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ESTIMATING PREDICTABILITY AND UNCERTAINTY IN SIMULATING THE WATER CYCLE WITH A REGIONAL CLIMATE MODEL

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1. INTRODUCTION

Modern climate models are highly complex numerical constructs, encoding the laws of dynamics and thermodynamics for relevant geophysical fluids. Furthermore, in these models, because of computational and theoretical limitations, explicitly resolved dynamical mechanisms coexist with parameterized physical processes. As stated by Palmer (2000), "the predictability of weather and climate forecasts is determined by the projection of uncertainties in both initial conditions and model formulation onto flow-dependent instabilities of the chaotic climate attractor". Loss of predictability occurs not only because of uncertainties in initial conditions (usually thought particularly relevant for weather forecasting), but also due to model formulation (particularly relevant to climate modeling). It is difficult to separate these two kinds of sources of error, and this seriously hampers the evaluation of climate modeling systems. In fact, the response of a climate model to parameterization changes can lead to truly mysterious biases, and the tuning, validation and improvement of these complex tools represents a difficult challenge to climate modelers. Of particular concern in this context is the compensation between model errors: such compensation may well produce seemingly correct results for incorrect reasons. A recent and still largely unresolved example is the representation of the seasonal water cycle over continental-scale land surfaces. Many atmospheric models currently suffer from an artificial summer drying and warming over major mid-latitude continents. Some investigators (e.g. Machenhauer et al. 1998) suggest that the causes may be ascribed to large-scale biases inducing subsidence; others have focused on physical parameterizations, addressing radiation and land surface processes (e.g. Betts et al. 1996; Wild et al. 1996; Murphy 1999; Seneviratne et al. 2002, Hagemann et al. 2002). The range of these investigations suggests that many different physical processes are probably relevant to the problem. At the same time, however, the absence of the artificial drying from a particular model simulation does not necessarily imply that the individual participating processes are correctly represented, but merely that their combined balance yields an appropriate seasonal soil moisture evolution.

The goal of this paper is to develop an improved methodology for the assessment of the quality of an RCM system in the presence of limited predictability. To this end, a detailed analysis of one RCM's ability to represent the natural inter-annual variability on monthly and seasonal time-scales within the ERA-15 period 1979-1993 is undertaken. The RCM is driven at its lateral boundaries by the observed synoptic-scale variability, and the model is evaluated for its ability to reproduce climatic fluctuations on monthly and seasonal time scales, within predictability bounds derived from an ensemble experiment. A previous version of this methodology has been used earlier in month-long integrations (Lüthi et al. 1996, Fukutome et al. 1999), and is here extended to cover a set of continuous simulations with durations of 15 years and to include a treatment of uncertainty due to both model formulation and to limited predictability.

The validation of a climate modeling system relative to the inter-annual variability has two major advantages. Firstly, unlike the validation based on seasonal or yearly climate means, the method is much less permissive with respect to the practice of model tuning and associated misleading effects. In fact, even a hypothetical perfectly-tuned model with an excellent representation of the longer-term mean climate may still exhibit deficiencies in representing inter-annual variations. Secondly, the methodology implicitly assesses simulated climatic differences (such as differences between warm and cold winters), and this may to some extent be taken as a surrogate for climatic changes. A validation based on inter-annual variability can also assess the role of model biases in the simulation of climatic differences, one of the major open issues when using a modeling system for the simulation of climate change (IPCC 2001).

The main disadvantage of our validation methodology is its restricted applicability to modeling systems that contain some degree of determinism. In an RCM, the monthly mean climate is largely controlled by the forcing at the lateral boundaries and by long-term memory effects (such as those associated with soil moisture and snow cover) in the interior (Jones et al. 1995), as well as model formulation. In contrast, our methodology is not applicable to a free GCM simulation, where comparison with observations on a month-to-month basis is not meaningful, due to the lack of deterministic forcing. For our particular choice of model configuration, the chaotic component is relatively small and will be estimated using an ensemble experiment.

As for the problem of model formulation, the suite of physical parameterizations to be investigated is well in tune with the need for completeness required in the study of such problems, and will address physically-based representations of the interactions of water, in its different phases, with dynamics, radiation, the land surface envi-

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ronment, turbulence and convection. The focus on water-cycle related processes is well justified, due to its importance for the climate system, but also due its significance in the event of climate change.

The outline of the paper is as follows: In section 2, the CHRM RCM is briefly outlined; section 3 discusses the model's ability to represent current climate variability, followed by a comparative assessment of the model's predictability and uncertainties; finally section 4 provides an interpretation of the mechanisms uncovered by the sensitivity studies, together with some concluding considerations.

2. METHODS

2.1 *The CHRM Regional Climate Model*

CHRM is a climate version of the former mesoscale weather forecasting model of the German and Swiss meteorological services, known as the HRM (High Resolution Model) or formerly EM (Europa-Modell). The model grid is a regular latitude/longitude grid (Arakawa type C) with a rotated pole and a hybrid vertical coordinate (Simmons and Burridge 1981) with 20 levels. It includes a full package of physical parameterizations, including a mass-flux scheme for moist convection (Tiedtke 1988); Kessler-type microphysics (Kessler 1969, Lin et al. 1983); a radiation package (Ritter and Geleyn 1992) including interaction with partial cloud cover (of the type described in Slingo, 1987); a land surface scheme (Dickinson 1984) with three soil moisture layers; an 'extended force-restore' soil thermal model (Jacobsen and Heise 1982), also capable of interacting with accumulated snow at the soil surface); and vertical diffusion and turbulent fluxes based on the flux-gradient approach (of the classic Louis et al. (1982), type in the surface layer, Mellor and Yamada (1974), in the boundary layer and above).

CHRM is nudged at the lateral boundaries using the Davies (1976) relaxation technique for temperature, moisture and wind with an updating frequency of six hours. The soil bottom boundary conditions are only initialized, so that the soil model is allowed to develop its own solution over the course of the climate simulation. The only substantial data ingestion deviations from the operational NWP modeling system, which is normally driven by the DWD GCM (GME), are due to the use of ECMWF Re-Analysis (ERA-15, Gibson et al. 1996) data for the lateral boundaries forcing. Recent changes in our regional climate modeling suite, in relation to previous work (Lüthi et al 1996, Schär et al. 1999, Heck et al., 2001) were inspired by the need to address longer simulation periods than used in the NWP context, and are fully described in Vidale et al. (2003).

2.2 *Data sets*

Data sets used for validation purposes were mainly extracted from the Climatic Research Unit analyses (New et al. 1999) at 50 km. Additionally, ECMWF reanalysis data (ERA-15), with T106 truncation (excluding of course the fields used for the nudging) were also used for validation purposes in the interior of the domain, although only in instances in which other data from independent origins were not available. All fields were interpolated to the CHRM rotated lat/lon grid (56 km).

2.3 *Model setup for the numerical experiments*

Three "model formulation" integrations will be presented: one with artificial in-soil water-flux limitations (SOIL, CHRM 2.1), one with corrections to the long-term treatment of soil moisture (HYD, CHRM 2.2), and one with corrections to the treatment of the cloud-radiation interactions (RAD, CHRM 2.3). The model version used in the ensemble experiment with different initial conditions is RAD.

In the NWP operation of the HRM model, the soil water profile is calculated by the driving GCM and used to initialize and nudge the model, with the intent of controlling 2m temperatures through a Bowen ratio approach, and not with multi-year soil water conservation objectives in sight. The first simulation, SOIL, corresponds closely to an earlier configuration of the original NWP version of the soil model. In this version, as a result, infiltration of precipitation is hindered by the numerics of the vertical grid stretching (with soil layers corresponding to 2, 8 and 190cm), and by physical limitations in the form of artificial impermeabilization deriving from soil (cold) temperature barriers affecting soil water conductivity. As previous studies had not included the full yearly cycle, the lack of appropriate soil moisture recharge had only been noted recently. Simulation SOIL has therefore a tendency to severely underestimate soil moisture recharge during the colder seasons and thus to underestimate transpiration of water originating in the root zone.

Simulation HYD, by contrast, retains a balanced soil water cycle which establishes itself completely a few years into the simulation and displays a stable yearly cycle until the end of the integration, at year 15, as will be seen in the next section. This is accomplished by relaxing all artificial in-soil water flux constraints, with the purpose of obtaining a more regular recharge and normalized latent heat fluxes including a reasonable seasonal contribution of transpiration originating in the root zone.

Simulation RAD is a further development from HYD and addresses climatologically significant negative surface short-wave radiative biases that are present in SOIL and HYD, with the intent of correcting the well-known surface negative temperature bias in the model. The method used here, rather than resorting to the tuning of the liquid water path fed to the radiation scheme, consists in improving the cloud liquid water estimation by implementing (grid-scale) physical-empirical cloud diagnostics in the form of the Xu and Randall (1996) parameterization. The latter replaces the standard Slingo-type diagnostics, which are based solely on relative humidity criteria. The setup of simulation RAD preserves otherwise the treatment of soil moisture fluxes in simulation HYD.

3. RESULTS

3.1 *Summary of previous findings about the model's climatology*

The three "model formulation" experiments were integrated from January 1, 1979 onwards for the entire 1979-1993 ERA-15 period, over a standard European domain, previously used in earlier studies (Lüthi et al 1996, Schär at al.1999, Heck et al. 2001) with a grid spacing of approximately 56 km and a time step of five minutes. The domain is shown in Fig. 1, along with the sub-domains to be used for time-series calculations. The two-letter labels have been in use historically at ETH, and are listed in the caption, briefly reminding of European political and geographical regions.

The mean climate reproduced by the model and its validation by means of CRU and ERA-15 datasets have been discussed in Vidale et al. (2003). The same initial conditions and lateral nudging data were applied to these three simulations. The horizontal distribution of precipitation, as shown in that paper, confirms that the CHRM is capable of meaningfully reproducing the European-scale climatology during the ERA-15 period. The precipitation and temperature biases which were uncovered show that the model has good skill at winter precipitation, while having a tendency to produce dry conditions over the southeast in the growing season, and suffering from a domain-wide cold bias in all seasons. The magnitude of the biases is well within the state of the art and some of the geographical signatures are similar to those in other European RCMs. The sign and magnitude of these biases are strongly dependent on model formulation, season and location, as will be seen in section

3.2 *Soil moisture evolution*

Before delving into the analysis of inter-annual variability, it is important to include an excursion into the soil moisture evolution in the three model simulations, which is essential for their interpretation. As an example of a regional soil moisture evolution, Fig. 2 compares the soil moisture levels from the first and last year of the three simulations, averaged over the Alps sub-domain (see Fig.1).

Bearing in mind that 1992 and 1993 were years of extremely low precipitation in this region (see Figs. 3-4), while 1978-79 was a very wet winter, the January 1979 initial condition, imposed from ERA-15 analysis, shows all three model versions very near the field capacity level (shown as a weighted average over the domain with continuous lines). Already by inspecting the soil water levels in December 1979, it is clear, however, that the soil moisture in the root zone is not re-charged equally in the three simulations, with SOIL recharging least and RAD recharging most. Simulations HYD and RAD achieve a stable, repeating soil moisture cycle between the first and fourth simulation years, depending on location, by exclusively interacting with the atmospheric water cycle. In simulation SOIL, on the contrary, the soil is losing water as a result of underestimating the recharge, despite sizable access to the climatological layer, the latter to prevent soil moisture values under the ADP. This behavior has a cumulative effect over the course of the fifteen years: simulation SOIL is clearly achieving a much lower water level by 1993 (about 100 mm less over the domain average, much more pronounced locally), with a smaller amplitude of the yearly cycle, than either HYD or RAD. The difference between simulations RAD and HYD can be ascribed to a slightly more vigorous water cycle in RAD and to the warmer temperatures, which help water infiltration into the soil due to the less frequent triggering of soil impermeabilization by freezing.

3.3 *Inter-annual variability of precipitation*

In this subsection we analyze the inter-annual variability in precipitation for the 1979-1993 period and the ability of the CHRM model to regionally represent it. The results are presented in the form of scatter diagrams of model and observed (CRU) sub-domain seasonal averages. Before proceeding, we use the top-left panel of Fig. 3 (sub-domain SW) to explain their use. On the abscissa are CRU observational data, while on the ordinate are model results. In each panel the results from the three simulations SOIL, HYD and RAD as well as the ERA-15 reanalysis, are represented (using different symbols and a common year label), while each of the three simulations, together with ERA-15 estimates, is summarized by its regression line. Perfect model simulations would be located on a diagonal line (left bottom to right top) across each panel. This type of plot allows distinguishing three different types of error. First, an overall wet or dry bias can be identified from a location of the regression line above or below the diagonal (e.g. ERA and RAD). Second, a systematic bias in representing the inter-annual variability is present when the slope of the regression line does not match that of the diagonal (e.g. ERA has a tendency to overestimate precipitation more in wet years than dry years in absolute terms, albeit not necessarily so in relative terms). This behavior will be referred to as a misrepresentation of the "precipitation sensitivity", and it pinpoints a problem in simulating differences (here between wet and dry seasons). This kind of consideration may be relevant to assess the suitability of a model for conducting climate change scenarios, as is recommended in the latest IPCC (2001) report. Third, the scatter of individual data points around the regression line represents an unsystematic error contribution. This error contribution may partly be explained by the limited predictability of the system (see the previous section), which is summarized for each variable and region by the grey polygon of height $2 \cdot \sigma$ (standard deviation of ensemble results from Vidale et al. 2003 for the RAD model, produced by perturbing the model's initial conditions) straddling the "perfect model" diagonal across each diagram. During summer (Fig. 4) the grey area is much taller in response to the reduced predictability. The results nevertheless show how the SOIL simulation tends to be consistently too dry, especially in the south and southeast, and also how the slope of the regression line (the precipitation sensitivity) is generally underestimated. The former of the two errors is substantially reduced in simulation HYD and RAD over most domains, while the underestimation of the precipitation sensitivity is not or only marginally improved. The regions displaying the most pronounced dry bias are the Alps and the Danube; Germany and France are relatively better represented, while Spain and the Mediterranean show surprisingly good skill at the representation of inter-annual variability despite the small signal and the identified bias. Simulation RAD is closest to the observational data in the majority of sub-domains, except in SW and FR. The uncertainty stemming from alternative initial conditions is larger than in winter, ranging from 0.2 to 1 mm/day, but is comparable to the one stemming from model formulation in some sub-domains, since individual model versions produce quite different bias and precipitation sensitivity results.The magnitude of the uncertainty is generally larger in the east and near mountain ranges. In general, it is quite clear how the signal under study displays enough inter-annual variability as to allow the (1979-1993) model errors to be relatively large while still enabling the model to claim skill at representing this variability over most sub-domains over the entire yearly cycle. This skill, however, is least in the summer period and furthest from the principal entry point of storms, at the NW corner of the domain.

3.4 *Inter-annual temperature variability*

The winter temperature scatter diagrams in Fig. 5 show for most domains a good skill at representing the temperature sensitivity (the slope of the regression lines), while there is a cold bias as large as 2K in several domains (e.g. France, Spain and Alps). Differences between individual simulations are quite small, but comparisons to the uncertainty associated with predictability (ranging from 0.1 to 0.6 K) indicate that model formulation is a more important source of uncertainty for this variable in winter. The winter precipitation in Fig. 3 shows very good skill of the model at reproducing inter-annual variability, as data lie principally along the diagonal over most regions. The sub-domains with the best reproduction of the signal are the Alps and France, for which both precipitation amount and sensitivity are almost perfectly represented for all four data sets. Germany, Spain, SE Mediterranean and the Danube region show good simulation quality, but slightly less so in years of high precipitation, which are overestimated in the North and under-estimated in the South; Scandinavia (SW) and the East (EA) domains displays the largest errors, with pronounced over-estimation in SW (but less so than ERA-15) and poor slope of the regression line for SP and ME. Modeled precipitation regression lines over sub-domains SW, EA, GE, DA show some degree of overestimation, but at the same time lie between ERA and CRU estimates. It is of interest to note that, for most of the data sets, the slope of the regression line corresponds very closely to reality (is parallel to the diagonal), but remains poorest in the south. The uncertainty associated with alternative initial conditions ranging from 0.2 to 0.6 mm/day, is most relevant in sub-domains further from the entry point of storms (NW), but tends to be comparatively important since individual model versions produce solutions that are very nearly identical. Summer temperature scatter diagrams in Fig. 6 show how most data are roughly aligned parallel to the diagonal (thus correctly representing temperature sensitivity), but the systematic errors are quite large, as much as 2K. The temperature field displays the largest differences between simulations, with simulation SOIL always much warmer and simulation HYD much colder than the other two. Over the Danube region simulation SOIL is systematically over 1 K warmer than CRU, while simulation HYD is systematically 1K colder; simulation RAD has the least bias, well in agreement with ERA-15. The regression line of simulation SOIL is closest to the diagonal in several domains, but this is a clear case of error compensation and occurs at the expense of pronounced underestimation of summer precipitation in most areas (contrast with Fig. 4). Simulation HYD is generally the coldest, while simulation RAD is a clear improvement over HYD in all sub-domains, being the one with the least bias over the Danube region, and being within 1K error bars over the Alps, Sweden, Germany, France and the SE Mediterranean, with the exception of Spain. It is also noteworthy that ERA-15 has quite an excellent behavior over most sub-domains, with the exception of Spain, which shows a bias signature very similar in geographic distribution and magnitude to the one in our model. The uncertainty stemming from model predictability (0.2 to 0.6 K) is comparatively much less important for a variable and period in which large discrepancies exist between solutions produced by alternative model configurations, and especially so in the south.

3.5 *Surface energy and water fluxes effects*

The soil-atmosphere feedbacks in the water cycle, which affect the land surface temperature and precipitation budgets, can better be understood by considering the surface energy and water fluxes and contrasting them in all three simulation cases. The fields that are mostly affected in the three different model formulation experiments are the surface net short wave flux and the surface latent heat flux. The three simulations are compared with the ERA-15 fluxes in Figs. 7 and 8, this time in the form of the mean seasonal cycle of the 15-year period, again organized by region. The use of ERA-15 solar fluxes as a proxy for observations is justified by Wild et al. (1998), who showed that the incoming solar radiation is in general well reproduced by ERA and well amenable to this type of basic validation in regional climate studies. The absorbed solar radiation of simulation SOIL (Fig. 7) is reasonably in agreement with the fluxes of ERA-15, with a maximum local over-estimation of 20 W/m2 in sub-domain DA (corresponding to summer positive temperature biases) and an under-estimation over sub-domain SW (-40 W/m2 at the peak). Most sub-domains exhibit however significant dry biases (in several regions as much as 40 W/m2 at the peak of the growing season), as evident from the depressed latent heat flux simulated by the model (Fig. 8), also associated with a general winding-down of the soil moisture annual cycle, as was seen in The restored surface latent heat fluxes (seen in Fig. 8) in model HYD are in better agreement with those of ERA-15 than those in SOIL (except over SW and GE where some over-estimation is present). This extra water flux into the atmosphere feeds however the almost exclusive growth of low-level clouds (LLCs, not shown) which have the general effect of depressing the net surface short wave over the growing season by 10-30 W/m2: in Sweden the June biases of 40 Wm-2 are made to be about 60 W/m2 by this model formulation. Model RAD, with about the same total water content as HYD but a different diagnostic of cloud cover by layer (and correspondingly liquid water path), displays solar radiation with the opposite tendency, substantially correcting the bias by almost 40 Wm-2 over Sweden and also over Germany, in eastern Europe and the Alps. The corrections due to RAD are most pronounced in central and northern Europe and are also found (although with slightly smaller magnitude) in the net radiation plots (not shown), so that the response to the introduction of the Xu and Randall cloud diagnostic is clearly of benefit to the surface energy balance and explains the improved results in the temperature plots. The representation of the surface latent heat fluxes in RAD is very similar to that in HYD. The short wave plots for the southern domains (SP, ME) show that radiation is rather well represented in this region and insensitive to model formulation. The latent heat fluxes biases for these regions are also significant, but also evidence spring and fall errors in the initiation and termination of vegetation activity.

4. DISCUSSION OF THE SIMULATED WATER AND ENERGY CYCLES

4.1 *Comparison of internal variability and model formulation*

The comparison of the uncertainties originating from model internal variability and those originating from alternative model formulations indicates that the latter are mostly predominant. Unlike the results from experiments with alternative model formulations, no systematic behavior was uncovered in the time frame of the three ensemble simulations, with a spread of solutions continuously converging and diverging, depending on location, variable and season, but no defined bias or trend. The summer precipitation field appears to be the one with the greatest sensitivity to initial conditions (although in general of comparable or smaller magnitude than the sensitivity to model formulation), arising from soil moisture and snow cover memory effects, the time scales of which appear to vary from months to several years, depending on the location over the domain.

4.2 *Mechanisms uncovered*

The results of the experiments with alternative model formulations uncovered clear mechanisms associated with the water cycle: a compromised soil moisture recharge (in SOIL) causes systematic over-use of soil moisture in order to sustain local precipitation processes, with a tendency to exhaust this reservoir. Less low cloud formation in the growing seasons and limited latent heat fluxes also contribute to a warmer summer climate. A more realistic, self-sustaining, water cycle (in HYD) also enhances summer precipitation, at the cost of allowing excessive interplay of low-level cloud-radiation feedbacks, which, together with the enhanced latent heat fluxes over the growing season, produces a balance climate significantly colder than the observed climate. An alternative cloud-radiation feedback intensity, achieved by altering the cloud diagnostic (in RAD) and the resulting short wave attenuation throughout the troposphere, produces a more reasonable radiative balance at the surface (and associated temperatures) while being still successful at producing a sustainable water cycle.

4.3 *Biases and their sources*

Interpreting these results in terms of biases and related compensation of model errors, it is clear that model SOIL is producing good growing season diagnostics of surface temperatures (except over the DA region, one of the “raisons d’être” of the MERCURE project) by compromising the soundness of its water cycle. This is characterized, for instance, by the significant dry biases and the winding-down soil moisture annual cycle. The resulting representation of precipitation displays substantial biases, which are more severe over the east of the domain and in years in which more abundant precipitation was observed. The representation of the energy and water cycles inter-play appears compromised and most of the good results are clearly attributable to wrong reasons.

Model HYD, on the other hand, is capable of representing a sound and self-sustaining water cycle, mostly addressing the precipitation, latent heat flux and soil moisture errors in model SOIL, but at the cost of introducing a severe surface temperature bias, partly explained by a negative bias in short wave radiation at the surface.

Model RAD comparatively retains the best ability in the representation of both energy and water cycles, with the smallest net short wave and latent heat flux biases, co-existing with a sustainable soil moisture cycle and one of the best representations of precipitation, in both seasons. The summer temperature bias is still significant, but is certainly an important improvement over the biases in models SOIL and HYD, while it also derives from a more meaningful net surface radiative balance.

It is particularly interesting to notice that the increase in solar radiation between simulations HYD and RAD, and the increase in evapo-transpiration between simulation SOIL and HYD, are just about the same and occur over the same regions. This again confirms the diagnostic of error compensation in the treatment of the soil-water and energy cycles in SOIL. The Xu and Randall corrections are also limited to regions where the yearly cycle of cloudiness is evolving around a high average value, such as Scandinavia, and is much smaller in regions of infrequent cloud cover, such as Spain, so that temperature biases are virtually unaffected. The summer positive bias in net short wave, which is present in model RAD over the DA sub-domain, corresponds to the largest deficit in latent heat flux over the domain. The same observation applies, with smaller involved amplitudes, to sub-domains SP and ME.

The uncovered mechanisms and related error compensations however do not explain all biases. A reasonable interpretation of the winter surface (2m) temperature bias is that it partially reflects the winter error in the ERA-15 data (which consists in a domain-wide –2K bias, see Viterbo et al., 1999), an argument which may come to mind by observing the geographical and temporal distributions of the CHRM and ERA-15 biases. A more pondered explanation needs to also take into account the characteristics of the force-restore soil model used in the CHRM, which has only two layers, and therefore introduces large phase and amplitude errors at time scales other than diurnal and annual (see also the discussion in Jacobsen and Heise 1984). The model cannot retain sufficient memory of the summer heat storage (and is also influenced by a too cold boundary condition at the lowermost level, corresponding to the 15-year surface temperature average in ERA-15) and therefore tends to quickly reflect and respond to the cold bias in the driving data traveling through the domain from the lateral boundaries. Moreover, the model has a tendency to develop a too narrow diurnal cycle of temperature (confirmed by a separate analysis of diurnal temperature range climatology versus CRU data), so that maximum diurnal temperatures are too cold and minimum nighttime temperatures are too warm. The bias is in general concentrated more in the maximum (daytime) 2m temperature field, both in summer and winter (albeit almost exclusively in the southern extremes of the domain for winter) which is the field mostly affected both by the evapo-transpiration corrections in HYD and the cloud-radiation alterations in RAD. The impact of the grid-scale liquid water diagnostics scheme, revealed by differences in simulation RAD versus simulation HYD, is also concentrated almost exclusively to daytime maximum temperatures.

Over the summer, when local conditions prevail, and when the ERA-15 bias is much smaller, the model is free to achieve its own surface energy balance, which is much more meaningful under the new conditions imposed by the Xu and Randall cloud diagnostics, despite the fact that its partitioning into sensible and latent heat is locally still favoring too high Bowen ratios.

As expected, winter precipitation appears to be well represented, despite some local over-estimation, and appears to be unaffected by the physical parameterization changes introduced.

5. CONCLUSIONS AND OUTLOOK

Consideration of both the predictability of the climate system and the uncertainties related to model formulation are at the same time necessary and useful in testing, understanding and improving a climate modeling system. The methodology presented here includes both approaches and expands the inter-annual variability method already applied in Lüthi et al. (1996), presenting results from multi-year integrations of different model formulations and with alternative initial conditions. The nature of the methodology, and the involved computational costs, indicate that RCMs can provide sound and affordable test-beds for physical parameterization packages in the context of climate studies. The following was found in analysis of our simulation results:

- The model has shown skill at representing inter-annual variability in precipitation and surface temperature, more so in winter, despite fairly sizeable (but within the state of the art) biases in both precipitation and temperature;
- The analysis of precipitation sensitivity favors a correct representation of dryer years, especially so in summer and the south, while temperature sensitivity is generally well represented;
- The comparison of model predictability and uncertainties stemming from different model formulations indicates that the latter are relatively more important over most of the European region, except for precipitation in summer, where some sub-domains indicate a moderate loss of predictability. The relevance of local physical processes is of course enhanced at times when the large scale driving has less influence, most notably in summer, and farther from the entry region of storms, but it is not exclusive of those periods;
- Severe limitations to the in-soil water flux, resulting in significant drying of the soil after few years into the simulation, create corresponding deficits in precipitation and large positive temperature biases in most central European regions, especially in the Danube catchment region;
- Correcting the large deficit in surface solar radiation has allowed the model to achieve a good balance between the energy and the water cycles, especially in summer; this is also true, in winter, of elevated regions such as the Alps;
- The inter-play and chain of physical parameterizations feedbacks revealed by the analysis of CHRM regional climate is sound.

The new series of simulations that will be undertaken in the course of the next year will use driving data from HadAM3 and ECHAM5 simulations for current climate conditions, and also, as soon as available from ERA-40 data; this should allow for better understanding of the influence of the lateral boundary forcing on the remaining biases. Tests will also be performed with an expanded domain, in order to study the ability of the model to develop its own solution in a larger interior region. Furthermore, a more advanced and comprehensive SVATS will be coupled, including a multi-layer diffusive soil thermal model, which should isolate the inadequacies of the force restore method for this type of long term studies.

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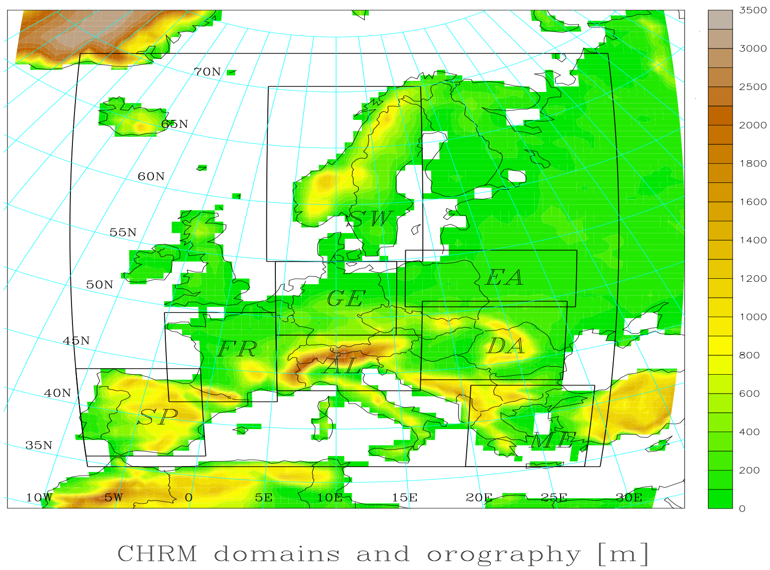

FIG. 1: The CHRM domain and sub-domains (boxes), superposed on the model orography (m). The domain comprises 81 (longitudinally) by 91 (latitudinally) grid points. The sub-domain labels will be used subsequently in area-average plots. AL is an abbreviation for Alpine region, DA for Danube catchment, EA for East Europe, FR for France, GE for Germany, ME for South-East Mediterranean, SP for Spain (Iberian Peninsula), SW for Sweden (Scandinavia). The model is relaxed to the driving data within the 8-point rim delimited by the outermost convex box, which marks the internal (free) integration region.

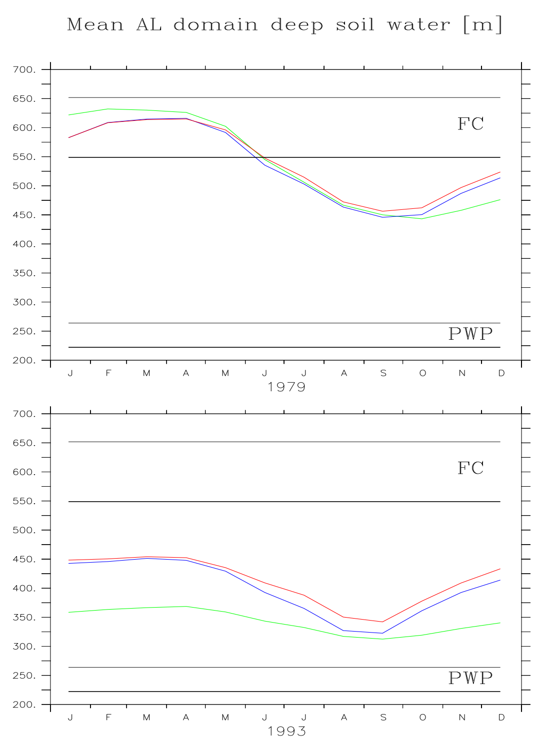

FIG. 2: Time series plot of domain-average deep soil water for the initial year (1979, top panel) and the final year (1993, bottom panel) of the simulations in mm. Simulations SOIL, HYD and RAD are represented by dotted, dash-dot and dashed lines respectively. The average field capacity (FC) and Plant Wilting Point (PWP) for the domain are also shown as a vertical range corresponding to the two soil model formulations.

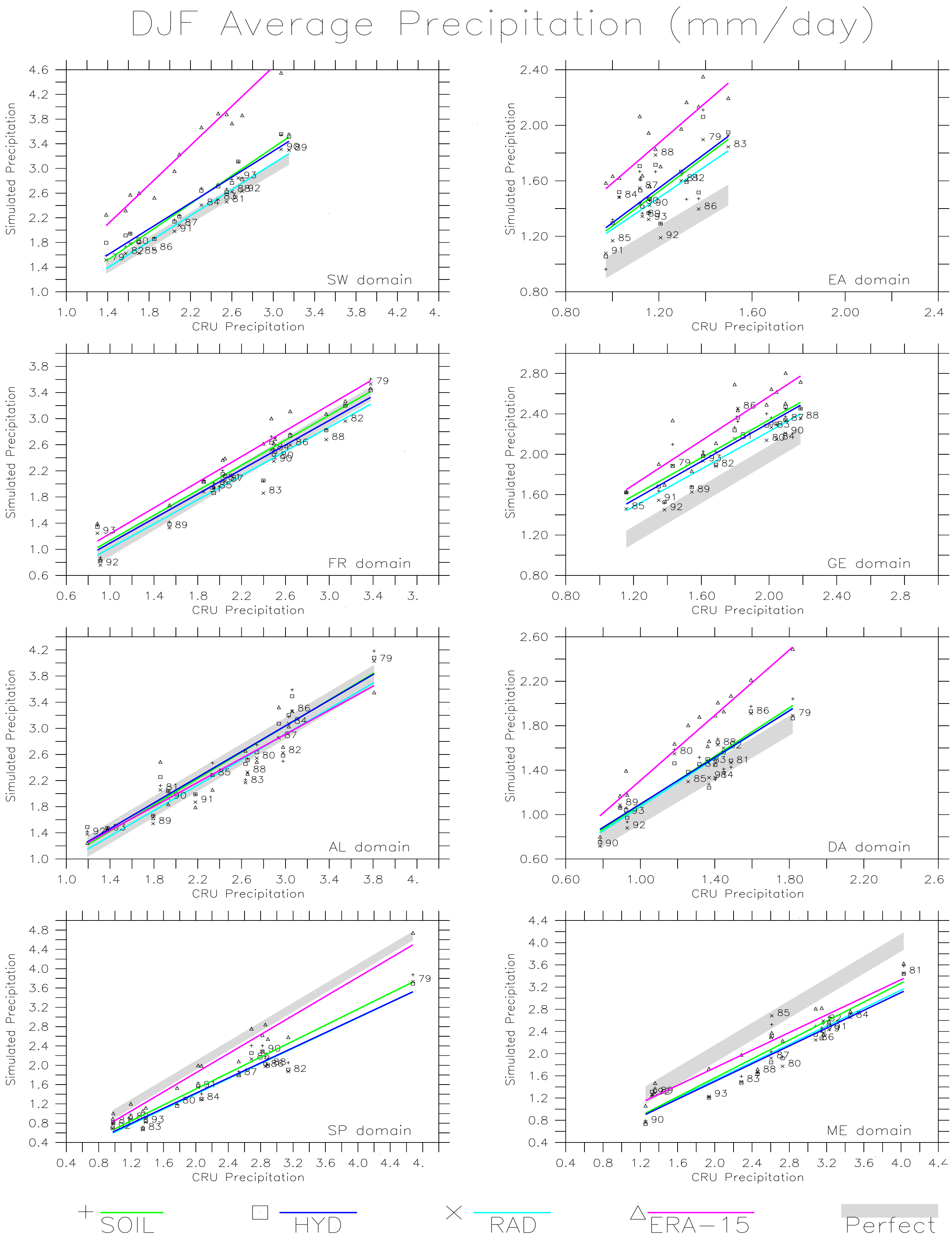

FIG. 3: Winter (DJF) scatter plots of precipitation (mm/day) showing monthly domain means of simulations (ordinate) versus observations (CRU, abscissa) for the sub-domains shown in Fig.1 and the 1979-1993 period. Each data set is represented by symbols and a regression line: ERA-15: triangles and double-dot-dashed line; SOIL: plus symbols and dotted line; HYD: square symbols and dash-doted line; RAD: (x) symbols and dashed lines. Individual data points for the RAD data set are also identified by year labels. Perfect model data would lie on a diagonal line across the plot (bottom left to top right).

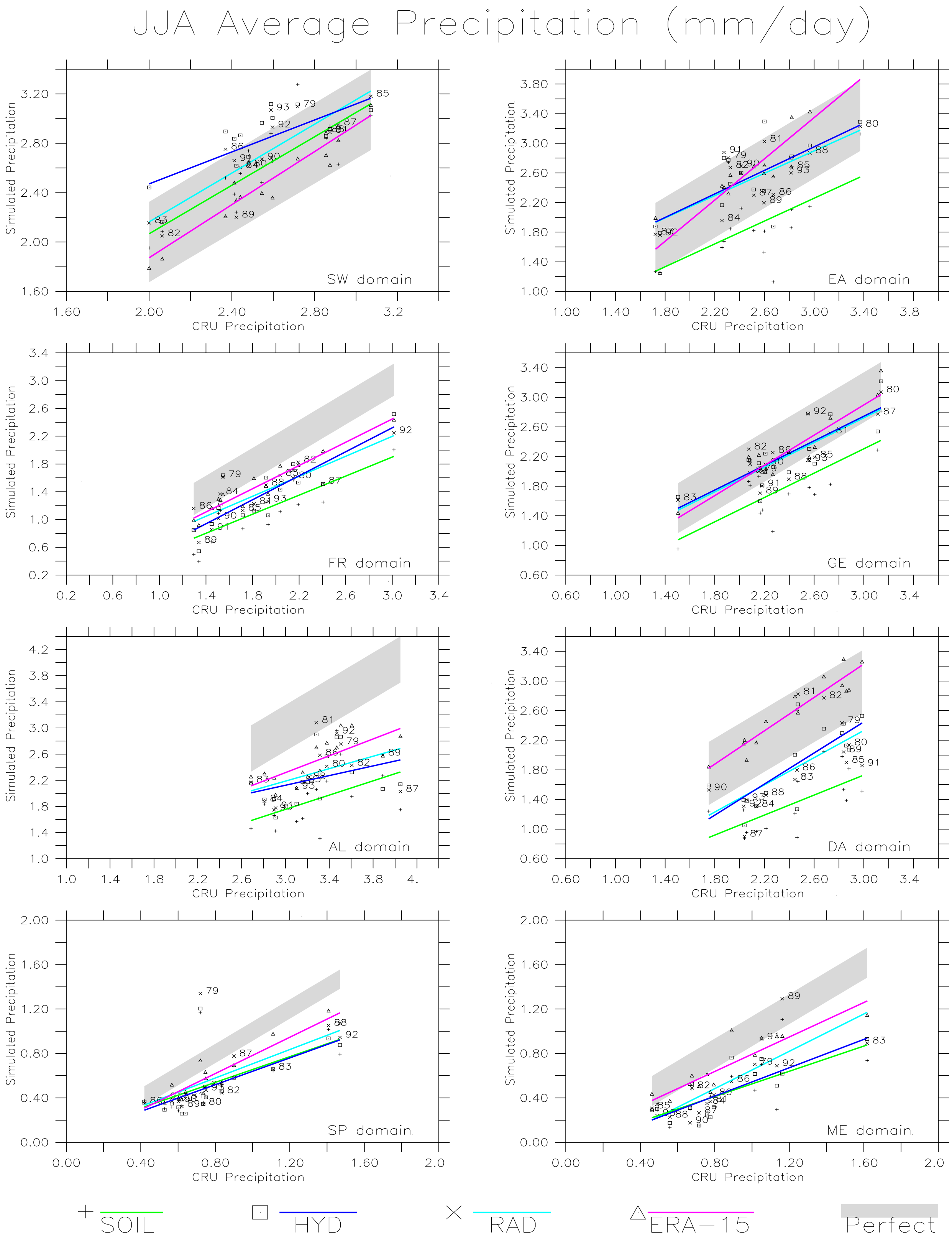

FIG. 4: Same as Fig. 3, but for JJA

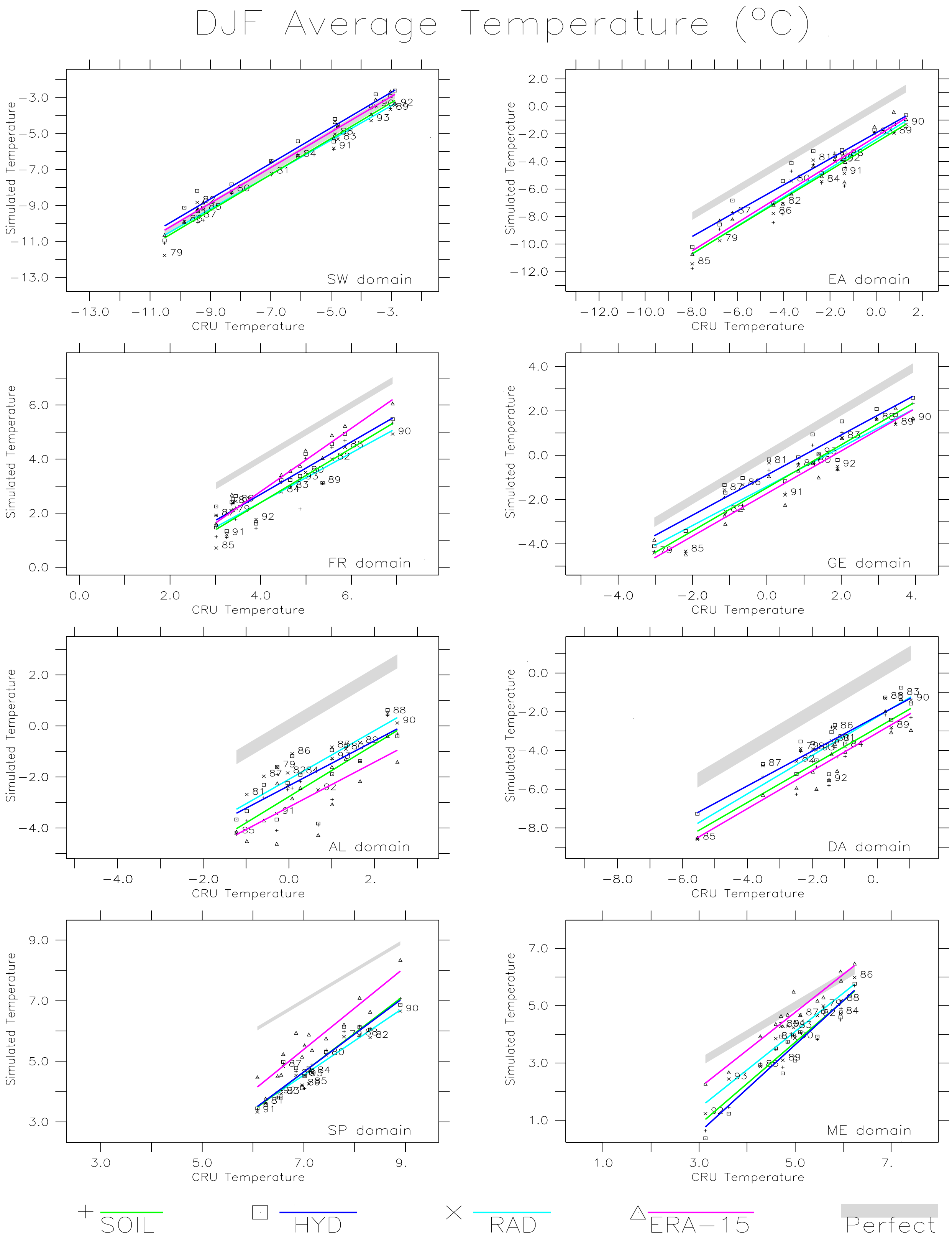

FIG. 5: Same as Fig. 3, but for DJF temperature (^{o}C).

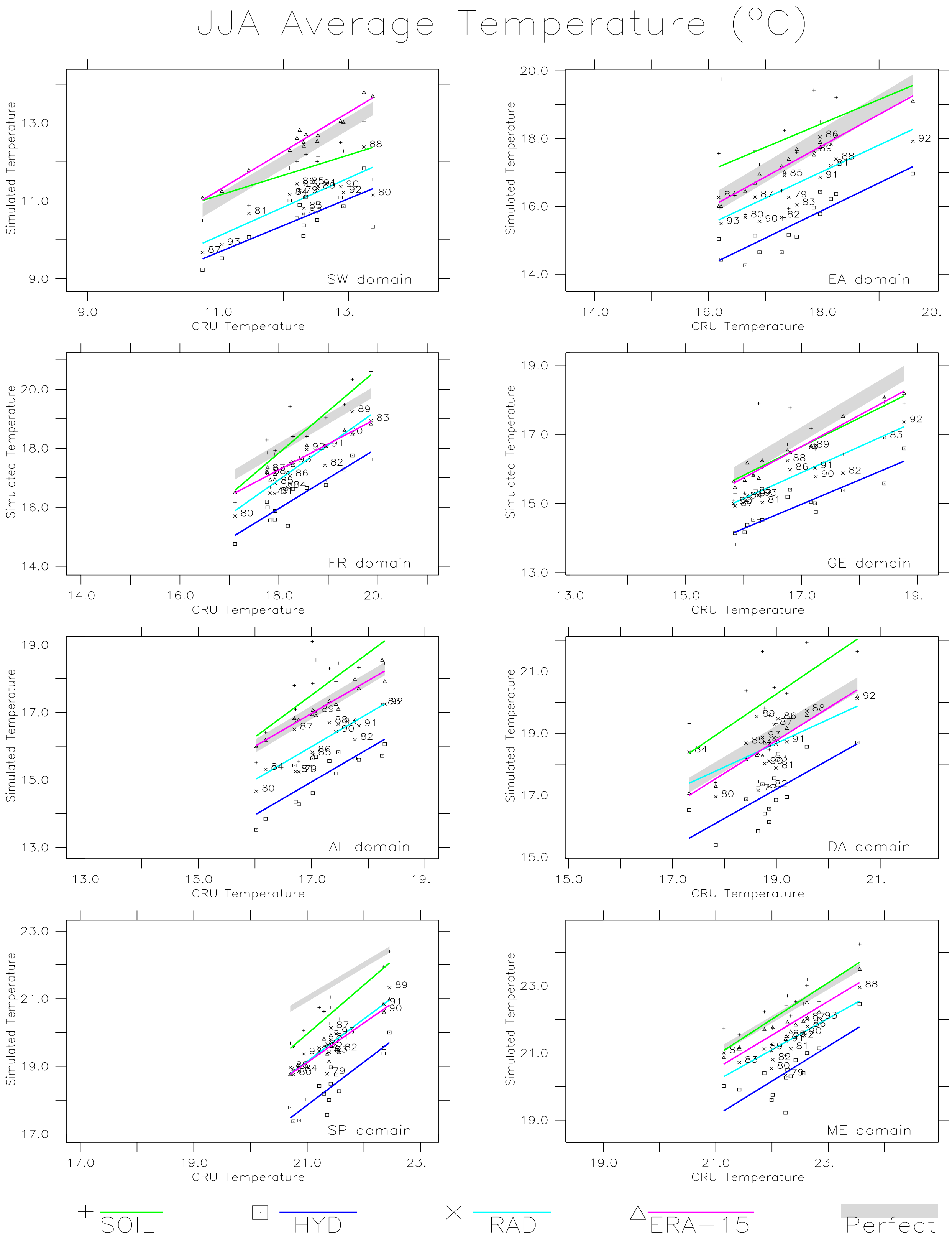

FIG. 6: Same as Fig. 3, but for JJA temperature (^{o}C).

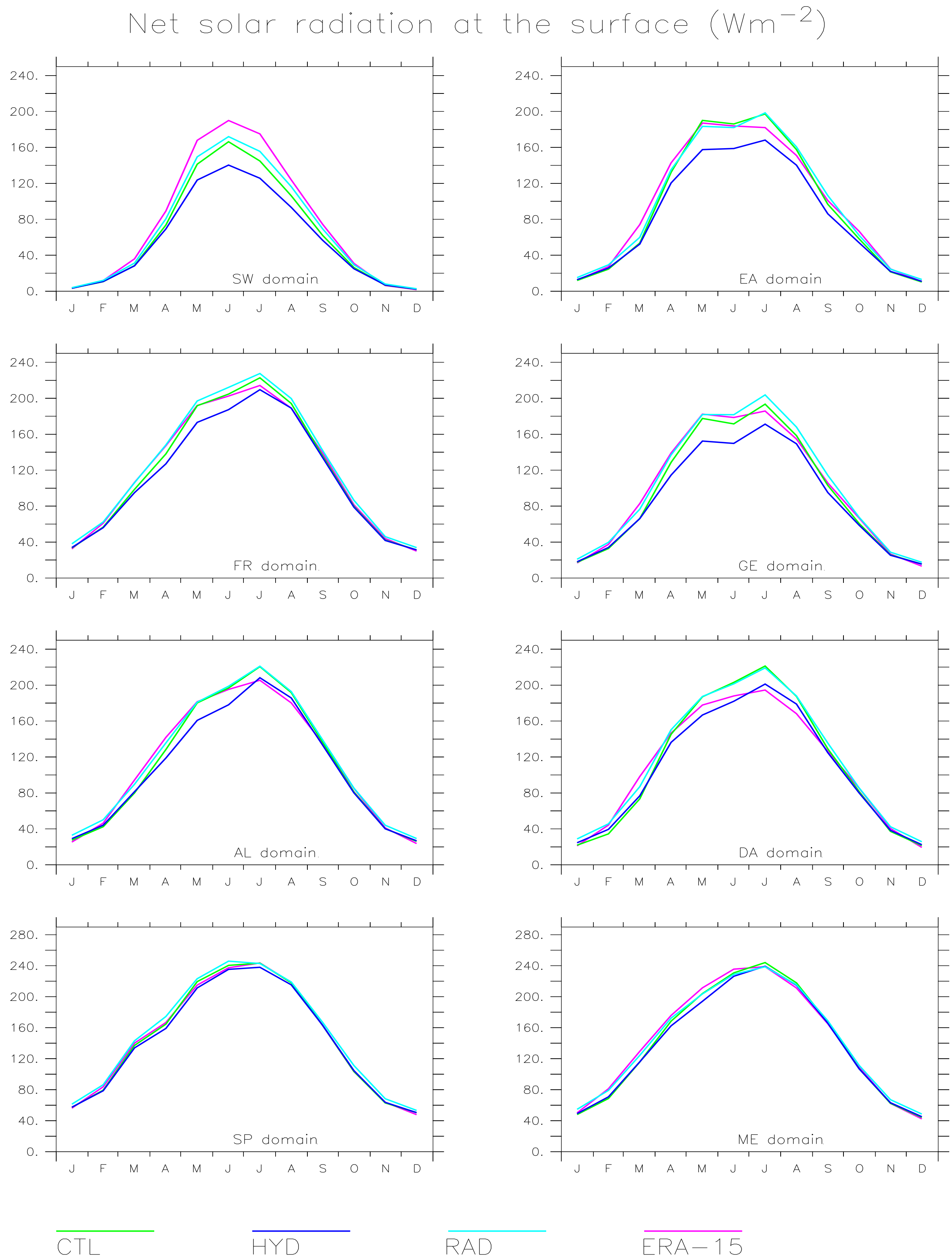

FIG. 7: Mean seasonal cycle (1979-1993) of net solar radiation at the surface, averaged over sub-domains (W/m2).

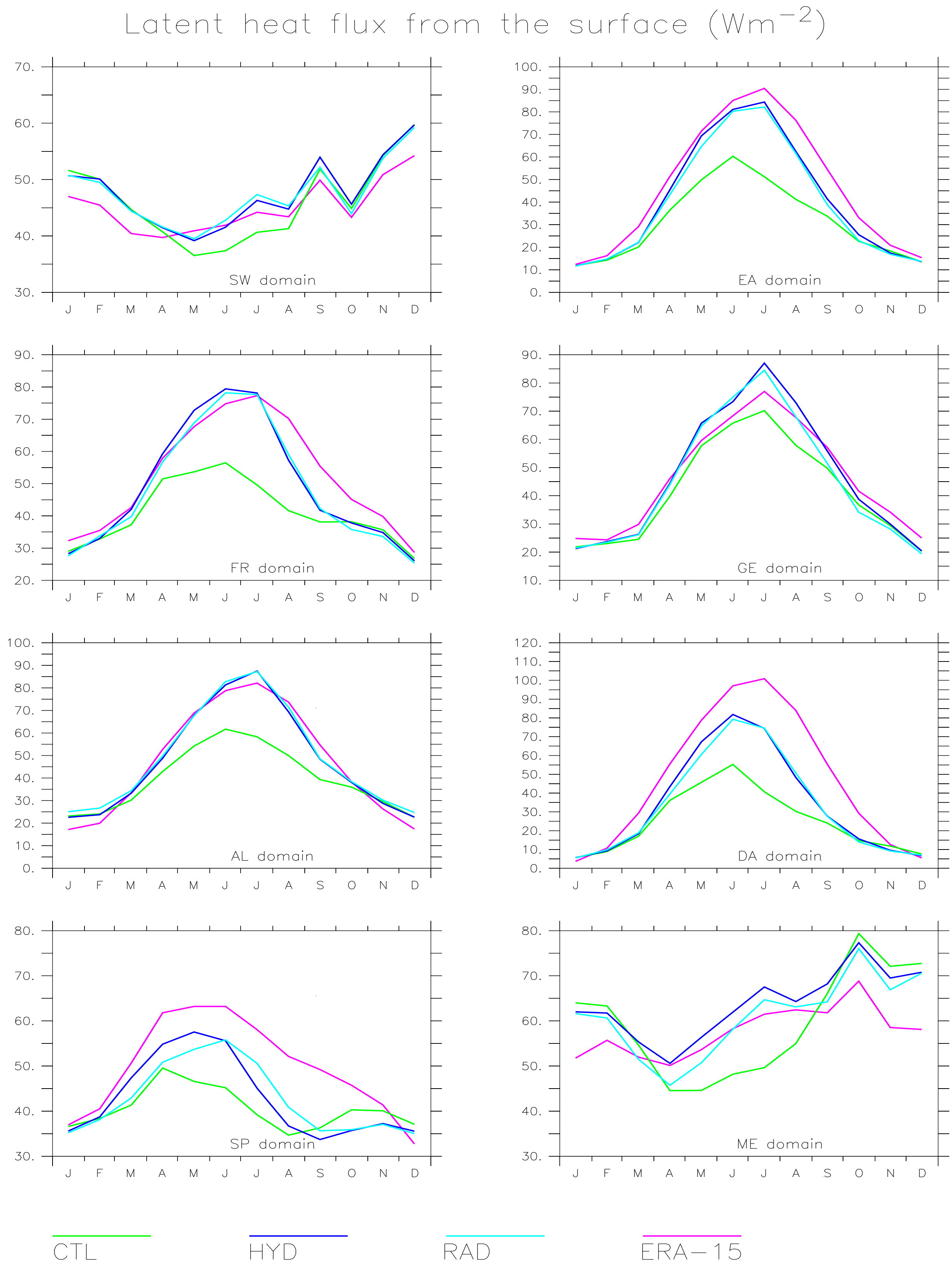

FIG. 8: Mean seasonal cycle of latent heat flux from the surface, averaged over sub-domains (W/m2).