Beyond the Budget Lifetime: Diagnosing Chemical Perturbation Lifetimes in GEOS-Chem from the Jacobian Eigenmodes



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The chemical lifetime of an atmospheric constituent is conventionally defined as its burden divided by its instantaneous gross loss rate. This "budget" lifetime is cheap to calculate and easy to explain, but it treats each constituent in isolation and so does not capture the timescale on which a perturbation to the coupled chemical system decays. This is why we think in terms of the O_x rather than the O_3 lifetime, and why the perturbation lifetime of methane is significantly longer than its budget lifetime. Prather (1994) showed that the decay of a chemical perturbation can be calculated from an eigenmode decomposition of the chemical Jacobian, but this approach has seen limited use as a routine diagnostic within chemistry models.

Here, we apply it within the GEOS-Chem chemistry transport model. For every grid box and timestep, we archive the chemical Jacobian (a 334 × 334 matrix whose element $J_{XY} = \partial(d[X]/dt)/\partial[Y]$ is the instantaneous sensitivity of the chemical rate of change of species X to the concentration of species Y) and perform an eigenmode decomposition. This gives a temporally and spatially resolved perturbation lifetime for each constituent. Globally, budget and perturbation lifetimes are similar for most species but differ for some key ones. The tropospheric CH_4 perturbation lifetime is ~40% longer than its budget lifetime, consistent with explicit CH_4 pulse studies, and the tropospheric CO perturbation lifetime is ~20% longer. The O_3 perturbation lifetime is ~300 times longer than its budget lifetime, but shorter than the budget lifetime of the O_x family, again consistent with previous pulse studies The same framework yields further diagnostics. The O_3 and OH produced by perturbations to NO and ALK4 (a lumped $\geq C_4$ alkane) allow the VOC/NO_x limitation of the atmosphere to be diagnosed directly from the model.

The Jacobian and its eigenmodes therefore encode the coupling and feedbacks between species that budget diagnostics miss. Applying the same metrics to box models and other chemistry transport models may provide a common basis for explaining why models differ and for identifying routes to improvement.

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Zoom Link (Mixed-mode)

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