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A nonlinear technique to identify optimal model errors

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We propose a nonlinear forcing singular vector (NFSV) approach to infer the effect of nonlinearity on the predictability associated with model errors. The NFSV is a generalization of the forcing singular vector (FSV) to nonlinear fields and acts as a tendency perturbation that results in a significantly large perturbation growth. In predictability studies, the NFSV, as a tendency error, may provide useful information about model errors that cause severe prediction uncertainties. In this paper, a two-dimensional quasi-geostrophic (QG) model is used to study NFSVs and make a comparison between NFSVs and FSVs. We choose two basic flows: the first is a zonal steady flow (Ref-1), and the second is a meridional steady flow (Ref-2). The results demonstrate that the corresponding NFSVs contain a phase where the perturbation stream function tends to be contracted around regions of strong velocity shear. Furthermore, the NFSVs for the Ref-1 tend to have a meridional asymmetric spatial structure. Due to the absence of nonlinearity, FSVs tend to have a larger spatial extension than NFSVs; in particular, the FSVs for the Ref-1 are almost symmetric in the perturbation stream function. The prediction errors caused by FSVs in the nonlinear QG model are generally smaller than those caused by FSVs in the linearized QG model; therefore, the nonlinearity in the QG model would significantly saturate the perturbation growth. Nevertheless, the prediction errors caused by NFSVs (especially for the Ref-1) in the nonlinear QG model are larger than those caused by FSVs, which further implies that the tendency errors of NFSV structures tend to reduce the damping effect of the nonlinearity on the perturbation growth and are more applicable than those of FSV structures to describing the optimal mode of the model errors. The differences between NFSVs and FSVs demonstrate the usefulness of NFSVs in revealing the effects of nonlinearity on predictability. The NFSV may be a useful nonlinear technique for exploring the predictability problems introduced by model errors.