SPECIAL PROJECT PROGRESS REPORT

All the following mandatory information needs to be provided. The length should *reflect the complexity and duration* of the project.

Reporting year	2025…………………………………………………
Project Title:	Coupled climate simulations using the ICON model
	…………………………………………………………..……
Computer Project Account:	SPDEKHAI…………………………………..……
Principal Investigator(s):	Pavel Khain………………………..……
	…………………………………………………………..……
Affiliation:	Israel Meteorological Service …………………………………..……
Name of ECMWF scientist(s) collaborating to the project (if applicable)	…………………………………………………………..……
	…………………………………………………………..……
Start date of the project:	1.1.2024…………………………………..……
Expected end date:	31.12.2026………………………………..……

Computer resources allocated/used for the current year and the previous one

(if applicable)

Please answer for all project resources

		Previous year		Current year	
		Allocated	Used	Allocated	Used
High Performance Computing Facility	(units)	304M	314.8M	303M	45.2M
Data storage capacity	(Gbytes)	630,000	200,000	630,000	300,000

Summary of project objectives (10 lines max)

Generally, the project goal is to advance climate-modelling focusing on coupled atmosphere-ocean simulations. The main objectives are: (1) Performing climate uncoupled simulations for the years 1980-2100 using the ICON model at a resolution of 12 km over the Mediterranean region and at a resolution of 2.5 km over the East Mediterranean; (2) Performing a 1000-year global simulation with ICON-Seamless (coupled configuration) with a horizontal resolution of about 80 km in the atmosphere and 40 km in the ocean; (3) Performing several research simulations on past periods of the ICON/NEMO coupled system with the aim of calibrating and adapting it to future coupled climate runs, both for the Mediterranean and European setups.

Summary of problems encountered (10 lines max)

During the first year of the project (2024) and the first 2 months of the second year (2025) we have made a significant progress. In relation to objective (1), we have performed climate uncoupled simulations for the years 1980-2100 using the ICON model at a resolution of 12 km over the Mediterranean and South-East Europe region and for the years 1980-2070 at a resolution of 2.5 km over the East Mediterranean. Although the simulation is highly beneficial, we encountered minor problems both technical and scientific. The technical ones were related to rare bugs in ICON output when running the model on ATOS using the intel compiler with Open-MP. The scientific ones were related to rare unphysically strong precipitation values in specific grid points in local convective situations. In relation to objective (3), we encountered technical difficulties to couple ICON to NEMO-MED ocean model. Although we got significant support from MEDCORDEX community, the coupled model was crashing due to numerical instability near the strait of Gibraltar. Therefore, with the help of DWD colleagues, we are now working on coupling ICON to a different ocean model, ICON-O, over the Mediterranean.

Summary of plans for the continuation of the project (10 lines max)

The plans remained similar. In relation to objective (1), we plan to accomplish 30 years of 2.5km simulation (until 2100), fix the scientific precipitation overestimation problem mentioned above, and to rerun the 12 km resolution and 2.5km resolution simulations over 1980-2100 again. In parallel, we plan to continue the work on ICON - ICON-O regional coupling, aiming to reproduce the historical evolution correctly, both in the atmosphere and the sea. Recently, good progress was achieved in this direction, and significant computer resources are planned to be invested in ICON - ICON-O coupled regional simulations already during 2025.

List of publications/reports from the project with complete references

International presentations:

1. Uzan, L., E. Vadislavsky, P. Khain, M. Cohen, I. Carmona and Y. Levi "Calibration of ICON-CLM in the East Mediterranean region", the ICCARUS (ICON/COSMO/CLM/ART USER Seminar) (4-8.3.2024), DWD Headquarters in Offenbach, Germany.
2. Vadislavsky E. and P. Khain: "Coupling ICON-CLM to NEMO-MED over the Mediterranean", the ICCARUS (ICON/COSMO/CLM/ART USER Seminar) (4-8.3.2024), DWD Headquarters in Offenbach, Germany.
3. Vadislavsky E., P. Khain, L. Uzan, Y. Levi and A. Givati: "Coupling ICON-LAM to NEMO-MED at IMS", the 8th Med-CORDEX workshop (14-16.5.2024), Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Rome, Italy.

Internal reports:

4. Uzan L. et al.: "Climate model calibration and simulations plan: status report for the Climate Centre Committee", Report #2, April 2024.
5. Uzan L. et al.: "Climate model calibration and simulations plan: status report for the Climate Centre Committee", Report #3, September 2024.

Summary of results

If submitted **during the first project year**, please summarise the results achieved during the period from the project start to June of the current year. A few paragraphs might be sufficient. If submitted **during the second project year**, this summary should be more detailed and cover the period from the project start. The length, at most 8 pages, should reflect the complexity of the project. Alternatively, it could be replaced by a short summary plus an existing scientific report on the project attached to this document. If submitted **during the third project year**, please summarise the results achieved during the period from July of the previous year to June of the current year. A few paragraphs might be sufficient.

During the first 1.5 years of the project (1.1.2024-30.6.2025) we have focused on three topics: tuning the ICON-CLM model over the Mediterranean in order to make it suitable for climate simulations, performing 1980-2100 climate simulations using 12 and 2.5 km resolutions, and coupling ICON to an ocean model.

As part of the first topic, we were able to tune the cloud cover, reducing the global radiation bias. Moreover, we have used soil water content dependent albedo tuning which significantly reduced skin and 2m temperature biases. Finally, we have tuned turbulence parameters in stable stratification, reducing 2m temperature and relative humidity biases. Figure 1 presents one of the results of our tuning related to global radiation bias over the Mediterranean at different seasons.

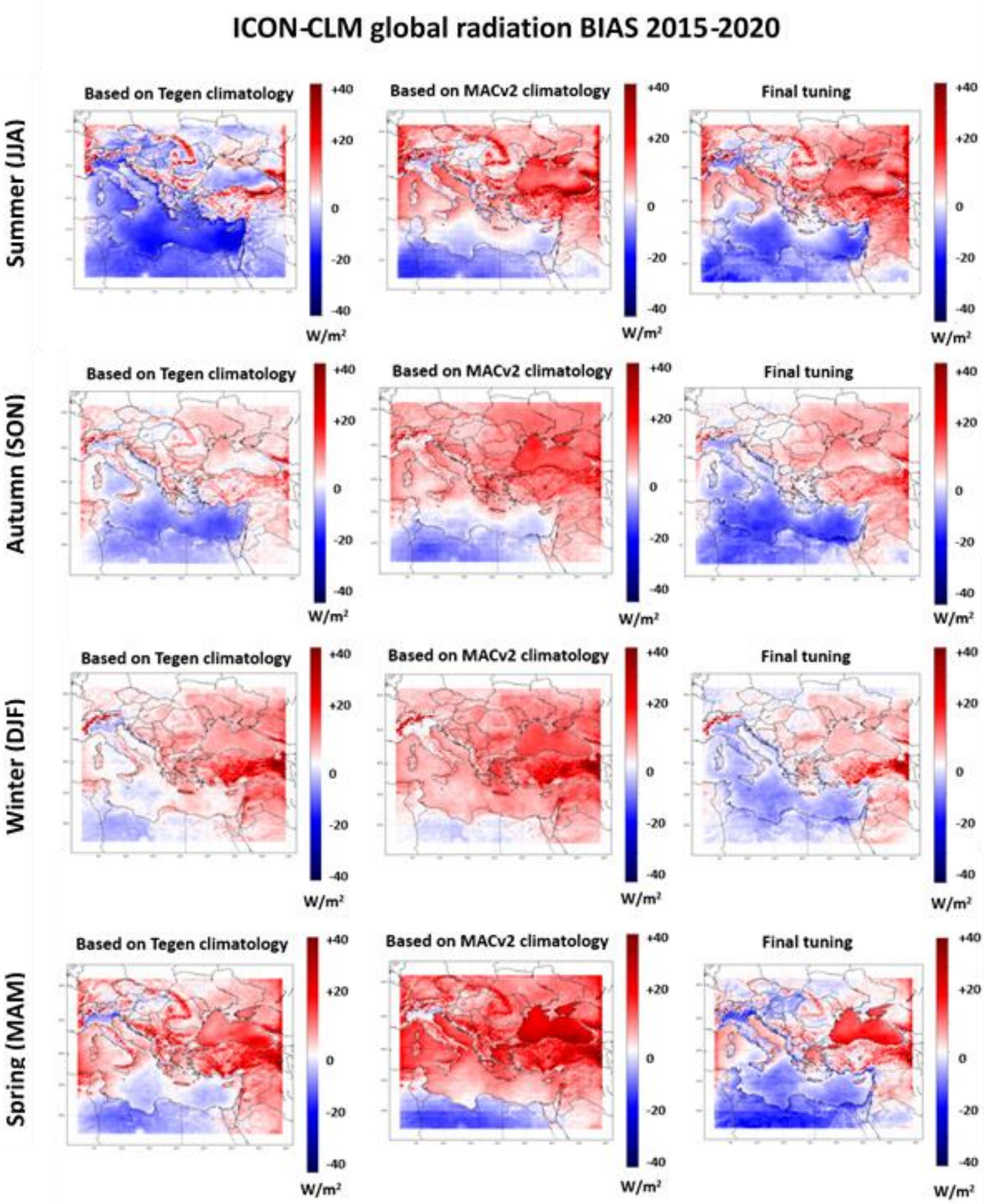

Fig. 1. Global radiation BIAS compared to hourly observations from EUMETSAT CM-SAF satellite measurements 0.05° by seasons. ICON results driven by ERA5 based on Tegen climatology (left column), MACv2 climatology (middle column) and after final tuning (right column).

As part of the third topic, with the support of colleagues from DWD, Hereon, Meteo-France, CERFACS and others, we have established a coupled ICON-NEMO-MED environment on ATOS@ECMWF. Following this achievement, several historical years of coupled ICON-NEMO-MED simulation were performed. Verification of the sea surface temperature (SST) versus buoy data over the Eastern Mediterranean reveal realistic yearly maximum temperatures, but too low minimum

temperatures. Analysis suggested that the problem was related to incorrect initialization of temperature and salinity profiles. Moreover, there was a problem in the water budget, with underestimated evaporation as compared to the rain and runoff sources. An attempt to force ocean initialization with ORAS5 and OSTIA SST reanalyses instead of slow damping towards the initial conditions yielded model instability near the strait of Gibraltar.
In parallel, during the last 2 years, there is a significant effort by DWD to develop a regional ocean model as part of the ICON model, called ICON-O. Since this development recently reached a mature stage, we decided to shift our focus to coupling ICON with ICON-O over the Mediterranean. With the help of DWD colleagues, we are now working on implementing this coupling on ATOS, first in global (default) and the in regional configuration. The plan here remained unchanged, i.e. performing several research simulations on past periods of the ICON/ICON-O coupled system with the aim of calibrating and adapting it to future coupled climate runs for the Mediterranean setup.

Below we describe our results related to the second topic mentioned above, namely the results of 1980-2100 climate simulations using 2.5 km resolution (driven by 12 km resolution). In addition to ICON driven by EC-Earth-Veg global climate model, performed on ATOS, we performed a similar climate simulation with ICON driven by MPI-ESM global climate model on a different HPC. Therefore, our analysis below includes conclusions regarding both ICON simulations.

The simulations performance analysis was performed by our colleagues Dr. Itzhak Yosef (IMS), Dr. Theodor Bughici (IMS), Dr. Assaf Tziporri (IMS) and Dr. Noam Halfon (IMS), and led by IMS director Dr Amir Givati. Since this analysis will be officially published by IMS in the following weeks, we present here the main preliminary highlights.

First, we performed a detailed verification of ICON simulations, performed as part of the Special Project, over the historical period, focusing on 2-meter temperature (table 1) over the Eastern Mediterranean. The summary of this verification is presented in table 1.

Table 1. Temperature verification of MPI-ESM driven and EC-Earth-Veg driven ICON simulations over the Eastern Mediterranean.

Variable	ICON driven by MPI-ESM	ICON driven by EC-Earth-Veg
Daily maximum temperature over the country	similar to the average of observations in the period 2009-1995, found to be underestimated by more than a	Significant underestimate of 1.0-1.2 degrees in the spatial average in both periods

	degree in the period 2006-2020	
Daily minimum temperature over the country	Significant overestimation of about a degree in the period 2009-1995 and 0.7 degrees in 2006-2020	Overestimation of about half a degree in both periods
Average daily amplitude	Amplitude about 1.8-1.7 degrees lower than the actual amplitude	Amplitude about 1.7-1.5 degrees lower than the actual amplitude
Maximum temperature warming trend	Not identified in the model at all	Identified in the model but its rate is less than half of the observed warming
Minimum temperature warming trend	Not identified in the model at all	Well identified and at a rate similar to the observations
Modelling the Desert regions	Significant overestimations of the average minimum temperature	Significant underestimations of the average maximum temperature
Coastal zone modelling	Significant overestimations of the minimum temperature. Underestimations of the maximum temperature, especially in the period 2006-2020	Significant overestimations of the average minimum temperature
Modelling of radiative cooling areas (valleys-plains)	hardly detects night-time cold pools and the minimum temperature is overestimated	Detects cold pools but cools them only slightly, therefore the minimum temperature is overestimated
Identification of mountain slopes as warm areas around them	Does not recognize well	Does not recognize well

Next, we present a detailed verification of ICON simulations over the historical period, focusing on precipitation over the Eastern Mediterranean.

In both ICON configurations, there appears to be an overestimation of the number of rainy days by the model (a rainy day was defined as a day on which at least 1 mm of rain or more was received), in amounts of up to 10 mm/day. In addition, a detailed examination of the number of heavy and extreme rainy days shows that both model configurations tend in most cases to overestimate the maximum amount of rain. ICON driven by EC-Earth-Veg configuration is particularly prominent in this compared to the ICON driven by MPI-ESM.

The multi-year averages over the validation period show that while the ICON driven by EC-Earth-Veg overestimates the averages, ICON driven by MPI-ESM underestimates the average annual amount. ICON driven by EC-Earth-Veg has an average absolute deviation of 83 mm compared to 62 mm in ICON driven by MPI-ESM. In addition, due to the overestimation of the maximum amounts, the standard deviations in the ICON driven by EC-Earth-Veg are larger than of ICON driven by MPI-ESM relative to the observations.

Regarding the spatial distribution of annual rainfall, the ICON driven by MPI-ESM succeeds in reproducing the spatial structure of rainfall in Israel relatively well, reflecting a distinct advantage over coarser climate models. There is a good identification of the boundaries of the desert and semi-arid regions, a clear reconstruction of the sharp precipitation gradient along the eastern slopes of the central mountains, and a good fit with the rainfall amounts in the Lower Galilee, around Lake Kinneret, and in the northern valleys. However, in several areas, notable local deviations are evident:

Reduced orographic amplification in the mountains: ICON driven by MPI-ESM tends to underestimate the orographic amplification on the western slopes, with deviations of about 100 mm per year recorded in some of these areas, and sometimes even more. On the other hand, on the slopes on the eastern side of the ridge (downwind), a slight overestimation is obtained.

Lack of identification of the "coastal convergence": The model does not reproduce well the coastal convergence mechanism, the area near the coastline, where the intensification and development of cloudiness occurs. In practice, when the wind is westerly, the peak of amplification usually occurs several kilometres east of the coast. The model in ICON driven by MPI-ESM shows an underestimate of tens of millimetres at the coastline, which increases to a strip between 5 and 15 km east of the coast, where the deviation reaches up to about 100 mm per year.

Lack of identification of the "coastal front": The model does not properly identify the “coastal front” mechanism, which increases the rainfall bands in the southern coastal plain during Mediterranean depressions. In these situations, a land breeze originating from Sinai converges over the sea with a cloud band moving from the west, leading to increased rainfall in the southernmost cloud band around the depression. In practice, areas on the central and southern coast and downwind of the coast benefit from this increase, and only south of the southern coastal region is there a sharp decrease in rainfall. In contrast, the model obtains a gradual decrease in rainfall from the north of the coastal plain towards the south.

Overestimation in desert areas: In the arid and extreme arid region (the Arava, southern and eastern Negev), ICON driven by MPI-ESM tends to overestimate. In this configuration, only a limited area appears to receive less than 50 mm of rainfall per year, while in reality, a large area in these areas is below this threshold.

The ICON driven by EC-Earth-Veg configuration shows a significant improvement in precipitation mapping compared to ICON driven by MPI-ESM. ICON driven by EC-Earth-Veg reproduces well the three climate zones in Israel, especially the semi-arid zone (intermediate zone), a zone that is difficult to identify accurately in models, especially global models, because it is an area with a sharp precipitation gradient. The first advantage of ICON driven by EC-Earth-Veg is in identifying the coastal front that increases rainfall in the southern coastal plain, the Judean slopes towards the coast, and the Judean Mountains. The second advantage is in highlighting the increase in precipitation in the interior of the coastal plain, although the effect is not reproduced in its full strength; it can be seen that the peak areas are located several kilometres east of the coastline, and not on the coastline itself. A third advantage concerns the representation of the extreme arid zone: ICON driven by EC-Earth-Veg identifies large areas where annual precipitation is less than 50 mm and presents an accurate location of the 100 mm line.

As in the ICON driven by MPI-ESM configuration, ICON driven by EC-Earth-Veg also underestimates the orographic amplification on the windward slopes and mountain ranges, although to a lesser extent than in the ICON driven by MPI-ESM. At the same time, the rain shadow effect is also weakened and therefore overestimated. Finally, ICON driven by EC-Earth-Veg shows a spatial average precipitation that is 15 mm higher than the observed values (compared to minus 10 mm in ICON driven by MPI-ESM), as well as a lower standard deviation of the differences (41 mm versus 52 mm, respectively). A summary of the main differences between the two configurations is presented in table 2.

Table 2. Yearly precipitation verification of MPI-ESM driven and EC-Earth-Veg driven ICON simulations over the Eastern Mediterranean.

Variable	ICON driven by MPI-ESM	ICON driven by EC-Earth-Veg
Simulation of rainfall amount in the non-desert region	Underestimation	Good
Simulation of rainfall amount in the arid region	Overestimation	Good
Identification of the sharp precipitation gradient in the south	Too moderate	Yes

Simulation of orographic amplification	Underestimation	Underestimation
Identification of a coastal front that increases rainfall in the central regions	No	Yes
Identification of a rain shadow effect	Weak	Weak
Identification of increased rainfall in the interior of the coastal plain	No	Weak

Finally, we present preliminary results of ICON SSP5-8.5 projections until 2100 over the Eastern Mediterranean.

First, we focused on the trends in the average annual maximum temperature, in the period 2020-2100, under the SSP5-8.5 scenario. The direction and rate of the trend in ICON driven by MPI-ESM are similar to the findings of our previous work (based on CMIP5 statistical downscaling). The average difference between the trends in ICON driven by MPI-ESM and those in CMIP5 is estimated at about 0.037 °C/decade among the stations examined. In addition, the temperature values of ICON driven by MPI-ESM are generally relatively low, compared to those calculated in the previous project. Next, the average annual minimum temperature trend direction and rate of the trend in ICON driven by MPI-ESM are similar to the findings of our previous work. The average difference between the trends in ICON driven by MPI-ESM, to those in CMIP5, is very similar to that of the maximum temperature and is estimated at about 0.038 °C/decade among the stations examined. In addition, the temperature values of ICON driven by MPI-ESM are generally relatively high, compared to those calculated in the previous project.
Figures 2 and 3 show the trends in the average daily maximum and minimum temperatures, respectively, at four selected stations for the two model configurations, in the period 2020-2070. In general, the rate of change in ICON driven by MPI-ESM is similar to that of ICON driven by EC-Earth-Veg, although slightly lower. The resulting trends are higher than those reported in previous works. In addition, in ICON driven by MPI-ESM, a decrease of about 0.5 °C in the average annual maximum temperature is observed until around 2040, and then a monotonic increase is recorded until the end of the century.

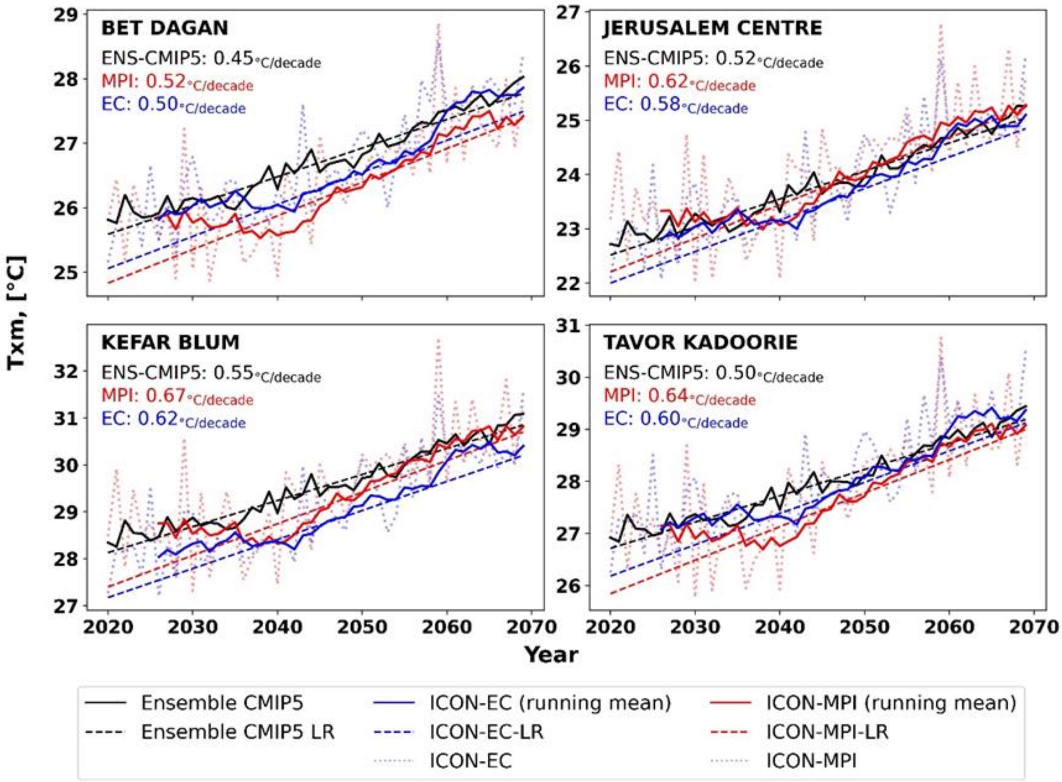

Figure 2. Trends in maximum temperature in the period 2020-2070. ICON driven by EC-Earth-Veg (blue); ICON driven by MPI-ESM (red); CMIP5 (black). Trend values [°C/decade] appear respectively, at the beginning of each panel. A 7-year moving average is shown as a solid line.

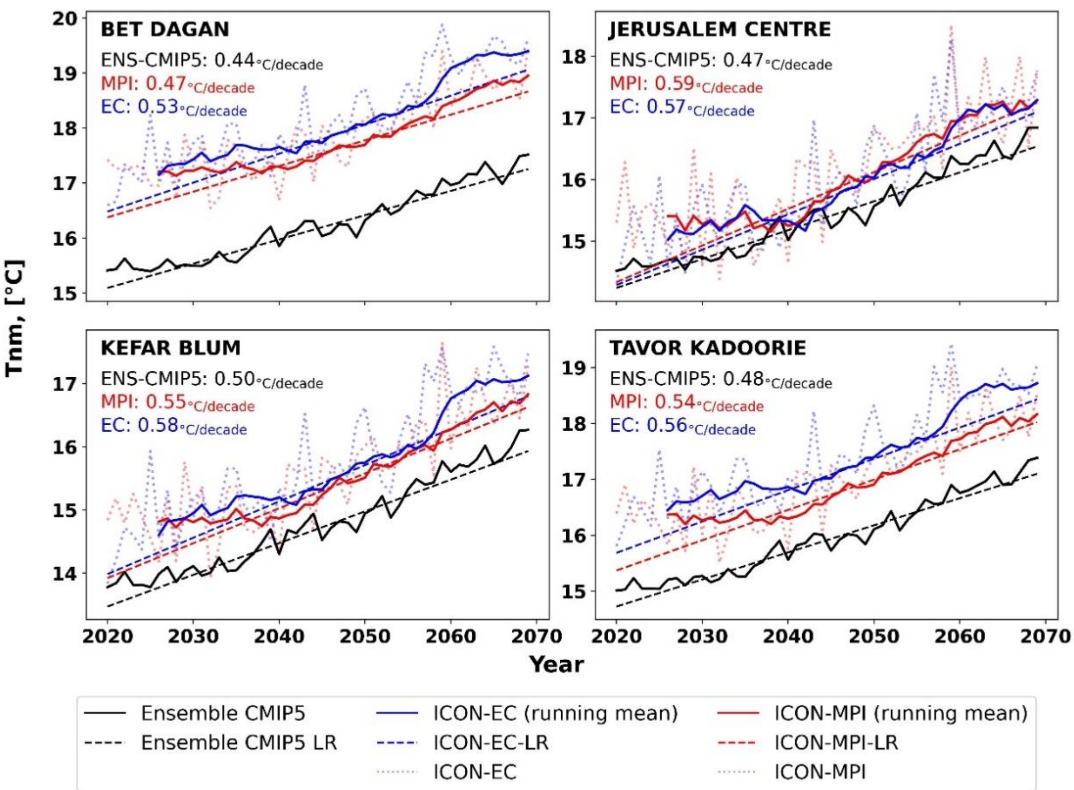

Figure 3. Same as Figure 2 but for daily minimum averaged temperature.

Examination of the maximum annual temperature indicates that ICON driven by MPI-ESM yields higher values compared to ICON driven by EC-Earth-Veg. In ICON driven by MPI-ESM, temperatures exceeding 50 °C were recorded at several stations, while in ICON driven by EC-Earth-Veg, this threshold was crossed only twice until 2070, and only at one station.

The use of a high spatial resolution model allows for a detailed description of the temperature fields. Below we discuss the average daily temperature values for the base period average (2001-2020) as well as for four periods projected until the end of the century. There are anomalies relative to the base period, as obtained from ICON driven by MPI-ESM. Moreover, there is a gradual increase in temperature over time and a noticeable warming trend as one moves eastward toward the interior parts of the country and up to the valley area. Spatial anomaly in temperature for ICON driven by EC-Earth-Veg for the first two periods (2040-2021 and 2060-2041) also show a clear warming trend and with the shift eastward to the interior parts of the country. However, the rate of warming in this configuration is higher than that observed in ICON driven by MPI-ESM and is estimated at an average rate of about 0.4 °C/decade.

Rainfall is a variable characterized by much higher seasonal and spatial variability than that of temperature. There is a change in annual rainfall between 2020 and 2100, at six different stations. ICON driven by MPI-ESM is alongside the ensemble average from the CMIP5 models. The ensemble average results indicate a gradual decrease in rainfall until the end of the century, while in ICON driven by MPI-ESM this trend is less consistent, and in some cases, even certain increase is observed towards the end of the period.

Examination of the linear trend until 2070 also includes ICON driven by EC-Earth-Veg. It demonstrates that ICON driven by MPI-ESM shows a decreasing trend in annual precipitation, similar to the trends generally obtained from the CMIP5 ensemble mean. ICON driven by EC-Earth-Veg also indicates a decreasing trend, but this is sharper and more significant.

The spatial distribution pattern of annual precipitation remains similar throughout the century, but there is a noticeable decrease in the amount relative to the base period 1991-2020. In the coming decades, a decrease in precipitation is expected, mainly in the north of the country and the central mountain range. It is interesting to note that the anomalies obtained at the end of the century (2071-2100) are less pronounced compared to those in the period 2051-2080.

During the validation period, ICON driven by EC-Earth-Veg presented better representativeness and precipitation amounts compared to ICON driven by MPI-ESM. There is an increase in the average precipitation amount in large areas from the centre of the country to the north.