Assimilation of DoD Sensor Data Into Operational Forecast Models

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LONG-TERM GOALS

Remotely-sensed observations from satellites hold great promise for providing a wealth of high-temporal and spatial resolution data, particularly over the oceans. However, it has been very difficult for numerical weather prediction systems to show consistent, positive forecast improvement attributable to satellite retrievals obtained in the conventional manner. By developing techniques for the direct assimilation of the satellite measured radiances, this project will lay the foundation for improved three- and four-dimensional data assimilation systems for global and mesoscale applications. These systems may be run at operational central-site forecast centers or run on-scene to provide operational mission support.

OBJECTIVES

The objective of this task is to develop variational data assimilation techniques for improving the impact of satellite data on numerical weather prediction systems. Variational techniques provide a means to utilize values that are not directly reflected by the traditional forecast model parameters. In the case of satellite data, variational methods allow for the direct use of the measured radiances, rather than the derived temperature and moisture soundings. Satellite radiances are a challenge to use correctly, and there are many quality control (QC) issues that are unique to each satellite sensor. Efforts at NRL will concentrate on the DMSP microwave sensors, since non-DoD research efforts are focusing on the civilian sensors. Optimal use of these rich data sources should reduce the errors in the analyses that provide initial conditions for forecast models and tactical decision aids, as well as provide valuable information to the forecasters in the field.

APPROACH

The use of remotely sensed observations is hampered by several fundamental limitations. First, the quantity measured is usually not the quantity needed by the forecast model. Second, there is typically not a one-to-one relationship between what is observed and the derived value. For the example of satellite temperature soundings, the radiance measured in a given spectral channel is emitted from a broad vertical region of the atmosphere rather than a specific pressure level. Consequently, the inverse or retrieval problem becomes formally ill-posed, and essentially an infinite number of temperature profiles are possible from a given set of radiance measurements. In order to constrain the solution, prior information must be specified. For temperature and moisture soundings, the final solution is strongly dependent upon the prior information, and is highly nonlinear for moisture.

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To reduce the errors introduced by the retrieval process, it is possible to use variational assimilation methods, which are soundly based on optimal nonlinear estimation theory, to assimilate the radiances directly. Proper use of the radiances in this manner is a difficult problem requiring knowledge of remote sensing and data assimilation methods. This approach requires an accurate forward radiative transfer model appropriate for microwave instruments, extensive data quality control techniques for the radiance measurements, and accurate specification of the error characteristics of the observations and background that are used to constrain the guess (including error correlations).

With variational algorithms, a penalty function is minimized with respect to control variables which describe the atmospheric state to be analyzed. The penalty function measures the fit of the maximum likelihood estimate of the atmospheric state to the observations and background (a priori) information. This approach requires computation of radiances computed from the forecast model variables using a forward radiative transfer model. The first step in reaching our goal is to develop a one-dimensional variational analysis (1DVAR) to assimilate satellite radiance data. The simpler, one-dimensional approach is ideal for developing the fundamental understanding of the problem. The most important aspects of the problem, such as development and validation of the forward radiative transfer model, quality control, bias correction algorithms, and specification of the error covariances, can all be developed in the one-dimensional context, using easily available workstation resources.

The 1DVAR algorithm also produces vertical profiles of temperature and humidity to replace the conventionally produced retrievals. With 1DVAR, the background or a priori information comes from the six-hour forecast from the Navy's operational forecast models. This background typically contains more information about the current state of the atmosphere than the a priori information used to produce conventional retrievals, and thus constrains the ill-posed problem better. Another important component of 1DVAR algorithms and some retrieval methods is the specification of the background error covariance. It is much easier to estimate this error covariance for the forecast model background than it is for first guess derived from averaged collocated rawinsondes or climatology. Finally, 1DVAR improves upon conventional retrievals because of its self-contained, rigorous quality control.

Together with better quality control algorithms, 1DVAR provides near-term deliverables which can be readily included into the current Multivariate Optimum Interpolation (MVOI) analysis. These two deliverables are expected to improve the forecast model in the short term, although most of the improvement is not expected until the full three-dimensional assimilation of radiances is implemented. The 1DVAR will be used as a radiance pre-processor for the three-dimensional variational (3DVAR) analysis that is being developed concurrently at NRL as a replacement for the MVOI.

Variational methods are also being developed to assimilate satellite retrieved parameters (such as SSM/I total column water vapor) that are not directly related to the model state variables. In this example, the link between radiances and the retrieved quantities is weakly nonlinear and not strongly dependent upon the prior information. Therefore, assimilation of the retrieved quantity will be close to optimal.

WORK COMPLETED

All of the necessary components for 1DVAR for the civilian infrared sensor TOVS have been completed, including the minimization algorithms, and software to test and evaluate the 1DVAR retrievals in NOGAPS assimilation/forecast tests. TOVS was used as a proxy due to various delays accessing DMSP data and appropriate forward models. Because TOVS 1DVAR assimilation tests using NOGAPS were so promising, the customer Fleet Numerical Meteorology and Oceanography Center (FNMOC) requested that TOVS remain a top priority over DMSP. Dr. Merilees and Dr. Hartwig concurred, and extensive testing of TOVS 1DVAR continued through the summer. It has now been transitioned to FNMOC, where it is being further tested and evaluated. Projected implementation date is early December 1998. Meanwhile, the capability to assimilate TOVS radiances directly has been added to NRL's developmental 3DVAR system, as has the ability to analyze integrated retrieved quantities such as DMSP SSM/I (and SSM/T-2) total precipitable water and wind speeds. A forward model suitable for SSM/T-1 and SSM/T-2 was obtained from NESDIS and modified for these instruments. Several microwave surface emissivity models were obtained from Code 7200 (Gene Poe) and evaluated. Extensive comparisons between measured and NOGAPS background radiances were made. This allowed for estimation of the instrument and forward model errors, and the development of techniques for quality control, data screening and flagging of thick clouds and precipitation.

RESULTS

Numerous 30-day NOGAPS TOVS 1DVAR assimilation tests were conducted during the 4^{th} quarter of FY98. The basic tests consisted of the 6-hour update cycle and 5 day forecasts (at 00 UTC). The control was a NOGAPS T79L24 run where NESDIS satellite retrievals were used per current operational practice. Because of technical issues, NESDIS retrievals were used south of 20^{O} for all tests. The resulting improvements to the 500 and 1000 hPa anomaly correlation scores were in general positive; rms errors for temperature also decreased. The largest improvements were for the Western Pacific where the forecast skill increased by 18 hours at 500 hPa and 13 hours at 1000 hPa. In other words, the 1DVAR run had as much skill at 500 hPa (as measured by anomaly correlation) at 5 days (120 hours) as the control run did at just over 4 days (102 hours). Second largest improvement at 500 hPa was for North America (12 hours) and at 1000 hPa for the Atlantic (8 hours). Overall, the Northern Hemisphere showed gains of up to 5 hours. Europe (at 500 hPa) and North America (at 1000 hPa) posted the worst results, with neutral to slight decreases in forecast skill. Overall, skill scores increased throughout the 30-day assimilation period so it is expected that TOVS 1DVAR will yield positive results in all areas operationally.

Extensive comparisons between measured and NOGAPS background radiances for the DMSP sounders were made, and from these, data screening, quality control, and precipitation flagging algorithms have been developed. When computing these differences, it is particularly critical that surface radiative contributions (primarily due to microwave surface emissivity) are properly accounted for. Over open oceans, variations in surface emissivity are small and the emissivity is easier to model. For this reason, we have confined ourselves to considering open ocean points only. Results indicate that the remaining quality controlled measured radiances have a high quality signal and that the surface emissivity model obtained from NRL/DC is adequate. Several issues remain to be solved concerning the level of pre-processing performed by NESDIS on the radiances transmitted to FNMOC.

Variational assimilation methods use a short-term forecast from the NWP model as the background or first guess. It is crucial that the forecast model error correlation structures for temperature and humidity are correctly specified. Using a method of transforming independent variables, new correlation functions have been derived that are simple to compute yet provide a closer fit to the data than methods currently in use. These new correlation functions, when used to generate TOVS 1DVAR retrievals for NOGAPS assimilation tests, led to an increase in forecast accuracy. It is expected that ongoing work in the this area will continue to lead to forecast skill improvements.

It is worth noting that significant positive results for TOVS 1DVAR required several key improvements. These included the higher vertical resolution NOGAPS (T79L24) with 24 instead of 18 vertical levels, improved specification of the background error correlation, and the development of extensive radiance quality control algorithms. Several NOGAPS improvements over the past year (including the higher vertical resolution) have substantially decreased the systematic temperature error in the 6-hour forecast in the upper troposphere and stratosphere. Since the 6-hour forecast is used as the background for 1DVAR, it is important that systematic errors are minimized and the remaining errors are properly characterized.

IMPACT

This research should lead to a meaningful improvement in the quality of the atmospheric analyses and a more consistent performance from the forecast models as a result of the improved assimilation of the abundant satellite information. Improvements in numerical prediction systems translate to improved mission support and cost savings for the Navy.

TRANSITIONS

The systems being developed are primarily designed to run at a central site like FNMOC. They are also candidates for other applications such as the on-scene systems being developed by the Navy. The prototype version for TOVS radiance assimilation using one-dimensional variational methods to produce retrievals was transitioned to 6.4 and is being tested with the operational NOGAPS system.

RELATED PROJECTS

PE 0602435N (Data Assimilation and Quality Control for Shipboard Analysis/ Prediction System) and PE 0603207N (Variational Assimilation and Physical Initialization) are closely related projects to develop data assimilation systems for shipboard and central-site use at FNMOC.