Report from Working Group 1

What are the sources of model error and how can we improve the physical basis of model uncertainty representation?

Group Members

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The aim of Working Group 1 (WG1) was to identify the key issues and recommend priorities for future research directions for ECMWF and the wider research community to understand the sources of uncertainty and improve the representation of uncertainty in models. This summary provides a brief record of some of the main points discussed by the Working Group and the recommendations that came out of the discussion, structured around four questions:

(1) What are the sources of model uncertainty?

(2) What are the characteristics of error growth/scale interactions?

(3) How can we improve the physical basis of model uncertainty representation?

(4) How can we enhance collaboration across the research community?

1) What are the sources of model uncertainty?

- There are various sources of uncertainty in models that can result in model error, arising from spatial and temporal truncation errors, and limitations of our knowledge of physical processes across the “Earth system” (atmosphere, ocean, land surface, sea-ice, atmospheric composition).
- Model error is dominated by the representation of physical processes (e.g. boundary layer turbulence, surface coupling, cloud microphysics, cloud-radiation interaction, aerosols, convection gravity waves, surface drag), but we shouldn’t neglect the uncertainty in the dynamics. Convective processes are a prominent source of model uncertainty due to strong non-linearities and upscale growth.
- Parametrization errors can arise from structural uncertainty (incorrect, or partial representation of the equations needed to describe the evolution), parameter uncertainty, and truncation errors. Errors can be thought of as either "systematic" or "random/intrinsic". Systematic errors are often related to particular meteorological regimes (i.e. due to regime-dependent errors in the physics which directly affect the meso/synoptic scales), whereas intrinsic errors can be considered to be due to upscale growth of uncertainty at the small scales, missing degrees of freedom and truncation errors. The former are visible in a deterministic forecast and have scope to be reduced by model improvements, the latter will always require stochastic perturbations in an ensemble. However, it can be very difficult to define and separate these different sources of error in models. Systematic errors may also be due to the non-linear response of the system to random perturbations. Regime-dependent systematic parametrization errors may appear as random error over some space or time scale due to the varying meteorological regimes.

- In practice it is difficult to disentangle different sources of model error (systematic error versus random error, truncation error versus physical process uncertainty, structural error versus parameter uncertainty) and model uncertainty schemes need to represent all these sources of error. Efforts should continue to try to define the different sources so that they can be represented more effectively. This will require different techniques such as coarse-graining studies, and sensitivity experiments to determine the most influencing parameters and terms in the equations. Multi-model/physics ensembles can provide improved spread in some situations – can we learn about structural errors from these?
- Data assimilation provides valuable information on model error in the short range and this should be exploited much more systematically.

Recommendations

1. *WG1 recognises the potential benefit of diagnosing model error from data assimilation, and recommends further work to understand the relationships between the representation of model error in the data assimilation system and the underlying dynamical and physical processes.*
2. *WG1 recommends that sensitivity/coarse-graining studies using convective-scale observations and models should continue to be pursued as they have further potential to inform model uncertainty representation and identify the most important processes.*
3. *WG1 recommends that sensitivity experiments of existing model uncertainty schemes (e.g. SPPT) should continue to be pursued as they have further potential for learning about the representation of model uncertainty (not just a tuning exercise).*
4. *WG1 recognises that multi-model/multi-physics-based ensembles can still add value for model uncertainty representation, particularly in the short-range, and recommends comparing different models to understand/inform how to better represent structural errors in model parametrizations.*

2) What are the characteristics of error growth/scale interactions?

- Representing uncertainty is not just a truncation/parametrization problem – we need to consider how errors propagate through the system.
- Some large scale errors are the result of small-scale errors that have propagated upscale, and some model errors are intrinsically large-scale in nature (e.g. due to regime-dependent systematic errors in parametrizations).
- To what extent do large-scale errors need to be represented at the small scale and propagated through the same processes, or can their large-scale effect be directly simulated as large-scale perturbations (for example, as suggested by the large spatial and temporal decorrelation times in SPPT)?
- Identification whether the errors are from small or large scales can help in targeting the latter where there is larger potential of improvement, compared to the former which may have already hit their intrinsic limit. Possible double counting should be avoided.
- The idea that the -5/3 energy spectrum, as emerged from observations (e.g. Nastrom and Gage), has an important role in getting correct error growth and in responding to stochastic perturbations was discussed. It is of course good to have the correct spectrum but the mechanisms responsible for the -5/3 mesoscale energy spectrum are not fully understood, so it is not clear whether a failure to represent this spectrum is associated with incorrect error growth.

- Is the -5/3 slope universal? Probably not in all regions, e.g. the tropics. The -5/3 spectrum may be a universal property of the system or it may be due to multi-scale interactions. What processes set this slope in the atmosphere – 3D turbulence, gravity waves, convection, orography? What processes set the slope in models – numerical schemes, physical parametrizations and their interaction with the dynamical core? Just because a model has the -5/3 spectra does not necessarily mean it is there for the right reasons.
- Some models represent the -5/3 spectra and some do not. The importance of capturing the correct spectrum could be examined by running two models with and without this spectrum and investigating the error growth from the same stochastic perturbations applied at varying scales.
- There are also scale interactions between land/ocean/atmosphere on different space and time scales which are not well understood and further work is required here.

Recommendations:

5. *WG1 recommends that model experiments are designed and performed to determine how error growth characteristics are captured, using models that do and do not represent the -5/3 spectra, and across different model resolutions (down to convective resolving scales).*
6. *WG1 recommends further analysis of observed atmospheric spectra to determine how universal the -5/3 is or how spectra vary with location, latitude, height, meteorological regime etc...*
7. *WG1 recommends exploring the importance of interactions within and between the uncertainty in various components of the Earth System with different error growth time scales (e.g. importance of resolving mesoscale eddies in ocean models versus stochastic representation of mesoscale eddy processes).*

3) How can we improve the physical basis of model uncertainty representation?

- WG1 discussed what "physically based" actually meant? One interpretation is a model uncertainty representation that is free from tunable parameters, instead based on universal properties that can be defined in some way from observations (e.g. are the dominant synoptic scale spatial patterns of perturbations used in SPPT intrinsic to all models, and if so, why?). An alternative interpretation is a representation of model uncertainty that is close to the relevant phenomena or processes (e.g. stochastically perturbed parameter (SPP) approach or stochastic convection schemes). "Physical consistency" is a different term that could be used. For example, tapering of the SPPT perturbations to zero in the boundary layer in the IFS is done for practical reasons and is not physically consistent with the perturbations in the rest of the column.
- Previous workshops have recommended building representations of uncertainty into the model physics parametrizations (e.g. stochastic convection schemes). We still think this is a priority, but benefits will only be realised if other parts of the model it interacts with are good enough. Model uncertainty is not just a parametrization problem; it also depends on, for example, upscale growth, scale interactions, dynamics and numerics.
- An improved physical consistency will need to address the different sources of model error as directly as possible and will likely consist of a combination of a number of approaches (e.g. representing subgrid-scale uncertainty, physics parameter uncertainty, uncertainty in all the components of the Earth system). We expect there will always be some uncertainty that we don't know how to represent explicitly.

- Stochastic advection (e.g. by a velocity containing a Brownian component with spatial correlations) is an example of how the dynamics and physics can be considered self-consistently. It potentially addresses two aspects of model error below the truncation scale: advective transfer by stochastic flow, and uncertainty and approximations in the physical parametrizations on the sub-gridscale flow.
- In many models there is missing smaller scale variability in the ensemble of near-surface parameters, which are important for forecast users (e.g. 2m temperature). Perturbations to soil moisture could be explored, or parameters in the land surface model, such as coupling coefficients or soil characteristics. Surface model perturbations could address the fast-coupling processes first, which should be climate neutral, but other perturbations may also be required to represent longer timescale uncertainties.

Recommendations

8. *WG1 recommends to continue working on improving the physical basis and physical consistency of model uncertainty representation, but it needs to be considered in the context of the whole ensemble prediction system and on improving our understanding of all the sources of model uncertainty, such as physics, dynamics, numerics and multi-scale interactions.*
9. *WG1 recommends investigation of stochastic advection processes to represent the advective transfer by stochastic flow below the truncation scale in models.*
10. *WG1 recommends a more concerted effort to improve the ensemble spread of near-surface fields, which are important for forecast users.*

4) How can we enhance collaboration across the research community?

- WG1 discussed how research in the area of model uncertainty could be enhanced by increased collaboration between the NWP community and the academic community.
- Specifically for ECMWF, links with the academic community are good, for example through the OpenIFS initiative, the ERA reanalysis projects or TIGGE datasets. These play a very important role in stimulating research. Links could be strengthened to enhance collaboration for mutual benefit, realising that this takes investment of time on both sides.
- Personal contacts are very important to facilitate collaboration, either through meetings and workshops, scientific visits (in both directions), joint research projects or PhD students.
- Improved representation of model uncertainty needs to be explored in an ensemble context, but it is difficult to run the ensemble system outside of an NWP centre and this needs to be made easier to encourage research.
- Model uncertainty is more than a parameterization problem – it includes dynamical meteorology, physical processes, numerics, and mathematics including stochastic methods. It is therefore a topic that would benefit from a range of ideas from different disciplines. The research community should be exploring alternative well-founded approaches to representing model uncertainty.

Recommendations

11. *WG1 recommends that ECMWF continues with and enhances collaboration with external researchers.*
12. *WG1 recommends that ECMWF consider how to facilitate access to the ensemble prediction system (ENS) for external researchers, so that modifications can be made without intensive ECMWF staff support and so that evaluation can be done more easily outside ECMWF or within a Special Project.*
13. *WG1 recommends that WWRP/WCRP and other organisations include model uncertainty as a topic in future meetings, to gain expert input, to focus interest and foster collaboration.*