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

Country: Germany   Centre: NMC Offenbach

1. Summary of highlights

On 20th January 2016 the 3D-Var data assimilation system for the global non-hydrostatic triangular grid point model ICON (grid spacing 13 km, 90 layers up to 75 km) was replaced by an En-Var (Ensemble Variational data assimilation system) and accompanied by an LETKF (Localised Ensemble Transform Kalman Filter). The LETKF ensemble data assimilation system provides initial conditions for a 40 member ICON ensemble at 40 km resolution (20 km over Europe). The En-Var uses the LETKF short range forecasts in order to derive a flow dependent background error covariance estimate which considerably improves the deterministic analysis.

Since January 2016 the 40 member global ICON-EPS (grid spacing 40 km) with a two-way nest over Europe (grid spacing 20 km) provides forecasts up to 180 h (based on 00 and 12 UTC), 120 h (based on 06 and 18 UTC) and 30 h (Based on 03, 09, 15 and 21 UTC), starting from the global LETKF initial conditions.

On 21th March 2017 the regional nudging data assimilation system for the convection-permitting model COSMO-DE (grid spacing 2.8 km) was replaced by an LETKF (Localised Ensemble Transform Kalman Filter). The LETKF ensemble data assimilation system provides initial conditions for a 40 member COSMO-DE DA ensemble as well as for the deterministic COSMO-DE.

Since 21th March 2017 the operational 20-member COSMO-DE-EPS uses initial conditions from the COSMO-DE ensemble data assimilation (LETKF) and lateral boundary conditions from the ICON-EPS which are interpolated from the 20 km nested grid in ICON over Europe to the 2.8 km COSMO-DE horizontal resolution. Verification shows a large increase in spread and a clear gain in skill scores compared to the previous multi-model setup of COSMO-DE-EPS.

The COSMO model (http://cosmo-model.org/) is used operationally at the national meteorological services of Germany, Greece, Israel, Italy, Poland, Romania, Russia and Switzerland, and at the regional meteorological service in Bologna (Italy). The military weather service of Germany operates a relocatable version of the COSMO model for worldwide applications. On 1st January 2017 the Meteorological Service of Israel (IMS) became full member of COSMO.

Seven national meteorological services, namely Botswana Department of Meteorological Services, INMET (Brazil), DHN (Brazil), Namibia Meteorological Service, DGMAN (Oman), NCMS (United Arab Emirates) and Turkmenhydromet (Turkmenistan) as well as the Center of Excellence for Climate Change Research (King Abdulaziz University, Saudi Arabia) use the COSMO model in the framework of an operational licence agreement including an annual license fee.
National meteorological services in developing countries (e.g. Egypt, Indonesia, Kenya, Madagascar, Malawi, Mozambique, Nigeria, Philippines, Rwanda, Tanzania, Ukraine, Vietnam, Zimbabwe) use the COSMO model free of charge for official duty purposes.

For lateral boundary conditions, ICON data are sent via the internet to the COSMO model users up to four times per day. Each user receives only data from those ICON grid points (at the grid spacing of 13 km for all 90 model layers plus all 7 soil layers) which correspond to the regional COSMO model domain. Currently DWD is sending ICON data to more than 40 COSMO model users worldwide.

2. Equipment in use

2.1 Main computers

2.1.1 Two Cray XC40 Clusters

Each cluster:

Operating System CLE 5.2
796 nodes (364 x 2 CPUs Intel Xeon E5-2670v2 (10-core), 432 x 2 CPUs Intel Xeon E5-2680v3 (12-core)) with 17648 CPU cores
560.3 TFlops/s peak system performance
A total of 76.75 TiB physical memory (364 x 64 GiB and 432 x 128 GiB)
Cray Aries interconnect
Infiniband FDR and 10 GbE attached global disk space (Cray Sonexion and Panasas Active Stor), see 2.1.3

One Cray XC40 cluster is used to run the operational weather forecasts; the second one serves as research and development system.

2.1.2 Two Cray/Megware Clusters

Operating System SuSE Linux SLES 11

Cluster A:

28 nodes Megware MiriQuid
- 14 nodes with 2 CPUs Intel Xeon E5-2670v2 (10-core), 14 nodes with 2 CPUs Intel Xeon E5-2690v3 (12-core), entire system 616 cores
- 24 nodes with 128 GiB physical memory per node, 4 nodes with 512 GiB physical memory per node, entire system 5120 GiB physical memory
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Cluster B:

22 nodes Megware MiriQuid
- 12 nodes with 2 CPUs Intel Xeon E5-2670v2 (10-core), 10 nodes with 2 CPUs Intel Xeon E5-2690v3 (12-core), entire system 480 cores
- 18 nodes with 128 GiB physical memory per node, 4 nodes with 512 GiB physical memory per node, entire system 4352 GiB physical memory

Infiniband FDR Interconnect for multinode applications
Network connectivity 10 Gbit Ethernet
Infiniband FDR and 10 GbE attached global disk space (Cray Sonexion and Panasas Active Stor), see 2.1.3

Cluster B is used to run operational tasks (pre-/post-processing, special product applications), cluster A research and development tasks.

2.1.3 Global Disk Space (Cray Sonexion and Panasas Active Stor)

Cray Sonexion (for work filesystems):
Hardware components: 4 x Cray Sonexion 1600
Total disk storage 3700 TiB
SAN connectivity: Infiniband FDR

2x 36 GB/s sustained aggregate performance
Software: Lustre 2.5

Panasas Active Stor 12 (for home filesystems):

Total disk storage 290 TiB
SAN connectivity: 10 Gb Ethernet
2x 3 GB/s sustained aggregate performance
Software: Panasas 5.5

Both global disk space (Cray Sonexion, Panasas) is accessible from systems in 2.1.1, 2.1.2.

2.1.4 Two NEC/Oracle/NetApp data management clusters

Oracle SUN Servers x2-4/x2-8 systems are used as data handling systems for meteorological data.

Two redundancy clusters for operational tasks and research/development each with:
Operating System Oracle Linux Server 6.4
5 servers (2x Oracle SUN Server x2-4 (4x Intel Xeon E7-4870 (10-core)) as database servers and 3x Oracle SUN Server x2-8 (8x Intel Xeon E7-8870 (10-core)) as data access servers)
A total of 320 CPU cores per cluster
4096 GiB physical memory per cluster
Network connectivity 10 Gbit Ethernet

NetApp storage systems (22x E5500 and 34x DE6000) providing 1382 TiB disk space on the research/development cluster and 1656 TiB disk space on the operational tasks cluster via Infiniband QDR

2.1.5 IBM System x3650 Cluster

Operating System RedHat RHEL5
9 IBM System x3650 M2 (2 quadcore processors, 2.8 GHz)
24 GiB of physical memory each
480 TiB of disk space for HPSS archives
30 Archives (currently 24 PB)
connected to 2 Oracle StorageTek SL 8500 Tape Libraries via Fibrechannel

This high-available cluster is used for HSM based archiving of meteorological data and forecasts.

2.1.6 STK SL8500 Tape Library

Attached are 60 Oracle STK FC-tape drives

20 x T10000B (1 TB, 120 MB/s)
40 x T10000C (5 TB, 240 MB/s)

2.2 Networks

The main computers are interconnected via Gigabit Ethernet (Etherchannel) and connected to the LAN via Fast Ethernet.

2.3 Special systems

2.3.1 RTH Offenbach Telecommunication systems

The Message Switching System (MSS) in Offenbach is acting as RTH on the MTN within the WMO GTS. It is called Weather Information System Offenbach (WISO) and based on a High-Availability-Cluster with two IBM x3650 M3 Servers running with Novell Linux SLES11 SP4 system software and Heartbeat/DRBD cluster software.

The MSS software is a commercial software package (MovingWeather by IBLsoft). Applications are communicating in real time via the GTS (RMDCN and leased lines), national and international PTT networks and the Internet with WMO-Partners and global customers like, EUMETSAT, ECMWF and DFS (Deutsche Flugsicherung = Air Navigation Services).

For the international and national dissemination via GISC-Offenbach the open source DWD software AFD is used (http://www.dwd.de/AFD/) for customers who not joined the RMDCN. The core high availability Linux cluster is running with scientific Linux and heartbeat. Standard protocols like ftp/sftp, http/https, smtp are in use.

2.3.2 Other Data Receiving / Dissemination Systems

Windows 2008 R2 Server

A Windows based Server System is used for receiving XRIT and LRIT data at Offenbach.

LINUX Server

2 Linux servers are used for the direct read out of L-Band and X-Band LEO Satellites.

LINUX servers are also used for receiving EUMETCast data (Ku-Band and C-Band)
There are four servers at DWD, Offenbach and 2 servers at Regional Office Leipzig.

Another LINUX server system is used for other satellite image processing applications.
The images and products are produced for several regions worldwide with different resolution from 250 m to 8 km. There are internal (NinJo, NWP) and external users (e.g. Internet). Five servers used for operational services and two servers for backup service.

FTP

HRPT, Aqua and Terra MODIS data (2 to 3 passes per day) DWD get from AGeoBW (Amt für Geoinformationswesen der Bundeswehr) Euskirchen as Backup.

2.3.3 Graphical System

The system *NinJo* (NinJo is an artificial name) has been operational since 2006. It is based on a JAVA-Software and allows for a variety of applications. As development of the software is very laborious and expensive the *NinJo* Project was realized in companionship with DWD, the Meteorological Service of Canada, MeteoSwiss, the Danish Meteorological Institute and the Geoinformation Service of the German Forces. The hardware consists of powerful servers combined with interactive *NinJo*-client workstations.

NinJo is an all-encompassing tool for anybody whose work involves the processing of meteorological information, from raw data right to the forecast.

For the user the main window is just the framework around the various fields of activity. Of course it is possible to divide up the displayed image over several screens. All products generated interactively on the screen can be generated in batch mode as well. Besides 2D-displays of data distributed over an extensive area also diagrams (e.g. tephigrams for radio soundings, meteograms or cross sections) can be produced.
Depending on the task to be accomplished it is possible to work with a variable number of data layers. There are layers for processing observational data such as measured data from observing stations, radar images etc. right through to final products such as weather maps, storm warnings etc. Data sources are constantly updated files in the relevant formats.
The *NinJo* workstation software comprises an

- modern meteorological workstation system with multi-window technology
- easily integrated geographical map displays
- meteograms, cross-sections, radiosoundings as skew-T-log-p or Stüve-diagrams
- a subsystem for monitoring of incoming data called *Automon*
- flexible client-server architecture
- high configurability via XML and immediate applicability without altering code

Tools for interactive and automatic product generation like surface analyses with isobars and fronts, surface prognostic charts and significant weather charts are in use.

A typical installation of the *NinJo* workstation on the forecasters desktop uses two screens. On a wide screen the weather situation can be presented in an animation.

3. Data and Products from GTS in use

At present nearly all observational data from the GTS are used. GRIB data from France, the UK, the US and the ECMWF are used. In addition most of the OPMET data are used.

No.	Obs Type	Used	Percent	Monitored	Comment
1	TEMP	64.000	2,6%	350.000	TEMP
2	PILOT	13.000	0,5%	95.000	PILOT+Wind profiler
3	SYNOP	140.000	5,8%	1.200.000	SYNOP LAND + SHIP
4	DRIBU	7.000	0,3%	16.000	BUOYs
5	AIRCRAFT	420.000	16,8%	725.000	AIREP+ACARS+AMDAR
6	AMV	194.000	7,8%	200.000	Satellite winds geostatationary + polar
7	SCATT	326.000	13,2%	940.000	Scatterometer ASCAT,OSCAT
8	RADIANCES	1.205.000	48,4%	60.000.000	Radiances (AMSU HIRS IASI)
9	GPSRO	115.000	4,6%	130.000	GPS radio occultations
	TOTAL	2.484.000	100.0%	63.656.000	

Table 1: Typical number of observation data input per day in the global EnVar data assimilation; the data have been recorded in February 2017 over 24 hours.

4. Forecasting system

4.1 System run schedule and forecast ranges

Preprocessing of GTS-data runs on a quasi-real-time basis about every 6 minutes on Sun Opteron clusters. Independent 4-dim. data assimilation suites are performed for all NWP models, ICON (**ICO**sahedral **N**onhydrostaticModel, including the ICON-EU refinement domain over Europe), and COSMO-DE. For ICON, analyses are derived for the eight analysis times 00, 03, 06, 09, 12, 15, 18 and 21 UTC based on an Ensemble-Variational (PSAS) scheme. For COSMO-DE an LETKF (Localised Ensemble Transform Kalman Filter) data assimilation suite provides analyses at hourly intervals.

Deterministic system
Forecast runs of ICON (including the ICON-EU refinement domain over Europe) with a data cut-off of 2h 14 min after the main synoptic hours 00, 06, 12 and 18 UTC perform 180-h forecasts for 00 and 12 UTC, 120-h forecasts for 06 and 18 UTC, and 30-h forecasts for 03, 09, 15 and 21 UTC. ICON-EU forecast data are provided up to 120h for 00, 06, 12 and 18 UTC and up to 30h for 03, 09, 15 and 21 UTC. 27-h (45-h for 03 UTC) forecasts are performed for COSMO-DE eight times per day with a very short data cut-off of 30 minutes after 00, 03, 06, …, 18 and 21 UTC. Additionally, three ocean wave models (3rd generation WAM, see Section 4.5.2.1.2), the global GWAM, a European wave model (Mediterranean, North, Baltic and Adriatic Sea areas) EWAM and a coastal model (German Bight, Western and Southern Baltic) provide guidance about wind sea and swell based on 00 and 12 UTC wind forecasts of ICON and ICON-EU.

Probabilistic system
The 40 member global ICON-EPS (grid spacing 40 km) with a two-way nest over Europe (grid spacing 20 km) provides forecasts up to 180 h (based on 00 and 12 UTC), 120 h (based on 06 and 18 UTC) and 30 h (based on 03, 09, 15 and 21 UTC), starting from the global LETKF initial conditions.
27-h (45-h for 03 UTC) forecasts are performed for the regional convection-permitting COSMO-DE-EPS with 20 ensemble members eight times per day with a data cut-off of 60 minutes after 00, 03, 06, …, 18 and 21 UTC.

4.2 Medium range forecasting system (4-10 days)

4.2.1 Data assimilation, objective analysis and initialization

4.2.1.1 In operation

As far as ICON (including the ICON-EU refinement domain over Europe up to 120h) is in use for medium range forecasting, the same procedures are applied as for short range forecasting described in item 4.3

4.2.1.2 Research performed in this field

See 4.3.1.2

4.2.2 Model

4.2.2.1 In operation

Medium range forecasts at the DWD are mainly based on the ECMWF system (deterministic model and EPS). Additionally, ICON (see 4.3) and ICON-EPS forecasts up to 7.5 days augment the model guidance available.

4.2.2.2 Research performed in this field

Non-hydrostatic global model ICON with local zooming option

The further development of the non-hydrostatic global model ICON with local zooming option is jointly undertaken by DWD and the German Climate Research Centre MPI-M in Hamburg. In particular, the dynamical core has been extended to the deep-atmosphere equation system in order to allow extending the model top beyond the middle mesosphere. Ongoing work in this context deals with extending various physics parameterizations to cover additional physical processes relevant in this height range (e.g. viscous diffusion, non-LTE radiation). The Karlsruhe Institute of Technology (KIT) contributes on-line coupled modules treating secondary aerosols, directly emitted components like soot, mineral dust, sea salt and biological material as pollen. Modules for the emissions of mineral dust, sea salt and pollen grains have also been developed by KIT. Processes as emissions, coagulation, condensation, dry deposition, and sedimentation are taken into account. A module to treat the washout in a consistent way has been developed.

(G. Zängl, F. Prill, D. Reinert, S. Borchert, M. Köhler, D. Rieger)

4.2.3 Operationally available Numerical Weather Prediction Products

ECMWF and ICON global forecasts are available up to day 7.5.
See Section 4.3.1.1 for ICON products.

4.2.4 Operational techniques for application of NWP products

4.2.4.1 In operation

ECMWF-EPS-data and MOS (Model Output Statistics) applied to the ICON and ECMWF model are in use to produce medium-range forecasts up to day 7 (MOS: 10 days). Forecasts are provided for the public both in tabular form and in plain language. The forecasts in tabular form comprise the parameters daily maximum and minimum temperatures, relative sunshine duration, daily precipitation amount and probability, probability of snow, wind speed and direction, probability of thunderstorm, probability of fog. Medium-range forecasts in plain language are produced by forecasters in the Central Forecast Office in Offenbach. In addition to this the automatic text production is in use for worldwide forecasts, which are available by dialling a premium rate number on a fax machine, on a telephone answering device or on mobile telephones using short message system (SMS). The latter ones are produced however without forecasters' intervention.

Progress was made in medium range forecasting concerning the risk assessment of extreme weather for the forecast interval 120 hours down to 36 hours by synoptic interpretation of model results in combination with the evaluation of the COSMO-LEPS (Limited Area Ensemble Prediction System) and EFI- (extreme forecast index) charts, provided by ECMWF. COSMO-LEPS is a dynamical downscaling of the ECMWF EPS, and was developed by the COSMO-Consortium (Members are Germany, Greece, Israel, Italy, Poland, Romania, Russia and Switzerland; see Section 7). The risk-assessment is made available as a bulletin called "5 day forecast of weather risks" and includes the probability of certain severe weather events like storm, heavy precipitation, severe thunderstorm situations, widespread snowfall or freezing precipitation, heat and cold waves. The bulletin is produced once a day in the late morning with actualisation according to new model results in the evening or night hours if necessary. It is available for the regional offices within DWD and for the public via the internet.

Agrometeorological forecasts cover a wide range of applications aiming at a reduction of the use of insecticides and fungicides or at an optimization of the water supply to plants. NWP results are combined with additional models which calculate the drying of leaves or the temperature and water balance in the ground.

4.2.4.2 Research performed in this field

Further refinement of physical modelling.
The forecast resolution of MOS for ICON and ECMWF is reduced from 3 hours to 1 hour. Forecasts will be provided in popular KML format.

4.2.5 Ensemble Prediction System (EPS)

See also section 4.3.5.2.

4.2.5.1 In operation

The EPS of ECMWF is in use for operational forecasting. A downscaling-system of the EPS with the name COSMO-LEPS (Limited Area Ensemble Prediction System) is in operation. COSMO-LEPS has been developed by the COSMO consortium (Consortium for Small Scale Modelling) under the leadership of ARPA-SIM, Bologna, see Section 7. From an ensemble of 20 forecasts for middle and southern Europe computed twice daily with a horizontal grid distance of 7 km, probability forecasts can be derived. The input data for COSMO-LEPS are provided by 20 representative members taken from the EPS of ECMWF.

4.2.5.2 Research performed in this field

10-day forecasts for Road Weather Information System (SWIS)

In order to meet various requests from users for medium-range forecast information in the Road Weather Information System of DWD, a new forecast product, based on the MOSMIX forecasts at DWD was introduced. These so-called trend forecasts for temperature and precipitation (liquid, solid, freezing) are given as probabilistic information, i.e. mean and standard deviation for temperature and probabilities for exceeding thresholds of precipitation amounts. The introduction of the new products was accompanied by a user workshop, in order to thoroughly explain the content, meaning and possible use of the products. During the winter season 2015/16 the forecasts were tested by the users, and the feedback is currently being evaluated by DWD.

Further research is done by ARPA-SIMC, Bologna, see Section 7!

4.2.5.3 Operationally available EPS Products

Primarily ECMWF EPS products like EPS-Meteograms and a variety of parameters derived like maximum and minimum temperatures and probabilities of snow are available. The Extreme Forecast Index (EFI) is in use for early warning.

From COSMO-LEPS probability charts are available for middle and southern Europe which give information whether accumulated rain or snow, wind gusts, temperatures or CAPE values will exceed thresholds defined by warning requirements. The products are available up to 120 hours.

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

Operational short-range forecasting is based on the products available from the global non-hydrostatic model ICON (grid spacing of 13 km, 90 layers) and its two-way nested refinement ICON-EU (grid spacing 6.5 km, 60 layers) over Europe and its surroundings.
For nowcasting and very short range forecasts (up to 27 hours / 45 hours from 03 UTC) the convection-permitting meso-gamma scale model COSMO-DE (grid spacing of 2.8 km, 421x461 grid

points/layer and 50 layers) provides numerical guidance eight times per day with a very short data cut-off of 30 minutes. Lateral boundary conditions of COSMO-DE are derived from ICON-EU forecasts.

Ensemble forecasts on the convective scale are provided by COSMO-DE-EPS (see Section 4.3.5.1).

4.3.1 Data assimilation, objective analysis and initialization

4.3.1.1 In operation

<u>Global Model (ICON)</u>

a) Global analysis of mass, wind field and humidity

Analysis method	Ensemble-variational assimilation (EnVar) in observation space (PSAS). Background error covariance matrix partly (30%) derived from climatology (NMC-Method) and partly (70%) from the flow-dependent 40-km (20 km over Europe) 40-member short-range EPS forecasts based on an LETKF ensemble analysis.
Analysed variables	p, T, u, v, relative humidity
Horizontal anal. grid	Icosahedral-triangular grid of the ICON (average mesh size of 13 km)
Vertical resolution	90 height-based layers (SLEVE, see ICON)
Products	a) on icosahedral-triangular grid of the ICON (2.949.120 grid points/layer, 90 layers) Variables: p, T, u, v, q_v, q_c, q_i, q_{rain}, q_{snow} b) on a regular geographical grid, 1440 x 721 points (0.25° x 0.25°) 27 pressure levels 1000, 950, 850, 700, 500, ..., 3, 2, 1, 0.3, 0.1 hPa Variables: p_{msl}, T, Φ, u, v, relative humidity
Assimilation scheme	Intermittent data assimilation. Insertion of data every 3 hours. 3-h forecast used as first guess. All observations within a ± 1.5-h window used as synoptic. Cut-off time is 2 h 14 min for main forecast runs.
Initialization	Incremental analysis update (*Bloom et al., 1996*; *Polavarapu et al., 2004*); analysis increments are interpolated from the global ICON domain to the ICON-EU

b) Global analysis of surface parameters

Analysis method	Correction method
Analysed variables	Sea surface temperature (SST), sea ice and snow cover
Horizontal anal. grid	On icosahedral-triangular grid of the ICON (average mesh size of 13 km, 6.5 km over Europe)
Data used	SST, sea ice: Synop-Ship, NCEP-SST analysis as background, NCEP analysis of sea ice distribution.

Snow cover:	Snow depth, present and past weather, precipitation amount, temperature analysis. History taken into account. NCEP analysis of snow cover.

Analysis method Optimal Interpolation using height correction

Analysed variables Temperature and relative humidity at 2 m

Horizontal anal. grid On icosahedral-triangular grid of the ICON (average mesh size of 13 km, 6.5 km over Europe)

Data used Model first guess T 2m, rh 2m and observations T 2m, Td 2m from reports of synop stations, aircrafts, ships and bouys

Analysis method Variational method (*Hess, 2001*)

Analysed variables Soil moisture content

Horizontal anal. grid On icosahedral-triangular grid of the ICON (average mesh size of 13 km)

Data used Analyses of 2m temperature, forecast of 2m temperature, soil moisture, surface fluxes relevant to surface energy balance from ICON

<u>Convection-permitting model COSMO-DE</u>

a) Limited-area analysis of atmospheric fields

The data assimilation system for COSMO-DE (DE = Deutschland) is based on a 40-member ensemble-based (LETKF: Local Ensemble Transform Kalman Filter after Hunt et. al., 2007) approach. At present, the scheme uses operationally conventional data of type TEMP, PILOT, SYNOP, BUOY, AMDAR and wind profiler. Additionally, precipitation rates derived from radar observations (5-min precipitation scans) are included via the latent heat nudging method (*Stephan et al., 2008*).

Analysis method LETKF and latent heat nudging

Directly analysed variables pressure at lowest model level, T, u, v, relative humidity

Horizontal anal. grid 421x461 points (0.025° x 0.025°) on a rotated latitude/longitude grid

Vertical resolution 50 hybrid layers

Products All analysis products are given on the 421x461 grid and available at hourly intervals.

a) On the 50 layers
Variables: p, T, u, v, w, q_v, q_c, q_i, q_{rain}, q_{snow}, $q_{graupel}$, TKE

b) On 10 pressure levels (1000, 950, 850, 700, 500, ..., 200 hPa)
Variables: p_{msl}, Φ, T, u, v, ω, relative humidity

c) On 4 constant height levels (1000, 2000, 3000, 5000 m)
Variables: p, T, u, v, w, relative humidity

Assimilation scheme LETKF in hourly cycles.
Cut-off time 30 min for COSMO-DE runs.

Initialization	None

b) Limited-area analysis of other surface parameters

Analysis method	Correction methods
Analysed variables	Sea surface temperature (SST) and sea ice cover, snow cover, temperature and relative humidity at 2 m
Horizontal anal. grid	421 x 461points (0.025° x 0.025°) on a rotated latitude/longitude grid
Data used	SST: Synop-Ship, US-data of ice border, sea ice cover analysis from BSH (German Institute for shipping and hydrology) for the Baltic Sea and indirectly satellite data (via NCEP-SST and ICON_SST analyses). Snow cover: Snow depth, present and past weather, precipitation amount, 2-m temperature analysis (plus model prediction)

4.3.1.2 Research performed in this field

Assimilation of satellite radiances in the global model ICON
Work is in progress to assimilate more remote sensing data. Work is carried out on a variety of new instruments and satellites. It includes different infrared radiances (e.g. IASI = Infrared Atmospheric Sounding Interferometer and CrIS) as well as humidity information of the microwave sensors, microwave sensors over land and under cloudy conditions. A new variational bias correction is under development.

(C. Köpken-Watts, O. Stiller, A. Walter, K. Raykova, S. Hollborn, R. Faulwetter, A. Fernandez del Rio)

Assimilation of cloud-affected and cloudy radiances
The assimilation of cloud related information from satellite radiances is an important topic of international research. We work on the reconstruction of cloud information within an atmospheric column based on a 1dvar-type approach, which is then integrated into our 3DVAR and EnVAR (Variational Ensemble Kalman Filter) systems. In this framework, appropriate regularization methods which take care of the particular statistics of the data and states under consideration (e.g. non-Gaussian statistics) are under investigation.

(C. Köpken-Watts, O. Stiller, R. Faulwetter, A. Fernandez del Rio, R. Potthast)

GNSS Slant Delay
The assimilation of GNSS (Global Navigation Satellite System) slant delays is under development in cooperation with the Geo Research Center (GFZ) in Potsdam. An efficient operator for STD (Slant Tropospheric Delay) has been implemented into COSMO-DE, experiments for STD assimilation are on the way.

(M. Bender, A. Rhodin, R. Potthast)

SEVIRI Cloud Products and Seviri Radiances
Supported by a EUMETSAT Fellowship and Special Research Area we work on the assimilation of SEVIRI (Spinning Enhanced Visible and Infrared Imager) cloud products and SEVIRI radiances within the COSMO model based on the LETKF framework. In particular, cloud type and cloud top height information is fed into the assimilation scheme with the help of innovative discrepancy functions to enhance the sensitivity of measurements towards the model state increments. First assimilation experiments with SEVIRI radiances have been carried out by A. Perinanez in collaboration with Otkin (Wisconsin/Reading) and by Harnisch (LMU Munich).

(A. Hutt, J. Otkin, C. Schraff, R. Faulwetter, R. Potthast)

Particle Filters for Numerical Weather Prediction

The use of particle filters is tested for large-scale numerical weather prediction. A framework for realizing different particle filters has been implemented into the EnVAR/LETKF assimilation software of DWD, with a first Local Adaptive Particle Filter (LAPF) being available, first tests in a complete cycle for the global ICON EDA (Ensemble Data Assimilation) have been successfully carried out by Walter, Rhodin and Potthast. Within cooperation projects with ETH Zürich (S. Robert, H. Künsch) and University of Potsdam (S. Reich) different further particle filters are being implemented into our software currently, with tests targeted on the convective scale. Further cooperation projects on particle filters are under discussion with RIKEN (Rikagaku Kenkyūjo Kobe, Japan) and LMU Munich.

(R. Potthast, A. Walter, A. Rhodin, H. Reich, C. Schraff, S. Reich)

Seamless Integrated Forecasting System (Sinfony)

Within the new research project "Seamless Integrated Forecasting System (Sinfony)" the forecasting of small-scale high-impact weather phenomena (severe convection and heavy precipitation) over a lead time of 12 hours is investigated. It is planned to combine further developed products of nowcasting with forecast lead times of two hours and high update rate with the forecasting results of a short-range rapid update cycle (RUC) ensemble prediction system to achieve a seamless forecasting of the atmospheric state and weather phenomena from the current state of the atmosphere to short-range NWP.

Sinfony plans to employ an ensemble approach on all relevant spatial and temporal scales, in particular for nowcasting and the short-range forecasts of NWP. To explicitly resolve deep convective clouds, a grid spacing of 1 km is planned as well as an increase of the number of vertical model layers. The homogenization of model forecasts and nowcasting needs improvements in the use of temporal spatial high-resolution data such as RADAR and geostationary satellite data of conventional and hyperspectral sounders in the framework of ensemble data assimilation on the convective scale.

(U. Blahak, A. Seifert, E. Bauernschubert, R. Potthast, H. Anlauf, K. Stephan, and others)

Assimilation of microwave radiances for soil moisture analysis

The microwave emissivity model CMEM, used at ECMWF has been adopted to assimilate 1.4 GHz microwave brightness temperatures from SMOS and SMAP satellite. The code is adapted to run the forward model for ICON. Tests are underway to evaluate the simulated brightness temperature against SMOS observations. Work on the implementation into the soil moisture analysis scheme still has to be done to make use of these satellite observations.

(M. Lange)

SST perturbations derived from multi-product SST-L4 ensemble GMPE (GHRSST Multi-Product Ensemble)

The multi-product SST ensemble is used to generate perturbed initial conditions for sea surface temperature fields in the global ICON ensemble system. Tests are outlined to assess the impact of SST perturbations generated from random linear combinations of the multi-product SST anomalies on the 40 ensemble members. Further tests are required to evaluate the impact against the unperturbed case and the present method which is based on stochastic perturbation patterns.

(M. Lange, A. Rhodin)

4.3.2 Model

4.3.2.1 In operation

a) Schematic summary of the Global Model ICON

Domain	Global with two-way nested higher resolution domain over Europe (ICON-EU)
Initial data time	00, 03, 06, 09, 12, 15, 18, 21 UTC
Forecast range	global domain: 180 h (from 00 and 12 UTC), 120 h (from 06 and 18 UTC), 30 h (from 03, 09, 15, and 21 UTC): European domain: 120 h (from 00, 06, 12 and 18 UTC), 30 h (from 03, 09, 15, and 21 UTC)
Prognostic variables	ρ, Θ_v, v_N, w, TKE, q_v, q_c, q_i, q_{rain}, q_{snow}
Vertical coordinate	Height-based, SLEVE (*Leuenberger et al., 2010*), 90 layers with top at 75 km for global domain; 60 layers with top at ~23 km for European domain
Vertical discretization	Finite-difference for momentum / finite volume for scalars; 2nd order
Horizontal grid	Icosahedral-triangular (*Sadourny et al., 1968*), average mesh size 13 km for global domain and 6.5 km for European domain; Arakawa-C grid
Horiz. discretization	Finite-difference for momentum / finite volume for scalars; 2nd order mass consistent transport of tracers (*Miura, 2007*)
Horizontal diffusion	Linear, 4th order; nonlinear 2nd order Smagorinsky
Orography	Grid-scale average (slightly smoothed) based on a 1-km data set
Parameterizations	Turbulent transfer based on prognostic TKE (*Raschendorfer 2001*)
	Non-orographic gravity wave drag (*Orr, Bechtold et al., 2010*)
	Sub-grid scale orographic effects (blocking and gravity wave drag) based on *Lott and Miller, 1997*
	Radiation scheme (RRTM, Mlawer et al., 1997; Barker et al., 2002) full cloud-radiation feedback based on predicted clouds
	Mass flux convection scheme after *Bechtold et al., 2008*
	Kessler-type grid-scale precipitation scheme with parameterized cloud Microphysics after *Doms and Schättler, 2004* and *Seifert, 2008*
	7-layer soil model *(Heise and Schrodin, 2002; Schulz et al., 2016)* including simple vegetation and snow cover; prescribed climatological value for temperature at about 14 m depth; for in-land lakes FLake (Mironov, 2008; Mironov et al. 2010; http://lakemodel.net); Tile approach with three dominant land-cover classes per grid point, separate treatment of snow-free and snow-covered parts
	Over oceans: Initial SST from SST analysis with climatology-based incremental daily update; for ice-covered ocean areas a sea ice model (*Mironov et al., 2012*) provides ice thickness, temperature and albedo; roughness length according to Charnock´s formula in ice-free areas

Analyses and forecasts (up to 180 h) data of ICON are sent up to four times per day (for 00, 06, 12 and 18 UTC) via the Internet to several other national meteorological services (Botswana, Brazil, Egypt, Georgia, Greece, Indonesia, Israel, Italy, Jordan, Kenya, Madagascar, Malawi, Malaysia, Mozambique, Nigeria, Oman, Pakistan, Philippines, Poland, Romania, Russia, Rwanda, Saudi Arabia, Serbia, South Africa, Switzerland, Tanzania, Turkmenistan, Ukraine, United Arab Emirates, Vietnam and Zimbabwe). These data serve as initial and lateral boundary data for regional modelling. For a detailed description of ICON, see *Zängl et al., 2015*.

c) Schematic summary of the limited area model convection-permitting COSMO-DE

Domain	Germany and surroundings
Initial data time	00, 03, 06, 09, 12, 15, 18 and 21 UTC
Forecast range	27 h (45 h from 03 UTC)
Prognostic variables	p, T, u, v, w, q_v, q_c, q_i, q_{rain}, q_{snow}, $q_{graupel}$, TKE
Vertical coordinate	Generalized terrain-following, 50 layers
Vertical discretization	Finite-difference, 2^{nd} order
Horizontal grid	421x461 points (0.025° x 0.025°) on a rotated latitude/longitude grid, mesh size 2.8 km; Arakawa-C grid, see Fig. 1.
Horiz. discretization	Finite-difference, 5^{th} order upwind advection; For the advection of moisture variables: *Bott (1989)* scheme with Strang-splitting
Time integration	Two-time-level, 3^{rd} order Runge-Kutta, split explicit (*Wicker and Skamarock, 2002*), Δt = 25 s.
Horizontal diffusion	Implicit in advection operators. Explicit horizontal hyperdiffusion (4^{th} order) for the velocity components and Smagorinsky-type diffusion In the full domain.
Orography	Grid-scale average based on a 1-km data set. Topography has been filtered to remove grid-scale structures.
Parameterizations	Surface fluxes based on a resistance model by vertical integration of a flux-gradient representation along a constant-flux transfer layer using a surface layer TKE equation (*Raschendorfer, 2001)* Free-atmosphere turbulent fluxes based on a level-2.5 scheme with prognostic TKE (*Mellor and Yamada, 1974*) with contributions from non-turbulent processes *(Raschendorfer, 2001)* Radiation scheme (two-stream with three solar and five longwave intervals) after *Ritter and Geleyn (1992)*, full cloud-radiation feedback based on predicted clouds Mass flux convection scheme after *Tiedtke (*1989) for shallow convection only. Deep convection is resolved explicitly by COSMO-DE. Kessler-type grid-scale precipitation scheme with parameterized cloud microphysics after Doms and Schättler, 2004 and Seifert, 2008 7-layer soil model *(Heise and Schrodin, 2002; Schulz et al., 2016)* including simple vegetation and snow cover; prescribed climatological value for

temperature at about 14 m depth.

Over ocean: Fixed SST from SST analysis over open water; for ice-covered ocean areas a sea ice model (Mironov et al., 2012) provides ice thickness and temperature;
roughness length according to Charnock´s formula in ice-free areas.

Over inland lakes: Lake model FLake (Mironov, 2008; Mironov et al. 2010; http://lakemodel.net).

4.3.2.2 Research performed in this field

Revision of the liquid water content in frozen soil of the land-surface scheme TERRA
The existing formulation in TERRA shows reasonable liquid water fractions in the frozen soil near the melting point but overestimates the fraction of liquid water at low temperatures, i.e. below -20 °C, especially for soils with large pore-size distribution index (clay). An alternative formulation (Schaefer and Jafarov, 2016) shows reasonable liquid water fractions at low temperatures but decrease the liquid water too fast near the melting point that could lead to numerical instabilities in the model. Therefore, the temperature range below the melting point is considered in several ranges, where different parameterizations are applied. In the range to -3 °C the existing formulation in TERRA is used to determine the liquid water content. Below -3 °C a logarithmic interpolation is applied to the value of the parameterization of Schaefer and Jafarov (2016) at -40 °C. Below -40 °C the fraction of liquid water in the soil is assumed as constant.

(J. Helmert and G. Zängl)

Prognostic parameterization of the sea-ice surface albedo
The sea-ice surface albedo with respect to solar radiation is computed from a relaxation-type rate equation. The sea-ice albedo does not immediately follow changes in forcing, but relaxes to its equilibrium value on a certain time scale. The equilibrium sea-ice surface albedo is computed as function of the ice surface temperature. In order to account for the increase of albedo after snowfall events, the relaxation towards the equilibrium ”snow-over-ice” albedo is applied. The equilibrium ”snow-over-ice” albedo is parameterized as a function of the ice surface temperature. The new prognostic parameterization of the sea-ice surface albedo is operational in ICON since May 2017.

(D. Mironov, D. Reinert and G. Zängl)

A new parameterisation of bare soil evaporation for the land surface scheme TERRA
The bare soil evaporation simulated by the land surface scheme TERRA (Heise and Schrodin, 2002; Schulz et al., 2016) of the DWD global and regional atmospheric models is systematically overestimated under medium-wet to wet conditions. This creates a dry bias in the soil, a moist bias of near-surface humidity and a cold bias of near-surface temperature (at daytime). Furthermore, it leads to a reduced diurnal near-surface temperature range. Under medium-dry to dry conditions, the bare soil evaporation in TERRA is systematically underestimated.
In the standard model configuration of TERRA, the formulation of bare soil evaporation is based on the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson, 1984). In extensive tests with other formulations it turned out that a scheme based on a resistance formulation (for a review see Schulz et al., 1998) yields the best results. A new scheme was developed and implemented in TERRA. Experiments in offline mode, utilizing measurements of the DWD observatory Lindenberg (Falkenberg site), show substantial improvements with respect to moisture and temperature errors. Experiments in coupled mode, with ICON, show significant improvements as well.

(J.-P. Schulz and G. Vogel)

Multi-layer snow model

The multi-layer snow model differs mainly in two points from the current one-layer snow model. These are 1) an arbitrary number of layers in snow instead of one bulk layer and 2) the possibility of water phase changes, existence of liquid water content, water percolation and refreezing within snowpack. The explicit vertical stratification (multi-layer structure) of various properties of snow (temperature, density etc.) allows a more correct representation of the temperature at the soil-snow and snow-atmosphere interface which is important for calculation of snow melting rate and surface turbulent fluxes. The accounting for liquid water and water phase changes within snowpack allows a more accurate calculation of the evolution of the snow properties, in particular, snow water-equivalent depth and snow density, which in turn determines snow heat conductivity.
An improved version of the multi-layer snow model became available in the latest COSMO model version. In this version, some issues related to numerical stability are solved and some bugs are corrected.

(E. Machulskaya)

Tile approach in ICON

Tile approach is a means to account for surface heterogeneity within each model grid box. Within the framework of the tile approach, each model grid box is divided into a number of sub-grid elements characterised by different surface types. The surface types (e.g. forest, bare soil or water) and the fractional area of the sub-grid elements are specified by external-parameter fields. The fractional snow cover is considered separately for each element. Individual values of surface temperature and humidity and, importantly, individual vertical profiles of soil temperature and moisture are computed for each tile, where snow-covered and snow-free parts of each sub-grid element are treated as separate tiles. The algorithm takes particular care of the conservation of soil heat and moisture when the fractional snow cover changes with time. The grid-box mean fluxes of sensible and latent heat are determined by means of averaging of fluxes over different tiles weighted with the tile fractional areas. It should be emphasised that these weighted-mean fluxes differ from the fluxes computed on the basis of grid-box mean values of surface temperature and humidity.

The tile approach to compute surface fluxes was implemented into the COSMO model first. Currently, there is no link between an external parameter database and the COSMO model code, so that only snow-covered/snow-free tiles and inland water tiles may be considered, because the information about the corresponding grid-box fractions of these surface types is available within the COSMO model itself. These two configurations of the tile approach were successfully tested through parallel experiments (see the GDPFS Report 2011). The results indicate that if snow is considered as a tile, the surface temperature of the snow-free tile can rise above freezing point independently of the surface temperature of the snow tile, which is physically plausible. Various case studies from the years 2011-2012 show that in the regions with fractional snow cover, the COSMO model without the tile approach keeps the surface temperature at freezing point, whereas with the tile approach the COSMO model is indeed able to reproduce the grid-box aggregated surface and air temperature several degrees higher than freezing point which is close to observations.

The tile approach has been implemented into the global model ICON (operational at DWD since January 2015). As compared to COSMO, the tiled surface scheme implemented into ICON operates with the full set of land surface types. Inland water, open ocean water and see ice are also treated as tiles. The approach selects a prescribed number of dominating surface types for each grid box. In the case of partial snow cover, the snow-covered part and the snow-free part are treated as separate tiles (with separate soil temperature and moisture profiles) for a number of land surface types, e.g. bare soil or grass. However, for some other surface types, e.g. forest, no separate profiles are treated, although the surface temperature and humidity are computed as weighted means of temperature and moisture over snow-covered and snow-free parts.

(E. Machulskaya and J. Helmert)

Determination of required soil physical parameters for the COSMO land surface scheme TERRA using new basic soil data

Numerical weather prediction (NWP) models need information about the soil state that is the lower boundary for atmospheric processes over land. Soil physical properties and soil moisture have an impact on the surface flux budget and therefore on the exchange of heat and moisture between land-surface and atmosphere**.**

Besides the influence of hydrological inputs, the observed high variability of soil moisture over space is partly due to soil properties and land surface characteristics (*Ashton, 2012*). The transport of moisture in the soil is controlled by soil hydraulic parameters. The NWP COSMO model uses these parameters for 6 aggregated soil types + information about glaciers, rocks, and sea water/ice, based on the FAO Digital Soil Map of the World (FAO-DSMW) in 5 arcminutes resolution.

Since 2008 the global Harmonized World Soil Database (HWSD) in 30 arc-second raster, provides over 16000 different soil mapping units that combines existing regional and national updates of soil information (*Nachtergaele, 2012*). With this comprehensive global data set it is possible to derive the soil types for the Soil-Vegetation-Atmosphere Transfer (SVAT) model TERRA of the NWP COSMO model as from the FAO-DSMW. However, the HWSD offers additionally a link between soil units and soil properties (e.g., fractions of sand, silt, clay, and organic carbon together with bulk density). By employing pedotransfer functions using these soil properties (e.g., *Wösten et al., 1999*) the required soil hydraulic parameters can be determined in TERRA from HWSD soil units together with a look-up table of soil properties *(Smiatek et al., 2015*).

Some benefit for the COSMO model can be derived from this approach. It preserves the high horizontal variability contained in the HWSD soils for the SVAT model and allows with a flexible look-up table of soil properties a quick adaptation for other soil data sets.

(J. Helmert, C. Becker, W. Janssen, E.-M. Gerstner, G. Smiatek)

Implementation of a vegetation canopy scheme in the land surface scheme TERRA

The missing stratification of the vegetation in the land surface scheme TERRA was upgraded by the discrimination of the energy budget for the canopy and the vegetation floor. A prognostic equation for the canopy temperature was introduced, which accounts for the heat capacity of the vegetation. It is expected that the model improves the simulation of the diurnal cycle of the screen-level temperature and decreases the overestimation of the soil-temperature amplitude compared to measurements.

(J. Helmert, E. Machulskaya, M. Raschendorfer, G. Zängl)

Climatological SST update

It has been recognized that keeping the SST constant during the 7.5-day global forecasts introduces systematic errors in the lower-tropospheric temperature during the transitional seasons. To alleviate this issue without incurring the complexity of adding a prognostic scheme for the upper ocean layer, an incremental daily update based on a monthly SST climatology has been introduced. Verification scores indicate a significant reduction of near-surface temperature biases over the extra-tropical oceans.

(J. Helmert, H. Frank, D. Reinert)

Tuning of convection scheme and convection-microphysics coupling to reduce the 'drizzle bias'

In collaboration with P. Bechtold (ECMWF), the Tiedtke-Bechtold convection scheme and its coupling to the microphysics scheme has been revised in order to reduce its tendency to overpredict the area covered with precipitation under weakly unstable conditions. Inside the convection scheme, several assumptions made in the calculation of the test parcel ascent (e.g. excess temperature and humidity of ascending parcel, entrainment during ascent) were modified in order to reduce the convective activity in marginal situations, and the mixed-phase parameterization in updrafts was changed to shift the freezing of liquid updraft water to lower temperatures. In addition, the water-ice partitioning of the cloud mass detrainment tendency passed to the grid-scale microphysics scheme is now modified depending on the cloud-top temperature in order to avoid an unrealistic triggering of the Bergeron-Findeisen mechanism in the grid-scale scheme in stratus / stratocumulus clouds with top temperatures above about -10°C.

(G. Zängl, M. Köhler; P. Bechtold)

4.3.3 Operationally available NWP products

Short-range forecasts are based on direct model output (DMO) of the ICON and COSMO-DE and on MOSMIX and WarnMOS guidance based on ICON and ECMWF data.

4.3.4 Operational techniques for application of NWP products

4.3.4.1 In operation

Forecasts are produced partly automatically, based on the data listed in 4.3. Forecasts in plain language and warnings for the public and for aviation are produced by meteorologists. Any kinds of fields, DMO, ensemble based data and MOS-data are available and used in combination with nowcasting techniques. Forecasts of significant weather (SWC) for Middle Europe are produced on the base of ICON-EU and special techniques. NWP results are used for a variety of further applications. Some of these applications are briefly described below.

DMO is used for the production of any weather situation imaginable in 2-D or 3-D modules as still picture, dynamic graphics, or as a complete film. A graphics system developed for the visualization of meteorological data supports the interactive or automatic presentation of DMO in single images or image sequences.

Short range forecasts of weather and temperature in pictorial form are automatically produced for online presentation on the Internet using MOS-MIX forecasts of ICON and ECMWF (worldwide and national).

The state of road surfaces (road surface temperature and road surface condition) is predicted by a road weather forecast system (AutoSWIS –Automatisches Strassenzustands- und Wetter-Informations-System) using MOS MIX data based on ICON and ECMWF and an energy balance model of the road surface.

A 10 day regional forecast based on the 50 ensemble members of the ECMWF EPS data has been re-designed for SWIS. The forecast includes daily maximum/minimum temperatures as well as snow and precipitation probabilities. The regions are in accordance to the SWIS regions (7 lowland and 7 mountain regions). The grid points are interpolated to stations and then assigned to the regions. The upper and lower limits for the maximum and minimum temperatures are calculated from the mean values and the standard deviations. Precipitation and snow probabilities are also calculated by the mean values of the regions. In addition, a 15 day regional forecast for the DWD website (7 lowland regions) has been re-designed. The Forecast variables are daily maximum/minimum temperatures which are also based on ECMWF EPS data and calculated like the previous product.

The influence of weather on human health is forecasted using a bio-synoptical weather classification scheme and the predicted vorticity, temperature and humidity in the surfaces - 850- and 500 hPa. The thermal strain on a prototype human being is calculated by a physiologically relevant energy balance model which employs forecasted temperature, humidity, wind and short- and long-range irradiances. Both weather classification and thermal strain data are calculated for all grid-points of the ICON-EU. Heat warnings are produced on the basis of GMOS-data. They base both on the thermal strain outdoors during daytime and the nocturnal thermal strain indoors. Latter is calculated using a thermal building simulation model. UV Index and resultant UV-warnings are forecasted within ICON / ICON-EU derived from the large scale UV Index forecasts. The large-scale UV Index is calculated depending on solar zenith angle and the column ozone forecast. Subsequently the large scale UV Index is adjusted by factors to variable aerosol amount and type, altitude, surface albedo of predicted snow cover and cloud optical thickness of predicted cloudiness of ICON / ICON-EU.

The aviation community needs forecasts of wind, temperature, air density and QNH for the planning and safe management of flights. These are provided as direct model output. Apart from the 2D QNH, the parameters are available in 3D for different height levels: for the lower atmosphere on geometric height levels, higher up on flight levels.

Two of DWD's meteorological watch offices (MWOs) issue the low-level significant weather chart (LL-SWC) for the middle European area from the surface up to FL245. LL-SWCs are in use as general guidance for the aeronautical consulting business and in general aviation. They contain information on the expected significant weather, jet axes, visibility, clouds, turbulence, icing and cloud coverage. The aeronautical meteorological forecaster produce interactively the charts on meteorological work-stations based on ICON-EU results combined with conventional synoptic methods.

For the planning of gliding flights in Germany and most parts of Middle Europe the software package TOPTHERM is used. TOPTHERM calculates the development of thermal lift for specific areas based on COSMO-DE. Aviation users can visualize the TOPTHERM results with the TOPTASK application available on DWD's online briefing platform http://www.flugwetter.de.
Access to this platform requires registration with DWD. During the gliding season an advice for gliding pilots is prepared which may be received by the system PCMET. It presents charts of the lowest cloud base or the height of thermal activity, precipitation, wind direction and wind speed for several times during the day. It is based on ICON-EU and COSMO-DE data.

Furthermore, ICON and ICON-EU model output provides the data base for the visualization software SkyView and the icing forecast algorithm ADWICE. SkyView visualizes forecasts of convection, cloudiness and wind at different levels on grid points in time steps of one hour up to 70h. Users can zoom into different areas in Europe. The flash application allows users to combine several parameters in the same map depiction. In this way, a common analysis of the requested parameters is possible.

The model ADWICE forecasts and diagnoses the atmospheric icing between surface and FL 360. In current operational use ADWICE provides hourly prognostic products up to 24h and 3 hourly forecasts up to 78h, updated four times a day. Furthermore there is an hourly updated diagnostic product that provides the actual risk of aircraft icing using METAR, SYNOP, RADAR and Satellite information in addition to ICON-EU model output data. At the moment results are visualised in NinJo (both, prognostic and diagnostic products) and in the Selfbriefing system pc_met Internet (only prognostic products up to 48h).

An additional automated MOS system is used for the calculation of worldwide international and regional airport forecasts. The system is based on the IFS model (ECMWF), SYNOP and METAR observations. For Central European stations radar and lightning remote sensing observations as well as the advection of these quantities are included into the MOS equations. The forecasts are distributed hourly as guidance and in a TAF coded format (AutoTAF) up to +30h. Many of the forecasting elements are adapted for aviation purpose and give probabilistic information.

All aviation meteorological products are offered to a closed user group over the web site: http://www.flugwetter.de.

Agrometeorological forecasts cover a wide span of applications aiming at a reduction of the use of insecticides and fungicides or at an optimization of the water supply to plants. NWP results are combined with additional models which calculate the drying of leaves or the temperature and water balance in the ground. These forecasts are presented in http://www.agrowetter.de.

In the maritime department programs are run to extract globally direct model grid point information from the weather and sea state models for German research vessels and other ships or yachts. The data is distributed by automatic e-mail.

WarnMOS is a grid-based MOS-System for the territory of Germany. On a $1x1km^2$ grid hourly updated probabilistic warning guidance for the next 24h and 188h (four times a day) is calculated. Input data are the NWP models ICON and IFS (ECMWF), SYNOP data and remote sensing observations from precipitation radar and lightning. The forecasts are visualised in NinJo and serve as input data for AutoWARN. In addition the forecasts are used in the DWD mobile app “WarnWetter”

4.3.4.2 Research performed in this field

Replacement of ‘Objective Optimized Guidance‘(OOG) by improved MOSMIX forecasts

The ‚Objective Optimized Guidance‘(OOG) as well as MOSMIX represents well-established operational products for statistically optimized point forecasts at DWD. Within the last two years, the temporal resolution of MOSMIX forecasts has been increased from three to one hour for forecasts up to +240 hours in advance and an hourly MOSMIX update cycle will be available as of 2018. Extensive verifications have shown that MOSMIX will thus provide point forecasts that reach or exceed the statistical forecast skills of the OOG. Therefore all OOG forecasts will be replaced by the newly developed 1h-MOSMIX in 2018.

Project AutoWARN

The semi-automatic warning decision support system AutoWARN developed at the German Meteorological Service (DWD) is operational since 2015. It is part of DWD's strategy of modernizing the weather warning service by further automation and centralization of the warning process. One aim is to help forecasters to deal with increasing amounts of Numerical Weather Prediction (NWP) and observational/Nowcasting data using semi-automatic assistance systems (Reichert, 2009; 2011; 2016; Reichert et al., 2015).

In a first step, available NWP model and ensemble forecasts (COSMO-DE-EPS, ECMWF-EPS, ICON) are combined into a single warn forecast product (ModelMIX). This is done using an Ensemble Model Output Statistics (Ensemble-WarnMOS) approach based on logistic regression on a probabilistic basis. DWD’s Nowcasting systems (KONRAD, CellMOS, RADVOR-OP, VIL derived from 3D-Radar data, Mesocyclone Detection) as well as observations and model output (COSMO-DE) are combined using a fuzzy logic approach to obtain a robust Nowcasting Warn Product (NowCastMIX), updated every 5 minutes. In a second step, both products with a spatial resolution of 1 km are used by AutoWARN in order to generate automated warn proposals for forecasters. Using the AutoWARN Status Editor (ASE) within the meteorological workstation NinJo, these warn event-based proposals can be quality-controlled and modified manually by forecasters or they just serve as a basis for issuing individual manual warnings by forecasters. The result is a final warn status used to automatically produce the full range of individual textual and graphical warning products for customers.

In 2016, DWD changed from rural district based-warnings (300 German rural districts) to much higher resolved warnings based on municipalities (11,000 German municipalities) using AutoWARN. Now, automatic products include internet and mobile app visualizations up to the resolution of municipalities with a high update frequency as well as more coarse warn products in space and time for individual client needs.

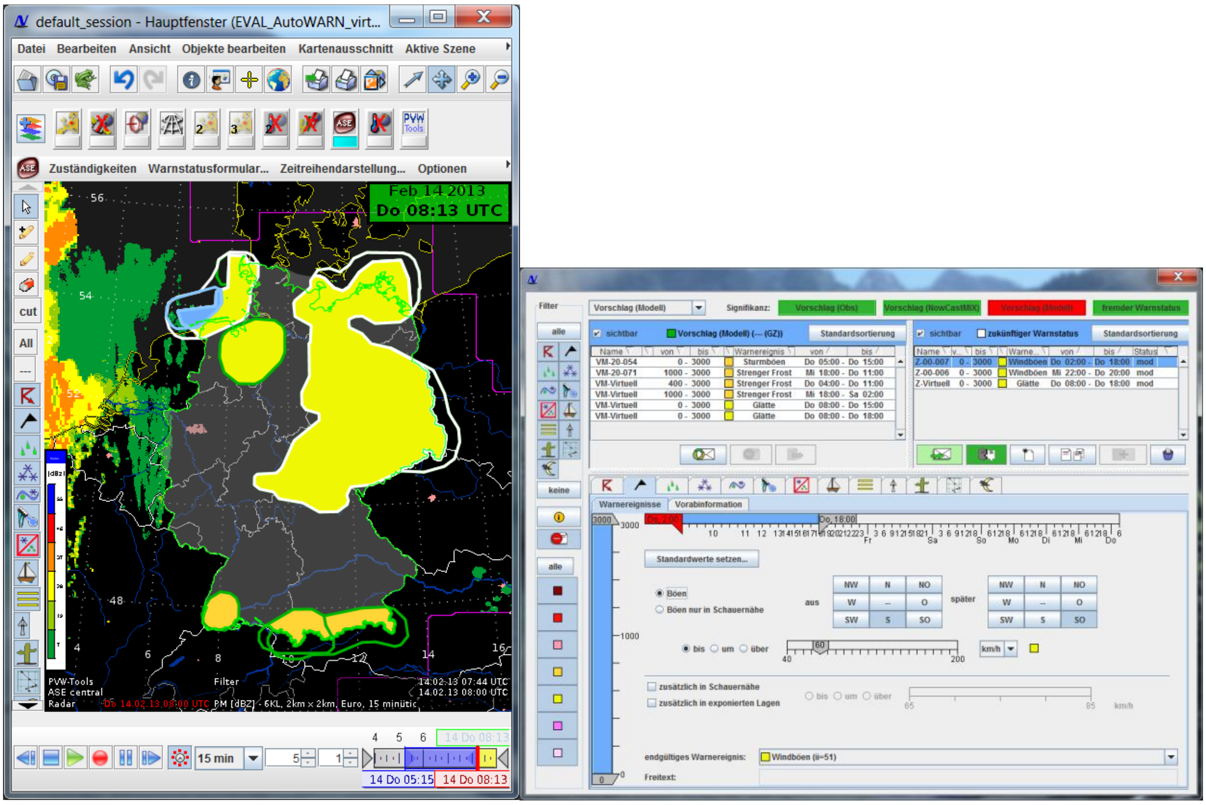

Figure 1: Graphical User Interface for AutoWARN within NinJo

Current work in AutoWARN focuses on ergonomic software improvements and an enhanced assistive support for the warning forecaster.

Project EnsembleMOS

As MOS Systems for ICON and ECMWF are operational, a system to statistically optimize and calibrate ensemble data is currently in development. The new EnsembleMOS system is enhanced for the special requirements and application of ensemble models such as COSMO-DE-EPS and EZMWF-EPS (later ICON-EPS as well). Based on the WarnMOS setup with a new logistic regression approach it is prepared to provide statistically optimized and calibrated probabilistic forecasts as input for AutoWARN (see above). EnsembleMOS is a major input for ModelMIX in the short range, which is planned to substitute WarnMOS by the end of 2017.

Project ADWICE

The postprocessing system ADWICE forecasts and diagnoses the atmospheric aircraft icing between surface and FL 360.

However, there have been many engines abnormally in the last years connected to a high concentration of ice crystals (“Ice Crystal Icing”, ICI). As ADWICE only considers aircraft icing due to supercooled liquid water yet, we will figure out possibilities to forecast and diagnose ICI on the basis of existing products and NWP output data by evaluating pilot reports.

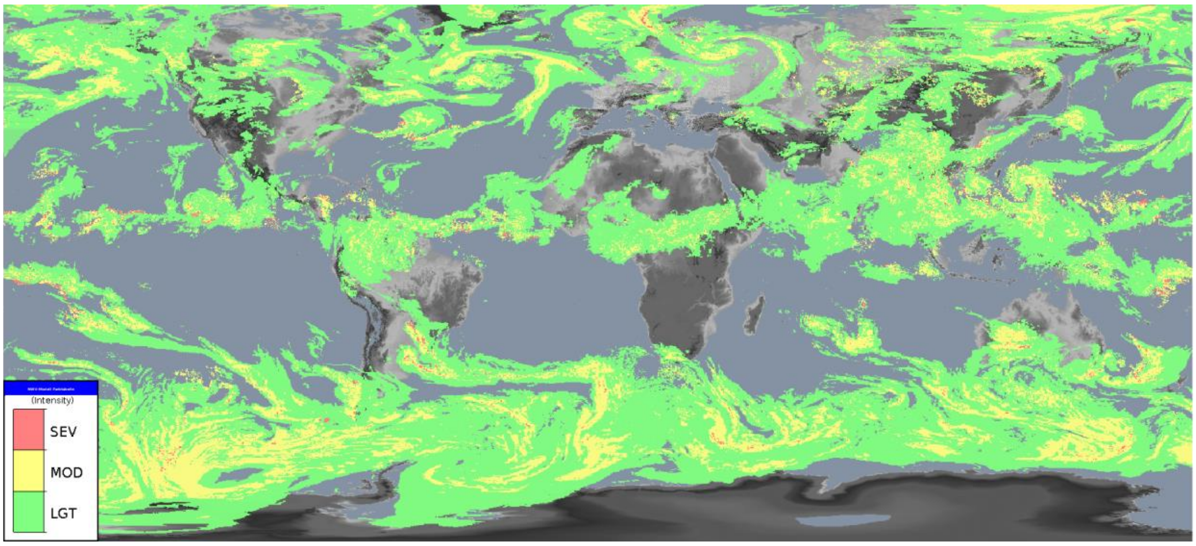

Figure 2: Example for a global icing intensity level forecast (maximum in column) with ADWICE on ICON: Light (green), Moderate (yellow) and Severe (red) icing.

Project Turbulence Forecast for aviation

The prediction of turbulence is an exercise for aviation forecast at DWD. A prognostic turbulent kinetic energy (TKE) scheme is used in the global model ICON. The Eddy Dissipation Rate (EDR) has the capability to assimilate the sources and depressions of the TKE equation. The EDR is to be linked up with the TKE over the Kolmogorov equation.

It is a principal question, whether the numerical prediction model will be able to reflect the relevant sources for aircraft turbulence. In a further step additional production terms were introduced into our prognostic TKE scheme related to the generation of turbulence by the action of shear of wind, subgrid scale orographic blocking and gravity wave breaking and subgrid scale convection. Measurements of EDR over the US are used together with EDP (“parameter”, because third root of EDR) from a COSMO model nested over the US domain. A satisfactory statistics (verification EDP vs. EDR-measurement) justified the start of the operational introduction of the EDP.

The EDP forecasts the turbulence between FL100 and FL490 currently and provides hourly prognostic products up to 24h, updated twice a day (00,12 UTC). Results are visualised in NinJo (used by MWO’s e.g. for SIGMET) and over Web Map Service.

However, we suffer from special problems related to EDR measurements based on power spectra of vertical velocity of the airplane and model deficits. We are going to introduce further improvements. All enhancements are to be realized with the global model ICON.

Project Integrated Terminal Weather System (ITWS) / Low Level Wind Shear Alert System (LLWAS)

At DWD is running a project to develop an Integrated Terminal Weather System (ITWS) for the hubs Frankfurt and Munich. In the first step analysis and NowCast of convective weather events with the System NowCastMix/ITWS will be considered. The NowCastMix/ITWS-System will be improved by implementation of a cell-cyclus module. Furthermore, the NowCastMix/ITWS-System for convective weather will be extended in a third-party funded project (LuFo WeAC – Weather for ATM and CDM) to winter weather situations. In an EC funded project within FP7 the benefit of using a high resolution airport model as NowCast Tool will be investigated (COSMO-MUC).

Further, a Low Level Wind Shear Alert System based on remote sensing measurement sensoric (combination of X-Band Radar and LIDAR) will be implemented at the airports of Frankfurt and Munich.

SESAR WP11.2 Meteorological Information Services and SESAR Demonstration Activities

DWD participates within an EUMETNET EIG consortium in both SESAR (Single European Sky Air Traffic Management Research Programme) projects in SESAR WP11.2 and SESAR

Demonstration activities. The goal of SESAR is to support the realisation of a homogenous European Sky.
The aim of the first project is to develop harmonised, consistent aviation meteorology fields / parameter for the local and en-route situations. Issues are convective weather situations (analysis, nowcasting and ensemble-based methods), icing, turbulence, winter weather and capacity studies. Beside DWD Météo France, UK Met Office, FMI, SMHI, Met Norway and KNMI join the project as EUMETNET member. Consolidated products have been developed and verified and will be made available for validation campaigns.

In the second project current national meteorological products have been validated during fight trials in the first half of 2014. DWD is engaged with ADWICE and ICON turbulence. Météo France and UK Met Office join the project with convective weather products as well as high level wind and temperature fields as well as convective weather products. Those three national weather services are considered as one project member (labelled as EUMETNET consortium). The project has ended September 2014 with a satisfying response by the users.

Project TAF-Guidance / AutoTAF by the Met Alliance
The MOS AutoTAF system (4.3.4.1) has been extended by embedding a further run of the IFS model to build a Lagged-Average-Forecast-Ensemble (LAF). The weighting of the current model run (00z or 12z) and the respective run 12 hours earlier is done by linear regressions. First, a single MOS of each run is calculated and these forecasts are used as predictors in an additional (final) MOS.
The impact is positive since forecast skill of the IFS at longer lead times is used and MOS forecast jumps at model run changes (here at 09z and 21z) become smoother. However, at shorter lead times of 1-6h the current run has the higher weight for the most elements because MOS equations are still dominated by the observations.

Projects EWeLiNE, ORKA2 and PerduS
In the research projects EWeLiNE (2012-2016 = Erstellung innovativer Wetter- und Leistungspro gnosemodelle für die Netzintegration wetterabhängiger Energieträger) and ORKA2 (2016-2018 = Optimierung von Ensembleprognosen regenerativer Einspeisung für den Kürzestfristbereich am Anwendungsbeispiel der Netzsicherheitsrechnungen und der Strombelastbarkeitsprognosen) the overarching objective are to improve the power forecasts of the electric power production from renewable energies. Both projects focus on forecasts for wind energy and photovoltaic (PV) since these energy sources are highly weather dependent and as such fluctuating with time. A very high potential for improving the power forecasts lays in the improvement of the quality of the underlying weather forecasts. In both projects, the collaboration with external partners in research and industry plays an important role.
In 2016, a further energy project has been started (PerduS, 2016-2020). In this project, the DWD, the Karlsruhe Institute of Technology (KIT) and the power forecast provider meteocontrol aim to improve weather and PV-power forecasts during Saharan dust outbreaks. The main objective is to establish one forecast system that combines all components which are necessary to account for Saharan dust and its implications on PV-power forecasts.

In EWeLiNE, the project has been focused on achieving better forecasts for the intraday and the day ahead time range. DWD is aiming at improving the deterministic and probabilistic weather forecasts and developing new user optimized products. COSMO-DE and COSMO-DE-EPS are the main focus of the work. The research aspects include optimized treatment of the parameterized processes, assimilation of newly available observations from wind or PV power plants and satellites, optimized ensemble generation and post-processing methods, and thereby in particular potential enhancements of MOS on the DMO. The verification of the forecasts is extended from traditional parameters (e.g., temperature, precipitation, and surface wind speed) to e.g., global radiation and wind speed at different altitudes. The verification of renewable energy relevant parameters has been carried out for the deterministic and the probabilistic forecasts to identify error characteristics of the forecasts compared to measurements (e.g., surface based pyranometer measurements, satellite retrieved data and wind towers). Figure 3 illustrates the work dealing with optimizations of the turbulence- and transfer scheme of COSMO-DE in order to allow for more stable conditions during night and by artificially increasing vertical mixing after sunrise and thereby reducing the error of the daily cycle. The improvement is shown here by the much better captured nightly Low-Level Jet.

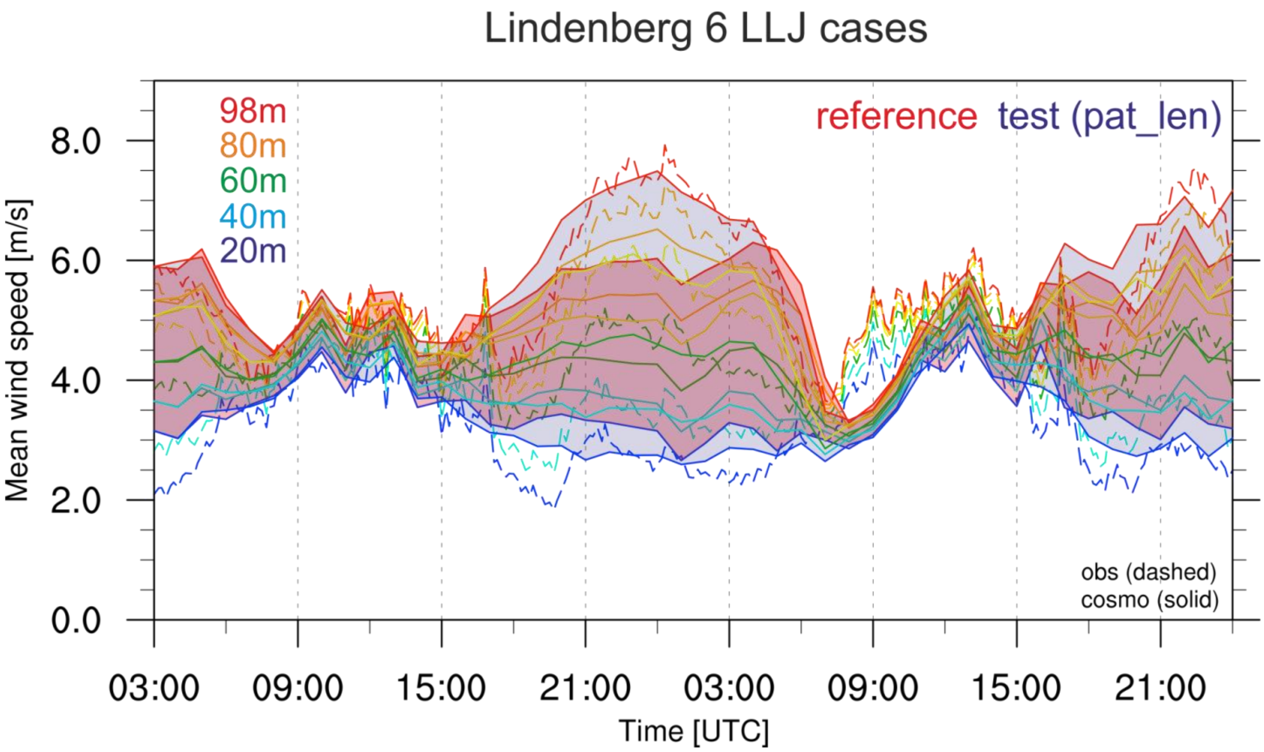

Figure 3:
Time series of observed and forecasted mean wind speed at five different heights at the meteorological tower Falkenberg for the NWP model COSMO-DE. Time averaging is done for six selected, stable nights with the formation of Low-Level Jets (LLJs).

Furthermore, ongoing work deals with improved ensemble generation. The first step considers the coupling of COSMO-DE-EPS to the LETKF scheme that has been developed within the KENDA (km-scale Ensemble Data Assimilation) project. In this way, COSMO-DE-EPS gains an ensemble of initial conditions directly from the data assimilation. In another step, the boundary conditions are used from the ICON-EPS in place of the BC-EPS (Boundary Condition Ensemble Prediction System). The results look promising and became operational in March 2017. In addition to the deterministic MOS, statistical post-processing methods of COSMO-DE-EPS for wind at e.g., 100m height and global radiation are being tested. The methods that are being considered involve quantile regression (for wind and solar radiation) and bivariate Ensemble Model Output Statistics (EMOS) (for wind forecasts). Based on user requirements, the focus is put on generation of calibrated scenarios at each model grid point. For this purpose a variation of the ensemble copula coupling (ECC) technique called dual-ECC (Ben Bouallègue et al, 2016) is being developed and tested, where the temporal and spatial error correlation is considered and added to the usual ECC approach. During the whole project, the requirements of the users, i.e. the Transmission System Operators (TSO), have been integrated into the research activities to obtain user optimized products. An effort is especially put on the development of probabilistic products and the integration of these into the systems of the users. The products have been tested in live-mode during the demonstration phase at the end of the project.

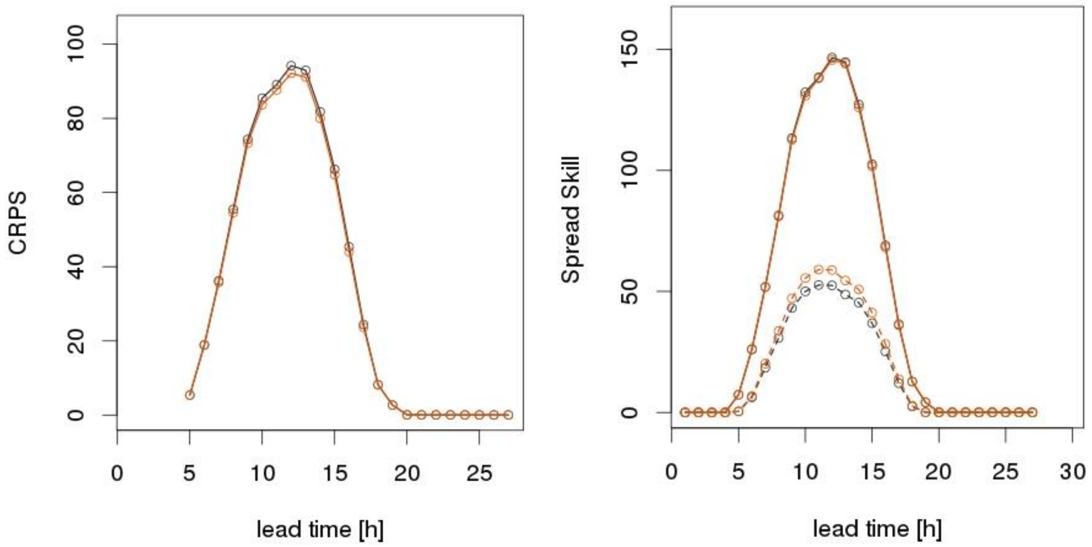

Figure 4:
Optimized solar radiation ensemble forecast based on COSMO-DE-EPS. Reference (operational setup) in black, and experimental setup with optimized model physics perturbations in orange. Left: CRPS, right: Spread (dotted line) and RMSE of solar radiation at the surface. The optimized physics perturbations lead to a slight improved CRPS at noon, and an increased ensemble spread. The effect on the RMSE of the ensemble mean remains neutral.

The focus of the project ORKA has been on improving probabilistic forecasts on the forecast range of 0-8 h, in particular by optimizing the generation of ensembles and by improving the representation of parameterized physical processes of the COSMO-DE-EPS. For improving the ensemble spread within the first few hours of the forecast, the vertical filter of the initial condition perturbations has been modified. Furthermore, the physics perturbations are being extended. Figure 3 illustrates experiments with respect to optimized solar irradiance ensemble forecasts. In the experiment, physics perturbations with respect to cloud water and cloud ice in the radiation scheme, and the thickness of shallow convection clouds have been combined with the operational setup. The effect on wind speed at hub height (not shown) was neutral, and the effect on solar radiation was positive, e.g. in terms of reduced CRPS (Conditional Ranked Probability Score) and improved ensemble spread. The follow-up project ORKA2 continues this work, adding the prediction of the current-carrying capacity to its aims. These forecasts are important for preventing cables from sagging due to high thermal load and optimizing the utilization of the transport net capacity.

In PerduS, the model system ICON-ART is applied, studied and improved. During the special weather situation of Saharan dust outbreaks, which influence Germany 5-15 times a year on average, operational numerical weather prediction (NWP) models make forecast errors as they do not consider the effects of the additional mineral dust in the atmosphere. ICON-ART instead combines the non-hydrostatic NWP model ICON and the ART modules for the treatment of Aerosols and Reactive Trace gases in the atmosphere in an online-coupled system. Specific research topics in PerduS concern the emission of mineral dust, its optical properties as well as the washout of aerosols. The soiling effect of PV panels and the subsequent cleaning by precipitation is investigated as well and an attempt is made to parameterize this process. In the end, ICON-ART will be operated in parallel to the conventional numerical weather predictions and will provide solar radiation forecasts that account for the additional dust in the atmosphere. These forecasts, in turn, will be used by the service provider meteocontrol to develop photovoltaic power predictions.

Figure 5 shows an example of a Saharan dust outbreak which occurred in April 2014. The case is of special interest, as huge day-ahead PV power forecast errors up to 10 GW arose for Germany, which represents a multiple of the available balance energy. The project PerduS aims to enhance the quality of weather and PV power forecasts during such weather situations and thereby support the incorporation of an increasing share of renewable energies in the German power mix.

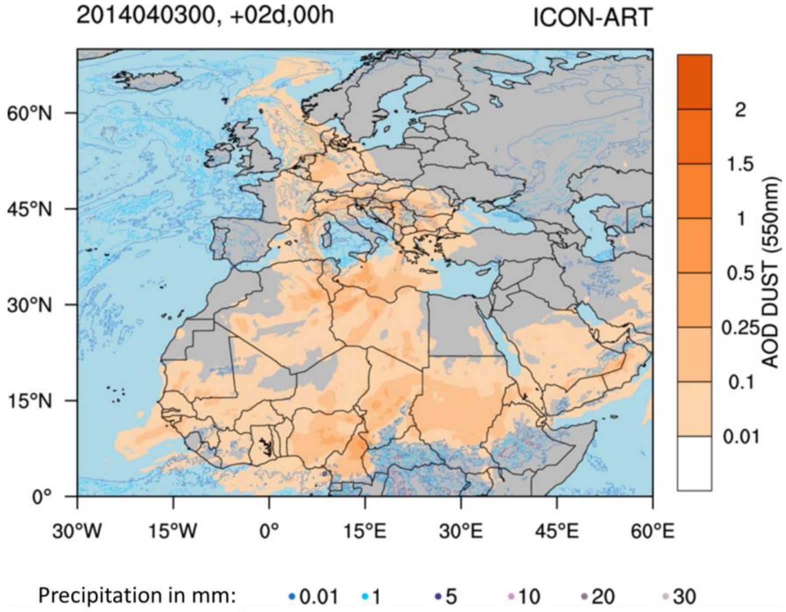

Figure 5:
48 hour forecast of a global ICON-ART simulation targeting 05.04.2014 with a horizontal resolution of 13 km. Three-hourly precipitation is illustrated in blue to violet contour lines and the aerosol optical depth (AOD) for 550 nm of the prognostic mineral dust is shown in orange contours. The latter one is a measure for the atmospheric opacity which is caused by the mineral dust aerosols.

4.3.5 Ensemble Prediction System (EPS)

4.3.5.1 In operation

Operational systems based on models with parameterized convection

EPS products from the ECMWF and COSMO-LEPS as described in 4.2.5.3 are in use also for short range forecasting as far as applicable. In addition to this, SRNWP-PEPS (Poor Man's Ensemble Prediction System) is in use since 2006.

SRNWP-PEPS ("Poor man's" Ensemble Prediction System of the Short Range Numerical Weather Prediction Program) is running in operational mode. The SRNWP-PEPS combines most of the operational LAM (Limited Area Modelling) forecasts of the European weather services. The products are generated on a grid with a horizontal resolution of approximately 7km (see figure 6).

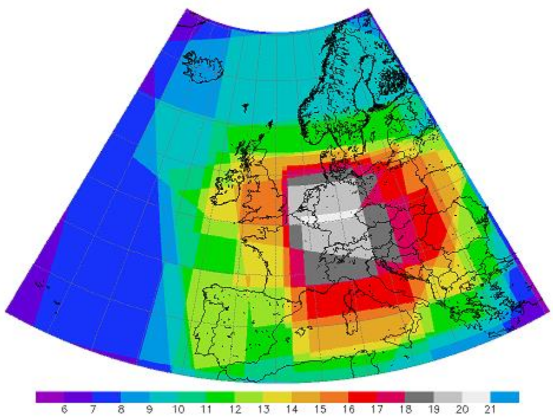

Figure 6: Domain and maximum ensemble size of the SRNWP-PEPS.

In Europe there are four different main operational limited area models (LAM) developed by different consortia. These four models are all representatives of today's state of the art in the Short-Range Numerical Weather Prediction field and are used by more than 20 national weather services to produce their operational forecasts (EUMETNET SRNWP = Short Range Numerical Weather Prediction Programme). The weather services run their models on different domains with different grid resolutions using different model parameterizations, data assimilation techniques and different computers producing a huge variety of different forecasts. Bringing together these deterministic forecasts, the **SRNWP-PEPS** provides an estimate of forecast uncertainty. Of course, this estimate is biased, e.g. due to model clustering in consortia, and some sources of uncertainty are still missing. However, ensemble post-processing would be able to generate calibrated probability forecasts from the **PEPS**. The main purpose is the improvement of European severe weather warning systems.

Meteorological Service	Regional Model	Coupling Model	Resolution (km)	Forecast Period (h)	Time interval (h)	Main Runs (UTC)
Austria	ALARO5	ECMWF	5	+72	1	0, 6, 12, 18
Croatia	ALADIN	ARPEGE	9	+72	1	0, 12
Czech. Repub.	ALADIN	ARPEGE	11	+48	1	0, 6, 12, 18
Hungary	ALARO	ARPEGE	11	+48	1	0, 6, 12, 18
Slovakia	ALADIN	ARPEGE	11	+48	3	0, 12
Slovenia	ALADIN	ARPEGE	9	+60	3	0, 12
Spain	HIRLAM	ECMWF	18	+48	1	0, 6, 12, 18
Netherlands	HIRLAM	ECMWF	22	+48	1	0, 6, 12, 18
Ireland	HIRLAM	ECMWF	11	+54	3	0, 6, 12, 18
Norway I	HIRLAM	ECMWF	8	+48	1	0, 12
Norway II	HIRLAM	ECMWF	12	+48	1	0, 12
Sweden	HIRLAM	ECMWF	11	+48	3	0, 6, 12, 18
Germany	ICON-EU	ICON	7	+78	1	0, 6, 12, 18
Switzerland	COSMO-7	ECMWF	7	+72	1	0, 12
Poland	ALARO	ARPEGE	14	+72	3	0, 12
Italy	COSMO	ECMWF	7	+48	1	0, 12

Table 2: Current members contributing to SRNWP-PEPS

Very short range convection-permitting COSMO-DE-EPS

COSMO-DE-EPS is a very short range ensemble prediction system based on the convection-permitting model COSMO-DE. The deterministic model COSMO-DE has a horizontal grid-spacing of 2.8 km, produces forecasts with a lead time of 0-27 hours (45 hours for 03 UTC)., covers the area of Germany and has been in operational mode at DWD since April 2007 (section 4.3.2).

The aim of COSMO-DE-EPS is the quantification of forecast uncertainties on the convective scale where the predictability is limited to very short forecast ranges. An estimate of uncertainties provides an added value compared to a single deterministic forecast, because it allows for an interpretation of the forecast in probabilistic terms. Such probabilistic information is essential in decision-making processes and risk management.

With the aim to quantify forecast uncertainties, variations are introduced to COSMO-DE model physics, initial conditions, and lateral boundary conditions (*Peralta et al., 2012, Gebhardt et al., 2011*). Variations of model physics are realized by non-stochastic perturbations of parameters in the parameterization schemes. Until March 2017 initial conditions and lateral boundary conditions were varied by nesting the COSMO-DE ensemble members into a boundary-condition EPS (BC-EPS). The BC-EPS consisted of different COSMO 7 km simulations which were nested into forecasts from different global models (ICON of DWD, IFS of ECMWF, GFS of NOAA/NCEP and GSM of JMA). Since March 2017 COSMO-DE-EPS uses lateral boundary conditions from the global ICON-EPS which are interpolated from the two-way nested grid in ICON over Europe (ICON-EU with a grid spacing of 20 km) to the 2.8 km COSMO grid spacing. Verification shows large increase in spread and some gains in skill scores compared to the previous operational multi-model setup.

Perturbations of the initial soil moisture fields have been included in the operational COSMO-DE-EPS since January 2014. They are derived from differences between ICON-EU und COSMO-DE soil moisture analyses in layers down to a depth of 1m below surface.

The current COSMO-DE-EPS version comprises 20 ensemble members, with a horizontal grid-spacing of 2.8 km. COSMO-DE-EPS is started 8 times a day (00 UTC, 03 UTC, …), and each ensemble run has a lead time of 27 hours (45 hours for 03 UTC). Probabilistic products (e.g. exceedance probabilities and quantiles) are calculated for parameters and thresholds relevant for the warnings issued by the DWD forecasters.

4.3.5.2 Research performed in this field

COSMO-DE-EPS

Verification results for COSMO-DE-EPS indicate that the perturbations have a beneficial effect on probabilistic precipitation forecasts when compared to deterministic forecasts. This benefit is most effective for convective summer precipitation. However, the ensemble forecasts are still underdispersive and overconfident.

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Regarding the representation of forecast uncertainty, research was carried out to use initial conditions from members of the COSMO-DE ensemble data assimilation and lateral boundary data from ICON-EPS. Furthermore, additional physics perturbations have been tested in order to increase the ensemble spread in lower level wind-speed, cloudiness and screen level temperature. Further research was done to include stochastics aspects in the representation of model error. Additional physics disturbances as well as a randomized method for the assignment of parameter perturbations to the ensemble members was put into operation in November 2016.

ICON-EPS

The ICON short range ensemble runs with 40 members and a global horizontal resolution of approximately 40 km (20 km over Europe) providing forecasts up to 7 days. The global Ensemble Data Assimilation system (ETKF = Ensemble Transform Kalman Filter) developed at DWD (see sec-

tion 4.3.1) provides the initial ensemble perturbations. For the moment no stochastic physics is implemented and the spread/skill properties of the ensemble are determined by the variations of the initial conditions only.
Evaluation with our new verification system at DWD shows that the ICON-EPS is over-dispersive with respect to its own analysis in the beginning of the forecast range due to strong initial perturbations from the ETKF system and becomes under-dispersive in the medium range. A detailed comparison of its spread/skill properties with those of the ECMWF-EPS on the global scale is under way and will be published in the near future. Although the perturbations in both ensembles originate from completely different techniques (see also IFS Documentation – Cy43r1, 2016) the evolution of the spread/skill relation from a lack of resolution to a good match after the medium range is quite similar in both systems.
The research activities at DWD concentrate on the deficits of the spread/skill relation at the beginning of the forecast to improve the quality of the boundary conditions for COSMO-DE-EPS. We work on techniques which will lead to some kind of "dynamical mode selection" by setting a bundle of initial perturbations depending on the growth properties of the local flow. We examine techniques that approximate singular vectors (SV, e.g. Magnusson et al., 2008) without the need for linearized and adjoint model versions like the Arnoldi approximation (e.g. Golub & van Loan, 1996) or the Limited Memory Broyden method (e.g. Ziani & Guyomarch, 2008), which both provide approximations for the local Jacobian.
To simulate model error, we did experiments with systematic variations of the model parameters for different ensemble members. Moreover, a stochastic physics package is provided by our physical aspects section based on a linear stochastic modelling approach using stochastic mode reduction. We recently started the implementation of this package in the ICON modeling framework.

(M. Denhard)

4.3.5.3 Operationally available EPS Products

Similar to COSMO-LEPS (see 4.2.5.3), also SRNWP-PEPS and COSMO-DE-EPS provide probability charts for Europe which give information whether accumulated rain or snow, wind gusts, temperatures or CAPE values will exceed thresholds defined by warning requirements. Products based on SRNWP-PEPS are available up to 42 hours and those based on COSMO-DE-EPS up to 27 hours Exceeding probabilities, quantiles, ensemble mean, spread, min, max are calculated for total precipitation, total snowfall, 10m wind gusts, 2m temperature, cloud cover, CAPE, and simulated radar reflectivities. For precipitation, also "upscaled" probabilities are provided. They refer to predefined regions which are substantially larger than the model grid (*Ben Bouallègue and Theis, 2014*).
The products of COSMO-DE-EPS are visualized within the visualization tool NinJo. The NinJo system has been complemented by an "ensemble layer". This layer is also used to visualize other ensemble systems such as ICON-EPS, COSMO-LEPS, PEPS and ECMWF EPS.

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

4.4.1 Nowcasting system

4.4.1.1 In operation

Nowcasting activities make use of a number of remote-sensing systems, focussing on radar-based precipitation monitoring and nowcasts (RADOLAN, RadVOR), real-time lightning detection (LINET, nowcast GmbH) and the NowCastMIX pre-processing tool for automatic warning generation, in combination with the high-resolution numerical weather prediction model, COSMO-DE.

An important component of the radar-focussed precipitation nowcasting is KONRAD (Konvektion in Radarprodukten), developed originally at the DWD observatory at Hohenpeissenberg, Bavaria, performing reflectivity-based cell identification and tracking. It is a very robust system which has been used consistently for some 15 years now. Further storm cell tracking is provided by the MOS-based system CellMOS, developed a few years after KONRAD. This utilises statistical relationships between observed thunderstorm data and various input datasets, including radar, lightning and NWP model data, to provide probabilistic estimates of cell tracks and their severe weather attributes, such as wind gusts, precipitation amount, hail and frequency of lightning.

Ultimately all of the above data sources are also pre-processed together in the nowcasting tool, NowCastMIX, which computes, on a 5-minute rapid updating cycle, an integrated, optimised set of automatic warnings for the next hour for thunderstorms, torrential rain, snowfall and freezing rain. NowCastMIX provides this warning data for the DWD’s forecast advisory centre, via the Auto-WARN process, for civil aviation advisory centres and even direct to the public via the DWD’s WarnWetter App.

Following the successful integration of NowCastMIX and the various radar-based nowcasting systems into the DWD’s warning service process and as a mark of the quality of these systems, the DWD has recently been named a “Regional Specialised Meteorological Centre (RSMC) for Nowcasting” by the WMO.

4.4.1.2 Research performed in this field

Project AutoWARN with NowCastMIX

The automated warning process in AutoWARN utilizes outputs from various nowcasting methods and observations, combined with NWP model data, to generate a forecast-time dependent automatic warning status. This is permanently manually controlled and modified by the forecaster before text and graphical warning products are generated. In order to provide a generic optimal solution for nowcast warnings in AutoWARN all nowcast input data is pre-processed together in a single grid-based system: the NowCastMIX. This provides an ongoing real-time synthesis of the various nowcasting and forecast model system inputs to provide a single, consolidated set of most-probable short-term forecasts, focussing on thunderstorm and heavy rain events, as well as on the winter events, snow and freezing rain.

NowCastMIX combines data intelligently from various radar-based sources with lightning strike data and NWP model output. The speed and direction of storm cells is assessed and used to forecast regions at imminent risk of storm developments. The potential severity of the storms is estimated by deploying a fuzzy logic system to assess the relative risk of each of the attributes involved: hail, severe guts and torrential rain.

4.4.2 Models for Very Short-range Forecasting Systems

4.4.2.1 In operation

Schematic summary of the convection-resolving model COSMO-DE

Domain	Germany and surrounding
Initial data time	00, 03, 06, 09, 12, 15, 18, 21 UTC
Forecast range	27 h (45 h from 03 UTC)
Prognostic variables	p, T, u, v, w, q_v, q_c, q_i, q_{rain}, q_{snow}, $q_{graupel}$, TKE

Vertical coordinate	Generalized terrain-following, 50 layers
Vertical discretization	Finite-difference, 2nd order
Horizontal grid	421 x 461 points (0.025° x 0.025°) on a rotated latitude/longitude grid, mesh size 2.8 km; Arakawa-C grid
Horiz. discretization	Finite-difference, 5th order upwind advection For the advection of moisture variables: *Bott (1989)* scheme with Strang-splitting
Time integration	Two-time-level, 3rd order Runge-Kutta, split explicit (*Wicker and Skamarock, 2002*), $\Delta t = 25$ s
Horizontal diffusion	Implicit in advection operators. Explicit horizontal hyperdiffusion (4th order) in the boundary zones and in the full model domain for the velocity components. Smagorinsky-type diffusion in the full domain
Orography	Grid-scale average based on a 1-km data set. Topography has been filtered to remove grid-scale structures
Parameterizations	Surface fluxes based on a resistance model by vertical integration of a flux-gradient representation along a constant-flux transfer layer using a surface layer TKE equation (*Raschendorfer, 2001*) Free-atmosphere turbulent fluxes based on a level-2.5 scheme with prognostic TKE (*Mellor and Yamada, 1974*) with contributions from non turbulent processes *(Raschendorfer, 2001)* Radiation scheme (two-stream with three solar and five longwave intervals) after *Ritter and Geleyn (1992)*, full cloud-radiation feedback based on predicted clouds Mass flux convection scheme after *Tiedtke (1989)* only for shallow convection Kessler-type grid-scale precipitation scheme with parameterized class-6 cloud microphysics 7-layer soil model *(Heise and Schrodin, 2002; Schulz et al., 2016)* including simple vegetation and snow cover; prescribed climatological value for temperature at about 14 m depth Over sea/ocean water: Fixed SST from SST analysis. Over inland water bodies: the lake parameterization scheme Flake (http://lakemodel.net) is used to predict the water surface temperature; for frozen lakes the ice surface temperature and the ice thickness are predicted. The Charnock formula for the water aerodynamic roughness is used over sea/ocean and inland water bodies.

4.4.2.2 Research performed in this field

Influence of diabetics processes on the pressure and temperature equation
In the COSMO model, the continuity equation is transformed to a pressure equation via the equation of state. At the moment, the contributions Q_h to the pressure tendency due to diabatic heating (phase changes, turbulent/convective transports, divergence of radiation fluxes) and the contributions Q_m due to mass transfer (internal exchange to/from hydrometeors by phase changes, external diffusion over the grid box boundaries changing system composition) are neglected in the pressure equation, which also affects the temperature equation via its pressure term. Effectively, this leads to a temperature equation which does not contain Q_m and which employs c_p as the relevant heat capacity.
Consistent to that, it is assumed that the "saturation adjustment" (an "infinitely fast" phase change process with corresponding temperature change towards vapor/liquid equilibrium) happens at constant pressure, which leads to the usual formulation of the adjustment equations. Note that one has to specify such an additional constraint otherwise the adjustment problem would not have a unique solution.
As a consequence, mass is not conserved during diabatic change processes. For example, during microphysical phase changes, there is locally a spurious mass loss during condensation / sublimation and a mass gain during evaporation / sublimation, equal in relative terms for all gaseous species including water vapour. Because normally there is more condensation than evaporation (thanks to precipitation) we expect a net mass loss in the model, and loss of water vapour might decrease subsequent precipitation.

In a new model version, the terms Q_h and Q_m due to diabatic processes (except turbulent dissipation and one thermodynamical cross-effect term) are included in the pressure equation. Correspondingly this influences the temperature equation in a way that now simply c_v replaces the former c_p as relevant heat capacity and a new contribution due to the Q_m term appears on the right hand side. For the saturation adjustment, this means that we now have to assume locally constant density during this process and that the relevant heat capacity is now c_v instead of c_p. Experiments have been conducted to investigate the influence of including the Q_h and Q_m terms on the precipitation forecast. The results suggest that there is a slight increase in total precipitation (1-3 %) and an insignificant shift in fine structure of precipitation patterns. Also we observe a slight enhancement of local precipitation maxima, which has a positive influence on our “fuzzy” precipitation verification scores. Also, there is a (weak) positive influence on geopotential and surface pressure. All other quantities and scores seem to behave neutral.

(U. Blahak, A. Seifert)

Extension of the COSMO-DE setup
It is planned for Q2 2018 to enhance the COSMO-DE setup in three respects. Firstly, the horizontal grid spacing will be reduced from 2.8 km to 2.2 km (0.02°). Secondly, the number of vertical levels will be increased from 50 to 65 levels. The additional levels will mainly contribute to increase the resolution of the boundary layer. The main purpose is a better initiation of convection. Thirdly, the domain will be slightly extended mainly in the western direction. In particular, the assimilation of additional radar data by latent heat nudging in this area can improve the forecast quality. Additionally, the domain extension to the south will include the whole Alpine region without cutting through its high mountains.

(M. Baldauf, B. Ritter)

Development of a TKE-Scalar Variance turbulence-shallow convection scheme for the COSMO model
The TKE-Scalar Variance (TKESV) turbulence-shallow convection scheme for NWP models has been developed within the framework of the COSMO priority project UTCS (Unified Turbulence shallow Convection Scheme). The TKESV scheme carries prognostic equations for the turbulence kinetic energy (TKE) and for the scalar variances (variances of total water specific humidity and of the liquid water potential temperature and their covariance). These prognostic second-moment

equations include the turbulent diffusion terms (divergence of velocity-velocity and velocity-scalar triple correlations) that are parameterised though the down-gradient approximation. Recall that the current COSMO-model turbulence scheme (referred to as the TKE scheme) computes the scalar variances from the diagnostic relations that are obtained from the respective second-moment equations by neglecting the turbulent diffusion and the time-rate-of-change terms. One more essential difference between the new and the current schemes is in the computation of scalar fluxes. The current scheme is based on the down-gradient approximation whereas the new scheme accounts for non-gradient terms (among other things, this allows for up-gradient scalar transfer). The non-gradient corrections to scalar fluxes stem from the buoyancy terms in the scalar-flux budget equations; those terms are parameterised with regard for the turbulence anisotropy. The formulation for the turbulence length (time) scale used within the TKESV scheme accounts for the effect of static stability (current operational COSMO model uses a Blackadar-type turbulence length scale formulation independent of static stability).
The TKESV scheme was successfully tested through single-column numerical experiments. The TKESV scheme outperforms the TKE scheme in dry convective PBL (Planetary Boundary Layer). The PBL is better mixed with respect to potential temperature. An up-gradient heat transfer that is known to occur in the upper part of the dry convectively-mixed layer is well reproduced. For cloudy PBLs, the application of the TKESV scheme leads to a better prediction of the scalar variances and TKE and to slight improvements with respect to the vertical buoyancy flux and to the mean temperature and humidity. Both schemes tend to overestimate fractional cloud cover in the cumulus-topped PBL. This error is attributed primarily to the shortcoming of quasi-Gaussian sub-grid scale (SGS) statistical cloud parameterization scheme used by both TKESV and TKE schemes to determine fractional cloudiness and the buoyancy production of TKE.
The TKESV scheme is implemented into the COSMO model and tested through a series of parallel experiments with the COSMO-DE configurations including the entire COSMO-model data assimilation cycle. Verification of results from parallel experiments indicates improvements as to some scores, e.g. two-metre temperature and humidity and fractional cloud cover. A detailed scientific documentation of the TKESV scheme is in preparation. Modifications associated with the TKESV scheme will soon be included into the official COSMO-model code (for details, see the Model Development Plan at the COSMO web site). The work is underway to implement the TKESV scheme into the global NWP model ICON.

(D. Mironov and E. Machulskaya)

Plans to achieve a consistent description of SGS processes by scale separation

On the way towards a scale separated set of SGS (sub-grid scale) parameterizations, we already have introduced additional scale interaction source terms in our prognostic TKE equations related to separated non-turbulent horizontal shear modes and to wake modes generated by SSO (sub-grid-scale orography). Finally, we introduced a first version of a similar scale interaction term from our convection parameterisation closely related to the buoyant production of SGS kinetic energy by the convection process. Recently we also introduced TKE-advection as well as horizontal diffusion by means of the separated horizontal shear eddies.
While the TKE-production by SSO is switched on in our operational version, the other two terms need to be verified in the next future. However, they are used as diagnostic source terms in order to derive an improved EDR (eddy dissipation rate) forecast for aviation purposes.
Besides operational testing, we are going to use EDR-measurements by aircrafts in order to estimate the value of undetermined parameters in the formulations of those additional TKE source terms.
We are further planning to reformulate our current version of a scale interaction term caused by non-turbulent thermals related to surface inhomogeneity using input parameters of the present SSO scheme. After substituting a before constant length-scale parameter of that scheme by the standard deviation of SSO height had already improved the model scores, we now want to adapt the parameterization to be more specific to nocturnal density flows along SSO slopes. Further we want to test now the contribution of TKE-advection and of TKE-production by separated vertical shear modes, as well as the impact of mixing by the additional non turbulent modes themselves (starting with horizontal diffusion by the separated shear eddies).

Finally it is aimed to reformulate in particular the current convection scheme in order to account for the counterpart of the scale interaction term in the convection scale budgets and to come along with a consistent overall description of SGS cloud processes. These last aims however belong to a longer time scale.

(M. Raschendorfer)

Activities and further plans to consolidate our surface-to atmosphere transfer and to account for inhomogeneity of surface roughness and tall effective roughness layers

We started implementing some reformulations of the transfer scheme allowing for a stronger influence of the resulting transfer coefficients on thermal surface layer stratification. We aim to continue this work and hope to remove some of our systematic errors related to the diurnal cycle of near surface variables. After single column component tests have shown that some numerical limits (as minimal diffusion coefficients) together with a so far supressed adaption of our assumed vertical profile functions of surface layer diffusion coefficients are due to a rather low sensitivity on stratification, we now are testing the adapted interpolation function and try to substitute the constant minimal diffusion coefficients by proper statistical and physical parameterizations.

Since near surface variables are also strongly influenced by the calculation of surface temperature as an result of the combined heat and moisture budgets of the soil, including the roughness elements above, the focus of this task during the last year was mainly about a more realistic combined description of surface fluxes and related budgets below the atmosphere. In order to include the effect of a stronger thermal decoupling of the rough surface from the compact soil, a vertically not resolved roughness layer model has been developed, based on (and hence in accordance with) the TKE-based description of transport-resistances between the lower atmosphere, the rigid layers of roughness elements and the surface of the dense soil.

This description results in an additional heat-budget of the roughness cover (formed, e.g., by leaves of a plant canopy, buildings of a city or the surface structure of the pure soil), being semi-permeable with respect of short-wave radiation. Through a linearization of latent heat fluxes and long-wave radiation in terms of surface temperature, this budget equation is coupled with the heat-budget of the soil layers below and provides an implicit, semi-prognostic estimate of surface temperature. The whole scheme also includes an adapted and consistent aggregation of sensible and latent heat fluxes from different surface classes by a concept of effective surface area indices. Related code has been implemented into a test-version of the COSMO-model, and some test runs showed reasonable results with a significant impact on the diurnal cycle of near surface variables. It further seems to result in a numerically much more stable simulation of surface temperature.

As the more recent versions of the surface-and-soil scheme (TERRA) and the surface-to-atmosphere transfer-scheme (TURBTRAN) are being re-implemented from the ICON-model into COSMO-model, the described approach is now going to be implemented into these schemes, before it will be further consolidated.

On a longer perspective, this task also includes the introduction of the vertically resolved roughness layer already mentioned in earlier plans, based on the concept of a spectral separation of equivalent topography described by an associated surface area index and a roughness height. By this procedure the large scale part of topographic land use structures are represented by additional source terms in all budget equations on the model levels being within the roughness layer, which is a generalization of the SSO approach. This includes a description of the roughness layer built by the change of land use within a grid box surface, being important for the aggregation of roughness parameters available for a couple of surface tiles within a grid box. We formally implemented these related extensions into the running test version of our turbulence scheme. However the description of the external input parameters is an issue for future investigation.

(M. Raschendorfer)

Adoption of the turbulence- and transfer-scheme for use in the ICON model

In order to run our COSMO turbulence scheme in ICON, we implemented a couple of modifications related to numerical stability and efficiency, modularity of the source code, as well as improvements in the way how to achieve positive definiteness of TKE and the stability functions.

Further we reformulated the code for implicit vertical diffusion in order to call a single subroutine for arbitrary tracers with a flexible setting of boundary conditions and of options related to the degree of implicitness and the treatment of vertical fluxes given not in a flux-gradient representation.
All these changes have been introduced to the ICON model and are running there as the default configuration. Further, some statistical parameterizations have been introduced, in order to substitute so far constant parameters (as the minimal diffusion coefficients) by some empirical functions of the model state. After this version has been merged with some further development of the COSMO version, a common turbulence package for both models, COSMO and ICON has been developed. As a next step we are going to find optimal parameter settings of this updated scheme for its use in COSMO.

(M. Raschendorfer)

4.5 Specialized numerical predictions

4.5.1 Assimilation of specific data, analysis and initialization

4.5.1.1 In operation

None

4.5.1.2 Research performed in this field

None

4.5.2 Specific Models

4.5.2.1 In operation

4.5.2.1.1 Trajectory Models

Trajectory model:

Forecast variables	r (λ, φ, p or z, t)
Data supply	u, v, w, p_s from NWP forecasts (or analyses)
Numerical scheme	1st order Euler-Cauchy with iteration (2nd order accuracy)
Interpolation	1st order in time, 2nd (ICON) or 3rd (Two-way nest ICON-EU) order in space

a) Daily routine (ca. 1500 trajectories)

Trajectories based on two-way nest ICON-EU forecasts:

Domain	Domain of two-way nest ICON-EU
Resolution	0.0625° (as ICON-EU)
Initial data time	00, 12 UTC
Trajectory type	Forward trajectories for about 110 European nuclear and 4 chemical installations, backward trajectories for scientific investigations
Forecast range	72-h trajectories, optional start/arrival levels

Trajectories based on global ICON forecasts:

Domain	Global

Resolution	13 km
Initial data time	00, 12 UTC
Trajectory type	168-h forward trajectories for ca. 120 European nuclear sites and 8 German regional forecast centres, backward trajectories for 37 German radioactivity measuring sites and 8 forecast centres using consecutive +6h to +18h forecast segments 168-h backward trajectories for all GAW stations and to the German meteorological observatories. 72-h backward trajectories for 5 African cities in the framework of the METEOSAT-MDD program, disseminated daily via satellite from Exeter 168-h backward trajectories for the German polar stations Neumayer (Antarctica) and Koldewey (Spitzbergen) and the research ships Polarstern and Meteor, disseminated daily Mainly backward trajectories for various scientific investigations
Forecast range	168-h forward and backward trajectories, optional start/arrival levels

b) Operational emergency trajectory system, trajectory system for scientific investigations:

Models	Two-way nest ICON-EU or ICON trajectory models
Domain	ICON-EU or global
Data supply	u, v, w, p_s from ICON-EU or ICON forecasts or analyses, from current data base or archives
Trajectory type	Forward and backward trajectories for a choice of offered or freely eligible stations at optional heights and times in the current period of 7 to 14 days
Forecast range	120-h (two-way nest ICON-EU) or 168-h (global ICON)
Mode	Interactive menu to be executed by forecasters

4.5.2.1.2 Ocean wave models

	GWAM	**EWAM**	**CWAM**
Domain	**Global**	**European Seas** south of 66°N, east of 10.5°W	**Coastal Seas** south of ~53°N, ~6°E – 15°E
Grid	reduced lat/lon	regular lat/lon	
Resolution	0.25° x 0.25°	0.05° x 0.10°	30“ x 50“ (~900m)
Numerical scheme	Shallow water, 3rd generation WAM		
Wind data supply (u,v at 10 m)	ICON	Two way nest ICON-EU refinement domain	
Assimilation (over last 12 hours)	Analysed wind fields Altimeter wave-heights	Analysed wind fields	Predicted wind fields
Initial data time	00 and 12 UTC		
Forecast range	174 h	78 h	48h

Model output	18 integrated spectral parameters (e.g. significant wave height, peak period and direction of wind sea and swell), as well as wave spectra at selected positions
Verification	Available on request

CWAM is running pre-operationally in a coupled mode with an ocean circulation model provided by the Federal Maritime and Hydrographic Agency of Germany (BSH).

4.5.2.1.3 Lagrangian particle dispersion model

As a part of the German radioactive emergency system a Lagrangian Particle Dispersion Model (LPDM) is in use at DWD. The LPDM calculates trajectories for a multitude of particles emitted from a point source using the grid-scale winds and turbulence parameters of the NWP-model and a time scale based Markov-chain formulation for the dispersion process. Concentrations are determined by counting the number and mass of particles in a freely eligible grid. Dry deposition parameterisation follows a deposition velocity concept and wet deposition is evaluated using isotope-specific scavenging coefficients. Radioactive decay, a vertical mixing scheme for deep convection processes and optionally particle-size depending sedimentation coefficients is included too. Additionally, an assimilation scheme for measured concentration data can be activated. Starting from these observed fields or from selected receptor points the LPDM can be run also in a backward mode to determine unknown source positions. The LPDM was successfully validated using data of the ANATEX (Asia North Atlantic Tracer Experiment) and ETEX (European Tracer Experiment) tracer experiments. In the ATMES-II report of the 1st ETEX release the model took the first rank of the 49 participating models. During the follow-up project RTMOD an evaluation of an accidental Cs-137 release (Algeciras, May 1998) was performed. The transport and dispersion of the cloud and the calculated dose rates were found to be in good agreement with the measurements. In the ENSEMBLE-ETEX reanalysis (2003) the ranking of the model was again excellent.

The LPDM can be run on basis of the DWD's operational weather forecast models (ICON including the two-way nest ICON-EU and COSMO-DE). In case of emergency the model output will be transmitted to the national 'Integrated Measurement and Information System' (IMIS) using slightly modified WMO codes. The calculations are also part of the European real-time decision system RODOS (Real-Time Online Decision Support System) in Germany. In this context data transfer and coupling with the operational RODOS system is tested several times a year. The model consistently assimilates the provided local scale source information, and calculates the transport and dispersion of selected (currently 9) standard nuclides simultaneously. The LPDM simulations can be also driven by COSMO-DE data. In this context snow pellets are included as a separate precipitation form in the wet deposition procedure. On request the model is operationally running in a backward mode to participate in the multi-model backtracking ensemble of the CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization).

The LPDM code is optimised for MPP/Vector computers (e.g. IBM P5 575, NEC SX9, CRAY-XC 40). For this purpose the code is supplemented by MPI-based parallelisation features. The model is also implemented at Meteo Swiss based on the Swiss COSMO-version.

In the context of the Fukushima-Daiichi catastrophe the model was extensively utilized. During the release phase of the accident (March/April 2011) DWD provided dispersion forecasts for the public mainly based on global NWP data. Additionally, the COSMO-LPDM (7 km grid spacing) was run in a quasi-operational mode for the relevant region covering Japan and its surroundings.

The global version of the LPDM is now based on ICON (operational since January 2015). As a member of the WMO multi-model backtracking ensemble of the CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) the LPDM was run for CTBTO-requests in backward mode. These calculations are also based on the ICON model. For high resolution simulation the ICON-EU-LPDM is operational since October 2016. Routinely, the model system was applied in several emergency tests at national (IMIS/RODOS) and international level (IAEA-WMO exercises).

(H. Glaab, A. Klein)

4.5.2.1.4 ICON-ART

ICON-ART (Rieger et al. 2015) where ART stands for 'Aerosols and Reactive Trace gases', is an extension of the operational ICON model. The complete set of ART modules developed at the Institute for Meteorology and Climate Research at the Karlsruhe Institute of Technology (KIT) is online coupled in a tightly integrated way to the ICON model. I.e. the same routines for transport and diffusion of the gas phase and aerosol tracers are used as for the prognostic moisture quantities in NWP. As a consequence of this harmonized approach ICON-ART benefits from the full flexibility and continuous improvement of the underlying global non-hydrostatic atmospheric modelling framework ICON (Zängl et al. 2015).

Operational on-demand application of ICON-ART is done for volcanic ash with regard to its relevance for aviation and the dispersion simulation of radionuclides.

In case of a volcanic eruption with potential influence of the German air space ICON-ART is run on the global operational domain with an equivalent mesh size of 13 km. The model results are made available on the NinJo workstations and are used by the aviation forecasters as a secondary source of information.

ICON-ART uses a modal 2-moment approach to simulate the dispersion of volcanic ash, as it forecasts the mass and number concentrations of three log-normal distributed modes. To get the shape parameters of the distributions they are fitted against aircraft measurements of the particle size distribution (Schumann et al. 2011). The emission of volcanic ash is parameterized following an empirical relation between the observed plume height and the mass eruption rate (Mastin et al. 2009). At KIT a LIDAR forward operator was developed. This operator eases the comparison of model results and observations of the ceilometer network of DWD and is a prerequisite for the data assimilation of such measurements.

With respect to the simulation of the dispersion of radionuclides ICON-ART is now used in addition to the LPDM described above. ICON-ART as an online-coupled Eulerian dispersion model allows the interaction between the simulated meteorological state of the atmosphere and the considered tracers or pollutants at the same time step as the rest of the model. In particular the advective and convective transport, the dry and wet deposition processes as well as the turbulent diffusion are treated in more detail. This leads to an advantage of ICON-ART compared to classical offline-coupled ATDMs. Namely the ability to provide products related to the atmospheric contamination for any height in the free atmosphere as a natural consequence of the fact that the radioactive contaminants are handled by the model algorithms in almost all aspects as the typical meteorological constituents.

In addition, as for all other ICON-ART applications, the same two-way nesting approach as in the operational NWP configuration can be used, e.g. a mesh refinement for the European region with 6.5 km distance between grid points. A two-way-coupling between global and regional domain allows a feedback from the higher resolved scales to the coarse grid solution on the global domain and avoids a de-coupling of solutions.

The capability of ICON to employ a mesh refinement for geographical regions of specific interest is of particular interest due to the fact that in the case of nuclear accidents the source of atmospheric contaminants is much localized. If necessary, the refinement area and model resolution of ICON respectively ICON-ART can be adapted to the task at hand, making ICON-ART an ideal tool for a variety of atmospheric dispersion modelling problems. However, in general ICON-ART will use the same grid configuration as the operational global NWP model of DWD.

(J. Förstner)

4.5.2.2 Research performed in this field

4.5.2.2.1 COSMO-ART

Following the explanation of ICON-ART in the previous section the COSMO-ART system is the likewise extension of ICON. The possible applications of COSMO-ART range from simple tracer dispersion problems to complete aerosol-radiation and aerosol-cloud interaction studies including the formation of secondary aerosol particles from the gas phase.
At DWD the model system was mainly employed for the dispersion modelling of volcanic ash and mineral dust. Different institutions use COSMO-ART to run forecasts of mineral dust. For example the United Arabian Emirates have set up daily model runs in their operational cycle.

(J. Förstner)

An additional application of COSMO-ART is the pollen forecast. The pollen module was initially developed by the IMK of KIT. Further development has been performed by KIT and MeteoSwiss and recently also by DWD. Up to now four pollen taxa are implemented: Alder, birch, grasses and Ambrosia. The pollen forecasts of these taxa are running operationally for the COSMO-7 domain at MeteoSwiss. The model output is provided to DWD. Since July 2016, the COSMO-ART pollen forecast is published on the DWD webpage.
In this context the pollen emission and the dry and wet deposition have been implemented. External data such as distribution maps has been adapted to the ICON grid.

(C. Endler)

4.5.2.2.2 ICON-ART

ICON-ART is currently under further development at the IMK of KIT and the DWD, aiming at the complete functionality mentioned for COSMO-ART above. New developments for the ART modules will actually first be implemented with ICON before to be taken over also for COSMO.
The most recent developments aim at an overall greater flexibility of ICON-ART also in comparison with COSMO-ART. In particular they include the interaction of the gas phase with a mixed phase aerosol module to treat the formation of secondary aerosols as well as the aging of insoluble particles. For a flexible configuration of the gas phase chemistry the Kinetic Pre-processor KPP is used. Aerosol-radiation and aerosol-cloud feedback processes are implemented, where the later is realized in combination with the 2-moment cloud-microphysics scheme, also available in ICON.
Basic building blocks to achieve this flexibility are the use of the modern object oriented capabilities of FORTRAN 2008 as well as the implementation of an XML interface to read in for example tracer meta as well as emission specific data from configuration files.

At DWD, in addition to the on-demand applications mentioned above, the model system ICON-ART will be employed for the dispersion modelling of mineral dust, chemical hazards and industrial as well as vegetation fires.

The project PerduS (see section 4.3.4.2) aims at an operational implementation of the mineral dust forecast with ICON-ART. For example the strong Saharan dust event beginning of April 2014 was investigated in a joint effort of DWD and KIT. Runs including the aerosol-radiation interaction of the simulated dust showed a significant reduction of the short-wave radiation at the surface. This for example had a big impact on the power produced by solar energy. The studies also included the aerosol-cloud interaction parts.

Point sources of radionuclides for the nuclear or of chemical substances for the non-nuclear emergency response application are defined via XML structures. However, for the simulation of the dispersion of non-nuclear contaminants, which pose a threat on a regional scale, a limited area configuration of ICON-ART will be employed. This configuration allows computations with a very high horizontal resolution (e.g. 1 km grid distance) which can be performed within the temporal constraints imposed by the requirements of an efficient emergency management.

The capability to treat vegetation fires is already present in COSMO-ART. The relevant modules will be adjusted and implemented also in ICON-ART.

(J. Förstner)

4.5.3 Specific products operationally available

The forward and backward trajectories are an important tool for emergency response activities. In addition to these forecasts for concentration and deposition of radionuclides are produced using a Lagrangian Particle Dispersion Model.

Based on the ocean wave models charts are produced for swell and significant wave height, frequency and direction.

Forecasts of the optimal (shortest and/or safest) route of ships are evaluated using the results of the global ocean wave model and of NWP in the ship routing modelling system of the DWD. The system calculates isochrones taking into account the impact of wave and wind on different types of ships.

A special application of the NWP result is a hydro-meteorological impact model-system called SNOW 4. It analyses and forecasts the snow-cover development. The model calculates grid-point values of the snow water equivalent and precipitation supply formed by the total amount of melt water and precipitation release from the snow deck every six hours. The snow cover development is computed with the help of physically-based model components which describe accumulation (build-up, increase), metamorphosis (conversion, change) and ablation (decrease, melting) of snow.

The model input data are

- hourly averages of air temperature, water vapour pressure/dew point temperature and wind velocity for the last 30 h
- solar surface radiation/sunshine duration/cloud cover and precipitation totals of the last 30h
- daily amounts of snow cover depth and three times a week water equivalent of snow cover
- output data of the ICON-EU model
- radar data of hourly total precipitation
- satellite data of snow coverage

The model output contains

- daily values of gridded snow depth observations (reference time 06.00 UTC)
- analysed values of snow cover development (30 h backward, 1-h-intervals):
  - snow depth (in cm)
  - water equivalent (in mm)
  - specific water equivalent (in mm/cm)
  - precipitation supply(in mm)

- forecast values of snow cover development (forecast interval 72 hours, forecasting for 1-h-intervals):
-
  - snow depth (in cm)

- water equivalent (in mm)
- precipitation supply (in mm)
- in addition forecast values of snow temperature and ice content can be derived

The results are provided grid-oriented and with a coverage for Germany and the surrounding basins of rivers flowing through Germany.

The UV index for all effective atmospheric conditions is operationally forecasted for up to 3 days with a global coverage and a high resolution European coverage. The UV Index on a global scale is forecasted in post-processing to DWD's global model ICON. The forecast is based on column ozone forecasts that are provided by the Royal Dutch Meteorological Institute KNMI (as part of the Copernicus Atmosphere Monitoring Service) in an hourly resolution and interpolated to the ICON grid.
First a large-scale UV Index is calculated depending on solar zenith angle and the column ozone forecast. Subsequently the large scale UV Index is adjusted by factors to variable aerosol amount and type, altitude, surface albedo of predicted snow cover and cloud optical thickness. The calculations include aerosol optical depth forecasts of the ECMWF provided as part of the Copernicus Atmosphere Monitoring Service.
The large-scale UV-Index forecasts are suited to interpolation to the grids of national higher resolution models (HRM). They can then be adjusted to the HRM topography and HRM forecasts of snow cover and cloudiness. The DWD UV Index forecast on a high resolution European scale is done in post-processing to ICON_EU that provides the detailed forecasts for the above mentioned adjustments of the large scale UV Index. Additionally site specific forecasts are available and are presented WHO-conform in the web.

All forecasts are supplied to the interested WMO member states of the Regional Association VI (Europe) by the RSMC Offenbach via its server ftp-outgoing.dwd.de. For more information see http://www.uv-index.de.

The department agrometeorology of DWD provides agrometeorological warnings on the basis of NWP:

- forest fire danger prognoses
- grassland fire index
- warnings for heat stress in poultry
- forecast of potato late blight

and other indices of plant pests and plant diseases. These are part of the advisory system AMBER (Agrarmeteorologisches Beratungsprogramm).

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

4.6.1 Models

4.6.1.1 In operation

None

4.6.1.2 Research performed in this field

None

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

Use of ECMWF Var-EPS products.

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

4.7.1 In operation

Since October 2016 seasonal forecasts performed by the German Climate Forecast System, Version 1 (GCFS1.0), based on the CMIP5 Version of the Earth System Model of the Max-Planck-Institute for Meteorology in Hamburg MPI-ESM are published on a website www.dwd.de/jahreszeitenvorhersage. The website is now also available in English www.dwd.de/seasonalforecasts. Three parameters are displayed on a global map and a zoom over Europe, namely temperature in 2 m height, sea surface temperature and precipitation. Deterministic as well as probabilistic forecasts are shown, as well as quality measures. Additionally, an ENSO outlook on the Nino3.4 region and the tropical pacific is displayed. DWD also applied in November to become a WMO GPC-LRF.

4.7.2 Research performed in this field

Based on research at University of Hamburg and Max-Planck-Institute for Meteorology and in cooperation with both institutions DWD has been setting up an operational system for seasonal forecasts at ECMWF. The coupled climate model MPI-ESM (Max-Planck-Institute-Earth System Model) has been prepared for this purpose. The model components are the atmospheric model ECHAM, the ocean model MPIOM with sea ice parameterisations, the land and vegetation model JSBACH and a runoff model to close the hydrological cycle. The current resolution of the ECHAM model is 1.9°x1.9° while the ocean has around 1.5 ° grid widths. More details on the model description can be found in Stevens et al (2013) and Jungclaus et al. (2013).
The operational set up is as follows: the model needs to produce reforecasts of the last 30 years for each start date (i.e. month) and forecasts which are then assessed on the basis of the reforecast statistics.
The initial conditions are produced in an assimilation run in which ECMWF-reanalyses data for atmosphere and ocean and sea-ice data from NSIDC are nudged for the reforecasts. ECMWF-IFS analyses are nudged in the forecast mode, while for the ocean temperature, salinity and sea-ice ORASS4 data are used.
An ensemble is set up by using the method of breeding in the ocean (Baehr and Piontek, 2013) and the perturbation of a physical parameter in the atmosphere. First results have been discussed and published in Baehr et al. (2014) and Domeisen et al. (2015).

The system is now being upgraded to a higher resolution version. GCFS1.0 also contributes its data to the Copernicus C3S climate data shop.

Reference:

Baehr J, K Fröhlich, M Botzet, DIV Domeisen, L Kornblueh, D Notz, R Piontek, H Pohlmann, S Tietsche, WA Müller, 2014: The prediction of surface temperature in the new seasonal prediction system based on the MPI-ESM coupled climate model. *J. Climate*, 1-13, 2014.

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Domeisen DIV, AH Butler, K Fröhlich, M Bittner, WA Müller, J Baehr, 2015: Seasonal predictability over Europe arising from El Niῇo and stratospheric variability in the MPI-ESM seasonal prediction system. *J. Climate*, **28**, 256-271, 2015.

Jungclaus J, N Fischer, H Haak, K Lohmann, J Marotzke, D Matei, U Mikolajewicz, D Notz, J von Storch, 2013: Characteristics of the ocean simulations in MPIOM, the ocean component of the

MPI-Earth System Model. *Journal of Advances in Modeling Earth Systems,* 422-446, DOI 10.1002/jame.20023

Stevens B, M Giorgetta, M Esch, T Mauritsen, T Crueger, S Rast, M Salzmann, H Schmidt, J Bader, K Block, R Brokopf, I Fast, S Kinne, L Kornblueh, U Lohmann, R Pincus, T Reichler, E Roeckner, 2013: The atmospheric component of the MPI-M Earth System Model: ECHAM6. *Journal of Advances in Modeling Earth Systems,* **5**, 146-172, DOI 10.1002/jame.20015

4.7.3 Operationally available EPS LRF products

Use of ECMWF Var-EPS products.

5. Verification of prognostic products

5.1.1.

Verification results of prognostic products are shown in the tables 3a - f.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	10	9	9	9	8	8	7	7	7	8	8	9	8.2
48.h	18	16	15	15	14	14	12	13	13	14	15	16	14.6
72.h	29	26	25	23	22	21	19	21	21	23	24	25	23.2
96.h	41	39	37	34	33	30	27	30	30	34	35	36	33.8
120.h	55	54	50	46	44	40	36	41	42	47	49	49	46.1
144.h	71	68	63	59	57	49	45	51	56	60	63	64	58.8
168.h	85	83	75	71	71	58	53	59	68	74	77	79	71.1

Table 3 a: **Verification of the DWD global model, RMS error (m), geopotential height 500 hPa. Area: Northern hemisphere, 00 UTC, 2016**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	9	9	10	11	10	11	11	11	11	10	9	9	10.1
48.h	17	16	17	19	18	20	20	20	20	17	16	16	18.0
72.h	26	26	27	30	29	32	31	33	31	28	25	23	28.4
96.h	37	38	41	44	42	46	46	49	45	41	35	33	41.4
120.h	51	50	54	58	59	60	61	66	62	55	47	45	55.7
144.h	66	65	70	76	76	77	74	84	79	69	59	57	71.0
168.h	79	80	84	94	88	91	89	101	95	84	71	70	85.5

Table 3 b: **Verification of the DWD global model, RMS error (m), geopotential height 500 hPa. Area: Southern hemisphere, 00 UTC, 2016**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	1.2	1.1	1.1	1.1	1.1	0.9	0.9	0.9	0.9	1.0	1.0	1.1	1.0
48.h	2.0	1.8	1.7	1.6	1.6	1.4	1.3	1.4	1.4	1.6	1.6	1.8	1.6
72.h	2.9	2.7	2.5	2.4	2.3	1.9	1.8	2.1	2.2	2.3	2.5	2.7	2.4
96.h	4.2	3.8	3.6	3.3	3.1	2.6	2.5	2.9	3.0	3.3	3.5	3.7	3.3
120.h	5.5	5.2	4.8	4.4	4.0	3.4	3.2	3.8	4.0	4.4	4.7	5.0	4.4
144.h	7.0	6.6	6.0	5.4	5.0	4.1	3.8	4.6	5.1	5.7	6.1	6.4	5.5
168.h	8.3	8.0	7.2	6.4	6.1	4.8	4.4	5.3	6.0	6.9	7.3	7.7	6.5

Table 3c: **Verification of the DWD global model, RMS error (hPa), mean sea level pressure. Area: Northern hemisphere, 00 UTC, 2016**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	0.9	1.0	1.0	1.2	1.2	1.3	1.3	1.3	1.2	1.1	1.0	0.9	1.1
48.h	1.6	1.6	1.7	2.0	1.9	2.1	2.2	2.2	2.1	1.8	1.7	1.6	1.9
72.h	2.5	2.5	2.7	3.1	3.0	3.3	3.4	3.5	3.2	2.8	2.4	2.3	2.9
96.h	3.5	3.6	3.9	4.4	4.2	4.6	4.7	5.0	4.5	4.0	3.4	3.3	4.1
120.h	4.8	4.6	5.1	5.7	5.7	6.0	6.2	6.7	6.0	5.5	4.4	4.4	5.4
144.h	5.9	5.8	6.4	7.2	7.2	7.5	7.5	8.4	7.5	6.7	5.4	5.5	6.8
168.h	6.9	7.1	7.6	8.8	8.2	8.8	8.8	9.8	9.0	8.0	6.7	6.6	8.0

Table 3d: **Verification of the DWD global model, RMS error (hPa), mean sea level pressure. Area: Southern hemisphere, 00 UTC, 2016**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	10	10	10	9	9	8	7	7	8	8	9	10	8.8
48.h	19	19	18	16	15	15	12	14	15	15	16	18	16.0
72.h	31	31	30	26	24	24	21	23	26	26	26	27	26.2

Table 3e: **Verification of the DWD global model, RMS error (m), geopotential height 500 hPa. Area: Europe-Atlantic, 00 UTC, 2016**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
24.h	1.2	1.2	1.2	1.1	1.0	0.9	0.8	0.9	0.9	0.9	1.0	1.2	1.0
48.h	2.1	2.0	1.9	1.7	1.6	1.5	1.3	1.5	1.6	1.6	1.7	2.1	1.7
72.h	3.2	3.2	3.0	2.6	2.3	2.2	2.0	2.3	2.6	2.6	2.6	3.2	2.6

Table 3f: **Verification of the DWD global model, RMS error (hPa), mean sea level pressure. Area: Europe-Atlantic, 00 UTC, 2016**

5.1.2.

PART VI VERIFICATION

Surface pressure (hPa)

Time	RMS	An. Cor.
T+24	1.0	0.993
T+48	1.7	0.981
T+72	2.6	0.955

Geopotential 500 hPa (gpm)

Time	RMS	An. Cor.
T+24	8.7	0.997
T+48	16.0	0.989
T+72	26.3	0.971

Temperature 850 hPa (K)

Time	RMS	An. Cor.
T+24	0.8	0.984
T+48	1.2	0.961
T+72	1.7	0.928

Temperature 500 hPa (K)

Time	RMS	An. Cor.
T+24	0.7	0.987
T+48	1.1	0.965
T+72	1.6	0.927

Relative Humidity 500 hPa (%)

Time	RMS	An. Cor.
T+24	11.2	0.892
T+48	17.0	0.748
T+72	21.3	0.607

Vector Wind 850 hPa (m/s)

Time	RMSE	Bias
T+24	2.3	-0.015
T+48	3.6	-0.010
T+72	4.8	-0.028

Vector Wind 250 hPa (m/s)

Time	RMSE	Bias
T+24	4.1	0.083
T+48	6.4	0.130
T+72	9.1	0.116

Table 4: **Verification results of the global model ICON, for the region where forecasts are submitted via facsimile, 2016**

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

6.1 Development of the GDPFS

6.1.1

None

6.1.2

None

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

6.2.1 Planned Research Activities in NWP

The model domain of the convection-permitting regional model COSMO-DE (and its ensemble system COSMO-DE-EPS) will be extended to the west, north and south, the grid spacing reduced from 2.8 km to about 2.2 km, and the number of layers increased from 50 to 65.

6.2.2 Planned Research Activities in Nowcasting

Project RADOLAN
A quantitative precipitation nowcasting method based on extrapolated real-time precipitation radar data, with hourly calibration against rain gauge measurements (RADOLAN: Radar-Online-Adjustment), has become operational at DWD. This Radar-Online-Forecasting (RADVOR) extrapolates the quantitative precipitation radar products in 15 minute time steps for up to two hours into the future. The basis of this method is the combination of two different extrapolation modules – one only for strong convective fields, the second especially for stratiform precipitation fields. Ongoing research is being undertaken to apply a module to use the COSMO-DE NWP wind field for tracking the radar data. This may allow one to extend the radar based quantitative precipitation forecast range until up to four hours into the future.

Project AutoWARN

Project Optimization of NowCastMIX within AutoWARN

In order to provide a generic optimal solution for nowcast warnings in AutoWARN all nowcast input data is pre-processed together in a single grid-based system: the NowCastMIX. This runs at the DWD to provide a single optimal set of gridded warning fields every 5 minutes. The goal of NowCastMIX is thus to provide and optimize an ongoing real-time synthesis of the various nowcasting and forecast model system inputs to provide a single, consolidated set of most-probable short-term forecasts.

In addition to its thunderstorm warnings NowCastMIX can also generate warnings for very heavy convective rainfall accumulations (where no lightning occurs). Until recently such warnings were limited to a strict one hour forecast time range and were rarely issued. However, recent severe weather events involved extreme flash flooding, such as were seen on several occasions in Germany in late May and early June 2016, have demonstrated that prolonged heavy rain falling locally over several hours can be very dangerous, even when the individual hourly totals are not especially large themselves. In view of this, heavy rainfall warnings have now been introduced by NowCastMIX for timescales of up to six hours, bridging the gap between pure nowcasting and the short-term forecasting covered in part by regional NWP models. This has been achieved by combining analyses of recent rainfall totals over the last few hours from the RADOLAN system with rainfall nowcasts from RadVOR and forecast rainfall totals for the next few hours from the COS-

MO-DE-EPS ensembles. This new technique represents NowCastMIX's first foray into the area of seamless prediction and has provided useful guidance since its implementation in August 2016.

In a further recent development, NowCastMIX now performs an explicit tracking of thunderstorm cells in order to provide a first insight into the lifecycle characteristics of storms, forming a basis for future research into improving the severity categories of thunderstorm warnings, and above all to improve the quality of the forecast cell motion vectors. In particular, it is well known that some severe supercells have motion vectors which can deviate strongly from other weaker cells in the vicinity. Often these supercells move rightwards compared to weaker cells. Until recently, NowCastMIX only calculated a general, smooth motion vector field which was applied to all cells equally. Although this field was statistically optimised to provide a good set of results overall, individual anomalously moving cells were not treated specially. Now, the introduction of explicit cell tracking, using an ensemble clustering technique to define cell objects and then employing a multiple hypothesis tracking to yield optimal vectors for each object, has allowed NowCastMIX to be able to follow anomalously moving supercells explicitly, yielding a significant improvement in determining the required warning areas for the next 60 minutes for such cells.

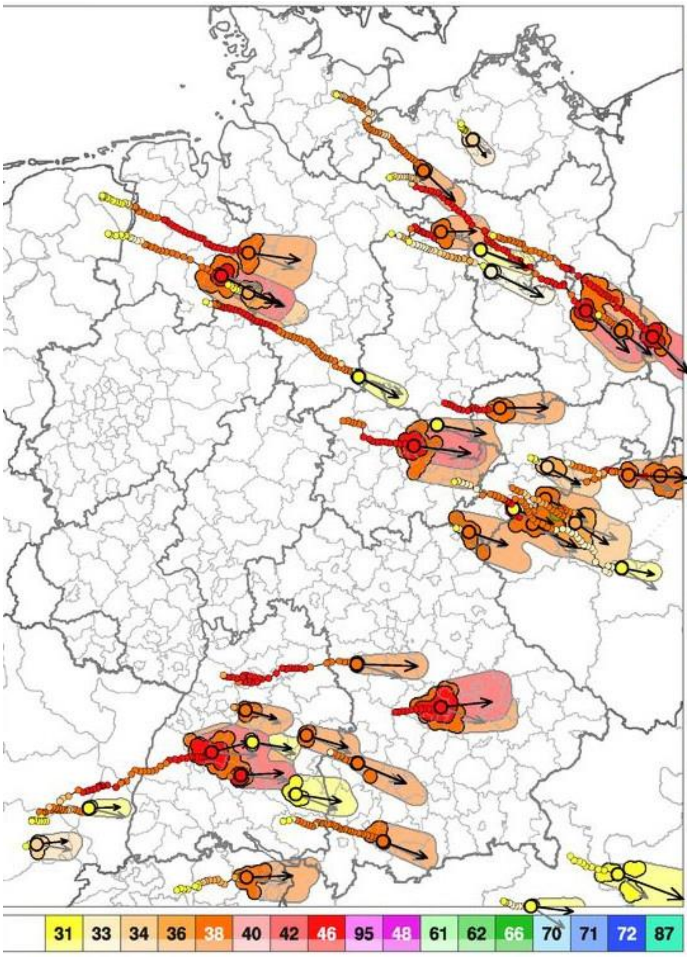

Figure7: NowCastMIX thunderstorm warnings for the hour starting at 17:45 UTC on 07.07.2017, showing an analysis of current storm category and locations (larger circles, saturated polygon areas), with recent motion tracks (small, joined-up dots), optimally derived forecast motion vectors (arrows) and subsequent warning areas covering the regions at risk over the following 60 minutes (opaque areas).

6.2.3 Planned Research Activities in Long-range Forecasting

DWD also takes part in the second research phase of the MiKlip project (http://www.fona-miklip.de/), starting mid of November 2015 with the final aim to perform operational decadal forecasts at DWD once a year. The model in use will be the coupled climate model MPI-ESM (Max-Planck-Institute-Earth System Model, as is already employed for seasonal forecasts. However the setup will slightly differ. Project scientists will start work in the field of setting up the operational system at DWD, continuing research on dynamical downscaling of global decadal predictions as well as in the field of user communication and product development.

7. Consortium

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 convection-permitting model COSMO-DE, which 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 20 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 4.4.2 for COSMO-DE and COSMO-DE-EPS and for other COSMO members.

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. 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 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, Ecuador, Indonesia, Kenya, Madagascar, 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 built-in 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 nudging technique is being replaced by a 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 ICON-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 a hybrid combination (EnVar) of an Ensemble-Kalman Filter (EnKF) with a 3D-Var scheme, which allows using the Ensemble-based information of flow-dependent error covariance matrices in the deterministic analysis. As a result ICON model forecasts used as an initial and boundary conditions for several COSMO model operational setups have 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 KENDA-O 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:

- 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

The LETKF DA is in operational use at MeteoSwiss and DWD, and implemented pre-operational at 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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