Empirical studies of unobservable parameters

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Note: this document briefly summarizes the presentation made at the workshop, which can be viewed on the Web at http://www.cdc.noaa.gov/~bem/ECMWF2001.htm.

1. The role of observations in the problem of unobservable parameters

Parameterization schemes for unresolved and diabatic processes reside deep inside atmosphere models, where their control parameters act as a major source of uncertainty in forecasts and simulations. The values of some parameter values can be directly observed, or at least locally sampled, in nature (e.g., particle size distributions). However, many others cannot, and these unobservable (often called 'free' or 'disposable') parameters typically form the weakest links in the chain of parameterization efforts.

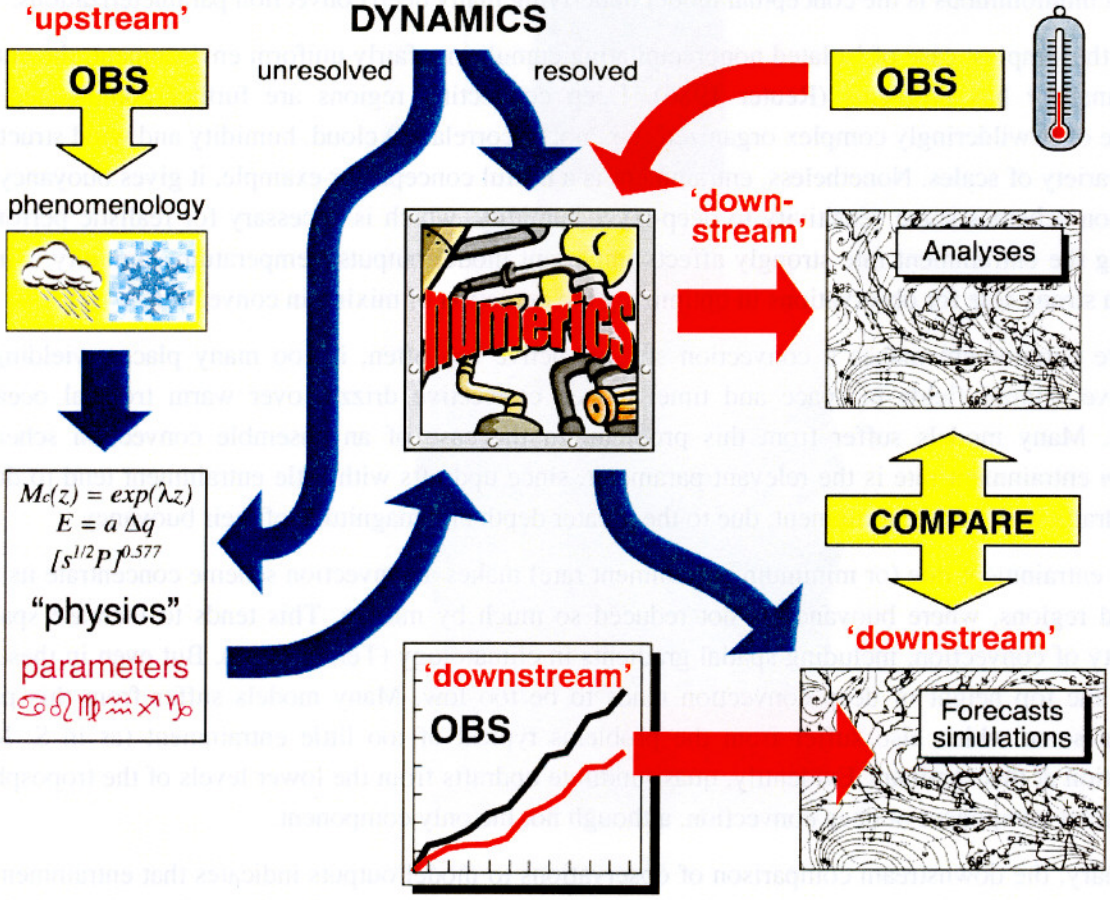

Figure 1: Schematic of the parts of a model, the upstream and downstream roles of observations, and the unobserved realm where parameters lurk.

The role of observations in constraining unobservable parameters is necessarily indirect. The most obvious approach is to find out what effects a parameter has on model outputs, and then choose a value which maximizes agreement with observations. This will here be called a "downstream" role for observations, because the data-model comparison takes place after the parameterized model equations are integrated forward in time.

Observations also have a crucial, if more qualitative, "upstream" role in parameterization efforts: they form the basis for phenomenological pictures, conceptual models, and detailed schematics underlying the equations behind parameterization schemes. The process of conceptual model development is complex and cultural, so this is a thoroughly humanistic area of knowledge. The complexity of conceptual models is derived more from the dimensionality of our minds than from the true dimensionality of the processes being parameterized. Cultural influences include inherited prejudices from the field's historical roots in exact sciences, and reverence for charismatic pioneers. The key observations in this upstream role may be very simple, e.g. visual impressions, although these are often bolstered after the fact by more "scientific" data analyses.

Example 1: Entrainment rate in convection schemes

Entrainment rate is unobservable, in the sense that it is well defined only with respect to an extremely idealized conceptual model: a well-mixed "cloud" rising in a homogeneous "environment." This idealization was based on the resemblance of cumulus clouds to laboratory plumes. However, most deep convection is organized on the mesoscale, obscuring visibility. Despite its unrepresentativeness, the visually appealing isolated cumulonimbus is the conceptual model underlying many deep convection parameterizations.

Even in the simplest case of isolated nonprecipitating cumuli in a fairly uniform environment, the entraining plume analogy has problems (Reuter 1986). Deep convecting regions are further complicated by the existence of bewilderingly complex organized (i.e., not uncorrelated) cloud, humidity and wind structures on a wide variety of scales. Nonetheless, entrainment is a useful concept: for example, it gives buoyancy-driven convection schemes some sensitivity to deep-layer humidity, which is necessary for realistic performance. Changing the entrainment rate strongly affects important model outputs (temperature, humidity, winds), so there is a strong role for observations in optimizing the depiction of mixing in convection.

Too little entrainment makes a convection scheme active too often, in too many places, yielding bland convective rainfall fields in space and time – deep convective drizzle over warm tropical oceans, for example. Many models suffer from this problem. In the case of an ensemble convection scheme, the *minimum* entrainment rate is the relevant parameter, since updrafts with little entrainment tend to dominate over updrafts with more entrainment, due to the greater depth and magnitude of their buoyancy.

A larger entrainment rate (or minimum entrainment rate) makes a convection scheme concentrate its activity in humid regions, where buoyancy is not reduced so much by mixing. This tends to increase space-time variability of convection, including spatial gradients in climatology (Terray 1998). But even in these humid regions, the top height of deep convection tends to be too low. Many models suffer from this problem, including some which also suffer from the problems typical of too little entrainment (as in S. Milton's presentation at this seminar). Evidenttly, quasi-undilute updrafts from the lower levels of the troposphere are an important component of deep convection, although not the only component.

In summary, the downstream comparison of observations to model outputs indicates that entrainment rate is simultaneously too large and too small. This seems to indicate that the entraining plume formulation itself may have some problems, i.e. that progress may require observation-driven improvements at the upstream end: devising new conceptual models.

My current effort is to formulate a discrete mixing process that captures the important restraining effect of environmental dryness on the development of convection, while permitting the convection, when present, to transfer substantial amounts of mass vertically without excessive dilution. One idea is "successive entrainment," which attempts to retain existing entraining plume concepts (and code) as much as possible.

This idea springs from visual impressions of the gradual but vigorous development of convection one night on a research cruise in the northeast Pacific ITCZ. After my duty shift ended at 0300 LST I retired to the upper deck to unwind in warm breezes under a beautiful full moon. Cumulus clouds were growing, and where several would happen to gather, the central region would ascend to higher altitudes. The image resembled a sphinx, with the head rising above the paws and haunches, and this image outweighs any objective data analysis or printed literature in my mind.

On the other hand, the formal idea of successive entrainment came much later, when I was struggling to devise a mixing scheme that produces an appropriate amount of middle-topped cumulus congestus convection, observed in nature (Johnson et al. 1999) but difficult to explain in terms of a parcel buoyancy, which tends to increase rapidly in the middle troposphere in calculations using observed soundings. The benefits of such a scheme to large-scale simulations might be far-reaching, as explored in examples 2 and 3 of the presentation.

Example 2: convection, clouds and radiation interacting

Lee et al (2001) performed aqua-planet GCM experiments and found that excluding the effects of cloud-radiation interaction dramatically changed the character of the model's subseasonal tropical variability. Several unobservable parameters conspire to produce this result: entrainment, as discussed above; but also parameters governing bulk cloud microphysics, partial cloudiness, cloud overlap, cloud optics, and radiation.

Closer examination suggested that all the cloud-radiation parameters largely act as one degree of freedom: the total amount of radiative heating per unit latent heating. The vertical heating profile of the model's tropical convective disturbances was remarkably similar in all experiments, as changes in cloud-radiation effects were compensated by changes in the profiles of convective heating and large-scale condensation. This universal total heating profile is likely set by the profile of destabilization averaged over a large region (perhaps the whole tropics). This destabilization is the difference between the profile of radiative cooling and the profile of surface-based heating ("shallow convection", including dry convection and precipitating cumulus congestus).

Downstream comparisons of the model to observations in this cloud-radiation area lead, as in the entrainment example discussed above, to contradictory conclusions. On the one hand, weaker cloud-radiation interaction leads to arguably more realistic intraseasonal variability. On the other hand, this weakened cloud-radiation interaction destroys the model's (tuned) planetary radiation balance. Although there are many parameters which may be adjusted to change the cloudiness and its radiative impacts, they are largely redundant, while something is apparently flawed with the simuations at a deeper level.

The heating profile in this model's disturbances is found to be insufficiently top-heavy, compared to the heating profile of deep convecting regions on Earth. Apparently this is because the model lacks sufficient heating by shallow convection, which must be taken to include condensation heating in middle-topped precipitating cumulus congestus clouds. If the formulation of entrainment controls congestus convection, as discussed in the previous section, then it may hold the key to the next step in this model's improvement – but in a very indirect way. Shallow precipitating convection is broadly distributed in space and time (Short and Nakamura 2000), so it is not locally a very important effect in the dynamics of this model's deep convective disturbances. Nonetheless, it may play a leading role (through the mean tropical destabilization profile) in determining their net heating profile, and thus their dynamics.

Example 3: when the numerics intervene in model performance

This hypothesized role of congestus clouds in a GCM's tropical dynamics is supported by the recent work of Inness et al. (2001; see also J. Slingo's contribution to this seminar). However, in that case, a numerical artifact – the computational mode of the Lorenz vertical grid staggering (Arakawa and Konor 1996) – appears to mediate the key interactions among the physical parameterizations. This example is raised as a cautionary tale: there may be unobservable parameters in model numerics (if grid-staggering assumptions may be though of as "parameters") with an important role in determining the outcomes of model integrations. Should these be optimized (i.e., accepted and utilized)? Or should they be rooted out through redesigns? In any case, it is a fact of life that there is more to a numerical model than the continuous PDE's it is nominally meant to solve.

2. Final thoughts: appropriate complexity in models and parameterization schemes.

As these examples show, there is a lot of room for mischief, nonsense, redundancy or obfuscation in the set of unobservable parameters. The size of this set is as large as the sum of all the complexities that designers of individual model components dare (or presume) to try to represent. This tends to be quite large, with some parameters like entrainment playing leading but not utterly dominant roles.

Ideally, the set of physical parameterizations in a model would interact in a way resembling the interactions of the corresponding processes in nature. In practice, unless these inter-scheme interactions are not only designed but also carefully diagnosed and checked, they tend to be misrepresented. Complexity itself presents a considerable barrier to such diagnosis and design, raising the possibility that our most complex models may not be the best ones.

Designing inter-scheme interactions requires a good functional grasp of each scheme's sensitivities and impacts, which are sometimes difficult to glimpse through layers of mechanistic complication. In some cases sophisticated parameterizations produce repetitious, inadequately diverse or too-regular behaviour (such as deep convective drizzle, example 1). Could it be that toy-like parameterizations – simple algorithms designed to have desired sensitivities and outcomes, perhaps even with random number generators operating within them – might improve models? If so, will the sense of credibility attached to the "serious" science of modeling be eroded?

Sometimes there is redundancy and compensation among several parameters (e.g. among convective heating, large-scale condensation, partial cloudiness, cloud overlap, optics and radiation in example 2). Can these all be separately and meaningfully compared against observations, or is this complex litany of "important effects" obscuring simpler underlying dynamics? If so, would it be better to fit these simple dynamics with a simple model, or try to capture them with an exhaustive physically elaborated model? The answer depends on one's purposes, budget, time horizon, and stomach for complication and detail.

3. References

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