Development of ICON modelling framework

WG3a and WG3b issues

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The present document outlines a number of issues that should be addressed in order to improve the ICON modelling framework in terms of the model physics. The COSMO members are welcomed to tackle those issues and contribute to the ICON development. Note that the following list is non-exhaustive; further issues may appear to be important as the ICON modelling framework is further developed and refined and its scope is extended.

One point should be emphasized at once. It would not be an exaggeration to say that the present-day numerical weather prediction (NWP) systems are very complex and rather advanced. This fact has an important implication for planning research and development activities. Any innovative contribution to an NWP system, be it the development of a new model component from scratch or further development/improvement of an existing model component, requires massive efforts and (usually) considerable human resources. This holds for verification, post-processing, data assimilation, and model numerics. It is particularly true for the NWP model physics, where uncertainties are often large and testing of new model components (both off-line and within a full-fledged NWP system) is tricky and time-consuming. As far as the development of new parameterization schemes is concerned, it hardly makes sense to formulate short-term plans. The development cycle, from the formulation of innovative parameterization ideas through the operational implementation, can only be completed within five to ten years. That is, medium-term and long-term perspectives should be considered. In the short-term perspective, only ongoing projects can be completed and extended. That is, if an essential part of the work planned is already successfully accomplished, then the completion of the task in question within ca. two-year time span can be planned.

Note that some issues outlined below have already been considered in much detail, and the outcomes of the respective projects have a good chance to become operational (or at least to enter the official ICON code) in the not too distant future. Other projects are at their infancy, i.e., only preliminary thoughts have been made as to how the problem in question should be tackled. For each issue, a few references are given and contact persons are indicated (even in the cases where the project is still at the embryonic stage). A key contact person (that typically assumes, or is expected to assume, responsibility for the model code) is listed first.

Permanent tasks

Upgrade of external-parameter data sets

This effort can hardly be formulated as a well-defined work package, rather it is a continuous (permanent) task. External-parameter fields loom increasingly large as the resolution of the NWP models is refined. For example, accurate treatment of the interaction of the atmosphere with the underlying surface becomes increasingly important and grows in its complexity, imposing heavy demands on the quality of surface external parameters, as, for example, orography, land use, and soil properties. The utilization of modern external-parameter data sets with an ever increasing resolution is vitally important for the quality of weather forecasts. Without high-quality external parameter datasets the (expensive!) increase in resolution to a mesh size of 1 km and below might only add noise but no significant skill. The new data sets should always be thoroughly quality-proved, and the software used to generate external-parameter fields should be carefully maintained. Processing the highest resolution global datasets currently available can be demanding in terms of computer resources. Hence, an efficient and scalable implementation is required. Recall that the emphasis is on the global data sets that allow both the global ICON applications and the limited-area applications over an arbitrary domain. Inter-consortium collaboration should be encouraged to exchange experience about the raw data sets, to help collect local data from different countries, and to facilitate communication with data providers.

Contact persons: Jonas Jucker (ETHZ), Jürgen Helmert (DWD), Jean-Marie Bettens (MCH)

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Maintain and extend a model calibration framework

All models used for NWP and climate studies have inherent uncertainties. NWP and climate models include various parameterization schemes, most of which include free or poorly confined parameters. Values of those parameters are usually determined manually by model developers so that to improve the agreement of forecasts with available observations. Such "expert tuning" is typically done once during the model development. It is often limited to a particular target area and to a particular model configuration and is difficult to replicate.

Following Bellprat et al. (2012), a more objective model calibration methodology was developed within the framework of the COSMO Priority Projects CALMO and CALMO-MAX (Voudouri et al. 2017). The primary aim was to complement the expert tuning with a more replicable and automatic approach. Using the CALMO methodology, an overall model performance (in terms of a number of performance scores) is optimized by adjusting the values of a set of disposable model parameters. The core of the calibration process is the determination of the so-called meta-model (model emulator), which uses a simple mathematical function to represent the dependency of some representative model fields on a number of selected model parameters. Once fully specified, the meta-model supports a fast sampling of the parameter space to find an optimal combination of the values of chosen model parameters. It has been shown (see Bellprat et al. 2016, PP CALMO and PP CALMO-MAX publications, and Duan et al. 2017) that the above approach is sound and is capable of improving the forecast quality.

The CALMO team invested a lot of effort into the development and refinement of the meta-model, and promising ideas and considerations concerning the optimization process have been proposed. Furthermore, continuous developments took place at ETH Zürich; a three-year PhD focused on the model calibration started in the autumn 2020. It is now necessary to synchronize the COSMO and the ETHZ developments in order to deliver a unified, consolidated, portable (based on Octave or Python) and well-documented (including a comprehensive user guide) meta-model code capable of providing a meaningful model performance score in an easy way. Once available, that code will be a very useful tool for both NWP and climate modelling communities.

The CALMO methodology is essentially "model independent" and can be applied to any NWP or climate model. The only pre-requisites are an up-to-date and well-documented list of disposable model parameters, and the information on the model parameter sensitivity which supports a first screening of relevant parameters for a planned calibration. Given the dynamic nature of the NWP and climate model development, maintenance and further development of the model calibration framework (including the meta-model and the list of disposable parameters) should become a permanent COSMO task.

Contact persons: Euripides Avgoustoglou (HNMS), Yoav Levi (IMS), Jean-Marie Bettems (MCH)

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Short-term to medium-term prospects

Ground water and run-off parameterization

A new parameterization scheme was developed for the vertical transport of ground water (which enables the build-up of the ground water storage) and the slope-dependent runoff. The new scheme was favourably tested through off-line single-column numerical experiments and through regional climate simulations with COSMO-CLM. The use of the new scheme improves the model performance in terms of the ground water spatial distribution (particularly in mountainous areas), the surface latent heat flux, and the near-surface temperature bias. The new scheme is included into the official code of the COSMO-model version 6.0. Implementation into ICON and comprehensive testing is the subject of future work.

Contact persons: Linda Schlemmer (DWD), Daniel Regenass (ETHZ), Jean-Marie Bettems (MCH)

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Multi-layer snow parameterization scheme

Development, testing and implementation into the COSMO model of a multi-layer snow parameterization scheme was the goal of the COSMO Priority Task SAINT. The work progressed successfully. The new snow scheme termed SNOWPOLINO was developed. It incorporates many attractive features of the very advanced and physically sound snow model SNOWPACK but it is much less complex than SNOWPACK and much more computationally efficient. Off-line tests show that a multi-layer snow parameterization scheme outperforms a one-layer scheme in terms of snow surface temperature, snow depth, and the time of snow melting. The new multi-layer snow scheme has been successfully tested within a full-fledged COSMO model and is now available in the official code of the COSMO-model version 6.0. The scheme is GPU capable. The new snow scheme is pre-operational at MCH within the COSMO model since the end of summer 2021.
Work is underway towards the implementation of the new snow scheme into ICON. Apart from technical work, such as harmonization with the ICON tile approach and possible adaptation of many snow-related features of various ICON procedures (e.g., dynamic snow tiles), comprehensive testing and tuning within ICON should be performed. A number of issues of research character, e.g., snow-forest interactions and dust on snow, could also be addressed (depending on available resources).
Development towards the use of an implicit solver for the equation of heat transfer through the snow pack and the soil layers is also under way; furthermore, coordination with PT ConSAT (see below) is also established.
The implementation of the new multi-layers snow scheme developed within the framework of PT SAINT and of the new surface analysis developed at DWD call for a new snow analysis package for the Consortium. Efforts are being coordinated between COSMO WG1 and WG3b.
Contact persons: Sascha Bellair (MCH), Jürgen Helmert (DWD), Jean-Marie Bettems (MCH), Matthias Raschendorfer (DWD)

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Bulk urban parameterization scheme

An urban-canopy parameterization scheme TERRA-URB was developed, implemented into the COSMO model, and tested through numerical experiments. The work was performed within the framework of the COSMO PT AEVUS. A general conclusion is that TERRA-URB is capable of realistically simulating the key features of the urban heat island. The effect of TERRA-URB on the COSMO-model performance is mostly positive. A follow-up PT AEVUS2, that ran until July 2021, was aimed at consolidating the development of TERRA-URB for COSMO. The TERRA-URB scheme has entered the official code of the COSMO-model version 6.0. A new PP CITTA has been accepted. The goal of PP CITTA is to transfer the results obtained within the framework of PTs AEVUS and AEVUS2 with respect to the urban canopy parameterization TERRA_URB and its external parameters from the COSMO model to the ICON model. Jan-Peter Schulz of DWD serves as the PP CITTA leader. In order to use TERRA-URB within ICON, external parameters should be provided globally, although default values of external parameters may be used in data sparse areas. A global coverage is necessary to ensure that both the global and the limited-area applications for an arbitrary domain are possible.

Contact persons: Jan-Peter Schulz (DWD), Paola Mercogliano (CIRA), Mikhail Varentsov (RHM), Jean-Marie Bettems (MCH)

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Dynamic vegetation scheme

Further improvement of the description of the interaction of the atmosphere with the underlying surface can be achieved through enhanced treatment of vegetation. The seasonal phenology of vegetation affects the energy and water cycle and can amplify extreme events through changes in the albedo and water availability. Photosynthesis provides moisture to the environment by evapotranspiration and is important for the atmospheric boundary layer; here, the stomatal conductance is a crucial regulating factor. Knowing the evolution and magnitude of the seasonal changes of the leaf area index together with the plant coverage allows for a more realistic estimation of the surface albedo that is important for accurate weather and climate modelling.

Most present-day NWP models, including COSMO and ICON, use simplified phenology schemes. Those schemes are in general not capable of realistically representing complex vegetation processes, such as the start of the growing season in spring, the evolution of the leaf area index and plant coverage, and the senescence in autumn. The above processes depend (among other things) on day length, temperature, and water availability, but these dependencies are not accounted for within the framework of simplified phenology schemes.

A COSMO PT VAINT scheduled for the period from September 2020 through August 2022 is underway. The PT is aimed at implementing into the latest COSMO version 6.0, validating, and updating as needed the CARAIB photosynthesis/phenology scheme. It is expected that the use of CARAIB will reduce the forecast errors in vegetated areas. CARAIB is an extensively validated scheme, which successfully participated (model results close to observations) in the ISIMIP2a inter-comparison study (Chang et al. 2017). The focus of PT VAINT is on a rather simple but robust vegetation scheme (no new external parameters, no new dynamic fields). The PT lays a solid basis for further development. It is a first step towards a future implementation into the ICON model.

Contact persons: Jürgen Helmert (DWD), Merja Tölle (University of Kassel), Jean-Marie Bettems (MCH)

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Parameterization of mires

A mire parameterization scheme was implemented into the COSMO model and was successfully tested through numerical experiments, including parallel experiments with the complete DWD data assimilation cycle. The effect of mires on the overall COSMO-model performance (in the domain-mean sense) is small but the local effect is often substantial. Mires considerably affect the surface fluxes of heat, moisture, and momentum (e.g., the Bowen ratio is strongly changed), leading to improved scores with respect to near-surface quantities including wind gusts. Preliminary tests of the mire parameterization within ICON indicate that dry mires and wet mires should be discriminated; otherwise, no positive effect in terms of performance scores can be achieved. To this end, a new external-parameter data set needs to be developed. It will be used to generate an external-parameter field indicating which type of mire (dry or wet) is being treated by the parameterization scheme. Importantly, the data set should be global in order to allow the ICON applications for the entire globe and for an arbitrary limited-area domain. The mire parameterization scheme itself should also be amended (minor changes are expected).

Contact person: Jürgen Helmert (DWD), Jean-Marie Bettems (MCH)

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Canopy layer for TERRA

The goal of this effort is to introduce a “true” canopy layer into the parameterization scheme TERRA. In the current version of TERRA, the canopy effects are not treated explicitly. A “virtual” canopy layer has zero thickness, and the influence of canopy on the heat, mass and momentum transfer near the surface is accounted for implicitly through the resistance (transfer coefficient) formulations. In other words, the idea is to account for the those effects of roughness elements that cannot be described by simply modifying the heat, water vapour and momentum transfer resistances between the soil and the atmosphere. To this end, an extra roughness layer above the dense soil, containing roughness elements as well as surrounding air, should be considered, for which (appropriately simplified) budget equations must be solved (at least the budget equation for heat). This will allow the representation of crucial effects of elevated parts of the surface on heat transfer and evapotranspiration, such as shading by leaves and non-atmospheric storage of heat and water constituents above the soil (interception of dew, rime, snow or black ice).

Two parallel lines of development have been pursued at DWD. (i) An advanced explicit canopy model developed for HIRLAM NWP system has been incorporated into COSMO and ICON and preliminary tests have been performed (Jürgen Helmert). The scheme has many attractive features (e.g., it can handle snow under forest canopy) and offers considerable promise (it fares well within HIRLAM), but a consistent coupling with the atmosphere and soil transport equations should still be achieved. (ii) An extension of the existing formulations of TURBTRAN and TERRA has been developed (Matthias Raschendorfer) within the framework of PT ConSAT. Among other things, thermal energy storage of a semi-permeable roughness layer and thermal decoupling of roughness elements (canopy) above the dense soil are accounted for.

It has already been demonstrated that the diurnal cycle of 2m temperature and humidity are considerably improved by the above extensions (which are implemented into a test version of COSMO and are to be implemented into ICON). The revision of TERRA with its new implicitly coupled heat equations for soil, snow, and a skin layer has already been formulated in such a way that the skin layer can easily be extended towards the full semi-permeable roughness layer. The canopy extension of TERRA and TURBTRAN [(ii) above] is that very part of well-designed and consistent development of an improved surface-atmosphere coupling in ICON, which contains the main outcome of all previously performed rather technical preparations. It should therefore be pursued further. This development will build the platform for a consistent incorporation into ICON of the HIRLAM canopy scheme [(i) above], or at least part of that scheme.

Contact persons: Jürgen Helmert (DWD), Matthias Raschendorfer (DWD), Jean-Marie Bettems (MCH)

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Improved coupling of the atmospheric surface layer and the soil parameterization schemes

This is an extensive work package being implemented within the framework of the WG3a PT ConSAT. A general goal is to improve the description of the surface-atmosphere transfer processes. To this end, various components of the soil parameterization scheme (TERRA) and of the atmospheric surface-layer parameterization scheme (TURBTRAN) are considered, various parameterizations rules are reformulated, new parameterizations are introduced, and, whenever possible, ad hoc tuning devices are replaced with more physically sound formulations. Since a large number of problems are tackled, ConSAT is in fact a continuous task rather than a well-defined work package. There are pressing problems, however, that should be solved with the minimum delay possible. One problem is related to solving the heat transfer equations in the soil, in the snow layer, and in the atmosphere which are coupled through the surface temperature and the surface fluxes. Explicit coupling causes numerical instability and leads to pathological large-amplitude oscillations of the surface temperature. This is a serious issue for the global ICON with its large time steps. This is a less serious issue for the ICON-LAM that typically utilizes smaller time steps. Still pathological oscillations in ICON-LAM are encountered, and the issue should be resolved. An implicit coupling procedure for the soil, snow and the atmosphere heat transfer equations has been developed and successfully tested by Matthias Raschendorfer. Implementation into the official ICON code is underway.

It is worth noting that various limiters and workarounds were implemented into the ICON code in order to cope with the explicit treatment of heat transfer. Those ad hoc devices are spread over the code of TERRA and many other ICON modules. With the new implicit formulation, all those devices are no longer needed, but it appeared to be necessary to make changes in many model routines (some changes being quite substantial). Those changes may have side effects. Although every effort was made to reduce side effects, further comprehensive testing is needed.

The new coupling procedure incorporates a heat transfer equation specifically tailored for the skin layer of the snow-free part of every surface land tile (new feature) and a revised formulation of the heat budget for the snow cover. Both the skin layer and the snow layer are treated implicitly, and the heat transfer budget for these layers is solved jointly with the heat transfer budget of the soil (a single linear system is formulated). Recall that a multi-layer snow scheme is used, which can be reduced to the previously used single-layer scheme (by simply setting the number of layers to one). The implicit procedure outlined above should be harmonized with the skin layer parameterization developed by Jan-Peter Schulz that is already implemented in ICON (note that the skin-layer parameterization may appreciably damp the abovementioned pathological oscillations). It should be further noted that the goal is to achieve an implicit, numerically stable and robust treatment of as many surface and near-surface processes as possible. Along this line, the new multi-layer snow hydrology will be an integral part of an implicit heat and mass transfer procedure. Among other things, phase transitions of precipitation, intercepted at the natural surface of the earth, will be included into a new formulation. This will allow to discriminate between snow interception at tall vegetation and the snow cover of the soil below.

Contact persons: Matthias Raschendorfer (DWD), Jan-Peter Schulz (DWD)

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ecRad radiation parameterization scheme for ICON

The implementation into ICON of the ecRad radiation parameterization scheme developed by Robin Hogan (Hogan and Bozzo 2018) is completed (Rieger et al. 2019). In April 2021, the ecRd radiation scheme replaced the RRTM radiation scheme within the operational ICON configuration at DWD. Further research and development efforts are in progress to improve various aspects of radiation calculations based on ecRad. The issues to be addressed include treatment of the surface albedo and emissivity, cloud overlap and horizontal inhomogeneity, particle size and effective radius parameterizations, extension from a single category of small ice particles to larger ice particles and multiple categories (snow and graupel), coupling to various aerosol climatologies (including three-dimensional effects) and to prognostic aerosols based on ICON-ART or two-dimensional advection scheme, and coupling to the two-moment microphysics scheme, cloud scheme, and stochastic shallow-convection scheme. ecRad can approximate the effects of horizontal radiative transfer and 3D cloud structure (Schäfer et al. 2016, Hogan et al. 2016), allowing to determine if neglecting these effects leads to significant errors. The radiation research team includes the DWD project scientists (e.g., Sophia Schäfer works on the radiation problems on a 100% basis), Robin Hogan of ECMWF, the KIT (Karlsruhe Institute of Technology) researchers, and the members of the COSMO PP CAIIR team. Coordination of efforts undertaken by various radiation-team members is crucial for the project success.

Contact persons: Sophia Schäfer (DWD), Daniel Rieger (DWD), Martin Köhler (DWD), Harel Muskatel (IMS), Bernhard Vogel (KIT)

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Parametrization of fractional cloud cover

The aim of this effort is to improve the description of cloudiness within ICON. The ultimate goal is a unified coherent parameterization whose output (fractional cloud cover and the amount of cloud condensate within a given model grid box) is used by the radiation scheme, the turbulence scheme, and eventually also the microphysics scheme. The approach taken in ICON is based on the statistical description of fractional cloudiness; an assumed-PDF cloud scheme is used that accounts for the sub-grid scale variability of temperature and humidity (and possibly also of the vertical velocity). A truly unified, consistent parameterization of fractional cloudiness is very difficult to develop. Such a parameterization can only be considered as a long-term goal. A short-term goal is to improve the representation of fractional cloud cover for radiation calculations (the turbulence and microphysics parameterizations can also benefit from this development but the emphasis is on the radiation). To this end, a statistical cloud scheme (either Gaussian or with non-Gaussian corrections) coupled to the turbulence scheme through the temperature and humidity variances should be extended to account for the contributions from cumulus clouds. That is, a more intimate coupling to cumulus parameterization schemes, both deep-convection schemes and new stochastic shallow-convection scheme, is required. The current implementation uses the volume detrainment from the convection scheme as a cloud-fraction source term balanced diagnostically by a decay term. As a first step, this framework will be extended to an assumed-PDF framework with the non-Gaussian contribution coming from the convective towers.

Contact persons: Martin Köhler (DWD), Maike Ahlgrimm (DWD), Matthias Raschendorfer (DWD)

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Stochastic shallow convection scheme

A DWD project (started in September 2019) is aimed at improving the representation of shallow convection in high-resolution NWP models. With the increasingly smaller (horizontal) mesh-size of atmospheric models the equilibrium assumption that stands behind traditional convection parameterization schemes breaks down (cannot be applied to individual grid boxes). Stochastic parameterizations are a viable approach for describing shallow convection at high spatial resolution characteristic of the present-day NWP models. A stochastic shallow-convection scheme developed by Sakradzija et al. will be comprehensively tested within ICON and tuned as needed. The goal is to make the scheme operational at DWD within ICON-D2.

Contact persons: Maike Ahlgrimm (DWD), Axel Seifert (DWD), Ekaterina Machulskaya (DWD)

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Further development of the STIC approach

According to the concept of STIC (Separated Turbulence Interacting with larger-scale sub-grid Circulations, the concpt was developed by M. Raschendorfer as a theoretical background for the operational turbulence scheme TURBDIFF), the second-order budget equations for small-scale turbulence (and especially the

prognostic TKE equation) should incorporate additional shear-production terms through the interaction of turbulence with other non-turbulent (but still sub-grid scale) circulations. The neglect of that interaction between parameterizations designed for different scale ranges appears to be the reason for many shortcomings of current NWP models, particularly with respect to stable density stratification and the representation of clear-air atmospheric turbulence and convectively induced turbulence. According to the concept of STIC, description of mixing phenomena, whose physical nature is not in accord with the closure assumptions made for small-scale turbulence (as applied, e.g., to treat the pressure-correlation terms), can be readily left to other parameterization schemes designed for larger length scales. Accordingly, turbulence parameterization schemes may (and even must) be restricted to small-scale structures, which reveal simple non-skewed distributions of prognostic variables. The STIC terms are the main contributors to the DWD product for aviation turbulence, namely, the EDP (Eddy-Dissipation Parameter). In the course of the implementation of STIC ideas, other novel parameterizations have been developed, e.g., a parameterization of non-turbulent Separated Horizontal Shear (SHS) eddies and a parameterization of direct Thermal circulations induced by Surface Inhomogeneity (TSI).
In the short-term perspective, the concept of STIC and its current applications will be documented and published. Furthermore, the TSI parameterization is being revised to describe katabatic and anabatic circulations near the surface as dependent on the sub-grid scale orography parameters. Finally, individual mixing terms and source terms related to the SHS and TSI will be considered in the first-order budgets, and transport from all non-turbulent sub-grid scale circulations needs to be added to the TKE equation.

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Turbulence Kinetic Energy – Scalar Variance (TKESV) turbulence parameterization scheme

The major differences between the TKESV scheme and the operational one-equation TKE scheme are (i) prognostic treatment of the variances and covariance of scalar quantities (liquid water potential temperature and total water specific humidity) with due regard for the third-order transport, and (ii) advanced treatment of the pressure-scrambling effects in the Reynolds-stress and scalar-flux equations through modified stability functions. Among other salient features of the TKESV scheme, stability-dependent formulations of turbulence length/time scales and the skewness-dependent formulations (to account for cumulus clouds) of the buoyancy terms in the second-moment budget equations are worth mentioning. The TKESV scheme has a number of advantages over the TKE scheme (e.g., consistent treatment of counter-gradient fluxes of scalars and a more intimate coupling with the cloud parameterization scheme) and is a favourable framework for describing turbulence and shallow convection with a unified approach. The TKESV scheme has been successfully tested in a single-column mode and within the full-fledged COSMO model. A baseline version of the TKESV scheme is implemented into ICON. The work is underway at DWD to test the new scheme through ICON numerical experiments and to introduce the TKESV scheme into the official ICON code. The focus at the time being is on the scheme performance in a high-resolution convection-permitting configuration, although global runs are also performed.

Contact persons: Ekaterina Machulskaya (DWD), Dmitrii Mironov (DWD)

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Mineral-dust and pollen forecast with ICON-ART

The aim of the project PerduS, implemented at DWD in close co-operation with the Karlsruhe Institute of Technology (KIT), was to make the mineral-dust forecast with ICON-ART quasi-operational. Now, after completion of the project, quasi-operational mineral-dust forecasts are performed at DWD. A global ICON-ART is run twice a day for 180 hrs (ICON-Nest is run for 120 hrs), starting at 00 UTC and 12 UTC. The mesh size of the global model is ca. 40 km, ICON-Nest has a mesh size of ca. 20 km. The direct effect of dust on radiation is accounted for. Results from runs preformed so far indicate improvements of some scores, e.g., two-meter temperature and especially the direct and diffuse radiative fluxes. ICON-ART forecasts are integrated into the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) of WMO. Since June 2019 the ICON-ART results, e.g., the dust aerosol optical depth (AOD) and the dust near surface mass concentration, are available online. The ICON-ART forecasts compare well with the forecasts by the other models (even though ICON-ART is run without any assimilation of dust information like AOD). Future plans concerning the application of ICON-ART in NWP include the extension to sea salt and biomass burning aerosols, and the coupling to the cloud microphysics (indirect aerosol effects). This is the focus of the new project PermaStrom which has a time frame from 2020 to 2024. Besides the continuation of the global ICON-ART application, the project does also include experiments in a convection-permitting ICON-ART-D2 setup and the use of ensembles for the statistical quantification and uncertainty estimation of the aerosol effects. Further effort goes into the development and eventual operationalization of the pollen prediction system with ICON-ART. The pollen code has been ported from COSMO-ART to ICON-ART. Work is underway (DWD, KIT) to develop a comprehensive external-parameter data set required to run pollen forecasts (e.g., fractional cover of various vegetation types should be specified), and to incorporate the pollen prediction modules into the numerical experimental system and operational environment.

Contact person: Jochen Förstner (DWD), Axel Seifert (DWD)

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Two-moment microphysics

A two-moment microphysics scheme is superior to the currently operational one-moment scheme in terms of essential physics. The two-moment scheme is computationally more expensive, however. It should be further tested and probably optimized before its operational use within ICON. Numerical experiments performed so far clearly indicate that within ICON-D2 the two-moment scheme outperforms the one-moment scheme in terms of various scores (e.g., precipitation and simulated radar reflectivity). Further comprehensive testing is required in order to see that the added value brought by the two-moment scheme warrants the increased computational costs. The work is underway at DWD as part of the SINFONY project aiming at the explicit prediction of individual deep convective storm in the 0-12 h time frame.

Contact person: Axel Seifert (DWD)

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Turbulent orographic form drag parameterization

The goal is to improve the description of the drag exerted by the sub-grid scale orography (unresolved hills and mountains). One way to represent the effect of unresolved orographic features is to enhance the roughness length with respect to momentum over orography. As a more attractive alternative to the effective roughness length, turbulent orographic form drag (TOFD) parameterizations were developed to describe the effect of unresolved orographic form drag. The TOFD scheme proposed by Beljaars et al. (2004) has been implemented into ICON, and preliminary tests have been performed with encouraging results. However, those results are based on the ECMWF filtered orography field (extrapolated from 1000 m to 10 m mesh size). A major work is required to create a realistic filtered orography on the native ICON grid using the 90 m resolution datasets (MERIT or TanDEM-X). Much work is also required to assess the performance of the TOFD scheme within ICON, to tune the scheme as needed, and (most notably) to make sure that the TOFD scheme is in harmony with the other ICON physical parameterization schemes and with the resolved dynamics. Among other things, the following outstanding issues should be addressed:

(i) spatial scales at which the TOFD scheme should operate within ICON;
(ii) external-parameter fields required to use the TOFD scheme within ICON (including the quality-proof of raw data used to generate the external-parameter fields);
(iii) partitioning of the total drag between the various schemes, e.g., the sub-grid scale orography (SSO) and the TOFD schemes;
(iv) dependence of turbulent orographic drag on the static stability of the atmosphere (particularly in stable stratification, when the boundary layer is shallow);
(v) effect of TOFD on the transport of scalar quantities.
As the issues (i) through (v) are scrutinised, modifications may appear to be necessary in the TOFD scheme and possibly in a number of other parameterization schemes, e.g., the SSO scheme, the turbulence scheme, and the surface-layer transfer scheme. To this end, a number of tricky issues of research character should be addressed. At the end of the day, it is not the TOFD scheme per se that matters, but a consistency between the various schemes that describe the momentum transport and the drag. Finally, comprehensive testing must be performed to assess the overall ICON performance, and, importantly, to avoid over-tuning. The above research issues, particularly (iv), are in line with the research efforts undertaken by a post-doc working within the HErZ team of the University of Frankfurt, Germany.

Contact persons: Martin Köhler (DWD), Günther Zängl (DWD)

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Medium-term to long-term prospects

Treatment of a vertically resolved roughness layer

According to the fundamentals of the abovementioned STIC approach, the resolution-dependent filter operator (used to derive the discretized model equations) does not commute with spatial differentiation if the model grid is affected by the sub-grid scale orography (either by non-atmospheric inclusions or deformations of a regular grid box). According to the STIC this approach, the direct impact of sub-grid surface structures (not only hills and mountains but also the land use) is expressed through specific correction terms in the budget equations.
An atmospheric model that incorporates the roughness corrections due to the above non-commutability in its first-order (or higher-order) equations can be applied within the roughness layer, which may be regarded as vertically resolved in this case. Usually (this is also the case with ICON), the roughness layer is excluded from the atmospheric part of the model as far as the land-use roughness is concerned. The roughness layer is included only with regard to the sub-grid scale orography (SSO) effects. However, roughness corrections (described by, e.g., the SSO or TOFD scheme) are only considered in the momentum budget via the form-drag terms that can be derived from the filtered pressure-gradient terms. An exception within ICON is a scale-interaction term in the TKE equation (wake production) that has been introduced in the course of the development of the STIC approach.
Since there is a growing interest in a more realistic simulation of the flow within the roughness layer of urban areas or the vegetated biosphere, it is a more distant aim to treat a (near) real-world vertically resolved roughness layer by accounting for the so far missing roughness corrections (including the impact of land use). With such a unified approach based on the formal STIC results, only a small-scale part of the surface roughness remains the emphasis of the surface scheme. A canopy scheme (see above) can then also be restricted to small-scale roughness elements.

Contact person: Matthias Raschendorfer (DWD)

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Effect of STIC on convection and cloud processes

Up to now, the scale separation of parameterizations has been mainly implemented into ICON as a one-way interaction only, accounting for the effect of Non-Turbulent Circulations (NTCs) on turbulence. However, as the concept of STIC implies, the budgets of statistical moments for NTCs are also influenced by the scale interaction. This effect shall be introduced into a convection scheme through the appropriately modified mass-flux equations. Further generalizations will include “turbulent” saturation adjustment for warm non-precipitating cloud processes. The aim is to achieve a coherent description of the overall effect of turbulence and convection on warm-cloud source terms in the first-order budgets. The grid-scale saturation adjustment procedure, which currently destroys the sub-grid scale action on warm non-precipitating clouds, will be replaced by a consistent statistical adjustment procedure that account for contributions from all considered scales. Within the framework of the new procedure, the saturated air fraction (resolution-dependent cloud fraction) will emerge as an inherent property through the spectral superposition of turbulence and NTCs (e.g., convective circulations).

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Interactive ocean

Full-fledged three-dimensional ocean models are computationally expensive. Coupling of a three-dimensional ocean model with an atmospheric model is a viable option for long-range NWP and climate modelling, but it is barely feasible for short-range and (arguably) for medium-range NWP. A simplified ocean model is required. A one-dimensional model (parameterization scheme) of the upper ocean, including the mixed layer and the seasonal thermocline, seems to be a reasonable compromise between the physical realism and computational economy. A two-layer upper-ocean parameterization scheme with a parameterized vertical structure is an attractive option. Such a scheme may be developed using the lake parameterization scheme FLake as a basis. To this end, a number of tricky issues should be resolved, e.g., coupling with the deep abyssal ocean (this amounts to setting boundary conditions at the bottom of the seasonal thermocline) and formulation of a convective adjustment algorithm with due regard for the effect of salinity on the buoyancy stratification. Preliminary considerations are made by FLake developers but physically sound solutions are still to be found. It should be emphasized that performance of a one-dimensional upper-ocean parameterization scheme may not be satisfactory in the regions where the oceanic thermohaline structure is strongly affected by horizontal heat and mass exchange processes. An intimate coupling with an advanced ocean data assimilation scheme may be needed to cure the trouble. As an interim solution to treat the diurnal cycle of sea surface temperature, the Zeng and Beljaars (2005) skin/warm layer parameterization has been implemented and verified against buoy data.

A further point to note is an explicit treatment of a snow layer above the sea ice. Analytical formulation (a bulk scheme with a parameterized vertical structure) is presented in Mironov et al. (2012), and the fresh-water formulation for snow over lake ice is a part of the FLake code. However, improved formulations of snow density and snow thermal conductivity are required to activate the snow module.

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Stochastic shallow convection scheme, further steps

The Sakradzija et al. stochastic shallow-convection scheme (see above) can be relatively expensive in terms of computational costs as the individual clouds have to be tracked for each atmospheric-model grid box. A more economic scheme (Machulskaya and Seifert 2019) that carries only two ordinary stochastic differential equations (for the cloud number and for the mass flux at cloud base) has been implemented into ICON and will be thoroughly tested. Finally, an attempt will be made to achieve a unified description of shallow convection and turbulence within the framework of the TKESV scheme. To this end, some stochastic features should be introduced into the TKESV scheme, e.g., into the statistical parameterization of the fractional cloud cover. Last but not least, the rain formation in shallow boundary-layer clouds needs to be revisited, and improved parameterizations should be developed that make full use of the stochastic representation of the cloud ensemble.

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Particle-based microphysics

The effort is aimed at developing a Lagrangian Monte-Carlo benchmark model (termed "McSnow") to improve our understanding of microphysical processes. A particle-based benchmark model is much more computationally expensive than one-moment and two-moment bulk microphysics models (parameterization schemes) but it incorporates more essential physics. In this sense, particle-based models are comparable to spectral bin microphysical models. In particular, it avoids simplifications related to a fixed form of size distribution and to a categorization of hydrometeors (cloud water, rain, cloud ice, snow, graupel). The latter is difficult in classic spectral bin models. McSnow is intended for use purely as a benchmark model to study the physical processes at work and to help improve operational parametrizations. McSnow is implemented into ICON; results from the first tests look reasonable. A detailed evaluation against observational data is planned. Current efforts aim, among other things, at extending the McSnow to include a habit prediction of primary ice single crystals. To derive parameterizations from the very detailed and comprehensive McSnow simulations, the use of machine learning techniques should and will be explored as an alternative to, e.g., look-up tables.

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<u>Miscellaneous</u>

(1) Work is underway at the University of Frankfurt am Main, Germany, to improve parameterizations of non-orographic wave drag. Expected results from the study are of potential utility to ICON.

(2) MeteoSwiss plans to re-implement a parameterization of the effects of topography on the surface radiation fluxes (COSMO lradtopo) into ICON.