Supermodeling by combining imperfect models (SUMO)
overview

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Parners

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Targeted breakthrough is to provide a more realistic simulation of the observed historical evolution of climate and make actual predictions of the climate with a “supermodel” consisting of an ensemble of interconnected state-of-the-art climate models that has “learned” to reproduce the observed, historical evolution of the climate.

Radically different computational strategy is suggested that combines ideas from the machine learning, dynamical systems and climate science in order to obtain more realistic estimates of future climate change using the existing ensemble of state-of-the-art climate models.
Long-term vision

- Supermodeling opens possibilities to **boost quantitative modeling** in other scientific disciplines that study complex systems, e.g. biology and economics.

- Supermodeling is a novel approach of combining ensemble of models in **machine learning**.

- The application domain is restricted to **climate research**.

- Complex systems of partial differential equations (PDEs) or lattice maps can represent **social, economical, biological, ecological, or physical processes**.

- The methods developed in the project could be applied to combine expert models of **processes generally**.
Climate models used by the Intergovernmental Panel on Climate Change (IPCC) **differ** in projections of globally averaged temperature increase in the next century by as much as a **factor of two**, and **differ completely** in regard to projections for specific regions of the globe.

**Averaging techniques** have been used in an attempt to improve the situation, so as to increase the reliability of the projections and of the resulting estimates of safe greenhouse gas levels.

**Intelligent consensus formation** could go well beyond averaging, and is a more immediately attainable goal than increasing the resolution and veracity of individual models.
Data assimilation as synchronization

Find model equations
\[ f \]
Find model parameters
\[ p \]
Find model initial conditions
\[ x(0) \]

\[ \frac{dx}{dt} = f(x, p) \]

Even finding the initial conditions could be a difficult task (100 000 variables but only 1000 variables are measurable): data assimilation

**Real system:** \( \hat{x} \)

Data assimilation is equivalent to synchronization \( x \rightarrow \hat{x} \) when \( t \rightarrow \infty \)

\[ \frac{dx}{dt} = f(x, p) + K(x - \hat{x}_i) \]

“We nudging”

We run the system until \( t<T \) starting with arbitrary initial conditions

Initial conditions: \( x(T) \)
Consider an ensemble of $n$ imperfect models that each evolve according to distinct dynamics.

Assume that the models are coupled to each other, and to the real system:

$$\frac{dx^i}{dt} = f^i(\hat{x}, p)$$

$$\frac{dx^i_\mu}{dt} = f_\mu(x_\mu, p_\mu) + \sum_{\mu \neq \nu} C_{\mu\nu} (x^i_\nu - x^i_\mu) + K^i (\hat{x}^i - x^i_\mu)$$

Adaptive observers (control theory)
Parameter estimation (machine learning, statistics)
Synchronization between oscillators in complex networks (physics, nonlinear science)
Consensus among agents in networked systems (distributed computing, control theory)
Learning interconnections

- Both form and coefficients
- Note that there may be different types of interconnections (WP2 and WP7 presentations)
  - ‘Connected’ SUMO:
    \[ \dot{x}_\mu^i = f_\mu^i(x_\mu) + \sum_{\nu} C_{\mu\nu}^i (x_\nu^i - x_\mu^i), \quad C_{\mu\nu}^i \geq 0 \]
    \[ \overline{x}_{\text{sumo}} = \frac{1}{M} \sum_{\mu} x_\mu \]
  - ‘Classical’ ensemble: Models simulated independently, only outputs combined (Cs set to 0)
  - ‘Weighted’ SUMO:
    \[ \dot{x}^i = \sum_{\mu} w_\mu^i f_\mu^i(x), \quad w_\mu^i \geq 0, \quad \sum_{\mu} w_\mu^i = 1 \]
Barotropic imperfect models (from WP2)

Attractor plots: 2-d projection
- Blue: ground truth
- Red: imperfect models
Barotropic imperfect models (from WP2)

Ensemble mean

Mean dynamics

Connected + cost

Weighted + cost

Weighted + one-shot
Super climate model coupled at ocean-atmosphere interface (from WP5)

Atmosphere

ECHAM5

IFS

OASIS3

Ocean

Fluxes of heat, momentum, and freshwater

SST, sea ice cover

\[ F_i^o = \alpha_i F_i^{a1} + (1 - \alpha_i) F_i^{a2} \]
Graphical representation of the nature of and interconnections between the work packages. The vertical ordering of the work package reflects the nature of the research from more fundamental at the bottom to more applied to the top. The colours indicate the prevailing expertise needed in each work package. The arrows reflect the flow of information between the work packages.
Models are identified for analyzing the supermodeling concept
Simple systems with few degrees of freedom; models governed by partial differential equations and intermediate climate complexity models (with up to 250,000 degrees of freedom); and the most complex state-of-the-art climate models with order $10^7$ degrees of freedom.

Metrics and appropriate test criteria are suggested to determine how closely the evolution of a supermodel follows the truth.

The proposed metrics (static, dynamic) based on Kullback-Leibler divergence performs well with tested models (Lorenz 63 and T5 models).
WP2 highlights

- Different supermodel classes and different approaches to optimize the supermodel parameters are designed.

- The analysis of supermodels in the limit of large connections and strong synchronization is performed, which linked them to a new class of weighted-average supermodels - which turn out to be very scalable to larger systems.

- Supermodels in the case where the imperfect models had fewer variables than the ground truth are investigated.

- OASIS -like coupling can be applied
Wp7 highlights

- The addition of WP7 and JSI strengthens the machine learning component of the project

- Allows for the learning of complete supermodels from data and domain knowledge including
  - Component models
  - Interconnections
  - Form
  - Coefficients
KS systems generally synchronize, with a correspondence function that is near to the identity even in the presence of a structural difference, as is required both for predictability and supermodeling – the first formal demonstration of GS in spatially extended systems.

The required density of spatial connections for synchronization and supermodeling depends on the coherent structures that exist within each system separately, a heuristic that could be readily applied to meteorological systems.

Synchronization-based learning appears to be as effective as optimization of extended trajectories, at much reduced computational cost, but the latter approach may produce more reliable results in more complex cases.

Work on a general supermodeling software framework using the Data Assimilation Research Testbed (DART) at the National Center for Atmospheric Research (NCAR) is underway.
WP4 highlights

- Partially connected atmosphere models can completely synchronize (15% of the variables need to be connected)

- Empirical Orthogonal Functions are 50% more efficient than original state variables

- Minimum connection strength for complete synchronization is 7 days
An initial design for the prototype super climate model was determined. The model will consist of two atmospheric models (ECHAM5 and IFS) coupled to one ocean model (NEMO or MPIOM).

The benefits of several coupling software were assessed, and a decision was made to use a pseudo parallel version of OASIS3. This version allows different fields to be exchanged between models on different processes, allowing an efficient exchange of data among model components and limiting the exchange bottleneck.

Work began on porting the Kiel Climate Model to a scalar architecture. This has involved updating OASIS3 to the pseudo-parallel version.
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.
  - 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
Annual general assemblies and project meetings

- The General Assembly met for the first time on 03.11.2010 in Skopje, Republic of Macedonia. This was considered as the SUMO’s kick off meeting.

- The Management Board met on the 03.11.2010 in Skopje Macedonia.

- The second Management Board was held on 04.05.2011 in Budapest, Hungary.

- Web-meetings are held on a regular basis (total of 8 in period October 2010 – October 2011).

- **Collaboration between partners:** 15 consultative meetings are held
Conferences attended by SUMO participants

- FET11 Conference, 4-5 May 2011.

- European Science Foundation held ESF Research Conference on Future Internet and Society, 2-7 October 2010.

- European Geosciences General Assembly, 3-8 April 2011.

- Engineering of Chemical Complexity Conference, 4-8 July.

- Dynamics Days Europe Conference, 12-16 September 2011.

Scientific output

- 5 Journal papers: 3 published (*2 join work between partners*) and 2 submitted
- 7 Book chapters (to be published by Springer 2012)
- 2 Conference proceedings

**Forthcoming conferences**
- Neural Information Processing Systems (NIPS), 12-17 December, 2011, Spain
- American Geophysical Union Meeting, 5-9 December, 2011, USA
Agenda for today meeting

08:45 - 09:00 Reviewers briefing (restricted meeting for the reviewers)
09:00 - 09:30 SUMO - overview (Kocarev, MANU)
09:30 - 10:00 WP1 Models and metrics (Kurths and Fujiwara, PIK)
10:00 - 10:30 WP2 Learning low complexity and intermediate complexity models (Wiegerinck, RU)
10:30 - 11:00 WP7 Learning complete supermodels (Dzeroski, IJS)
11:00 – 11:15 Coffee break
11:15 - 11:45 WP3 Connections learning approaches for PDEs (Duane, MANU)
11:45 - 12:15 WP4 Connections in climate models of intermediate complexity (Selten and Hiemstra, KNMI)
12:15 - 12:45 WP5 Super climate model with manually chosen connections (Keenlyside, UIB)
12:45 - 14:00 Lunch break
14:00 - 14:30 Greg Duane (MANU): On the limits of supermodeling
14:30 - 15:00 Wim Wiegerinck (RU): Coupling, synchronisation and averaging
15:00 - 15:30 Saso Dzeroski (IJS): Modeling the mechanisms of major climate shift with machine learning approaches
15:30 - 15:45 coffee break
15:45 - 16:30 Reviewers debriefing (restricted meeting for the reviewers)
16:30 - 17:00 Reviewers feedback to the consortium (feedback and discussion).