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Sense and Sensitivity: improving regional climate simulation analysis with uncertainty-based diagnostics

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Introduction

Climate-modeling research has evolved toward ensemble-based studies with the aim of obtaining more robust climate change projections as well as an estimation of uncertainty. International collaborations led to multi-model ensembles concentrated on quantifying inter-model uncertainty for both GCMs and RCMs. At the same time, some regional modeling groups focused on smaller single-model ensembles to explore uncertainty sources that are specific to RCMs. For simulation-rich areas, it is possible to take advantage of valuable uncertainty estimates to design diagnostic tools that can be helpful in the interpretation of regional climate model outputs.

The development of these kinds of diagnostic tools is part of a general evolution towards a more mindful practice of regional climate modeling. At the stage of planning or analysis of climate simulations, such tools provide a practical way of examining the solidity of our working hypotheses.

Ouranos Regional Climate Modeling Framework

The basics…

- 30-year seasonal means for historical (1961-1990) and future (2041-2070) simulated climates
- Regional climate simulations with CRCM V4.2.0, CRCM V4.2.3 (de Elía and Côté, 2010) and CRCM V3.7.1 (Plummer et al., 2006)
- Most CRCM simulations are driven by CGCM3.1 member 4 (Scinocca et al., 2008)
- All simulations take into account IPCC SRES A2 GHG scenario
- Most CRCM simulations are on AMNO (201X193 pts) domain

The sensitivity experiments to …

- the initial conditions (internal variability estimate) ***"INT_VAR"***. Using CRCM4.2.0 with a 1-month lag initial time
- the lateral boundary condition nesting interval ***"LBC_UP"***. With CRCM V4.2.0 driven by CGCM3 available at every 12 hours vs 6 hours
- the driving GCM ***"GCM"***. With CRCM V3.7.1 driven by CGCM3.1 and CGCM2 (Flato and Boer 2001)
- the driving GCM member (natural variability of the driver) ***"GCM_M"***. With CRCM V4.2.3 driven by CGCM3.1 member 4 and 5
- the nudging technique ***"LS_NUDG"***. With CRCM V4.2.3 with and without spectral nudging
- the CRCM version ***"CRCM"***. With CRCM V4.2.3 vs CRCM V3.7.1 sharing the same driver
- the domain size ***"DOM_SZ"***. With CRCM V4.2.3 on AMNO grid (201X193 pts) vs QC grid (112 X88 pts)

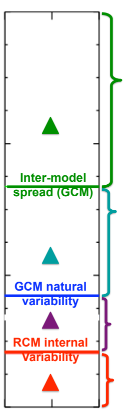
Uncertainty Scale Diagnostic based on physically meaningful thresholds in a regional climate modeling system

Definitions

Inter-model Spread (IMS):
Uncertainty estimate for the large–scale climate resulting from limitations in the representation and formulation of climate processes in GCMs. Varies according to location, variable and season.
(Derived from the IPCC AR4 SRES A2 18 GCM ensemble)

GCM Natural Variability (NV):
Estimate of the large-scale climate noise resulting from the chaotic nature of model equations. Below this threshold 2 GCM runs are considered identical. Varies according to location, variable and season.
(Derived from CCCma CGCM3.1 SRES A2 5 member ensemble)

RCM Internal Variability (IV):
Estimate of regional-scale climate noise resulting from the chaotic nature of model equations. Triggered by any modification to a regional climate modeling system. Varies according to location, variable, season, grid size and driving technique.
(Derived from Ouranos CRCM ensemble of 6 pairs of runs performed on AMNO grid with perturbed initial conditions)



Interpretation

IMS < Perturbation
- A climate change signal greater than IMS is stronger than the known uncertainty sources in a climate modeling system for a given GHG scenario.
- Suspicious zone for a perturbation between 2 RCM runs sharing the same driver. The relevance of such perturbation must be evaluated with extra diagnostics (validation, scale decomposition, added value, etc).

NV < Perturbation ≤ IMS
- Comfort zone for differences between RCM runs driven by different GCM.
- Suspicious zone for the response to a modification between RCM runs sharing the same driver. Such perturbation is comparable to what is expected from different GCM and its relevance must be assed by extra diagnostics.
- Danger zone for the response to a modification to a RCM configuration (e.g. grid size, driving technique, etc).

IV < Perturbation ≤ NV
- Zone were the difference between RCM runs is physically significant.
- Comfort zone for the response to a modification in a RCM configuration.
- Comfort zone for differences between RCM ensemble members.
- Exploration zone for regional-scale uncertainty for a given large-scale (same driver).

Perturbation ≤ IV
- Below this threshold, the difference between RCM runs is not physically significant.
- Comfort zone for modification to a RCM code with the objective to keep the same results (optimization).

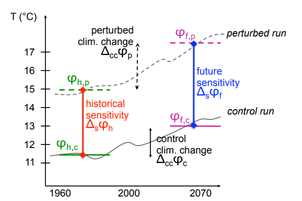
Climate and Climate Change Sensitivity Unified Diagram

A convenient ranking and visualization tool to evaluate how the modification of various parameters in a regional climate modeling system are projected on climate and climate change

Methodology

Each source of uncertainty can be analyzed using a set of simulations that produce four climates:

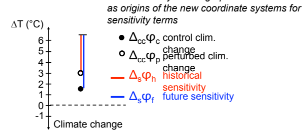
$\varphi_{h,c}$: historical control climate
$\varphi_{f,c}$: future control climate
$\varphi_{h,p}$: historical perturbed climate
$\varphi_{f,p}$: future perturbed climate



From these four climates, we can derive four results: impact of the source on historical and future climate, a control and a perturbed climate change. From the combination of these results, we can build two additional coordinate systems with:

$$\Delta_s\varphi_f = \Delta_{cc}\varphi_p + \Delta_s\varphi_h - \Delta_{cc}\varphi_c$$
$$\Delta_s\varphi_h = \Delta_{cc}\varphi_c + \Delta_s\varphi_f - \Delta_{cc}\varphi_p$$

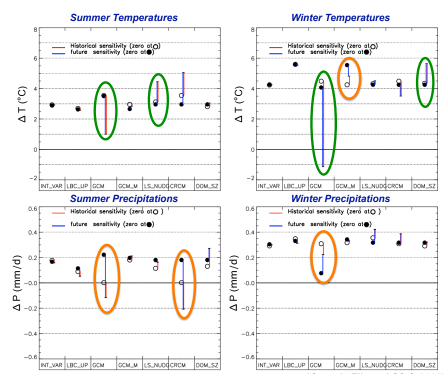
Plotted directly on the graph and then used as origins of the new coordinate systems for sensitivity terms



Results interpretation

(green circle) These uncertainty sources perturb historical and future climate in a similar way (sometimes strongly) resulting in negligible impact on climate change signal

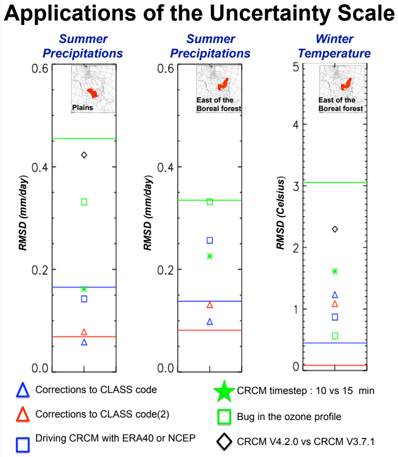
(orange circle) In these cases, the climate change is affected by the uncertainty source because the model response to the perturbation is quite different for the historical and future climate.



(from de Elia and Côté, 2010)

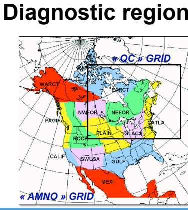
Climate and climate change sensitivity unified diagram of the East of the Boreal Forest for internal variability (INT_VAR), frequency of the lateral boundary condition update (LBC_UP), choice of the driving GCM (GCM), choice of the driving GCM member (GCM_M), large-scale nudging technique (LS_NUDG), CRCM version (CRCM) and the domain size (DOM_SZ)

Applications of the Uncertainty Scale Diagnostic



- Evolutive tool. Other uncertainty sources can be added.
- The quality of the uncertainty estimate improves the quality of the diagnostic...
- When comparing the response of the modification to the IV, NV and IMS levels, the physical meaning of these thresholds becomes instrumental in determining whether the amplitude of the response is consistent with the nature of the model modification.
- Provides a quantitative guidance for choosing an optimal RCM configuration (grid size, driving technique, driving intensity, etc.) for a regional climate simulation.
- Additional tool for bug detection.
- Complement to statistical testing
- Useful for the characterization of climate sensitivity to a parameter change.

Diagnostic regions



North American Climatic Regions for diagnostic purpose as defined on Ouranos regional integration domains
(from de Elia and Côté, 2010)

- Western Arctic (WARCT)
- Eastern Arctic (EARCT)
- Pacific Coast (PACIF)
- Rocky Mountains (ROCK)
- Western Boreal Forest (NWFOR)
- **Eastern Boreal Forest (NEFOR)**
- Coastal Atlantic (CATLA)
- Great Lakes (GLACS)
- **Great Plains (PLAIN)**
- Coastal California (CALIF)
- Southwestern USA (SWUSA)
- Gulf of Mexico Bassin (GULF)
- Mexico (MEXI)

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Conclusions

- **The reliability of the diagnostic tools increases with the quality of the uncertainty estimation**
- **These diagnostics provide a hierarchy of uncertainty sources in a regional climate modeling system. This hierarchy varies according to the variable, the season and the location.**
- **They contribute to the valorization of ad-hoc modeling experiments by integrating their results into daily operations.**
- **Beside the significance of the perturbation, uncertainty–based diagnostics give an insight on the relative amplitude of its response.**
- **Before using an ensemble of simulations, the unified diagram helps to figure out if linear assumptions required by some treatment (statistical downscaling, bias reduction, etc.) will be violated.**

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