

Predictability Studies Using Adjoint Methods

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LONG-TERM GOAL

The goal of this research is to increase our understanding of the theoretical and practical limits on atmospheric predictability to guide the development of new strategies for observing and utilizing data in an optimal manner, including defining the scientific principles for the development of an adaptive observation capability for the Navy's environmental prediction systems. In principle, this adaptive approach could revolutionize the methodology for determining initial conditions for numerical environmental prediction by coupling the data assimilation process interactively to the observation process.

OBJECTIVES

The objective of this research is to investigate the origin and growth of amplifying disturbances that profoundly influence atmospheric predictability in the 1-3 day time range using adjoint and singular vector methods. Increased understanding of rapid error growth is essential for identifying and controlling structures in forecast initial conditions that lead to large forecast errors, exercising intelligent control of our environmental observing systems, and improving methods of data assimilation. These objectives include the development and use of adjoint- and inverse-based tools to diagnose rapidly growing analysis errors in a post-time setting, which may have applications for real-time analysis corrections. The improvement of forecasts of high-impact weather, including landfalling tropical cyclones, is a major focus of this work.

APPROACH

The adjoint operator of a numerical weather prediction model is the key tool for studying atmospheric predictability on time scales of 1-3 days. The adjoint provides an efficient means of identifying regions of strong initial condition sensitivity for a particular forecast situation. The output fields from the adjoint model can be interpreted as 'sensitivity patterns' which identify the structures in the initial conditions that produce the maximum changes over the forecast trajectory. These patterns, and the closely related singular vectors of the tangent linear forecast model, are used to diagnose systematic errors in the current data assimilation scheme, determine optimal locations and required accuracy of in-situ and remotely sensed data, and improve estimates of key analysis error statistics.

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WORK COMPLETED

- (1) Predictability and targeted observing studies involving extensive experimentation with geostationary satellite wind data from the North Pacific Experiment (NORPEX) have been completed. Using the Navy Operational Global Atmospheric Prediction System (NOGAPS) forward and adjoint modeling systems and data assimilation scheme, we addressed the question of whether a particular component of the satellite analysis changes (increments) could be identified as having produced the majority of the forecast improvement, and what implications the results might have for targeted observing and the design of future observing systems.
- (2) The relationships between singular vectors (SVs) and transient features in the background flow were examined through both composite techniques and case studies using NOGAPS SVs and NOGAPS 48hr forecasts and analyses during the NORPEX period. The primary motivation for this work is to try to reconcile perceived differences between the adjoint- and potential vorticity- (PV) based paradigms for atmospheric perturbation growth.
- (3) The relationship between transient and asymptotic instabilities in nonlinear, time-dependent flows was examined in the context of a quasi-geostrophic model. Transient and asymptotic instabilities were represented in terms of the model SVs optimized to grow for 24 hrs and 40 days, respectively. The initial-time, leading 40-day SVs were used as proxies for the leading forward Lyapunov vectors (LVs), following Reynolds and Errico (1999). Our focus was on characterizing the time-dependent structure of the leading LV and ascertaining whether its evolution, and, in particular, significant variations in its incremental growth rate, may be linked to transient instabilities of the time-dependent basic state. The establishment of a linkage between these two types of instability properties will provide a more complete description of dynamical system behavior.
- (4) The formulation and initial testing of singular vector calculations that use NAVDAS estimates of analysis error variance as a metric, or norm, at initial times has been completed. These variance-based singular vectors (VARSVs) are designed to reflect more accurately the true probability distribution of rapidly growing analysis errors compared with singular vectors based on a total energy norm (TESVs).

RESULTS

- (1) The large positive impact of assimilating geostationary satellite wind data during the NORPEX period results mainly from the reduction of analysis errors that project onto the leading singular vectors derived from the linearized forecast model. These errors account for only a small fraction of the total analysis error and, during NORPEX, were confined mostly to the middle and lower troposphere with maxima over the central Pacific. These errors do not necessarily coincide with the locations of the largest analysis errors. Experiments in which the satellite information is retained only at prescribed vertical levels in the analysis confirm that the increments in the middle and lower troposphere account for most of the forecast impact.
- (2) Both composite results and case studies reveal significant spatial relationships between the SVs and transient features in the background flow. The SV perturbations often occur below distinctive high-PV features in the middle-to-upper troposphere. Case studies reveal that the SVs propagate upward rapidly, have two distinct growth phases and have a large impact on these PV features through

the end of the optimization interval. The SV perturbations, while scaled to have a very small impact on the temperature and wind fields, have a very large impact on the mid-tropospheric quasi-geostrophic forcing.

(3) The growth rates of the leading Lyapunov vectors (LVs) vary significantly about their mean values over periods of a few days. For the leading LV, episodes of greater (or lesser) growth correspond to significant variations in vertical structure and are highly correlated with its projection onto the leading SVs. For example, results confirm that the fraction of LV variance explained by the leading SVs increases (decreases) by a factor of two during the large- (small-) growth phase of the LV. Experiments in which the leading SV components were systematically filtered from the evolving LVs reveal that the fast growing subspace of the leading LV is captured by a relatively small ensemble (~20) of leading SVs. Moreover, the mean growth rates of the leading LVs are reduced to near zero (neutral growth) by filtering the 20 leading SV components over successive 24-hr intervals, while filtering additional SV components causes the LV to decay, on average.

(4) The use of NAVDAS analysis error variance estimates as an initial norm provides a relatively straightforward means of computing SVs that reflect a realistic distribution of analysis error. Compared with TESVs, VARSVs appear more consistent with the expected distribution of analysis error, but exhibit only moderate differences in structure and slightly smaller growth rates than the TESVs. The VARSVs explain a similar fraction of forecast error variance as the TESVs in a linear context, but perform less well as “optimal” perturbations to the nonlinear forecast. Improvements in the specification of NAVDAS background errors will greatly enhance the utility of the VARSVs.

IMPACT/APPLICATION

(1) These findings clearly support the key underlying principles of targeted observing, namely: (i) the early stages of error growth in most numerical weather forecasts are dominated by a relatively small number of growing structures, and (ii) preferentially reducing analysis errors that project onto these structures can produce significant improvements in forecast skill. Comparisons with forecasts using pseudo-inverse corrections to the initial conditions---which provide a way of estimating the maximum forecast improvement obtainable by reducing the initial error in the SV subspace---support the idea that targeting is most likely to provide benefit beyond that of the conventional observing network in cases of rapid error growth. The results provide encouragement for continued research and development of adaptive observing strategies. More generally, the results indicate that the most important analysis errors in a forecast context are not necessarily the largest analysis errors, nor is the structure of these important errors necessarily similar to that of the total analysis error.

(2) These findings establish a significant relationship between the SV perturbations and dynamically active regions in the middle troposphere and point toward an integral link between SVs and upper-level PV precursors in synoptic development. Moreover, this is an important first linkage between adjoint-based paradigms of perturbation growth and more traditional paradigms based on conceptual models.

(3) The results make clear the importance of transient growth in maintaining the positive mean growth rates of the leading LVs, and in determining the asymptotic stability properties of time-dependent flows. The implication is that the asymptotic instability of the large-scale flow may be characterized in terms of a piecewise-continuous evolution of transient instabilities, as represented by the leading SVs

optimized for short intervals. While it is clear that the atmosphere evolves in a continuous, rather than piecewise-continuous, manner, the above characterization is a reflection of the fact that non-modality is a key (and conceptually complicating) factor in this evolution.

(4) Solution of the optimal observing problem requires knowledge of the distribution of initial errors, the ability to propagate—or map—key aspects of this error distribution forward in time, and knowledge of the errors in the model and assimilation systems used in the forward mapping process. Because the analysis error variance is the diagonal component of the full analysis error covariance matrix, the VARSVs are a tractable first step toward the use of metrics that constrain dynamic perturbation growth according to the complete structure and probability distribution of initial error. This information is critical for a range of applications including adaptive observing and ensemble generation.

TRANSITIONS

This work is a basic research initiative in atmospheric predictability, which has just completed its third year. Real-time ingestion of adaptively targeted dropsonde and satellite wind measurements into NOGAPS continued in conjunction with the NOAA-led Winter Storms Reconnaissance Program (WSRP). Adaptive observing is now operational at NOAA/NWS/NCEP.

RELATED PROJECTS

The methodology and tools developed in support of this research have direct application to ongoing NRL 6.1 and 6.2 programs in model development and data assimilation. ONR has initiated a 6.1 directed research initiative (DRI) on theoretical and environmental predictability; our effort is highly coordinated with this ONR initiative. Ongoing collaborative research efforts on this and related work have been established with NOAA/National Center for Environmental Prediction, NOAA laboratories Environmental Technology Laboratory and Pacific Marine Environmental Laboratory, the National Center for Atmospheric Research, and the European Centre for Medium-range Weather Forecasts. Participation in the The Hemispheric Observing System Research and Predictability Experiment (THORPEX), a multi-agency, international program of coordinated laboratory and field research planned for 2001–2006, is considered a key resource for important new data sets and high-level community connectivity for this program.

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