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Periodic report: 1st □ 2nd □ 3rd ■ 4th □
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¹ Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.
² The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.
Declaration by the scientific representative of the project coordinator

I, as scientific representative of the coordinator of this project and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

- The attached periodic report represents an accurate description of the work carried out in this project for this reporting period;
- The project (dark box is used instead of tick as appropriate)\(^3\):
  - □ has fully achieved its objectives and technical goals for the period;
  - ■ has achieved most of its objectives and technical goals for the period with relatively minor deviations
  - □ has failed to achieve critical objectives and/or is not at all on schedule;
- The public website, if applicable
  - ■ is up to date
  - □ is not up to date
- To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 3.4) and if applicable with the certificate on financial statement.
- All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 3.2.3 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name of scientific representative of the Coordinator: Ljupco Kocarev

Date: 13/05/2014

For most of the projects, the signature of this declaration could be done directly via the IT reporting tool through an adapted IT mechanism.

\(^3\) If either of these boxes below is ticked, the report should reflect these and any remedial actions taken.
1. Publishable summary

Summary: SUMO

Consensus formation among a small group of expert models of an objective process is challenging because the separate models have already been optimized in their own parameter spaces. In SUMO we address consensus formation in a connectionist framework, by introducing connections, with coefficients to be determined, between some restricted set of pairs of corresponding variables in the different expert models. By applying machine learning techniques, as well as methods from nonlinear dynamics, we can adapt the connection coefficients linking the corresponding variables in the different models. Using a recipe for extending synchronization between a pair of dynamical systems to adapt system parameters as well as states, for instance, we can adapt the connection coefficients linking the corresponding variables in the different models.

In the SUMO project we apply this procedure to the pressing problem of fusing different models of the Earth's climate system, which give different predictions regarding the details of climate change. The fusion scheme, which is referred to as supermodelling, is developed and validated in a hierarchy of increasingly complex model types, ranging from simple ODE's to models that are actually used for climate prediction.

This new computational approach to the simulation and prediction of complex, real systems can only be developed by bringing together experts from different disciplines: nonlinear dynamics, machine learning and, in this case, climate science, disciplines that are well represented in the SUMO project.

The extended SUMO project consists of the following 8 work packages:

- WP1 – General Theory of Supermodelling with ODEs
- WP2 – Learning of connection coefficients in ODEs
- WP3 – Learning of connection coefficients in PDE systems
- WP4 – Supermodelling with intermediate complexity climate models
- WP5 – Supermodeling with large climate models
- WP6 – Management
- WP7 – Learning complete supermodels
- WP8 - Development of a trans-Atlantic climate supermodel

Most of the work in the first three work packages concerns relatively low-dimensional systems of up to a hundred dimensions and is extended to infinite dimensions in the work on partial differential equations in WP3. WP1 focuses on the possibility of synchronizing different models, given that the connections can be chosen manually, WP2 on strategies to learn the connections from observational data. WP4 is a step up in the hierarchy in that it uses the results from these work packages in the construction of a supermodel consisting of interconnected intermediate complexity climate models of order several thousand degrees of freedom. Results from this work package feed into the construction of a supermodel consisting of state-of-the-art climate models in WP5. Problems encountered in WP4 and WP5 are fed back to the other work packages that suggest solutions on the basis of additional work on lower dimensional systems or theoretical considerations. In the extended SUMO project, a new work package has been added (WP7), concerned with learning
complete supermodels. The figure provides a graphical representation of the nature of and interconnections between the work packages. The horizontal dimension of the ovals indicating each work package reflects the dimensionality of the model systems that are subject of research, the vertical dimension the amount of experimentation that is possible in that work package. The vertical ordering of the work package reflects the nature of the research from more fundamental at the bottom to more applied research to the top. The colors indicate the prevailing expertise needed in each work package. The arrows reflect the flow of information between the work packages. The overlap indicates the amount of joint work on the same model systems.

![Graphical representation of the nature of and interconnections between the work packages.](image)

**Figure 1** Graphical representation of the nature of and interconnections between the work packages.

**Work performed for the period 1.10.2012 to 31.03.2014**

The work performed and the main results achieved in the second year of the project can be summarized as follows.

**WP1 (General theory of supermodeling with ODEs)**

- The dependence of the behavior of networks of chaotic systems on the coupling strength is further analyzed for more complex units. One study is focused on network of time-delayed Ikeda system, which generates hyperchaotic dynamics, while in the other line of study a network of connected atmospheric models is used in order to investigate whether the phenomenon of amplitude death can emerge in higher dimensional chaotic systems. Early findings show that the results for the time-delayed Ikeda system differ from the other considered systems in the sense that further increasing the coupling strength, we do not
regain back synchronized chaos as for the Lorenz 63 (or 84) systems. These studies are ongoing and the publications are in preparation.

- We initiated a study for better understanding of the solution spaces of the supermodel connections, and the performance of the supermodeling approach. As toy examples we are using modifications of the Lorenz and Rössler systems with an additional non-linear term. The term is used for enabling continuous tuning of the original models towards a higher degree of nonlinearity. The studies are ongoing and the publications are in preparation.

WP2 (Learning of coefficients with ODEs)

- Ensemble studies were performed with three imperfect T21 models compared with one assumed ground truth T42 model. One of the imperfect models has the same parameters as the T42 while the other two models are symmetrically perturbed around this imperfect model. A uniformly fused supermodel (weighted as well as connected) was compared to the individual models and with the posterior ensemble approach. It was found that the uniform supermodel improved on the predicted climate variance. We have also compared the performance of the supermodel with uniform weights as interactive ensemble versus the non-interactive ensembles of randomly perturbed models for long-term statistics. With small perturbations, there was hardly any difference between interactive and non-interactive ensemble results, while with larger perturbations, connecting models in the ensemble sometimes improved results, while sometimes worsened them. Regarding the attractor statistics, it was obtained that when it is linear in the model perturbations, interactive ensembles results in the same statistics as the mean of the model statistics in a non-interactive ensemble. In the nonlinear case, the results appeared strongly dependent on the situation at hand and sometimes lead to undesired effects, even worse than the worst individual model. This means that in a supermodel, learning of the weights is needed to get improved results.

- Learnability of dynamical systems with respect to both short-term (vector field) and long-term (attractor) behaviour was studied for a simple toy situation consisting of a chaotically driven Lorenz 63 system as ground truth, and a third order interaction system as model. In the spirit of the Bayesian approach we have defined a joint log-likelihood that consists of two terms, one is the vector field error and the other is the attractor error. We have used the elliptical slice sampling, a sampling method for systems with a Gaussian prior and a non-Gaussian likelihood where each sample is a rolled-out trajectory of a dynamical system. Simulations showed that solutions that considerably improve upon the vector-field learned solutions can be found with less than 100 roll-out samples.

WP3 (Learning coupling coefficients in PDE systems)

- A revised paper that stresses the relationship between coherent structures in PDE systems and the required density of connections for synchronization or supermodeling has been published. Work is underway to test the hypothesized relationship in the SPEEDO model by varying the coupling density in the configuration described in the WP4 report, and comparing with synoptic length scales. Results will be reported at the final review meeting.

- It has been shown that an ensemble of supermodels is readily generated in the configuration of two ECHAM models coupled to a common ocean that has been studied in WP5. The different supermodels are defined by different sets of weights, that are found by use of the training history to sample weight-space and select combinations that give high performance.
Thus interaction in the supermodel among the constituent models does not imply the complete loss of spread information.

- We have developed software that extends NCAR’s Data Assimilation Research Testbed (DART) to a generic framework for combining any combination of models into a supermodel. The software uses Python scripts to nudge the models together, and the DART capability to stop and restart the models. It has been tested using different versions of the Community Earth System Model, but the restart component, taken from DART-related software, needs repair.

- We have shown that a general method in the neural network literature for training recurrent neural networks, FORCE, is formally equivalent to standard data assimilation by Kalman filtering. Adaptation of a small set of weights in the FORCE scheme is equivalent to re-initialization of states in data assimilation. The equivalence will help to establish the paradigm of truth-model synchronization, and perhaps that of supermodeling, as relevant to cognitive processes.

- A semi-philosophical review paper has been written on the implications of chaos synchronization, including supermodeling, for the relationship between mind and matter and between apparently disconnected material systems. A parallel is drawn with the “synchronicity” concept of Jung and Pauli, but our synchronicity is based in material reality. We are still trying to find an appropriate journal.

WP4 (Supermodeling with intermediate complexity climate models)

- A supermodel consisting of three SPEEDO climate models was constructed. Synchronization between the 3D atmospheric states is a prerequisite for the SUMO approach, so connections between the 3D atmospheric temperature fields were implemented. With manually chosen connection weights the atmospheres of the constituent members synchronized to a common solution different from the individual solutions. Learning of the coefficients is ongoing work.

- The SUMO approach was pioneered in an ensemble weather prediction system based on the state-of-the-art WRF model. The supermodel was constructed by taking a weighted average of the tendencies from the different parameterization schemes. Only equal weights were considered in the first experiments, while learning the weights is under way. First results indicate improvement in skill in the surface winds, but not in temperature.

WP5 (Supermodelling with large climate models)

- A set of optimal weights for coupling two atmospheric GCMs (AGCM) with one ocean GCM (OGCM) was found by using Nelder-Mead method. With these optimal coefficients the synchronization of surface wind field of two AGCMs was increased and the well-known systematic errors over tropical Pacific were reduced, and the simulated climate variability was improved. Furthermore, ocean-atmosphere interaction over the tropical Pacific was better simulated in the model with optimal coefficients, and this appears to be the main reason for the improved model performance. This also leads to a substantially improved simulation of the El Niño Southern Oscillation. The robustness of these results was demonstrated by applying the same approach to another climate model with higher model resolution.
The supermodel was tested in historical simulations covering the period 1900-2010. The performance of the model in terms of the global mean temperature is comparable to other models. A good representation of tropical climate was maintained. Climate change projections were performed with the three models (two individual coupled models and the supermodel). We focused on the response over the tropics, because of the models improved performance in this region. The individual coupled models simulated a strengthening of the zonal equatorial SST gradient, strong precipitation increase over the western Pacific, and an eastward shift of the Walker Circulation. In contrast, the supermodel showed a weakening of the zonal equatorial SST gradient, weak precipitation increase over the tropics, and a weakening of the Walker Circulation. The supermodels better representation of the basic state and ocean-atmosphere interaction suggests it may depict a more realistic global warming response in the tropics.

WP7 (Learning complete supermodels)

- We have developed equation discovery methods for learning supermodels, i.e., ensemble models of dynamic systems, where both the structures of the constituent ODE models and their parameters are learnt from observed data. The ensembles can contain models with different structure, which is a novelty as compared to ensembles, which are based on (random) variation of the initial conditions or parameter values of the ODE models. The ensembles consist of ODE models learnt by using the bagging and boosting approach to sampling the observed data and their predictions are combined by using simple averaging of the predicted trajectories.

- We empirically evaluated the two approaches (bagging and boosting) on 15 different data sets, coming from three aquatic ecosystems, comparing them between themselves and to individual models. The ensembles learned by bagging perform best and significantly outperform individual models in terms of predictive power. Note that previous approaches to computational scientific discovery have focused on explanatory models of dynamics and their descriptive power and haven't investigated the predictive power of such models.

- Besides learning ensembles of (continuous-time) ODE models, we have also addressed the task of learning ensembles of non-parametric regression models for modelling dynamic systems in discrete time. We have used the external dynamics approach, which formulates this task as a regression task of learning a difference/ recurrence equation/ model. We address this task both in the batch learning and on-line/ data stream context.

- We have developed novel methods for learning ensembles of regression and model trees on data streams, such as on-line bagging and on-line random forests. We have also proposed the approach of on-line learning of model trees with options, which present an effective compromise between learning a single model and an ensemble. We have successfully applied these approaches to several tasks of discrete-time modelling of dynamic systems.

WP8 (Development of a trans-Atlantic climate supermodel)

- An interactive ensemble of models is developed such that multiple atmosphere, land and ice component models can be simultaneously coupled to a single ocean component model. A “coupling wrapper” is developed so that any AGCM (whether or not it includes an independent land or ice component model) can be incorporated into the interactive ensemble in a multi-model sense. Current experiments, besides NCAR models in the ensemble include
the ECHAM and the US Navy NoGAPS models.

- Interactive ensemble technique is applied for better understanding of the interactions between the weather and climate. The importance of weather noise forcing of natural variability such as ENSO is analyzed in one study. The other work is focused on the interaction between the atmosphere and the ocean eddies.

Expected results and potential impact

Upon completion, the project will have constructed at least a prototypical supermodel that will greatly reduce uncertainty regarding the details of expected climate change, including the magnitude of global warming and specific regional effects. The increased confidence in the projections will facilitate policy decisions at all levels and will increase public support for such decisions, as the public becomes informed about expected changes in each locality, and not just global averages.

In the realm of computational science, there are other situations in which there are a handful of expert dynamical models of the same real-world process that could be efficaciously combined. One can envision applications to complex biological, social, economic, and environmental processes, in situations where there are a small number of competing models, e.g. created in academic institutions, or by a handful of leading business entities in a given field. The only requirement is that the constituent models be equipped with a methodology to incorporate new data from the objective process, as the model runs. In that situation, the models can also assimilate data from each other, as here, and an adaptation procedure for connection coefficients can be defined.

Promotional activities

A dedicated website has been set up for the main purpose of dissemination of the project results at the following web address: http://www.sumoproject.eu/.

Other promotional activities have been conducted including:

- Presentation at the European Future Technologies Conference and Exhibition – FET11 held in Budapest, 4-6 May, 2011.
- Wim Wiegerinck and Frank Selten gave an interview on SUMO, which is published in the geolog weblog-post "Supermodels!", 9 April 2013 (http://geolog.egu.eu/2013/04/09/supermodels/)
- Lasko Basnarkov presented the SUMO project at the “Young Scientists and science in the region” conference, held by the Montenegrin Academy of Sciences and Arts in Podgorica, Montenegro, 17-18 October 2013.
- A popular science article describing the objectives of the SUMO project has appeared in research*eu focus magazine.
- Project flyer
- Broadcast of a TV documentary regarding the SUMO project on the Macedonian state TV
- Regular updates are provided on http://www.sumoproject.eu/.
The project flyer has been updated with the new partners and the new WPs.
A Facebook page dedicated to the SUMO project is open: http://www.facebook.com/sumoproject

List of partners and contact details

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Project entry/exit month: 1/42

**Partner 2**: Leibniz Institute of Marine Sciences (IFM-GEOMAR)
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Project entry/exit month: 1/9

**Partner 3**: Potsdam Institute for Climate Impact Research (PIK)
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**Partner 4**: Royal Netherlands Meteorological Institute (KNMI)
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Project entry/exit month: 10/42

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Project entry/exit month: 31/42
2. Project objectives for the period

According to the Annex I – Description of work, the following describes the objectives of the project along the different work packages. Also, for each work package the tasks on which work should have started according to annex 1 are described.

WP1: General theory of supermodeling with ODEs

Objectives – The main objective of WP1 is to develop the general theory of a supermodel apart from the learning aspect, to specify how models with different structure should be connected and examine what are the conditions under which connecting variables among different models will lead to superior skill, and the form of those connections. Another goal of this WP is to determine limitations of the supermodeling strategy. In addition to machine learning we will develop a strategy on how to define connections based on insight and mathematical arguments that might lead to a useful supermodel. We do this because the automatic learning might be too complex or lead to suboptimal solutions and we spread the risk this way. Also, the developing of domain knowledge for machine learning of the structure of models and interconnections is considered in this WP. This material developed here will serve as input for WP 2-5, as well as WP7.

Tasks – The following tasks are foreseen in the WP1:

Task 1.4: Potential and limits of supermodeling: We will research the potential benefit and limits of supermodeling assuming knowledge of the ground truth. This enables us to explore the solution spaces of the connections as well as to explore the application range in which the supermodeling approach might be beneficial (i.e. better than any single model and the result of averaging models) as function of the degree of model imperfections. We will also research its potential added value when considering models with slowly changing parameters, this to anticipate on its application in the research of climate change.

Task 1.5: Interpretation of connections determined by learning: Can we understand why the supermodel works with a certain set of connections.

WP2: Learning of coefficients with ODEs

Objectives – The goal of work package two is to research and develop efficient, robust and scalable learning strategies to optimize connection coefficients for dynamical systems of low and intermediate size complexity (up to 1000 variables). The resulting learning strategies are to be used to guide the development of methods in WP3 and WP4. A second objective is to assess performance of the obtained supermodeling learning strategies and research and develop methods to estimate model performance based on available data. The main research effort will be focused on exploring and improving existing learning strategies. Methods will be experimentally assessed by their performance on systems agreed upon in WP1 while keeping their scalability to the higher dimensional climate models of WP4 and WP5 in mind. Later in the project, feedback from WP3-5 will further guide the research directions in this WP. Issues that arise in those work packages will be referred back to WP1 and this WP for further analysis and improvement.

Tasks – The following task is foreseen in the WP2:
Task 2.3: Potential of learning of supermodeling: In this task we study the application range in which the supermodeling learning approach might be beneficial compared to more straightforward approaches. Questions that we address are divided in subtasks:
- Learnability: We will study the ability to successfully learn the coefficients of the supermodel in relation with underlying model complexity (as in task 2.1.2), the degree of imperfection of the individual models, the amount of data, and the number of independent connection coefficients.
- Performance estimation: We will research validation methods and measures that aim to estimate the supermodel’s future performance using only data that is available at current time.

WP3: Learning of connection coefficients in PDE systems

Objectives – This work package consists of two objectives. Firstly, to prescribe learning algorithms to determine optimal connection coefficients in a general PDE supermodel that will be applicable to large climate models and secondly to understand the importance of local vs. global optima in such coefficients, and to prescribe algorithms to avoid local optima if necessary. The goals of WP3 are to validate and refine the learning algorithms for a supermodel formed from several systems of partial differential equations that are imperfect counterparts of a single “true” system of PDE’s. General lessons from this investigation will be applied to climate models in WP4 and WP5. Issues that arise in those work packages will be referred back to WP2 for further exploration.

Tasks – The following task is foreseen in the WP3:

Task 3.4: Develop learning strategies for state-of-the-art climate supermodels: While with T3.1, T3.2 and T3.3 most issues regarding training of connections coefficients in climate supermodels will be resolved, this task will focus on some remaining issues that are peculiar to full climate simulations. One of those issues is that of possible trends due to gradual changes in CO2 forcing; another arises from the arbitrariness in radiative forcing in climate models. This will further increase in complexity of the learning algorithms.

WP4: Supermodelling with intermediate complexity climate models

Objectives – In this work package we develop and test the super modelling approach using climate models of intermediate complexity. We follow the suggestions from WP1, WP2 and WP3 that developed and tested the approach in simpler systems guided by theoretical considerations and report back whether the approach needs rethinking and redesigning. The main objective is to develop a super modelling approach that is applicable to the state-of-the-art climate models of WP5. In this work package we will create imperfect models by perturbing model parameters and formulations and regard the original model as a virtual truth. We will employ different climate model systems, starting from a relatively simple climate model and add to the complexity in small steps and address a specific issue at each step. We will assume a ground truth model at each step and create an ensemble of imperfect models by perturbing parameters and/or using different formulations for unresolved processes.

Tasks – The following task is foreseen in the WP4:

Task 4.4: Investigate the ability of the supermodel to simulate a realistic response After learning the supermodel to reproduce the present-day climate, we will test its ability to simulate a realistic response to increasing concentrations of greenhouse gasses.
WP5: Supermodelling with large climate models

Objectives – Work package five has 3 objectives. Firstly, to develop a super climate model by coupling three different climate models together using observations for the period 1870-1980 to train the model. Secondly to assess the benefits and drawbacks of the super climate modelling strategy against conventional approaches (i.e., multi-model mean) and the best model through simulating climate from 1980-2010 and retrospective-prediction of seasonal-to-decadal fluctuations during the same period. Finally, the third objective is to demonstrate that the super modelling strategy can be applied to make climate projections, by performing a scenario simulation for the 21st century with the super climate model and contrasting it with conventional multi-model scenario simulations. For the purpose of achieving these objectives three different climate models will be applied: ECHAM5/NEMO, ECHAM5/MPIOM, and IFS/NEMO coupled models; the first two will be provided by UiB and the last by KNMI. Two classes of simulations will be performed to assess the super climate model: externally forced (i.e., boundary value problem) and initialized (i.e., initial condition and boundary value problem).

Tasks – The following tasks are foreseen in the WP5:

Task 5.3 (month 13-20), construct a super climate model using a learning strategy: A first version of the super-climate model will be developed based on initial results of WP 1-4. The development will involve continued input from other WPs. Recommendations will be taken on the following:
  • Whether to couple state variables or physical tendencies
  • How to reduce of data dimensionality
  • How to deal with fast atmospheric and slow ocean processes
  • How to train the model on observational data

The supermodel will be trained over the period 1870-1980. [UiB, MASA, KNMI, RU, PIK]

Task 5.6 Define a second version of the super-climate model: A refined version of the model will be made based on results of task 1-4 and recommendations from WP1-4. It will be trained over the period 1870-1980, and tested on the period 1980-2010. [UiB, MASA, KNMI, RU, PIK, UMiami]

Task 5.7 Perform a scenario simulation for the 21st century with the super climate model and contrast it with conventional multi-model scenario simulations. [UiB, UMiami]

Task 5.8 Final recommendation on the super climate modelling strategy: Results of the application of the super-modelling strategy to the hierarchy of models in the whole project will be summarised. The utility of the approach to climate modelling and the potential to reduce uncertainties in future climate projections will be assessed. Recommendations on future work on this topic will be made. These will be described in a report. [UiB, MASA, KNMI, RU, PIK, UMiami]

WP6: Management

Objectives – The objectives of the management work package are the following:

1. Efficiently manage the project.
2. Communication between the European Commission and SUMO, including all forms of reporting specified in the consortium contract agreement.
3. Provide the communication tools for the project: public and internal web sites.
4. Organize annual general assemblies and project meetings.
5. Organize a SUMO international dissemination Workshop.
6. Ensure promotion of clustering and cooperation with related projects (both in FP7 and other international and national projects).

**Tasks** – The following tasks are foreseen in the WP6:

**Task 6.1**: (Months 1-42): The coordinator supported by the project office and the administrative staff are in regular contact with the Management Board of SUMO and the European Commission. The project office prepares the necessary scientific and financial reports for the EC. The project office communicates all necessary information from the EC to the participants for the preparation of the due reports and for the financial aspects. The project maintains a public and an internal project website.

**Task 6.3**: (Months 1-42): Contribution to portfolio and concentration activities at FET-Open level. The project office will actively promote dissemination activities. It will make sure that all scientific knowledge acquired in SUMO is freely available for external users. This will be done through promotion of the SUMO achievements, tools and data in meetings of national and international organizations and through a SUMO organized summer school in the 3th year for a wide scientific audience. The project office will produce a flyer and a brochure.

**WP7: Learning complete supermodels**

**Objectives** – The objective of this WP is to develop methods for computational scientific discovery that can learn complete supermodels (ensembles of ODE models) of dynamic systems. Its sub-objectives include the development of techniques for the (semi)automated generation of constituent models, for the selection of an appropriate subset of models, and for learning the form and coefficients of the interconnections among the models.

**Tasks** – The following tasks are foreseen in the WP7:

**Task 7.3**: Learn to interconnect ODE models

In learning the interconnections between the constituent models of the ensemble, we will consider searching through the space of possible structural forms of the interconnections, coupled with parameter fitting for a selected functional form of the possible connections. For parameter fitting, we will use global optimization methods based on meta-heuristic approaches. The use of such parameter estimation methods is of crucial importance in supporting the use of different quality criteria, as well as avoiding local optima in search.

**WP8: Development of a trans-Atlantic climate supermodel**

**Objectives** – WP8 will be concerned with fusing climate models originating in the U.S. and in Europe to form a more complete and powerful supermodel\(^4\). Toward this end we will first enhance the flexible software framework being developed in the US, capable of coupling any pair of corresponding variables in two constituent models; this is an alternate approach to that in WP5. The

\(^4\) A parallel effort in the United States will construct a supermodel using the wrappers and inter-model nudging software being developed at U. Miami, at the National Center for Atmospheric Research (NCAR) under DOE Grant#DE-SC0005238: “An Interactive Multi-Model for Consensus on Climate Change”.
work naturally divides into three tasks: (1) the incorporation of the European models into the US coupling framework, (2) enhancement of the supermodeling software framework to couple three-dimensional state-space vectors, and (3) training and assessing the trans-Atlantic climate supermodel.

**Tasks** – The following tasks are foreseen in the WP8:

**Task 8.1 Incorporation of European models into the IE software.** The proposed supermodeling research will first enhance the ongoing multi-model IE software development to include ECHAM5. U. Miami is currently developing a wrapper to integrate AM2.1 into the CESM system; the proposed research will extend the wrapper to include ECHAM5. Technically, the integration of AM2.1 and ECHAM5 with CESM requires the development of translation methods between the data types in the model coupling toolkit (MCT) interfaces used by CPL7 and the data types in the GFDL’s Flexible Modeling System (FMS) interfaces used by AM2.1 and the data types used in OASIS3 coupling interface of ECHAM5. Our strategy to accomplish this will borrow heavily from the implementation of the Earth System Modeling Framework (ESMF) interface in CPL7. Currently, ESMF interfaces in CPL7 are supported via methods that translate between the data types in the MCT interfaces and the data types in the ESMF interfaces. To facilitate translation, each component provides an additional layer where the MCT interfaces are translated to the ESMF interfaces and data is copied between data types on entry and exit of each method. We will use these translation methods as a template for translation between AM2.1/ ECHAM5 and MCT data types.

**Task 8.2 Computational Innovation for Inter-Model Coupling.** The software to be developed will implement model-to-model nudging for model fusion experiments, using Newtonian relaxation terms that act to drive the state variables (or subsets of these) towards each other. Specifically, the software will add artificial terms to the right hand sides of the equation sets for, say model A, state vector \( X_A \) and model B, state vector \( X_B \):

\[
\frac{\partial X_A}{\partial t} = \text{dynamics} + \text{physics} + \frac{X_B - X_A}{\tau_{relax}^A} \quad \frac{\partial X_B}{\partial t} = \text{dynamics} + \text{physics} + \frac{X_A - X_B}{\tau_{relax}^B}
\]

where the relaxation times \( \tau_{relax}^{A,B} \) are not necessarily constant, but rather may be functions of space and are the inverses of the corresponding connection coefficients used in the original SUMO project.

Once ECHAM5 has been incorporated into the multi-model IE infrastructure in Task 7.1, the model-to-model Newtonian nudging is straightforward to implement. U. Miami has already developed and thoroughly tested the Newtonian nudging implementation in CAM5 within the IE infrastructure and the Newtonian nudging is already available in ECHAM5. It still remains to be implemented into AM2.1.

**Task 8.3 Assessing performance of the ‘trans-Atlantic’ climate supermodel.** The trans-Atlantic climate supermodel developed in 8.1 and 8.2 shall be trained using methods developed in other WP3 and tested in WP4 and WP5 on intermediate and full climate complexity models, respectively. Following the strategy in WP5, the model will be trained using observations over the period 1870-1980. The model will then be used to simulate the independent period 1980-2010, and seasonal prediction experiments will be performed for the period 1980-2010. These experiments are similar to those in WP5 (and reported in D5.2) that are performed with the European climate supermodel. The seasonal predictions shall be initialized as in WP5 using SST restoring technique (Keenlyside et al., 2005).
3. Work progress and achievements during the period

Progress and achievements: WP1 (General Theory of supermodeling with ODEs)

We augmented our studies on the collective behavior of a network of connected chaotic systems as a function of the connection strength. Therefore, we extended the scope of our numerical simulations. First, we additionally did simulations with the time-delayed Ikeda system where hyperchaotic dynamics can be observed. Second, we investigated a network of connected atmospheric models in order to investigate whether the phenomenon of amplitude death can also be observed in higher dimensional chaotic systems and reported on new results in the context of so-called "ghost attractors" in these systems.

Although the initial numerical findings are interesting enough, some bits and pieces of the method have no theoretical foundation. For example the factor $\gamma$ and the integration length $\Delta$ seem to appear in the cost function, since "it works". Therefore it is a valid question to ask "Why?". Thus, we started to focus on a couple of related new questions:

- Why do certain values for $\gamma,\Delta$ work and are they the only one?
- Do we need to couple all equations, or is it possible to just couple a sub-set?
- Can we define an alternative cost function?
- How good does the method work for a real imperfect model scenario?

Based on these findings, we further proposed new methods, ideas and measures in order to gain a more thorough understanding of the solution spaces of the supermodel connections. In particular, we were interested in measuring the performance of the supermodeling approach. Therefore, we modified the Lorenz as well as the Rössler system with an additional non-linear term. This term enabled us to continuously tune the original models towards a higher degree of nonlinearity. We were thus able to study how the supermodel can forecast the ground truth that structurally varies from the supermodel ensemble.

These projects are still ongoing work and publications thus only in preparation, respectively.

Details on the results obtained have been thoroughly described in Deliverable D1.3: Report on potentials and limits.

Highlight of clearly significant results:

- Different dynamical regimes – including amplitude death and ghost attractors – are investigated within the study of networks of nonidentical oscillators in dependence on the global coupling strength.
- New methods, concepts, ideas and measures are introduced in order to further understand the solution space of SUMO connections and to estimate the SUMO performance

There are no critical objectives missed.
Deviations from the original work plan.

Parts of our work were delayed because the corresponding researcher (Naoya Fujiwara) left the group after one year (he got a position in Japan at University of Tokyo) while his follower (Carsten Grabow) newly entered the project; a situation that could not have been foreseen in the planning of the description of work. Additionally, the amount of work planned for year 2 was very ambitious. The work planned in the third year of WP1 seemed to be much more realistic. But the corresponding researcher Carsten Grabow was also awarded for a 3-months JSPS stipend at the University of Tokyo in the end of 2013. In this context, we started to investigate further applications of SUMO in the field of Neuroscience. In addition, due to our broad conference activities we managed to establish other new collaborations as well. This means that we received new input and ideas from outside with the consequence being that new questions arose.

Resources
Resources for this work package have been used as was planned in Annex 1.

Progress and achievements: WP2 (Learning coupling coefficients in ODEs)

We started this period by performing ensemble studies with three imperfect T21 models compared with one assumed ground truth – T42 model. One of the imperfect models has the same parameters as the T42. The other two models are symmetrically perturbed around this ”optimal” imperfect model. In addition, the imperfect models have forcings that are tuned to the observed climatology of the ground truth. In this study we compared a uniformly fused supermodel (weighted as well as connected) to the individual models and the posterior ensemble approach. We found that the uniform supermodel improved on the predicted climate variance.

The question aroused whether there is in general an advantage in a dynamical averaging approach compared to the more straightforward a posteriori averaging in a conventional uncoupled ensemble of models. The answer to this question sheds light to the question how important learning is in supermodeling. If uniformly fusing dynamical models on its own were often already helpful, then the role of learning from data is less relevant and the need for efficient learning algorithms is less urgent than when this is not the case.

When taking a posteriori multi-model means in conventional non-interactive examples, ensemble statistics improves on average over individual model statistics due to cancellation of errors in the model outcomes, while there are guarantees that the ensemble mean statistics is not worse than the statistics of the worst model in the ensemble. We were interested if such results would also hold for the interactive ensemble approach. To research this, we performed several experiments with interactive ensembles, some in the perfect model class setting (where imperfect models and ground truth are in the same model class) and some in the imperfect model class setting (where ground truth model has a higher complexity than the imperfect models). We restricted ourselves to interactive ensembles that are modelled as weighted supermodels with uniform weights. We validated performance on long-term statistics, either in terms of some metrics, or by visual inspection of the attractor. Results with interactive ensembles of randomly perturbed models showed varying results. With small perturbations, there was hardly any difference between
interactive and non-interactive ensemble results. With larger perturbations, connecting models in the ensemble sometimes improved results, but occasionally, it seemed to do more harm.

Analysis of attractor statistics of interactive ensembles shows that when the attractor statistics is linear in the model perturbations, interactive ensembles results in the same statistics as the mean of the model statistics in a non-interactive ensemble. In general this means that with supermodeling, prior to learning some error reduction can already be expected. When the attractor statistics are nonlinear in the model perturbations, however, results are strongly dependent on the situation at hand and an interactive ensemble approach could lead to undesired effects due to nonlinearities in the integration, even worse than the worst individual model. This was indeed what has been observed in numerical experiments.

The conclusion is that in general one should take care and that validation and fine tuning e.g. by learning weights, in supermodels according to appropriate metrics may be needed to obtain appreciable results.

The other item is learnability of dynamical systems with respect to both short-term (vector field) and long-term (attractor) behaviour. In particular we are interested in learning in the imperfect model class setting, in which the ground truth has a higher complexity than the models, e.g. due to unresolved scales. As running example we took the partially observable chaotically driven Lorenz 63 system. We took a Bayesian approach and we define a joint log-likelihood that consists of two terms, one is the vector field error and the other is the attractor error, for which we take the $L_1$ distance between the stationary distributions of the model and the assumed ground truth. In the context of linear models (like weighted supermodels), and assuming a Gaussian error model in the vector fields, vector field learning leads to a tractable Gaussian solution. This solution can then be used as a Bayesian prior for attractor learning with the attractor likelihood. This is done by elliptical slice sampling, a sampling method for systems with a Gaussian prior and a non-Gaussian likelihood. Each sample is a rolled-out trajectory of a dynamical system. Simulations with the partially observable driven Lorenz 63 system shows that solutions that considerably improve upon the vector-field learned solutions can be found with less than 100 roll-out samples.

**Highlights of significant results**

- Comparative analysis of interactive and non-interactive ensemble approaches. Unlike conventional non-interactive ensembles, there are no a-priori performance guarantees in interactive ensembles and interactive ensembles may perform worse than the worst model. This implies that one should take care and that validation and fine tuning e.g. by learning weights, in supermodels according to appropriate metrics will be needed to obtain appreciable results.

- Bayesian approach to learning of dynamical systems, combining vector field learning for short-term prediction with attractor learning for long-term statistics. In so-called linear models (in which the modelled vector-fields are linear combinations of a fixed set of basis functions), an algorithmic approach is described and demonstrated in the context of learning a low dimensional partially observable chaotic dynamical system.

There are no critical objectives missed. There is no significant deviation of the schedule.

**Resources**
Resources for this work package have been used as was planned in Annex 1.

**Progress and achievements: WP3 (Learning coupling coefficients in PDE systems)**

The SPEEDO supermodel has been prepared for comparing different densities of connections for efficacy in inter-model synchronization. That will allow a test of our hypothesis that the minimum density required is related to synoptic length scales. The existing configuration will also allow the quick implementation of the crude synchronization-based learning algorithm to optimize connection coefficients.

A criticism of the supermodeling approach has been that allowing members of an ensemble to interact would remove the utility of the ensemble for estimating model error or background error from ensemble spread. We have given a demonstration that, to the contrary, spread is maintained in the connection coefficients that define an interactive ensemble, so that the constituent models may effectively “agree to disagree”. The preliminary demonstration was in the configuration of two ECHAM models coupled to a common ocean that was studied in WP5.

By considering combinations of weights for the several ocean-atmosphere fluxes that give the relative contributions of the two atmospheric models, that give near-optimal performance. Each near-optimal combination of weights gives a different SST field. The spread among such fields appears realistic.

If supermodeling is to be widely used, it would be very helpful if not essential to have a software framework into which new constituent models can be readily inserted. The view of supermodeling as inter-model data assimilation suggests that data assimilation software might be adapted for this purpose. Scripts have been written to couple three CESM (Community Earth System) models defined by different versions of the Community Atmosphere Model (CAM), to be used in conjunction with software from NCAR’s Data Assimilation Research Testbed (DART) to stop and restart the models. The hope is to extend DART in such a way that when any new model is interfaced with DART, it is automatically interfaced with any existing supermodel. A demonstration of this strategy will follow upon repair of the DART-CESM interface.

Synchronization of neural oscillators plays an important role in brain functioning. It has been argued that perception and motor control are usefully conceived as synchronization of brain with reality. If one combines internal brain synchronization with brain-reality synchronization, the resulting configuration resembles a supermodel. To establish the relevance of this analogy, it is first necessary for data-assimilation/perception-as-synchronization to make contact with models of real neural processes. Our showing that the FORCE (first-order reduced and controlled error) learning procedure for general recurrent neural networks is equivalent to standard data assimilation via Kalman Filtering therefore constitutes noteworthy progress toward a cognitive role for supermodeling.

Details on the results obtained have been thoroughly described in Deliverable D3.3.

**Highlights of significant results**

- Supermodeling (interactive ensemble) does not negate the role of ensembles of models in estimating error from ensemble spread. An ensemble of connection values or weights naturally emerges from the learning procedure.
- A general data assimilation software package, DART, has been extended, in a very preliminary way, for general supermodel construction.
There are no critical objectives missed. There is no significant deviation of the schedule.

Resources
Resources for this work package have been used as was planned in Annex 1.

Progress and achievements: WP4 (Supermodeling with intermediate complexity climate models)

For the SUMO approach to work, the connections between the imperfect models should enable the models to synchronize. In case of the climate model SPEEDO, which consists of a coupled atmosphere-land-ocean-sea-ice model, we found in the second year of SUMO that by connecting through the surface fluxes, only partial synchronization was achieved, mainly in the tropics, close to the surface. Therefore we introduced connections between the 3D atmospheric temperature fields in the third year in order to achieve synchronization of the full 3D atmospheric states. The coding required to do so involved more work than anticipated, as the original code was not designed to exchange 3D fields and connect multiple atmospheres. We managed to implement the connections and perform synchronization experiments with imperfect models. Indeed, we found with manually chosen connections that the atmospheres synchronize on a common solution that is different from the individual solutions, a prerequisite for the SUMO approach. We plan to develop the learning in a subsequent project financed by the Netherlands science foundation NWO.

Since we realized that the SUMO approach is potentially more suited for the weather predictability problem, we started collaboration with Dr. Judith Berner of NCAR in Boulder Colorado with the aim to test the SUMO approach in a state-of-the-art weather prediction system using the WRF model. In weather prediction systems, ensembles of forecasts are produced that sample uncertainties in the forecast due to initial condition errors and model errors. Model errors are sampled in WRF by selecting different parameterization schemes for the physical processes (like the land surface, micro-physics, planetary boundary layer, cumulus parameterization and radiation) in the different ensemble members. In a first SUMO setup, we decided to take the partial weighted SUMO approach and construct a supermodel by taking a weighted average of the tendencies from the different parameterization schemes. So far we have taken equal weights and have not yet implemented the learning. First results indicate there is some improvement in skill in the surface winds, but not in temperature. Clearly learning is required in order to improve the skill of the SUMO. In addition we experimented with the T21QG atmosphere model to gain more insight into the impact of model errors on the probabilistic predictions and how the SUMO approach might be applied in this setting. We hope to continue the collaboration with NCAR beyond the SUMO project.

Details on the results obtained have been thoroughly described in Deliverable D4.3.

Highlights of significant results

- The software infrastructure to exchange 3 dimensional state variables in the SPEEDO climate model has been build and tested and it was found that connecting N imperfect atmospheres through the 3D temperature field with a 6hr nudging time scale enabled the ensemble to synchronize on a common solution. This proves the feasibility of the full SUMO approach in a climate model that is in many aspects as complex as state-of-the-art climate models.
The partial weighted SUMO approach has been implemented in an ensemble weather forecasting system based on the state-of-the-art regional weather model WRF. First experiments indicate that learning needs to be implemented as equal weighting just slightly improves the skill for surface winds, but deteriorates the skill for surface air temperature.

**Deviations from the original work plan.**

It was foreseen to study the climate change problem with a connected SUMO of imperfect SPEEDO models with connections sufficient to enable synchronization of the ensemble. We managed to implement the changes in the software that allowed for an exchange of all state variables in 3D and prove that with sufficient connections the models indeed synchronize on a common solution. However, we did not manage to learn the connections and investigate the ability of the SUMO to simulate climate change by the end of the project. One reason being that the software development turned out to be more involved as originally thought, as the software was not written originally with the exchange of 3D variables in mind and the coupling of several atmospheres to a single ocean component. The SUMO approach in that sense is quite different as the traditional modeling strategies. Another factor has been that the postdoc that started to implement the changes left the project for a job in software engineering after 5 months into the third year and another person had to continue the programming of the 3D connections which caused a delay in the development of the necessary software. However, the system is in place and the work will continue beyond SUMO provided that we are awarded a grant by the Dutch science foundation.

Other work not foreseen in the original work plan has been started with the aim of starting a collaboration that could possibly extend beyond SUMO. During a 4-week visit to Judith Berner of NCAR in Boulder Colorado the partially weighted SUMO approach was implemented in the WRF ensemble forecasting system. This work is at the stage that learning can now be implemented. We hope to find funding to continue this work beyond SUMO as we can show the potential benefits of the SUMO approach in this context.

**There are no critical objectives missed. There is a deviation from the original work plan.**

**Resources**

Resources for this work package have been used as was planned in Annex 1.

**Progress and achievements: WP5 (Supermodeling with large climate models)**

The utility of supermodel approach to climate modeling was demonstrated by constructing an interactive ensemble of two atmospheric GCMs (AGCM) coupled to one ocean GCM (OGCM). This approach is able to produce partial synchronization of the atmospheric models over the tropical Pacific. The two AGCMs only differ in their convective scheme. We performed experiments with machine learning algorithm suggested by WP2 to obtain the optimal coefficients for the air-sea fluxes in the interactive ensemble. We trained the model with a metric designed to reproduce the observed climatology of tropical Pacific sea surface temperature (SST). This was based on recommendations from WP1 and WP4, where the coupling strategy was tested. We show that through this strategy we are able to simulate reasonably tropical Pacific climate. In comparison to coupled models using the individual AGCM versions, the cold tongue bias of the tropical Pacific is substantially reduced and the double intertropical convergence zone (ITCZ) problem is largely
ameliorated. The seasonal cycle of SST and precipitation is much more realistic, and the interannual variability in terms of pattern and strength is improved. The improvements of the supermodel appear related to improved representation of ocean-atmosphere interaction. Beyond the tropical Pacific, the trained supermodel performs less well.

The robustness of the model was tested by performing historical simulations driven by increasing greenhouse gas concentration for the period 1900-2010. The model performance was evaluated in terms of pattern correlation as well as standard deviation for different decades for the equatorial Pacific. The model was found to maintain a robust climatology. The global warming response was comparable to other models and observations. Climate projections were initiated from the historical run following the greenhouse gas changes from the Representative Concentration Pathways 8.5 (RCP8.5) of CMIP5. Globally, the climate change integrations show that the trained supermodel behavior falls between the coupled models based on the individual AGCMs. In contrast, the results over the tropics show marked differences. In the two standalone-coupled models the zonal SST gradient in the tropical Pacific is enhanced, and there is an eastward shift of the Walker Circulation. While in the trained supermodel there is a weakening of the zonal SST gradient and a weakening of the Walker Circulation. It is difficult to assess whether the climate projection of the trained supermodel is superior to the standalone-coupled models. Nevertheless, as the mean state and ocean-atmosphere interaction are improved, we may have more confidence in the results of the trained supermodel.

In collaboration with colleagues from GEOMAR in Kiel, the supermodeling strategy was applied to another climate model (the Kiel Climate Model) with higher model resolution. With manually chosen weights we were able to construct a supermodel that performed better than the individual models over the tropical Pacific, in terms of the mean state and interannual variability. The results confirmed the robustness of the supermodeling approach for the tropical Pacific.

**Highlights of significant results:**

- SUMO was a pilot project that served to demonstrate the great potential of supermodeling to improve global climate model simulations and lead to more reliable climate model projections.
- A super climate model for the tropical Pacific was produced through partial synchronization of two AGCMs that were coupled to a single ocean model (i.e., an interactive ensemble). The model outperformed the individual coupled models, and the ensemble mean. The improvements appear related to better representation of ocean-atmosphere interaction. Performing historical simulations and developing a supermodel using a different climate model with higher model resolution showed the robustness of the strategy.
- Climate change projections were performed and the results of the supermodel were shown to differ markedly over the tropical Pacific. The supermodel simulated a general weakening of the tropical circulation and an El Niño like warming. The individual models showed a La Niña like pattern and a shift tropical circulation.

**Recommendations**

- A super climate model that performs well at global scales can be only achieved through synchronization of the 3D ocean and atmosphere states. For the atmosphere this can be achieved through coupling of temperature fields (WP4), and similar results can be expected
for the ocean. Nevertheless, 3D coupling of climate models is not a trivial task, and new non-intrusive approaches to achieve this should be investigated.

- The performance of the supermodel depends ultimately on the ability to compensate model errors. Thus, the inclusion of more global model in the supermodel can be expected to lead to a more superior supermodel than one based on two single AGCMs differing only in convection scheme.

There are no critical objectives missed. There is no significant deviation of the schedule.

Resources
Resources for this work package have been used as was planned in Annex 1.

Progress and achievements: WP7 (Learning complete supermodels)

The objective of WP7 is to develop methods for computational scientific discovery that can learn complete supermodels (ensembles of ODE models) of dynamical systems. This involves generation of diverse candidate models (Task 7.1), selection of models for the ensemble (Task 7.2), and selecting a method to combine the models and their predictions (Task 7.3). The focus for WP7 in Year 3 was Task 7.3 (combining the model predictions), but this required polishing and revisiting certain aspects of Tasks 7.1 and 7.2 (generating and selecting constituent models) and implementing all of the above within an integrated software environment.

The constituent models (ODEs) are learnt from observed data and domain knowledge by the process-based modelling tool ProBMoT. Note that both the structure and the parameters of the process-based models (and the corresponding ODEs) are learnt. Thus, the ensembles can contain models with different structure, which is a novelty as compared to ensembles, which are based on (random) variation of the initial conditions or parameter values of the ODE models. ProBMoT searches a space of possible model structures, defined by the domain knowledge given and fits the parameter values to each structure considered, based on the input data. The model structures considered are ranked in terms of their error, either on the training data set or on a separate validation data set. The highest ranked model is the output of ProBMoT.

To generate (diverse) base-level models, we have extended ProBMoT to support the three steps outlined above. First, it allows for two types of sampling of the (time-course) data given as input: bootstrap sampling and error-weighted sampling. Second, it allows for two (independent) kinds of selection of constituent models for the ensemble, one based on the error on training/validation data and the other on simulation stability: The latter is used for dynamic prediction-time selection of models to be used for prediction within the ensemble. Finally, it is possible to use three different methods for combining the predictions of the constituent models, using three different types of aggregation (taking a simple average or a weighted average/median).

We empirically evaluated the bagging and boosting approach to learning ensembles of process-based (ODE) models on 15 different data sets, coming from three aquatic ecosystems. In the evaluation we focus on the predictive power of the two types of ensembles and individual models. Note that previous approaches to computational scientific discovery have focused on explanatory models of dynamics and their descriptive power and haven't investigated the predictive power of such models.
The results of the empirical evaluation can be summarized as follows. The ensembles learned by bagging significantly outperform individual models. The ensembles learned by bagging perform better than those learned by boosting, but not significantly. Finally, the ensembles learned by boosting perform better than individual models, but not significantly. Overall, the ensembles learned by bagging perform best.

In addition to developing methods for learning ensembles of ODE models, we have applied these methods (as well as learning individual models) to practically relevant problems from environmental and life sciences. These include modelling phytoplankton dynamics in three lakes (Bled, Slovenia; Kasumigaura, Japan; and Zürich, Switzerland) and modelling hydrological and nutrient leaching processes at watershed level. They also include an application in systems biology, i.e., modelling the process of endocytosis, a crucial part of the immune response, as well as applications in the area of synthetic biology.

Besides learning ensembles of (continuous-time) ODE models, we have also addressed the task of learning ensembles of non-parametric regression models for modelling dynamic systems in discrete time. We have used the external dynamics approach, which formulates this task as a regression task of learning a difference/recurrence equation/model. This model predicts the state of the system at a given discrete time point as a (nonlinear) function of the states and inputs of the system at several previous time points.

In particular, we propose methods for learning fuzzy linear model trees and ensembles thereof. These are used as the function approximators within the external dynamics approach. Trees for predicting either a single-output (one state variable) or multiple-outputs (the entire system state) trees/ensembles can be learned by our methods.

We evaluate the proposed methods on a number of problems from the area of control engineering. We show that they perform well and are resilient to noise. Among the different approaches proposed, ensembles of trees for predicting multiple outputs can be recommended, since they perform best and yield the most succinct overall models.

Finally, we also tackle the task of learning ensembles of non-parametric regression models for modelling dynamic systems in discrete time in a streaming context. The data stream paradigm matches the concept of modelling dynamic systems very well, as the continued observation of the state and inputs of dynamic systems over (discrete) time results in a (potentially infinite) stream of data. Within this paradigm, we can handle large quantities of data (both a large number of variables and a large/infinite number of observations), which makes it suitable for some novel application areas (such as global systems science).

We have developed novel methods for learning ensembles of regression and model trees on data streams, such as on-line bagging and on-line random forests. We have also proposed the approach of on-line learning of model trees with options, which present an effective compromise between learning a single model and an ensemble. We have applied these approaches to several tasks of discrete-time modelling of dynamic systems.

All of the above contributions are described in detail in the WP7 report (Deliverable 7.3) and the associated papers/dissertations.

**Highlights of significant results:**
- We have developed bagging and boosting methods for learning ensembles of ODE models, incl. candidate model generation, selection, and combination. The ensembles contain models with different structure (as compared to other ensembles of ODE models) and allow for making predictions of system behaviour. In terms of predictive performance, these perform clearly better than individual ODE models as evaluated on several aquatic ecosystems.
- We have also developed methods for learning ensembles of non-parametric models of dynamic systems in discrete time. These include ensembles of fuzzy model trees learned in batch mode and ensembles of model trees (as well as option trees) learned from data streams in an on-line fashion. These approaches can handle large quantities of data, which makes them suitable for some novel application areas (such as global systems science).

There are no critical objectives missed. There is no significant deviation of the schedule.

Resources
Resources for this work package have been used as was planned in Annex 1.

Progress and achievements: WP8 (Development of a trans-Atlantic climate supermodel)

Early works with interactive ensembles from NCAR family of models were based on multiple realizations of an atmospheric model (CAM) coupled to a single realization of the ocean model (POP), a single realization of the sea-ice model and a single realization of the land-surface model. The coupling of the multiple realizations of CAM to the single realizations of the other component models aims at significantly reducing the stochastic forcing of the ocean due to internal atmospheric dynamics. This strategy works fine for the ocean but leads to differences in the climatology of ice and land that are too large. We have enhanced the interactive ensemble so that multiple atmosphere, land and ice component models can be simultaneously coupled to a single ocean component model. This is a major code development that is expected to be part of the next official release of CESM. The new implementation of the interactive ensemble has shown substantially reduced impact on the model climatology. Another major code development was to implement a “coupling wrapper” so that any AGCM (whether or not it includes an independent land or ice component model) can be incorporated into the interactive ensemble in a multi-model sense. This coupling wrapper has been fully tested with a data model and is currently being tested with ECHAM and the US Navy NoGAPS models.

The interactive ensemble technique was used to better understand the importance of weather noise forcing of natural variability such as El Niño Southern Oscillation (ENSO). To study the impact of weather noise and resolution in the context of a CGCM, two interactive experiments were performed at different atmospheric model resolutions (T85 vs. T42), since the noise statistics depends on the spatial scales resolved. The interactive ensemble noise reduction has a major impact on the coupled simulation and the magnitude of this effect strongly depends on the horizontal resolution of the atmospheric component model. The noise reduction technique reduces the overall climate variability more effectively at higher resolution. This suggests that “weather noise” is more important in sustaining climate variability as resolution increases. ENSO statistics, dynamics, and phase asymmetry are all modified by the noise reduction, in particular ENSO becomes more regular with less phase asymmetry when noise is reduced. We have found that applying the interactive ensemble noise reduction technique at higher resolution (T85) leads to a significantly larger
reduction in amplitude than in the T42 model.

We have completed multi-decadal simulations with the interactive ensemble using the eddy permitting (LRIE) and the eddy resolving ocean models (HRIE). In both of these simulations 10 atmospheric (land and ice) instantiations are coupled to one ocean. It was shown that atmospheric weather noise interacts with the ocean eddies and that when this interaction is “short circuited” via the IE coupling the ocean eddies are amplified relative to the control.

**Highlights of significant results:**

- The existing interactive ensemble for NCAR family of models is enhanced so that multiple atmosphere, land and ice component models can be simultaneously coupled to a single ocean component model.
- A “coupling wrapper” is developed so that any AGCM (whether or not it includes an independent land or ice component model) can be incorporated into the interactive ensemble in a multi-model sense, and inclusion of ECHAM5 was tested.
- Interactive ensemble technique is used to better understand the interactions between the weather and climate.

**There are no critical objectives missed. There is no significant deviation of the schedule.**

**Resources**

Resources for this work package have been used as was planned in Annex 1.

**Published work**

**Publications, including journal papers and conference papers/abstracts**

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• N. Fujiwara, J. Kurths, and A. Diaz-Guilera, Spectral Analysis of Synchronization in Mobile Networks, AIP Conference Proceeding 1389

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4. Project management during the period

Progress and achievements: WP6 (Management)

- Task 6.1: The coordinator supported by the project office and the administrative staff are in regular contact with the Management Board of SUMO and the European Commission. The project office prepares the necessary scientific and financial reports for the EC. The project office communicates all necessary information from the EC to the participants for the preparation of the due reports and for the financial aspects. The project maintains a public and an internal project website.
- Task 6.2: Annual general assemblies and project meetings are being held (see list below)
- Task 6.3: The project office produced a flyer for the project and promotes the project in national and international environment.

Changes within beneficiaries

On the tenth month of the project, the Leibniz- Institut fuer Maerewissenschaften der Universitaet Kiel (IFM-GEOMAR) terminated its participation.
On the tenth month of the project, the Universitetet I Bergen (UIB) joined the project. The start day of participation was 01 July 2011. UIB replaced IFM-GEOMAR in SUMO with the existing budget.

On the tenth month of the project the Jozef Stefan Institute (JSI) joined SUMO. JSI is the lead beneficiary in the newly added WP7. The start day of participation was 01 July 2011. However, due to the change of IFM-GEOMAR with UIB, the signature of the contract amendment for adding IJS was delayed to October 2011.

On the thirtieth month of the project the University of Miami (UMiami) joined SUMO. UMiami is the lead beneficiary in the newly added WP8. The start day of participation was 01 April 2013.

Budget adjustment

The new beneficiary UIB took over the commitments and the budget from the previous beneficiary IFM-GEOMAR. For the new beneficiary IJS in the budget were added 387,594.00 Euros, also, MASAs budget was increased by 137,400.00 Euros. Overall, the budget for the first enlargement of the project was increased by 524,994.00 Euros.

The budget for SUMO was increased a second time, for the new beneficiary UMiami in the budget were added 269,590.00 Euros, also, UiB’s budget was increased by 185,100.00 Euros. Overall on the second enlargement, the budget for the project was increased by 454,690.00 Euros.

The overall budget increase was 979,684.00 Euros.

Meetings:
According to the Consortium Agreement for SUMO, the General Assembly should meet at least once a year, whereas the Management Board should meet at least semi-annually.

2011

The General Assembly met for the first time on the third of November 2010 in Skopje, Republic of Macedonia. This was considered as the SUMO’s kick off meeting. It was chaired by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), presentations were made by Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK), Noel Keenlyside from Leibniz Institute, University of Kiel (IFM–GEOMAR), Ralf Hand from Leibniz Institute, University of Kiel (FM–GEOMAR), Wim Wiegerinck from Radboud University (RU), Willem Burgers from Radboud University, Greg Duane from Macedonian Academy of Sciences and Arts (MASA), Naoya Fujiiwara from Potsdam Institute (PIK), Saso Dzeroski from Josef Stefan Institute (JSI), and was attended by Igor Tomovski, Anastasios Tsonis, Daniel Trpevski, Igor Trpevski, Daniel Smilkov, Angel Stanoev, Miroslav Mirchev, Lasko Basnarkov, Igor Mishkovski, Dimitar Solev and Vanja Askapova.

The Management Board met on the 03.11.2010 in Skopje Macedonia, and it was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK), Noel Keenlyside from Leibniz Institute, University of Kiel (IFM–GEOMAR), Ralf Hand from Leibniz Institute, University of Kiel (FM–GEOMAR), Wim
Wiegerinck from Radboud University (RU), Willem Burgers from Radboud University and Naoya Fujiwara from Potsdam Institute (PIK).

The second Management Board was held on fourth of May 2011 in Budapest, Hungary. This meeting was also attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK) and Wim Wiegerinck from Radboud University (RU).

The General Assembly met for the second time on the twenty-third of November 2011 in Skopje, Republic of Macedonia. The assembly was chaired by Ljupco Kocarev from the Macedonian Academy of Sciences and Arts (MASA), presentations were made by Ljupco Kocarev and Gregory Duane from Macedonian Academy of Sciences and Arts (MASA), Jurgen Kurths and Naoya Fujiwara from Potsdam Institute (PIK), Wim Wiegerinck from Radboud University (RU), Frank Selten and Paul Hiemstra from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB) and Saso Dzeroski from Jozef Stefan Institute (JSI). The meeting was also attended by Igor Tomovski, Daniel Trpevski, Igor Trpevski, Daniel Smilkov, Angel Stanoev, Miroslav Mirchev, Lasko Basnarkov and Vanja Askapova.

The third Management Board was held on the twenty-third of November 2011 in Skopje, Macedonia. This meeting was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK) and Wim Wiegerinck from Radboud University (RU), Noel Keenlyside from the University of Bergen (UiB) and Saso Dzeroski from Jozef Stefan Institute (JSI).

The first review meeting was held on the twenty-fourth of November 2011 in Skopje, Republic of Macedonia. The review board consisted of prof. dr. Klaus Hasselmann, prof. dr. Michael Ghil and prof. dr. Witold Dzwinel. The meeting was attended by Aymard.De-Touzalin, project officer. On the meeting presentations were made by Ljupco Kocarev and Gregory Duane from Macedonian Academy of Sciences and Arts (MASA), Jurgen Kurths and Naoya Fujiwara from Potsdam Institute (PIK), Wim Wiegerinck from Radboud University (RU), Frank Selten and Paul Hiemstra from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB) and Saso Dzeroski from Jozef Stefan Institute (JSI). The meeting was also attended by Mao-Lin Shen, Darko Cerepalkovski, Nikola Simidjievski, Jovan Tanevski, Igor Tomovski, Daniel Trpevski, Igor Trpevski, Daniel Smilkov, Angel Stanoev, Miroslav Mirchev, Lasko Basnarkov, and Vanja Askapova.

2012

The General Assembly met for the third time on 22-24 May 2012 in Bergen, Norway. It was chaired by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), presentations were made by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Wim Wiegerinck from Radboud University (RU), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB), Greg Duane from Macedonian Academy of Sciences and Arts (MASA), Saso
Dzeroski from Josef Stefan Institute (JSI), and was attended by Mao-Lin Shen, Carsten Grabow, Nikola Simidjievski, and Lasko Basnarkov.

The fourth Management Board was held on the twenty-third of May 2012 in Bergen, Norway. This meeting was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Wim Wiegerinck from Radboud University (RU), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB) and Saso Dzeroski from Josef Stefan Institute (JSI).

The fifth Management Board was held on the nineteenth of November 2012 in Potsdam, Germany. This meeting was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK) and Wim Wiegerinck from Radboud University (RU), Noel Keenlyside from the University of Bergen (UiB) and Saso Dzeroski from Josef Stefan Institute (JSI).

The second review meeting was held on the twentieth of November 2012 Potsdam, Germany. The review board consisted of prof. dr. Klaus Hasselmann, prof. dr. Michael Ghil and prof dr. Witold Dzwinel. The meeting was attended by Aymard.De-Touzalin, project officer. On the meeting presentations were made by Ljupco Kocarev and Gregory Duane from Macedonian Academy of Sciences and Arts (MASA), Jurgen Kurths and Carten Grabow from Potsdam Institute (PIK), Wim Wiegerinck from Radboud University (RU), Frank Selten and Paul Hiemstra from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB) and Saso Dzeroski from Jozef Stefan Institute (JSI).

2013

The General Assembly met for the fourth time on 6th of May 2013 in Ljubljana, Slovenia. It was chaired by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), presentations were made by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Wim Wiegerinck from Radboud University (RU), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB), Greg Duane from Macedonian Academy of Sciences and Arts (MASA), Saso Dzeroski from Josef Stefan Institute (JSI), and was attended by Carsten Igor Trpevski, Lasko Basnarkov, Miroslav Mirchev, Mao-Lin Shen, Carsten Grabow, Nikola Simidjievski and Pance Panov.

The sixth Management Board was held on the 7th of May 2013 in Ljubljana, Slovenia. This meeting was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Wim Wiegerinck from Radboud University (RU), Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB) and Saso Dzeroski from Josef Stefan Institute (JSI).

The seventh Management Board was held on the 1st of September 2013 in Ohrid, Macedonia. This meeting was attended by Ljupco Kocarev from Macedonian Academy of Sciences and Arts (MASA), Wim Wiegerinck from Radboud University (RU), Frank Selten
from Royal Netherlands Meteorology Institute (KNMI), Noel Keenlyside from University of Bergen (UiB), Saso Dzeroski from Josef Stefan Institute (JSI) and Benjamin Kirtman from University of Miami (Umiami)

Conferences:

2011

From the fourth to the sixth of May 2011 the European Research Consortium for Informatics and Mathematics held the FET11 Conference. This conference was attended by Ljupco Kocarev (MASA), Gregory Duane (MASA) Frank Selten from Royal Netherlands Meteorology Institute (KNMI), Jurgen Kurths from Potsdam Institute (PIK) and Wim Wiegerinck from Radboud University (RU).

From the second to the seventh of October 2010 the European Science Foundation held ESF Reserach Conference on Future Internet and Society. This conference was attended by Naoya Fujiwara (PIK).

From the third to the eighths of April 2011 the European Geosciences Union held the General Assembly. This conference was attended by Jurgen Kurths (PIK) and Naoya Fujiwara (PIK).

From the fourth to the eighths of July 2011 the conference Engineering of Chemical Complexity was held. This conference was attended by Naoya Fujiwara (PIK).

From the twelfth to the sixteenth of September 2011 the conference Dynamics Days Europe 2011 was held. This conference was attended by Naoya Fujiwara (PIK).

From the nineteenth to the twenty fifth of September 2011 the 9th International Conference on Numerical Analysis and Applied Mathematics was held. This conference was attended by Naoya Fujiwara (PIK).

From 3-4 November 2011 at the BNAIC 2011, The 23rd Benelux Conference on Artificial Intelligence, in Ghent, Belgium, W. Wiegerinck presented a poster.

At the American Geophysical Society Fall Meeting, 5-9 December, 2011, San Francisco, CA, USA, Greg Duane organized a session on super-modeling, oral presentation and 2 poster presentations (together with Frank Selten).


2012

Mao-Lin Shen delivered an oral presentation on 2-3 April 2012 at Origins of the Kuroshio and Mindanao Currents OKMC workshop, Kaohsiung, Taiwan.

Wim Wiegerinck attended a seminar on Uncertainty Quantification for Climate and Environmental Models, 29 June 2012, UCL, London, UK.


Mao-Lin Shen presented a poster at Bjerknes Centre 10-Year Anniversary Conference: Climate Change in High Latitudes in Bergen, Norway, 3-6 September 2012.

Wim Wiegerinck and Frank Selten presented a poster at the Climate, Informatics Workshop, 18-19 September 2012, NCAR, Boulder, Colorado, US.

Carsten Grabow presented a poster at the DAMES conference - Data analysis and modelling in Earth sciences, 8-10 October 2012, Potsdam, Germany.

2013

Carsten Grabow delivered an oral presentation at the DPG-Tagung, Regensburg, Germany, March 10th - 15th 2013.

Ljupcho Kocarev attended the international conference on "Nonlinear Data Analysis and Modeling: Advances, Applications and Perspectives" held on the 21st- 22nd of March in Potsdam, Germany.

Frank Selten and Wim Wiegerinck presented a poster at the international conference on "Nonlinear Data Analysis and Modeling: Advances, Applications and Perspectives" held on the 21st- 22nd of March in Potsdam, Germany.

Carsten Grabow attended the international conference on "Nonlinear Data Analysis and Modeling: Advances, Applications and Perspectives", held on the 21st- 22nd of March in Potsdam, Germany.

Carsten Grabow presented a poster at the EGU General Assembly, Vienna, Austria, April 6th - 13th 2013

Carsten Grabow delivered an oral presentation at the SIAM conference, Snowbird, USA, May 18th - 25th 2013.
Wim Wiegerinck delivered an oral presentation at Benelearn 2013, 3 June 2013, Nijmegen, Netherlands.

Lasko Basnarkov presented a poster titled “Contemporary tools for reducing the model error in weather and climate forecasting models” at the XXXIII Dynamics Days Europe, held 3-7th June 2013 in Madrid, Spain.


Kocev Dragi delivered an oral presentation at ECML-PKDD 2013: European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases, September 23th to 27th, 2013, Prague.

Carsten Grabow was awarded a JSPS BRIDGE Fellowship, Collaborative Research Center for Innovative Mathematical Modelling with the director Prof. Kazuyuki Aihara, University of Tokyo, Japan, September - November 2013.

Saso Dzeroski delivered an oral presentation at DS2013: Discovery Science Conference October 6–9, 2013, Singapore, 2013.

Carsten Grabow delivered an oral presentation at the Aihara lab, University of Tokyo, Japan, October 7th 2013.

Carsten Grabow delivered an oral presentation at the Toyoizumi Lab, RIKEN Brain Science Institute, Wako-Shi, Tokyo, Japan, October 17th 2013.

Carsten Grabow delivered an oral presentation at the Kohda/Jitsumatsu lab, Kyushu University, Japan, October 28th 2013.

Nikola Simidjievski delivered an oral presentation at ISEM2013:Ecological Modelling for Ecosystem Sustainability in the context of Global Change, 28th to 31st October 2013, Toulouse, France.

Saso Dzeroski delivered an oral presentation at ISEM2013:Ecological Modelling for Ecosystem Sustainability in the context of Global Change, 28th to 31st October 2013, Toulouse, France.

Carsten Grabow delivered an oral presentation at the Aihara lab, University of Tokyo, Japan, November 1st 2013.

2014

Mao-Lin Shen delivered an oral presentation at ZMAW/KlimaCampus Seminar, Max-Planck-Institut für Meteorologie, Germany, 14th Jan 2014.

Carsten Grabow attended the DPG-Frühjahrstagung, Dresden, Germany, April 1st - 3rd 2014.

Mao-Lin Shen delivered an oral presentation at Research Center for Environmental Changes, Academia Sinica, 7 May 2014, Taipei City, Taiwan

**AGU Fall meeting**

**Oral**
Interactive vs. Non-Interactive Multi-Model Ensembles
Gregory S. Duane

Reducing Model Systematic Error through Super Modelling – The Tropical Pacific
Mao-lin Shen; Noel S. Keenlyside; Frank Selten; Wim Wiegerinck; Gregory S. Duane

**Poster**
Synchronization and super modeling experiments with a complex climate model
Frank Selten

Forecast improvement by interactive ensemble of atmospheric models
Lasko Basnarkov; Gregory S. Duane; Ljupco Kocarev

**European Geosciences Union General Assembly 2014 Vienna | Austria | 27 April – 02 May 2014**

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Synchronization and super modeling experiments with a complex climate model
Frank M. Selten

Reducing Model Systematic Error over Tropical Pacific through SUMO Approach
Mao-Lin Shen, Noel Keenlyside, Frank Selten, Wim Wiegerinck, and Gregory Duane

Climate Change Projection with Reduced Model Systematic Error over Tropic Pacific
Noel Keenlyside, Mao-Lin Shen, Frank Selten, Wim Wiegerinck, and Gregory Duane

Interactive vs. Non-Interactive Ensembles for Weather Prediction and Climate Projection
Gregory Duane
Reducing Model Systematic Error through Super Modelling
Mao-Lin Shen, Noel Keenlyside, Frank Selten, Gregory Duane, Wim Wiegerinck

Supermodeling With A Global Atmospheric Model
Wim Wiegerinck, Willem Burgers, and Frank Selten

Poster

Synchronization and super modeling experiments with a complex climate model
Frank Selten

Forecast improvement by interactive ensemble of atmospheric models
Lasko Basnarkov; Gregory S. Duane; Ljupco Kocarev

Software Engineering Designs for Super-Modeling Different Versions of CESM Models using DART
Erik Kluzek, Gregory Duane, Joe Tribbia, and Mariana Vertenstein

Decomposing model systematic error
Noel Keenlyside and Mao-Lin Shen

Comparing error reduction in interactive and non-interactive ensemble approaches
Wim Wiegerinck and Gregory Duane

Interactive Ensembles Without Loss of Spread Information
Gregory Duane, Mao-Lin Shen, and Wim Wiegerinck

The simulated tropical Pacific variability by applied supermodelling to the Kiel Climate Model
Jin Ba, Mao-Lin Shen, Wonsun Park, Noel Keenlyside, and Mojib Latif

The Performance of the Supermodeling Approach In the Real Imperfect Model Scenario
Carsten Grabow, Thomas Stemler, and Jürgen Kurths

Improvement in predictive modeling by combining imperfect models Carsten Grabow and Jürgen Kurths

Synchronization Experiments With A Global Coupled Model of Intermediate Complexity
Frank Selten, Paul Hiemstra, and Mao-Lin Shen

Structural and Initial Conditions Uncertainties In Seasonal Forecasts
Noel Keenlyside and Mao-Lin Shen

Supermodel - Interactive Ensemble of Low-dimensional Models
Lasko Basnarkov, Gregory Duane, and Ljupco Kocarev

A Computational Framework for Supermodeling As Inter-model Data Assimilation
Daniel Trpevski, Alicia Karspek, and Gregory Duane
Attractor Learning In Interactive Ensembles
Wim Wiegerinck and Lasko Basnarkov

Session at the AOGS

A Revisit to the Interactive Ensemble Coupling Strategy with Examples of Application
Wu & Kirtman,

Understanding the change in the tropical Pacific mean state due to global warming using the interactive ensemble model
Yeh & Kirtman

Interactive Ensembles with Spread Information
Duane et al.

Reducing Model Systematic Error over Tropical Pacific through Interactive Ensemble and Synchronization
Shen et al.

The simulated tropical Pacific variability by applied supermodelling to the Kiel Climate
Ba et al.

Impact of systematic error over the Tropical Pacific on climate change projections
Keenlyside et al.

Consultative meetings:

2011

From the sixteenth to the twentieth of November 2010, Gregory Duane from MASA was in Potsdam, Germany to work on SUMO with PIFK.
From the nineteenth to the twenty-first of January 2011, Gregory Duane from MASA was in Potsdam, Germany to work on SUMO with PIFK.
From the sixth to twelfth of February 2011, Naoya Fujiwara from PIK was in Barcelona, Spain, at University of Barcelona for a consultation about SUMO.
On the fourteenth of March 2011, Gregory Duane from MASA was in Potsdam, to discuss about SUMO with PIFK.
In March 2011, Gregory Duane from MASA was in Kiel, Germany, for discussions about SUMO with IFM-GEOMAR.
At 24 March 2011, Gregory Duane from MASA was in Utrecht and Nijmegen, Netherlands, to work on SUMO with KNMI and RU.
On the twenty-eighth of March 2011 Greg Duane from MASA, Paul Hiemstra, and Frank Selten from KNMI were in Nijmegen, Netherlands, at Radboud University (RU) for a consultation about SUMO.
On sixteenth and seventeenth of June and from twenty seventh of June to the first of July 2011, Naoya Fujiwara from PIK was in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

From the nineteenth to twenty fifth of June 2011, Naoya Fujiwara from PIK was in Nijmegen, Netherlands, at Radboud University (RU) for a consultation about SUMO.

From the nineteenth to the twenty-sixth of June 2011, Lasko Basnarkov from MASA was in Nijmegen, Netherlands, at Radboud University (RU) for a consultation about SUMO.

On the twenty-first of June 2011 Frank Selten from KNMI was in Nijmegen, Netherlands, at Radboud University (RU) for a consultation about SUMO.

From the twenty-sixth of June to the third of July 2011, Lasko Basnarkov, as a representative from MASA was in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

On the thirtieth of June 2011 Wim Wiegerinck and Willem Burgersen from RU were in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

On the twenty-eighth of August 2011 Paul Hiemstra from KNMI was in Nijmegen, Netherlands, at Radboud University (RU) for a consultation about SUMO.

In August 2011, Frank Selten from KNMI visited NCAR (Boulder, Colorado) for the purpose of consultation about SUMO.

From the twenty-fifth to the twenty-ninth of October 2011, Gregory Duane as a representative of MASA was in Ljubljana, Slovenia at the Josef Stefan Institute (JSI) for the purpose of consultation about SUMO.

From the twenty-fourth to the twenty-fifth of October 2011, Ljupco Kocarev as a representative of MASA was in Torino, Italia at the Politehnico Torino for the purpose of consultation about SUMO.

On the twenty-fourth of November 2011, the first annual review meeting was held in Skopje, Macedonia. The review board consisted of prof. dr. Klaus Hasselmann, prof. dr. Michael Ghil and prof. dr. Witold Dzwinel, The meeting was attended by Aymard.De-Touzalin, project officer.

From 20-23th December, 2011 Gregory Duane as a representative of MASA was in Miami, Florida, USA at the University of Miami for the purpose of consultation about SUMO.

2012

On the 3th of February 2012, Wim Wiegerinck, as a representative from RU was in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

From the 13-17th of February 2012, Mao-Lin Shen, as a representative from UiB was in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

From the 11-16th of March 2012, Ljupco Kocarev, as a representative from MASA was in Ljubljana, Slovenia at the Josef Stefan Institute (JSI) for the purpose of consultation about SUMO.

From the 2-6th of April 2012, Saso Dzeroski and Nikola Simidjievski, as a representatives from JSI were in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.

From the 13-18th of May 2012, Miroslav Mirchev, as a representative from MASA was in Gottingen, Germany at the Max Plank Institute for the purpose of consultation about SUMO.
From the 2-6th of July 2012, Carsten Grabow, as a representative from PIK was in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.
On the 4th July 2012, Wiegerinck, Burgers, Duane, Grabow were in DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.
From the 5-7th of September 2012, Gregory Duane as a representative of MASA was in Potsdam Germany at Potsdam Institute for climate impact research (PIK) for the purpose of consultation about SUMO.
From 10-14 September, 2012, Gregory Duane as a representative of MASA was DeBilt, Netherlands at the Royal Netherlands Meteorology Institute (KNMI) for the purpose of consultation about SUMO.
On 6 December 2012, Wim Wiegerinck and Willem Burgers as representatives from RU were in de Bilt at KNMI for a work visit relating to SUMO.

2013

From the 17-20th of March 2013, Ljupcho Kocarev, as a representative from MASA was in Potsdam, Germany at Potsdam Institut Fuer Klimafolgenforschung (PIK) for the purpose of consultation about SUMO.
From the 5-18th of May 2013, Igor Trpevski, as a representative from MASA was in Ljubljana Slovenia at Jozef Stefan Institute (JSI) for a work visit relating to SUMO.
From the 5-19th of May 2013, Miroslav Mirchev, as a representative from MASA was in Ljubljana Slovenia at Jozef Stefan Institute (JSI) for a work visit relating to SUMO.
From the 8-10th of May 2013, Wim Wiegerinck as a representative from RU was in Ljubljana Slovenia at Jozef Stefan Institute (JSI) for a work visit relating to SUMO.
On the 16th of July 2013, Saso Dzeroski, as a representative from JSI was in Ohrid, Macedonia at for a meeting with Ljupcho Kocarev relating to SUMO.
From the 7-10th of October 2013, Ljupcho Kocarev, as a representative from MASA was in Potsdam, Germany at Potsdam Institut Fuer Klimafolgenforschung (PIK) for the purpose of consultation about SUMO.
On 22 October 2013, Wim Wiegerinck as representative from RU was in de Bilt at KNMI for a work visit relating to SUMO.

SUMO Summer school

From the 2nd to the 7th of September 2013 in Ohrid, Republic of Macedonia was held Summer School on Non-linear Dynamics, Machine Learning and Climate Modeling.
The seven day event had 14 presentations:
Aneta Koseska: Introduction to theory of dynamical systems and Dynamics of complex systems: synchronization and oscillation quenching mechanisms
Lasko Basnarkov: Short- and long-term predictability. Relation to weather and climate models
Frank Selten: Modeling of the climate system
Noel Keenlyside: Climate prediction
Mao-Lin Shen: Limitations of climate modelling
Wim Wiegerinck: Parameter estimation in models and supermodels of dynamic systems
Saso Dzeroski: Learning models of dynamic systems and ensembles thereof
Joao Gama: An introduction to learning from data streams
Juergen Kurths: Synchronization from coupled oscillators to complex networks
Greg Duane: Introductory remarks on supermodeling
Ben Kirtman: How the Interactive Ensemble Coupling Strategy Was Developed to Understand How Weather Affects ENSO
Leonard A Smith: Aims and Means of Supermodeling by Cross-Pollination in Time

5 exercises were held over the course of the Summer School, and over 40 participants from various countries attended.

**Web-meetings** are held on a regular basis, where different aspects and issues about the project are discussed.
Deliverables and milestones tables

Deliverables

The deliverables due in this reporting period, as indicated in Annex I to the Grant Agreement have to be uploaded by the responsible participants (as indicated in Annex I), and then approved and submitted by the Coordinator. Deliverables are of a nature other than periodic or final reports (ex: "prototypes", "demonstrators" or "others"). If the deliverables are not well explained in the periodic and/or final reports, then, a short descriptive report should be submitted, so that the Commission has a record of their existence.

If a deliverable has been cancelled or regrouped with another one, please indicate this in the column "Comments".
If a new deliverable is proposed, please indicate this in the column "Comments".

This table is cumulative, that is, it should always show all deliverables from the beginning of the project.
<table>
<thead>
<tr>
<th>Del. no.</th>
<th>Deliverable name</th>
<th>Version</th>
<th>WP no.</th>
<th>Lead beneficiary</th>
<th>Nature</th>
<th>Dissemination level</th>
<th>Delivery date from Annex I (proj month)</th>
<th>Actual / Forecast delivery date Dd/mm/yyyy</th>
<th>Status No submitted/Submitted</th>
<th>Contractual Yes/No</th>
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<tr>
<td>D1.3</td>
<td>Report on potentials and limits</td>
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<td>4</td>
<td>R</td>
<td>PU</td>
<td>36</td>
<td>01/10/2013</td>
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<td>D2.3</td>
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<td>2</td>
<td>5</td>
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<td>3</td>
<td>3</td>
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<td>D4.3</td>
<td>Report on the behaviour of the supermodel in a perturbed climate regime</td>
<td>4</td>
<td>6</td>
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PU = Public  
PP = Restricted to other programme participants (including the Commission Services).  
RE = Restricted to a group specified by the consortium (including the Commission Services).  
CO = Confidential, only for members of the consortium (including the Commission Services).  

Make sure that you are using the correct following label when your project has classified deliverables.  
EU restricted = Classified with the mention of the classification level restricted "EU Restricted"  
EU confidential = Classified with the mention of the classification level confidential " EU Confidential "  
EU secret = Classified with the mention of the classification level secret "EU Secret "
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<td>D5.3</td>
<td>Report on updated super climate model and summarizing results on super climate modeling</td>
<td>5</td>
<td>7</td>
<td>R</td>
<td>PU</td>
<td>42</td>
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<td>D6.5</td>
<td>Project periodic report 3</td>
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<td>D6.7</td>
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<td>D6.8</td>
<td>Final report</td>
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<td>Report on learning to interconnect ODE models</td>
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<td>6</td>
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<td>D8.1</td>
<td>Report on the trans-Atlantic climate supermodel performance</td>
<td>8</td>
<td>8</td>
<td>R</td>
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<td>01/04/2014</td>
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Milestones

Please complete this table if milestones are specified in Annex I to the Grant Agreement. Milestones will be assessed against the specific criteria and performance indicators as defined in Annex I.

This table is cumulative, which means that it should always show all milestones from the beginning of the project.

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<th>Milestone no.</th>
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<td>Decision on model classes</td>
<td>WP1, WP2, WP3, WP4, WP5</td>
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<td>MS2</td>
<td>Decision on initial super modeling strategy for climate super models</td>
<td>WP1, WP2, WP3, WP4, WP5</td>
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<td>Evaluate the initial super model experience with climate super models</td>
<td>WP1, WP2, WP3, WP4, WP5</td>
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<td>Showcase for intermediate and complex climate super models</td>
<td>WP4, WP5</td>
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<td>MS6</td>
<td>Domain knowledge and methods for generating diverse models developed</td>
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<td>MS7</td>
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<td>MS8</td>
<td>Methods for learning functional form and coefficients of interconnections developed</td>
<td>WP7</td>
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<td>MS9</td>
<td>Technical capabilities for a trans-Atlantic supermodel consisting of ECHAM5, AM2.1 and CAM5 coupled</td>
<td>WP8</td>
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<td>01/04/2014</td>
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