.2 Research performed in this field

The focus of research efforts lies on the development of a novel data assimilation scheme based on the Local Ensemble Transform Kalman Filter (LETKF) technique in the frame of the KENDAO priority project. Its main purpose is to deliver perturbed initial conditions for convection-permitting ensemble prediction systems as well as initial conditions for such deterministic systems. For more information, see
http://www.cosmo-model.org/content/tasks/priorityProjects/kendaO/default.htm.

Following encouraging test results, including comparison with nudging, the project aims at operationalization and further development of the LETKF assimilation system. The current research includes, in between,:

- use of remote sensing data (3D radar radial velocity, satellite soil moisture analysis, SEVIRI radiance, GNSS slant total delay) and observations related to the boundary layer, humidity, cloud and precipitation, and surface
- algorithmic developments and extensions of the system, including multi-scale multi-step approaches, and particle filters (PF)
- work started for implementing KENDA in ICON-LAM
- exploratory research towards hybrid extensions of the system LETKF-PF

After pre-operational testing, the system was already implemented for operational use in MeteoSwiss in 2016 and implemented preoperational at DWD , ARPAE-SIMC and COMET.

7.5 Operationally available Numerical Weather Prediction (NWP) Products

See section 4.3.3.

As for COSMO-LEPS, the available operational products include the following:

- “deterministic products”, different weather scenarios (one per member) for the model variables, at several forecast ranges
- “probabilistic products”, probability of exceedance of user-defined thresholds for the different model variables, at several forecast ranges
- “pointwise products”, meteograms over station points in terms of the main model variables.

7.6 Verification of prognostic products

See section 5 in reports of COSMO members.

7.7 Plans for the future (next 4 years)

7.7.1 Major changes in operations

See section 6.1 in reports of COSMO members

7.7.2 Research performed in this field

The 6-year science plan covering the period 2015 – 2020

- **(**http://cosmo-model.org/content/consortium/reports/sciencePlan_2015-2020.pdf**)** summarizes the current strategy and defines the main goal of the joint development work within COSMO. The main goal is the development of a model system for short to very short range forecasts with a convective-scale resolution to be used for operational forecasting of mesoscale weather, especially high impact weather. The research-oriented strategic elements to achieve the goal are: an ensemble prediction system, an ensemble-based data assimilation system and a verification and validation tool for the convective scale, extension of the environmental prediction capabilities of the model, use of massively parallel computer platforms. The actions for achieving the goal are undertaken within the current priority projects and task (see section 7.1.2), most of which were already defined based on the recent version of the Science Plan.

Moreover, until 2020 a gradual transition of the COSMO model system to the regional mode of the ICON modelling framework is planned.

The science plan has been accepted by the COSMO Steering Committee in March 2015. In 2016-2017, a review of the COSMO scientific strategy is planned with the aim to prepare plans of new priority projects for the period 2018-2020.

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