BAMS Article

ICON: Toward Vertically Integrated Model Configurations for Numerical Weather Prediction, Climate Predictions, and Projections

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ABSTRACT: A wide range of important societal and economic applications on national and international levels strive for an integrated understanding and forecasting of weather and climate, at high spatial resolution ranging from days to decades. The global to regional model system Icosahedral Nonhydrostatic (ICON) has been applied to weather as well as to climate time scales with joint developments of the model infrastructure. However, ICON's model configurations share the same dynamical core but differ substantially in their physical parameterization and the coupling of Earth system components, depending on whether they were designed for numerical weather prediction (NWP) or climate applications. Starting in 2020, a new modeling initiative has been launched as a joint project between climate modeling institutes and the Deutscher Wetterdienst. The initiative "vertically" integrates NWP, climate predictions, climate projections, and atmospheric composition modeling based on the ICON framework and targets a unified treatment of the respective subgrid-scale parameterizations. This initiative aims at the development of coupled model configurations of ICON to conduct operational weather and ocean forecasts for several days, climate predictions with time scales up to 10 years ahead as well as climate projections, and it provides a model baseline for joint research for NWP and climate. This paper illustrates the strategic direction of this modeling initiative, isolates key challenges, and reports on first results.

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SIGNIFICANCE STATEMENT: For many years, numerical weather prediction and climate modeling were largely separated and only weakly interacting as they operated on vastly different spatiotemporal scales. This picture is changing because the trend of high-performance computing toward massively parallel computing architectures now allows high-resolution simulations for increasingly longer integration times. The global model Icosahedral Nonhydrostatic (ICON) has a common architecture for operational weather prediction and climate applications, but so far, they are configured only for the respective time scales. Here, we describe the way forward to formulate modeling configurations within the single modeling framework of ICON, for integrating a continuum of scales from weather to climate. This opens a new joint development space of basic research areas combining weather forecasts and climate research.

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1. Introduction

Weather and climate are strongly interwoven, since their dynamics are generated by fundamental multiscale processes and their nonlinear interactions. On a physical level, one notes a great similarity between the governing equations underlying the models for numerical weather prediction (NWP) and for climate predictions and projections. The basic difference between weather and climate, according to classical understanding, is that weather prediction poses an initial value problem, while climate projection is a boundary value problem, with near-term climate prediction as an exception (Boer et al. 2016). However, for many years, NWP and climate model developments have been largely separated and only weakly interacting as they operated on vastly different spatiotemporal scales. NWP, aiming for the highest possible spatial resolution, was willing to save integration time by simplifying or neglecting processes with long time scales. In contrast, climate projections were sacrificing spatial resolution for long integration times and increasing model complexity of Earth system components.

This general picture is changing. The "scale gap" between weather prediction and climate projections is narrowing for several reasons, thereby blurring the clear distinction between weather and climate modeling (e.g., Hohenegger et al. 2023). One reason is that the climate modeling community, after having established the fundamental fact of global warming, has started to study its regional implications, and this demands higher spatial resolution. A second reason is the strong—and perhaps inevitable—sensitivity of coarsely resolved climate model solutions to tuning details of subgrid-scale parameterization. This tuning determines fundamental properties of the climate system, such as climate sensitivity, and is not allowed to evolve dynamically but is set by parameter choices.

In the area of high-performance computing (HPC), the ongoing trend toward massively parallel computing architectures will allow high-resolution simulations for increasingly longer integration times. More fundamentally, the HPC trend has led several modeling centers to rethink their modeling strategy, for example, by abandoning classical spectral models (e.g., Tomita et al. 2005; Stevens et al. 2019). The outcome of one of these initiatives is Icosahedral Nonhydrostatic (ICON).

ICON is a modeling framework for weather, climate, and environmental prediction. It builds upon almost two-decade-long collaboration between the Deutscher Wetterdienst (DWD) and the Max Planck Institute (MPI) for Meteorology, with developments for the atmosphere (Bonaventura and Ringler 2005; Wan et al. 2013; Zängl et al. 2015; Giorgetta et al. 2018), the ocean and sea ice (Korn 2017; Korn et al. 2022), and the land surface (Nabel et al. 2020; Reick et al. 2021; Schneck et al. 2022) and provides a common modeling infrastructure (Zängl et al. 2015). In 2024, ICON was released as open source code. However, different development lines result in the establishment of different model configurations, reflecting the specific needs for NWP and climate research (see Fig. 1a and model component specifications therein). The global ICON NWP is the baseline for numerical weather forecasting and became operational in 2015. ICON NWP further provides the baseline for the regional ICON on the European domain (operational since 2016), which is accomplished using a two-way nesting technique (Zängl et al. 2022), and provides the technical basis for a limited-area mode. The latter is used for a convection-permitting configuration of ICON over central Europe (operational since 2021) and regional climate projections (Pham et al. 2021). The development line for global climate research results in coupled atmosphere–ocean Earth system model configurations for low Coupled Model Intercomparison Project (CMIP)-like and kilometer-scale resolutions (Jungclaus et al. 2022; Hohenegger et al. 2023).

The purpose of this paper is to describe the way forward to formulate modeling configurations within the single modeling framework ICON, for integrating a continuum of scales from weather to climate. Of particular interest are (i) how ICON's unique model design facilitates the development of a fully integrated modeling system, (ii) which new opportunities arise for such an integrated system, and (iii) how our approach differs from early initiatives (e.g., Hurrell et al. 2009; Hazeleger et al. 2010; Senior et al. 2011; Brown et al. 2012). The great advantage of ICON is a bidirectional improvement of NWP and climate simulations through a multiscale modeling approach. At an early stage of our integrated system development, we already see exciting prospects, which are illustrated here.

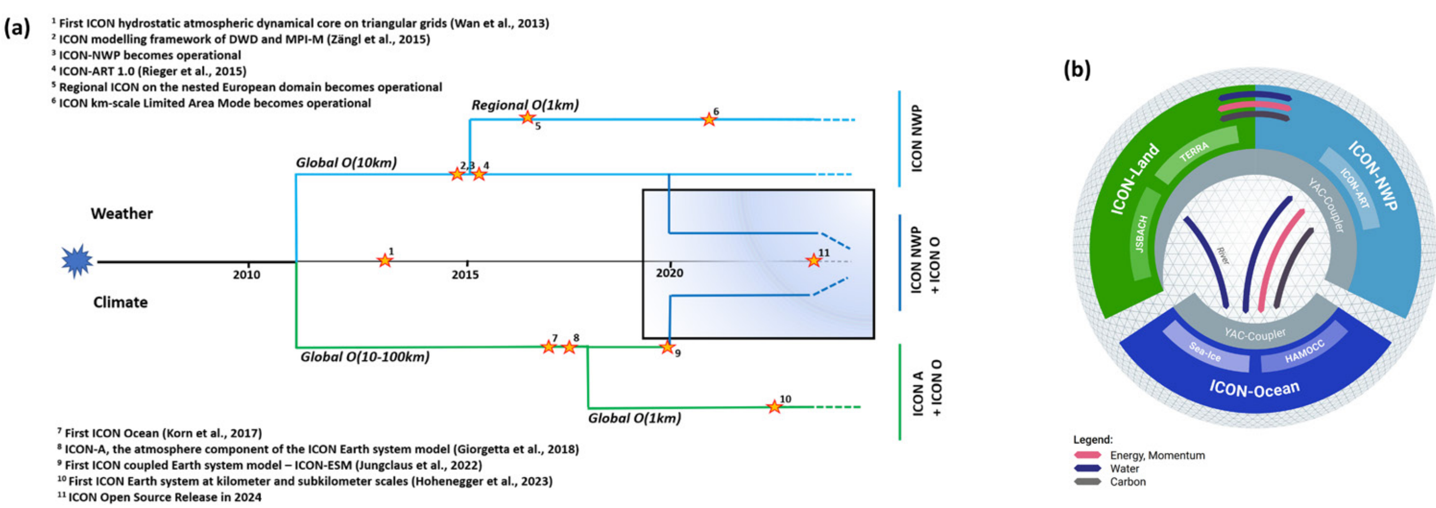

Fig. 1. (a) Schematic illustration of the key development lines of ICON with their typical order resolution and key accomplishments. The weather branch (light blue) consists of the operational atmospheric model component ICON NWP, which includes global and regional configurations. The climate branch (green) refers to the coupled Earth system models up to kilometer scale and consists of the atmospheric and ocean components ICON A and ICON O. An example of this branch is the coupled configuration ICON ESM (Jungclaus et al. 2022). The weather and climate branch (dark blue) is the integrated ICON model presented here, which consists of ICON NWP coupled to ICON O. An example of this branch is the coupled Earth system model configuration ICON XPP. (b) Schematic illustration of the integrated ICON. The model components include ICON NWP for the atmosphere, ICON ocean, ICON ART for the aerosol and tracer transport, and suitable land components (JSBACH, TERRA) embedded in the ICON land framework. Further, an ocean biogeochemistry component [the Hamburg Ocean Carbon Cycle model (HAMOCC); Ilyina et al. 2013] and a sea ice model consisting of a dynamic and a thermodynamic component (Korn et al. 2022) are integrated into ICON O. The components are coupled using the Yet Another Coupler (YAC).

The concept of integrating into a single model system for time scales from days to centuries has prominent predecessors (e.g., Hurrell et al. 2009; Hazeleger et al. 2010; Senior et al. 2011; Brown et al. 2012). Starting in the early 1990s, the Met Office provided the first success story with the unified model (UM) for both weather and climate prediction (Brown et al. 2012). A second example, covering seasonal to climate time scales, is the EC-EARTH system developed by various European partners (Hazeleger et al. 2010). EC-EARTH builds upon the ECMWF Integrated Forecasting System (IFS) coupled to various Earth system components (Döscher et al. 2022). Both initiatives use the ocean model NEMO with integrated sea ice and ocean biogeochemistry. EC-EARTH and UM have demonstrated the advantage of the multiscale and multi-institutional nature of integrated modeling. Among others, there is a considerable overlap in the development structure of both NWP and climate models. Examples are common repositories and a common model development decision process, or applications relevant for both weather and climate time scales. Most important, however, are the shared commonalities to further improve the functionality of an integrated model, such as the continuous incorporation and evaluation of new processes.

In addition, it can be expected that the respective expert knowledge of pursuing numerical weather forecasts and climate modeling will complement each other in a unified system. A systematic improvement of the climate state can result from the high precision of weather processes. Also, weather forecasts may benefit from accurately resolving large-scale processes, and from using a well-tuned coupled mean climate. An example is the high accuracy of the NWP model to predict the synoptic disturbances in the midlatitudes. Eddy–mean flow interaction and resulting momentum transfer on a daily basis are known to impact the midlatitude jets (Hoskins et al. 1983). A high precision of the weather dynamics from NWP could therefore result in a reduction of the error of the midlatitude basic state. At the same time, the basic mean state plays a central role for the small-scale disturbances. The position and strength of the midlatitude jets act as a waveguide for the propagation of synoptic disturbances. Moreover, large-scale motion can have a control on small-scale weather processes, and errors at large scale are able to propagate to the smallest scales of weather forecasts (Anthes et al. 1985; Durran and Weyn 2016). A single-model system covering both the high accuracy of small-scale weather processes by NWP models and an accurate basic mean state thoroughly estimated by climate modeling can help to reduce both the up- and downscaling error propagation.

Our principal goal to integrate scales from weather to climate into a single model system shares similarities with previous efforts mentioned above. However, the way how ICON accomplishes this goal is unique. The different model components are "vertically integrated," meaning that in the design and structure of ICON, all components—atmosphere, ocean, land, and sea ice—use the same horizontal grid type (allowing different grid size though) and use the same variable staggering. All model components rely on common flexible data structures of an object-oriented software concept. This not only provides benefit from commonalities but also permits differences between components. More specifically, the common grid is advantageous in closing budgets and reducing interpolation errors across interfaces of model components. Fundamental differential operators on the icosahedral grid are identically used between model components, and a multitude of algorithms such as tracer transport are shared, while at the same time, differentiations are possible whenever this is considered advantageous, for example, in the time stepping or with regard to vertical coordinates. The common use of fundamental building blocks between atmosphere and ocean components capitalizes on similarities between their hydrodynamical kernels. Our approach integrates these similarities directly into the foundation of the integrated model. As a consequence, the differences between the weather and climate configuration occur conceptually, algorithmically, and codewise within the subgrid-scale parameterizations.

This concept of vertical integration goes beyond previous efforts. The goal "to keep atmosphere components aligned with one another," as stated by UM (Brown et al. 2012), is already ingrained into ICON's model structure. This is the natural consequence of a fundamental model design decision made at the beginning of the ICON initiative. We expect to improve weather prediction as well as climate predictions/projections by jointly working on the spectrum of scales from days to decades, instead of focusing on separated regimes.

The key challenge at the heart of our endeavor is to unify the treatment of the unresolved scales for the whole spectrum of weather up to the climate scale. This constitutes a formidable modeling challenge as well as an eminent development task. Subgrid-scale parameterizations are usually strongly tied to specific resolutions either by their tuning or through implicit assumptions. ICON responds to this challenge by taking advantage of the special conditions of this initiative. First, we target a range of resolutions that allows us to investigate individual parameterizations on a hierarchy of scales. Second, at our disposal are also different parameterizations of the same process, coming from NWP and climate modeling, resting on different assumptions. Both aspects enable us to create a hierarchy of model configurations. This hierarchy is essential for understanding the behavior of parameterizations. Our approach forms a specific instance of a "model hierarchy" that was considered decisive for the understanding of climate models (Held 2005). This theme has emerged very prominently in the first phase of our initiative and will accompany us for many years to come. An important practical prerequisite of this challenge is that all model components work within the same software infrastructure that rests upon ICON's common data structures. This is possible since the ICON consortium is in full control of the source code of all model components.

The primary applications are to perform climate predictions as well as coupled atmosphere–ocean forecasts on the time scales of daily weather. Climate predictions (here spanning the time range from seasons to 10 years ahead) provide reliable forecast skill and thus are valuable climate information for many stakeholders (Marotzke et al. 2016; Smith et al. 2020). Climate forecasts are routinely operated by DWD (Fröhlich et al. 2021) and are integral parts of multimodel initiatives in consultation with the global producing centers of long-range forecast and annual-to-decadal climate predictions (Kushnir et al. 2019). The current DWD climate prediction system is based on the Max Planck Institute Earth System Model (Müller et al. 2018), which will no longer be supported. ICON will be its successor and provides the baseline for the next generation climate prediction system. Furthermore, ICON provides the platform for Germany's contribution to phase 7 of CMIP (CMIP7). The coupled atmosphere–ocean forecasting is furthermore targeted as a member of the global weather forecasting system of DWD.

2. Ways forward to integrated model configurations for weather and climate

a. ICON development lines for weather and climate. The ICON model framework encompasses the basic model equation system on a triangular grid for both "weather" and "climate" (Zängl et al. 2015; Korn 2017). Most noteworthy is the incorporation of the dynamics—physics coupling split into fast physics, to update the state at every time step, and slow physics which may be computed with less frequent time stepping (Zängl et al. 2015; Prill et al. 2024). This allows a computationally efficient integration. For example, land surface processes, turbulent diffusion, and microphysics are related to fast physics, whereas convection, cloud cover, radiation, and orographic and gravity wave drag parameterizations are called less frequently.

However, the physical parameterization packages differ between weather and climate applications. For numerical weather forecasting, the physics packages in ICON NWP stem from the previously operational regional model for the fast physics (Doms and Schättler 2004) and from the Integrated Forecasting System by the ECMWF for the slow physics (Zängl et al. 2015). No coupling to an ocean component has been developed at this stage. For climate, the atmospheric component uses the physics packages that have been inherited from the ECHAM6 model and aims at the comparability of meaningful climate simulation with ICON and its predecessors (see Giorgetta et al. 2018, cf. their Table 2). From this, a climate-based coupled Earth system model (ESM) has been developed (ICON ESM; Jungclaus et al. 2022). This physics package, however, has further been modified with a focus on kilometer-scale integrations (Giorgetta et al. 2022). Table 1 gives a summary of the actual basic differences in the parameterization schemes used for NWP and climate.

In addition to the parameterization schemes, the NWP and climate development lines differ in the coupling of the Earth system components. As an example, different land surface models are currently used for NWP and Earth system modeling. The land surface model TERRA (from the Latin for Earth) is integrated into ICON NWP and optimally balanced with its physics (Schulz et al. 2016; Schulz and Vogel 2020). As an example, TERRA uses an explicit coupling to ICON NWP and applies its own transfer scheme at the interface to the atmosphere. By contrast, the JSBACH land surface model considers additional processes relevant for climate time scales, such as biogeochemistry, a full carbon cycle, dynamic vegetation, and land-cover changes for land-use and forest management, and is tailored to the ECHAM physics (Reick et al. 2013, 2021).

Table 1. Comparison of physical parameterizations for the global atmospheric model, their coupling with Earth system components, and data assimilation methods used in climate (ICON A), weather (ICON NWP), and the integrated weather and climate configurations (ICON NWP/XPP). The parameterizations refer to a resolution on the order of *O*(1) km for ICON A, *O*(1–10) km for ICON NWP for operational weather predictions, and *O*(10–100) km for ICON NWP/XPP as used for the weather and climate prototypes. Entries for parameterizations are taken from Giorgetta et al. (2022) and Prill et al. (2024). The asterisk (*) indicates the physical parameterization for ICON A used for a resolution on the order of *O*(10–100) km is no longer supported (see Giorgetta et al. 2018). The double asterisk (**) indicates the vertical diffusion is chosen with respect to the land model and still treated differently in the integrated configurations, TERRA for weather and JSBACH for climate applications. The triple asterisk (***) indicates not yet implemented.

	Climate [ICON A, *O*(1) km]	Weather [ICON NWP, *O*(1–10) km]	Weather and climate [ICON NWP/XPP, *O*(10–100) km]
Key physical processes*			
Radiation	RTE + RRTMGP (Pincus et al. 2003)	ecRad (Hogan and Bozzo 2018)	
Cloud cover	Either 0% or 100%, depending on cloud condensate mass fraction	Diagnostic probability density function coupled with convective detrainment and turbulence (Prill et al. 2024)	
Cumulus convection	—	Mass flux schemes with shallow and deep convection (Tiedtke 1989; Bechtold et al. 2008)	
Cloud microphysics	Single-moment scheme (Seifert 2008)	Single-moment scheme (Seifert 2008)	
Subgrid-scale orographic drag	—	Lott and Miller scheme (Lott and Miller 1997)	
Subgrid-scale nonorographic wave drag	—	Wave dissipation at critical level (Orr et al. 2010)	
Vertical diffusion	Total turbulent energy (TTE) scheme (Mauritsen et al. 2007) or Smagorinsky scheme	Prognostic turbulent kinetic energy (TKE) scheme (Raschendorfer 2001)	TKE/TTE**
Earth system coupling			
Land surface model	JSBACH (Reick et al. 2021)	TERRA (Schulz et al. 2016)	TERRA/JSBACH** (Reick et al. 2021)
Ocean model	ICON O (Korn et al. 2022)	—	ICON O (Korn et al. 2022)
Atmospheric composition	—	ICON ART (Rieger et al. 2015)	ICON ART***
Data assimilation			
Atmosphere	—	LETKF combined with EnVar	
Ocean/sea ice	—	—	EnKF/nudging

Furthermore, the coupling of the ocean component and the treatment of the atmospheric composition vary with respect to the development lines. The ocean component of ICON so far is developed and applied for climate modeling only and applications therein. It solves the hydrostatic Boussinesq equations of large-scale dynamics with a free surface (Korn 2017; Korn et al. 2022). The ocean component is able to perform simulations on uniform as well as on nonuniform grids, where the most interesting nonuniform configurations being the "telescoping configurations" allow zooming locally into ocean dynamics (Korn et al. 2022). Such a grid configuration is applied with higher resolutions toward the coast, for example, to improve the representation of tides (Logemann et al. 2021) or of coastal carbon dynamics (Mathis et al. 2022). The telescoping configuration offers an opportunity to simulate regional aspects of the coupled climate system in a global context, at the same time keeping the computational efforts to a feasible range.

For the atmospheric composition, an ICON-based weather and climate model configuration with aerosols and reactive trace gas components is developed (ICON ART; Rieger et al. 2015). It is implemented within ICON NWP, and weather predictions are complemented by the forecast of concentrations of selected aerosols and, as needed, of gaseous components. By using an online coupling, parameters for additional processes that are of meteorological relevance can be used, such as interactions of atmospheric composition with radiation and cloud microphysics. Special processes like emission, sedimentation, and wet and dry deposition at the surface or transformation processes like chemical conversion are provided by the ART modules. ICON ART is operational at DWD for pollen forecast (since 2021) and mineral dust forecasting (since 2024). For climate time scales, only prescribed aerosol optical properties from natural and anthropogenic sources are used, similar to those applied for CMIP.

Since our aim is to integrate operational forecast and modeling at the various time scales, the accomplishments in data assimilation have to be included. Data assimilation methods are in principle generic on the weather and climate time scales, but there are significant differences in the current configurations. Weather data assimilation is performed in real time with a large set of observations, and observation processing, such as bias correction and quality control, carried out minutes to hours after observations is made. The data assimilation in ICON employs a combination of an ensemble–variational (EnVar) data assimilation scheme (Buehner et al. 2005) with a localized ensemble transform Kalman Filter (LETKF; Hunt et al. 2007). The EnVar provides the analysis of the high-resolution global system and its nest. The ensemble analysis is carried out by the LETKF. The LETKF ensemble mean is relaxed toward the high-resolution variational analysis, which improves ensemble forecast scores of the global ICON ensemble predictions system. For climate predictions, the data assimilation methods use longer time-scale observations such as monthly means. The initial conditions are achieved by an ensemble Kalman filter (EnKF) for ocean observations, typically profiles of salinity and temperature, and nudging methods for atmospheric dynamical fields and temperature. These methods are successfully applied with the precursor of ICON (Baehr et al. 2015; Brune et al. 2018), but early attempts also indicate their use for ICON, such as the implementation of EnKF in the ocean component (Pohlmann et al. 2023).

b. Toward integrated ICON configurations for "weather and climate". We set up a new combination in ICON consisting of ICON NWP, the ICON ocean component, ICON ART, and a suitable land component embedded in the ICON land surface framework appropriate for NWP and long-term climate applications (Fig. 1b). This combination bundles a number of parameterizations available in NWP and climate modeling (Table 1). Further, this set up merges the coupling of existing Earth system components and data assimilation methods.

Most notably is the coupling of the ocean component to ICON NWP, which offers a wide-range of operational ocean forecast products on a daily basis.

A way forward to an integrated configuration is the unifying of the land model component. As previously indicated, both land components are adapted to their turbulence parameterization and diffusion schemes in their respective global model configurations to conduct meaningful simulations for weather and climate, respectively. Furthermore, TERRA is optimized to reproduce the diurnal cycle of 2-m temperature and humidity, as it is coupled to the data assimilation scheme and makes use of satellite data to estimate the climatology of several land surface quantities (Zängl 2023). The choice of the land surface scheme has a significant effect on the boundary layer physics and dynamics and impacts the forecast skill of daily surface quantities. In an intermediate step, JSBACH and its climate functionalities are integrated into ICON NWP toward an integrated model configuration for climate time scales. This implementation is done by coupling JSBACH with its parameterization of the vertical diffusion as an implicit unit into the ICON NWP (Schulz et al. 2001). For weather forecasts, the full functionality of TERRA is still used. This decision is made to enable a direct comparability of the coupled configuration with the current operational system. However, the principal aim is the integration of all the relevant land modules and processes (such as from TERRA, JSBACH, or others) into one framework for the modeling of land surface processes (Schulz et al. 1998; Nabel et al. 2020; Schneck et al. 2022) and specific process implementations such as a new model for coupled carbon and nitrogen in the terrestrial biosphere (Thum et al. 2019). This integration is ongoing.

ICON NWP successfully improved the quality of weather forecasting compared to previous NWP model generations and achieves high skill among medium-range forecast models (Magnusson et al. 2022). However, to make ICON NWP also applicable for climate time scales, a few developments are required. As an example, ICON NWP is driven by weather-scale relevant boundary forcing agents and initialization. For a time scale of a few days, only temporally constant external forcing is typically considered. For simulations of several months and years ahead, the effects of long-term time-varying aerosol, ozone, and greenhouse gas concentrations become relevant. An adjustment that meets the criteria for NWP and climate is ongoing.

Finally, the data assimilation methods are integrated for NWP and climate prediction. We employ the two methods described above into the data assimilation coding environment (DACE[1]) for all ICON components. The coding environment considers the atmosphere and ocean state at each analysis time step. Figure 2 illustrates the data assimilation concept.

[1] https://www.cosmo-model.org/content/support/software/dace.pdf.

In summary, the integrated design of the presented ICON model configuration combines the separate development lines and data assimilation methods of NWP and climate, into one joint modeling concept. We profit from the inherent design for all available Earth system components, such as grid structure and discrete operators. Further, a common code development already exists on many levels, such as the supervision of any code changes by gate keepers, or a regular release of the ICON open source code. This initiative bundles capacities to merge available Earth system components and data assimilation methods to an Earth system model at one place, for NWP and climate applications. An outcome of this is that the number of physical parameterizations converges by using the same atmospheric model for weather and climate, though the integrated configurations are not fully unified, such as the treatment of the land processes which has implications for parameterizations of the vertical diffusion.

3. Integrated prototypes for weather and climate

To-date, two complementary initiatives develop the integrated model configurations for weather and climate time scales, respectively. First, a coupled atmosphere–ocean forecasting prototype configuration is under development to conduct operational weather and ocean forecasts for several days ahead. Here, ICON builds upon the coupled model with TERRA underlying the ICON NWP component. This prototype carries out variational and ensemble data assimilation for the atmosphere, land, and ocean on an hourly and daily time scale and calculates coupled global forecasts for the atmosphere and the ocean. It is to become a part of the operational global ensemble forecasting system of DWD, integrating atmospheric, environmental, and ocean components.

Second, a joint effort prepares ICON as the baseline for climate predictions at DWD, for climate projections for CMIP7, and for climate research [for this configuration, we choose the name ICON extended predictions and projections (XPP)]. Here, ICON builds upon the coupled model with JSBACH underlying ICON NWP. This prototype is being tuned toward the climatological benchmarks (e.g., top-of-atmosphere radiation balance, global mean temperature, sea ice, and mean ocean circulation). Data assimilation to produce climate forecast with ICON XPP is ongoing.

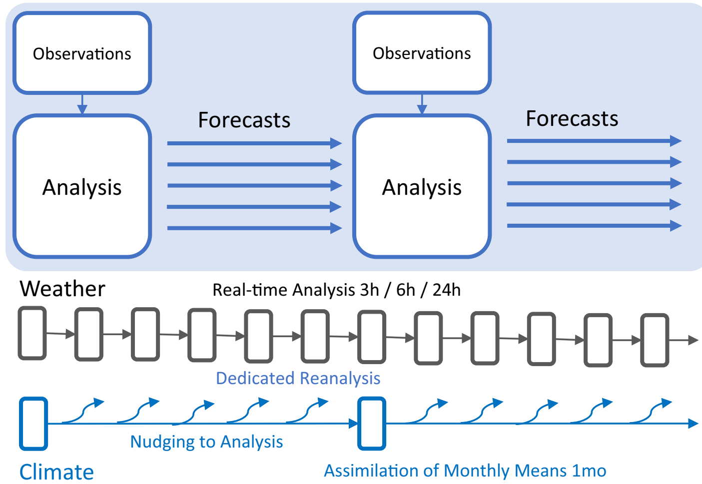

Fig. 2. Concept of data assimilation in ICON. For NWP, an En-Var plus LETKF analysis system based on DACE is being applied 3-hourly in the coupled atmosphere–ocean model. (top) The basic concept of data assimilation: at each analysis time step, the atmospheric and ocean states are adjusted to observations. The differences between (middle) weather and (bottom) climate time scales. For weather times scales, a global ensemble analysis is calculated every 3 h, with snow, SST, and soil moisture assimilated at 3-, 6-, or 24-h windows. At climate time scales, nudging to reanalysis is employed for the atmospheric components and the assimilation of monthly means for the ocean components once per month (1 month). Climate data assimilation is used to spin up ocean components over longer periods of time, before weather time-scale analysis can be used successfully. The atmosphere–ocean is weakly coupled, both in NWP and climate predictions.

ICON XPP is currently being tested with varying resolution (160–80-km atmosphere, 40–20-km ocean), indicating the full functionality of the model configuration for climate applications. A benchmark of any climate model is the execution and analysis of Diagnostic, Evaluation and Characterization of Klima (DECK) experiments (Eyring et al. 2016). Preindustrial climate experiments are well tuned with respect to the global mean top-of-atmosphere radiation balance (TOA_rad = 0–0.5 W m^{-2}), global mean temperature at 2-m height (GMT = ~13.8°–14°C), and stable Atlantic meridional overturning circulation [AMOC = ~15 Sv (1 Sv ≡ 10^6 m^3 s^{-1})]. Figure 3 shows examples of the preindustrial control experiment of ICON XPP and its precursor for 2-m temperature and zonal-mean zonal wind. This figure illustrates bias patterns typically found in CMIP-like climate models. Examples are the large positive temperature biases in the upwelling region or the underestimated temperature in Arctic regions. A considerably large positive temperature bias appears in ICON XPP over the Southern Ocean. A large negative bias occurs over the continental Arctic.

Remarkable is the substantial reduction of the zonal-mean zonal wind bias in both hemisphere subtropical jet regions, from 10 m s^{-1} in ICON ESM to 5 m s^{-1} in ICON XPP. Both configurations use the same ocean component, but differ in the use of the atmospheric components and their physical parameterizations. Further diagnostics point to the specific role of synoptic-scale eddies, which momentum transfers are able to modulate the jet

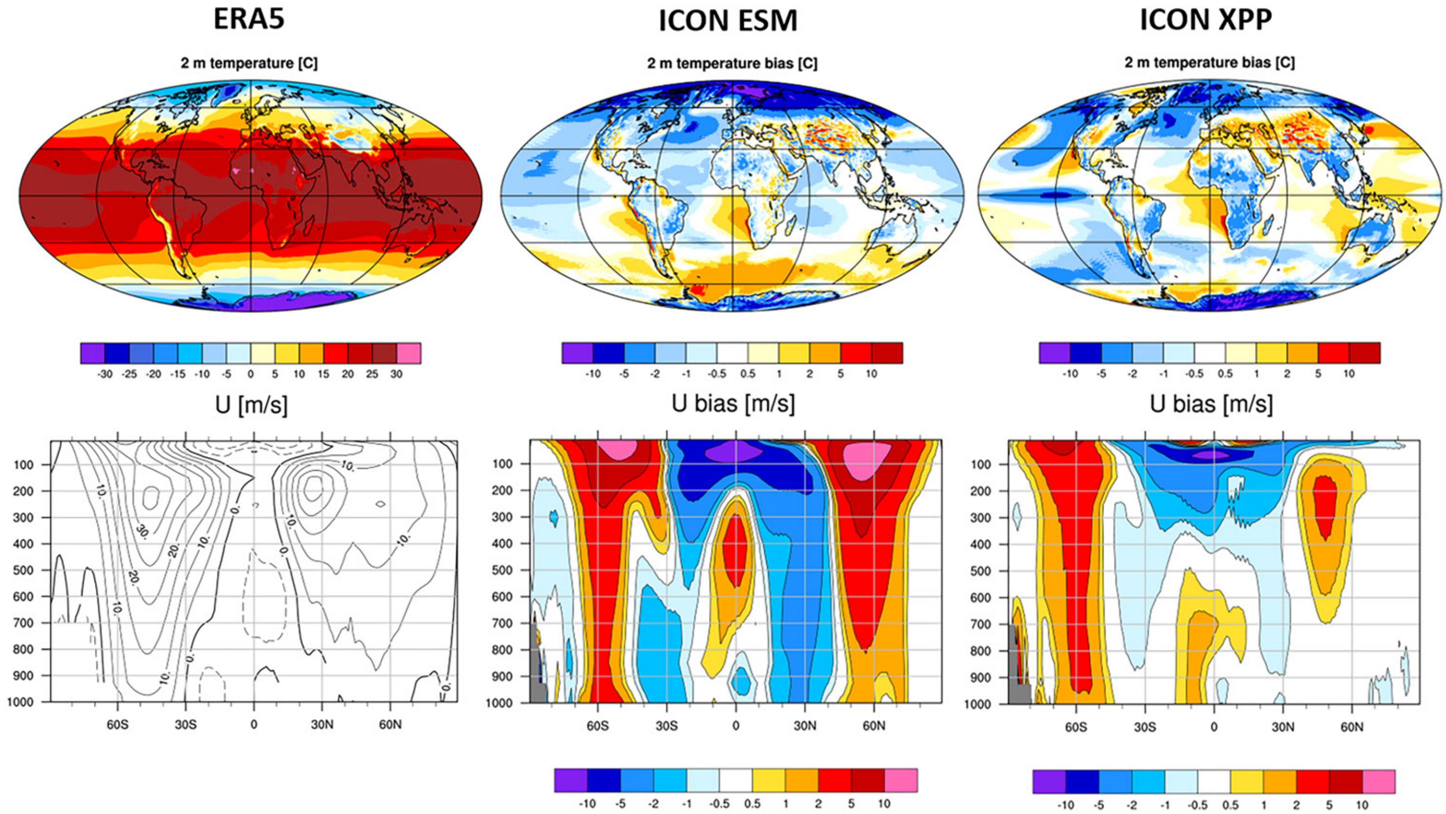

Fig. 3. Preindustrial control experiments. (top) The 2-m temperature for (left) ERA5 and (middle) temperature bias relative to ERA5 for ICON ESM in 160 km (40 km)$^{-1}$ resolution, and (right) the climate configuration ICON XPP in 160 km (40 km)$^{-1}$ resolution. The experiments are run in a preindustrial climate. Shown is the mean climate for a 30-yr time slice. ICON ESM refers to a climate-only configuration of ICON according to Fig. 1a (°C). (bottom) As in (top), but for zonal-mean zonal wind bias in the troposphere (m s^{-1}).

streams in the midlatitudes (Fig. 4, Hoskins et al. 1983). Clearly, the southwest to north-east shape over the North Atlantic and the magnitudes of the eddy-mediated effects onto the mean flow over the Atlantic and Pacific in ICON XPP are closer to ERA5 than they are in ICON-ESM. The shape of the momentum transfer results in north-eastward elongation of the mean jet in ICON XPP, whereas in ICON ESM, the jet becomes a zonal distribution. This has consequences for the storm tracks, which are known to have a biased southern pathway in the precursors of ICON XPP. We assume this improvement is related to the higher accuracy of the resolved synoptic disturbances in ICON NWP compared to those established in ICON ESM.

In addition to the preindustrial control experiments, climate sensitivity experiments are pursued. The magnitude of the equilibrium climate sensitivity (ECS) is 2.5 K and is comparable with the CMIP6 ensemble, for which a 90% chance is found that the ECS is in the range of 2 and 5 K (e.g., Sherwood et al. 2020). The transient climate response (TCR) of ICON XPP is TCR = 1.7 K, which is also in the range of CMIP6-like climate models (TCR = 1.3–3 K, e.g., Meehl et al. 2020). A full evaluation of the DECK experiments is planned and will be published in a global model development documentation.

Another example illustrates the prospects of combining the NWP with climate modeling and research. Figure 5 shows the model error of total precipitation across time scales with respect to the ERA5 reanalysis (Hersbach et al. 2020), for a 1-day forecast error of the NWP prototype (Fig. 5b) and the 30-yr mean bias of total precipitation of ICON XPP in a preindustrial control experiment (Fig. 5c). Both error distributions show similarities of precipitation such as the dry bias over the Amazonian region, or in the western tropical Pacific and north of the equator, linking 1-day forecast errors with the long-term climate mean. Such behavior is

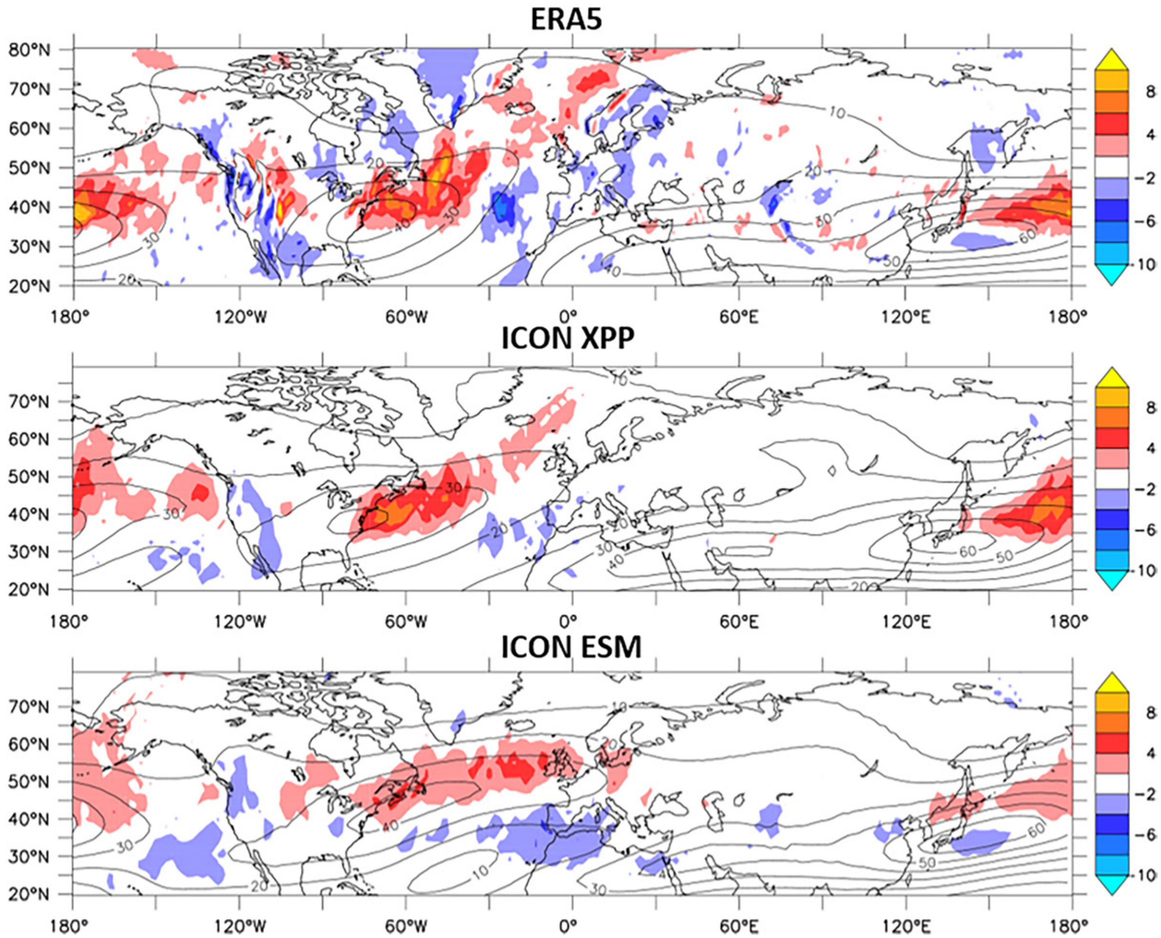

Fig. 4. **The eddy-mediated effect on to the mean flow shown by the divergence of the E vector (shading) and the mean zonal wind (contours). Shown are results for winter (DJF) for (top) ERA5 (period 1990–2000) and 10-yr averages for (middle) ICON XPP and (bottom) ICON ESM. Positive values of the divergence indicate momentum transfer to the mean flow. The E vector is calculated by $\nabla(u^2 + \upsilon^2, -u\upsilon)$, where u and υ are the 2–6-day bandpass-filtered zonal and meridional wind anomalies (Hoskins et al. 1983). The E vector and mean zonal wind are averaged over 200–300 hPa, where the maximum zonal wind of the jets appears.**

found in other models, such as the unified model of Met Office (cf Fig. 2 in Brown et al. 2012), supporting the role of fast and local physical processes for error upscaling in the modeling of long-term mean climate. Other regions such as along the south of the equator in the eastern Pacific exhibit a strong precipitation bias found in the climate prototype only.

4. Institutional framing and perspectives

a. Framing. The merging of an interinstitutional model development at various weather and climate time scales inevitably requires an enhanced degree of organization and communication at various levels. The maintenance of the software development (e.g., code standards, reproducibility) with other branches of ICON development is a major challenge. Here, we have decided that the code development for NWP and climate applications is carried out in a common repository monitored by DWD. This ensures that new model features, bug fixes, etc., are stored and approved at one place.

Further, the development of integrated model configurations of ICON has far-reaching implications for a number of consortia. As an example, new functionalities through ICON for climate time scales (e.g., CO_2 cycle, coupled regionalization) allows a more complex view on the regional climate and its change. The use of the model system seamlessly in space and time results in synergies in the software development in the periphery of the model system and in the evaluation for a wide range of applications and focus regions. It can therefore be assumed that the regional and global communities will work much more closely together in the future.

b. Perspectives. The integrated global model configurations described here have resolutions on the order of $O(10–100)$ km. In the hierarchy of models, this typically fits with the type of general circulation models (GCMs), and mass-flux schemes are used to parameterize unresolved convection processes. Here, methods have been developed which assess the multiscale cloud-process spectrum, such as superparameterization, in which cloud system–resolving models replace cloud parameterizations (Randall et al. 2003), or asymptotic matching between cloud-resolving models and climate models (Miura et al. 2023). High-order resolutions $O(1)$ km require considerations of more ambitious turbulence schemes and cloud microphysics. ICON responds on this by available three-dimensional turbulence diffusion schemes (Smagorinsky scheme) that enable vertical and horizontal exchange processes and a cloud microphysics that contains additional processes, such as an additional prognostic variable for graupel. A natural way forward is to extend the integrated model to atmospheric convection-permitting and ocean mesoscale to submesoscale eddy-resolving resolutions. Single-model kilometer-scale climate setups meanwhile are available with ICON and run multidecades to analyze the mean coupled climate.

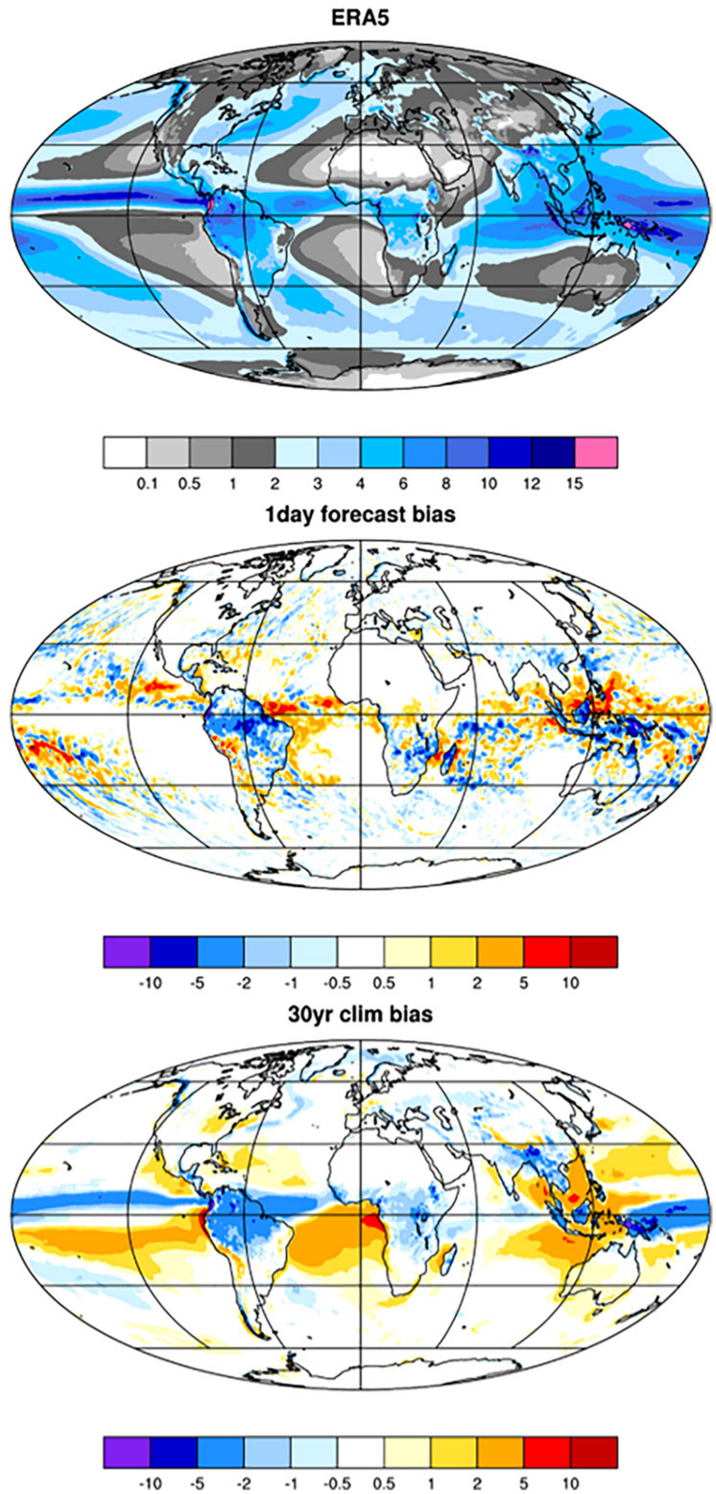

Fig. 5. Small-scale NWP processes affecting long-term mean climate. Total precipitation of (top) ERA5 and bias relative to ERA5 in ICON for a (middle) 1-day forecast and (bottom) 30-yr climatological mean. Error of 1-day forecast of ICON started from ICON analysis 1–31 Jan. Shown is the average of 1-day forecasts with respect to ERA5. Here, ICON is run with TERRA as the underlying land model with 160 km (40 km)$^{-1}$ atmosphere/ocean resolution and 90/72 vertical levels. Climatological mean of the total precipitation is calculated for a preindustrial control setting of the climate configuration ICON XPP. Here, ICON is run with JSBACH as the underlying land model and 160 km (40 km)$^{-1}$ atmosphere/ocean resolution and 90/72 vertical levels (mm day^{-1}).

The ultimate goal is to develop one integrated model configuration for time scales ranging from days to several decades. Of course, one single-model configuration and initialization for all time scales is overambitious, given the nature and technical prerequisites underlying the weather and climate forecasting. However, making the physical states in the NWP more congruent to climate and vice versa is a realistic objective and offers prospects for predictions. As an example, finding a single tuning of ICON XPP competitive to the current state of numerical weather forecast makes it particular appealing for short-term climate predictions. Another is the coupling of NWP with Earth system components such as the ocean, which allows new scientific research questions such as how far a coupled configuration can influence or eventually extend the range of weather forecasts. This allows to address the transition of weather to climate predictability, for which long-lasting predictability regimes have manifested, such as for the North Atlantic Oscillation and others. In summary, the integrated modeling approach opens a new joint development space of basic research areas combining weather forecasts and climate research.

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