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Two remarks on future developments of climate simulation, with strong impact on computing and data processing

Jean-Claude André, EESI2/WCES Co-chairman, Toulouse

Toward the numerical convergence of climate simulations

One of the most pressing questions facing numerical simulation of climate is concerned with the representation of thermal convection: energy is transferred from the lower to the upper layers of the atmosphere, especially via clouds and large convective systems. As most of these convective phenomena take place at a scale significantly smaller than the climate model grid, the necessary «subgrid scale parametrizations» are still a major source of uncertainties affecting the results of climate models. A necessary path for solving this issue will consist in running climate simulations with a grid size small enough, so that convection parameterizations are no longer crucial, and possibly no longer necessary! An estimate for this physical threshold is thought to be a grid size slightly smaller or equal to *ca.* 1 kilometer.

One will then be in a position to mathematically address the fundamental question, *i.e.*, whether or not the grid size of the numerical model is small enough so that the model results have *converged numerically*? The simulations results should indeed remain mostly unchanged for grid sizes still decreasing under some critical grid size, obviously smaller than the physical grid size threshold of 1 kilometer. This is a usual issue when addressing problems from an applied mathematical point of view.

Up to now very few climate modelers have addressed this problem. For example, climate models aimed at simulating cyclonic activity, either for the present climate or for future climate with increased greenhouse gases concentration, do exhibit *unstable* results, where unstable means that the number of tropical cyclones, and their intensity, varies non-uniformly and unexpectedly when considering models run with smaller spatial resolution. A large number of such examples can be found in the scientific literature. It is only recently that the first serious attempt to overcome this issue has been tried (Fig. 1, from Strachan *et al.* 2013).

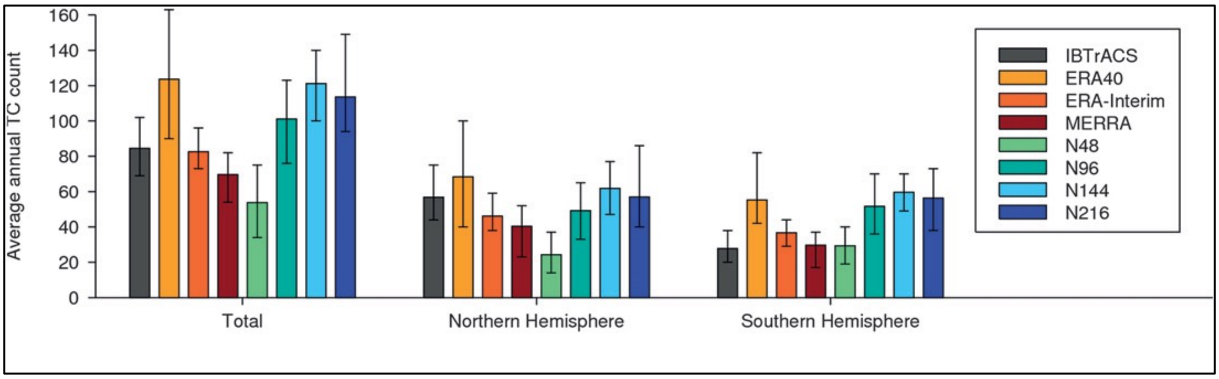

Figure 1: An example of preliminary convergence of climate model results (annual number of tropical cyclones) as a function of spatial resolution, when decreasing the grid size from 270 km (N48) to 135 km (N96), 90 km (N144) and finally 60 km (N216).

Of course, when it will be possible to start checking numerically whether or not the mathematical convergence of climate simulations has been reached, the demand for computing time will increase massively.

From climate *predictions* to climate *forecasting*

Climate evolution is driven by both anthropogenic forcing (greenhouse warming) and by natural fluctuations. Most of the work done up to now has been devoted to improving the description of greenhouse warming and to evaluate its impacts. On the other hand natural climate variability is driven, among others, by oceanic fluctuations which take place in the Atlantic and/or in the Pacific, with characteristic time-scales of a few years to a few decades.

Besides improving the description of greenhouse-induced climate change and its course over the next decades and centuries, what we call climate *predictions*, it will be more and more important to *forecast* what detailed climate will occur in 5 years, or 10 years, of 30 years in the future, because such climate characteristics are crucial for planning most of the industrial and societal activities.

What will be required for *forecasting* climate over yearly-to-decadal time scales?

- As for meteorological forecasting, where the detailed description of the initial state of the atmosphere is of critical importance, *forecasting* the climate will require an adequate description of the initial state of the natural fluctuations, *i.e.* a detailed description of both the atmospheric and, more importantly, oceanic states. This implies processing a much larger amount of data as compared to what has been done up-to-now;
- Data assimilation will also be needed, as the initial state of the climate, both in the ocean and in the atmosphere, must be compatible with the coupled ocean-atmosphere model that will be used to *forecast* future time steps. Much larger computing resources for optimizing the initial climate state wrt the coupled ocean model will be crucially needed. It should, *e.g.*, be recalled that in actual numerical meteorological forecasting, the computing resources devoted to defining an adequate initial state through data assimilation is significantly larger that the amount of resources needed for advancing in time from this initial state;
- Assuming that the above two requirements are correctly satisfied, the societal demand will increase for performing regularly updated climate *forecasts*, *e.g.*, monthly for multi-year forecasts and at least yearly for multi-decadal forecasts.

Quite obviously, entering the climate *forecasting* era, which might happen quite soon, will require an increase of one order of magnitude, or more, for data processing capacities and for computing resources as compared to the actual state of climate modeling.

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Reference

Strachan, J., P.L. Vidale, K. Hodges, M. Roberts et M.E. Demory, 2013, Investigating global tropical cyclone activity with a hierarchy of AGCMs: The role of model resolution. *Journal Climate*, **26**, 133-152.