Ocean Data Impacts in the Real Time Ocean Forecast System: RTOFS-v2

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Introduction

It is likely that not all observations assimilated have equal value in reducing ocean model forecast error. Estimation of which observations are best and the determination of locations where forecast errors are sensitive to the initial conditions are essential for improving the data assimilation system itself and for the design and implementation of future observing systems. This paper describes application of the adjoint-based procedure to estimation of the impact of observations assimilated on reducing ocean model forecast error in the Real-Time Ocean Forecast System (RTOFS-v2). The technique computes the variation in forecast error due to the assimilated data. Observation impacts are estimated simultaneously for the complete set of observations assimilated. The method is computationally inexpensive and can be used for routine observation monitoring. This aspect of the adjoint technique is advantageous since ocean observing and assimilation/forecast systems are in continuous evolution requiring an efficient procedure that allows the impact of observations to be regularly assessed. Data impacts can be partitioned for any subset of the data assimilated: instrument type, observed variable, geographic region, or vertical level, with traceability to individual platforms based on station identifying call signs. The results shown here illustrate some of the types of diagnostics that can be routinely obtained with the adjoint method in an operational context.

RTOFS-v2

The ocean forecast component of RTOFS-v2 is the Hybrid Coordinate Ocean Model (HyCOM), which is configured on a global tri-polar grid with horizontal equatorial resolution of .08º or ~1/12º (~7 km mid latitude). This configuration makes HyCOM eddy resolving. Eddy resolving is important for ocean model dynamical interpolation skill in data assimilation. HyCOM is configured with 41 hybrid vertical coordinate surfaces. The data assimilation component of RTOFS-v2 consists of a three-dimensional variational (3DVAR) analysis. The analysis variables are temperature, salinity, geopotential, and u, v vector velocity components. All variables are analyzed simultaneously in a multivariate procedure that permits adjustments to the mass fields to be correlated with adjustments to the flow fields. The 3DVAR observation vector contains all of the synoptic temperature, salinity and velocity observations received at the center within the 24-hour update cycle interval. The analysis makes full use of all sources of the operational ocean observations. RTOFS-v2 routinely assimilates about 2 million observations per day onto the global HyCOM grid, which contains more than 520 million grid points.

Adjoint Procedure

Adjoint-based observation sensitivity provides a feasible all at once approach to estimating observation impact. Observation impact depends on the forecast error metric, the innovations (model-data differences at the update cycle interval), and the number of observations. Since forecast errors grow and decay at different rates throughout the model domain, a large model-data difference does not necessarily lead to a large data impact. Observations can make small changes to the initial conditions and still have a large data impact if the location of the observation is in a dynamically sensitive region. Here, the forecast error metric is defined as the difference between forecasts of 48 and 72 hours valid at the same time. Forecast errors result from inaccuracies in the initial conditions, the atmospheric forcing, and the non-linear forecast model. However, differences between forecast errors from forecasts of different lengths verifying at the same time are solely due to the assimilation of observations, which makes it an appropriate cost function for data impact studies. For example, if there were no observations assimilated 48 hours ago, then the trajectory of the 48 and 72 hour forecasts will be the same and their differences will be zero at the verifying analysis time. Observations, however, are usually assimilated and the two forecast trajectories will differ as a result. Forecast error gradients in model space are projected into observation space using the adjoint of the 3DVAR. This yields an observation sensitivity vector $\partial \mathbf{J}/\partial \mathbf{y}$, with its elements at the observation locations. $\partial \mathbf{J}/\partial \mathbf{y}$ is then used in the observation impact equation:

$\boldsymbol{\delta}\mathbf{e}_{48} = \langle (y - Hx_f), \partial J/\partial y \rangle$, where the brackets represent a scalar inner product and ($\mathbf{y}$-$\mathbf{Hx}_f$) is the innovation vector (Langland and Baker, 2004). A negative $\boldsymbol{\delta}\mathbf{e}_{48}$ value indicates a beneficial observation in that assimilation of the observation reduced HyCOM 48 hour forecast error, while a positive $\boldsymbol{\delta}\mathbf{e}_{48}$ value indicates a non-beneficial observation (forecast error actually increased from assimilation of the observation). Non-beneficial impacts are not expected since the assimilation is expected to decrease forecast error by producing improved initial conditions. However, if non-beneficial impacts occur, and they are persistent, then that may indicate problems with the observing system or model performance. Thus, the data impact system can be used as an effective monitoring tool for diagnosing data quality issues or identifying areas where the model has significant predictability limits.

Results

Forecast error gradients are computed daily for differences between 48-hour and 72-hour HyCOM forecasts of temperature, salinity, and the verifying analysis. The 3DVAR adjoint is then executed to obtain the observation sensitivities for use in the observation impact equation. Data impacts are available every day for each observation assimilated and can be partitioned into contributions made by instrument type, geographic domain, and vertical level. Figure 1a shows instantaneous temperature forecast error gradients at the surface. Positive and negative areas of forecast errors are seen indicating that on any given day HyCOM forecast errors are both increasing (positive values) and decreasing (negative values). These patterns will vary with depth and evolve over time in accordance with changes in the observing systems assimilated and the variable skill of the HyCOM forecast. Temperature forecast error gradients averaged over 10 days are shown in Fig. 1b. In general, negative values are found almost everywhere, an indication that the assimilation is consistently reducing HyCOM 48-hour forecast error. Beneficial impacts are the greatest in western boundary currents, Antarctic circumpolar current, and eastern tropical Pacific. However, persistent non-beneficial (positive) impact areas are also seen. These areas of forecast error growth could be due to localized, reduced HyCOM predictability arising from instabilities in the system and need further investigation.

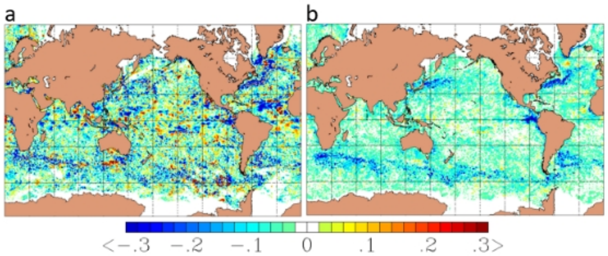

Figure 1. Surface temperature forecast error gradients.

It has been demonstrated that routine assimilation of large numbers of observations work together to consistently reduce global HyCOM 48-hour forecast error. An advantage of the adjoint method is that it allows quantification of impacts from the assimilation of individual observations. To summarize these results, impacts are partitioned by data type and averaged over a 10-day period. Impact results presented for any group partition is the sum of all individual observation impacts in that group normalized by the number of observations. Figure 2 shows the locations of beneficial and non-beneficial impacts of Argo temperature profiles assimilated during the 10-day period. A large number of Argo profiles have beneficial impacts from the assimilation, but some Argo profiles have non-beneficial impacts that occur in a fairly random pattern. Figure 3 shows a comparison of the impacts of temperature observations from various observing systems. Profiles from animal borne sensors are found to have the greatest impact at reducing HyCOM forecast temperature errors, followed by Argo. The animal sensor data are profiles from CTD instruments attached to animals, in particular Elephant Seals. The foraging behavior of the animals brings them to ocean frontal zones in search of food, primarily in hard to reach polar-regions. The seals basically serve as targeted observing platforms providing high impact data in dynamically sensitive areas.

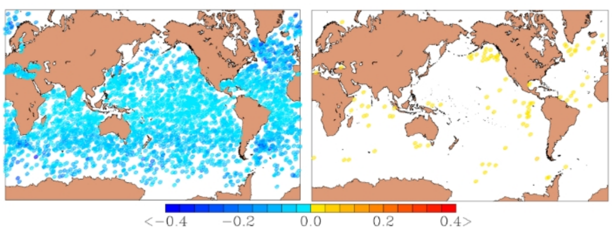

Figure 2. Beneficial (left) and non-beneficial (right) impacts of Argo temperature profiles: 27 Mar – 5 Apr 2021.

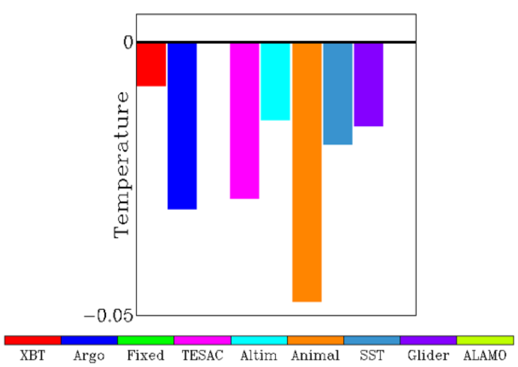

Figure 3. Temperature observing system impacts.

Summary

The adjoint method has successively been applied to RTOFS-v2 to assess data impacts. The method is computationally efficient and can be used for routine observation monitoring in operations. There is no need to selectively remove observing systems to determine impacts as in a data denial experiment. As such, the method automatically adjusts to changes in the observation suite assimilated as new observing systems are introduced and to changes in the forecast model as model resolution increases or new physics are introduced. It is now possible to efficiently and routinely evaluate the entire global set of oceanographic observations assimilated in RTOFS-v2, determining which data are most valuable and which data are redundant or do not add significant value.

References

Langland, R. and N. Baker, 2004: Estimation of observation impact using the NRL atmospheric variational data assimilation adjoint system. *Tellus* 56A, 189-201.