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*The COSMO Priority Project CAIIR:
Clouds and Aerosols Improvements
in ICON Radiation Scheme
Final Report*

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*The COSMO Priority Project CAIIR:
Clouds and Aerosols Improvements
in ICON Radiation Scheme
Final Report*

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1 Introduction

The integration of the latest version of the Rapid Radiative Transfer Model (RRTM)- ecRAD, a radiation scheme developed for the ECMWF Integrated Forecasting System (IFS) (Hogan and Bozzo, 2018), into ICON, laid the groundwork for further development and testing. This project proposes substantial advancements in the representation of cloud optics, aerosol-radiation interactions, and aerosol-cloud processes within ICON, specifically targeting their activation within ecRAD. Much of this development was carried out during the priority project T²(RC)² and was already implemented in the COSMO model. While certain extensions have been adapted for the current RRTM implementation in ICON, ecRAD has yet to receive similar enhancements. Additionally, new sources of relevant aerosol data remained inaccessible in ICON until now. Radiative transfer models constitute a fundamental component of numerical weather prediction (NWP) systems, as they play a critical role in determining atmospheric heating and cooling rates across all vertical levels. These radiative effects can significantly influence atmospheric dynamics and, consequently, the overall performance and accuracy of the model. However, the development of radiative transfer schemes remains a complex task due to the involvement of numerous atmospheric constituents—including gases, hydrometeors, and aerosol species—each of which interacts with radiation in distinct ways. For accurate representation, the optical properties of these constituents must be parameterized within each spectral interval considered by the model. These parameterizations are typically expressed as functions of bulk microphysical properties, most notably the effective radius, averaged over the spatial scale of a model grid box.

During the period 2015-2019, comprehensive revisions to the radiation scheme of the COSMO model were implemented within the framework of the Priority Project (PP) Testing and Tuning of the Revised Cloud-Radiation Coupling T²(RC)². The modifications encompassed the incorporation of updated optical property parameterizations for water droplets (Hu & Stamnes, 1993) and ice particles (Fu, 1996, 1998). These revised parameterizations published in Muskatel et al. (2021) significantly extended the applicable size range of hydrometeors, encompassing particles up to the dimensions of rain and snow. Additional improvements included the integration of the MACv2 aerosol climatology (Kinne, 2013), prognostic ICON-ART dust fields, and prognostic CAMS aerosol data for direct aerosol-radiation interactions. These aerosol datasets were further utilized to parameterize water and ice nucleation processes, thereby incorporating indirect aerosol effects on radiative transfer. The project additionally introduced an enhanced parameterization for water droplet effective radius and a refined formulation for representing the radiative impact of sub-grid scale (SGS) cloud processes. Comprehensive validation of the revised code and its constituent features was conducted through systematic comparison with ground-based and satellite observations acquired across diverse meteorological conditions in Israel, Germany, and Russia. These evaluations demonstrated measurable improvements in simulated net radiation fluxes and near-surface temperature fields.

The first goal of our project was to address cloud optical properties. As previously noted, novel ice optical property parameterizations based on Muskatel et al. (2021) have been successfully implemented and validated within the COSMO framework. The ecRAD scheme employs ice optics derived from the same foundational work by Fu (1996) albeit utilizing a distinct spectral averaging methodology (Hogan and Bozzo, 2018). However, the forthcoming development strategy for ecRAD involves transitioning to a look-up table (LUT) methodology as proposed by Robin Hogan (ECMWF), necessitating a systematic conversion from analytical formulations to tabulated values in high spectral and size resolutions. This transition is needed for the adaptation to both the new general-cloud-optics and the new gas optics (ecCKD) frameworks recently introduced in ecRAD.

With respect to liquid water droplet optical properties, ecRAD currently utilizes the SOCRATES package (Hogan and Bozzo, 2018 and references therein), and also Mie calculation dataset in a LUT format. The later is by definition a more accurate than the new parametrization based on Hu and Stamnes (1993) introduced in Muskatel et al. (2021), since it does not average over wide spectral intervals. For that reason, no further development was needed in respect to liquid water cloud optics in this project.

The second objective was to implement novel aerosol parameterizations for radiative transfer calculations suitable for operational deployment within the ICON modeling framework. The current operational configuration of ICON utilizes the Tegen (1997) 2D aerosol climatology, which provides monthly-averaged aerosol optical depth values. These climatological data are employed to prescribe vertical profiles of aerosol number concentration that remain invariant with respect to model dynamics. It is well-established that aerosols constitute a fundamental component in both radiative transfer processes and cloud microphysical development. While the direct radiative effects of aerosols are most conspicuous during extreme events such as mineral dust outbreaks and volcanic ash emissions, the substantial day-to-day variability in aerosol concentrations under ambient conditions introduces significant uncertainties when climatological means are applied. In response to these limitations, three advanced aerosol data sources have been integrated into ICON. The first comprises the Copernicus Atmosphere Monitoring Service (CAMS) prognostic aerosol products (Morcrette et al., 2009), which provide global forecasts extending to five days lead time in a 3-hours temporal resolution. These data encompass three-dimensional mixing ratios for five aerosol species, further subdivided into eleven distinct tracers: 3 size bins of mineral dust, 3 size bins of sea salt, sulphate, hydrophobic and hydrophilic tracers of both black carbon and organic matter. The optical properties of CAMS aerosol species are already incorporated within the ecRAD radiative transfer scheme and are relative-humidity dependent. The second data source consists of the CAMS climatology (Bozzo et al., 2017). It is based on the reanalysis (2003-2014) of CAMS model for the mentioned aerosol species. In this case, the vertical profiles are a result of actual dynamics resulting a monthly climatology of aerosols profiles (Bozzo et al., 2020). The dataset contains monthly averages of layer integrated mass from which the 3D mixing ratios are calculated and used as an input to ecRAD scheme. The third is the computationally efficient two-dimensional prognostic scheme for mineral dust which has been originally developed by Günther Zängl (DWD), utilizing the Tegen (1997) climatology for initialization. Within the scope of this project, we evaluated this methodology and extend its applicability to additional aerosol species and alternative initialization datasets. Furthermore, these aerosol inputs may serve as cloud condensation nuclei for both frozen and liquid hydrometeors.

The applied microphysical scheme significantly influences the radiation scheme. First, it determines the development and lifetime of a cloud. Second, it determines the cloud's optical properties via the liquid water content and the effective radius. Spectral Bin Microphysics (SBM) is a state-of-the-art microphysical scheme. It is included in several models worldwide, such as WRF, SAM, HUCM, JMA-NHM, and the Goddard Cumulus Ensemble model. Due to the significant computational resources required to run the scheme, it is usually applied for research purposes and the analysis of test cases. The implementation of SBM will provide similar possibilities in ICON, allowing us to identify the pros and cons of the existing microphysical schemes with special regard to their impact on the simulation of radiation transport.

The final component of our project encompasses comprehensive testing and validation procedures. Preliminary investigations (Poliukhov et al., 2018) revealed that the Tegen aerosol climatology (1997) systematically overestimates aerosol loading, while sensitivity analyses have demonstrated pronounced aerosol-induced effects on near-surface temperature fields

(Chubarova et al., 2018). In this study, we conducted validation of ICON model surface radiation fluxes utilizing both CAMS climatological and prognostic CAMS aerosol inputs, with the Tegen aerosol dataset serving as the reference baseline. This validation protocol was systematically applied to each newly developed scheme within this project. Model performance was evaluated against ground-based measurements.

2 Tasks and achievements

The project plan was originally constructed of 12 tasks:

- Implementation of new ice optical properties based on Muskatel et al. 2021 in ecRAD (Task 1)
- Introduction of new liquid clouds optics based on Hu & Stamnes (1993) in ecRAD (Task 2)
- Coupling of CAMS forecasted aerosols with cloud droplets and ice nucleation schemes (Task 3)
- Implementation of CAMS prognostic aerosols 3D fields as input for ICON radiation scheme (Task 4)
- Implementation of CAMS climatology aerosols as input for ICON radiation scheme (Task 5)
- Improvements/testing of the 2D aerosols advection scheme in ICON (Task 6)
- Implementation of Kinne (2013) aerosols climatology fields as input for ICON radiation scheme (Task 7)
- Testing the radiation code using different aerosol inputs against experimental datasets for clear/cloudy sky conditions (Task 8).
- Analysis/Revision of shallow convection scheme/SGS cloudiness in ICON radiation scheme (Task 9)
- Systematic tuning (CALMO methodology) of the different ICON-RRTM versions for finding the best operative setup (Task 10)
- Implementation of Spectral Bin Microphysics in ICON

The project lasted 4.5 years from March 2020 to September 2024. With the total amount of 10.97 FTEs in human resources.

Main achievements

- New optical properties for ice particles. The extinction coefficient, single scattering albedo and asymmetry factors were parametrized following Muskatel et al. (2021). This allows the extension of the effective size range allowing the inclusion of snow, graupel and rain. The optical properties were calculated in high size and spectral resolution into a LUT format aligned with the latest ecRAD framework. The new data set is now an official part of ecRAD and ICON.

- Implementation of CAMS climatology and forecasted aerosols as an input for ICON ecRAD radiation scheme. The details were published in ICON report issue 011.
- New ice heterogeneous nucleation scheme by DeMott (2015) was introduced in ICON. The new scheme uses either Tegen (1997), CAMS climatology or CAMS forecasted dust concentrations as an input to parametrize the ice nucleating particles (INP) number concentrations.
- The 2D AOD advection scheme was updated with new mineral dust optical depth source function parametrization after Kok et al. (2014). A new Sea-Salt optical depth source function after Grythe et al. (2014) and a new parametrization for anthropogenic emissions (sulfate, black carbon, organic carbon) using the Emission Database for Global Atmospheric Research (EDGAR) and the GFAS (Kaiser et al. 2012) for wildfires emissions.
- Implementation of the warm-phase Spectral-Bin-Microphysics (SBM) in ICON
- Extensive verification campaigns against ground-based and satellite data for all of the mentioned developments.

Tasks initially planned but subsequently removed or partially completed

- Introduction of new liquid clouds optics based on Hu & Stamnes (1993). This data set was not implemented since a more accurate Mie-calculation data set is already available in ecRAD (Task 2)
- Implementation of Kinne (2013) aerosols climatology as an input for radiation.

This task was performed by Trang Van Pham, DWD (Task 7).

- A new parametrization of effective radius of shallow cumulus clouds using an adiabatic parcel model. Will be done in the proceeding project Aerosol-Cloud Interactions in ICON Model (ACLIIM) (Task 9).
- Substantial effort was devoted to improving precipitation forecasts at 2.5 km resolution using the ICON model with the one-moment microphysics scheme, focusing in particular on the Mediterranean region. The main objective was to increase the frequency of weak and moderate precipitation while reducing the overestimation of very intense precipitation events. The work followed two complementary directions: (1) optimizing the balance between the shallow convection parameterization and the grid-scale microphysics, and (2) tuning the one-moment microphysics scheme together with the saturation adjustment. Within the first direction, we evaluated the stochastic shallow convection scheme over the Eastern Mediterranean. This analysis was carried out in close and productive collaboration with M. Ahlgrim. The results showed that, although the stochastic scheme produced a more realistic cloud field structure than the standard Tiedtke–Bechtold shallow convection scheme in ICON, its overall impact on precipitation biases over the Eastern Mediterranean was limited. In contrast, tuning the one-moment microphysics and the saturation adjustment led to a substantial reduction in precipitation biases. During 2024, G. Zängl and A. Seifert introduced new tuning parameters controlling the dependence of the saturation adjustment on updraft velocity and the dependence of the raindrop size distribution on rainwater content. As part of the project, we significantly reduced the intercept parameter of the raindrop

size distribution, resulting in an increase in weak and moderate precipitation. At the same time, we increased the supersaturation remainder in the saturation adjustment under conditions of strong updrafts, which substantially reduced the overestimation of precipitation during intense convective events. These results have not yet been published, but they were presented at the COSMO General Meetings and the ICCARUS conferences (Task 9).

- Systematic tuning (CALMO methodology) of the different ICON-RRTM versions for finding the best operative setup. The task was removed due to lack of computational and human resources (Task 10).

3 Implementation of new ice optical properties based on Muskatel et al. 2021 in ecRAD

(H. Muskatel, A. de Lozar, D. Rieger, M. Köhler)

3.1 Introduction

Radiation transfer through clouds is a key factor in Earth's energy cycle and greatly affects atmospheric dynamics. Numerical weather prediction models must forecast cloud amount, thickness (liquid water content - LWC, ice water content - IWC), hydrometeor concentration, and effective particle size to calculate the amount of radiation transferred, absorbed, and scattered by clouds. With these parameters correctly described, the radiation module can calculate cloud-radiation interactions using three optical properties: the extinction coefficient, the single scattering albedo, and the asymmetry factor (β_{ext}, ϖ, g). These properties must be defined for each hydrometeor type separately (ice, liquid, and aerosols), as well as for each wavelength interval and particle effective size.

In the T²(RC)² project, we introduced a practical parameterization of both liquid droplet and ice particle optical properties based on the single-wavelength data of Fu (1996, 1998) and Hu and Stamnes (1993). The new ice particle optical properties were introduced in both COSMO and ICON radiation schemes. The calculation was based on Fu's single-particle data, but instead of using the in-situ PSDs employed by Fu, we generated 7,500 PSDs based on the generalized gamma distribution function, allowing the extension of the effective size validity range from 70 to 300 micrometers which enabled the effective size range to be extended to include larger hydrometeor categories such as rain, snow, and graupel. The full formal derivation of the method is thoroughly explained in Muskatel et al. (2021). Using these functions and a refined spectral averaging technique, we calculated the bulk optical properties as a function of the effective size of needle-shaped particles or their aspect ratio in the case of the asymmetry factor parameterization. The parameterization was based on fitting rational functions division in the Padé approximation form:

$$f(x) = \frac{\sum_{i=0}^n a_i x^i}{\sum_{i=0}^m b_i x^i} \quad (3.1)$$

where f represents each of the optical properties and x is either the effective size or the aspect ratio. This parameterization is asymptotically stable even for particles as large as a few centimeters. The spectral averaging was adapted for both COSMO and ICON spectral intervals and was separately tested and verified extensively. The current ecRAD scheme also uses Fu's

ice parameterization but with different spectral averaging and bulk optical property parameterizations. Previously, the radiation scheme in ICON only accounted for two hydrometeor phases: liquid and frozen. In the default configuration, the liquid phase corresponds to cloud water while the frozen phase combines ice and a small portion of snow, with all other hydrometeors neglected. However, a new option, `ecrad_use_general_cloud_optics = .true.`, now allows for independent consideration of each hydrometeor type in the radiation calculations. This enhancement utilizes optical properties as a function of effective radius, which are provided in external files for each hydrometeor. The effective radii of snow, graupel, and rain are calculated by the effective radius module, which also determines the effective radius of cloud water and ice when large hydrometeors are included in the simulation. It should be noted that ECCKD gas optics require the general cloud optics option to be enabled, though large hydrometeors are not necessary for this gas optics scheme. The general cloud optics require high spectral and size resolution hence the optical properties were re-calculated hundreds of narrow spectral intervals and size bins and resulted in a LUT format which is also needed when the new gas optics ECCKD is used. The new high resolution optical properties parametrizations are shown in Figure 1.

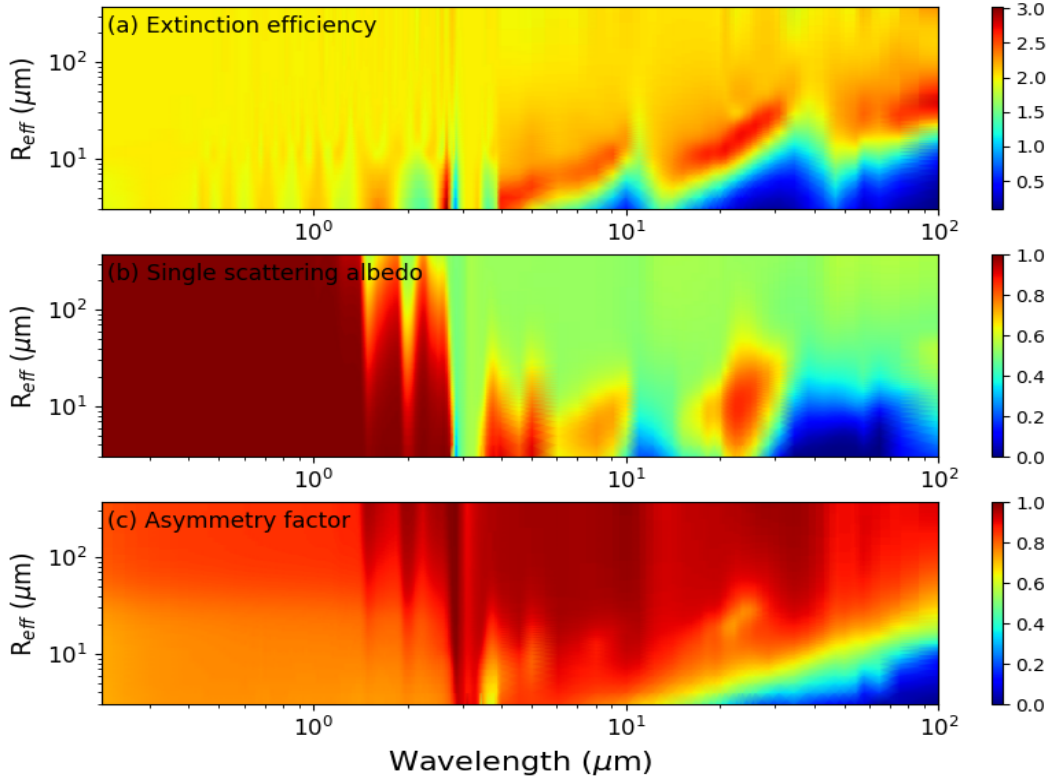


Figure 3.1. Extinction efficiency, single-scattering albedo, and asymmetry factor of hexagonal ice particles as a function of effective radius and wavelength (Adapted from Muskatel et al. (2021)).

The asymmetry factor presented in Fig. 1 was calculated for particles with smooth surfaces, where the forward scattered peak (delta fraction f_d) is large because of the plane-parallel surfaces of the ice particles. However, real particles might have rough surfaces, where the forward scattering is smaller. The asymmetry factor for rough surfaces can be defined as (Fu 2007):

$$g_r = \frac{g - f_d}{1 - f_d} \quad (3.2)$$

In the current ICON implementation both smooth and rough surfaces parametrizations can be selected using name list parameter *ecrad_ice_scatt*: 0 for rough surfaces (default), 10 for smooth surfaces and 11 for the baum-general-habit-mixture-ice parametrization. Notice that these numbers are valid only when *use_general_cloud_optic* = *.TRUE.* is selected. Otherwise, the default ice optical properties parametrizations are based on Fu (1996, 1998) which are in a formula representation and not in a high resolution LUT format. The rough surfaces data set is chosen to be the default setup since it is more suitable for a variety of ice particles including snow and was recommended in Fu et al. (2007) to better represent realistic ice particles in NWP models.

3.2 Test cases and sensitivity Experiments

Example 1: Squall Line over Germany

We examined the impact of the new optical property parametrizations on radiative transfer and compared the results with the default ICON radiation scheme. The primary advantage of our new ice optics is the inclusion of large hydrometeors. Therefore, we present the combined impact of both the inclusion of large particles and the new optical property parametrizations.

For our first example, we simulated a squall line event over Germany. This squall line flooded the Frankfurt South train station during the night of August 16, 2023. The domain is shown in Figure 2. The left panel shows a snapshot of 850 hPa reflectivity at 21:00 UTC, where deep convection is observed in many locations, indicating high concentrations of rain, graupel, and snow. The right panel illustrates the top of atmosphere (TOA) longwave upward flux.

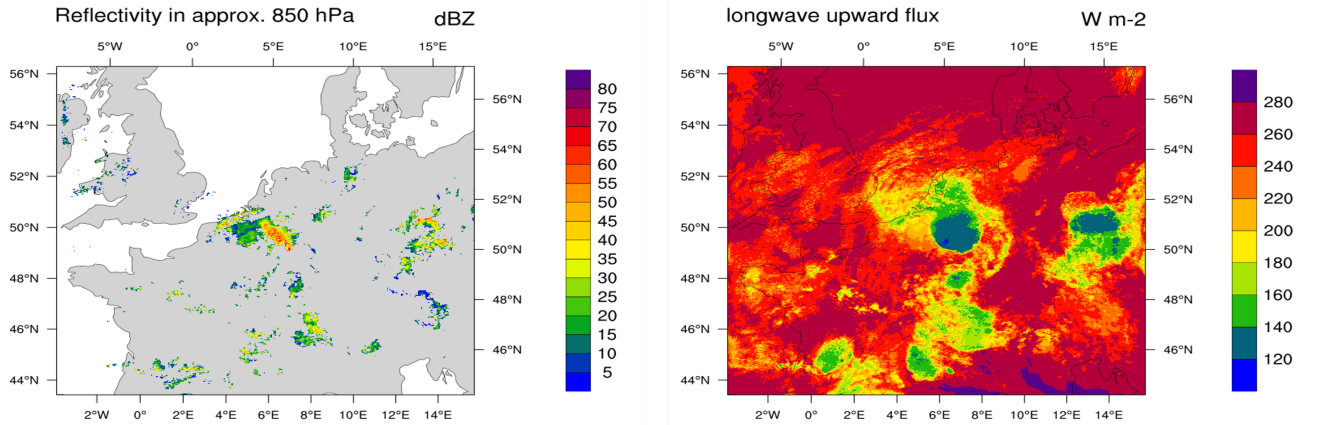


Figure 3.2. Snapshot at 21:00UTC of reflectivity at ~850 hPa (left) and top of atmosphere longwave upward flux (right) for the August 16, 2023 squall line event in Germany.

We compared radiation calculations using identical fields and setups, with the only difference being which large hydrometeors were included. We employed our RUC configuration (two-moment scheme) and ECCKD gas optics. Model configurations are summarized in Table 1.

	iliquid_scatter	iice_scatter	isnow_scatter	igraupel_scatter	irain_scatter
Reference	Mie Droplet Scattering (0)	Fu (1996, 1998) (10)	No contribution to radiation (-1)	No contribution to radiation (-1)	No contribution to radiation (-1)
Snow	Mie Droplet Scattering (0)	Smooth Muskatel et al. (2021) (10)	Smooth Muskatel et al. (2021) (10)	No contribution to radiation (-1)	No contribution to radiation (-1)
Full	Mie Droplet Scattering (0)	Smooth Muskatel et al. (2021) (10)	Smooth Muskatel et al. (2021) (10)	Smooth Muskatel et al. (2021) (10)	Mie Rain Scattering (0)

Table 3.1. Model configurations for the August 16, 2023 squall line test case. Three setups (Reference, Snow, and Full) are compared, with columns showing optical properties for cloud droplets, ice, snow, graupel, and rain hydrometeors. The Reference configuration uses `ecrad_use_general_cloud_optics = .FALSE.`, while Snow and Full configurations use `.TRUE.` to include large hydrometeors in the radiation scheme. Listed values indicate the optical property settings for each hydrometeor type, with corresponding namelist parameter numbers shown in red.

To examine radiation sensitivity to the inclusion of large hydrometeors and their new optical properties, we compared top-of-atmosphere (TOA) longwave radiation. Figure 3 (left panel) shows a snapshot of the radiation field differences between the 'Reference' and 'Full' configurations. High-altitude graupel and snow block surface longwave radiation, reducing upwelling radiation at TOA. Figure 3 (right panel) displays the frequency distribution of TOA longwave radiation differences for both the 'Snow' and 'Full' configurations relative to the 'Reference' configuration. Domain-averaged differences are -0.05 W/m^2 and -0.31 W/m^2 , respectively.

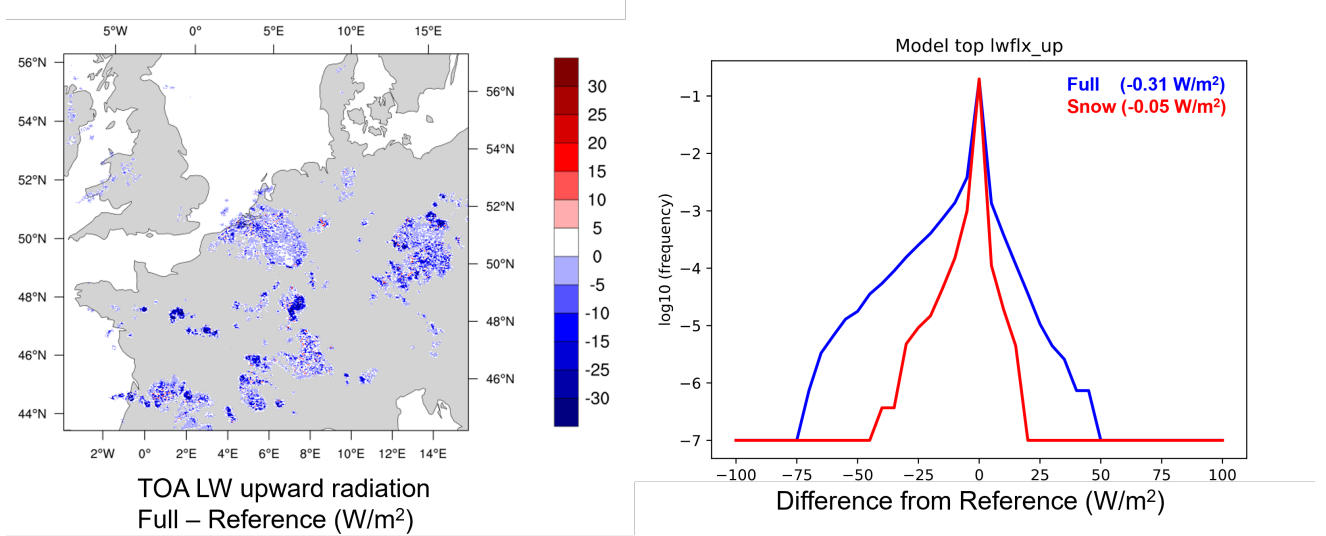


Figure 3.3. Snapshot at 21:00UTC of TOA LW upward radiation differences between the 'Full' and 'Reference' configurations (left) and the differences frequencies of both 'Full' and 'Snow' configurations compared with the 'Reference'.

Example 2: Radiation sensitivities in January 2022 over the East-Mediterranean

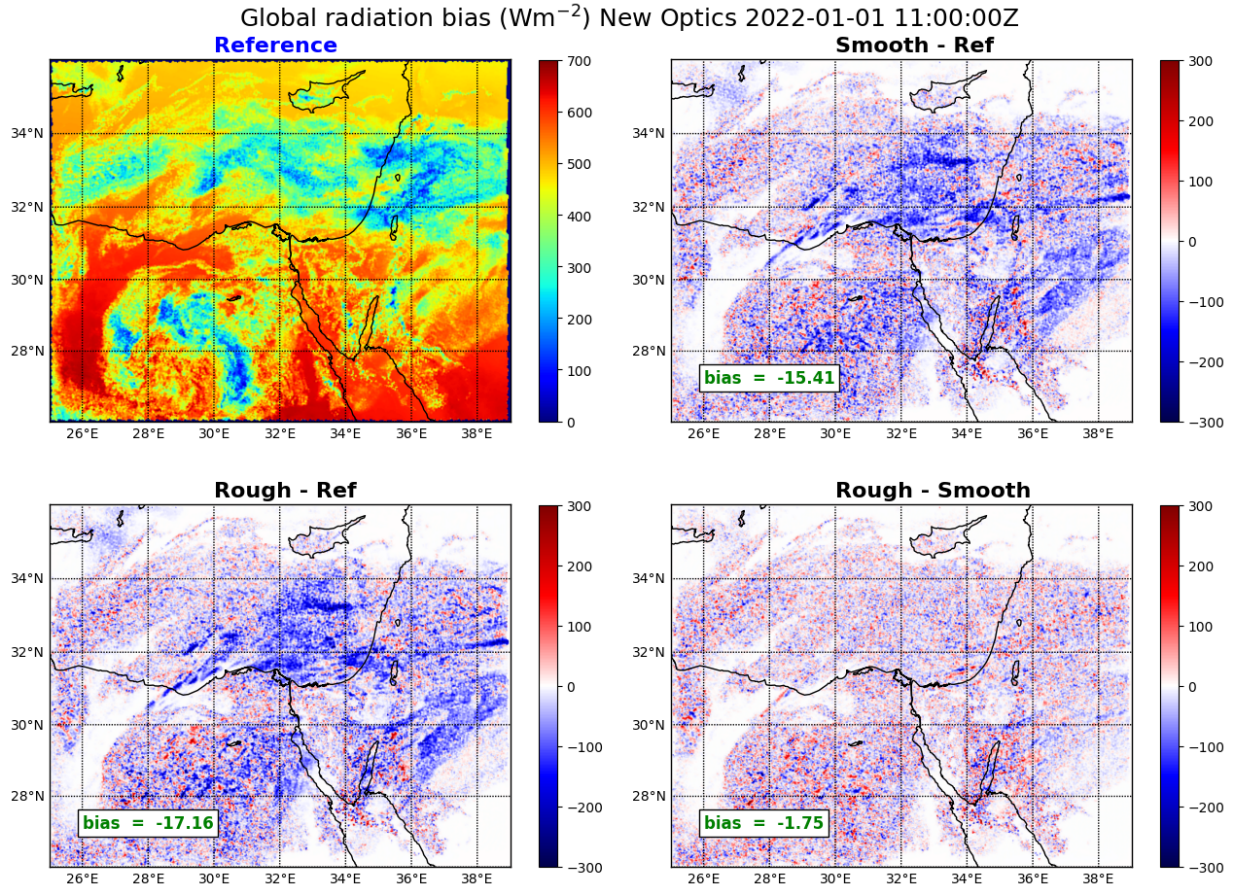


Figure 3.4. Surface downward radiation in the IMS domain on 01-01-2022 at 11:00 UTC. (Upper-left) Radiation from the 'Reference' configuration (Table 1). (Upper-right) Differences in surface radiation between the 'Full' and 'Reference' configurations using smooth ice particle optical properties. (Lower-left) As in upper-right but for rough surface ice particles. (Lower-right) Differences between rough and smooth parameterizations for the 'Full' configuration. Domain-averaged biases are shown in text boxes within each panel.

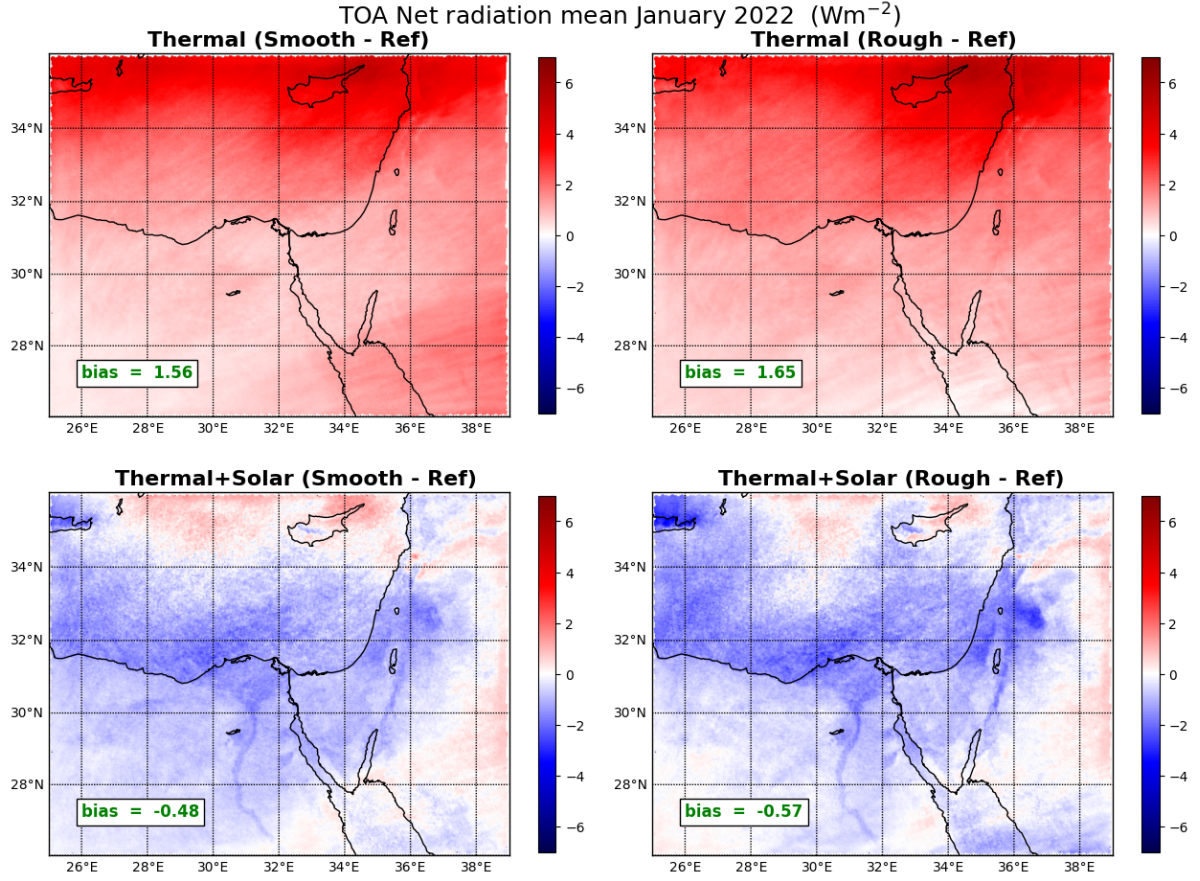


Figure 3.5. TOA upward radiation in the IMS domain averaged for January 2022. (Upper-left) Thermal (LW) radiation difference between the ‘Full’ configuration and ‘Reference’ (see Table 1). (Upper-right) As in upper-left but for rough surfaces optics. (Lower-left/Lower-right) As in upper panels but for the total thermal and solar (LW+SW) TOA radiation. Domain-averaged biases are shown in text boxes within each panel.

Example 3: Global ICON simulations

Figures 7 and 8 show the surface and TOA shortwave irradiance biases, respectively, in global ICON simulations resulting from the introduction of the large hydrometeor optics. The globally averaged biases are on the order of 10 W/m^2 , with a maximum cooling effect reaching up to 50 W/m^2 . The largest magnitudes are observed near the equator during summer—July in the Northern Hemisphere and January in the Southern Hemisphere.

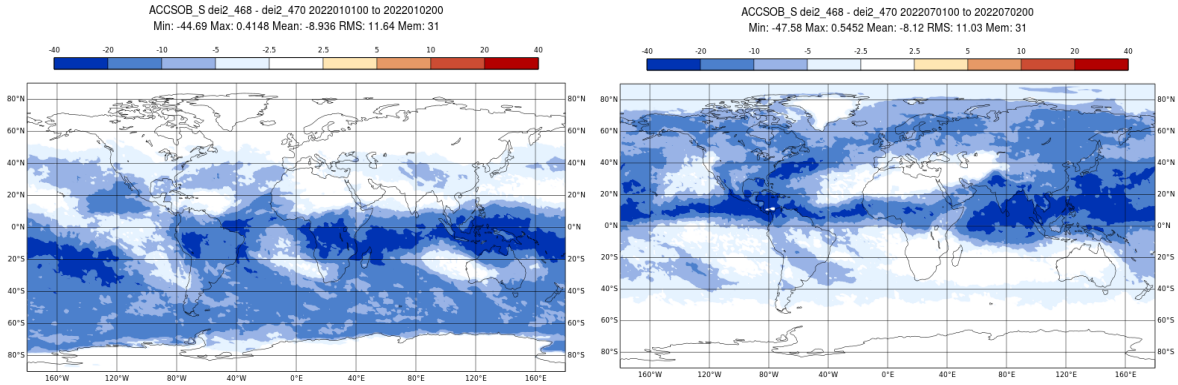


Figure 3.6. Global ICON simulations showing the differences in surface SW irradiance

January 2022 (upper panel) and July 2022 (lower panel) between the large-hydrometeors optics setup and the reference setup.

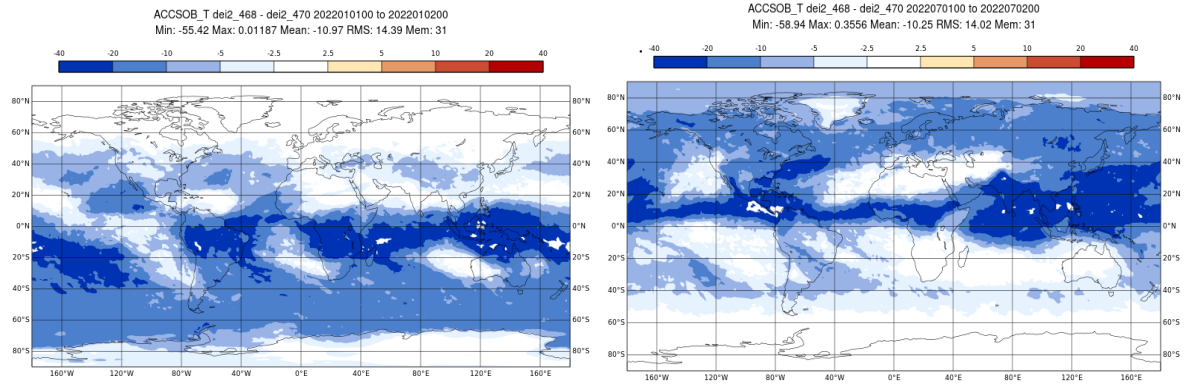


Figure 3.7. Global ICON simulations showing the differences in TOA SW irradiance January 2022 (upper panel) and July 2022 (lower panel) between the large-hydrometeors optics setup and the reference setup.

3.3 Conclusions and recommendations

The implementation of the new cloud optics scheme based on Muskatel et al. (2021) enabled the inclusion of large frozen hydrometeors in the ICON radiation scheme. A squall line test case over Germany demonstrated a significant reduction in upward longwave radiation when these large hydrometeors were incorporated into the model. A similar effect was observed over the IMS domain in the eastern Mediterranean during an extended simulation covering the entire month of January 2022. This experiment further revealed that the overall impact of the new cloud optics also reduced incoming shortwave radiation, producing an average cooling effect of approximately 0.5 W/m^2 . These findings were consistent with monthly global ICON simulations for January and July 2022, which showed global surface shortwave radiation reductions of 8 W/m^2 and 11 W/m^2 , respectively. Comparable magnitudes were simulated for the top-of-atmosphere (TOA) shortwave radiation. The largest biases appeared during summer—July in the Northern Hemisphere and January in the Southern Hemisphere—when the baseline radiation is highest. The sensitivities reported here are substantial and should be carefully considered, particularly in climate simulations, as their effects are considerably larger than the radiative forcing attributed to CO_2 .

4 CAMS 3D climatology and forecasted aerosols as an option in ecRAD radiationin ICON

(H. Muskatel, D. Rieger, M. Ahlgrimm, P. Khain and M. Köhler)

4.1 Implementation in ICON code

The implementation of the CAMS climatology and forecasted aerosols was presented in detail in the 011 issue of Reports on ICON. Since this publication, the format of the CAMS aerosol climatologies has changed: aerosol is now provided as mixing ratio (kg/kg) rather than layer-integrated mass. Moreover, a new CAMS aerosol climatology (49R2) is available,

which corrects some unrealistic artefacts present in the previous version (43R3)—for example, excessive dust in the stratosphere. The vertical interpolation method was also changed compared to the one illustrated in the 011 ICON report. The details of the new implementation are explained in the ICON documentation. Further instructions on how to run both options in ICON are given there.

4.2 Limited area model simulations

Global simulations with the ICON model, using CAMS climatological and forecasted aerosols, were performed for January and July 2022. The radiative sensitivities were reported in issue 011 of Reports on ICON (see details therein). Limited-area model runs were also performed, and their verification is presented here. Figure 4.1 shows the two model domains used at the IMS: the first (in blue) is the South-East Europe (SEE) domain, and the second (in green) is the Eastern Mediterranean domain. Both setups use a horizontal resolution of 2.5 km (R02B10) with 65 vertical levels and driven with lateral boundary (LBC) and initial conditions (IC) from IFS (ECMWF) model. The results shown here are from daily 00Z runs with a lead time of 72 hours. The results are verified against selected stations in Israel.

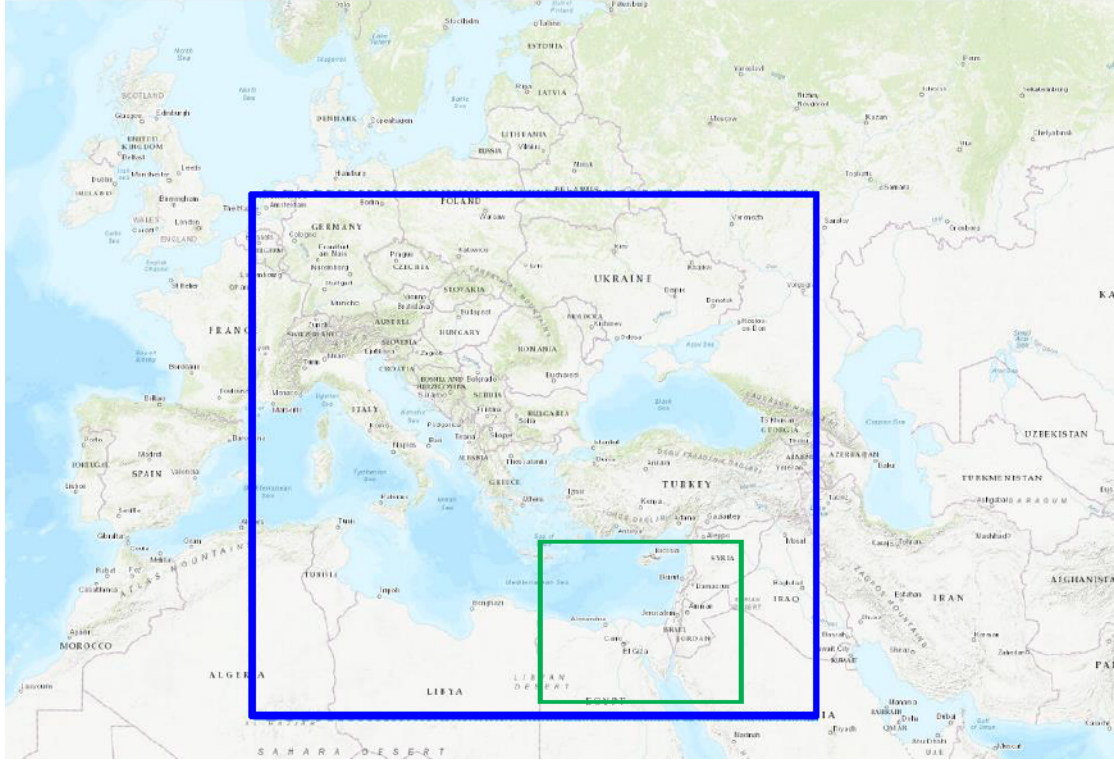


Figure 4.1: ICON simulation domains used at the IMS. The blue rectangle marks the South-East Europe (SEE) domain; the green rectangle marks the Eastern Mediterranean (EM) domain.

Figure 4.2 shows the scores of several atmospheric variables verified against measurements from a few dozen meteorological observation stations (the number varies from variable to variable). Three models are considered: the operational COSMO at 2.5 km, the operational ICON setup at 2.5 km using the Tegen aerosol climatology, and ICON at 2.5 km with CAMS forecasted aerosols as input to the radiation scheme. All three models run over the EM domain, and the RMSE is computed relative to the score of the IFS global model, which also uses the CAMS climatology as input to its radiation scheme. In other words, a value of 0 means "same as IFS", a positive value means worse than IFS, and a negative value

means better than IFS. The upper panel shows the results for the entire year 2020; the lower panel shows the results for the 30 most polluted days in Israel in 2020. These 30 days were selected as those in which the average ground-based PM_{2.5} measurements (averaged over all stations in Israel) were at least twice the yearly average. The first conclusion from these plots is that the ICON model outperforms the COSMO model. For temperature, relative humidity, precipitation, wind speed, and wind direction, the two ICON setups perform almost identically; however, for global radiation — and even more so for direct radiation — the ICON setup with CAMS forecasted aerosols performs markedly better. On the polluted days, the advantage of the ICON-CAMS configuration is even more pronounced.

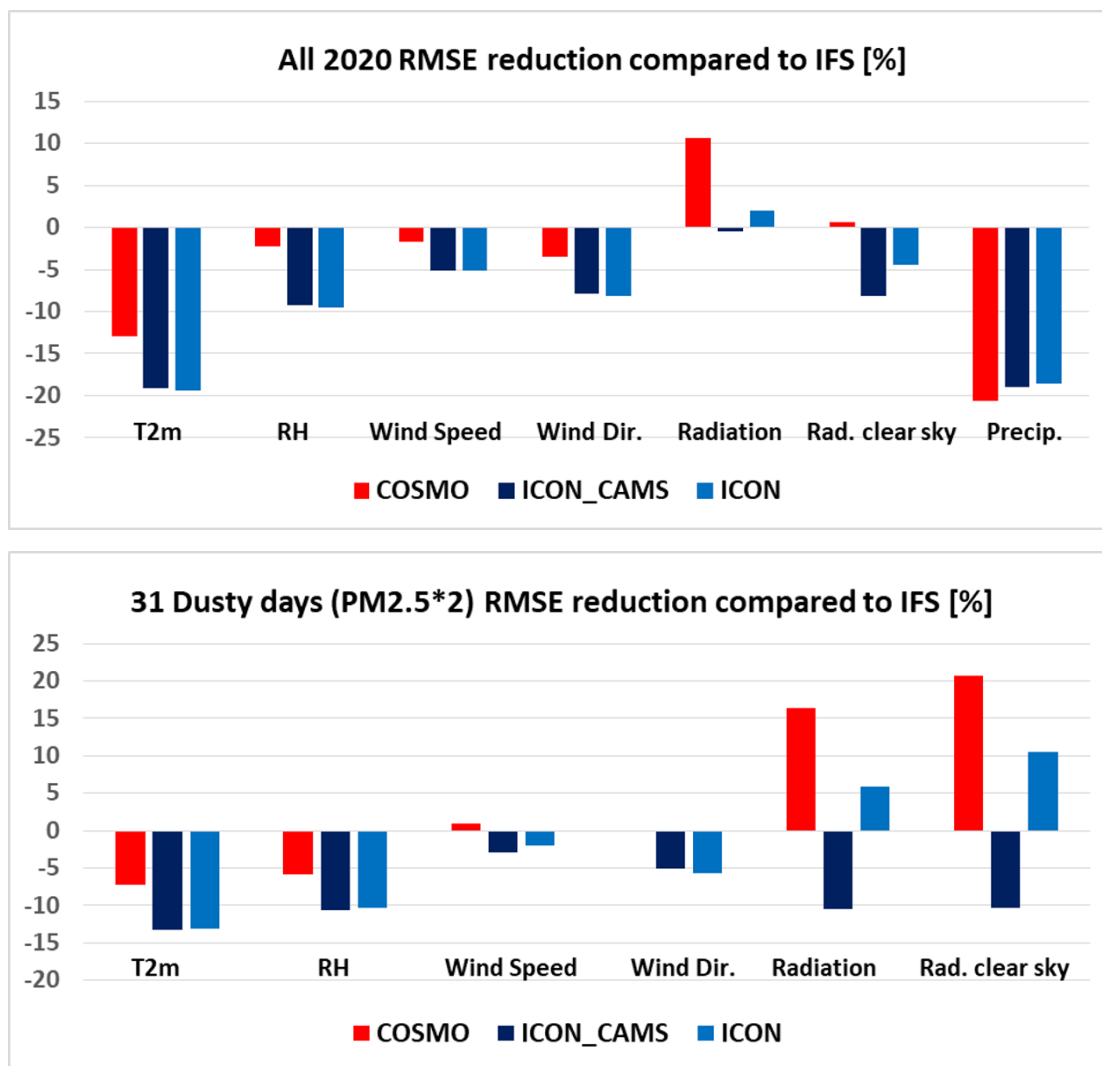


Figure 4.2: RMSE of several atmospheric variables relative to the IFS global model score (0 = same as IFS; positive = worse; negative = better), verified against meteorological observation stations in Israel. Shown are the operational COSMO 2.5 km (red), the operational ICON 2.5 km with the Tegen aerosol climatology (light blue), and ICON 2.5 km with CAMS forecasted aerosols (dark blue). Upper panel: the entire year 2020. Lower panel: the 30 most polluted days in Israel in 2020.

Figure 4.3 shows surface incoming short-wave radiation (global radiation) as a function of the hour of day. The results are averaged over the full 72-hour model lead time and verified against 10 radiation measurement stations in Israel. Six months of verification are averaged: December 2021–January 2022, April–May 2022, and September–October 2022. The models included are: the global IFS (orange; bias = 2.6 W/m^2 , RMSE = 78.8 W/m^2), the default

ICON with the Tegen climatology (magenta; bias = 25.9 W/m^2 , RMSE = 86.5 W/m^2), ICON with CAMS forecasted aerosols (red; bias = 26.6 W/m^2 , RMSE = 84.8 W/m^2), and ICON with the CAMS aerosol climatology (black; bias = 0.9 W/m^2 , RMSE = 82.5 W/m^2), together with the observations (lime). Note that both the IFS and ICON with the CAMS climatology closely follow the observed curve, but the latter outperforms all other models in terms of bias. These results are for the ICON runs over the EM domain; very similar results were obtained for the SEE domain.

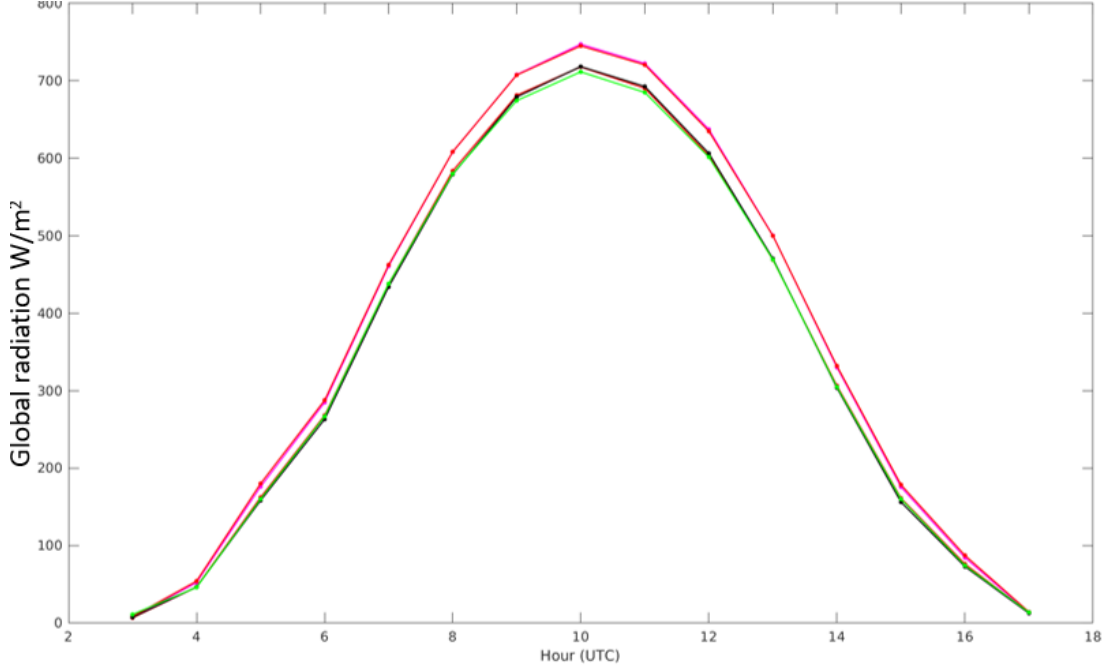


Figure 4.3: Mean diurnal cycle of surface incoming short-wave (global) radiation, verified against 10 radiation stations in Israel and averaged over the 72-hour lead time and six months of runs (Dec 2021–Jan 2022, Apr–May 2022, Sep–Oct 2022), for the EM domain. Shown are IFS (orange), ICON with Tegen climatology (magenta), ICON with CAMS forecasted aerosols (red), ICON with CAMS climatology (black), and observations (lime).

4.3 Conclusions and recommendations

The impact of aerosol representation on the ICON model was evaluated in both global and limited-area configurations. Global simulations using CAMS climatological and forecasted aerosols were performed for January and July 2022, and the radiative sensitivities were reported in issue 011 of Reports on ICON. Limited-area runs at 2.5 km resolution were carried out over the South-East Europe (SEE) and Eastern Mediterranean (EM) domains and verified against surface observations in Israel.

The main conclusions are as follows:

1. **Aerosol input matters primarily for radiation.** For temperature, relative humidity, precipitation, and wind, the choice of aerosol input (Tegen vs. CAMS) had little effect. For global radiation, and even more so for direct radiation, using CAMS aerosols as input to the radiation scheme substantially improved the scores relative to the default Tegen climatology.
2. **The benefit is largest under polluted conditions.** On the 30 most polluted days of 2020 in Israel, the advantage of the CAMS-based configuration was even more pro-

nounced, indicating that a realistic aerosol load is essential when aerosol concentrations deviate strongly from climatological values.

3. **CAMS climatology provides the best overall radiation bias.** In the diurnal-cycle verification against 10 radiation stations in Israel, ICON with the CAMS aerosol climatology achieved a near-zero bias (0.9 W/m^2), closely following the observations and outperforming the other ICON configurations. Similar results were obtained over both the EM and SEE domains.

Based on these findings, ICON with the CAMS aerosol climatology has been the operational configuration at the IMS since August 2023. In addition, a hybrid approach has been adopted: when a dust outbreak is foreseen, the configuration using CAMS forecasted aerosols is activated in place of the climatology. This strategy combines the low bias of the climatological aerosols under typical conditions with the responsiveness of forecasted aerosols during exceptional aerosol-loading events.

5 New ice heterogeneous nucleation scheme by DeMott (2015)

(H. Muskatel, A. de Lozar)

5.1 Overview

In Chapter 3 we examined the new optical properties of ice particles implemented in ICON and emphasized the importance of realistic particle number concentrations and effective sizes for ice cloud optical thickness. Cloud radiative properties are an important factor, but secondary to the sizes and concentrations of the particles in the cloud. Diagnosing ice nucleating particle (INP) concentrations is therefore a first and essential step in determining ice particle concentrations in NWP models, although large uncertainty remains regarding the relative weight of primary nucleation compared to secondary ice production processes. In the default ICON 1-moment microphysics scheme, INP concentration is parametrized using the Cooper (1986) formula (`icpl_aero_ice` = 0), in which it depends only on temperature:

$$n_{INP}(T) = 5 \bullet \exp^{0.304(T_0-T)} \quad (5.1)$$

Where n_{INP} is the INP number concentration m^{-3} , T is the temperature and T_0 is the melting point of water (K). This parametrization was based on observational data from many regions worldwide, and Cooper attributed the large observed variability not to secondary processes but to the variability of the INP population itself. The formula, however, suffers from a lack of information on the aerosols acting as ice-nucleating embryos. In this project we therefore added an alternative ice nucleation scheme, following the empirical immersion-freezing parametrization of DeMott et al. (2015), which was derived from an integration of field measurements and laboratory data sets and combines both temperature and dust number concentration n_{dust} :

$$n_{INP}(T, n_{dust}) = 1000 \bullet n_{dust}^{1.25} \exp^{0.46(T_0-T)-11.6} \quad (5.2)$$

Where n_{dust} is the number concentration of dust particles larger than $0.5 \mu m \text{ cm}^{-3}$. Since the original DeMott formula yields n_{INP} in L^{-1} , a factor of 1000 is applied to convert to

m^{-3} as required in ICON. The parametrization was derived for the temperature range 238 K < T < 252 K; as a first guess, we did not restrict its validity range, since it appears more realistic than the default Cooper formula even outside this range. For temperatures colder than 238 K the Steinke et al. (2015) parametrization would be a preferred choice (Nickovic et al. 2016), but it was not implemented in this project. The dust concentrations can be taken either from CAMS climatology/forecasted (icpl_aero_ice = 1, irad_aero = 7/8) or from Tegen climatology (icpl_aero_ice = 2, irad_aero = 6). When coupling CAMS aerosols to the DeMott formula, number concentrations are computed from CAMS aerosol mixing ratios via:

$$n_{dust} = 10^{-6} \bullet q_{cams} \bullet \rho_{air} / m_p \quad (5.3)$$

Where q_{cams} is the CAMS aerosol mixing ratio (kg/kg), ρ_{air} is the air density kg/m^3 and m_p is the mean particle mass in the specific size bin (kg); the factor 10^{-6} converts from m^{-3} to cm^{-3} as needed in the DeMott formula. CAMS dust is divided into three size bins (μm): aermr04 [0.03, 0.55], aermr05 [0.55, 0.9] and aermr06 [0.9, 20]. Only the contributions from aermr05 and aermr06 are considered, since only particles larger than $0.5 \mu m$ act as ice nucleating particles in the DeMott scheme. These aerosol number-concentration coefficients were subsequently updated with the new CAMS climatology (49R2 / IFS cycle 38R1), where the new coefficients — corresponding to mean particle masses of $3.92434437 \cdot 10^{-15}$ kg and $8.591950322 \cdot 10^{-14}$ kg for aermr05 and aermr06, respectively — represent dust number per unit aerosol mass integrated over the relevant size bins, computed using the CAMS team script. When coupling Tegen aerosols to the DeMott formula, n_{dust} is calculated in the subroutine `ncn_from_tau_aerosol_specnconst_dust`, a shortened version of `ncn_from_tau_aerosol_specnconst`, where the 10^{-6} conversion to cm^{-3} is likewise applied. Note that n_{dust} is very sensitive to the mean mass radius of dust particles r_{dust} , taken from Wong et al. (2021), which can therefore be treated as a tuning parameter.

5.2 Test case analysis

In order to quantify the sensitivity of INP concentrations to the choice of ice nucleation scheme, we performed three ICON simulations over the ICON-EM domain (see Figure 4.1) at 2.5 km horizontal resolution for April 5, 2020: the first using the default Cooper formula, the second using the DeMott parametrization with Tegen dust climatology as input, and the third using the DeMott parametrization with CAMS forecasted aerosols as input. Figure 5.1 shows the grid-point occurrence density in INP L^{-1} vs. temperature ($^{\circ}C$) space, averaged over all time steps within 0–24 hours lead time. Yellow colors represent higher occurrence densities and purple colors lower ones, while the lime line denotes the mean INP concentration at each temperature. The simple exponential temperature dependence of the Cooper scheme is clearly visible, yielding the lowest number concentrations of the three schemes. The DeMott–Tegen case exhibits a wider spread around the exponential decay, owing to a nearly constant dust number concentration, but with overall higher values. The DeMott–CAMS combination produces the most diverse results, with higher INP concentrations and with INP present at warmer temperatures ($> -25 \text{ }^{\circ}C$), which are absent in the other two schemes.

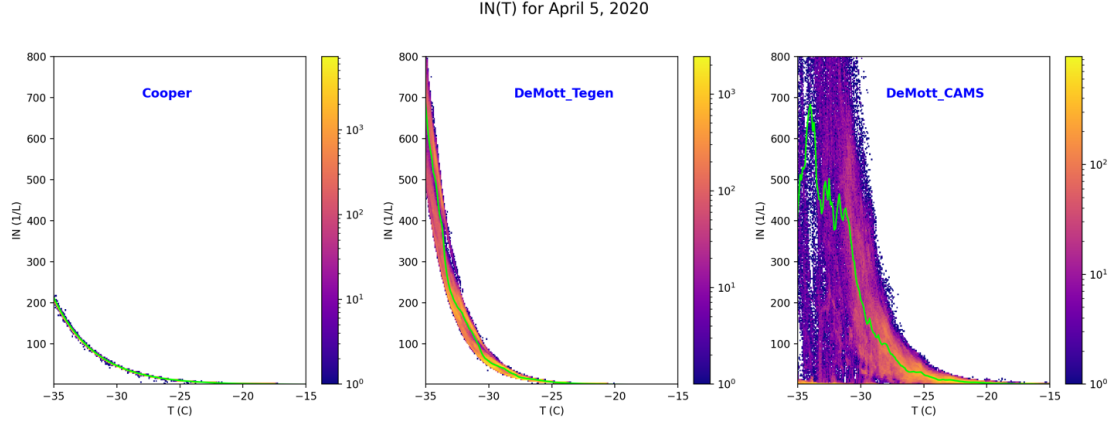


Figure 5.1: INP grid-point occurrence density as a function of INP concentration L^{-1} and temperature ($^{\circ}\text{C}$) for three ice nucleation schemes: Cooper (left), DeMott with Tegen dust climatology (center), and DeMott with CAMS forecasted aerosols (right). Densities are averaged over all time steps within 0–24 h lead time of the ICON-EM simulations (2.5 km resolution, April 5, 2020). Yellow (purple) shading indicates higher (lower) occurrence density; the lime line shows the mean INP concentration at each temperature.

Ice nucleation can affect radiation directly by altering the average effective size of ice particles: for the same ice content, higher INP numbers reduce the particle size accordingly — an effect that also depends on particle shape. A second, microphysical effect is that the ice particle number concentration can modify the conversion rates to other hydrometeors. The model runs described above were integrated for three days starting on 5 April 2020 at 00:00 UTC, and Figure 5.2 shows a snapshot of these simulations at 08:00 UTC on 7 April 2020. The upper-left panel shows the surface shortwave (SW) radiation difference between the default setup, which uses the Tegen climatology as input to the radiation scheme, and a run using CAMS forecasted aerosols as input. Both runs use the same Cooper ice nucleation scheme, so this map represents the aerosol direct radiative effect, with a positive average bias of 7.19 W/m^2 . The upper-right panel shows the same aerosol comparison, but here the INP concentrations in the microphysical scheme are calculated with the DeMott–CAMS scheme vs. the Cooper scheme (average bias of 9.34 W/m^2). The lower-left panel is the same, but additionally includes the indirect INP effect on the effective radius (average bias of 4.16 W/m^2). The lower-right panel uses the same CAMS aerosol background in both runs, thereby eliminating the aerosol direct effect, and thus isolates the indirect effects of ice nucleation alone (DeMott–CAMS vs. Cooper), yielding a net surface cooling of -1.89 W/m^2 .

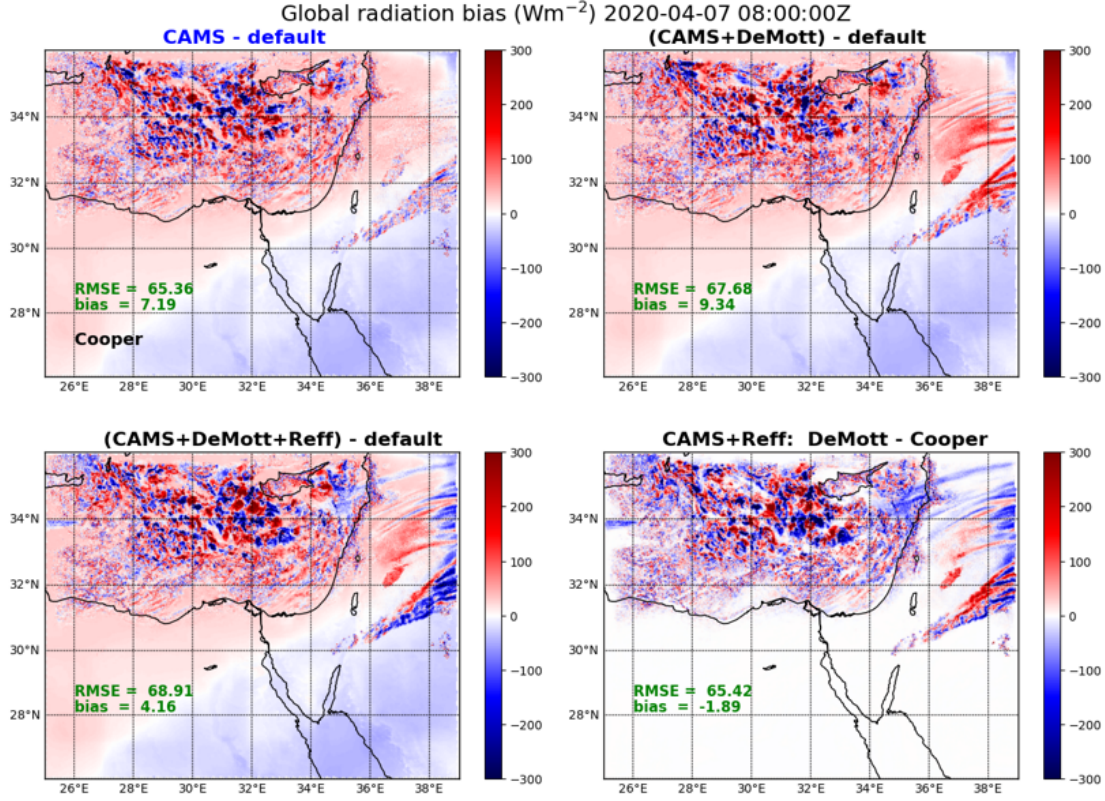
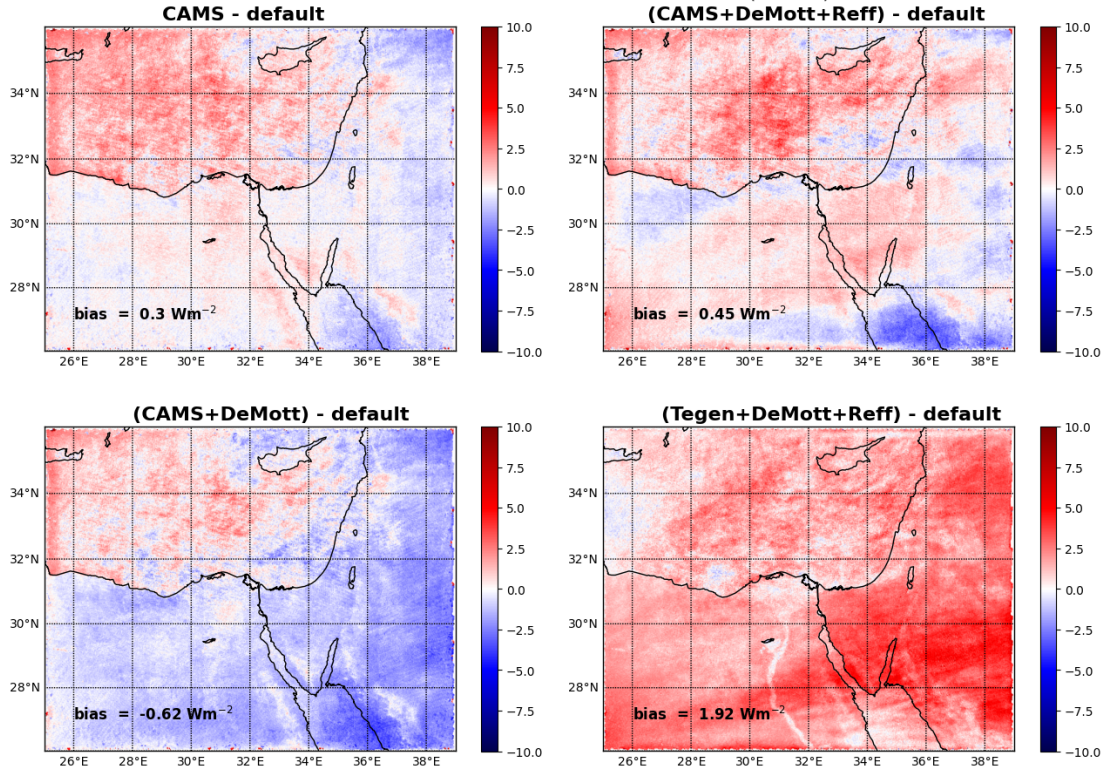


Figure 5.2: Surface SW radiation differences (W/m^2) at 08:00 UTC on 7 April 2020, from ICON simulations initialized at 00:00 UTC on 5 April 2020. Upper left: Tegen vs. CAMS aerosols as radiation input, both with the Cooper ice nucleation scheme (aerosol direct effect). Upper right: as upper left, but with INP computed by the DeMott–CAMS scheme vs. Cooper (mean bias $+4.16 \text{ W/m}^2$). Lower left: as upper right, but including the indirect INP effect on ice effective radius. Lower right: identical CAMS aerosol background in both runs, isolating the ice nucleation indirect effects only (DeMott–CAMS vs. Cooper).

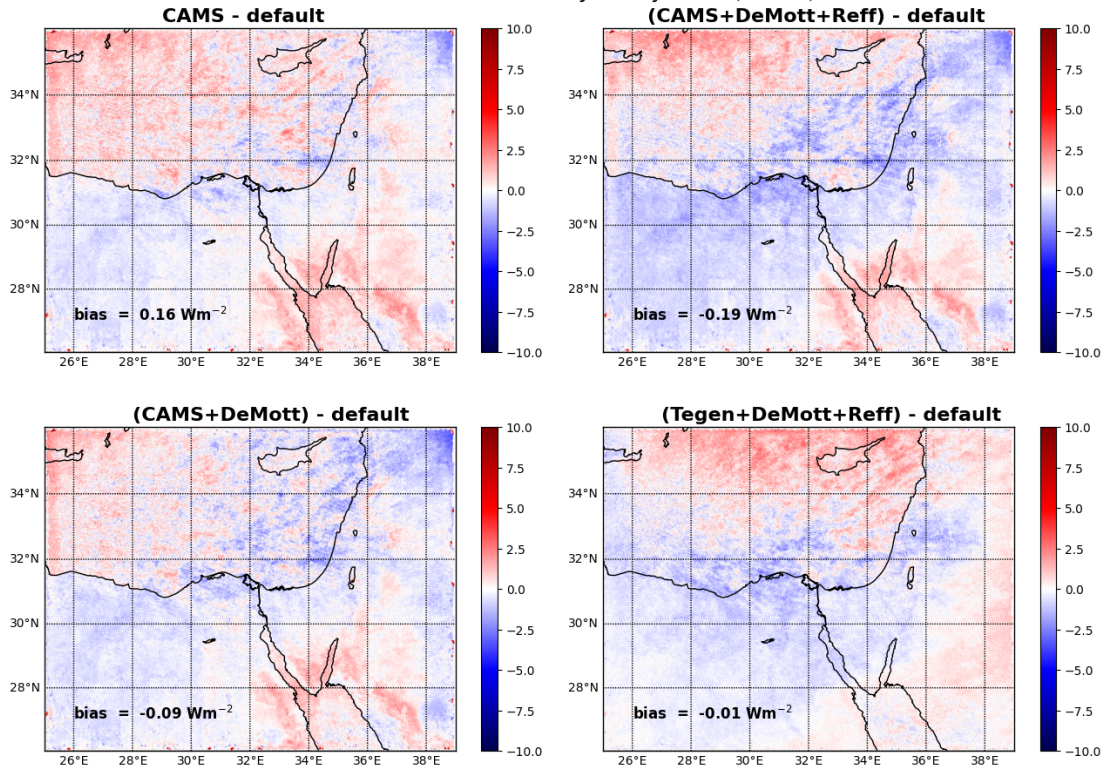
5.3 Long term 6-months analysis

We performed six months of simulations as described in the previous section. Figures 5.3a–f show the averaged TOA net radiation differences for December 2021, January, April, May, September and October 2022, while Figure 5.3g presents the average over the entire six-month period. In each figure, the upper-left panel shows the aerosol direct effect (both runs using the default Cooper ice nucleation scheme), while the upper-right and lower-right panels show the full direct and indirect aerosol effect using the DeMott–CAMS and DeMott–Tegen ice nucleation schemes, respectively, compared to the default Cooper scheme. The lower-left panel is similar to the upper-right panel but includes only the microphysical indirect effect, excluding the effective-size effect. Blue colors indicate a net cooling effect on the atmosphere and reddish colors a warming effect. The results are averaged over the full 72-hour lead-time range of all 00Z runs in the respective period. The most pronounced feature of these figures is the land–sea contrast: sea areas generally show positive values (warming effect) while land areas show negative TOA net radiation differences (cooling effect). The magnitude and sign of the effect depend on the season, and the average bias of each effect is indicated on the corresponding panel. In general, dust-laden months such as April and September exhibit larger magnitudes than the winter months of December and January.

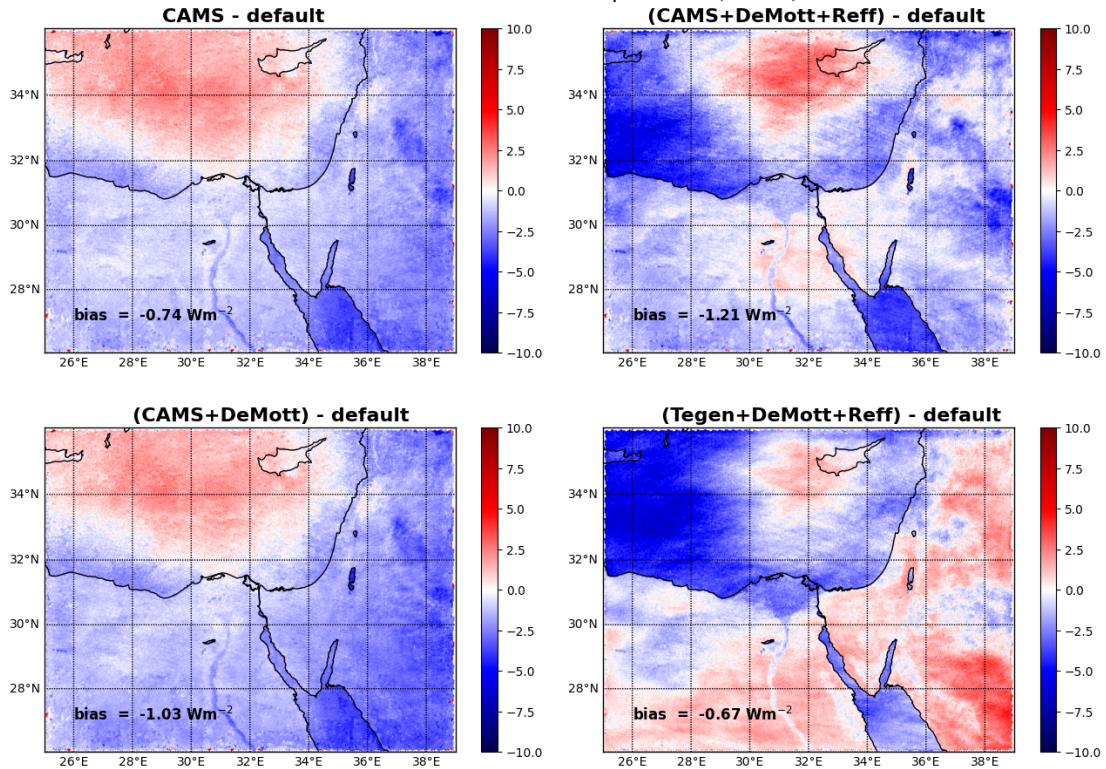
TOA net radiation mean December 2021 (Wm^{-2})



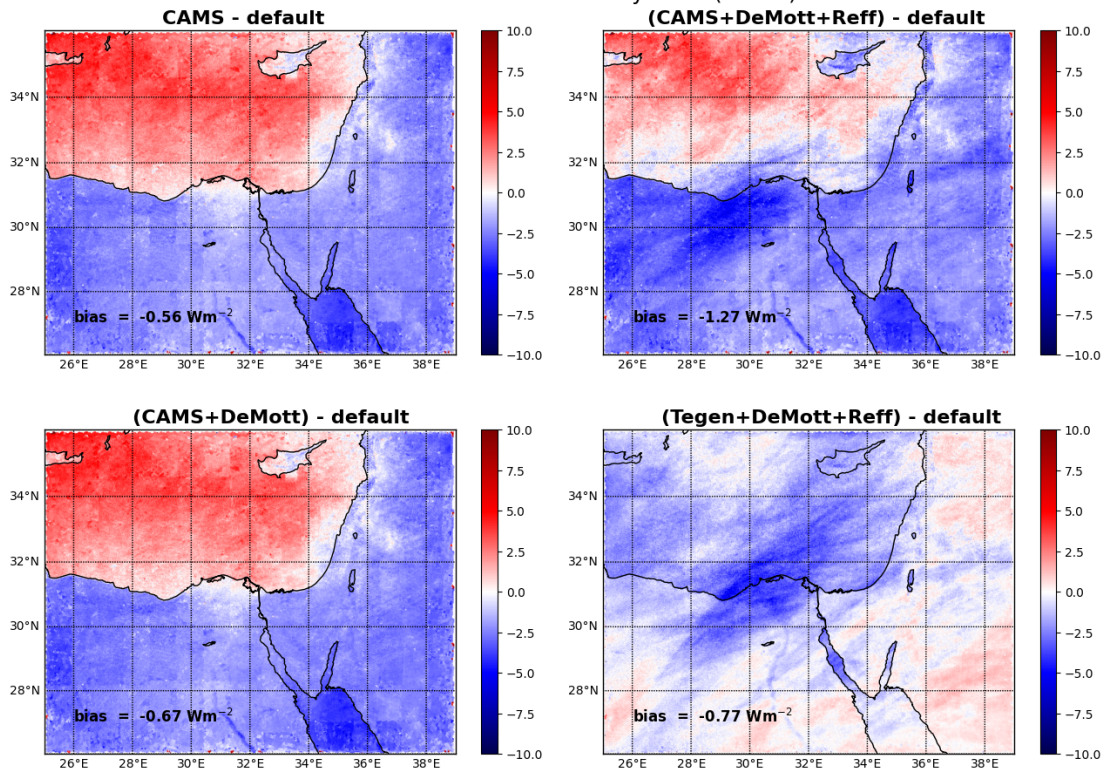
TOA net radiation mean January 2022 (Wm^{-2})



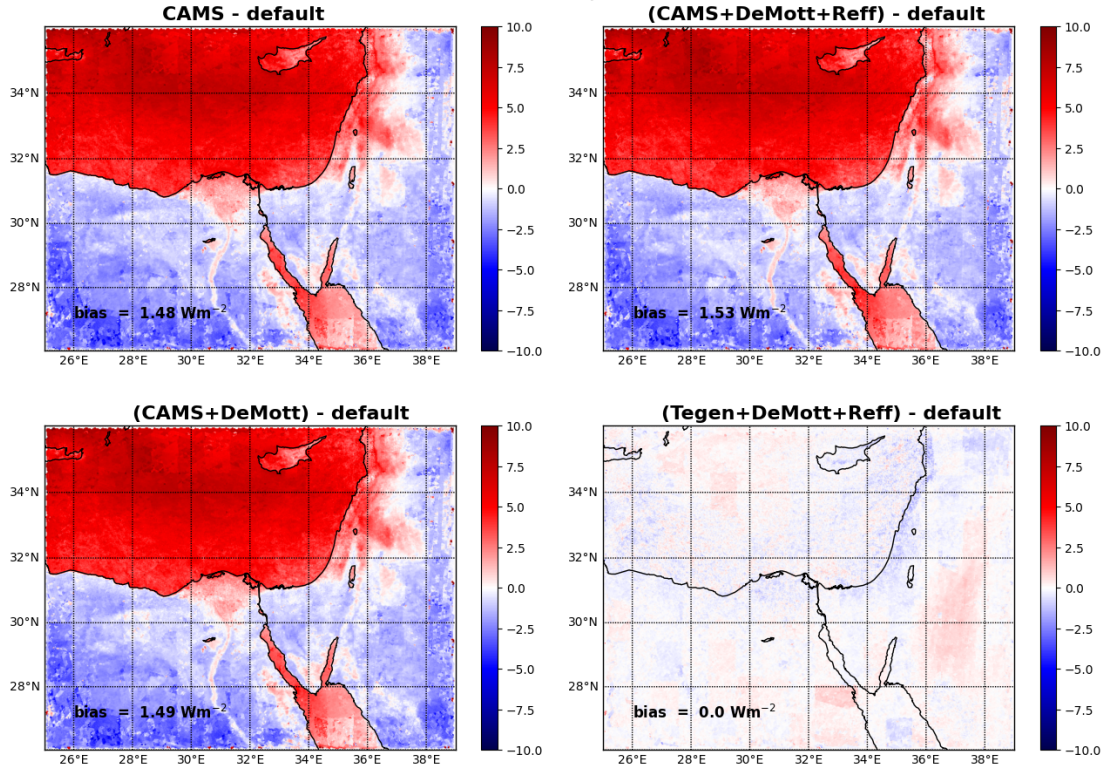
TOA net radiation mean April 2022 (Wm^{-2})



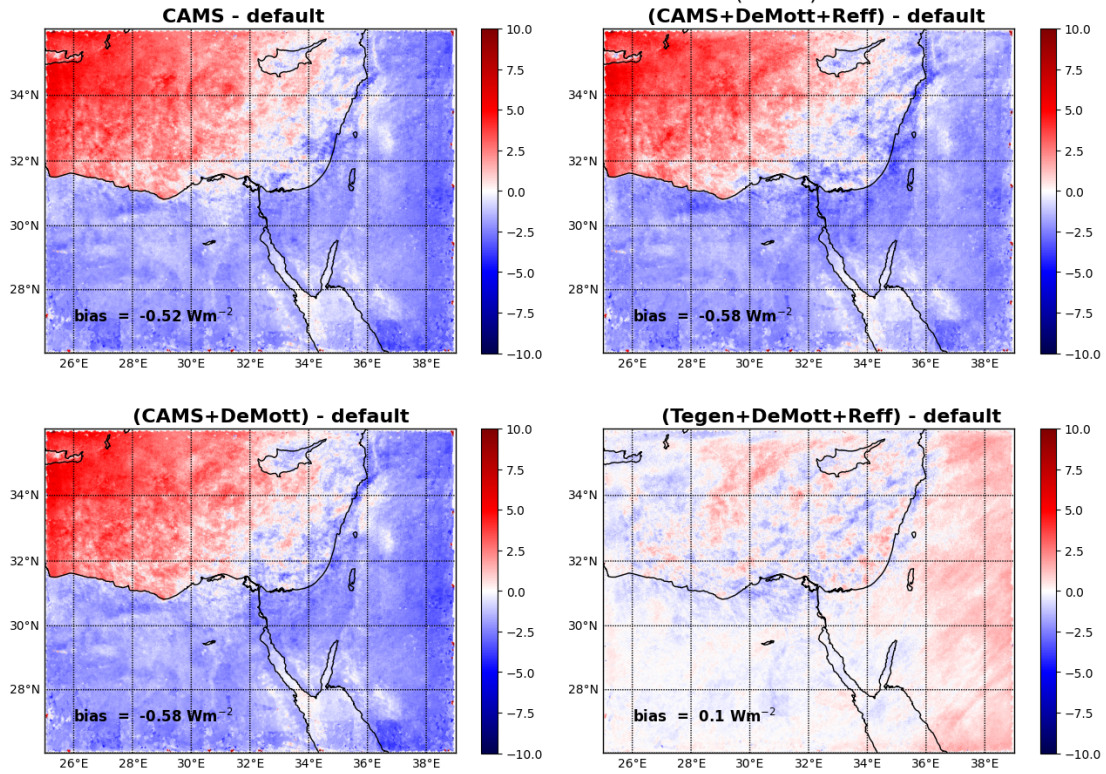
TOA net radiation mean May 2022 (Wm^{-2})



TOA net radiation mean September 2022 (Wm^{-2})



TOA net radiation mean October 2022 (Wm^{-2})



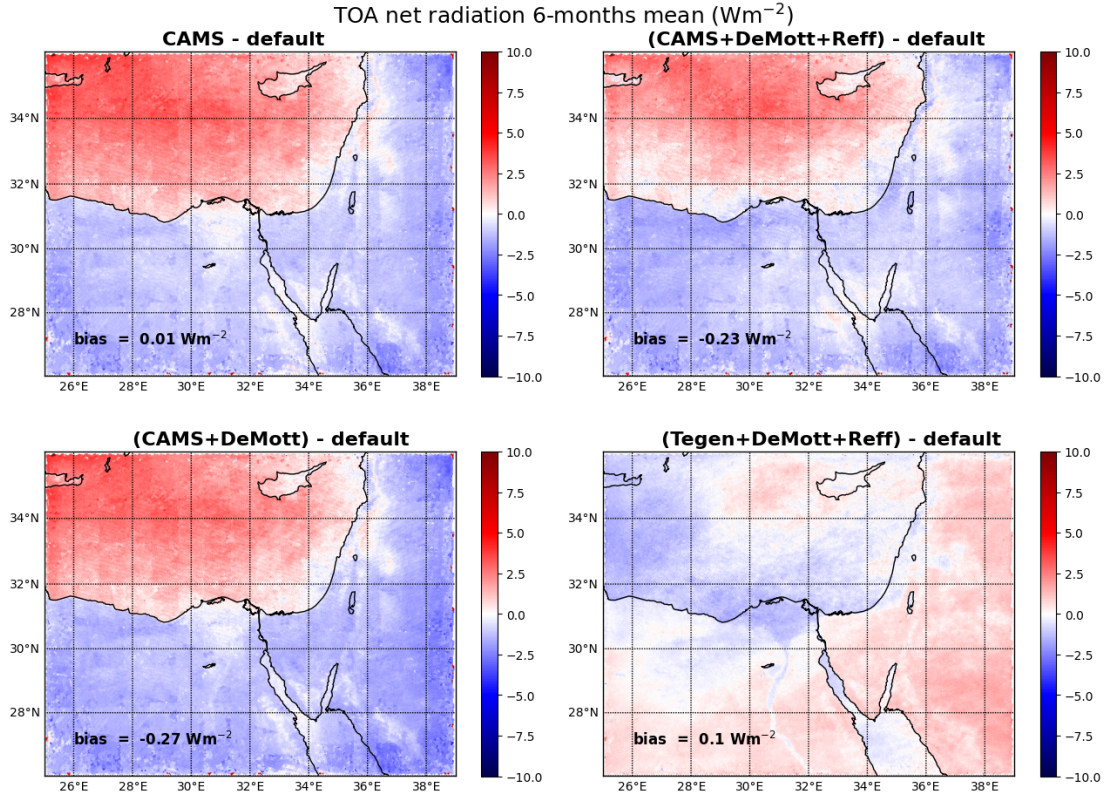


Figure 5.3: Monthly averaged TOA net radiation differences (W/m^2) for (a) December 2021, (b) January, (c) April, (d) May, (e) September and (f) October 2022, and (g) the average over the entire six-month period. In each figure: upper left — aerosol direct effect (Tegen vs. CAMS, both with Cooper ice nucleation); upper right — full direct and indirect effect with the DeMott–CAMS scheme vs. the default Cooper scheme; lower right — as upper right, but with the DeMott–Tegen scheme; lower left — as upper right, but including only the microphysical indirect effect (excluding the effective-size effect). Blue (red) shading indicates net cooling (warming). Values are averaged over the full 72-hour lead time of all 00Z runs in the respective period, with the mean bias of each effect indicated on the panels.

Figure 5.4a shows global radiation verification results for the aforementioned six-month period. The model results were compared against 10 ground-based radiation stations in Israel over the full 72-hour lead-time range. The y-axis shows the global radiation and the x-axis the hour of day (UTC). The ICON model versions compared are: the default configuration (Tegen aerosols with Cooper ice nucleation, magenta), CAMS forecasted aerosols with Cooper ice nucleation (red), CAMS aerosols with the DeMott nucleation scheme (blue), CAMS aerosols with the DeMott nucleation scheme excluding the effective-size effect (yellow), Tegen aerosols with the DeMott ice nucleation scheme (black), and the observations (lime). Figure 5.4b is the same as Figure 5.4a, but for 19 cases in which the forecasted dust AOD exceeded 0.2 over more than 80% of the grid points at least once within the 72-hour range. In both the full six-month period and the 19 dust-laden cases within it, the CAMS–DeMott configuration outperformed the other versions in terms of radiation bias, while the RMSE values of all versions were similar.

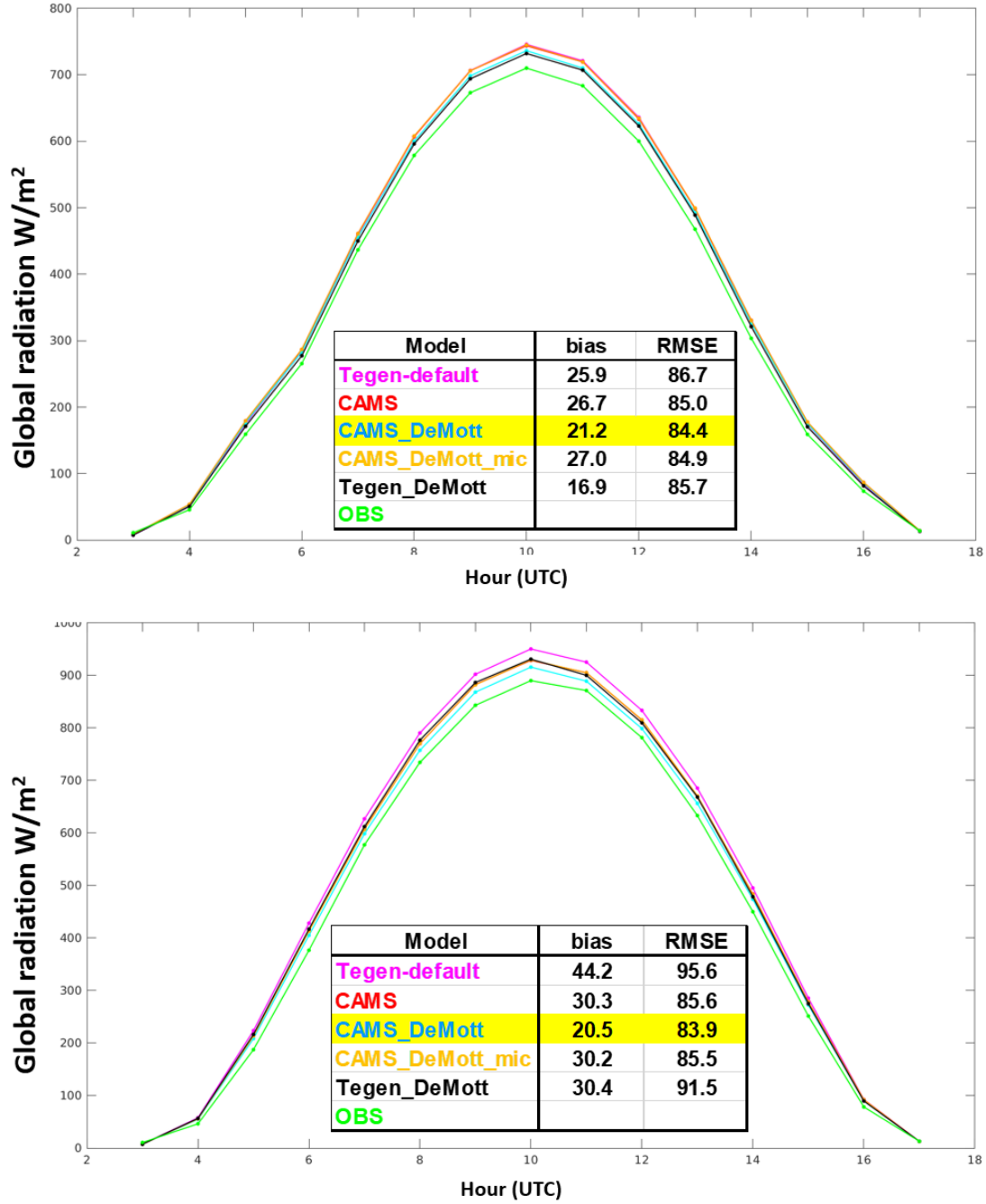


Figure 5.4: Global radiation verification against 10 ground-based radiation stations in Israel for (a) the full six-month period and (b) 19 dust-laden cases (forecasted dust AOD > 0.2 over more than 80% of grid points at least once within the 72-hour range). Shown is the mean diurnal cycle (UTC) over the full 72-hour lead time for the observations (lime) and five ICON configurations: default Tegen aerosols with Cooper ice nucleation (magenta), CAMS aerosols with Cooper ice nucleation (red), CAMS aerosols with DeMott ice nucleation (blue), CAMS aerosols with DeMott ice nucleation excluding the effective-size effect (yellow), and Tegen aerosols with DeMott ice nucleation (black).

5.4 Conclusions and Recommendations

In this work, the DeMott et al. (2015) ice nucleation parametrization was implemented in the ICON 1-moment microphysics scheme as an alternative to the default temperature-only

Cooper (1986) formula. Unlike the Cooper scheme, the DeMott parametrization accounts for the availability of ice nucleating aerosols by combining temperature with the number concentration of dust particles larger than $0.5\ \mu\text{m}$. The dust concentrations can be supplied either from the Tegen climatology (`icpl_aero_ice` = 2) or from CAMS climatology or forecasted aerosols (`icpl_aero_ice` = 1, `irad_aero` = 7/8). The sensitivity simulations demonstrated that the choice of ice nucleation scheme has a substantial impact on the simulated INP population. The Cooper scheme produces a simple exponential temperature dependence with the lowest INP concentrations, while the DeMott–Tegen configuration yields higher values with a wider spread around the exponential decay. The DeMott–CAMS combination provides the most diverse and arguably most realistic INP distributions, with higher concentrations and with INP present at warmer temperatures ($> -25\ ^\circ\text{C}$) that are entirely absent in the other two schemes. These microphysical differences translate into meaningful radiative effects. The case study of April 2020 showed that the aerosol direct effect and the ice nucleation indirect effects act in opposite directions at the surface, with the isolated indirect effect of the DeMott–CAMS scheme producing a net surface cooling of $-1.89\ \text{W}/\text{m}^2$. The six-month TOA net radiation analysis revealed a pronounced land–sea contrast — a general warming effect over sea and cooling over land — with seasonally dependent magnitudes that are largest in dust-laden months such as April and September and weakest in the winter months. Most importantly, the verification against 10 ground-based radiation stations in Israel showed that the CAMS–DeMott configuration outperformed all other model versions in terms of global radiation bias, both over the full six-month period and in the subset of 19 dust-laden cases, while maintaining RMSE values comparable to the other configurations. This indicates that the combination of forecasted CAMS aerosols with an aerosol-aware ice nucleation scheme improves the representation of the surface radiation budget without degrading forecast skill, and its advantage is retained precisely in the dust events where aerosol–cloud interactions matter most.

Beyond NWP applications, the results carry an important implication for climate modeling: the demonstrated sensitivity of the TOA net radiation to the choice of ice nucleation scheme reaches magnitudes comparable to (and regionally exceeding) the radiative forcing associated with a doubling of CO_2 (approximately $3.7\ \text{W}/\text{m}^2$). Since ICON also serves as a global climate model (e.g., ICON-ESM), such a structural sensitivity in the parametrized aerosol–ice interaction could rival or mask greenhouse-gas radiative signals in long climate integrations. A careful assessment of the ice nucleation scheme, constrained by observations, is therefore essential for global ICON climate simulations, and the choice of scheme should be regarded as a first-order source of uncertainty in the simulated radiation budget rather than a technical detail.

6 Simplified Prognostic Aerosols

(D. Rieger, G. Zängl)

6.1 Overview

ICON contains a simplified, computationally cheap aerosol module *Prog2DAero*. The additional cost in a global simulation is typically far below 1%. The idea is to account for the main causes of variability in atmospheric aerosol concentrations not reflected in climatological values. It is based on the Tegen climatological aerosol which is used for operational numerical weather prediction with ICON.

6.2 Aerosol used in the operational configurations at DWD

The operational version of ICON uses climatological aerosol based on the Tegen et al. (1997) climatology. This option has the following main characteristics:

- Optical thicknesses at the wavelength 550 nm of the 5 species Sea Salt, Soil Dust, Sulfate, Organic Carbon and Black Carbon are provided in the external parameter file.
- The annual cycle is considered by providing monthly data which is linearly interpolated inside ICON to the target date.
- The original data is vertically integrated optical thickness. For the use in ecRad, an exponentially decaying, normalized vertical profile is added by ICON.
- The target variables optical thickness (SW/LW), single scattering albedo (SW) and asymmetry parameter (SW) at the radiation wavelength bands are derived based on lookup tables in the ICON code.

6.3 2-dimensional prognostic aerosol *Prog2DAero*

Several design choices for *Prog2DAero* were made based on characteristics of the climatology described above. *Prog2DAero* makes use of the vertically integrated optical depth of the five species Sea Salt, Soil Dust, Sulfate, Organic Carbon and Black Carbon as prognostic variables and adds the following process descriptions:

- Horizontal transport using vertically averaged wind fields
- Artificial diffusion to account for vertical wind shear
- Emissions based on physical parameterizations for natural aerosol species (sea salt, soil dust)
- Emissions based on datasets for anthropogenic and wildfire emissions
- Source term for sulfate to account for nucleation from the gas phase
- Wet deposition due to grid-scale and convective processes
- Relaxation approach to account for other sink terms (sedimentation, dry deposition)
- Particle growth depending on atmospheric humidity

Parts of *Prog2DAero* can be activated individually. By choosing the namelist parameter `i2daero_dust=1`, the simplified prognostic description for soil dust can be activated. Likewise, `i2daero_seas=1` activates sea salt. The three species Sulfate, Organic Carbon and Black Carbon can be activated by `i2daero_anthro=1`. In addition, emissions from wild fires can be added to these species using the namelist option `i2daero_fire`.

The prognostic equation for aerosol species j can be written as

$$\frac{\partial \psi_j}{\partial t} = \overline{v_{H,j}} \nabla \psi_j + c_{diff,j} \nabla^2 \psi_j + S_{e,j} + S_{w,j} + \frac{\psi_{clim,j} - \psi_j}{\tau_{clim,j}} \quad (6.1)$$

where the right hand side terms are advection, artificial diffusion, source terms, sink terms and relaxation. ψ_j denotes the vertically integrated optical depth, $\bar{v}_{H,j}$ the vertically averaged horizontal wind, $c_{diff,j}$ a diffusion coefficient, $S_{e,j}$ source terms (emission), $S_{w,j}$ sink terms (washout), $\psi_{clim,j}$ the climatological value of vertically integrated optical depth and $\tau_{clim,j}$ a relaxation time scale.

The emission process of soil dust and sea salt is described by adapted versions of physically based parameterizations, namely Kok et al. (2014) for soil dust and Grythe et al. (2014) for sea salt. Adapted in a sense that calculations of soil characteristics are kept simple and that the result is converted into an AOD flux instead of an emissions flux. Anthropogenic emissions are based on global emissions for 2018 from the Emission Database for Global Atmospheric Research (EDGAR; Crippa et al. 2016). For wildfire emissions, there exist two options. The first is to read emission data from GFAS data (Kaiser et al., 2012) which fits to the simulation date. The second option is to use seasonal fire emission data which was compiled based on ten years of GFAS data from 2015 to 2024. This seasonal fire climatology is then interpolated to the simulation time based on a quadratic function. For sulfate, there is an additional correction term to account for nucleation due to photocatalytic reactions taking into account temperature, relative humidity, zenith angle, and sulfate concentration.

An ad-hoc parameterization to account for particle growth depending on atmospheric humidity using a similar polynomial function as in the visibility diagnostic was introduced. This parameterization had a major impact on the verification results, since it improves the daily cycle of AOD by accounting for the higher humidity and thus larger particles during night and lower humidity and thus smaller particles during the day.

6.4 Selected Results

6.4.1 Mineral Dust Emissions

Using the parameterization based on Kok et al. (2014), we performed simulations to get a picture of the mineral dust emission characteristics produced by ICON. We performed 10-day slices of simulations for the whole year 2019, each started from interpolated initialized analysis data from DWD's deterministic ICON forecasting system. This approach using 10-day slices has the advantage that the simulations are close to the real weather patterns without the need of too many short simulations over the course of one year. The simulations were performed on an R2B6 grid (i.e., 40 km) which does not require extensive computational resources. In addition, this resolution was also used for DWD's global ensemble forecast at that time.

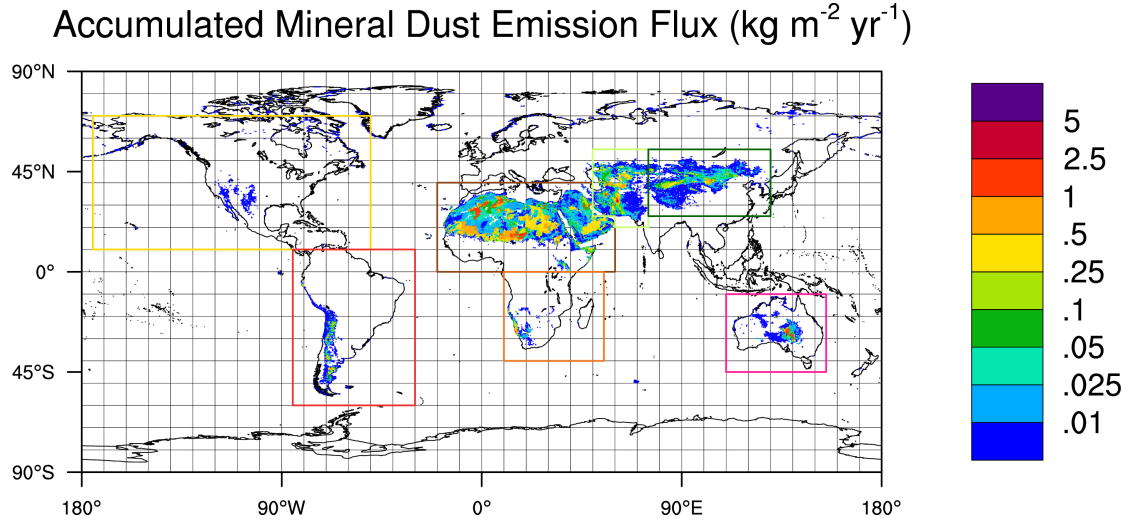


Figure 6.1: Accumulated mineral dust emissions calculated by an R2B6 simulation with ICON. This results in annual mineral dust emissions for 2019 of 3533 Tg yr^{-1} . The regions marked by colors will be used to assign contributions of individual regions to the total emissions in the following. North America is marked in yellow, South America in red, North Africa and the Arabian Peninsula in brown, South Africa in orange, the Middle East and Central Asia in light green, East Asia in dark green and Australia in pink color.

Figure 6.1 shows the mineral dust emission flux calculated with ICON. These sum up to a global emission flux of 3533 Tg yr^{-1} . To bring this value into a context, Tanaka et al. (2006) report a global emission flux of 1877 Tg yr^{-1} and Zender et al. (2003) report $1490 \pm 160 \text{ Tg yr}^{-1}$. Evan et al. (2014) compare mineral dust fluxes for North Africa from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (CMIP5) models with satellite-based estimates. While the CMIP5 models produce mineral dust emission fluxes of a similar magnitude as the previously mentioned studies, estimates from satellite measurements are in the order of 4500 Tg yr^{-1} . A possible explanation for this apparent mismatch is that models are tuned towards AOD measurements and, thus, a systematic bias in the size distribution leads to significantly wrong dust emission fluxes (Kok et al. 2011; Evan et al. 2014).

The horizontal distribution of the dust emissions closely resembles the well-known dust source regions (a comprehensive summary is given by Schepanski, 2018), with particularly strong emissions in regions that are known to be major source regions. The Sahara in general is the strongest source region. There are, however, regional differences. One hot spot of dust emission in the Sahara is the Bodele Depression. There are further hot spots in the Grand Ergs in the north-western part of the Sahara. The dominating source region in South Africa is the Namib Desert. On the Arabian Peninsula, the Rub' al Khali stands out. Further east, the Lut Desert in Iran shows a strong peak. The dust emissions of Karakum Desert are also distinctive. In Eastern Asia, Taklamakan and Gobi Desert are significant source regions. In Australia, the dominating source region is Lake Eyre. In South America, a dry region producing emissions spans from Altiplano down south to Patagonia. The Great Basin in North America shows some weak emissions.

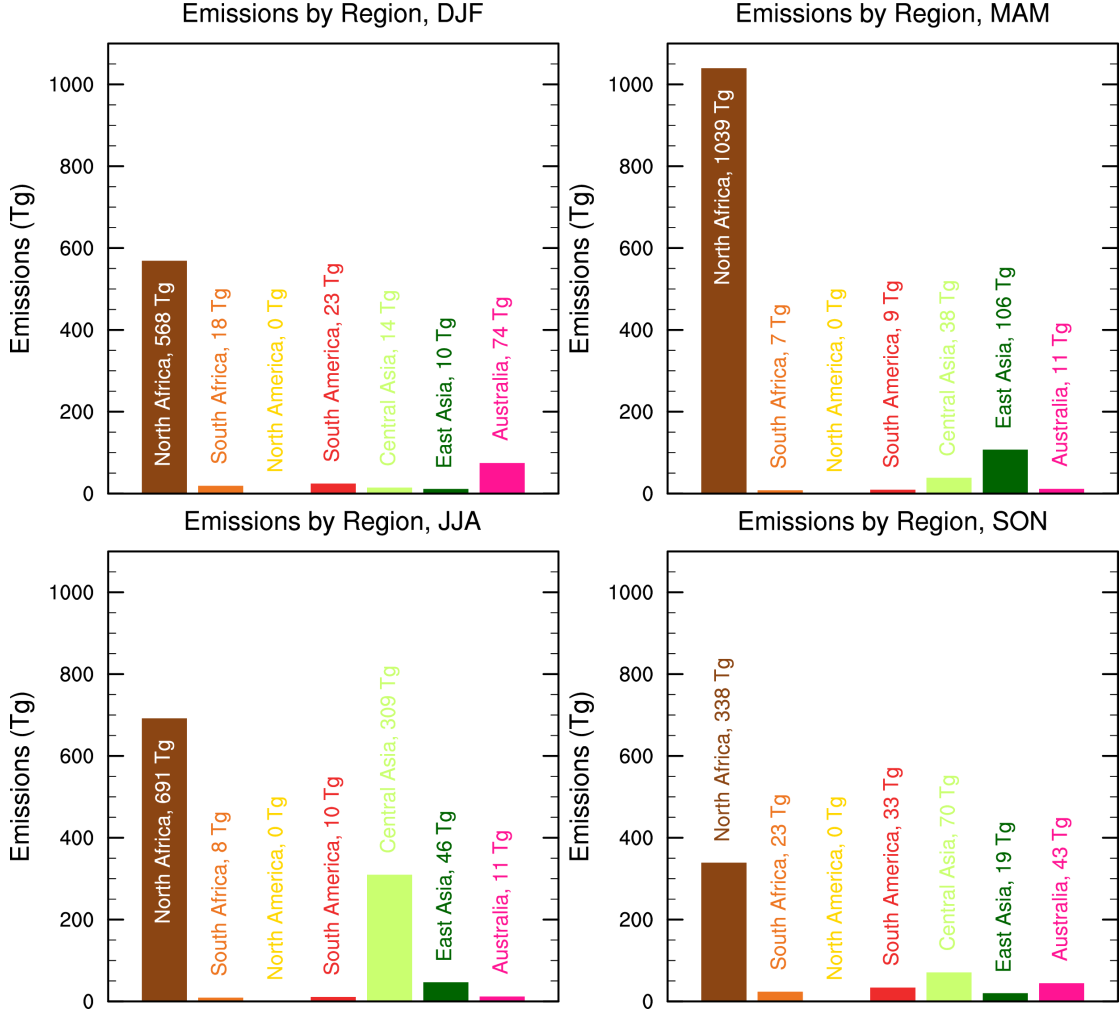


Figure 6.2: Seasonal mineral dust emissions fluxes for the source regions defined in Figure 6.1 for boreal winter (top left), spring (top right), summer (bottom left) and fall (bottom right).

The temporal evolution of the emissions is displayed in Figure 6.2. North Africa shows a strong peak during boreal spring and summer. In Central Asia, the Shamal winds lead to a peak during summer. Dust production in Eastern Asia happens mostly during spring. For source regions on the Southern Hemisphere, the peaks are in austral summer and spring. Although there are strong interseasonal differences, North Africa and the Arabian Peninsula are dominating the emissions in general. Besides that in boreal winter only Australia is showing a significant share. In summer, Central Asia has a large contribution. These results are in good agreement with previous studies (Schepanski, 2018) and show that, in general, the meteorological conditions necessary for dust emission are met well by our ICON simulations.

6.4.2 Sea Salt Emissions

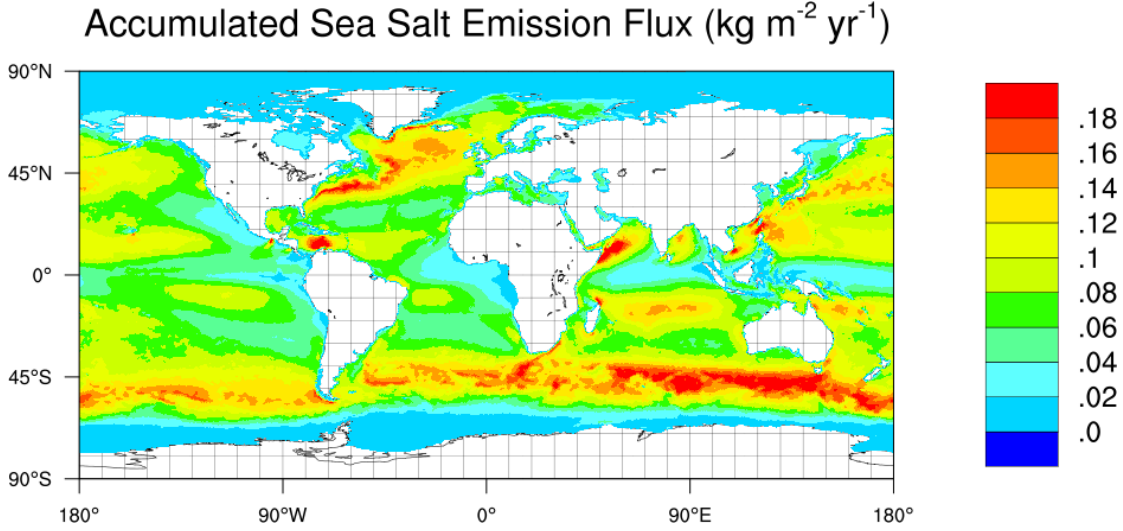


Figure 6.3: Accumulated sea salt emissions calculated by an R2B6 simulation with ICON

The annual sea salt emissions from a one year simulation similar to the simulation described above for mineral dust are shown in Figure 6.3. The results closely resemble the reference results from Grythe et al. (2014) and are, thus, not further discussed here.

6.4.3 Anthropogenic

Since the anthropogenic sources from the original Tegen data are not up-to-date, we add sources based on emission data from the Emissions Database for Global Atmospheric Research (EDGAR, <https://edgar.jrc.ec.europa.eu/>, Crippa et al. 2016). The data used corresponds to emissions for the year 2022. Black carbon, organic carbon, sulfur dioxide, ammonia and nitrogen oxides are added using an ad-hoc tuning factor to the corresponding AOD species of the Tegen aerosol. The gaseous precursors sulfur dioxide, ammonia and nitrogen oxides are simply added (with the tuning factor) to sulfate AOD species, since sulfur dioxide is the direct precursor of sulfate. Ammonia and nitrogen oxides are precursors for aerosol species with rather similar optical properties as sulfate.

The above described simplification leads to systematic sulfate underestimation in remote regions caused by (i) different lifetime of sulfur dioxide and sulfate and (ii) nucleation of sulfur dioxide at low temperatures. To account for this, a simplified nucleation parameterization was introduced which artificially creates sulfate if conditions for nucleation are favorable, i.e. if the sulfate concentration is low, temperature is low, relative humidity is high and solar radiation is available for photocatalytic reactions.

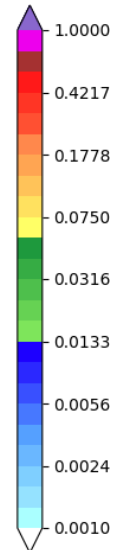
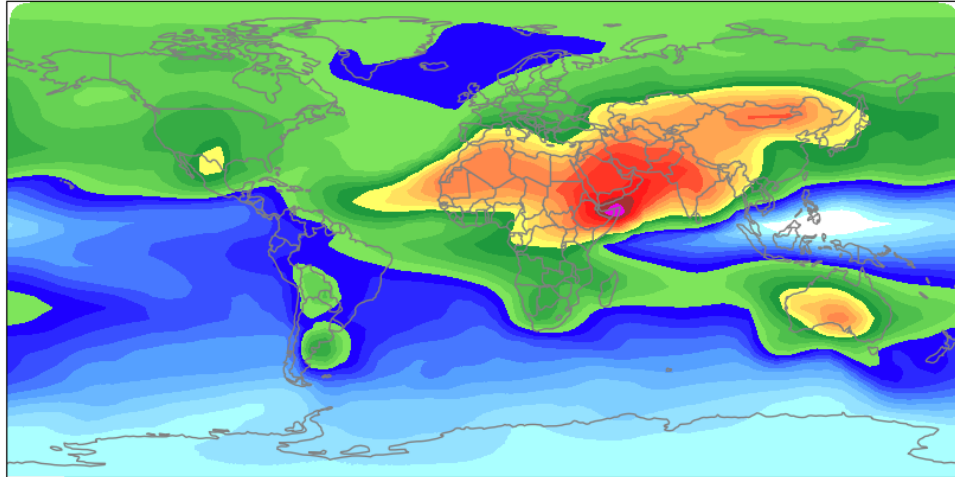
6.4.4 Wildfire

On a coarse scale, the seasonal cycle of Wildfire presence in the major source regions of wild fire emissions is remarkably similar each year. With all the simplifications used by *Prog2DAero*, using sophisticated modelling of wild fire occurrence or even daily satellite products would add expensive details which get obscured by other simplifications in *Prog2DAero* anyways. Thus, we decided to add wildfire emissions based on a seasonal climatology which was created for this purpose. This approach significantly reduced biases during these seasons as will be shown in the verification later. The climatology is based on the CAMS Global

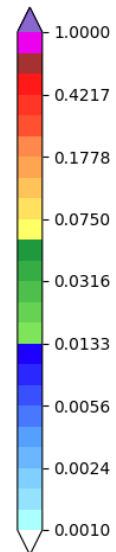
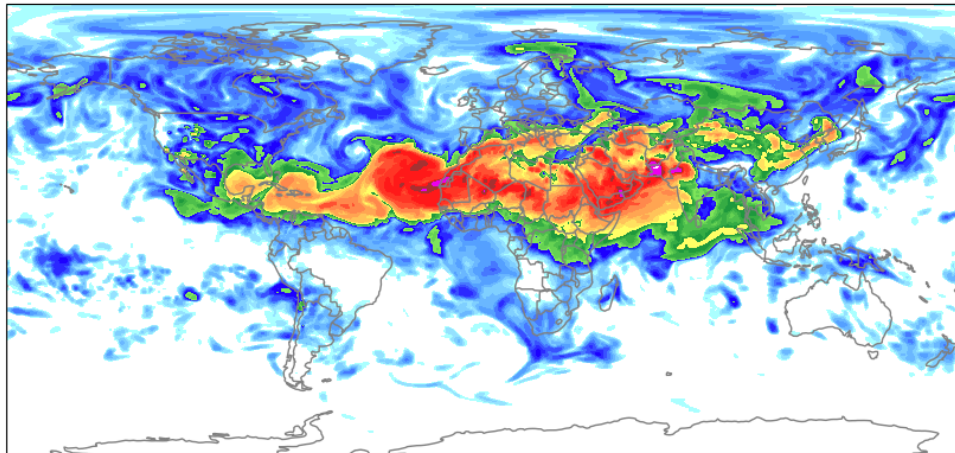
Fire Assimilation System (GFAS) data set (Kaiser et al., 2012) and combines averaged data per season (DJF, MAM, JJA, SON) from the years 2014 to 2023 for black carbon, sulfur dioxide and organic carbon.

6.4.5 Horizontal distribution of AOD

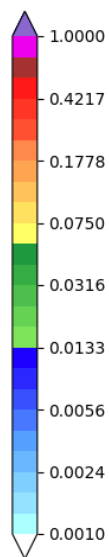
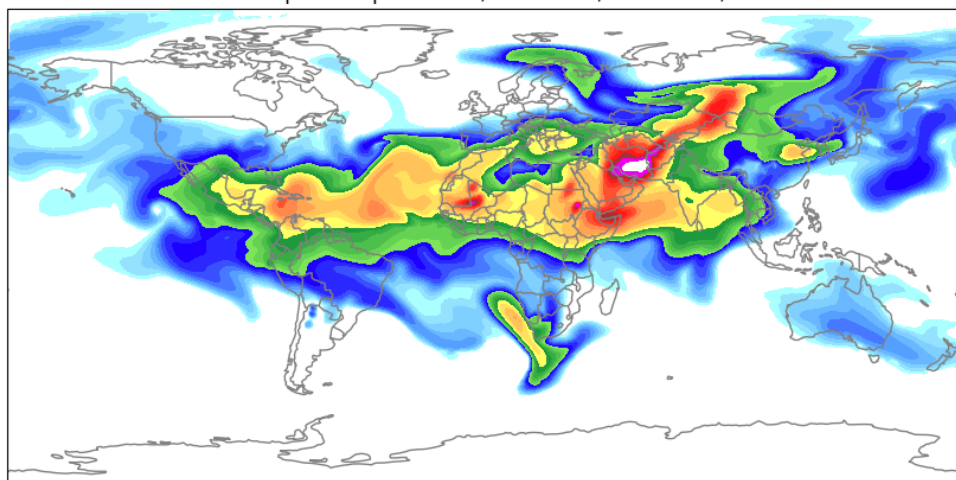
2023071500 Mineral Dust Optical Depth 550nm, Min: 0.001, Max: 0.991, Median: 0.014



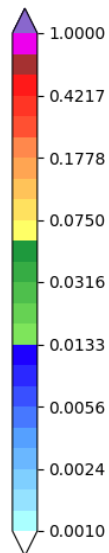
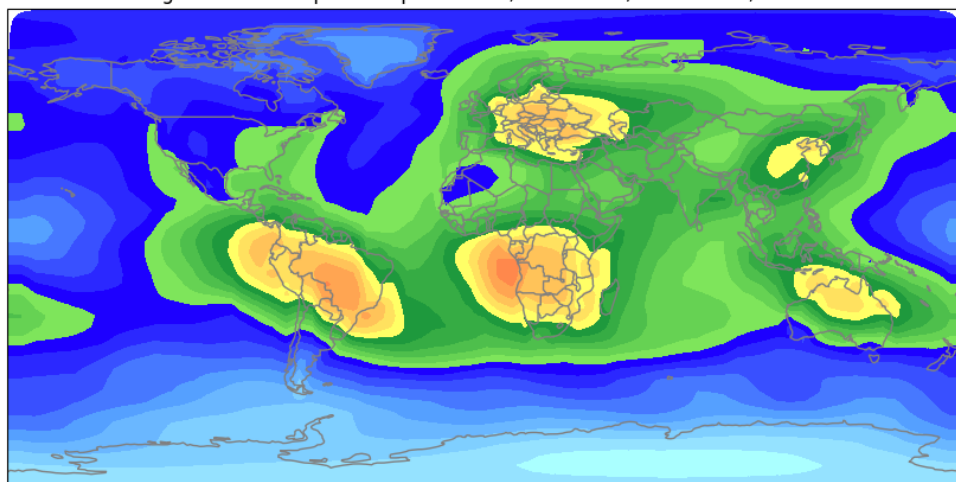
2023071500 Mineral Dust Optical Depth 550nm, Min: 0.000, Max: 1.427, Med: 0.001



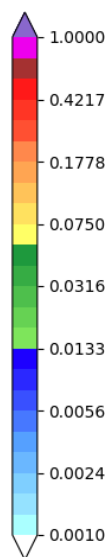
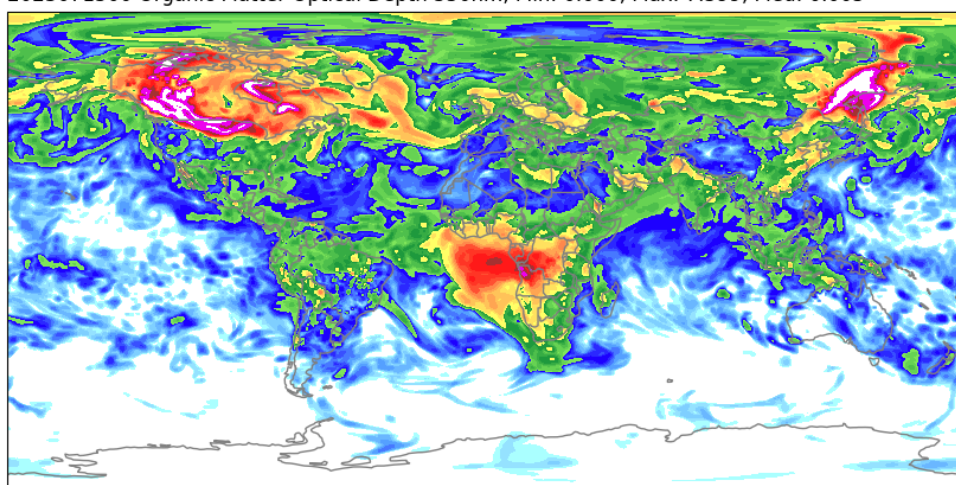
2023071500 Mineral Dust Optical Depth 550nm, Min: 0.000, Max: 1.913, Median: 0.001



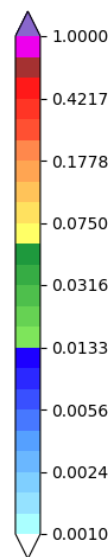
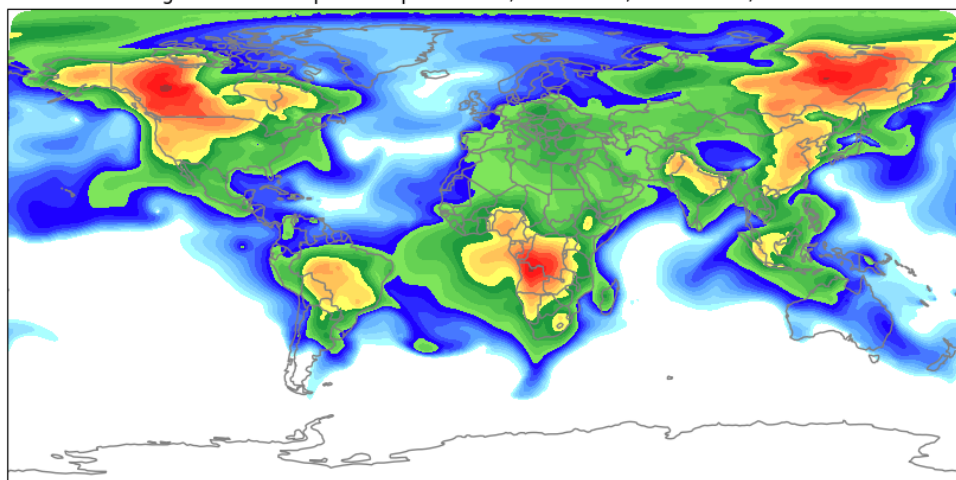
2023071500 Organic Carbon Optical Depth 550nm, Min: 0.001, Max: 0.213, Median: 0.015



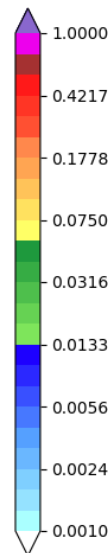
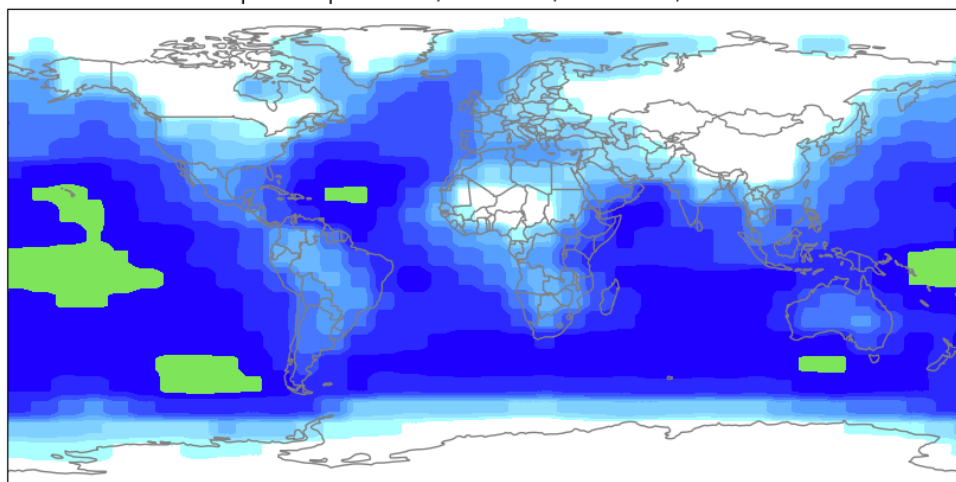
2023071500 Organic Matter Optical Depth 550nm, Min: 0.000, Max: 7.599, Med: 0.005



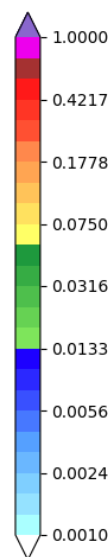
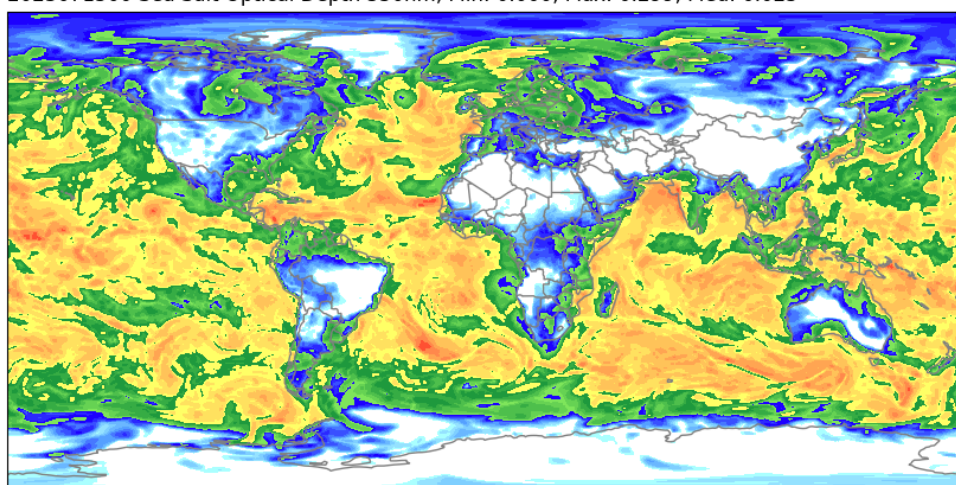
2023071500 Organic Carbon Optical Depth 550nm, Min: 0.000, Max: 0.631, Median: 0.004



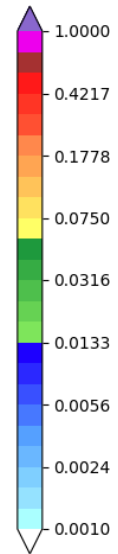
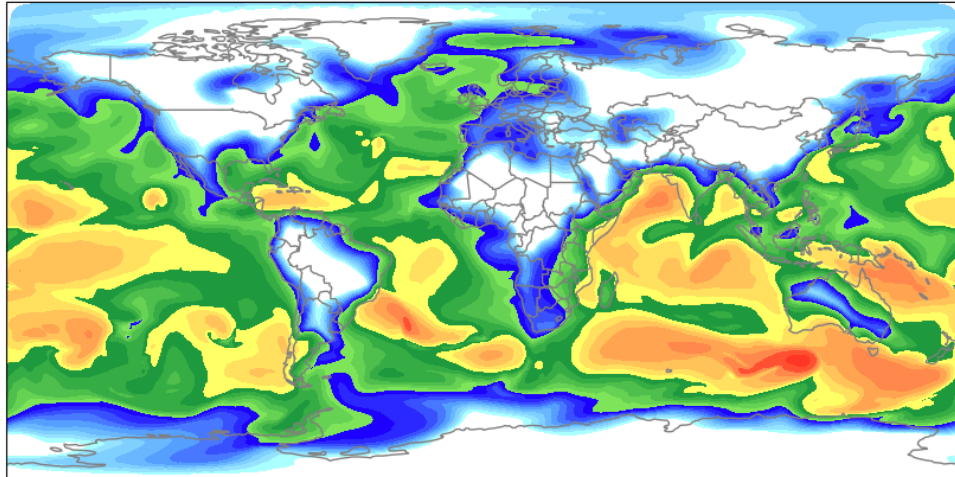
2023071500 Sea Salt Optical Depth 550nm, Min: 0.000, Max: 0.017, Median: 0.007



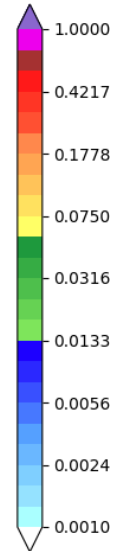
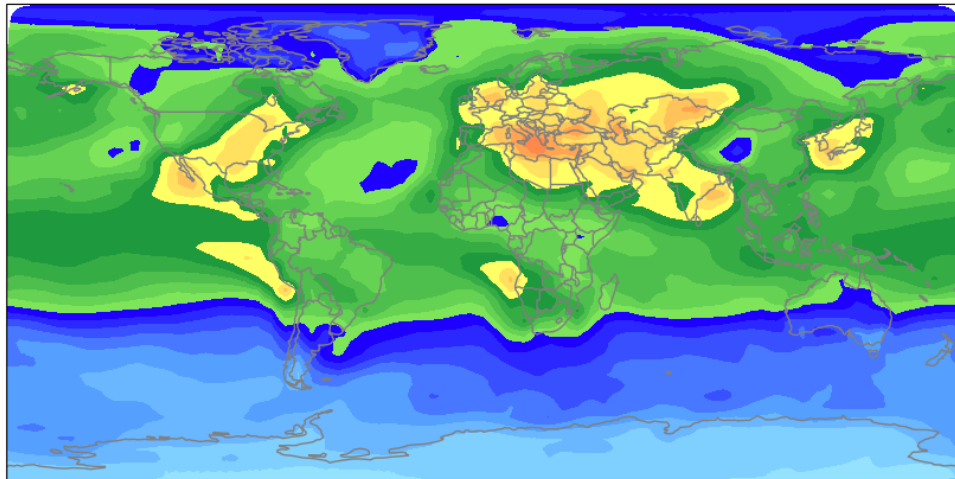
2023071500 Sea Salt Optical Depth 550nm, Min: 0.000, Max: 0.299, Med: 0.025



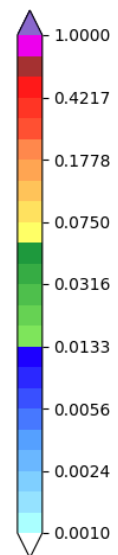
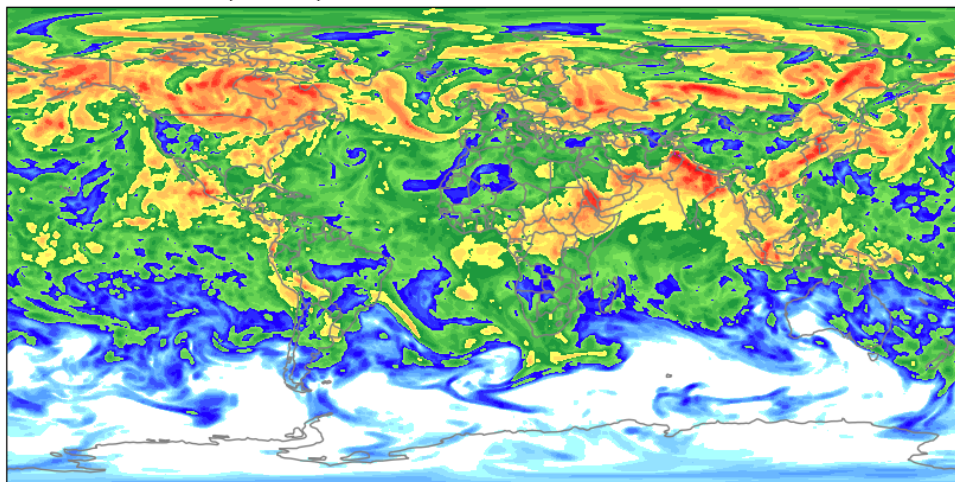
2023071500 Sea Salt Optical Depth 550nm, Min: 0.000, Max: 0.353, Median: 0.030



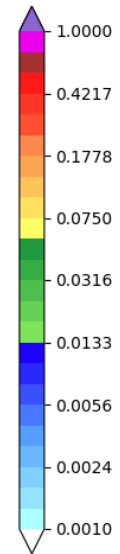
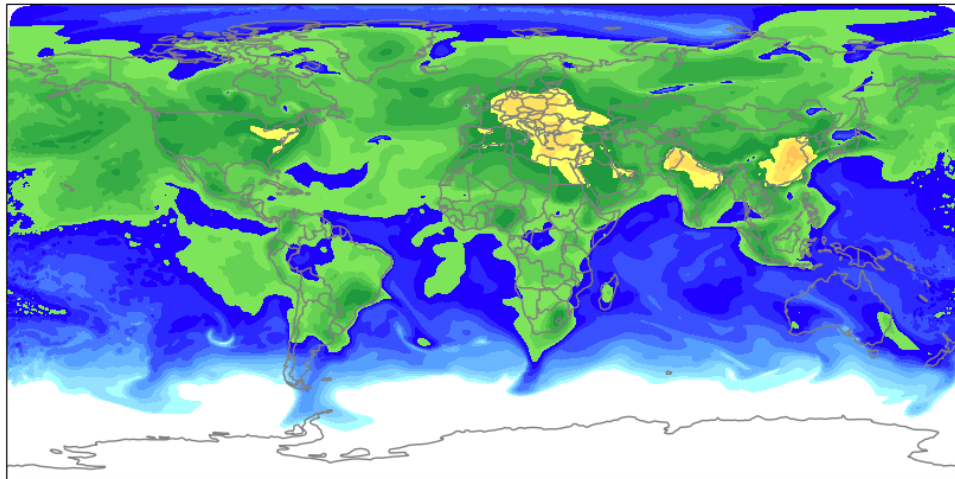
2023071500 Sulfate Optical Depth 550nm, Min: 0.002, Max: 0.216, Median: 0.023



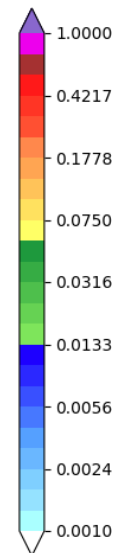
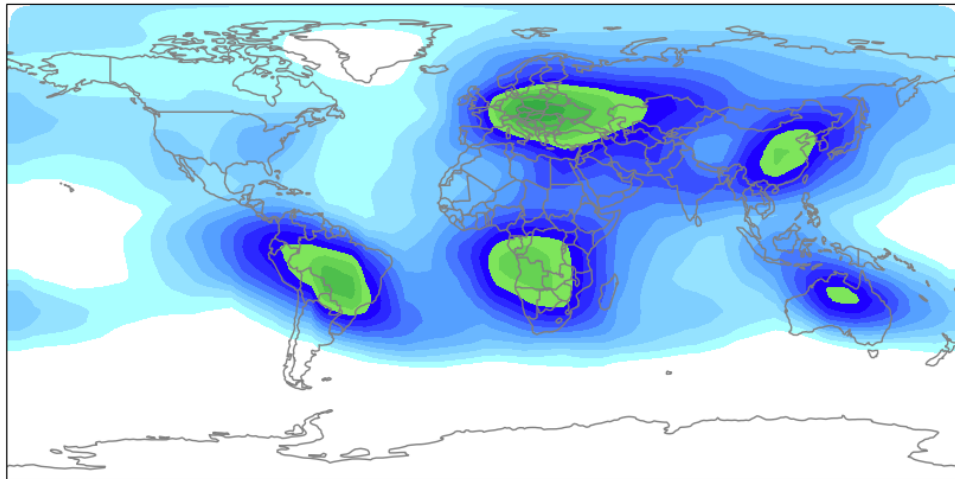
2023071500 Sulfate Optical Depth 550nm, Min: 0.000, Max: 0.827, Med: 0.020



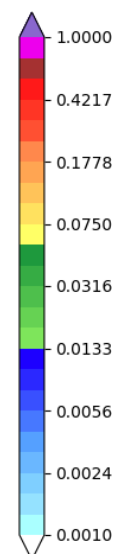
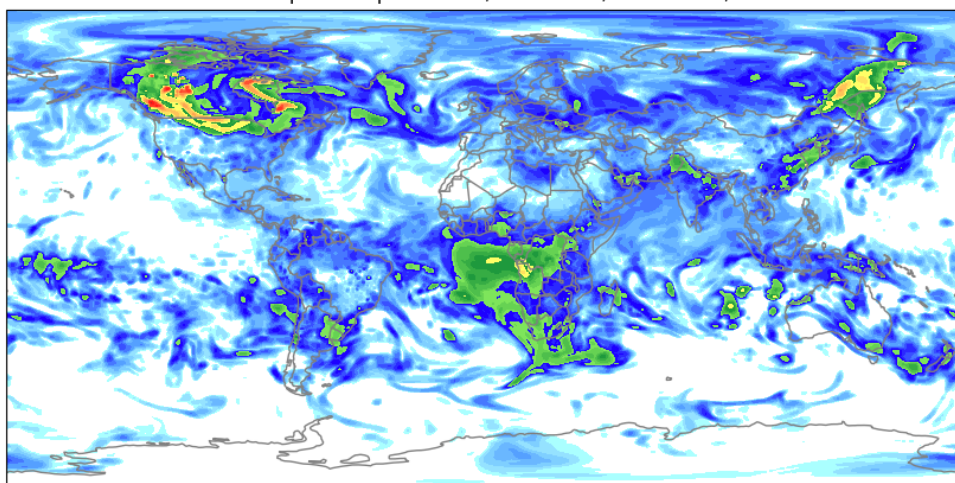
2023071500 Sulfate Optical Depth 550nm, Min: 0.000, Max: 0.100, Median: 0.012



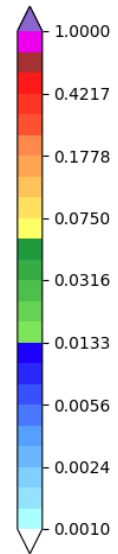
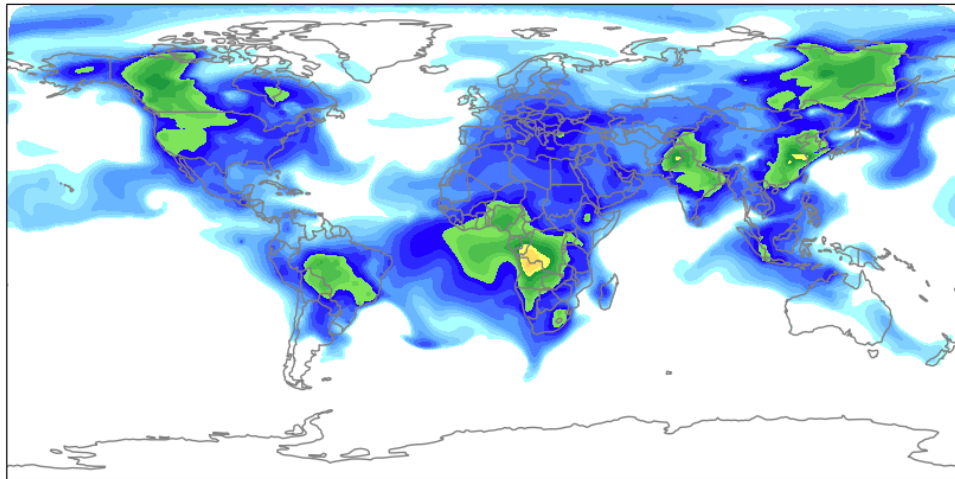
2023071500 Black Carbon Optical Depth 550nm, Min: 0.000, Max: 0.039, Median: 0.002



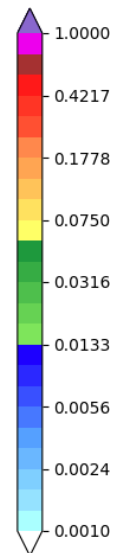
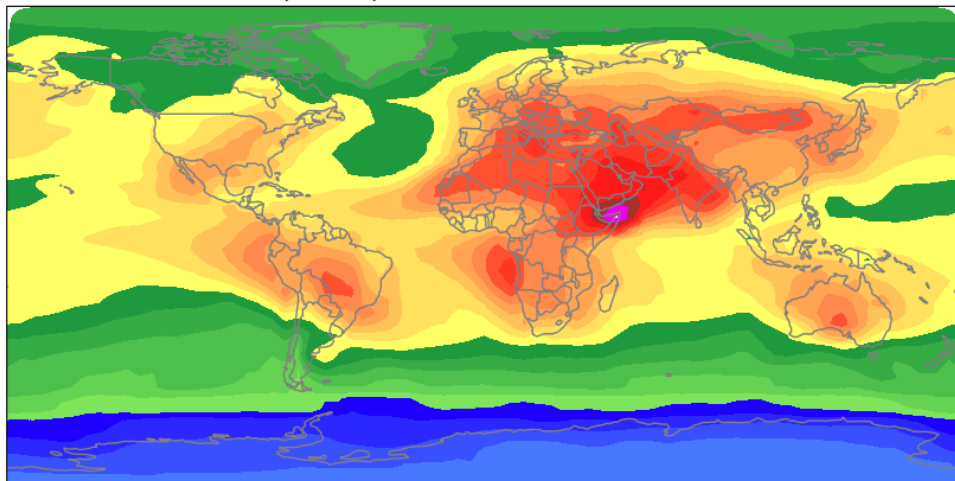
2023071500 Black Carbon Optical Depth 550nm, Min: 0.000, Max: 0.582, Med: 0.002



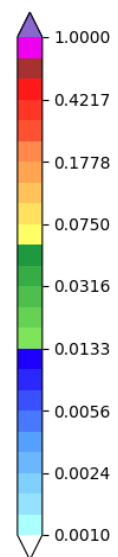
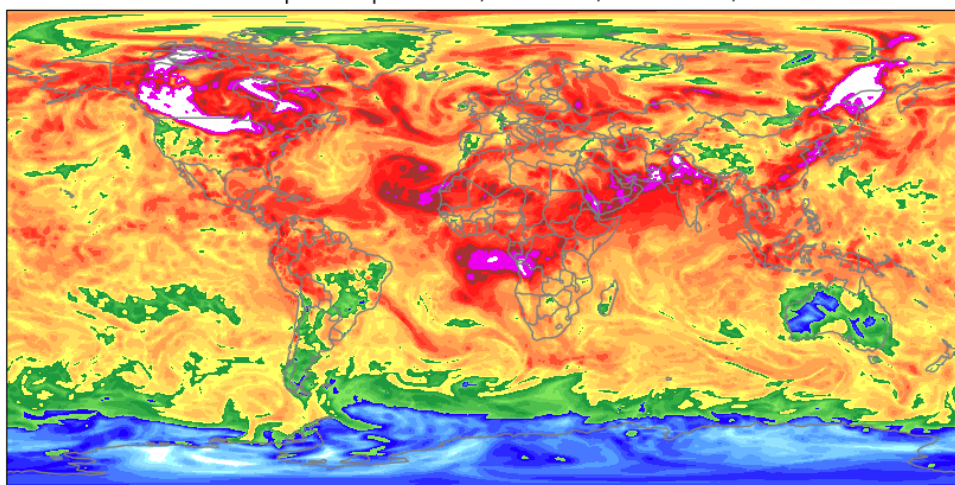
2023071500 Black Carbon Optical Depth 550nm, Min: 0.000, Max: 0.102, Median: 0.001



2023071500 Total Aerosol Optical Depth 550nm, Min: 0.005, Max: 1.055, Median: 0.071



2023071500 Total Aerosol Optical Depth 550nm, Min: 0.000, Max: 11.886, Med: 0.101



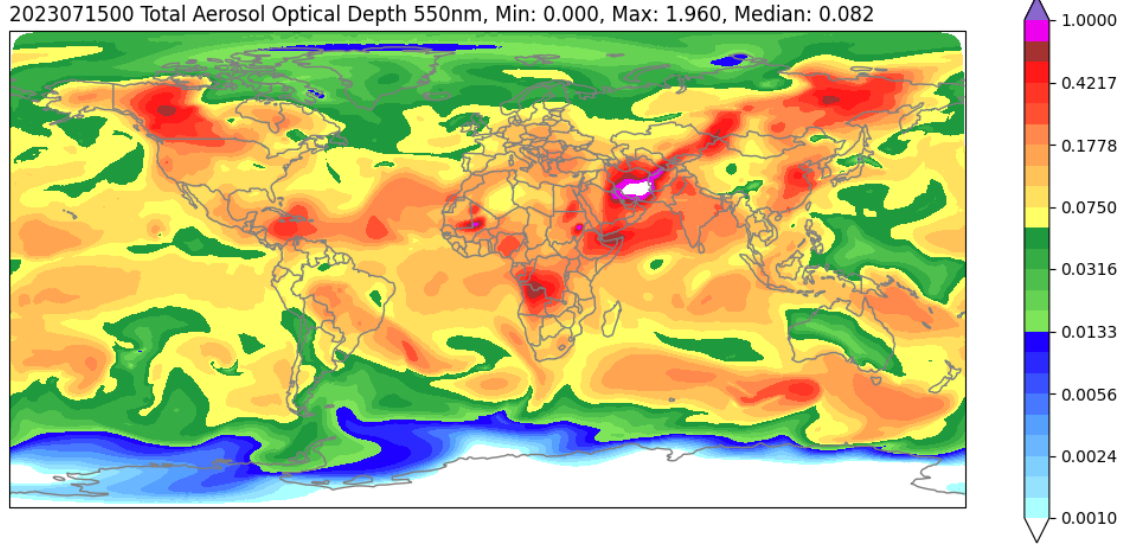


Figure 6.4: AOD of the five different species and total AOD on 15 July 2023. For each species, the panels show Tegen, Prog2DAero and CAMS from top to bottom.

In order to get an impression of the global AOD distribution, figure 6.4 shows an example for the distributions of the original Tegen climatology, the results of Prog2DAero and CAMS reanalysis data (Copernicus Atmosphere Monitoring Service, 2020; Inness et al., 2019) which can be seen as a reference since it includes a sophisticated aerosol scheme in combination with data assimilation. The simulations used to generate these data are similar to the above described simulations with 10-day slices, reinitializing the meteorology from DWD analysis every 10 days. The aerosol is cycled and can thus spin up. The example in figure 6.4 shows the distribution for July 15, 0 UTC. For all the different species and for the total AOD, the Prog2DAero results are closer to the distributions of CAMS than the original Tegen aerosol. This is not only the case for this example date, but for the whole year (not shown). While it can not be expected from Prog2DAero to resemble fine-scale details due to the simplicity of the parameterization, the general patterns are reflected quite well, with the major plumes in the right places throughout the year. It should be pointed out that this is also the case for the individual species which is quite important since the optical properties are significantly different between the species. Throughout the whole year, the wildfire climatology has a major impact on the dominating patterns in black carbon, organic carbon and sulfate improving the overall picture in an eyeball comparison tremendously.

6.5 Comparison to Measurements

HohenpeissenbergDWD, 47.801900°N, 11.011900°E

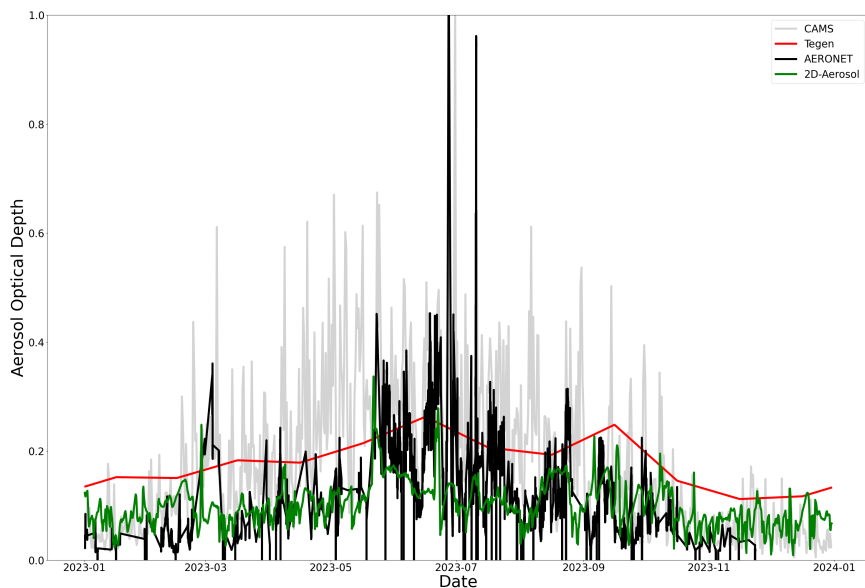


Figure 6.5a: Comparison of simulated total AOD at 550nm with sun photometer (AERONET) measurements for DWD's measurement station at Hohenpeissenberg. The black line are the measurements, the red line is Tegen aerosol, the grey line is CAMS data and the green line is Prog2DAero.

MetObs_Lindenberg, 52.209275°N, 14.120870°E

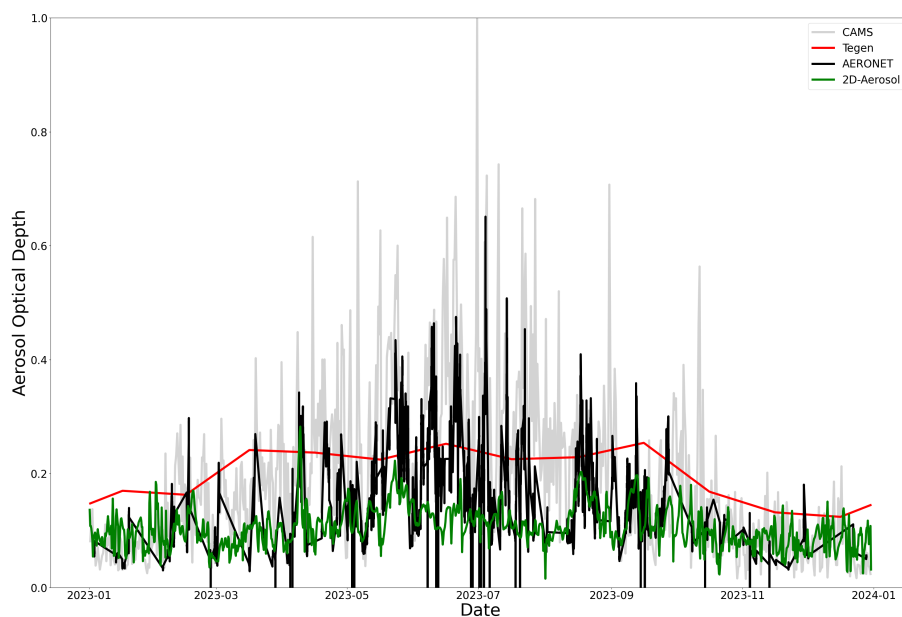


Figure 6.5b As Figure 6.5a, but for Lindenberg, Germany.

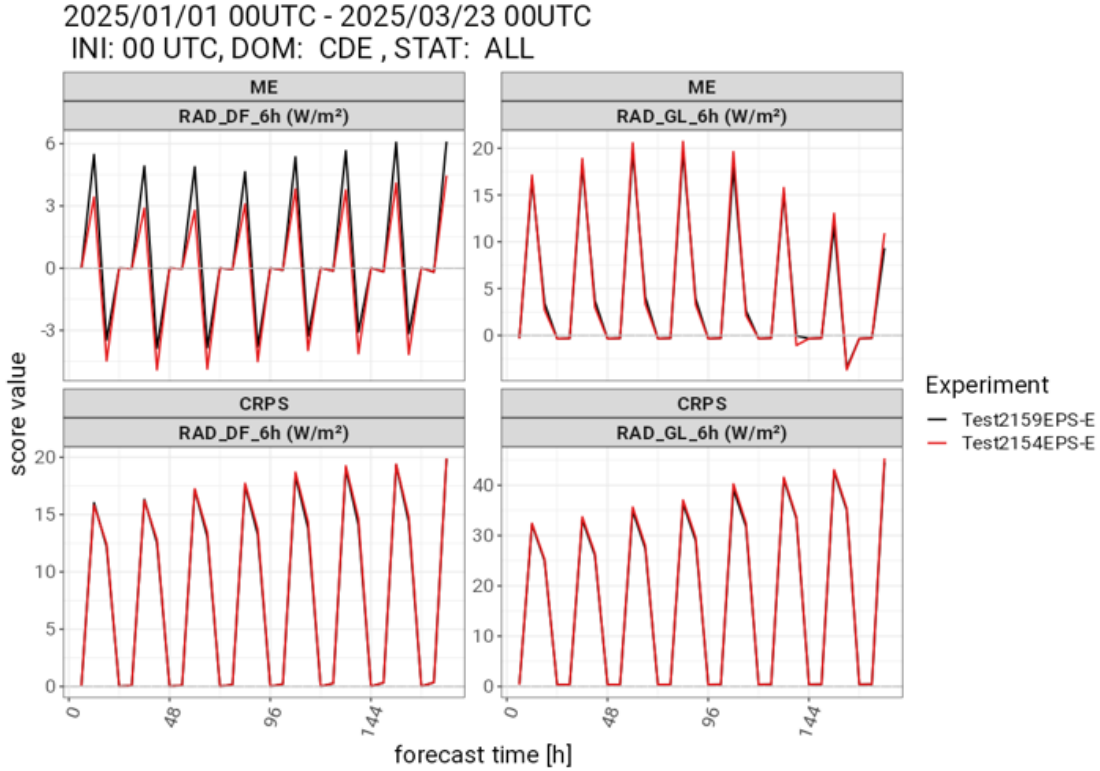
While the previous section provided a more qualitative comparison to a dataset that contains measurements data (i.e. reanalysis data), we want to provide some direct comparison with

measurements in this section. Since our focus region is Germany, we are using AERONET data from the two sites operated by DWD in Hohenpeissenberg (Figure 6.5a) and Lindenberg (Figure 6.5b).

It directly catches the eye that Tegen systematically overestimates the AOD under present day conditions. Technical improvements and stricter environmental regulations have decreased the particulate matter load in Germany steadily since the 1980s, which is why Tegen, generated in the mid 90s does not reflect present day conditions well anymore. This was also part of the motivation to update the aerosol in ICON-NWP. Especially during autumn, winter and early spring, CAMS as well as Prog2DAero are closely around the measurements, without a significant bias. During late spring and summer, Prog2DAero seems to underestimate peak concentrations. At least partly, this is due to an underestimation of mineral dust outbreak strength. Overall, most of the time, Prog2DAero is closer to the measurements than Tegen and thus should provide a better estimate of AOD than the currently used climatology. This is not only true for the two shown stations, but with few exceptions for all 450 AERONET stations that provide data during 2023 (not shown).

6.6 Verification

In order to verify the impact of Prog2DAero on NWP forecasts, we performed simulations for global ICON from 1 January to 15 March 2025 (winter period) and from 1 May to 15 July 2025 (summer period) using the operational NWP setup at DWD. Mineral dust from Prog2DAero was not included for these simulations since it did not show a beneficial impact. The aerosol cloud coupling is, since Prog2DAero uses the same species as Tegen, done with the same methods as in the reference.



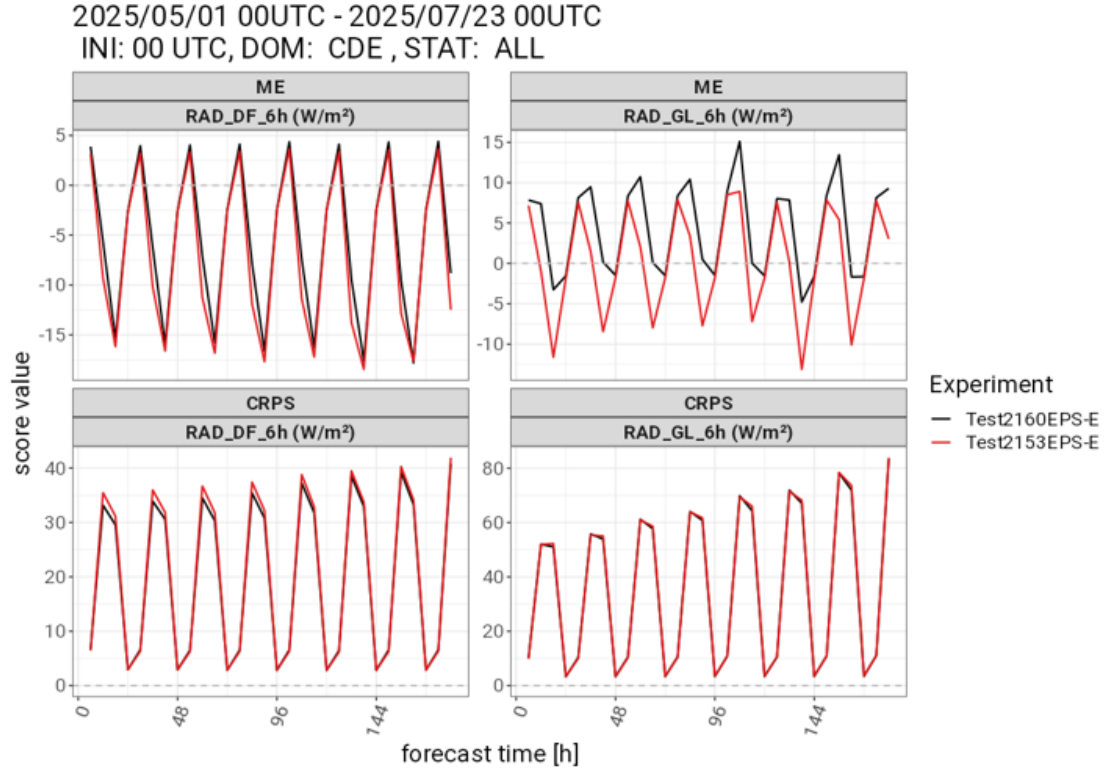


Figure 6.6a: Radiation scores in the EPS forecasts in winter for Germany. Top: Mean error, bottom: CRPS, left: diffuse radiation, right: global radiation, black: Prog2DAero, red: reference. **Figure 6.6b:** Radiation scores in the EPS forecasts in summer for Germany. Top: Mean error, bottom: CRPS, left: diffuse radiation, right: global radiation, black: Prog2DAero, red: reference.

Figure 6.6a and 6.6b show the radiation scores in the EPS system for summer and winter. The slight reductions in radiation biases lead to significant improvements in the EPS scores while the deterministic scores are neutral or mixed (not shown).

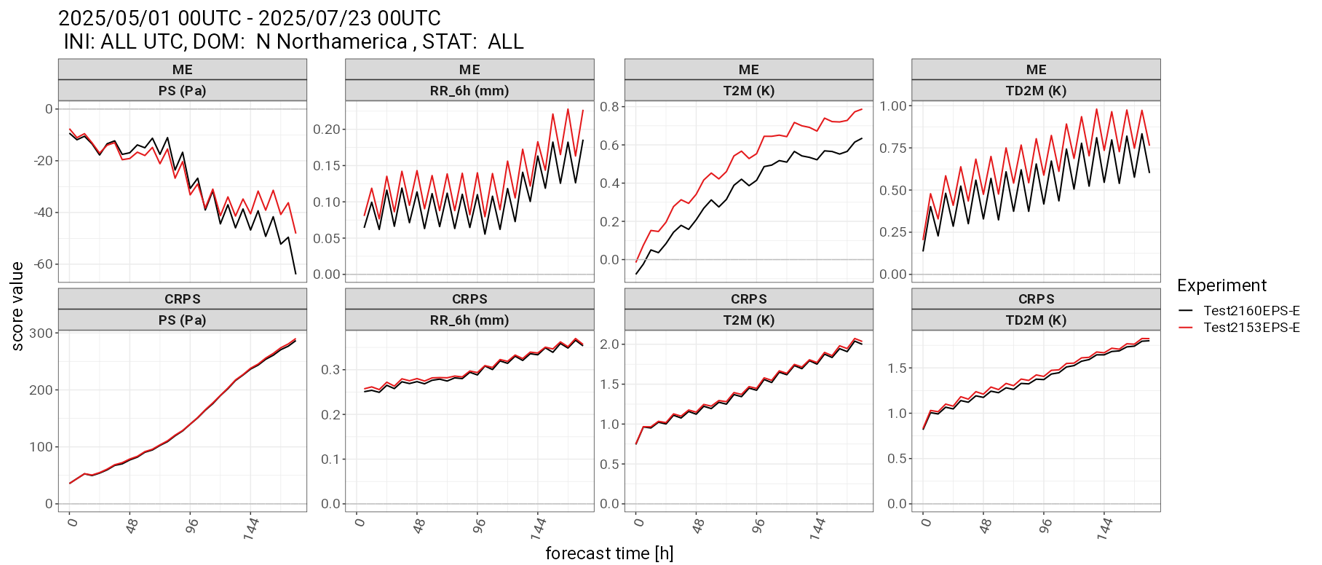
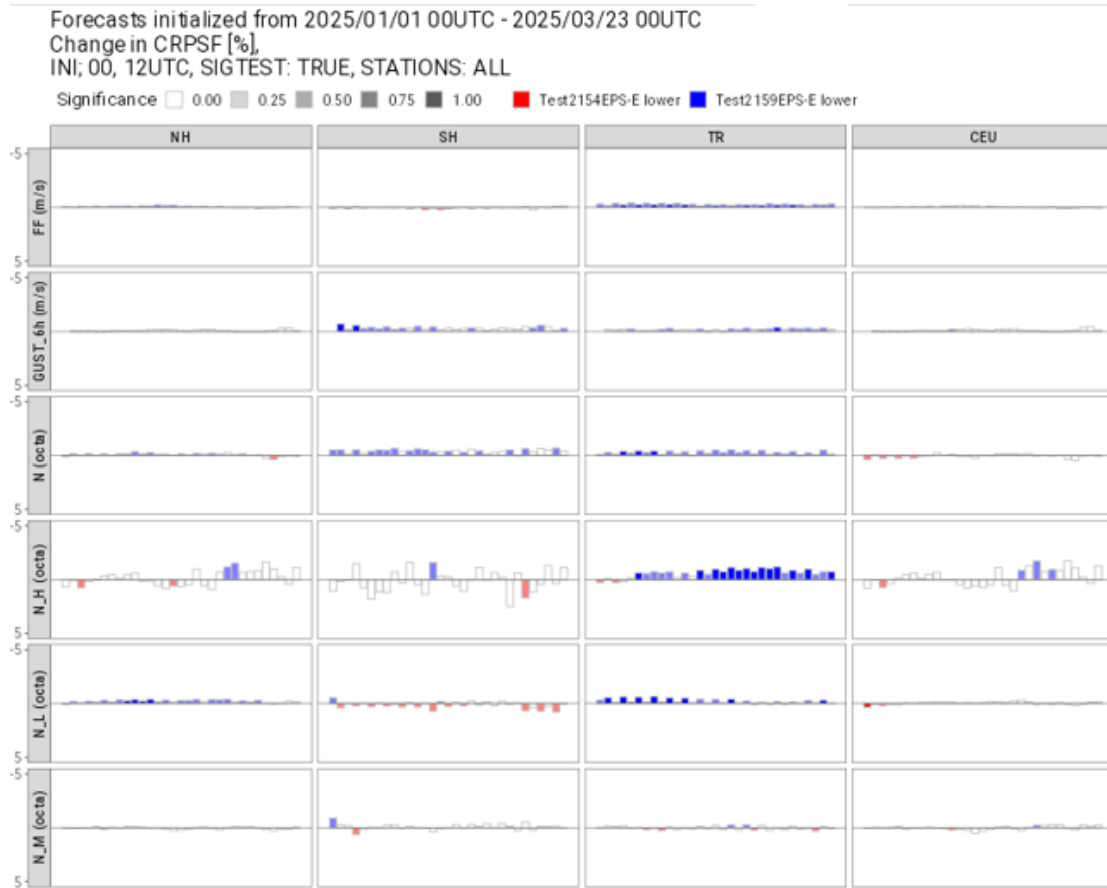


Figure 6.7: Selected EPS scores in summer for North America. Top: mean error, bottom: CRPS, black: Prog2DAero, red: reference, from left to right: surface pressure, 6-hourly rain rate, Temperature in 2m height, dew point in 2m height.

The impact of the wildfire emissions can, for example, be clearly seen in the summer 2025 scores for North America in Figure 6.7 with significant improvements even for indirectly related variables like rain rate. This is remarkable, since the wildfire climatology as described above, uses seasonal averages for the years 2015-2024 and confirms the assumption that the major wildfire events with a large-scale impact depend mostly on the season and less on the year.



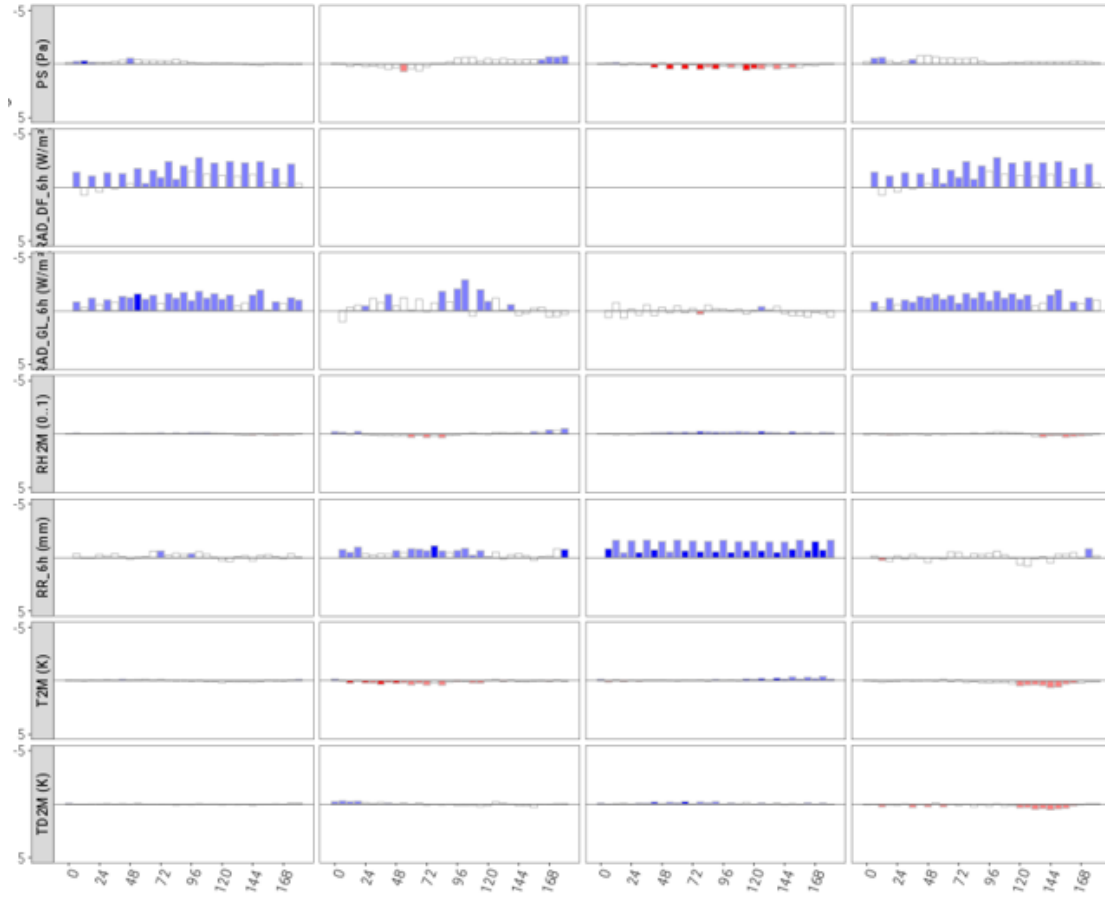


Figure 6.8a+b: Synop scorecard for winter, EPS. Blue shows an improvement in CRPS score with Prog2DAero. From left to right: Northern Hemisphere, Southern Hemisphere, Tropics, Europe. From top to bottom: wind speed, 6-hourly gusts, total cloud cover, high cloud cover, low cloud cover, mid cloud cover, surface pressure, diffuse radiation, global radiation, relative humidity in 2m height, 6-hourly rain rate, temperature in 2m height, dew point in 2m height.

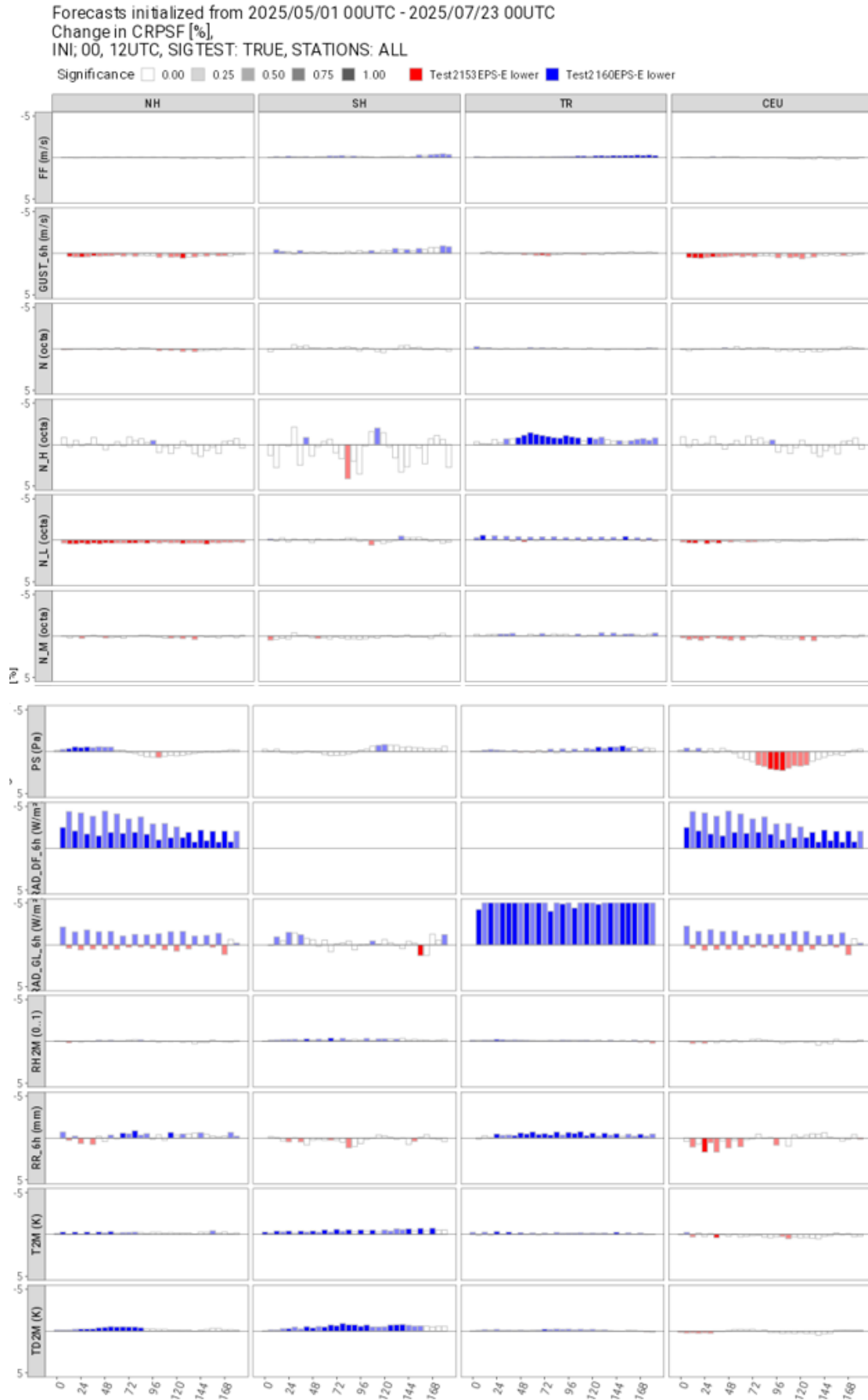


Figure 6.9a+b: Synop scorecard for summer, EPS. Blue shows an improvement in CRPS

score with Prog2DAero. From left to right: Northern Hemisphere, Southern Hemisphere, Tropics, Europe. From top to bottom: wind speed, 6-hourly gusts, total cloud cover, high cloud cover, low cloud cover, mid cloud cover, surface pressure, diffuse radiation, global radiation, relative humidity in 2m height, 6-hourly rain rate, temperature in 2m height, dew point in 2m height.

Figures 6.8 and 6.9 show the scorecards for winter and summer in the ensemble prediction system. As pointed out before while the deterministic scores are mostly neutral/mixed, the reductions in biases show their impact mostly in the EPS. There are significant improvements especially in the radiation scores for all regions. The slight degradation of gust scores is due to a double penalty effect caused by slightly higher gusts.

6.7 Combination with ICON-ART

Since the more sophisticated aerosol from ICON-ART uses Tegen climatological aerosol complementary for species that are not considered by the ICON-ART setup, *Prog2DAero* can be used complementary to ICON-ART in a similar way. For example by using natural aerosol (Mineral Dust, Sea Salt) from ICON-ART and anthropogenic and wildfire species (Sulfate, Organic Carbon, Black Carbon) from *Prog2DAero*. Please note, however, that the combination of *Prog2DAero* with ICON-ART has not been thoroughly tested yet.

6.8 Summary

A strongly simplified, 2-dimensional aerosol scheme *Prog2DAero* has been introduced in ICON. It builds upon the currently used Tegen climatology and adds simplified transport, horizontal diffusion as well as source and sink terms for AOD. Comparisons to measurements data (Aeronet) and to more sophisticated aerosol schemes which include data assimilation (CAMs) show strong improvements compared to the original Tegen climatology. This is partly due to changes in the anthropogenic emissions since Tegen climatology was created in the mid 90s, but partly also due to the transport being able to account for the impact on current weather conditions on the AOD. The most remarkable impact on the overall results was caused by the addition of a seasonal wildfire climatology and accounting for hygroscopic growth of particles. The scheme increases the runtime typically less than 0.5%. DWD is currently in the final steps to prepare *Prog2DAero* for operational usage. The verification results show an overall neutral to positive impact, especially on the ensemble prediction system. The next steps will be to investigate combining *Prog2DAero* with mineral dust from ICON-ART and to add boundary data supply to allow for a usage within limited-area simulations.

Acknowledgements: We thank Ralf Becker and Frank Wagner for operating and providing AERONET data for Lindenberg and Hohenpeissenberg. We acknowledge the use of Copernicus Atmosphere Monitoring Service Information.

7 Implementation of spectral-bin microphysics in ICON

(P. Khain, K. Shpund, A. Seifert, D. Reinert, U. Schättler, H. Muskatel, Y. Levi, A. Givati and A. Khain)

7.1 Introduction

The Spectral Bin Microphysics (SBM) parametrization is a detailed cloud microphysics scheme used in atmospheric models that explicitly represents the size (or mass) distribution of cloud particles by dividing them into discrete size (or mass) bins. The implementation of SBM in ICON, alongside the existing 1-moment and 2-moment (2M) microphysics schemes, was divided into two stages: implementation of a simplified "Warm-Phase" version first, and implementation of the "Mixed-Phase" version second. In the following, we describe each of the two stages separately. Finally, we briefly describe our development status as part of the ongoing ACLIIM project.

7.2 Implementation of Warm-Phase SBM in ICON

The Warm-Phase SBM version was implemented in ICON in 2022. The implementation was followed by comprehensive testing in an idealized supercell storm simulation. The results of the 2M scheme and SBM were compared in all aspects related to warm processes, especially with regard to sensitivity to aerosols. In all simulations, a strong storm with maximum updrafts exceeding 25 m/s was simulated. The maximum vertical velocity in the 2M scheme does not depend on aerosols. However, the maximum vertical velocity in SBM with high aerosol concentration was found to be substantially higher than in the case of low aerosol concentration. Despite the insensitivity of the maximum vertical velocity to aerosols, the microphysics of the 2M scheme is sensitive to aerosols. Both the SBM and 2M schemes showed faster rain formation in the case of low aerosol concentration; both schemes indicate that the first raindrops form when the mean volume radius exceeds $\sim 15 \mu\text{m}$. In both schemes, the first raindrops form near cloud top in an undiluted core and fall along the cloud edges at the mature stage. At the decaying stage, raindrops fall through the cloud core. The zone of rainfall in the lower few kilometres coincides with the zones of strong downdrafts. A substantial effect of aerosols on the intensity and spatial distribution of precipitation was found. In the case of low aerosol concentration, raindrops form earlier and at lower altitudes. As a result, the area covered by rain is smaller, but the maximum rain intensity is higher than in the case of high aerosol concentration.

As part of that implementation, a paper was published [Khain et al., 2022], "Warm-phase spectral-bin microphysics in ICON: reasons of sensitivity to aerosols." In this paper we also discussed the hindering effects of large supersaturation, via mass loading, on cloud development in the case of low aerosol concentration, and examined the validity of the well-known saturation adjustment procedure.

An example of this comparison of the SBM and 2M schemes in a warm-phase scenario is presented in Fig. 7.1.

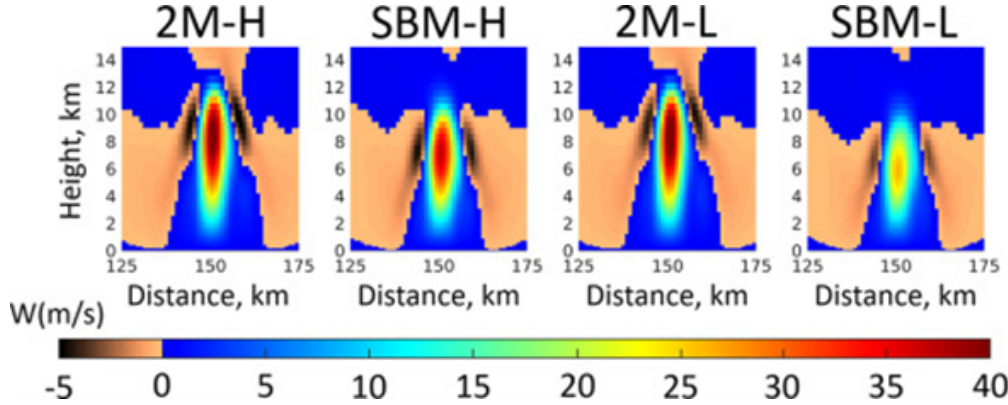


Fig 7.1. The vertical velocity fields in all simulations in x-z cross-sections through the cloud cores at 27 min. The simulations are: 2M with high aerosol concentration (2M-H), SBM with high aerosol concentration (SBM-H), 2M with low aerosol concentration (2M-L), and SBM with low aerosol concentration (SBM-L).

7.3 Implementation of Mixed-Phase SBM in ICON

In summer 2025, the mixed-phase version of the SBM scheme was implemented in the ICON model, and since October 2025 it has been included in the official public release.

The SBM scheme is activated using the namelist parameter `itype_gscp=8`. In contrast to the bulk schemes, the SBM scheme does not use the saturation adjustment procedure before and after the call to the microphysics scheme. To solve the equation of diffusional growth/evaporation, SBM uses the supersaturation change during the last time step, which occurs due to advection, with contributions from other physics processes. The coupled equation system for diffusional growth and supersaturation is solved so that supersaturations over water and ice are non-zero until the end of the microphysical time sub-steps. Therefore, it is required to turn off saturation adjustment, i.e. to set the namelist parameter `inwp_satad=0`.

In order to calculate the supersaturation change during the time step, a special "SBM storage" (see `mo_sbm_storage.f90`) was implemented, which allows the temperature and water vapor of the previous time step to be saved and restored. The main "fast-physics" parametrizations called in ICON at every time step are the turbulent mixing ("turbdiff") and the microphysics. It is reasonable for SBM to use the supersaturation right after the advection, rather than the smoothed supersaturation after "turbdiff." Therefore, it is required to set the corresponding namelist parameter `lmicrophysicsFirst=.true.`.

In order to fully couple SBM to ICON's dynamics, it is required to set the corresponding namelist parameter `lsbm_coupled=.true.`. For testing purposes, there is an option to run ICON with 2M dynamics and microphysics and, on top of it, run SBM every time step with an option to analyze its output (e.g. using `extra_3d` variables). To choose this option, in which SBM does not have any influence on the model dynamics or microphysics, one needs to set the namelist parameter `lsbm_coupled=.false.`.

In addition to the already existing tracers in ICON, SBM includes 132 advected tracers. Three hydrometeor size distributions, for drops, ice/snow, and graupel/hail, are defined on a logarithmic mass-doubling grid containing 33 bins (tracers). The minimum particle radius is 2 μm and the maximum radius is 3.4 mm. Drops with radii exceeding 50 μm (bin number `krdrop=15`) are attributed to raindrops, while smaller drops are considered cloud droplets. Similarly, ice/snow particles with a bin number exceeding `krice=18` are attributed to snowflakes, and smaller particles are considered ice crystals. In contrast, the

33 graupel/hail bins are defined as either pure graupel or pure hail distributions via the `hail_opt` parameter. The size distributions of dry CCN are defined on a logarithmic mass grid, also containing 33 bins (tracers). The maximum CCN radius is taken to be 2 μm . The initial size distribution of aerosols playing the role of cloud condensation nuclei (CCN) applied in SBM is described as a sum of three log-normal distributions, representing a nuclei mode (ultrafine aerosols) centered at a radius of 0.005 μm , an accumulation mode centered at 0.035 μm , and a coarse mode centered at 0.31 μm (Ghan et al. 2011). Supersaturation and CCN properties are used to calculate the critical size using Köhler theory. CCN with sizes exceeding the critical value are converted to droplets, and the corresponding bins in the aerosol size distribution become empty. Non-activated aerosols are advected similarly to hydrometeors, so wind transports both hydrometeors and non-activated CCN. The settling velocity of CCN is neglected.

There are several options in SBM to define an initial vertical profile of CCN. Among others, the code includes definitions of theoretical maritime and continental options. By default, SBM uses a continental initial profile. A namelist scaling factor `tune_sbmcn` [0–1] allows the initial CCN concentration profile to be reduced with respect to the continental case. `tune_sbmcn=1` corresponds to the use of a pure continental profile, and `tune_sbmcn=0` is an approximation of the maritime case.

When implementing mixed-phase SBM in ICON, the interaction with other parametrizations was taken into account. ICON uses total water and ice contents (`qc`, `qr`, `qi`, `qs`, `qg`) in many places in the code. When using SBM, we keep advecting these total water contents but overwrite them with the integrals over the corresponding size distributions, right after the call to the microphysics. The vertical turbulent diffusion ("`turbdiff`") also uses cloud water, ice, and snow (`qc`, `qi`, `qs`). For consistency, the corresponding SBM bins (tracers) were added to the vertical turbulent diffusion as well. The convection scheme might also detrain `qc`, `qi`, `qr`, `qs`. For mass conservation, we "evaporate" this water, transferring it to water vapor `qv`, and subtract the corresponding latent heat release. Under appropriate conditions, this water vapor may condense into hydrometeors as part of SBM. Total water contents are used in ICON's initial and boundary conditions. In the case of SBM, a similar transformation to water vapor is applied.

Detailed documentation of the mixed-phase SBM implementation in ICON is available here: [SBM Overview — ICON documentation](#).

Fig. 7.2 compares the development of an idealized supercell near the equator in 2M (first row) and SBM (second row) 1-km ICON mixed-phase simulations. It nicely shows a similar cell evolution for various model time steps, from 2 to 10 seconds.

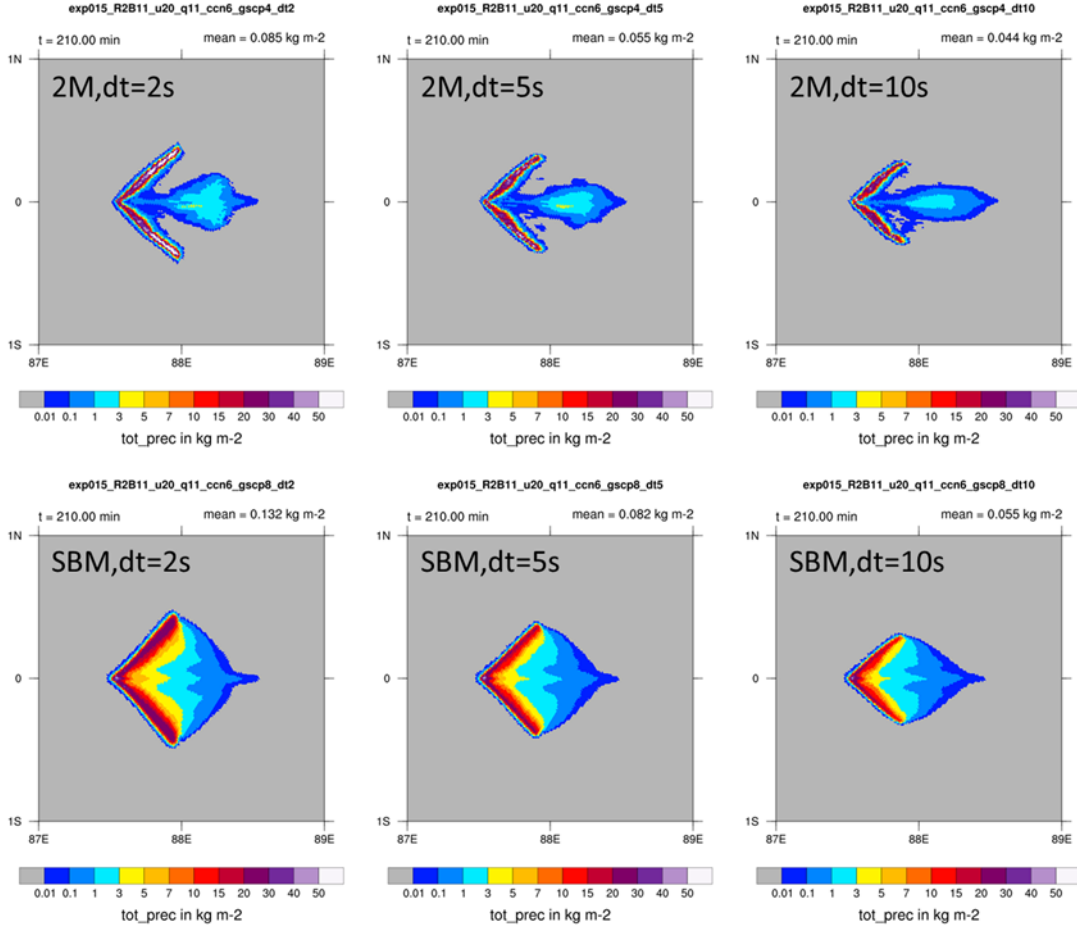


Fig 7.2. Development of an idealized supercell near the equator in 2M (first row) and SBM (second row) 1-km ICON simulations. A similar cell evolution is obtained for various model time steps, from 2 to 10 seconds.

7.4 Development status as part of the ACLIIM project

More recently, processes accounting for collision enhancement due to turbulence and concentration inhomogeneity have been implemented in a private development branch. The implementation is physically based for drop-drop collisions, and its extension to mixed-phase collisions is being evaluated. Validation is carried out using idealized supercell storm simulations as well as real-case studies over the Eastern Mediterranean. Results are analysed in comparison with the 2M and 1M ICON microphysics schemes under both maritime and continental aerosol conditions. Moreover, an alternative scheme of turbulent enhancement of collisions by Onishi and Seifert (Onishi and Seifert, 2016, ACP) was implemented in ICON-SBM, and the comparison with the Pinsky and Khain scheme is ongoing.

The mechanism of turbulence enhancement is a major driver of the rapid onset of light precipitation. It produces a fast, non-linear intensification of precipitation: cloud droplets initially grow by diffusion into precipitation embryos, which then rapidly collide and accrete mass, forming larger drops that sediment and eventually reach the surface as precipitation. Fig. 7.3 presents the evolution of the liquid water content of a cumulonimbus cloud in an idealized Weisman-Klemp setup (Weisman and Klemp, 1982) after 30 minutes (a) and 40 minutes (b), in the warm-microphysics setup of ICON-SBM. From left to right, the following simulations are presented: polluted conditions without consideration of turbulent enhance-

ment of collisions (hereafter "no enh"), clean (maritime) conditions and "no enh," polluted conditions with consideration of turbulent enhancement of collisions (hereafter "enh"), and clean (maritime) conditions and "enh." Polluted conditions provide stronger cloud development with higher updrafts (not shown) in comparison with clean conditions, where larger drops collide faster, leading to earlier rain development. Turbulent enhancement shows a similar effect to simulating cleaner conditions, providing more efficient collisions, faster drop growth, and consequently faster rain development. In the following, real-case simulations are planned to verify the benefit of considering turbulent enhancement of collisions in ICON-SBM simulations (both Pinsky-Khain and Onishi-Seifert), by comparing them to radar and rain gauge data.

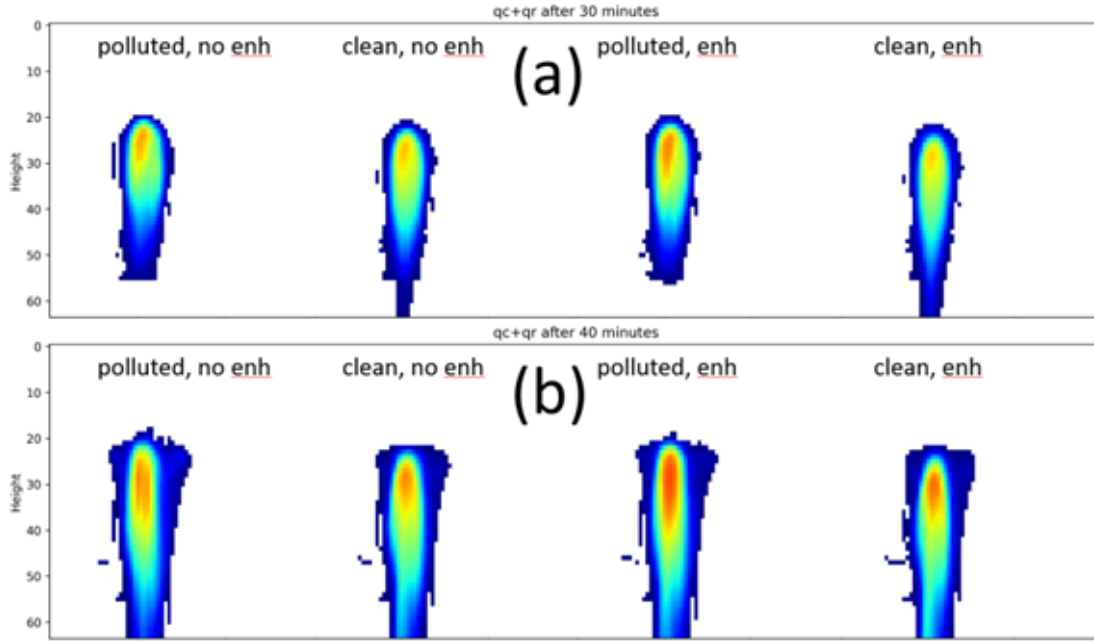


Fig 7.3. The evolution of the liquid water content of a cumulonimbus cloud in an idealized Weisman-Klemp setup after 30 minutes (a) and 40 minutes (b), in the warm-microphysics setup of ICON-SBM.

8 Test Case Verifications: The ICON model precipitation performance over central Greece during the storm "Daniel"

(E. Avgoustoglou, H. Muskatel)

8.1 Introduction

Storm Daniel is widely regarded as one of the most severe Mediterranean tropical-like cyclones (medicanes) ever recorded. Greece, particularly the central regions, experienced the most intense impacts, with extreme precipitation and extensive flooding. These exceptional conditions also provided a valuable opportunity to evaluate the regional configuration of the ICON model, building on earlier work by Avgoustoglou et al. (2025), in which results from the model's default aerosol climatology were published.

Under the methodology developed in that publication, the present report expands the analysis by incorporating four additional ICON model setups. This extended experimental frame-

work enables a broader assessment of how different climatological assumptions influence short-range precipitation forecasts during an extreme Mediterranean cyclone. A sequence of simulations was carried out for each climatology, covering the period when Storm Daniel produced its most destructive impacts.

Following this expanded setup, ICON was forced by boundary conditions from the operational ECMWF Integrated Forecast System (IFS). Forecasted accumulated precipitation was compared against observations from synoptic stations across the affected areas, while the evolution of the medicane was examined in reference to the minimum PMSL values, relating them to the corresponding ECMWF analysis fields. This ensured consistency with the established methodology while enabling a deeper exploration of aerosol-related sensitivities.

Research has shown that Mediterranean cyclones respond distinctively to aerosol loading, with dust particles from North Africa significantly modifying the thermal structure of the atmosphere during cyclogenesis. Observational studies have documented this feature during intense dust episodes, while model simulation errors due to Saharan dust episodes were reported by Hermes et al. (2024). The impact of aerosols on Mediterranean precipitation exhibits complex patterns through both direct and indirect effects (Solomos et al., 2011). Furthermore, the timing and intensity of precipitation in Mediterranean cyclones show strong sensitivity to aerosol loading. The precipitation response varies seasonally, with stronger aerosol effects observed during transitional seasons when Mediterranean cyclones are most active. Long-term satellite observations combined with modelling studies indicate that aerosol radiative effects can modify the track and intensity of Mediterranean cyclones by altering the regional temperature gradients and consequently the steering flow patterns (Nabat et al., 2015).

In medicanes, aerosol–radiation interactions demonstrate particularly complex effects due to the region's unique geography and frequent dust intrusions from the Sahara. Although mineral dust is the dominant aerosol type in the Mediterranean, sea-salt particles can significantly influence the tropical-like cyclones in the region through aerosol–cloud interactions (Pravia-Sarabia et al., 2021). Regarding aerosol climatology versus forecasted aerosols, the transition from climatological to real-time aerosol data represents a significant advancement in weather prediction capabilities (Benedetti et al., 2018). Comparative studies have demonstrated that using real-time aerosol data can improve temperature forecasts, especially during dust events. Real-time aerosol assimilation has shown particular success in improving radiation forecasts, with studies reporting a 15–30% reduction in shortwave radiation bias compared to climatology-based approaches (Martín Pérez et al., 2024; Muskatel et al., 2021). Analysis of forecast skill indicates that precipitation timing and intensity predictions improve significantly when using real-time aerosol data, especially during intense dust episodes (Muskatel et al., 2021; Xin and Aijun, 2021; Muskatel et al., 2024). Studies have shown that dynamic aerosol representation can better capture the diurnal cycle of radiative effects, leading to improved prediction of convective initiation timing and wind speeds (Rémy et al., 2015). Real-time aerosol data also enables better representation of aerosol–cloud interactions, with significant improvements observed in precipitation predictions compared to climatology-based approaches (Jiang et al., 2017). The primary disadvantage of fully coupled aerosol models is their enormous computational resource requirements compared to conventional NWP models that use aerosol climatology. These costs manifest in both computational effort and memory consumption, as the additional chemical and particle tracers can double both memory usage and CPU time. Such resource demands typically force compromises in spatial and temporal resolution, which can degrade the model's performance to the point of negating the improvements gained from the fully coupled approach.

A pragmatic compromise between these two approaches is to use fully coupled aerosol forecast

model output as input to a higher-resolution NWP model (Muskatel et al., 2021). The aerosol predictions can then replace aerosol climatology and serve as input to both the radiation scheme (direct effect) and the microphysical scheme for droplet and ice nucleation parameterizations. While this method sacrifices some dynamical consistency between the NWP model and the aerosol model, specifically in terms of aerosol washout and convection processes, we argue that these compromises are acceptable, particularly for synoptic-scale events such as Saharan dust storms.

In this study, we enhanced the ICON model with new aerosol and cloud features. A key addition was the integration of the aerosol climatology of Bozzo et al. (2017), derived from the Copernicus Atmosphere Monitoring Service (CAMS) model reanalysis spanning the years 2003–2014 (Morcrette et al., 2009).

The five resulting model configurations were realized in corresponding ICON model setups applied over the active period of the development of the "Daniel" medicane (4–12 September 2023). The results were based on 48 h runs forced by IFS 3 h operational runs, initialized at 00 UTC every day, in order to keep the short-range character of the model forecast, which is useful for practical purposes. Their mutual differences are highlighted mainly in reference to precipitation over the most heavily affected area of central Greece, Thessaly, in comparison to the values registered by the available meteorological stations of HNMS in the area.

8.2 Generic ICON model setup

The limited-area model version of ICON that was implemented follows the configuration established as a critical application at ECMWF by IMS (Khain et al., 2022). The integration domain (Figure 8.1) includes the wider area of the central and eastern Mediterranean along with significant portions of the surrounding areas of Europe, Africa, and Asia, stretching between 4.00–45.50°E, 25.50–53.00°N and centered at 24.750°E, 39.250°N (the SEE domain). According to the references associated with the tracking and the synoptic analysis of the medicane (EUMETSAT, 2024; Wikipedia, 2024; Dimitriou et al., 2024; Flaounas et al., 2024; Hewson et al., 2024), this domain can be considered an excellent choice to investigate the local features of the storm from the qualitative standpoint.

The model resolution is about 2.5 km (R2B10), with a size of 41.5°×27.5° and 1,783,780 triangular cells, realized in 65 vertical levels up to 23 km. The work is based on eight distinct 48 h runs forced by the deterministic IFS of ECMWF as initial and 3 h boundary conditions, starting at 00 UTC and covering the dates 03–10 September 2023. The runs were performed over the period of the development of the medicane, placing emphasis on the dates of extreme precipitation over Thessaly. This approach is consistent with the short-range forecast value of a regional model and also allows comparisons between the first 24 hours of a run and the last 24 hours of the model run of the previous day. In addition to gauging the model performance, this run period was also sufficient to highlight the differences among the different aerosol climatologies that were employed.

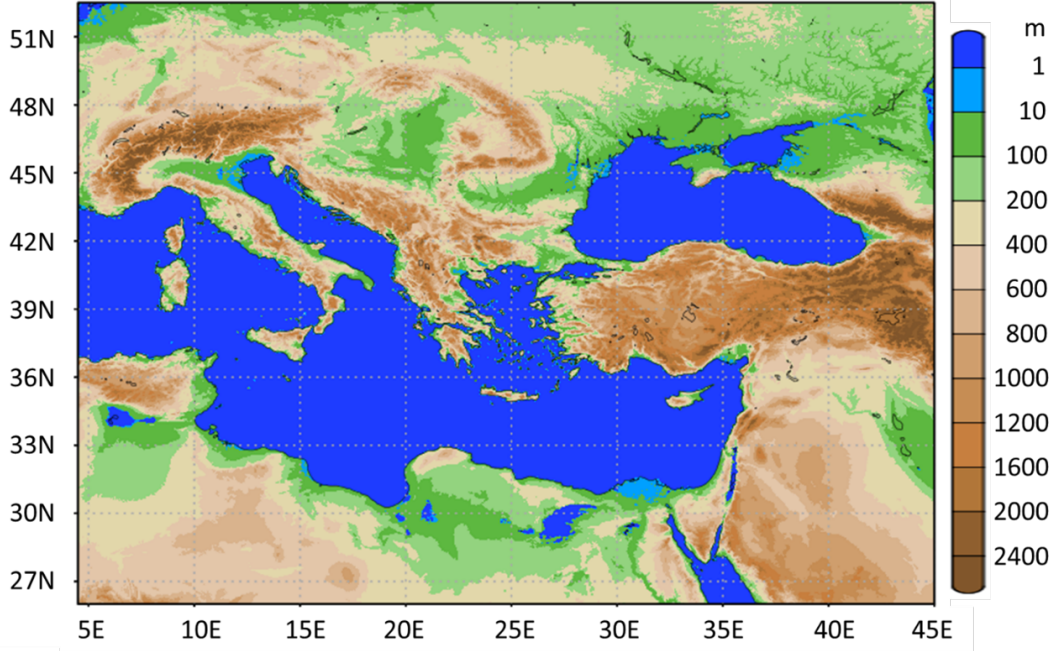


Figure 8.1. Integration domain of the ICON model.

8.3 Status of aerosol effects on ice nucleation processes

The ICON default radiation scheme employs Fu’s ice optical properties (Fu, 1996; Fu et al., 1998), hereafter the "Fu parameterization", to calculate the extinction coefficient, single-scattering albedo, and asymmetry factor (β_{ext}, ω, g) based on effective particle size. These parameterizations for the solar and thermal spectral regimes were originally limited to frozen particles smaller than 60 micrometers, which complicated the inclusion of larger particles like snow, graupel, and hail in the radiation scheme. This limitation could lead to significant radiative errors, particularly at high latitudes and in convective clouds. To address this limitation, we implemented and tested a newer parameterization (Muskatel et al., 2021), hereafter the "Fu-Muskatel parameterization", that extends the size limit. The authors used particle-size-distribution ensembles instead of original in-situ measurements, expanding the effective size range to 570 μm . This enhancement enables the inclusion of larger hydrometeor categories in the ICON radiation scheme. Additionally, the new parameterization offers a choice between smooth and rough surface treatments. Following Fu (2007), we opted for rough surface parameterizations in our experiments. In this work we compared the results of five ICON model setups, which are listed in Table 8.1.

The models differ in their treatment of aerosols, ice nucleation processes, and ice optical properties. For aerosol representation, we utilized both the two-dimensional Tegen et al. (1997) climatology and the more advanced CAMS framework, which offers both three-dimensional climatological data and forecasted aerosol distributions, as detailed in Muskatel et al. (2024). Ice nucleation processes were simulated using either the Cooper (1986) parameterization or the DeMott et al. (2015) approach, with the latter incorporating dust concentration data from the CAMS climatology. The treatment of ice optical properties followed two distinct approaches: the classical Fu parameterizations (Fu, 1996; Fu et al., 1998), where we excluded large frozen hydrometeors from radiative calculations, and the newer Fu-Muskatel framework (Muskatel et al., 2021), in which we comprehensively accounted for large ice particles, snow, and graupel in the radiation scheme.

Model Version name	Aerosol input for radiation	Ice nucleation	Ice optics
default	Tegen	Cooper	Fu
DeMott	CAMS	DeMott	Fu
IceOpt	Tegen	Cooper	Fu-Muskatel
camsclim	CAMS	Cooper	Fu
camsforc	CAMS (forecasted)	Cooper	Fu

Table 8.1. Configuration details of the five ICON model versions employed in this study.

8.4 Results

Medicane "Daniel" developed over a period of approximately two weeks and across a wide geographical area, starting from the western parts of Greece and covering almost the complete coastline of Libya. Therefore, a suitable strategy had to be followed, on the one side to keep the features of the short-range model and on the other to address the colossal amounts of precipitation associated with the catastrophic floods, as well as the complexities of its tracking. Our approach was set within the framework of EUMETSAT (2024), in which "Daniel" is established in two phase-periods, the first (4–8 September 2023) associated with the devastating floods in central Greece and the second (8–11 September 2023) with those in Libya. As the synoptic situation associated with medicane "Daniel" has been extensively analyzed by several studies (EUMETSAT, 2024; Wikipedia, 2024; Dimitriou et al., 2024; Flaounas et al., 2024; Hewson et al., 2024), we developed our findings on the analysis of mean sea-level pressure (PMSL), the most characteristic meteorological field associated with the medicane development over both phases. However, regarding precipitation, we focus on the first phase, associated with central Greece, leaving the devastating floods in Libya out of the scope of the present study. All the analyses are provided with respect to the default ICON model setup, along with their differences to the setups according to the other configurations in Table 8.1 and the corresponding comparisons regarding the accumulated precipitation of the most affected Greek synoptic stations.

8.4.1 PMSL development of medicane "Daniel"

As mentioned above, the evolution of the storm was simulated with sequential 48 h model runs starting at 00 UTC every day over the period 3–10 September 2023, forced by the global model forecast of ECMWF-IFS. The incentive behind this approach was to outline the medicane evolution from the perspective of a forecaster who is consulting a short-range NWP model in daily practice. Usually, the first 48 hours of the local model run are used operationally, especially in severe weather situations where the model output changes critically between successive runs. In principle, these runs are updated at least every 12 hours. Nevertheless, for the purposes of this work, the runs were considered every 24 hours as a sufficient time slot.

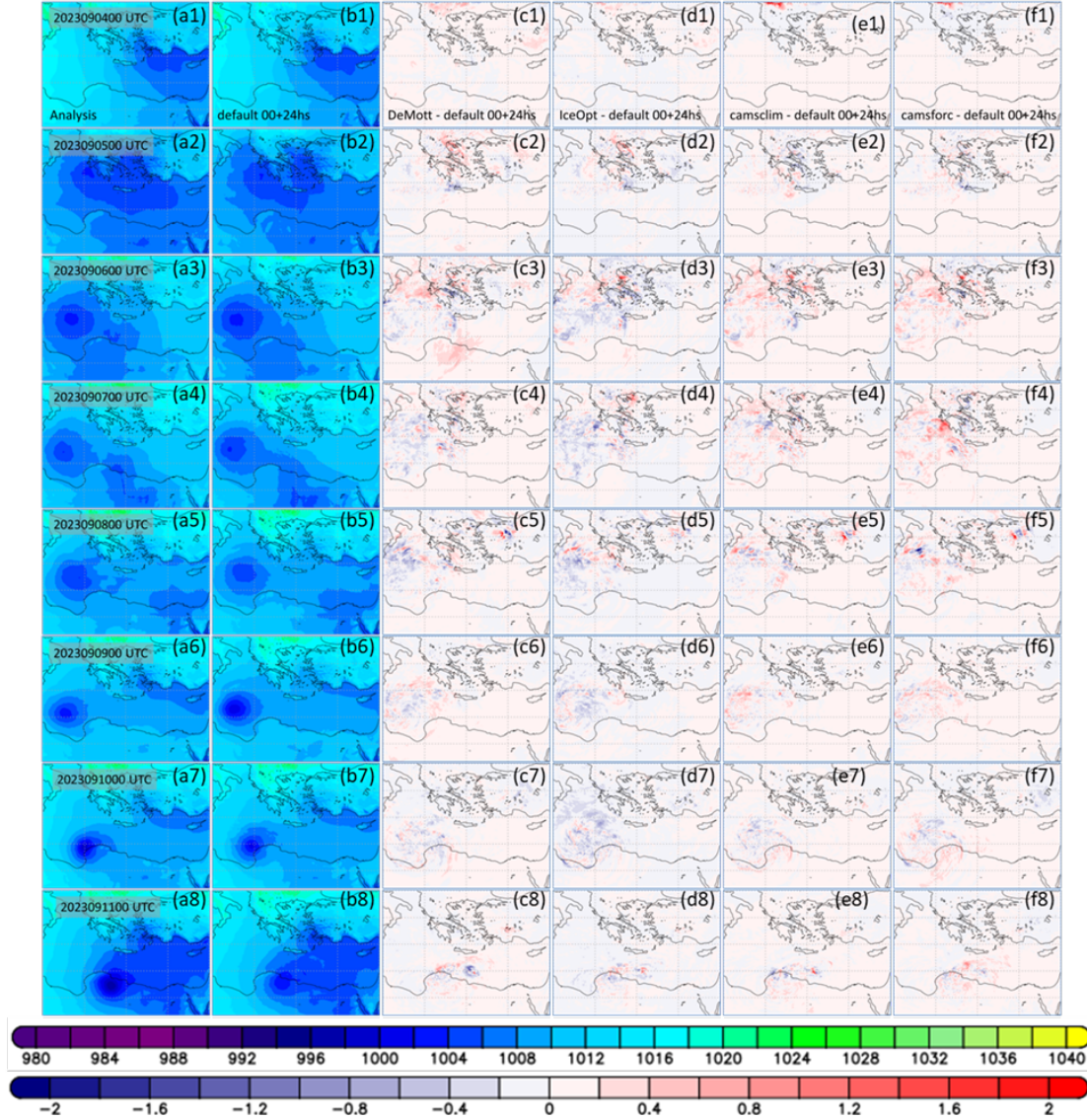


Figure 8.2. PMSL (in hPa, upper scale) over the period 20230905 to 20230911 at 00 UTC: analysis (a1)–(a8), 24 h forecast of the default run (b1)–(b8), and the differences (in hPa, lower scale) from DeMott (c1)–(c8), IceOpt (d1)–(d8), camscim (e1)–(e8), and camsfrc (f1)–(f8) as denoted in Table 8.1. Area limits: 170–250°E, 290–420°N. All row figures refer to the same time as the one in the first column, and all column figures refer to the same climatology as the one in the first row.

At first, the PMSL graphs from the IFS analysis are compared with the model runs (Figure 8.2) over the designated area of the cyclone development (17.0–25.0°E, 29.0–42.0°N). In the first column, the analysis graphs are given (Figure 8.2: (a1)–(a8)) in 24 h time periods (4–11 September 2023 at 00 UTC), when the storm was most active. These graphs are compared with the corresponding "default" 24 h model version forecast configured in Table 8.1 (Figure 8.2: (b1)–(b8)). Indicatively, Figure 8.2(b1) refers to the 24th PMSL forecast hour of the 48 h model run started on 3 September 2023 at 00 UTC. Although the agreement between analysis and forecast is quite good, certain differences can be spotted, especially around the areas of PMSL minimum. The most notable highlight is reflected in Figure 8.2(a7) versus Figure 8.2(b7) and Figure 8.2(a8) versus Figure 8.2(b8) respectively, when the medicane is in the area of Libya, where the PMSL minimum is visibly underestimated by the model.

8.4.2 Investigation of the ICON model accumulated precipitation over Greece

A main feature of the previous investigation is that all five model setups denoted in Table 8.1 did not display any significant differences among them regarding PMSL over the whole considered domain (Figure 8.2), as well as in the position and value of the PMSL minimum (Figures 8.3–8.5) upon the medicane development. Also, their differences from the IFS analysis were small over the period 4 to 7 September 2023, when the storm affected Greece hazardously (EUMETSAT, 2024). Consequently, this period was considered suitable to investigate the precipitation associated with the corresponding different model configurations that have been implemented. The expectation was that, although PMSL, the most critical dynamical meteorological field, varies modestly among the corresponding different model setups, the extreme accumulated precipitation would show noticeable variations due to the significant differences in the implemented physical processes described before. In this approach, the precipitation for this period is presented in Figure 8.3. According to the WMO convention followed, the daily 24 h accumulated precipitation that is displayed for a specific date starts at 18 UTC of the previous day and concludes at 18 UTC of the next day. Indicatively, the 24 h precipitation for 4 September 2023 covers the period from September 3 at 18 UTC to September 4 at 18 UTC.

In contrast to PMSL (Figure 8.2), the differences in the daily accumulated precipitation are quite distinct, rising to the order of 50 mm in the cyclone area but also over the region of Greece, especially the central/northern parts of the country where floods took place. These areas display the highest amounts of accumulated precipitation, reaching the order of 300 mm daily.

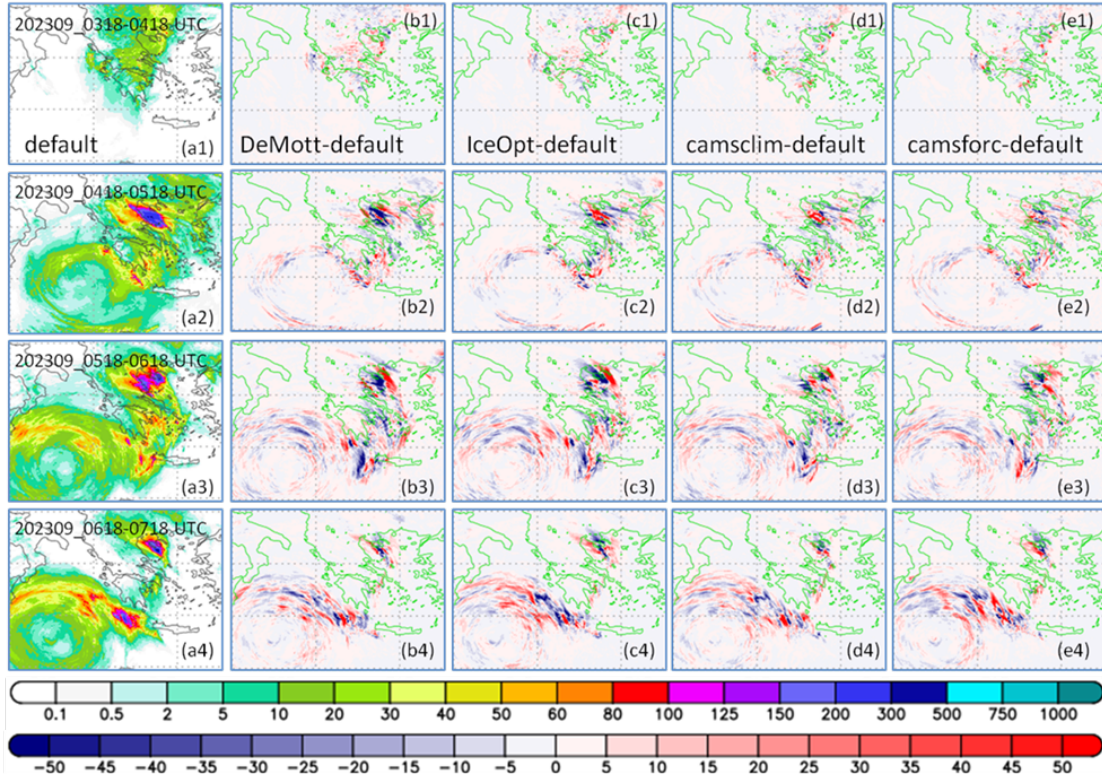


Figure 8.3. The 24 h (+18 to +42) accumulated precipitation (in mm) from the default climatology model setup (a1–a4) 00 UTC runs, along with the corresponding differences of the other climatologies configured in Table 8.1 in the subsequent columns, over the wider area of the storm development. Area limits: 170–250°E, 290–420°N. All row figures refer to the same time period as the one in the first column, and all column figures refer to the same

climatology as the one in the first row.

8.4.3 Comparisons of the accumulated ICON model precipitation with observations

The performances of the different model setups of Table 8.1 are evaluated against the accumulated precipitation of selected HNMS stations that recorded the highest precipitation values over the 4-day period 04–07 September 2023, when the medicane affected Greece most hazardously. The positions of these stations are depicted with bold yellow and red "X" marks in Figure 8.4, where the network of HNMS synoptic stations is displayed. This selection has been determined in the corresponding bulletins of the Climatology Department of HNMS that become available to the public on a monthly basis (HNMS, 2024). In particular, the stations of Larissa, Skiathos, Volos, and Lamia (bold red "X" marks) have been referenced in the 18th EFAS Annual Meeting as the most affected by medicane "Daniel" (Papapetrou, 2023). The corresponding accumulated precipitation of this critical period is presented in Figure 8.5a. Although the overall 4-day forecasted precipitation is underestimated, it is important to note that some noticeable sensitivity is displayed among the different model configurations denoted in Table 8.1, especially in favor of the implementation of the CAMS forecasted climatology "camsforc". This feature remains for "camsforc" also for the daily accumulated precipitation given in Figures 8.5b–8.5e, irrespective of whether precipitation is overestimated or underestimated by the different model setups. Even for 07 September 2023 (Figure 8.5e), "camsforc" very slightly preponderates, although the model performance is rather modest for all setups.

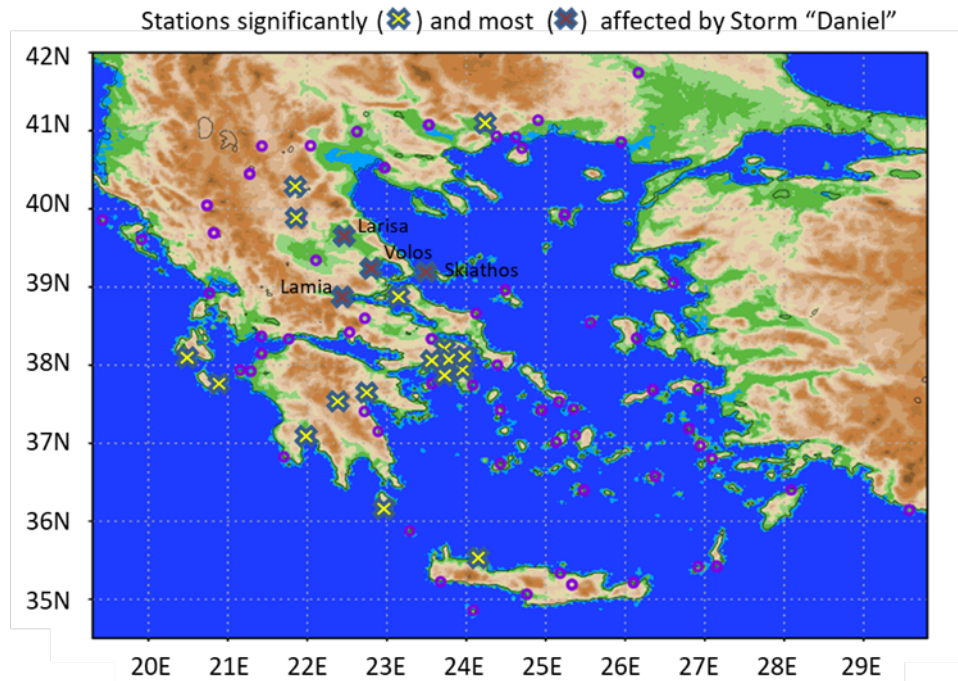


Figure 8.4. The network of synoptic station positions of HNMS. The positions of the stations significantly and most affected by storm "Daniel" are depicted with bold yellow and red "X" marks respectively. The rest of the stations are represented with purple circles.

The overall model performance for the most affected stations (Figure 8.6a–8.6e) turned out to be more modest due to the exceptional local character of the extreme precipitation, which accounts for approximately 50% of that for all stations (Figure 8.5a vs. Figure 8.6a). Nevertheless, the overall model performance of Figure 8.6a is similar to that of Figure 8.5a. The

"camsforc" model setup preponderates also for the Larissa and Skiathos stations, but for the Volos and Lamia stations the "camsclim" and "IceOpt" model setups preponderate respectively. However, the model performance for the Volos and Lamia stations is rather modest for all model setups, as the accumulated precipitation is 30% and 40% of the corresponding observations respectively.

8.5 Discussion

The hazardous nature of medicane "Daniel", associated with extreme precipitation over Greece, provided the motivation to investigate the performance of a well-established version of the regional ICON model (Khain et al., 2022). In addition to the "default" model setup based on the Tegen scheme for the aerosol input for radiation (Tegen et al., 1997), the Cooper scheme for ice nucleation (Cooper, 1986), and the Fu scheme for ice optical properties (Fu, 1996; Fu et al., 1998; Fu, 2007), this endeavor was realized from the perspective of four more model setups (Table 8.1) associated with CAMS climatologies for the aerosol input for radiation (Martín Pérez et al., 2024; Muskatel et al., 2024; Bozzo et al., 2017) and the DeMott scheme for ice nucleation (DeMott et al., 2015). Our investigation was based on a sequence of 48 h model runs starting at 00 UTC for the period 3 to 10 September 2023, forced by the ECMWF-IFS global model. Good performance was found, especially for the period 4–7 September 2023, the first phase of the medicane as designated by EUMETSAT.

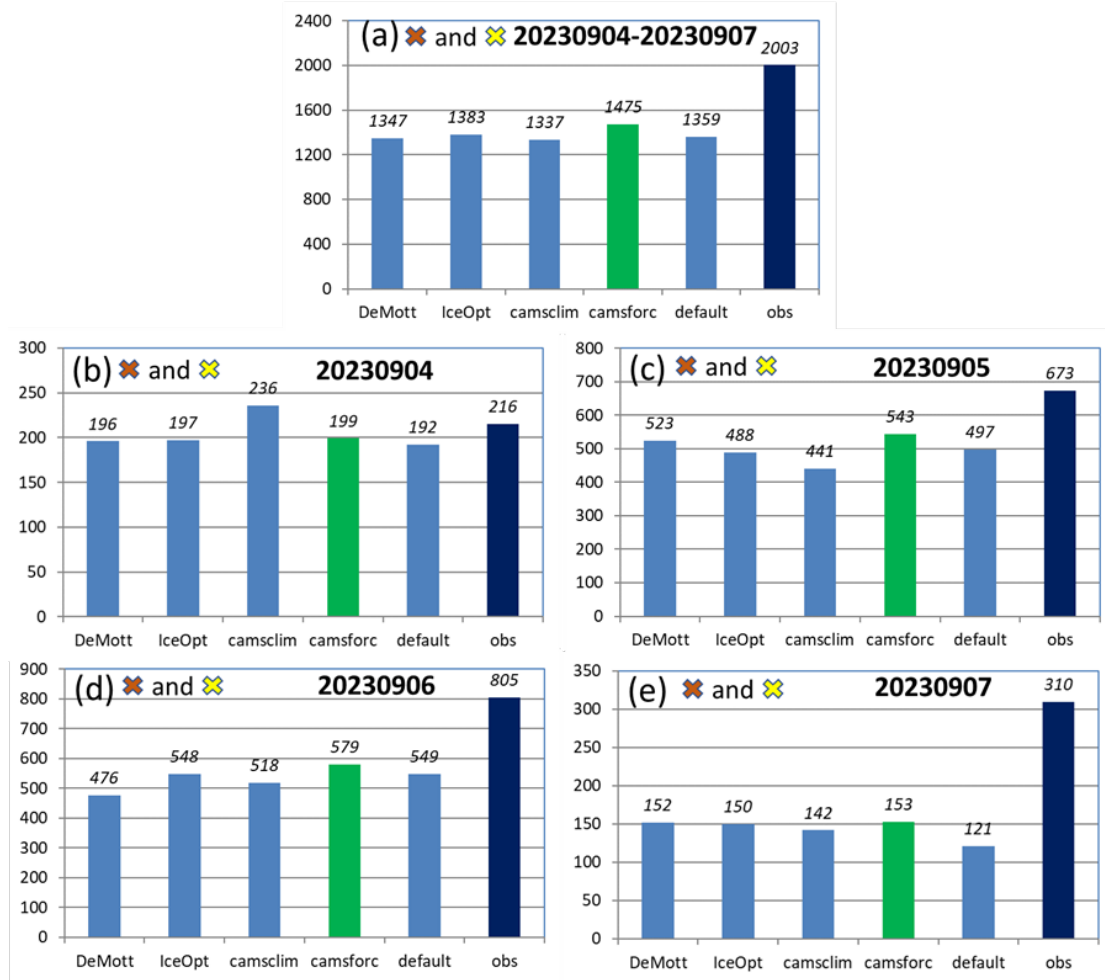


Figure 8.5. Height of total accumulated precipitation (mm) for all the selected stations of Figure 8.4 over the period 04–07 September 2023 (a), as well as for every individual day, i.e.,

04 (b), 05 (c), 06 (d), and 07 (e) September 2023.

Although, regarding PMSL, the differences between the different model setups (Figure 8.2) were not impressive (~ 2 hPa), the differences in 1-day accumulated precipitation (Figure 8.6) were very large (~ 50 mm) over the wider area of medicane activity. In this respect, our approach to focus on the physical processes associated with the aerosol input for radiation, ice nucleation, ice optical properties, and CAMS climatologies was well justified by the corresponding model setups configured in Table 8.1. As a comparative validation, the 24 h accumulated precipitation of the 21 most affected synoptic stations, as officially stored by the Climatology Department of HNMS, was used for the period 4–7 September 2023. The comparisons were performed with the 24 h accumulated precipitation of the 18–42 h model forecasts, which was considered most suitable from the operational standpoint of the ICON model implementation at HNMS.

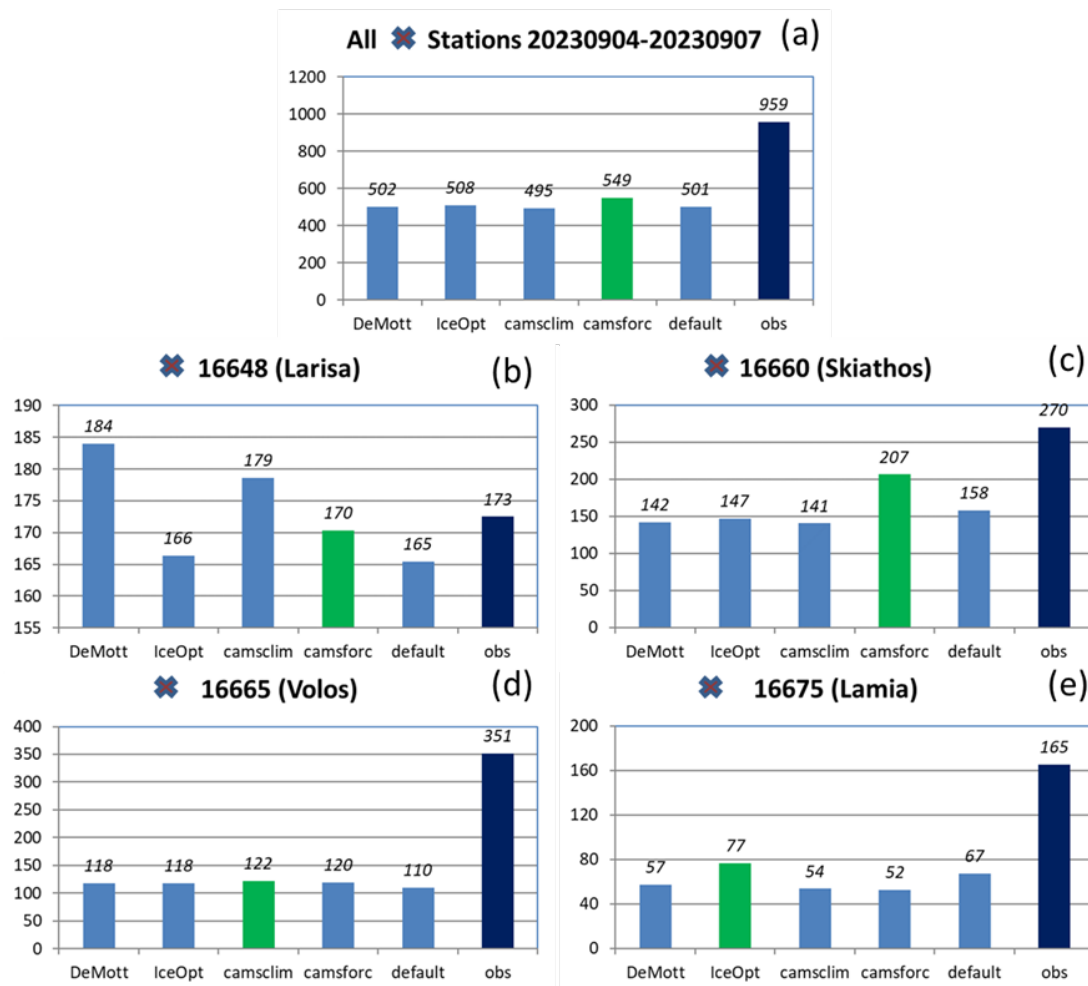


Figure 8.6. Height of total accumulated precipitation (mm) for the stations that displayed the highest precipitation (Tegen et al., 1997) of Figure 8.4 over the period 04–07 September 2023 (a), as well as for every individual station, i.e., Larissa (b), Skiathos (c), Volos (d), and Lamia (e) over the same period.

It was very interesting to note that the setup associated with the CAMS forecasted climatology (camsforc) preponderated in the overall station performance against observations, both over the complete 4-day period as well as the daily ones (Figure 8.5). The situation was not so clear for the most affected stations, but still the "camsforc" setup performed better for the synoptic stations of Larissa and Skiathos, where the overall model agreement was better

for all model setups (Figure 8.6).

In addition to these results, the ICON simulations for the entire 2023 period, incorporating all available aerosol climatologies, have been carried out. The further processing and analysis of this extensive dataset are expected to provide a much-needed bridge between the operational application of ICON and the broader understanding of cloud–radiation interactions. The inclusion of multiple aerosol climatologies enables a more detailed assessment of how different aerosol representations influence radiative and microphysical processes, particularly under extreme weather conditions. The outcome of this endeavor is anticipated to motivate and guide researchers in evaluating diverse NWP physics implementations during high-impact events, thereby advancing the understanding of the complex physical processes that make this field both challenging and scientifically rewarding. Building on these results, additional targeted studies are planned to extend the methodology and deepen the investigation of aerosol–radiation–cloud interactions across the central–eastern Mediterranean.

Acknowledgments

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References

- Abakumova, G., and E. Gorbarenko, 2008: *Transparency of the Atmosphere in Moscow over the Last 50 Years and Its Changes in Russia*. LKI Publishing House, 192 pp. (in Russian).
- Alapaty, K., J. A. Herwehe, T. L. Otte, C. G. Nolte, O. R. Bullock, M. S. Mallard, J. S. Kain, and J. Dudhia, 2012: Introducing subgrid-scale cloud feedbacks to radiation for regional meteorological and climate modeling. *Geophys. Res. Lett.*, **39**, L24809, <https://doi.org/10.1029/2012GL054031>.
- Alpert, P., B. U. Neeman, and Y. Shay-El, 1990: Climatological analysis of Mediterranean cyclones using ECMWF data. *Tellus*, **42A**, 65–77.
- Avgoustoglou, E., B. H. Muskatel, P. Khain, and Y. Levi, 2025: The performance of ICON (Icosahedral Non-Hydrostatic) regional model for storm Daniel with an emphasis on precipitation evaluation over Greece. *Atmosphere*, **16**, 1043, <https://doi.org/10.3390/atmos16091043>.
- Baldauf, M., A. Seifert, J. Förstner, D. Majewski, M. Raschendorfer, and T. Reinhardt, 2011: Operational convective-scale numerical weather prediction with the COSMO model: Description and sensitivities. *Mon. Wea. Rev.*, **139**, 3887–3905, <https://doi.org/10.1175/MWR-D-10-05013.1>.
- Baum, B. A., A. J. Heymsfield, P. Yang, and S. T. Bedka, 2005: Bulk scattering properties for the remote sensing of ice clouds. Part I: Microphysical data and models. *J. Appl. Meteor.*, **44**, 1885–1895.
- Baum, B. A., P. Yang, A. J. Heymsfield, C. G. Schmitt, Y. Xie, A. Bansemer, Y. Hu, and Z. Zhang, 2011: Improvements in shortwave bulk scattering and absorption models for the remote sensing of ice clouds. *J. Appl. Meteor. Climatol.*, **50**, 1037–1056.
- Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft. *J.*

Atmos. Sci., **33**, 851–864.

Ben Bouallègue, Z., and S. E. Theis, 2014: Spatial techniques applied to precipitation ensemble forecasts: From verification results to probabilistic products. *Meteor. Appl.*, **21**, 922–929, <https://doi.org/10.1002/met.1435>.

Benedetti, A., and Coauthors, 2018: Status and future of numerical atmospheric aerosol prediction with a focus on data requirements. *Atmos. Chem. Phys.*, **18**, 10615–10643, <https://doi.org/10.5194/acp-18-10615-2018>.

Blahak, U., 2015: Simulating idealized cases with the COSMO-model. Consortium for Small-Scale Modelling, http://www.cosmo-model.org/content/model/documentation/core/artif_docu.pdf.

Blahak, U., and B. Ritter, 2013: Towards revised cloud radiation coupling for the COSMO model. *COSMO/CLM User Seminar*, Offenbach, Germany, 5–8 March 2013.

Bott, A., 1998: A flux method for the numerical solution of the stochastic collection equation. *J. Atmos. Sci.*, **55**, 2284–2293, [https://doi.org/10.1175/1520-0469\(1998\)055<2284:AFMFTN>2.0.CO;2](https://doi.org/10.1175/1520-0469(1998)055<2284:AFMFTN>2.0.CO;2).

Bozzo, A., S. Remy, A. Benedetti, J. Flemming, P. Bechtold, M. J. Rodwell, and J.-J. Morcrette, 2017: Implementation of a CAMS-based aerosol climatology in the IFS. ECMWF Tech. Memo. 801, <https://www.ecmwf.int/en/elibrary/80028-implementation-cams-based-aerosol-climatology-ifs>.

Bozzo, A., A. Benedetti, J. Flemming, Z. Kipling, and S. Remy, 2020: An aerosol climatology for global models based on the tropospheric aerosol scheme in the Integrated Forecasting System of ECMWF. *Geosci. Model Dev.*, **13**, 1007–1034, <https://doi.org/10.5194/gmd-13-1007-2020>.

Chou, M.-D., and M. J. Suarez, 1999: A solar radiation parameterization for atmospheric studies. NASA Tech. Memo. NASA/TM-1999-104606, Vol. 15.

Chubarova, N. E., A. Smirnov, and B. N. Holben, 2011: Aerosol properties in Moscow according to 10 years of AERONET measurements at the Meteorological Observatory of Moscow State University. *Geogr. Environ. Sustain.*, **4** (1), 19–32.

Chubarova, N. Y., A. A. Poliukhov, and I. D. Gorlova, 2016: Long-term variability of aerosol optical thickness in Eastern Europe over 2001–2014 according to the measurements at the Moscow MSU MO AERONET site with additional cloud and NO₂ correction. *Atmos. Meas. Tech.*, **9**, 313–334, <https://doi.org/10.5194/amt-9-313-2016>.

Chubarova, N., J. Khlestova, M. Shatunova, V. Platonov, G. Rivin, U. Görsdorf, and R. Becker, 2018a: Cloud characteristics and cloud radiative effects according to COSMO mesoscale model and measurements. *Proc. SPIE*, **10833**, 108331N, <https://doi.org/10.1117/12.2504340>.

Chubarova, N., A. Poliukhov, M. Shatunova, G. Rivin, R. Becker, and S. Kinne, 2018b: Clear-sky radiative and temperature effects of different aerosol climatologies in the COSMO model. *Geogr. Environ. Sustain.*, **11** (1), 74–84, <https://doi.org/10.24057/2071-9388-2018-11-1-74-84>.

Cooper, W. A., 1986: Ice initiation in natural clouds. *Precipitation Enhancement—A Scientific Challenge*, *Meteor. Monogr.*, No. 43, Amer. Meteor. Soc., 29–32, <https://doi.org/10.1175/0065-9401-21.43.29>.

Copernicus Atmosphere Monitoring Service, 2020: CAMS global reanalysis (EAC4). Copernicus Atmosphere Monitoring Service Atmosphere Data Store, <https://doi.org/10.24381/d58bbf47>.

Crippa, M., G. Janssens-Maenhout, F. Dentener, D. Guizzardi, K. Sindelarova, M. Muntean,

- R. Van Dingenen, and C. Granier, 2016: Forty years of improvements in European air quality: Regional policy–industry interactions with global impacts. *Atmos. Chem. Phys.*, **16**, 3825–3841, <https://doi.org/10.5194/acp-16-3825-2016>.
- Dagan, G., I. Koren, O. Altaratz, and R. Heiblum, 2016: Aerosol effect on the evolution of the thermodynamic properties of warm convective cloud fields. *Sci. Rep.*, **6**, 38769, <https://doi.org/10.1038/srep38769>.
- Davis, C. A., B. G. Brown, and R. G. Bullock, 2006a: Object-based verification of precipitation forecasts. Part I: Methodology and application to mesoscale rain areas. *Mon. Wea. Rev.*, **134**, 1772–1784.
- Davis, C. A., B. G. Brown, and R. G. Bullock, 2006b: Object-based verification of precipitation forecasts. Part II: Application to convective rain systems. *Mon. Wea. Rev.*, **134**, 1785–1795.
- Davis, C. A., B. G. Brown, R. G. Bullock, and J. Halley Gotway, 2009: The Method for Object-Based Diagnostic Evaluation (MODE) applied to numerical forecasts from the 2005 NSSL/SPC Spring Program. *Wea. Forecasting*, **24**, 1252–1267.
- Deardorff, J. W., 1970: Preliminary results from numerical integrations of the unstable planetary boundary layer. *J. Atmos. Sci.*, **27**, 1209–1211.
- DeMott, P. J., and Coauthors, 2015: Integrating laboratory and field data to quantify the immersion freezing ice nucleation activity of mineral dust particles. *Atmos. Chem. Phys.*, **15**, 393–409, <https://doi.org/10.5194/acp-15-393-2015>.
- Dimitriou, E., and Coauthors, 2024: Post-analysis of Daniel extreme flood event in Thessaly, central Greece: Practical lessons and the value of state-of-the-art water-monitoring networks. *Water*, **16**, 980, <https://doi.org/10.3390/w16070980>.
- Doms, G., and Coauthors, 2011: A description of the nonhydrostatic regional COSMO model. Part II: Physical parameterization. Consortium for Small-Scale Modelling, <http://www.cosmo-model.org>.
- Duc, L., K. Saito, and H. Seko, 2013: Spatial–temporal fractions verification for high-resolution ensemble forecasts. *Tellus*, **65A**, 18171, <https://doi.org/10.3402/tellusa.v65i0.18171>.
- Ebert, E. E., 2009: Neighborhood verification: A strategy for rewarding close forecasts. *Wea. Forecasting*, **24**, 1498–1510, <https://doi.org/10.1175/2009WAF2222251.1>.
- Edwards, J. M., and A. Slingo, 1996: Studies with a flexible new radiation code. I: Choosing a configuration for a large-scale model. *Quart. J. Roy. Meteor. Soc.*, **122**, 689–719.
- EUMETSAT, 2023: Extreme floods in Libya and central Greece. EUMETSAT case study, accessed 17 December 2024, <https://user.eumetsat.int/resources/case-studies/extreme-floods-in-libya-and-central-greece>.
- Evan, A. T., C. Flamant, S. Fiedler, and O. Doherty, 2014: An analysis of aeolian dust in climate models. *Geophys. Res. Lett.*, **41**, 5996–6001.
- Fan, J., M. Ovchinnikov, J. M. Comstock, S. A. McFarlane, and A. Khain, 2009: Ice formation in Arctic mixed-phase clouds: Insights from a 3-D cloud-resolving model with size-resolved aerosol and cloud microphysics. *J. Geophys. Res.*, **114**, D04205, <https://doi.org/10.1029/2008JD0107>.
- Field, P. R., R. J. Hogan, P. R. A. Brown, A. J. Illingworth, T. W. Choularton, and R. J. Cotton, 2005: Parametrization of ice-particle size distributions for mid-latitude stratiform cloud. *Quart. J. Roy. Meteor. Soc.*, **131**, 1997–2017, <https://doi.org/10.1256/qj.04.134>.

Flaounas, E., and Coauthors, 2024: Dynamics, predictability, impacts, and climate change considerations of the catastrophic Mediterranean storm Daniel (2023). *EGUsphere*, preprint, <https://doi.org/10.5194/egusphere-2024-2809>.

Fu, Q., 1996: An accurate parameterization of the solar radiative properties of cirrus clouds for climate models. *J. Climate*, **9**, 2058–2082, [https://doi.org/10.1175/1520-0442\(1996\)009<2058:AAPOTS>2](https://doi.org/10.1175/1520-0442(1996)009<2058:AAPOTS>2).

Fu, Q., 2007: A new parameterization of an asymmetry factor of cirrus clouds for climate models. *J. Atmos. Sci.*, **64**, 4140–4150, <https://doi.org/10.1175/2007JAS2289.1>.

Fu, Q., and K. N. Liou, 1993: Parameterization of the radiative properties of cirrus clouds. *J. Atmos. Sci.*, **50**, 2008–2025.

Fu, Q., P. Yang, and W. B. Sun, 1998: An accurate parameterization of the infrared radiative properties of cirrus clouds for climate models. *J. Climate*, **11**, 2223–2237, [https://doi.org/10.1175/1520-0442\(1998\)011<2223:AAPOTI>2.0.CO;2](https://doi.org/10.1175/1520-0442(1998)011<2223:AAPOTI>2.0.CO;2).

Gasch, P., D. Rieger, C. Walter, P. Khain, Y. Levi, P. Knippertz, and B. Vogel, 2017: Revealing the meteorological drivers of the September 2015 severe dust event in the eastern Mediterranean. *Atmos. Chem. Phys.*, **17**, 13573–13604, <https://doi.org/10.5194/acp-17-13573-2017>.

Gasparini, B., and U. Lohmann, 2016: Why cirrus cloud seeding cannot substantially cool the planet. *J. Geophys. Res. Atmos.*, **121**, 4877–4893.

Ghan, S. J., and Coauthors, 2011: Droplet nucleation: Physically-based parameterizations and comparative evaluation. *J. Adv. Model. Earth Syst.*, **3**, M10001, <https://doi.org/10.1029/2011MS000074>.

Gilleland, E., D. Ahijevych, B. G. Brown, B. Casati, and E. E. Ebert, 2009: Intercomparison of spatial forecast verification methods. *Wea. Forecasting*, **24**, 1416–1430, <https://doi.org/10.1175/2009WAF2220.1>.

Gilleland, E., D. A. Ahijevych, B. G. Brown, and E. E. Ebert, 2010: Verifying forecasts spatially. *Bull. Amer. Meteor. Soc.*, **91**, 1365–1376, <https://doi.org/10.1175/2010BAMS2819.1>.

Giorgetta, M. A., and Coauthors, 2018: ICON-A, the atmosphere component of the ICON Earth system model: I. Model description. *J. Adv. Model. Earth Syst.*, **10**, 1613–1637, <https://doi.org/10.1029/2017MS001242>.

Gruber, S., and Coauthors, 2019: A process study on thinning of Arctic winter cirrus clouds with high-resolution ICON-ART simulations. *J. Geophys. Res. Atmos.*, **124**.

Grythe, H., J. Ström, R. Krejci, P. Quinn, and A. Stohl, 2014: A review of sea-spray aerosol source functions using a large global set of sea salt aerosol concentration measurements. *Atmos. Chem. Phys.*, **14**, 1277–1297, <https://doi.org/10.5194/acp-14-1277-2014>.

Hermes, K., J. Quinting, C. M. Grams, C. Hoose, and G. A. Hoshyaripour, 2024: Impact of Saharan dust outbreaks on short-range weather forecast errors in Europe. *Quart. J. Roy. Meteor. Soc.*, **150**, 1704–1723, <https://doi.org/10.1002/qj.4666>.

Hess, M., P. Koepke, and I. Schult, 1998: Optical properties of aerosols and clouds: The software package OPAC. *Bull. Amer. Meteor. Soc.*, **79**, 831–844.

Hewson, T., and Coauthors, 2024: Medicane Daniel: An extraordinary cyclone with devastating impacts. *ECMWF Newsletter*, No. 179, ECMWF, 33–47, <https://www.ecmwf.int/sites/default/files/eli-newsletter-no-179-spring-2024.pdf>.

HNMS, 2024: Climate bulletins and studies. Hellenic National Meteorological Service, accessed 26 December 2024, <https://www.emy.gr/en/bulletins-studies>.

- Hogan, R. J., and A. Bozzo, 2018: A flexible and efficient radiation scheme for the ECMWF model. *J. Adv. Model. Earth Syst.*, **10**, 1990–2008, <https://doi.org/10.1029/2018MS001364>.
- Hogan, R. J., and A. J. Illingworth, 2003: Parameterizing ice cloud inhomogeneity and the overlap of inhomogeneities using cloud radar data. *J. Atmos. Sci.*, **60**, 756–767.
- Hogan, R. J., M. P. Mittermaier, and A. J. Illingworth, 2006: The retrieval of ice water content from radar reflectivity factor and temperature and its use in evaluating a mesoscale model. *J. Appl. Meteor. Climatol.*, **45**, 301–317.
- Hu, Y. X., and K. Stamnes, 1993: An accurate parameterization of the radiative properties of water clouds suitable for use in climate models. *J. Climate*, **6**, 728–742.
- Huang, X., and A. Ding, 2021: Aerosol as a critical factor causing forecast biases of air temperature in global numerical weather prediction models. *Sci. Bull.*, **66**, 1917–1924, <https://doi.org/10.1016/j.scib.2021.05.009>.
- Illingworth, A. J., and Coauthors, 2007: Cloudnet: Continuous evaluation of cloud profiles in seven operational models using ground-based observations. *Bull. Amer. Meteor. Soc.*, **88**, 883–898, <https://doi.org/10.1175/BAMS-88-6-883>.
- Inness, A., and Coauthors, 2019: The CAMS reanalysis of atmospheric composition. *Atmos. Chem. Phys.*, **19**, 3515–3556, <https://doi.org/10.5194/acp-19-3515-2019>.
- Jiang, H., G. Feingold, H. H. Jonsson, M.-L. Lu, P. Y. Chuang, R. C. Flagan, and J. H. Seinfeld, 2008: Statistical comparison of properties of simulated and observed cumulus clouds in the vicinity of Houston during the Gulf of Mexico Atmospheric Composition and Climate Study (GoMACCS). *J. Geophys. Res.*, **113**, D13205, <https://doi.org/10.1029/2007JD009304>.
- Jiang, M., and Coauthors, 2017: Potential influences of neglecting aerosol effects on the NCEP GFS precipitation forecast. *Atmos. Chem. Phys.*, **17**, 13967–13982, <https://doi.org/10.5194/acp-17-13967-2017>.
- Joseph, J. H., W. J. Wiscombe, and J. A. Weinman, 1976: The delta-Eddington approximation for radiative flux transfer. *J. Atmos. Sci.*, **33**, 2452–2459, [https://doi.org/10.1175/1520-0469\(1976\)033<2452:TDEAFR>2.0.CO;2](https://doi.org/10.1175/1520-0469(1976)033<2452:TDEAFR>2.0.CO;2).
- Kaiser, J. W., and Coauthors, 2012: Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. *Biogeosciences*, **9**, 527–554, <https://doi.org/10.5194/bg-9-527-2012>.
- Key, J. R., P. Yang, B. A. Baum, and S. L. Nasiri, 2002: Parameterization of shortwave ice cloud optical properties for various particle habits. *J. Geophys. Res.*, **107** (D13), <https://doi.org/10.1029/2001JD000742>.
- Khain, A. P., and M. Pinsky, 2018: *Physical Processes in Clouds and Cloud Modeling*. Cambridge University Press, 642 pp.
- Khain, A. P., M. Ovchinnikov, M. Pinsky, A. Pokrovsky, and H. Krugliak, 2000: Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmos. Res.*, **55**, 159–224.
- Khain, A. P., A. Pokrovsky, M. Pinsky, A. Seifert, and V. Phillips, 2004: Simulation of effects of atmospheric aerosols on deep turbulent convective clouds using a spectral microphysics mixed-phase cumulus cloud model. Part I: Model description and possible applications. *J. Atmos. Sci.*, **61**, 2963–2982.
- Khain, A., T. V. Prabha, N. Benmoshe, G. Pandithurai, and M. Ovchinnikov, 2013: The mechanism of first raindrops formation in deep convective clouds. *J. Geophys. Res. Atmos.*,

118, 9123–9140, <https://doi.org/10.1002/jgrd.50641>.

Khain, A. P., and Coauthors, 2015: Representation of microphysical processes in cloud-resolving models: Spectral (bin) microphysics versus bulk parameterization. *Rev. Geophys.*, **53**, 247–322, <https://doi.org/10.1002/2014RG000468>.

Khain, P., H. Muskatel, and U. Blahak, 2016: Priority Project T2(RC)2: Determination of governing parameters in the new radiation scheme. COSMO User Seminar 2016.

Khain, P., I. Carmona, A. Voudouri, E. Avgoustoglou, J.-M. Bettems, F. Grazzini, and P. Kaufmann, 2017: CALMO—Progress report. COSMO Tech. Rep. 31, Consortium for Small-Scale Modelling.

Khain, P., and Coauthors, 2019: Parameterization of vertical profiles of governing microphysical parameters of shallow cumulus cloud ensembles using LES with bin microphysics. *J. Atmos. Sci.*, **76**, 533–560, <https://doi.org/10.1175/JAS-D-18-0046.1>.

Khain, P., J. Shpund, Y. Levi, and A. Khain, 2022a: Warm-phase spectral-bin microphysics in ICON: Reasons of sensitivity to aerosols. *Atmos. Res.*, **279**, 106388, <https://doi.org/10.1016/j.atmosres.2022.106388>.

Khain, P., and Coauthors, 2022b: Israel uses ECMWF supercomputer to advance regional forecasting. *ECMWF Newsletter*, No. 171, ECMWF, 29–35, <https://doi.org/10.21957/bk22p3fs9d>.

Khairoutdinov, M. F., and D. A. Randall, 2003: Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.*, **60**, 607–625.

Khlestova, J., N. Chubarova, and M. Shatunova, 2019: Radiative and temperature effects of clouds based on the results of numerical experiments of the COSMO mesoscale model and measurement data. *Proc. SPIE*, **11208**, 112080K, <https://doi.org/10.1117/12.2540929>.

Khvorostyanov, V. I., and J. A. Curry, 1999: Toward the theory of stochastic condensation in clouds. Part I: A general kinetic equation. *J. Atmos. Sci.*, **56**, 3985–3996.

Kinne, S., 2019: The MACv2 aerosol climatology. *Tellus*, **71B**, 1–21.

Kinne, S., and Coauthors, 2013: MAC-v1: A new global aerosol climatology for climate studies. *J. Adv. Model. Earth Syst.*, **5**, 704–740, <https://doi.org/10.1002/jame.20035>.

Kogan, Y. L., and D. B. Mechem, 2014: A PDF-based microphysics parameterization for shallow cumulus clouds. *J. Atmos. Sci.*, **71**, 1070–1089, <https://doi.org/10.1175/JAS-D-13-0193.1>.

Kok, J. F., 2011a: A scaling theory for the size distribution of emitted dust aerosols suggests climate models underestimate the size of the global dust cycle. *Proc. Natl. Acad. Sci. USA*, **108**, 1016–1021.

Kok, J. F., 2011b: Does the size distribution of mineral dust aerosols depend on the wind speed at emission? *Atmos. Chem. Phys.*, **11**, 10149–10156, <https://doi.org/10.5194/acp-11-10149-2011>.

Kok, J. F., and Coauthors, 2014: An improved dust emission model—Part 1: Model description and comparison against measurements. *Atmos. Chem. Phys.*, **14**, 13023–13041, <https://doi.org/10.5194/acp-14-13023-2014>.

Kunz, M., U. Blahak, J. Handwerker, M. Schmidberger, H. J. Punge, S. Mohr, E. Fluck, and K. M. Bedka, 2018: The severe hailstorm in southwest Germany on 28 July 2013: Characteristics, impacts and meteorological conditions. *Quart. J. Roy. Meteor. Soc.*, **144**, 231–250, <https://doi.org/10.1002/qj.3197>.

- Larson, V. E., and B. M. Griffin, 2013: Analytic upscaling of a local microphysics scheme. Part I: Derivation. *Quart. J. Roy. Meteor. Soc.*, **139**, 46–57, <https://doi.org/10.1002/qj.1967>.
- Lindner, T. H., and J. Li, 2000: Parameterization of the optical properties for water clouds in the infrared. *J. Climate*, **13**, 1797–1805.
- Löhnert, U., E. van Meijgaard, H. Klein Baltink, S. Groß, and R. Boers, 2007: Accuracy assessment of an integrated profiling technique for operationally deriving profiles of temperature, humidity, and cloud liquid water. *J. Geophys. Res.*, **112**, D04205, <https://doi.org/10.1029/2006JD007379>.
- Lu, M.-L., and J. H. Seinfeld, 2005: Study of the aerosol indirect effect by large-eddy simulation of marine stratocumulus. *J. Atmos. Sci.*, **62**, 3909–3932, <https://doi.org/10.1175/JAS3584.1>.
- Macke, A., J. Mueller, and E. Raschke, 1996: Single scattering properties of atmospheric ice crystals. *J. Atmos. Sci.*, **53**, 2813–2825.
- Magaritz-Ronen, L., A. Khain, and M. Pinsky, 2016: About the horizontal variability of effective radius in stratocumulus clouds. *J. Geophys. Res. Atmos.*, **121**, 9640–9660, <https://doi.org/10.1002/2016JD024977>.
- Martin Pérez, D., E. Gleeson, P. Maalampi, and L. Rontu, 2024: Use of CAMS near real-time aerosols in the HARMONIE-AROME NWP model. *Meteorology*, **3**, 161–190, <https://doi.org/10.3390/meteorology3020008>.
- Mittermaier, M., and N. Roberts, 2010: Intercomparison of spatial forecast verification methods: Identifying skillful spatial scales using the fractions skill score. *Wea. Forecasting*, **25**, 343–354, <https://doi.org/10.1175/2009WAF2222260.1>.
- Morcrette, J.-J., and Coauthors, 2009: Aerosol analysis and forecast in the European Centre for Medium-Range Weather Forecasts Integrated Forecast System: Forward modeling. *J. Geophys. Res.*, **114**, D06206, <https://doi.org/10.1029/2008JD011235>.
- Müller, R., and C. Träger-Chatterjee, 2014: Brief accuracy assessment of aerosol climatologies for the retrieval of solar surface radiation. *Atmosphere*, **5**, 959–972, <https://doi.org/10.3390/atmos5040959>.
- Müller, R., U. Pfeifroth, C. Träger-Chatterjee, R. Cremer, J. Trentmann, and R. Hollmann, 2015: Surface Solar Radiation Data Set—Heliosat (SARAH), Edition 1. Satellite Application Facility on Climate Monitoring, https://doi.org/10.5676/EUM_SAF_CM/SARAH/V001.
- Muskatel, H. B., U. Blahak, P. Khain, Y. Levi, and Q. Fu, 2021a: Parametrizations of liquid and ice clouds' optical properties in operational numerical weather prediction models. *Atmosphere*, **12**, 89, <https://doi.org/10.3390/atmos12010089>.
- Muskatel, H., and Coauthors, 2021b: The COSMO Priority Project T2(RC)2: Testing and tuning of revised cloud radiation coupling. COSMO Tech. Rep. 43, Consortium for Small-Scale Modelling, https://doi.org/10.5676/DWD_pub/nwv/cosmo-tr_43.
- Muskatel, H., D. Rieger, P. Khain, and M. Kohler, 2024: CAMS 3D climatology and forecasted aerosols as an option in ecRad radiation in ICON. *Reports on ICON*, No. 011, DWD, https://doi.org/10.5676/DWD_pub/nwv/icon_011.
- Nabat, P., S. Somot, M. Mallet, F. Sevault, M. Chiacchio, and M. Wild, 2015: Direct and semi-direct aerosol radiative effect on the Mediterranean climate variability using a coupled regional climate system model. *Climate Dyn.*, **44**, 1127–1155, <https://doi.org/10.1007/s00382-014-2205-6>.
- Nickovic, S., B. Cvetkovic, F. Madonna, M. Rosoldi, G. Pejanovic, S. Petkovic, and J. Nikolic, 2016: Cloud ice caused by atmospheric mineral dust—Part 1: Parameterization of

ice nuclei concentration in the NMME-DREAM model. *Atmos. Chem. Phys.*, **16**, 11367–11378, <https://doi.org/10.5194/acp-16-11367-2016>.

Oreopoulos, L., and Coauthors, 2012: The Continual Intercomparison of Radiation Codes: Results from phase I. *J. Geophys. Res.*, **117**, D06118, <https://doi.org/10.1029/2011JD016821>.

Ovchinnikov, M., and Coauthors, 2014: Intercomparison of large-eddy simulations of Arctic mixed-phase clouds: Importance of ice size distribution assumptions. *J. Adv. Model. Earth Syst.*, **6**, 223–248.

Papapetrou, A., 2023: Devastating floods in Thessaly, Greece. *18th EFAS Annual Meeting*, Offenbach, Germany, 28–29 September 2023, https://european-flood.emergency.copernicus.eu/sites/default/files/2023-09/18th_EFAS_Annual_Meeting_Programme.pdf.

Petty, G. W., and W. Huang, 2011: The modified gamma size distribution applied to inhomogeneous and nonspherical particles: Key relationships and conversions. *J. Atmos. Sci.*, **68**, 1460–1473.

Phillips, V. T. J., P. J. DeMott, and C. Andronache, 2008: An empirical parameterization of heterogeneous ice nucleation for multiple chemical species of aerosol. *J. Atmos. Sci.*, **65**, 2757–2783, <https://doi.org/10.1175/2007JAS2546.1>.

Pinsky, M., and A. P. Khain, 2002: Effects of in-cloud nucleation and turbulence on droplet spectrum formation in cumulus clouds. *Quart. J. Roy. Meteor. Soc.*, **128**, 1–33.

Pinsky, M., and A. Khain, 2018: Theoretical analysis of the entrainment–mixing process at cloud boundaries. Part I: Droplet size distributions and humidity within the interface zone. *J. Atmos. Sci.*, **75**, 2049–2064, <https://doi.org/10.1175/JAS-D-17-0308.1>.

Pinsky, M., A. P. Khain, and M. Shapiro, 2001: Collision efficiency of drops in a wide range of Reynolds numbers: Effects of pressure on spectrum evolution. *J. Atmos. Sci.*, **58**, 742–764.

Pinsky, M., A. Khain, I. Mazin, and A. Korolev, 2012: Analytical estimation of droplet concentration at cloud base. *J. Geophys. Res.*, **117**, D18211, <https://doi.org/10.1029/2012JD017753>.

Pinsky, M., I. Mazin, A. Korolev, and A. Khain, 2014: Supersaturation and diffusional droplet growth in liquid clouds: Polydisperse spectra. *J. Geophys. Res. Atmos.*, **119**, 12872–12887.

Pinsky, M., A. Khain, and A. Korolev, 2016: Theoretical analysis of mixing in liquid clouds—Part 3: Inhomogeneous mixing. *Atmos. Chem. Phys.*, **16**, 9273–9297, <https://doi.org/10.5194/acp-16-9273-2016>.

Poliukhov, A. A., N. E. Chubarova, G. S. Rivin, and M. V. Shatunova, 2015: The assessments of the accuracy of radiative calculations by the COSMO-Ru mesoscale prognostic model and the aerosol influence on the forecast of meteorological elements. *Int. Symp. Atmospheric Radiation and Dynamics*, St. Petersburg–Petrodvorets, Russia, 23–26 June 2015.

Poliukhov, A., N. Chubarova, S. Kinne, G. Rivin, M. Shatunova, and T. Tarasova, 2017: Comparison between calculations of shortwave radiation with different aerosol datasets and measured data at the MSU MO (Russia). *AIP Conf. Proc.*, **1810**, 100006, <https://doi.org/10.1063/1.4975561>.

Poliukhov, A. A., N. E. Chubarova, M. V. Shatunova, G. S. Rivin, T. A. Tarasova, A. P. Makshtas, and H. Muskatel, 2018: Radiative effect of different aerosol types in clear-sky conditions according to the COSMO-Ru model. *Proc. SPIE*, **10833**, 1083308, <https://doi.org/10.1117/12.2504299>.

Poliukhov, A. A., N. E. Chubarova, D. V. Blinov, T. A. Tarasova, A. P. Makshtas, and H. Muskatel, 2019: Radiation effects of different types of aerosol in Eurasia according to observations and model calculations. *Russ. Meteor. Hydrol.*, **44**, 579–587.

- Pontikis, C. A., 1996: Parameterization of the droplet effective radius of warm layer clouds. *Geophys. Res. Lett.*, **23**, 2629–2632.
- Pravia-Sarabia, E., J. J. Gómez-Navarro, P. Jiménez-Guerrero, and J. P. Montávez, 2021: Influence of sea salt aerosols on the development of Mediterranean tropical-like cyclones. *Atmos. Chem. Phys.*, **21**, 13353–13368, <https://doi.org/10.5194/acp-21-13353-2021>.
- Reid, J. S., P. V. Hobbs, A. L. Rangno, and D. A. Hegg, 1999: Relationships between cloud droplet effective radius, liquid water content, and droplet concentration for warm clouds in Brazil embedded in biomass smoke. *J. Geophys. Res.*, **104**, 6145–6153, <https://doi.org/10.1029/1998JD200119>.
- Rémy, S., and Coauthors, 2015: Feedbacks of dust and boundary layer meteorology during a dust storm in the eastern Mediterranean. *Atmos. Chem. Phys.*, **15**, 12909–12933, <https://doi.org/10.5194/acp-15-12909-2015>.
- Rieger, D., A. Steiner, V. Bachmann, P. Gasch, J. Förstner, K. Deetz, and H. Vogel, 2017: Impact of the 4 April 2014 Saharan dust outbreak on the photovoltaic power generation in Germany. *Atmos. Chem. Phys.*, **17**, 13391–13415, <https://doi.org/10.5194/acp-17-13391-2017>.
- Ritter, B., and J.-F. Geleyn, 1992: A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. *Mon. Wea. Rev.*, **120**, 303–325.
- Roberts, N. M., and H. W. Lean, 2008: Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. *Mon. Wea. Rev.*, **136**, 78–97, <https://doi.org/10.1175/2007MWR2123.1>.
- Rosenfeld, D., 2006: Aerosol–cloud interactions control of Earth radiation and latent heat release budgets. *Space Sci. Rev.*, **125**, 149–157, <https://doi.org/10.1007/s11214-006-9053-6>.
- Rosenfeld, D., and I. M. Lensky, 1998: Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. *Bull. Amer. Meteor. Soc.*, **79**, 2457–2476.
- Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, S. Fuzzi, A. Reissell, and M. O. Andreae, 2008: Flood or drought: How do aerosols affect precipitation? *Science*, **321**, 1309–1313, <https://doi.org/10.1126/science.1160606>.
- Rossow, W. B., and R. A. Schiffer, 1999: Advances in understanding clouds from ISCCP. *Bull. Amer. Meteor. Soc.*, **80**, 2261–2288.
- Sakradzija, M., and D. Klocke, 2018: Physically constrained stochastic shallow convection in realistic kilometer-scale simulations. *J. Adv. Model. Earth Syst.*, **10**, 2755–2776, <https://doi.org/10.1029/2018MS001358>.
- Sakradzija, M., A. Seifert, and A. Dipankar, 2016: A stochastic scale-aware parameterization of shallow cumulus convection across the convective gray zone. *J. Adv. Model. Earth Syst.*, **8**, 786–812, <https://doi.org/10.1002/2016MS000634>.
- Sassen, K., Z. Wang, and D. Liu, 2008: Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements. *J. Geophys. Res.*, **113**, D00A12, <https://doi.org/10.1029/2008JD009972>.
- Schepanski, K., 2018: Transport of mineral dust and its impact on climate. *Geosciences*, **8**, 151, <https://doi.org/10.3390/geosciences8050151>.
- Schröter, J., and Coauthors, 2018: ICON-ART 2.1: A flexible tracer framework and its

- application for composition studies in numerical weather forecasting and climate simulations. *Geosci. Model Dev.*, **11**, 4043–4068, <https://doi.org/10.5194/gmd-11-4043-2018>.
- Schwartz, C. S., and R. A. Sobash, 2017: Generating probabilistic forecasts from convection-allowing ensembles using neighborhood approaches: A review and recommendations. *Mon. Wea. Rev.*, **145**, 3397–3418, <https://doi.org/10.1175/MWR-D-16-0400.1>.
- Segal, Y., and A. P. Khain, 2006: Dependence of droplet concentration on aerosol conditions in different cloud types: Application to droplet concentration parameterization of aerosol conditions. *J. Geophys. Res.*, **111**, D15204, <https://doi.org/10.1029/2005JD006561>.
- Sharon, D., and H. Kutiel, 1986: The distribution of rainfall intensity in Israel, its regional and seasonal variations and its climatological evaluation. *J. Climatol.*, **6**, 277–291.
- Shatunova, M. V., Yu. O. Khlestova, and N. E. Chubarova, 2019: Forecast of microphysical and optical characteristics of grid-scale clouds and its radiative effects using the COSMO mesoscale numerical weather prediction model. *Atmos. Oceanic Opt.*, **32**, 824–831.
- Shay-El, Y., and P. Alpert, 1991: A diagnostic study of winter diabatic heating in the Mediterranean in relation to cyclones. *Quart. J. Roy. Meteor. Soc.*, **117**, 715–747.
- Siebesma, A. P., and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *J. Atmos. Sci.*, **60**, 1201–1219.
- Slingo, A., 1989: A GCM parameterization for the shortwave radiative properties of water clouds. *J. Atmos. Sci.*, **46**, 1419–1427.
- Slingo, A., and H. M. Schrecker, 1982: On the shortwave radiative properties of stratiform water clouds. *Quart. J. Roy. Meteor. Soc.*, **108**, 407–426.
- Solomos, S., G. Kallos, J. Kushta, M. Astitha, C. Tremback, A. Nenes, and Z. Levin, 2011: An integrated modeling study on the effects of mineral dust and sea salt particles on clouds and precipitation. *Atmos. Chem. Phys.*, **11**, 873–892, <https://doi.org/10.5194/acp-11-873-2011>.
- Steinke, I., C. Hoose, O. Möhler, P. Connolly, and T. Leisner, 2015: A new temperature- and humidity-dependent surface site density approach for deposition ice nucleation. *Atmos. Chem. Phys.*, **15**, 3703–3717, <https://doi.org/10.5194/acp-15-3703-2015>.
- Stephens, G. L., 1979: Optical properties of eight water cloud types. CSIRO Division of Atmospheric Physics Tech. Paper 36.
- Stephens, G. L., 1984: The parameterization of radiation for numerical weather prediction and climate models. *Mon. Wea. Rev.*, **112**, 826–867.
- Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 2003: Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteor. Atmos. Phys.*, **82**, 75–96.
- Takano, Y., and K. N. Liou, 1989: Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals. *J. Atmos. Sci.*, **46**, 3–19.
- Tanaka, T. Y., and M. Chiba, 2006: A numerical study of the contributions of dust source regions to the global dust budget. *Global Planet. Change*, **52**, 88–104.
- Tanre, D., J.-F. Geleyn, and J. M. Slingo, 1984: First results of the introduction of an advanced aerosol–radiation interaction in the ECMWF low resolution global model. *Proc. Meetings of Experts on Aerosols and Their Climatic Effects*, Williamsburg, VA, WMO/IAMAP, 133–177.

- Tarasova, T. A., and N. E. Chubarova, 1994: On the calculation of optical thickness of extended low and middle clouds using measurements of solar radiation in three solar spectrum ranges on the Earth's surface. *Izv. Atmos. Ocean. Phys.*, **30**, 253–257.
- Tarasova, T. A., and B. A. Fomin, 2007: The use of new parameterizations for gaseous absorption in the CLIRAD-SW solar radiation code for models. *J. Atmos. Oceanic Technol.*, **24**, 1157–1162.
- Tarasova, T. A., and E. V. Yarkho, 1991: Determination of aerosol optical thickness according to ground-based measurements of integral solar irradiance. *Russ. Meteor. Hydrol.*, No. 12, 66–71.
- Tegen, I., P. Hollrig, M. Chin, I. Fung, D. Jacob, and J. Penner, 1997: Contribution of different aerosol species to the global aerosol extinction optical thickness: Estimates from model results. *J. Geophys. Res.*, **102**, 23895–23915, <https://doi.org/10.1029/97JD01864>.
- Twomey, S., 1977: The influence of pollution on the shortwave albedo of clouds. *J. Atmos. Sci.*, **34**, 1149–1152, [https://doi.org/10.1175/1520-0469\(1977\)034<1149:TIOPOT>2.0.CO;2](https://doi.org/10.1175/1520-0469(1977)034<1149:TIOPOT>2.0.CO;2).
- Vergara-Temprado, J., and Coauthors, 2018: Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *Proc. Natl. Acad. Sci. USA*, **115**, 2687–2692.
- Voudouri, A., P. Khain, I. Carmona, O. Bellprat, F. Grazzini, E. Avgoustoglou, J.-M. Bettems, and P. Kaufmann, 2017: Objective calibration of numerical weather prediction models. *Atmos. Res.*, **190**, 128–140.
- Ware, R., R. Carpenter, J. Güldner, J. Liljegren, T. Nehrkorn, F. Solheim, and F. Vandenberghe, 2003: A multichannel radiometric profiler of temperature, humidity, and cloud liquid. *Radio Sci.*, **38**, 8079, <https://doi.org/10.1029/2002RS002856>.
- Wikipedia, 2024: Storm Daniel. Accessed 9 December 2024, https://en.wikipedia.org/wiki/Storm_Daniel.
- Wiscombe, W. J., 1977: The delta-Eddington approximation for a vertically inhomogeneous atmosphere. NCAR Tech. Note NCAR/TN-121+STR.
- Yanai, M., S. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.
- Yang, P., and K. N. Liou, 1995: Light scattering by hexagonal ice crystals: Comparison of finite-difference time domain and geometric optics models. *J. Opt. Soc. Amer.*, **12A**, 162–176.
- Yang, P., and K. N. Liou, 1996: Finite-difference time domain method for light scattering by small ice crystals in three-dimensional space. *J. Opt. Soc. Amer.*, **13A**, 2072–2085.
- Yang, P., K. N. Liou, K. Wyser, and D. Mitchell, 2000: Parameterization of the scattering and absorption properties of individual ice crystals. *J. Geophys. Res.*, **105**, 4699–4718.
- Yang, P., L. Bi, B. A. Baum, K. N. Liou, G. W. Kattawar, M. I. Mishchenko, and B. Cole, 2013: Spectrally consistent scattering, absorption, and polarization properties of atmospheric ice crystals at wavelengths from 0.2 to 100 μm . *J. Atmos. Sci.*, **70**, 330–347.
- Zängl, G., D. Reinert, P. Rípodas, and M. Baldauf, 2015: The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. *Quart. J. Roy. Meteor. Soc.*, **141**, 563–579, <https://doi.org/10.1002/qj.2378>.
- Zender, C. S., H. Bian, and D. Newman, 2003: Mineral Dust Entrainment and Deposition (DEAD) model: Description and 1990s dust climatology. *J. Geophys. Res.*, **108** (D14), <https://doi.org/10.1029/2002JD002775>.

Ziv, B., U. Dayan, Y. Kushnir, C. Roth, and Y. Enzel, 2006: Regional and global atmospheric patterns governing rainfall in the southern Levant. *Int. J. Climatol.*, **26**, 55–73.

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- (2019):
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- No. 51 E. Russo, B. Geyer, R. Petrik, K. Keuler, M. Adinol, H. Feldmann, K. Goergen, A. Kerkweg, P. Khain, P. Ludwig, M. Mertens, P. Pothapakula, M. Raffa, B. Rockel, J.-P. Schulz, M. Sulis, H. Thi Minh Ho-Hagemann, H. Truhetz, L. Uzan, U. Voggenberger, C. Steger (2024):
CLM Community WG EVAL, COordinated PArameter Testing project 2 (COPAT2): COSMO-CLM 6.0 clm1 recommended model configuration.
- No. 52 D. Boucouvala, J. Linkowska, J. Gehring, V. Garbero, A. Vocino E. Brainin, R. Dumitrache, A. Canessa (2025):
The COSMO priority Project ICON-COMFORT: (COMpetence in FORecasTing).

COSMO Technical Reports

Issues of the COSMO Technical Reports series are published by the *CO*nsortium for *S*mall-*s*cale *MO*delling at non-regular intervals. COSMO is a European group for numerical weather prediction with participating meteorological services from Germany (DWD, AWGeophys), Greece (HNMS), Italy (USAM, ARPA-SIMC, ARPA Piemonte), Switzerland (MeteoSwiss), Poland (IMGW), Romania (NMA) and Russia (RHM). The general goal is to develop, improve and maintain a non-hydrostatic limited area modelling system to be used for both operational and research applications by the members of COSMO. This system is initially based on the COSMO-Model (previously known as LM) of DWD with its corresponding data assimilation system.

The Technical Reports are intended

- for scientific contributions and a documentation of research activities,
- to present and discuss results obtained from the model system,
- to present and discuss verification results and interpretation methods,
- for a documentation of technical changes to the model system,
- to give an overview of new components of the model system.

The purpose of these reports is to communicate results, changes and progress related to the LM model system relatively fast within the COSMO consortium, and also to inform other NWP groups on our current research activities. In this way the discussion on a specific topic can be stimulated at an early stage. In order to publish a report very soon after the completion of the manuscript, we have decided to omit a thorough reviewing procedure and only a rough check is done by the editors and a third reviewer. We apologize for typographical and other errors or inconsistencies which may still be present.

At present, the Technical Reports are available for download from the COSMO web site (www.cosmo-model.org). If required, the member meteorological centres can produce hard-copies by their own for distribution within their service. All members of the consortium will be informed about new issues by email.

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