The EC-Earth modelling challenges

Bart van den Hurk[1], Emanuel Dutra[2], Ben Smith[3], Martijn Brandt[1], Martina Weiss[1], Rein Haarsma[1], Wilco Hazeleger[1], Gianpaolo Balsamo[4] and Michiel van der Molen[5]

[1] KNMI, The Netherlands, [2] Univ. of Lisbon, Portugal, [3] Univ of Lund, Sweden, [4] ECMWF, UK, [5] VU University Amsterdam, The Netherlands correspondence: hurkvd@knmi.nl

1.   The challenges

Developing a new Earth System Model (ESM) by coupling the ECMWF Integrated Forecasting System (IFS) to describe the atmosphere and land surface, the NEMO ocean model and the LIM sea-ice model with a group researchers from a dozen countries and three times as many institutions, in a time frame that allows participation in the currently ongoing CMIP5 enterprise is truly a challenge. The idea to transform IFS into a Global Climate Model emerged a couple of years ago in several smaller ECMWF memberstates, particularly at KNMI (The Netherlands) and SMHI (Sweden). This "EC-Earth" project was more than just a desire to join this high-visibility IPCC driven CMIP-projects. A common GCM allows generation of climate projections that support specific demands for national climate change assessments. It also can serve as an integrating platform for many scattered research activities, both nationally and internationally. And it may contribute to the development of the various model components (particularly IFS), feeding back to their skill while applied for weather forecasting at the medium-range and seasonal time scales.

But the challenges are manifold. How to glue the various components together into a model system that has sufficient skill on multiple time scales? How to find a balance between the need to consolidate model versions, and the ever ongoing process of development and refinement of the model components at the various institutes? How to adjust the model to accommodate new components, such as terrestrial carbon cycle and vegetation processes? What about diagnosing, verifying and improving the many feedbacks that play a role in the climate system? And how to keep such a big group of involved individuals engaged?

This manuscript does not give an overview of all these technical, scientific and organizational challenges of the EC-Earth project. Being embedded in an ECMWF/GLASS workshop focusing on land surface issues, a number of example studies is presented, in order to illustrate some of the challenges mentioned above. They refer to the issue of model version updates, by demonstrating the introduction of a new snow scheme in the model. Also the issue of diagnosing climate feedbacks is illustrated, by elaborating on results from two major land-related multi-GCM projects, being LUCID (addressing land use change in climate projections) and GLACE2 (addressing added value of realistic soil moisture initializations). Finally, the anticipated coupling between an external vegetation dynamics model (LPJ) and the EC-Earth land surface scheme is illustrated by an example study that is currently in progress. A final section will elaborate a bit more on the challenges still ahead of us.

2.   Recent refinements of the land surface hydrology and snow treatment

In any NWP or climate modeling centre model updates take place very frequently. A recent revision of the IFS land surface scheme (HTESSEL, a successor of the earlier TESSEL scheme) was put into operations in the medium-range forecasting model, but not yet in the Seasonal Prediction System version on which the first release of EC-Earth was build. However, the demonstrated improvements of HTESSEL and the relatively simple necessary technical adjustments were reason to incorporate HTESSEL in the reference EC-Earth version. As shown by Balsamo et al (2009), the hydrological updates in HTESSEL were beneficial for the quality of calculated river discharge for many major catchments across the world. However, a deterioration compared to TESSEL was seen for many high latitude catchments, where snow processes dominate the river discharge dynamics. In fact, the too early snowmelt in the model was compensated by a lack of surface runoff in TESSEL, and a (beneficial) delay in the discharge resulted from the strong infiltration of meltwater in the soil. A classical example of compensating model errors.

Dutra et al (2009) took the initiative to revise the snow scheme, motivated both by the performance of the ECMWF NWP system and by the obvious need for a better snow representation in EC-Earth climate integrations. The modifications addressed the albedo of forest snow, the storage and refreezing of liquid water in the snow pack, and the snow density and snow cover description. These updates were implemented in two subsequent operational cycles of IFS and in the EC-Earth reference version. Over all, the net river runoff was slightly reduced and compared better to observed river discharge for many catchments across the world (Figure 1).
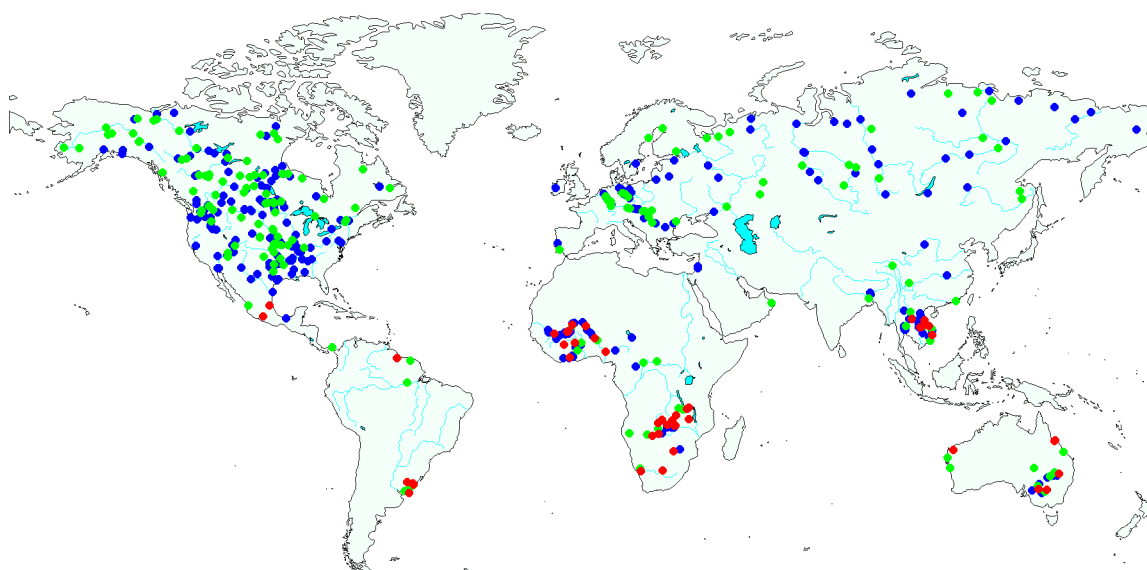

Figure 1: colored symbols indicate which land surface model version yielded the best correlation with observed discharge during a 10-year model integration (1986-1995). Red = TESSEL, green = HTESSEL and blue = HTESSEL + snow adjustments.

3.   Land use change experiments

A fair amount of the global mean temperature increase observed during the 20th century is believed to be offset by a strong increase of the areal fraction of crops and pasture, that generally have higher albedo values than the forest areas they replaced. This large scale deforestation thus leads to a radiative cooling. In an attempt to make a multi-model consensus estimate of this radiative forcing in comparison with the greenhouse gas forcing, Pitman et al (2009) initiated the LUCID experiment, in

which an (atmosphere-only) version of EC-Earth also participated. The major consensus resulting from this exercise was that there is surprisingly little consensus on how land use change (provided by the project office to 7 different GCM groups) is actually implemented in the model schemes. Most models agreed that a major temperature response outside the areas where the large scale land use change took place were negligible, but the responses within the changed areas were very different and sometimes even of opposite sign.

An analysis of the EC-Earth results by Van de Molen et al (subm) focused on the (local) feedbacks that were triggered by the land use change, primarily by changing the surface albedo. In EC-Earth, a given albedo change in the tropics (the tropical deforestation areas around the equator) leads to a smaller temperature change that a similar albedo change in the extra-tropics (where a lot of crop land was created in the US and Eurasia) (see Figure 2).
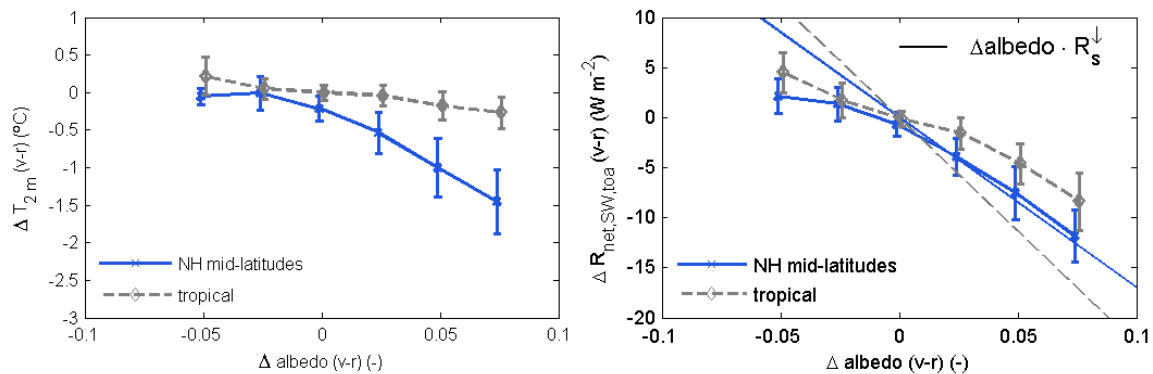

Figure 2: Left: temperature change per unit albedo change for tropical and NH mid-latitude areas, constructed by comparing EC-Earth simulations with different fractions of low and high vegetation and related different surface albedo values. Right: differences in the net shortwave radiation at the surface. The straight lines indicate the direct radiative response of the albedo change.

Inspection of the equivalent changes in the radiative and turbulent fluxes revealed the existence of a number of feedbacks of different magnitude for the tropical and mid-latitude areas. In the tropics, the reduced surface heating lead to a reduced cloud cover, leading to an increase in the net surface shortwave radiation offsetting the temperature decrease by the albedo increase. In the extra-tropics such shortwave radiation response was not present (see Figure 2, right panel). In addition, the evaporative cooling also reduced strongly in the tropics while in the extra-tropics the response of surface evaporation to the albedo change was much smaller, which also helps to explain the difference in surface temperature response.

This experience is currently being used in the preparation for the CMIP5 climate projections, in which land use change scenarios are embedded in the climate forcings. Rather that a few time slice experiments as employed in LUCID, a transient land use change is prescribed for the period 1850 – 2100, following observed changes until 2000 and using a number of distinct scenarios for the future. This introduces the need to define a reference land use map for either 1850 or 2000, from which the transient changes of land use can be projected forward or backward in time. It appears difficult to ensure that a reference land use map for 2000 matches the current IFS/EC-Earth land use distribution derived from GLCC, and test runs are underway to map the consequences of this inconsistency.

4.   Soil moisture initialization

Also the Global Land Atmosphere Coupling Experiment (GLACE) can be seen as a feedback study, where a multi-model ensemble is used to highlight the dominant patterns of the soil moisture – precipitation feedback. A classical result of this experiment is a global map showing that in areas situated at transitions between climatologically dry and wet areas (basically, the edges of the major monsoon areas) precipitation variability is sensitive to the variability of the soil moisture. In a follow-up experiment, Koster et al (2009; see also another chapter in these proceedings) extend this finding with the question whether models will actually provide better seasonal forecasts when they are supplied with realistic initial soil moisture conditions. For this forecast skill improvement, it is not only required that the proper feedback pathways are represented, but also the information content that is transported through those pathways should be realistic. This applies to the quality of the initial soil moisture, the verifying observations, and the way the model treats the relevant processes underway.

EC-Earth/IFS participated with two model versions to GLACE2: one in which SSTs were initialized from reanalyzed states and relaxed towards a climatological value, and one where SST-forecasts from the seasonal prediction system 3 were used. Results from the first set of experiments were subjected to a statistical analysis aimed at revealing patterns of soil moisture anomalies in Europe that would give rise to possible changes of temperature (or precipitation) with dissimilar spatial patterns, pointing at remote impacts of soil moisture anomalies via changes in the regional atmospheric circulation. In an earlier KNMI study using a large ensemble of the ECHAM5 climate model, it was found that excessive drying in the Mediterranean area would give rise to a systematic increase in the occurrence of eastern geostrophic wind conditions at higher latitudes, leading to an extra warming and drying in these remote areas. In spite of the large number of GLACE2 ensemble forecasts, the 10-year period for which the experiment was run probably was not long enough to include a sufficient number of occasions for which such a remote coupling could be relevant (Figure 3).
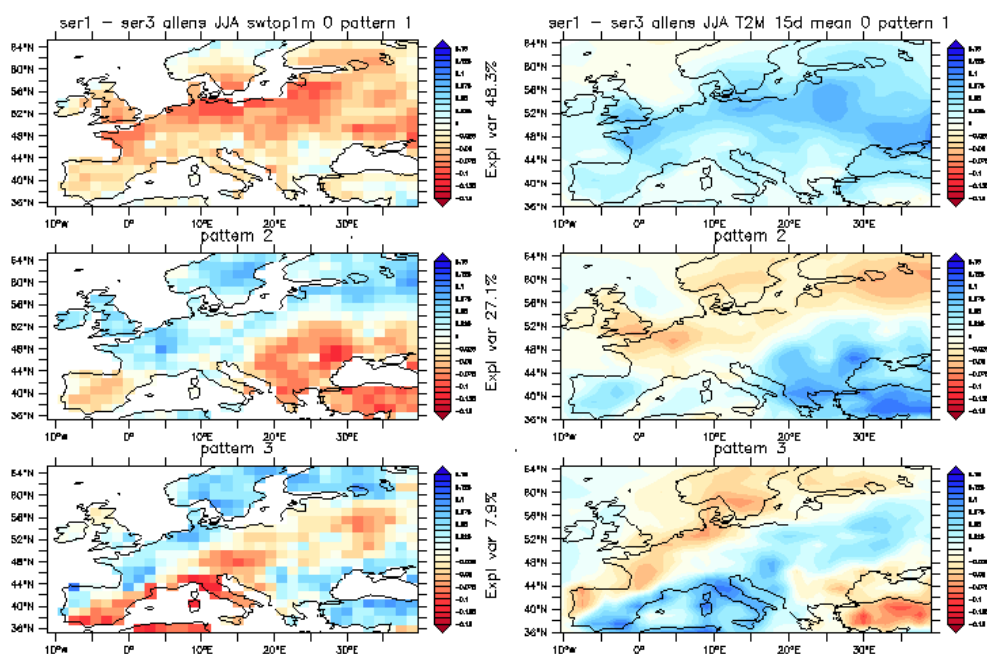

Figure 3: Maximum Covariance Analysis of patterns of initial soil moisture (left) and mean 2m temperature (right) averaged for the first 15 days after initialization, derived from 600 parallel simulations covering the summer season of 1986 – 1995. Shown are the leading 3 patterns, showing a strong resemblance between soil moisture anomalies and local temperature responses.

In addition, a multi-model based probabilistic ROC score for Europe was calculated, to complement the US-oriented evaluation of explained variance in the multi-model ensemble by Koster et al (2009). The ROC skill score measures the likelihood that a given (extreme) event (like the occurrence of a temperature in the upper tercile of the climatological distribution) is captured by an ensemble of forecasts. Figure 4 shows the results for anomalously warm temperatures in JJA at two different lead times (16-30 days and 31-45 days after initialization). Especially for the shorter lead time the use of realistic soil moisture does increase the probability that warm events are predicted correctly. However, when conditions are selected in which the initial soil moisture in either of two regions (Mediterranean and Central Europe, as indicated by the boxes) is known to be relatively low, the skill changes strongly. Particularly by conditioning on low Mediterranean soil moisture conditions the skill does improve in a major part of the European area, also for longer lead times. However, the noise level is also increased, as shown by the increased scatter in the results. Thus, although the main climatological features of the European circulation and hydrological cycle do not indicate a strong remote coupling between soil moisture and temperature (Figure 3), the results presented by Koster et al (2009) and in Figure 4 do indicate that soil moisture is not equally informative or influential in all conditions. Particularly extreme soil moisture conditions may impose a relatively strong control on the surface energy and water balance, exerting a stronger-than-average influence on the regional hydrological cycle.
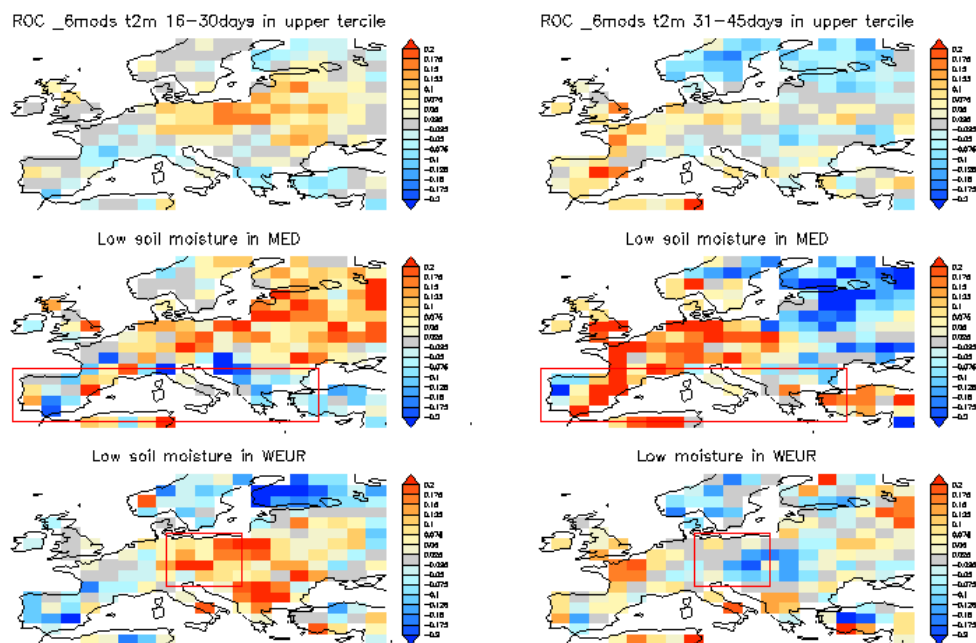

Figure 4: ROC score differences for temperature being anomalously warm (in the upper 33% of the climatological distribution) using a super-ensemble comprising 6 GLACE2 models each running 600 forecasts verifying in the JJA season. Shown is the difference in ROC scores when using realistic initial soil moisture conditions relative to using a random soil moisture value, redder colors indicating an improvement when using realistic initial soil moisture. Left column shows 16-30 day lead times, right column 31-45 days. The top row shows all dates. The second row only includes time slots for which soil moisture in the Mediterranean box (indicated) was anomalously low (lowest 33% of the ensemble), the bottom row for low soil moisture in the indicated Central European area.

5. Implementation of bio-geochemical feedbacks in EC-Earth

Entering the realm of climate projection in the current scientific arena needs a consideration of how to include major bio-geochemical cycles, such as the cycles of carbon (CO_2, CH_4, carbon pools in vegetation, soil and ocean) and nitrogen (fertilizer and nutrients for vegetation, N_2O). Several climate modeling systems have spent a couple of years of research into incorporating and updating these cycles into their ESMs. EC-Earth is clearly lacking behind in this area. Some developments in the recent past have yielded initial representations of vegetation phenology (LAI) and photosynthesis, but these have not yet lead to mature and stable model versions. Interactions with hydrological features like soil moisture, wetlands and inland lakes, and with atmospheric chemistry are important but not trivial (Figure 5). Incorporating all these cycles into the EC-Earth land surface scheme quickly becomes an unmanageable task, with a risk of serious delays in credible model versions, and with a risk of excluding a great deal of scientific expertise of people not used to work with land surface schemes in general or the TESSEL family in particular.
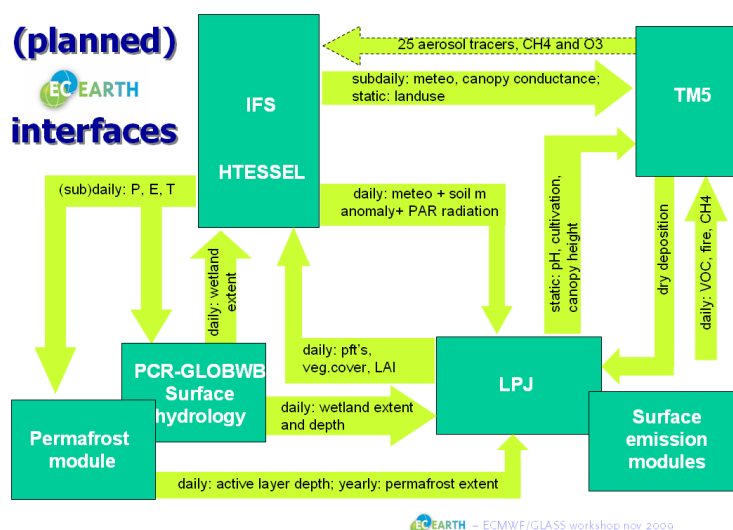

Figure 5: sketch of the multiple interactions between various modules comprising the EC-Earth modeling system. Green squares denote major component modules, light green arrow denote information flow at various time scales between the modules. LPJ is a family of (dynamic) vegetation models, PCR-GLOWBW a terrestrial hydrological model, and TM5 an atmospheric chemistry transport model.

Therefore, it was decided to start with a fairly loose, offline coupling between the EC-Earth land surface scheme on one hand, and modules that treat bio-geochemistry and complex hydrology on the other. The basic philosophy is that the HTESSEL land surface module will receive regular updates of essential surface characteristics (like LAI and associated albedo, vegetation types, wetland extend) derived from modules that are forced by climate variables supplied by the IFS-HTESSEL system. To allow this information exchange some technical adjustments need to be developed. The interface between IFS and the atmospheric chemistry transport model TM5 via OASIS is already established, and it is aimed for a similar interface to couple the terrestrial modules for vegetation (LPJ) and hydrology (PCR-GLOBWB). This allows a flexible experimental playground for multiple (feedback) studies involving a range of external modules. Apart from implementing the OASIS coupler in the various modules, some adjustments to HTESSEL are also required, particularly with respect to the representation of vegetation phenology and the links to surface characteristics like albedo or roughness, and of wetlands occupying a part of the terrestrial grid box.

An example of a similar interface between a climate model and an offline vegetation module is described by Wramneby et al (2009). In a joint SMHI/Univ. Lund experiment a coupling was realized between the regional climate model RCA, and the vegetation dynamics model LPJ-GUESS. RCA carries a land surface model structure that is very similar to HTESSEL. LPJ-GUESS simulates the succession of vegetation over seasonal and decadal time scales, in response to a climate forcing provided at a daily time scale. In a simple experimental set-up, these two models were coupled offline by a daily exchange of relevant information: atmospheric and surface climate variables (including soil moisture and snow) from RCA to LPJ-GUESS, and vegetation types and LAI from LPJ-GUESS to RCA. With this set-up a European climate integration for the 21st century was applied and compared to an RCA-integration where a vegetation response to climate change was not incorporated (Figure 6). Overall a relative cooling is observed by incorporating the vegetation feedback, apart from an area at high latitudes where the increase in evergreen trees result in a reduced surface albedo in the presence of snow in MAM. The overall increase in LAI in warmer conditions leads to extra evaporative cooling for a majority of the continent, with a particularly strong signal in JJA in the south-east of the domain.
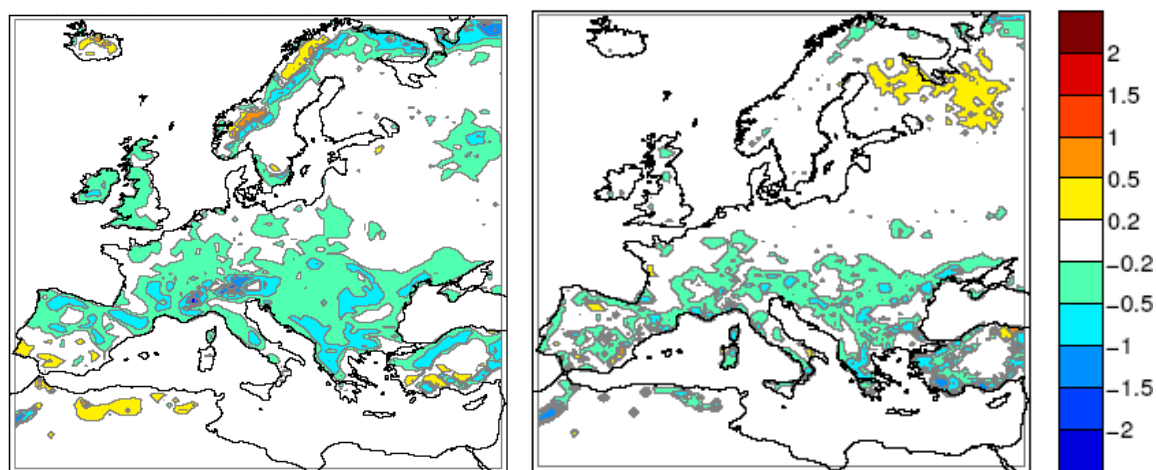

Figure 6: Difference in 30-yr mean temperature response to an enhanced greenhouse gas concentration between 1961-1990 and 2071-2100 (ΔT) between a simulation with RCA coupled with LPJ-GUESS (RCAG) and an RCA version with fixed vegetation (RCA), i.e. ΔT(RCAG) – ΔT(RCA), for two seasons (left: MAM; right: JJA)

6.   Discussion

The EC-Earth enterprise is currently in a rapid development phase. The critical mass in terms of number of scientists involved, topics to be studied and applications to support has been reached, and the model will certainly continue to mature as time and input proceed. However, in several ways the current stage of EC-Earth is also a bit delicate: major organizational, scientific and technical challenges are still around and need to be resolved.

As any actively developing ESM, EC-Earth continuously deals with the complex issue of model upgrading, verification and synchronization with other institutions, in particular ECMWF. The present release used to meet the CMIP5 demands was branched off the System 3 version of the ECMWF seasonal forecasting system, with some upgrades in the convection and land surface schemes. The new snow scheme is developed and implemented in both the current operational NWP cycle of IFS and in EC-Earth, and could be seen as a successful modification where increased model skill and synchronous version upgrades were both met. However, there are many model components that are under continuous development at both centers and often more or less independently, and keeping up to

date with each other is a real challenge. The current version management protocol of EC-Earth foresees a continuous close link with the seasonal forecasting version of IFS, but with the opportunity to develop new or modify existing components that are back-synchronized every 3 years or so. The future will learn how relevant and manageable this strategy will be.

Another issue that is raised with the snow example, and similarly applicable to other modeling systems, is the presence (and in fact, need) of compensating errors. There are many of these around, and spotting and effectively removing them is and will remain to be a real challenge.

Increasing the number of components, and thereby the number of degrees of freedom of an ESM, will continue to reveal new feedback loops that will be important at different spatial or temporal scales. The examples with the land use change and soil moisture initialization are just a few in the endless list of possible feedbacks that will be studied with EC-Earth and other ESMs. Probably the largest challenge in this area is to distinguish between stronger and weaker, or more or less relevant feedback cycles. Also, the diagnosis and subsequently the proper representation of these feedbacks is another challenge. This is a typical "learning-by-doing" area, and the EC-Earth team is eager to join this area, partly in European and nationally funded multi-model and multi-disciplinary research projects.

Finally, a technical and organizational challenge is the interface between the core meteorological/ oceanographic model, and the multiple modules that are coupled to this (Figure 5). Such a coupling has technically already been realized between TM5 and IFS, but the interfacing to the terrestrial hydrological and vegetation modules is still to be implemented. Some of this seems quite straightforward (such as the land use change examples where a change in vegetation types are imposed) but the covariation of ancillary variables (albedo, roughness, rooting depth etc), not linked within the current version of the land surface model, needs to be carefully considered. Coupling with modules that require a high temporal synchronization, such as wetlands or phenology, is not yet routinely applied. This will continue to need considerable technical and scientific developments in the near future.

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