EMI R&D 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	2026
Project Title:	Impact of Land-Use Changes on Past and Future Regional Climate over the EURO-CORDEX domain
Computer Project Account:	spptcard
Principal Investigator(s):	Rita Margarida Cardoso
Affiliation:	Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa
Name of ECMWF scientist(s) collaborating to the project (if applicable)	-
Start date of the project:	01/01/2024
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)	35 M SBU	19,770,859 SBU	27M SBU	25,211,940 (93.4%)
Data storage capacity	(Gbytes)	60 000 GB	13 000GB	60 000 GB	161 300 GB

Summary of project objectives (10 lines max)

The project seeks to improve the understanding of the influence of LUC in the main physical mechanisms and systems governing European climate and is integrated in EURO-CORDEX Flagship Pilot Study "LUCAS – Land Use and Climate Across Scales". Land-surface models and, by extension, regional climate models, produce contradicting results even for idealised experiments. Thus, large uncertainties in climate scenarios are associated to land use representation. More realistic simulations of land use/land cover changes may be important towards reducing the uncertainty and inconsistencies in these scenarios. The project seeks to understand how spatial resolution affects the magnitude and robustness of LUC-induced climate changes and how strongly can local LUC attenuate negative impacts of climate change, e.g., extreme events in Europe.

Summary of problems encountered (10 lines max)

None

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

We will pursue the future climate simulations for the Historical and SSP450 scenario, driven by MPI-ESM1-2-HR.

List of publications/reports from the project with complete references

The results from the Evaluation Simulations performed in 2025 are being distilled within the consortium and several papers being drafted using the ensemble cmorised variables. Here we present some of the titles of the papers in preparation:

1. Evaluation of Fire Weather Index Performance in EURO-CORDEX Simulations
2. EURO-CORDEX Regional Climate Model Performance in European Mountainous Areas
3. From Means to Extremes: A Comprehensive Assessment of EURO-CORDEX Evaluation Regional Climate Simulations
4. Evaluation of the snow-albedo effect in land-atmosphere interactions in sub-polar and alpine climates in the EURO-CORDEX Evaluation Simulations
5. Assessment of climate trends in EURO-CORDEX Evaluation Simulations
6. Water budget Analysis within the EURO-CORDEX Evaluation Simulations
7. How do land-use changes shape the occurrence of extreme temperatures across Europe?
8. Land Use Changes and Atmosphere Feedbacks in an Evolving Climate

Due to the need for ensemble analysis, the papers are late in production. The table with the proposed papers can be found in:

euro-cordex/joint-evaluation: Joint evaluation of the CMIP6 downscaling within EURO-CORDEX.

Within these, the following links show four that have been discussed more regularly.

EURO-CORDEX joint evaluation papers

EURO-CORDEX FWI Evaluation - Google Docs

EURO-CORDEX Joint Evaluation "Mountains"

CORDEX-CMIP6_eval_terr-water-budget - Google Drive

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.

Additionally, our team has pursued research on the effects of land-use changes on extreme heat and its feedbacks into the energy and water fluxes. To force the RCM with a future land-cover evolution consistent with the driving GCM, the ESA-CCI 2015 land-cover map was first reclassified into 16 plant functional types (PFTs) using a Holdridge ecosystem classification driven by E-OBS temperature and precipitation, complemented by irrigated-cropland information from LUH2 and a potential C4-grass map. The Land Use Harmonized dataset version 2 (LUH2; Hurtt et al., 2020), which provides annual, 0.25° historical (850–2015) and SSP/RCP-based future land-use states and transitions, was then used to evolve this PFT map forward and backward in time through a purpose-built Land Use Translator (LUT). Because LUCAS LUC closely tracks LUH2, it inherits some of its known artefacts, such as block-like change patterns and abrupt, locally confined PFT transitions in the future projections, which are not apparent once results are spatially aggregated. The resulting annual land-cover fields were used to drive two sets of WRF simulations over the EURO-CORDEX domain at 0.11° (~12 km) resolution. A set of continuous climate-change runs forced by MPI-ESM1-2-HR from 1950 to 2100 under SSP370, with prescribed aerosols from the driving ESM, were performed. For the scenario, two configurations were run in parallel – one with land cover fixed at 2015 conditions and average 1999–2013 leaf-area index, and one with yearly evolving vegetation and leaf-area index following the LUCAS LUC – isolating the additional effect of land-use change from that of greenhouse-gas forcing alone. The differences between the land cover maps are displayed in figure 1.

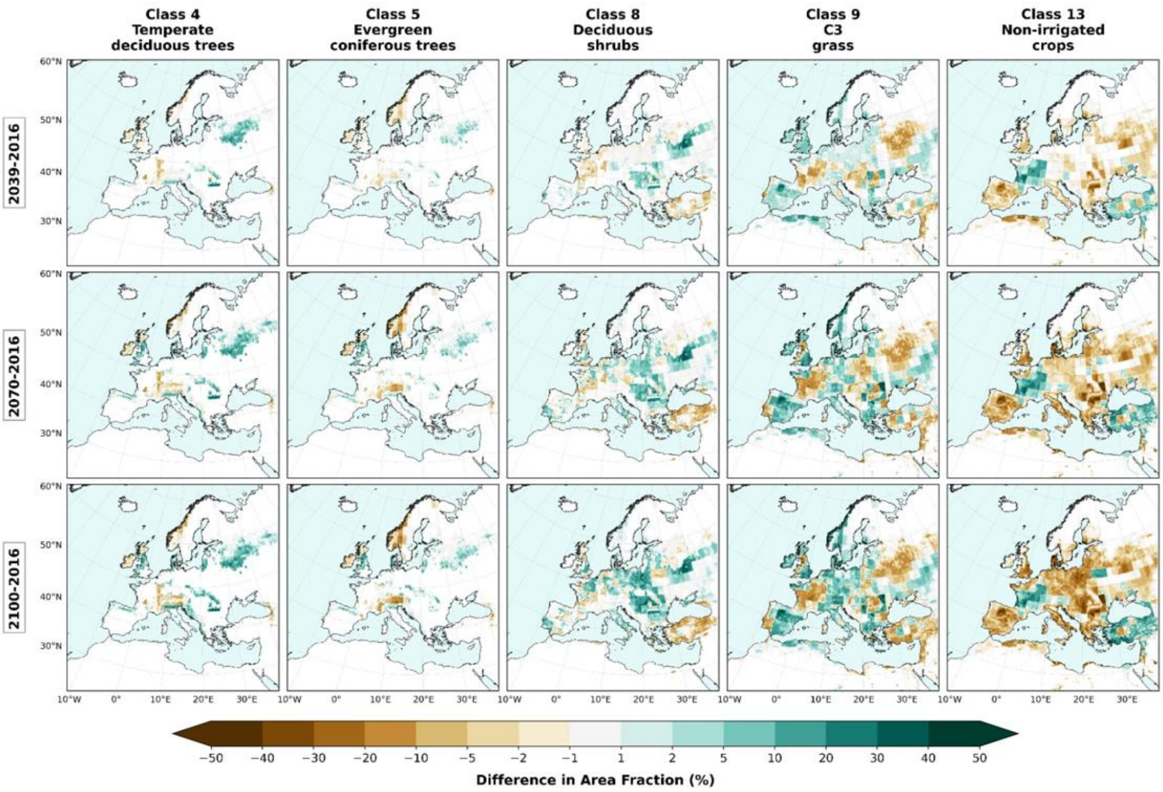

Figure 1 – Differences in Landcover maps for three time periods and five types of vegetation.

Land–atmosphere coupling under extreme heat was quantified with the same normalised coupling metric developed for the Evaluation Simulations (see last year's report): a magnitude index built from the 25th/75th seasonal percentiles is computed for the daily maximum temperature on days exceeding the 90th percentile (MT) and for a second variable, here latent heat flux or soil moisture (MV); the product of the two magnitudes (CM = MT × MV) yields the coupling, with strongly negative values indicating tight land/vegetation control of the surface fluxes and positive values indicating atmospheric control.

Spatial pattern of latent-heat coupling under extreme temperatures

Figure 2 presents the Heat Magnitude vs Latent Heat Magnitude (MT×MLH) coupling metric over the full EURO-CORDEX domain for three future periods (2015–2040, 2041–2070 and 2071–2100) under SSP370 - fixed land cover (CORDEX, top row), evolving land use (LUCAS, middle row) and their difference (LUCAS − CORDEX, bottom row). The latent-heat coupling maps reveal that a large portion of the EURO-CORDEX domain is characterised by strongly positive MT×MLH values (orange and red shading) throughout the simulated period. This positive regime, concentrated above roughly 48–50°N and extending across Scandinavia, the Baltic states, the British Isles and most of eastern Europe, indicates an energy-limited or atmosphere-controlled behaviour: on extreme-heat days, latent heat flux increases (or is anomalously high), so the land surface is not acting as a moisture limit on temperatures.

In the CORDEX row, a transitional band of near-zero to weakly negative MT×MLH values occur roughly between 40–50°N, encompassing much of central Europe, the Alps and the Iberian interior. This band is co-located with the central European transition zone and is the region where land-use change is expected to have the strongest impact on coupling. South of approximately 35°N (North Africa, parts of the eastern Mediterranean) strong negative values reflect the arid and semi-arid fringe of the domain where evapotranspiration is structurally constrained during all conditions, not only heat extremes. Over the three periods the CORDEX pattern evolves relatively slowly: the northern orange/red zone is persistent, and the central European transitional band shifts only gradually northward.

In the LUCAS experiment, even in the earliest period (2015–2040), the negative-coupling zone in the central European belt is more pronounced and extends slightly further north than in CORDEX. By 2041–2070 the contrast is unmistakable: a coherent band of blue and dark-blue values (strongly negative MT×MLH) runs from France and the Iberian plateau eastward through Germany, Poland and into the western Ukraine, sitting within and above the latitude belt that was merely transitional under fixed land cover. By 2071–2100 this band has both deepened in magnitude and expanded further eastward and northward, reaching into areas that remain within the positive (atmosphere-controlled) regime under CORDEX. The northern orange/red zone contracts poleward under LUCAS, with the transition from positive to negative coupling occurring at progressively higher latitudes, mirroring the northward displacement of the coupling transition zone reported in the seminar's summary.

The LUCAS − CORDEX difference maps (bottom row) isolate this land-use signal explicitly. In 2015–2040 the differences are small and spatially fragmented, with only scattered patches of negative difference (more negative coupling under LUCAS) in central Europe and weak positive patches (less coupling under LUCAS) in parts of Scandinavia and the British Isles. By 2041–2070 a coherent negative band emerges, broadly following the central European transitional zone and extending eastward; conversely, positive differences (LUCAS producing weaker or more positive coupling than CORDEX) remain confined to higher latitudes and to parts of Iberia. By 2071–2100, the negative band in the difference maps is by far the dominant feature: a broad, dark expanse covering much of the 45–55°N corridor from western France to the western Eurasian interior, indicating that evolving land use shifts this entire region from a near-neutral or weakly positive latent-heat coupling regime into a distinctly negative (land-controlled) one.

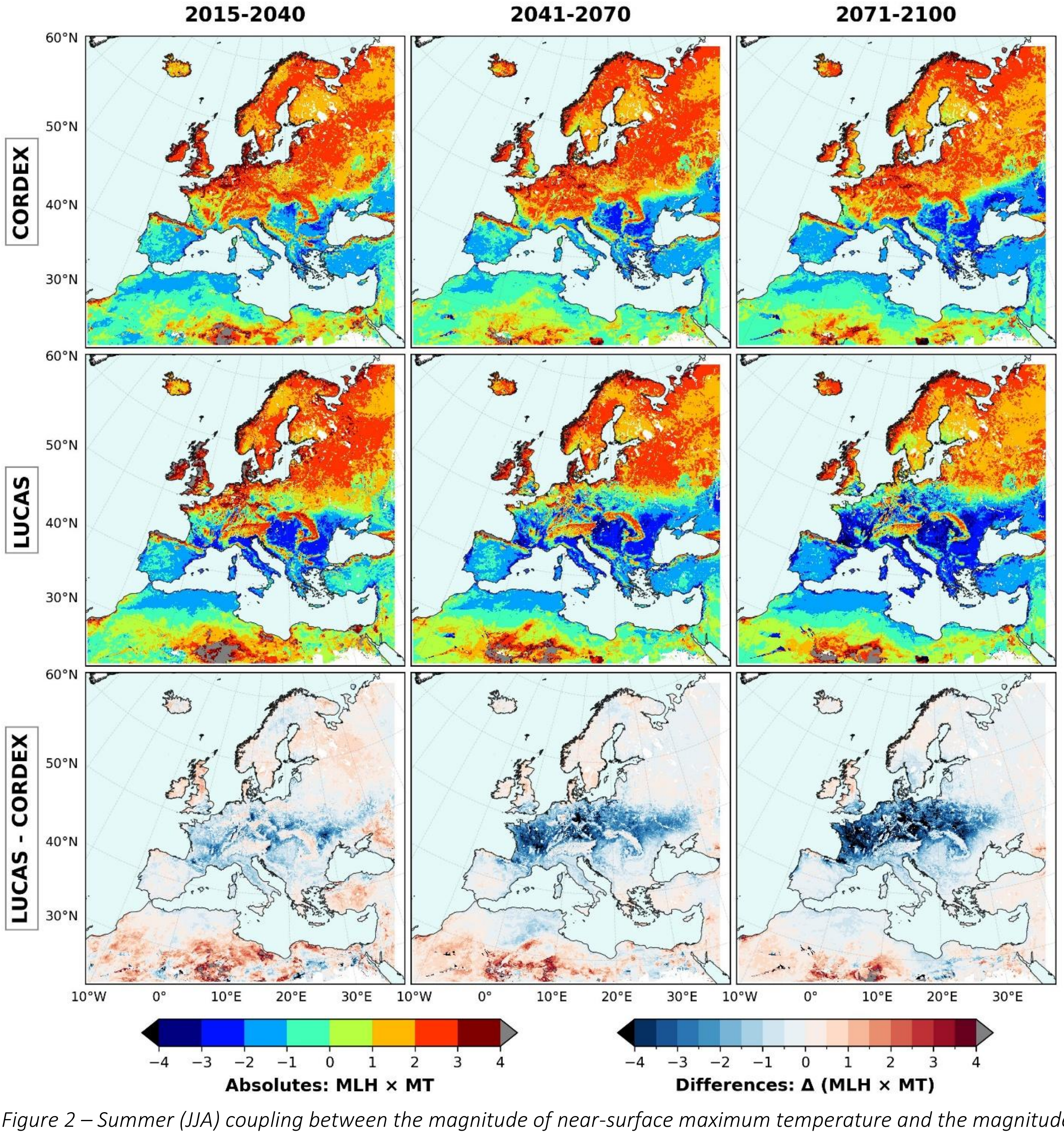

Figure 2 – Summer (JJA) coupling between the magnitude of near-surface maximum temperature and the magnitude of latent heat (Coup(MT,MLH)) in HW for the EURO-CORDEX simulation, LUCAS simulation and the difference between the two

Figure 3 shows the distribution of the magnitude of Latent Heat against the Heat Wave magnitude over central Europe. The fraction of extreme-heat days falling in the strongly coupled (red) quadrant rises steadily through the century in both configurations, but consistently more so once evolving land use is included: from 13% to 22% of events under fixed land cover (CORDEX), versus 28% to 45% under evolving land cover (LUCAS). In relative terms, evolving land use raises the strongly coupled fraction by 115% in 2015–2039 (13%→28%), by 124% in 2041–2070 (17%→38%), and by 105% in 2071–2100 (22%→45%) – i.e. roughly a doubling of the strong-coupling fraction at every horizon, attributable to the concurrent redistribution of crop, grassland and shrub cover represented in the LUCAS forcing. The transitional (blue) quadrant changes much less between configurations (7–10% for CORDEX vs. 8–11% for LUCAS) and trends only mildly upward over time, indicating that land-use evolution mainly pushes already-coupled regions into stronger coupling rather than creating new transitional areas.

Period	Fixed land cover (CORDEX) – transitional %	Fixed land cover (CORDEX) – strong coupling %	Evolving land use (LUCAS) – transitional %	Evolving land use (LUCAS) – strong coupling %
2015–2039	7%	13%	8%	28%
2041–2070	13%	17%	11%	38%
2071–2100	10%	22%	9%	45%

Table 1 – Central Europe: share of summer extreme-heat events in the transitional (blue) and strongly coupled (red) MT×MLH quadrants, fixed (CORDEX) vs. evolving (LUCAS) land cover, SSP370.

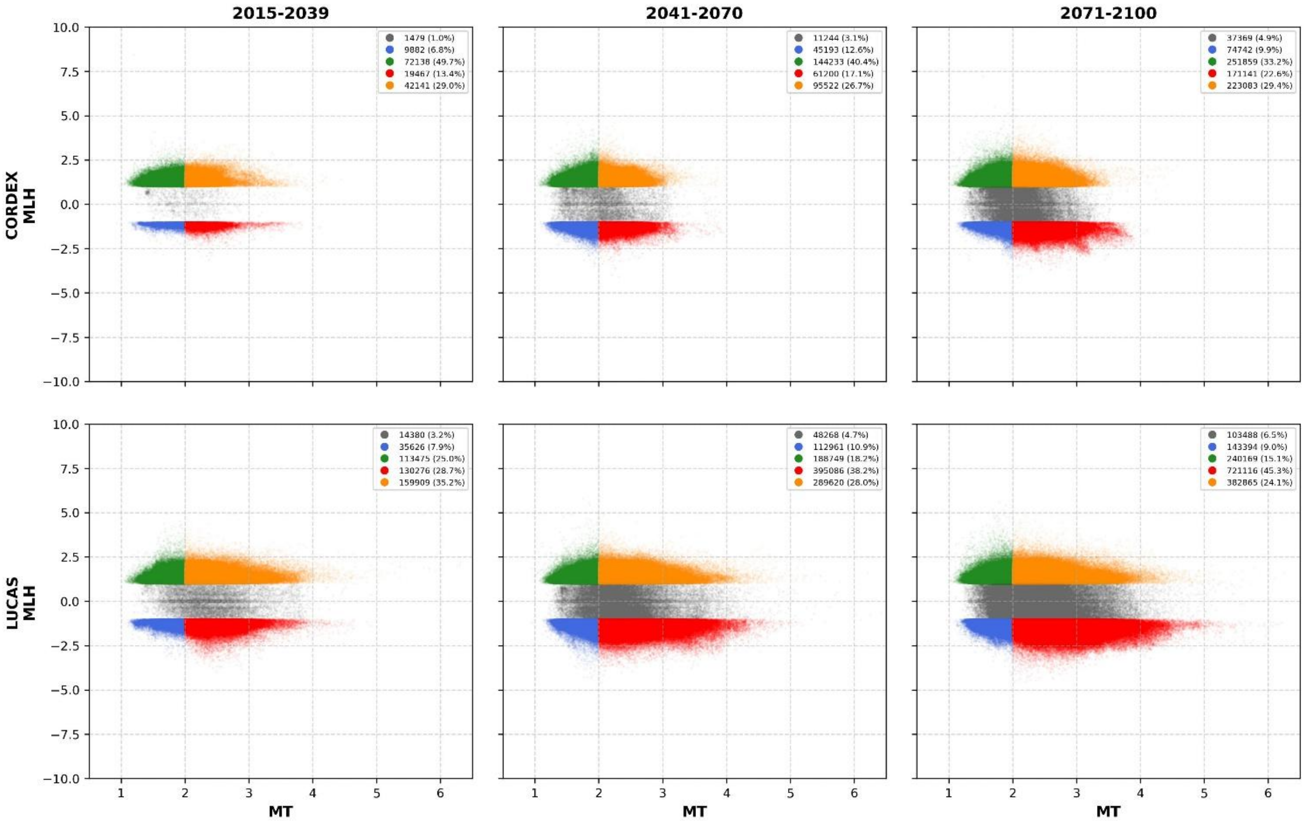

Figure 3 – Summer (JJA) coupling between the magnitude of near-surface maximum temperature and the magnitude of latent heat (Coup(MT,MLH)) in HW for the EURO-CORDEX simulation, LUCAS simulation for central Europe.

Over southern Europe (Figure 4), strong coupling (red) is already substantial under present-day-like conditions and increases under both configurations, but the relative amplification from land-use change is smaller than in central Europe and, unlike central Europe, is concentrated in the second half of the century. The strongly coupled fraction grows from 24% to 30% under fixed land cover and from 23% to 46% under evolving land cover; the relative increase from land-use change is modest in the near term (−4% in 2015–2039, where LUCAS is briefly slightly below CORDEX) and in the mid-century period (+53%, 19%→29%), but becomes comparable to central Europe by the end of the century (+53%, 30%→46%). At the same time, the transitional (blue) quadrant is far larger in southern than in central Europe (42–51% under fixed land cover) and contracts markedly under evolving land cover as the century progresses (50%→32%), consistent with transitional days converting into strongly coupled days rather than the overall extreme-heat frequency changing. This pattern – a large pool of transitional events being progressively reassigned to the strongly coupled regime – is the southern European signature of the northward-shifting transition zone reported in the summary.

Period	Fixed land cover (CORDEX) – transitional %	Fixed land cover (CORDEX) – strong coupling %	Evolving land use (LUCAS) – transitional %	Evolving land use (LUCAS) – strong coupling %
2015–2039	42%	24%	50%	23%
2041–2070	51%	19%	45%	29%
2071–2100	46%	30%	32%	46%

Table 2 – Southern Europe: share of summer extreme-heat events in the transitional (blue) and strongly coupled (red) MT×MLH quadrants, fixed (CORDEX) vs. evolving (LUCAS) land cover, SSP370.

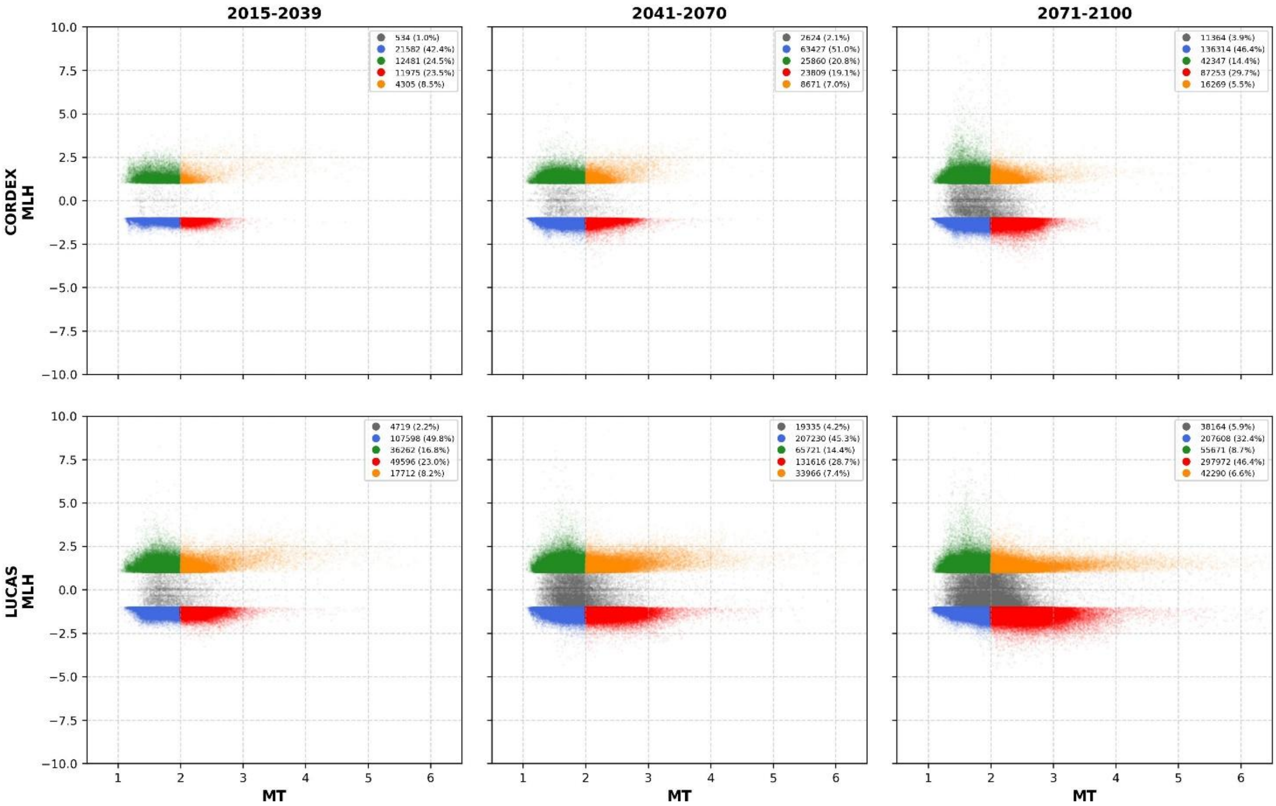

Figure 4 – Summer (JJA) coupling between the magnitude of near-surface maximum temperature and the magnitude of latent heat (Coup(MT,MLH)) in HW for the EURO-CORDEX simulation, LUCAS simulation for Southern Europe.

Soil-moisture coupling fields and Latent Heat

The MT×MSM and MTxMLH coupling are presented as bivariate density distributions in figure 5; again contrasting fixed land cover (CORDEX, top row) with evolving land use (LUCAS, bottom row) for the same three future periods. – latent heat flux (MLH, W/m²) on the vertical axis and soil moisture (MSM, kg/m²) on the horizontal axis – and shows, via nested density contours, how the

joint distribution depends on the severity of the temperature extreme (blue contours: 1≤MT<2; green: 2≤MT<3; red: MT≥3). In every panel the events split into two dominant clusters, both located at negative MSM (roughly −3 to 0 kg/m²): one with positive MLH (energy-limited regime, where evapotranspiration still increases despite the moisture deficit) and one with negative MLH (water-limited regime, where evapotranspiration is suppressed). Two much smaller, low-density clusters also appear at positive MSM, indicating that a minority of extreme-heat events occur even when soil moisture is not anomalously low. Within each panel, the more severe temperature bin (red, MT≥3) is consistently displaced towards more negative MSM relative to the moderate bin (blue, 1≤MT<2), in both clusters and in both configurations, showing that the most extreme heat events are systematically associated with the driest soils.
Comparing the CORDEX and LUCAS rows reveals a clear structural shift introduced by evolving land use: the energy-limited (positive-MLH) cluster contracts markedly from CORDEX to LUCAS, especially by 2071–2100, while the water-limited (negative-MLH) cluster remains broad and, shifts to slightly more negative MSM. The event counts roughly double under evolving land use at every horizon, but the relative excess narrows from +130% in 2015–2040 to +93% in 2071–2100, even though the absolute number of events keeps growing in both configurations (CORDEX events increase 4.7-fold and LUCAS events 4.0-fold from the first to the last period). In other words, fixed-land-cover simulations slowly catch up in event frequency as background warming itself increasingly drives temperatures above the 90th-percentile threshold everywhere, even as the LUCAS runs continue to show a distinctly more water-limited character in the contour shapes described above. This indicates that the land-use signal identified here acts mainly on the nature and spatial distribution of the coupling – shifting events from an energy-limited to a water-limited regime and intensifying coupling over central Europe – rather than solely on the raw frequency of extreme-heat days, which is increasingly dominated by the SSP370 warming signal common to both configurations by the end of the century.
Across both regions, the spatial transition zone separating strongly coupled (land-controlled) from weakly coupled (atmosphere-controlled) regimes shifts progressively northward over the 21st century, and soil moisture declines broadly across Europe, with the largest reductions concentrated in this transition zone once land-use change is taken into account.

Conclusions

Temperature extremes intensify across Europe throughout the 21st century under SSP370, accompanied by a northward migration of the land-atmosphere coupling transition zone. Accounting for evolving, scenario-consistent land-use change – rather than holding land cover fixed – substantially amplifies this coupling: over central Europe the strongly coupled fraction of extreme-heat days roughly doubles relative to the fixed-land-cover runs at every future horizon (a ~105–125% relative increase, driven by shifts among crop, grassland and shrub cover), while over southern Europe the amplification is smaller through mid-century but converges towards a comparable relative increase (~+53%) by 2071–2100, as a large pool of transitional events is progressively reassigned to the strongly coupled regime. Soil moisture decreases across the domain over the century, with the sharpest losses occurring in the transition zone when land-use change is included, underlining the importance of representing realistic LUC trajectories – rather than static land cover – in regional climate-change projections.

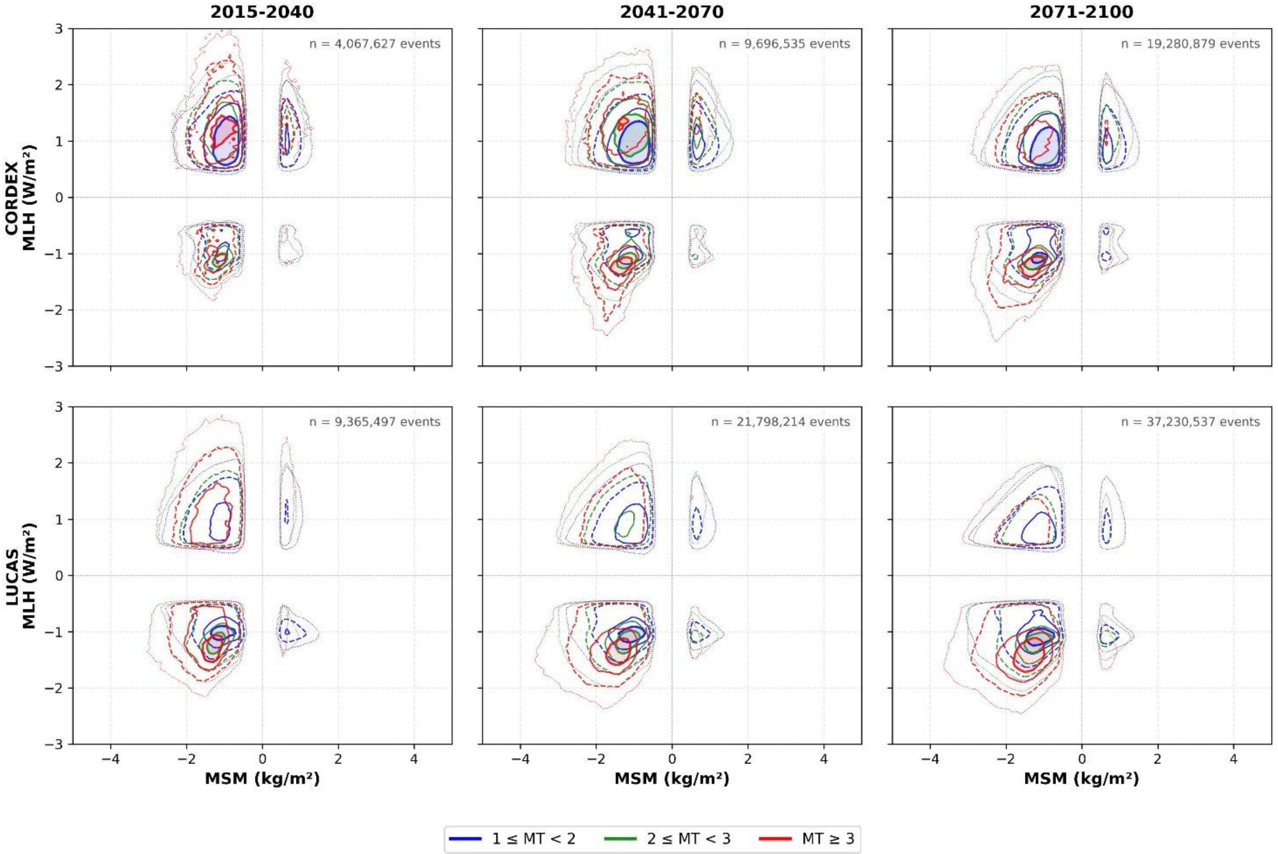

Figure 5 – Summer (JJA) coupling between the magnitude of near-surface maximum temperature, the magnitude of latent heat and soil moisture in HW for the EURO-CORDEX simulation and LUCAS simulation.