Analysis of the Numerics of Physics-Dynamics Coupling[i]

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Physics parametrization packages are key elements in the success of numerical weather and climate prediction models. The accuracy and complexity of these schemes continues to increase apace. Similarly, the accuracy of dynamical cores has continued to steadily improve. However, a chain is only as strong as its weakest link, e.g. two 2nd-order components coupled in a 1st-order manner imply a 1st-order model. The link coupling the physics package to the inviscid, adiabatic dynamical core has received little attention. It is therefore important for the continued improvement of models that the virtues and vices of the various strategies employed in such coupling are well understood, and that the vices are addressed.

However, in a model there are several distinct processes (e.g. the dynamical core and each component of the physics package) each with their own timescale(s). The use of an implicit scheme to solve simultaneously for the time tendency of the complete model, though appealing, is currently prohibitively expensive, at least in an operational setting, and is likely to remain so for the foreseeable future. This is because of the expense of solving a modified Helmholtz problem which consists of contributions from both the dynamics *and* the physics package. The solution is to apply some form of splitting in which the time tendency due to the different elements of a model are evaluated separately, and then combined in some way to generate the complete model tendency. All operational models employ some form of splitting. The problem is that splitting in general introduces errors additional to the truncation errors associated with each individual process. With large timesteps, of the size permitted by semi-implicit semi-Lagrangian schemes, such errors can dominate the model error. The question is therefore: "How to determine the optimal way of performing such splitting?"

A methodology for analyzing the numerical properties of such splitting schemes is developed in Staniforth et al. (2002*a*) and Staniforth et al. (2002*b*). A canonical problem is introduced to idealize both the dynamics (with terms to represent both fast and slow propagating modes), and the parametrizations of fast and slow, oscillatory and damped, physical processes. It permits the examination of a broad set of physics-dynamics coupling issues, whilst keeping the analysis tractable. Any given coupling scheme can be assessed in terms of its numerical stability and of the accuracy of both its transient and steady-state responses.

For the reasons discussed above, fully implicit coupling is impracticable, as is fully explicit coupling due to timestep restrictions. A popular approach is "split-implicit" coupling in which a dynamics predictor is followed by a physics corrector. It addresses the stability issue of an explicit coupling whilst keeping the physics discretization distinct from the dynamics discretization. However, using the framework of Staniforth et al. (2002*a*) and Staniforth et al. (2002*b*), it is found that the steady-state solution is corrupted and the forced response can be spuriously amplified by an order-of-magnitude. This motivated the "symmetrized split-implicit" coupling in which two physics discretizations are arranged symmetrically around a dynamics sub-step. The analysis shows that this addresses the stability and accuracy deficiencies of an explicit coupling whilst still correctly representing the exact steady-state solution for constant forcing. It also keeps the physics discretization distinct from the dynamics one. It partially shares the disadvantage of the fully implicit model inasmuch as the second physics sub-step is an implicit discretization of the highly nonlinear physics. However the usual column-based physical parametrizations are such that the discrete set of nonlinear equations can be solved column-by-column, greatly reducing the computational cost.

This early work was done in the context of a physics package comprising only one component. In a typical model, however, there are at least four distinct components, each with different characteristics. The work of Dubal et al. (2004) and Dubal et al. (2005) therefore extends the above-described framework to examine the coupling of a mix of physical parametrizations of various damping and oscillatory processes associated with a range of timescales. Various coupling strategies have been examined but none has been found which performs uniformly well. Only rather general conclusions can be drawn. For example, there are two generic splitting schemes: sequential-splitting, in which the model's tendency is updated sequentially using the tendency due to each physics component in turn; and parallel-splitting, in which the model's tendency is updated simply by summing, independently, the tendencies of each physics component. It is found that sequential splitting is more flexible in its ability to eliminate splitting errors than parallel splitting. A disadvantage is that the sequential approach is sensitive to the order in which the physics components are applied. In practice a mix of sequential schemes for the fast timescale physics, and parallel schemes for the slow timescale ones, appears to optimize the overall coupling strategy. It is then found that the slower processes, such as radiation, should appear near the centre of the timestep, with the faster processes, such as boundary layer diffusion, coupled implicitly at the end of the timestep.

The framework of Staniforth et al. (2002*a*) and Staniforth et al. (2002*b*) can also be used to analyze the problem of spurious computational resonance in a semi-implicit semi-Lagrangian model. Traditionally, this has arisen in the presence of stationary spatial forcing, specifically that due to orography (Rivest et al. 1994). In this case, spurious resonance is absent when a Courant number restriction on timestep is satisfied. Staniforth et al. (2002*a*) show that time-dependent forcing, such as that due to the physics package, can also give rise to spurious resonance. Importantly though, the Courant number limitation on the timestep is then twice as restrictive as that for stationary forcing, thereby exacerbating the problem of spurious computational resonance with long timesteps.

References

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