A Posteriori Diagnostics of the Impact of Observations on the AROME-France Convective-Scale Data-Assimilation System.

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AROME-France is an operational convective-scale Numerical Weather Prediction system that uses a 3D-Var Data Assimilation (DA) scheme in a 3-h continuous assimilation cycle in order to determine its initial conditions at the horizontal resolution of the model (2.5 km). In addition to conventional and satellite observations, regional high-resolution observations are assimilated, such as, screen-level observations, total zenith delays from ground based GPS stations and radar measurements (radial winds and reflectivities).

The impact of the various observation types on AROME-France analyses is assessed using an *a posteriori* diagnostic, the reduction of the estimation error variance. It can be shown that, if observation and background error covariance matrices are well specified in a variational DA system, the analysis error covariance matrix is given by $\mathbf{A} = \mathbf{B} - \mathbf{KHB}$ where **B**, **K** and **H** respectively stand for the assumed background error covariance matrix, the Kalman gain matrix and the linearized observation operator. The total variance reduction provided by the assimilation of the observation $r=\mathrm{Tr}(\mathbf{B})-\mathrm{Tr}(\mathbf{A}) = \mathrm{Tr}(\mathbf{KHB})$ is a measurement of the ability of a DA system to pull the analysis from the background with respect to the observations (Tr stands for the trace of a matrix). A direct estimate of the variance reduction Tr(**KHB**) is not possible in practice in an operational variational DA system, since neither **B** nor **K** are explicitly known. Then, the variance reduction which allows one to investigate observation impact depending on the control variable field, model levels, date, analysis time, and spatial scales considered, and the contributions of the different observation types, are estimated in the AROME-France DA system with a randomization method ([1],[2]).

The observations with the largest impact in the AROME-France 3D-Var system are given by aircraft (for temperature and wind fields) and radar (specific humidity and wind fields) observations in the middle and high troposphere, in accordance with the vertical distribution of these observations. Screen-level measurements (2 m temperature, 2 m relative humidity and 10 m wind) are the main contributors at the lowest atmospheric levels. These large impact values are explained by the number of these observations assimilated at each analysis time. On a rainy day, aircraft, radar and screen-level observations account for respectively 22%, 30% and 18% of the total account of assimilated observations. One can note that it is possible to evaluate the impact of an observation of a given physical quantity (resp. at a given model level) on the analyzed field of an other physical quantity (resp. on other levels) through the **B** matrix cross- (resp. vertical) correlations. The total variance and the different observation contributions are also evaluated depending on the spatial scale of the analyzed fields: most of variance reduction concerns length scales above 100 km with a maximum around 500-800 km. Only the radar measurements, with an horizontal density of 15 km, contribute to the variance reduction at scales lower than 100 km.

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Impact on the Use of Different Error Objective Function on the Forecast Sensitivity to Observation Diagnostic Tool

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Over the years, data assimilation and forecast schemes have evolved towards very complicated systems such as the four-dimensional variational ECMWF system. The system handles a large variety of both space- and surface-based meteorological observations. It combines the observations with prior (or short-range forecast) information of the atmospheric state and also uses a comprehensive linearized forecast model to ensure that the observations are given a dynamically and statistically likely response. Analysis and forecast models are therefore blended into a single numerical weather prediction system. Efficient monitoring of such a complex system, with the order of 10^9 degrees of freedom and more than 10^7 observations is a necessity.

Recently, adjoint method has been used to evaluate the impact of the observations on the short-range forecast and more generally, forecast error sensitivity is used as a performance monitor tool. The forecast error reduction due to a particular measurement or collectively to a specific instrument or data type is calculated with respect to a global forecast error objective function, typically, the energy norm. In this paper the impact on the forecast error reduction from the assimilated observations of a different error cost function is presented and discussed.

Adjoint Estimation of the Forecast Impact of Observation Error Correlations Derived from A Posteriori Covariance Diagnosis

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A posteriori error covariance consistency studies indicate that both spatial and interchannel error correlations are present in the radiances assimilated from hyperspectral sounders [1]. An open research question is to assess whether modeling the observation error correlations in the data assimilation system (DAS) will entail substantial improvements in the model forecast skill.

This talk presents a practical approach to provide guidance on the forecast impact of an error covariance model *prior to* its actual implementation in the DAS. A synergistic framework is considered that combines the computational efficiency of the *a posterior*i covariance diagnosis estimates with the comprehensive amount of derivative information extracted from the adjoint-DAS observation error covariance sensitivity (**R**-sensitivity). This approach extends our work [2] to the observation error correlation structures. An estimate $\check{\mathbf{R}}$ of the observation error covariance is obtained from the statistical analysis of the observation residuals [3]; subsequently, the adjoint-DAS **R**-sensitivity evaluated in the *status quo* DAS is used to obtain a first-order assessment of the forecast error impact induced by the variation $\delta\mathbf{R}=\check{\mathbf{R}} - \mathbf{R}$ in the error covariance specification.

Theoretical aspects are discussed and a proof-of-concept to covariance diagnosis and impact estimation is provided in idealized experiments with a simple Lorenz-40 variable model. The practical applicability of the proposed methodology is shown with the adjoint versions of the Naval Research Laboratory Atmospheric Variational Data Assimilation System-Accelerated Representer (NAVDAS-AR) and the Navy Operational Global Atmospheric Prediction System (NOGAPS). Estimates of spatial and interchannel error correlations derived from an a *posteriori* diagnosis are presented for AIRS and IASI radiances; a *priori* first-order estimates to the forecast error impact are obtained from the adjoint-DAS derivative information. Our preliminary analysis indicates that an increased benefit to the forecasts may be obtained by modeling the error correlations, as compared with covariance tuning procedures that ignore the correlation structures and adjust only the assigned observation error variance parameters.

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Development, Validation, and Applications of OSSEs at NASA's Global Modeling and Assimilation Office

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Well-designed OSSEs can be very informative since they are not restricted by presently existing observation types and the simulated truth is precisely known, both properties being a consequence of the simulated context of the experiments. Although most often motivated by the first property, the second can also be exploited to better understand the behavior of data assimilation systems. Essentially, analysis and background error can be explicitly calculated without invoking questionable assumptions about their character. Another consequence of this simulated context, however, is that what is learned from the OSSE only applies to the assimilation of real observations to the degree that the OSSE is realistic. Validation of any OSSE framework using a variety of metrics is therefore critical to its useful applications.

The OSSE framework recently developed at the GMAO has been validated using several informative metrics that have not been examined in previous OSSEs. These include statistics of innovations (both variances and correlations), analysis increments, observation impacts (estimated using model and data assimilation adjoints), and forecast errors. It was relatively easy to match innovation variances by adding random errors to the observations, but in order to match innovation correlations and analysis increment variances, these errors had to be channel or spatially correlated. For most observation types, tuning of these errors was fairly easy.

After presenting a sample of validation results, application of the OSSE to estimate analysis and background error characteristics will be presented. This will include direct calculation of error variances and spatial correlations, error spectra, and the percentages that background errors are reduced during the assimilation of observations. A typical value of the latter for most fields at most locations is only 10-20%, as can be expected from theoretical consideration of the Kalman filter. Error reductions primarily occur at synoptic scales (spherical harmonic wave-number $n<30$). The divergent wind is relatively poorly analyzed at most vertical levels and horizontal scales. Horizontal and vertical scales of background error correlations are very different than what is estimated using the NMC method; i.e., using statistics of 48 minus 24-hour forecast errors verifying at the same time as proxies for background error statistics. The usual dry, forecast skill metrics in the OSSE context are rather insensitive to a reasonable range of observation error characteristics, rendering it difficult to tune the OSSEs realism regarding such metrics. This is partly due to the influence of model error on forecast error but also due to the effectiveness of present data assimilation algorithms at filtering observation errors.

Most applications of the GMAO OSSE thus far have concerned its aid in understanding the behavior of the data assimilation system by validating against truth itself. Results from some additional studies of this kind will be presented as well as plans for the future.

Improving Ensemble-based Observation Impact Estimate using a Group Filter Technique

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An ensemble-based observation impact estimate [3] is straightforward to be applied for ensemble data assimilation systems. However, due to relatively small ensemble sizes compared to the large number of degrees of freedom in models, it is necessary to apply localization techniques to obtain accurate estimates. Fixed localization techniques do not guarantee accurate impact estimates, because as forecast time increases the error correlation structures evolve and move with the flow. For longer lead times, we should expect the optimal localization function to be shifted downstream from the observation and be spread by various model flow dependencies. Kalnay et al. [3] showed improvements in the accuracy of the impact estimate by employing a time-dependent displacement term to a Gaspari-Cohn localization function.

The goal of this study is to explore methods to improve the observation impact estimate by improving the method of localization. Our experiments use the LETKF together with a two-layer primitive equation model and simulated observations as in Holland and Wang [2]. We employ a Monte Carlo "group filter" technique developed by Anderson [1] to limit the effects of sampling error. For each group of ensemble members, a regression coefficient, β, is calculated between the analysis and a forecast of some length. Then a *regression confidence factor* (RCF) is computed to minimize expected RMS differences between sample β's. An envelope of RCF values is then applied to the observation impact estimate. Our results have shown that the shape, location, time-dependency and variable-dependency of the localization function is consistent with underlying dynamical process of the model. Results of applying the RCF on observation impact estimate will be presented in the symposium.

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Scaling of GNSS Radio Occultation Impact with Observation Number Using an Ensemble of Data Assimilations

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Global Navigation Satellite System Radio Occultation (GNSS-RO) measurements are an important component of the current Global Observing System (GOS) used for Numerical Weather Prediction (NWP). Currently, about 2,000 bending angle profiles per day are assimilated, and these account for around 2–3 % of the total number of observations assimilated at ECMWF. The GNSS-RO measurements have a statistically significant positive impact on the analysis and forecast accuracy, particularly in areas with significant model biases. There is no indication of saturation of forecast impact with the current GNSS-RO observation numbers, but there is very little guidance on where this effect might occur.

This presentation will discuss results of a study which aims to estimate the optimal number of GNSS-RO measurements required for NWP. The impact as a function of observation number is analysed using simulated GNSS-RO observations. The study is based on Ensemble of Data Assimilations (EDA) approach using ten ensemble members. The EDA system provides a statistical estimate of the analysis and short-range forecast uncertainty of the NWP system, based on the spread of the ensemble members. A set of EDA experiments is performed with different numbers of simulated GNSS-RO profiles, ranging from 2000 to 128000 profiles per day, in addition to the real conventional and satellite observations assimilated operationally. The use of the EDA approach for estimating observation impact will be discussed. It is shown that the impact of 16000 GNSS-RO profiles per day in the upper tropospheric and lower stratospheric temperatures is clearly not saturated, based on the behaviour of the ensemble spread as a function of observation number.

Inclusion of linearized moist physics in NASA's Goddard Earth Observing System Data Assimilation Tools

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Inclusion of moist physics in the linearized version of a weather forecast model is beneficial in terms of variational data assimilation. Further it improves the capability of important monitoring and research tools, such as adjoint based observation impacts and sensitivity studies. A linearized version of the Relaxed Arakawa-Schubert (RAS) convection scheme has been developed and tested in NASA's Goddard Earth Observing System (GEOS) data assimilation tools. A previous study of the nonlinear RAS scheme showed it to exhibit a reasonable degree of linearity and stability. This motivates the development of a linearization of a version of the RAS scheme that has only minor modifications to the algorithm. Linearized large scale condensation is included through a simple scheme that converts super saturation into precipitation. The linearization of moist physics is validated against the full nonlinear model for 6-hour and 24-hour intervals, which are relevant to variational data assimilation and observation impacts respectively. For a small number of profiles sudden large growth in the perturbation trajectory is encountered. Efficient filtering of these profiles is achieved though the diagnosis of steep gradients in a reduced version of the operator of the tangent linear model. With filtering turned on, the inclusion of linearized moist physics increases the correlation between the nonlinear perturbation trajectory and the linear approximation of the perturbation trajectory. A month long observation impact experiment is performed and the effect of including moist physics on the impacts is discussed. Impacts from moist sensitive instruments and channels are increased. Discussion is presented on the inclusion of moisture in the error metric. The effect of including moist physics is examined for adjoint sensitivity studies. A case study examining an intensifying northern hemisphere Atlantic storm over a 24-hour period is presented. The results suggest that in regions of active moist physics the magnitude of the sensitivity with respect to moisture is equivalent to the sensitivity with respect to other model variables. Results from updating the observation operator with the new linearized moist physics are shown.

Observation Impact on Tropical Cyclone Forecasts: An Adjoint Approach

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Using the adjoints of the data assimilation system and NWP forecast model, the impact of individual observations can be estimated for some function of the model forecast state. The Navy currently uses this technique to assess the impact of observations on the 24-hour forecast as measured by a global energy-based error norm [1]. In this study, this system is adopted for monitoring the impact of observations on the 24-hour tropical cyclone (TC) forecast for selected cases in the 2012 hurricane season, by restricting the verifying area over the location of the TC and adopting a TC intensity response function rather than an energy-based error norm cost-function.

An examination of observation impact on TC forecasts indicates that a very small minority of high-impact observations within the TC's environment is responsible for the bulk of the impact on TC intensity, following a power-law-like distribution. This is in stark contrast to the observation impact on the global error norm, which is contributed to mostly by the integrated impact of many low-impact observations, while high-impact observations contribute little overall. In addition, the relative importance of various observing systems to TC intensity can vary strongly from forecast to forecast, based on the context of the TC's environment. For example, land observations can be of relatively low importance compared to satellite-derived winds while the TC is remote from land, but this relationship can shift dramatically as the TC approaches landfall.

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Comparison of Met Office and ECMWF Background Fields with Conventional Observations

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Met Office and ECMWF background fields (short range forecasts) of near-surface temperature, humidity and wind have been compared with *in situ* observations, especially land surface reports. The 10 meter forecast wind speeds from both centers are slightly stronger than the reported wind speeds, especially at night. The night-time bias is a known issue in that forecast models have too much mixing under stable conditions [1]. In both models the wind speed biases are particularly large over the Indian sub-continent, this could be due to the roughness lengths used and/or to observational errors. The results for temperature and humidity show less consistency between the models: overall the Met Office forecasts appear slightly too wet and the ECMWF forecasts slightly too dry - probably related to biases in precipitation [2]. The Met Office forecasts show a moist bias in the Northern Hemisphere spring - this moves northwards as spring progresses and appears to be related to snow-melt being a few weeks early in this model. Temperature biases vary by region and season; both models are slightly too warm over the North American Great Plains (and to some extent Siberia) in summer. This may be due to the lack of propagation of convective storms triggered by the Rockies [3], but agricultural irrigation (not represented in the models) may also play a part.

The dependence of biases on the proximity of the coastline has also been examined, in the Met Office model the transition zone for wind seems slightly too wide [4]. Representation of near surface conditions in global forecast models has improved in recent years due to increased resolution and improvements to soil, boundary layer and cloud parameterization. At the Met Office assimilation of most surface temperature, humidity and wind observations has also made some improvements [5]. The remaining biases between background fields and observations often provide valuable insight into model errors, but observation and representativity errors also have to be borne in mind. Met Office analysis increments show humidity biases peaking around the top of the boundary layer [6].

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Ensemble Forecast Sensitivity to Observations: Applications for Proactive Quality Control

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A new formulation of the Ensemble Forecast Sensitivity to Observations (EFSO, Kalnay et al., Tellus, 2012) is more accurate and efficient than the original ensemble sensitivity formulation of Liu and Kalnay, (2008), and can be applied to the EnSRF used in the NCEP hybrid. Ota et al. (2013, Tellus, under review) applied EFSO to the GFS coupled with the operational EnSRF used at NCEP, and assimilated all the observations used operationally during one month, after one week of spin-up.

In addition to obtaining the average forecast sensitivity to different observing systems, Ota et al. (2013) developed a new approach to identify regional "24hr forecast skill dropouts" rather than the usual 5 days used at NCEP to define "skill dropout". 24hr forecast skill dropouts were identified regionally when two conditions were satisfied: the 24hr RMS forecast error was at least twice as large as the average RMS error for the region, and the 24hr forecast error was larger than the 36hr error by at least 20%. Seven cases of 24hr regional forecast skill dropout were identified during that month, as well as the observations that had a regional negative impact, and denying these observations reduced the forecast error in every case identified. The case with largest impact corresponded to a problem with MODIS polar winds that occurred in two contiguous regions. The estimated negative impact using this method was shown to be very similar in amplitude and shape to the impact obtained with a repetition of the experiment without using the MODIS winds. Denying these observations reduced the regional forecast error by almost 40%.

We will explore whether this approach can be used to provide a proactive QC tool and will present the results at the WMO DA conference. The method will be used to estimate the occurrence of large "12hr skill dropouts" with the GFS coupled with the LETKF. If successful, this method would have important properties that can improve operational forecasts: a) The data assimilation in the operational system can be repeated without the identified flawed observations soon after real time; b) The detailed diagnostics on the flawed observations obtained with this method can help the developers of the instrument algorithms to identify the origin of the observational flaws and correct them.

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Investigation of Model Covariance with Low-Order Dynamics

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Knowledge of a dynamical model's covariance is a critically important element of Bayesian data assimilation as practiced at operational weather prediction centers worldwide. This covariance is controlled by uncertainty in initial conditions and forcing as well as the effect of overall model formulation deficiencies. When these uncertainties are combined with covariance of observations, the optimal *a posteriori* state of the system can be determined. This estimated state improves the link between existing ensembles of data assimilation and assessment of alternative methods for creating initial conditions [1].

There are three ways to obtain a model's covariance: (1) stochastic – dynamic prediction (SDP) that delivers the moments of the probability density function (pdf), (2) Monte Carlo methods that generate the covariance through a series of forecasts stemming from a random body of initial states and random perturbations to the parameterization schemes, and (3) solution to Liouville's equation that yields the exact pdf and therefore the exact covariance through a "continuity of probability" principle.

The determination of a model's covariance is explored through use of Platzman's low-order spectral model of nonlinear advection [2] where uncertainty in initial conditions and forcing is considered. The consequence of inexact model covariance on optimal sequential Bayesian assimilation becomes the focus of the investigation. For the 2-mode system with uncertainty in initial conditions alone, an analytic solution to the governing dynamics can be found and used to solve Liouville's equation by the method of characteristics. Higher-mode systems are considered for exploration of covariance error due to both initial conditions and forcing. In the absence of an analytic solution for this case, Liouville's equation is solved by numerical methods.

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Ensemble-Variational Data Assimilation Methods – Modelling and Diagnosis of Localized Covariances

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Most data assimilation (DA) methods use covariances to characterize the errors they are trying to correct. This enables them to spread the information from scattered observations to all the variables needed to define the analysis and start a forecast. In the ensemble Kalman filter (EnKF) the covariances come from an ensemble of forecasts, giving estimates which reflect both the meteorological situation, and the recent observing network. In applications like numerical weather prediction (NWP), the ensemble has to be very small (O(100)) compared to the degrees of freedom to be analyzed; the usual compensation is to localize the ensemble covariances. Modern NWP models have billions of degrees of freedom, so the effectiveness of localization at supplying the extra degrees of freedom while retaining the real feature in the ensemble covariance is key to the success of the DA algorithm.

Many EnKF algorithms directly localize the error covariance between the observation locations and model variables; this constrains the design of localization methods. Variational (Var) algorithms on the other hand manipulate model fields, making available operators for differentiation, variable transform, balance, scale-decomposition and smoothing. Var traditionally uses a time-averaged “climatological” error covariance estimate, but, using an “alpha control variable” [6], localised ensemble covariances can also be used in “Ensemble-Variational” (EnVar) DA. A combination of the two gives a hybrid method.

We explore the greater scope for sophisticated localization algorithms within hybrid-EnVar. As well as the original horizontal [4] and vertical, localization can be applied between variables, and in spectral space [1]. 4DEnVar methods [5] directly use the 4D covariance from an ensemble of trajectories, so 4D-localisation is also applied. On the other hand hybrid-4D-Var [2] localizes the 3D covariance and gets the time-dimension from its linear and adjoint models.

These methods have all been implemented as options in the Met Office’s VAR system. This paper presents diagnostics of the effect of various localization methods on the implied covariances used. Trials of some of the DA systems are presented in a companion paper [3].

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A Critical Comparison of Methods to Assess Observation Impact in NWP

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In numerical weather prediction the value of a particular observing system can be assessed both in terms of its impact upon atmospheric analyses and forecasts. Understanding this impact allows the data assimilation and forecast system to be optimised to make best use of the available observations.

The classical approach is to perform Observing System Experiments (OSEs) where a particular observation is deliberately withheld (or added) and the quality of the resulting analyses and forecasts compared to a control system. However these are computationally very expensive to perform. Significantly less expensive measures of impact of assimilated observations on analysis or forecast can be obtained from evaluations of degrees of freedom for signal (DFS), adjoint-based methods and the impact of a given observing system upon the analysis fit to other measurements.

This study takes a critical look at the extent to which these different measures of impact can be considered consistent and complementary to each other.

Observation Impact on Forecasts for lead-times beyond 24 hours

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Observation impact on forecasts evaluated using adjoint-based techniques (e.g. Langland and Baker, 2004) are limited by the validity of the assumptions underlying the forecasting model adjoint. Most applications of this approach have been restricted to deriving observation impacts on 24-hour forecasts to stay well within linearization assumptions. The most widely used measure of observation impact relies on the availability of the analysis for verifying the corresponding 24-hour forecasts. As pointed out by Gelaro et al. (2007), and more recently by Todling (2013), this introduces undesirable correlations in the measure that are likely to affect the resulting assessment of the observing system.

Stappers and Barkmeijer (2012) introduced a technique that, in principle, allows extending the validity of tangent linear and corresponding adjoint models to longer lead-times. The methodology provides the means to better represent linearized models by making use of Gaussian quadrature relations to handle various underlying non-linear model trajectories. The formulation is exact for particular bi-linear dynamics; it corresponds to an approximation for general-type nonlinearities and must be tested for large atmospheric models.

The present work investigates the approach of Stappers and Barkmeijer in the context of NASA's Goddard Earth Observing System Version 5 (GEOS-5) atmospheric data assimilation system (ADAS). The goal is to calculate observation impacts in the GEOS-5 ADAS for forecast lead-times longer than 24 hours, both to extend the estimate toward the medium-range and to reduce the potential for undesirable correlations that occur at shorter forecast lead times.

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A posteriori diagnostics in an ensemble of variational assimilations

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Several consistency diagnostics have been proposed to evaluate variational assimilation schemes [4]. In particular, the value of the cost function should be close to its statistical expectation that is directly related to the number of observations in the system. This simple yet powerful diagnostic has been implemented by several authors, in particular with the purpose of tuning variances [1] and testing hypothesis testing [3]. The aim of this work is to extend those results to the covariances of subparts of the background and observation cost functions, using standard theory of quadratic forms in random variables [2].

We will first show that it is possible to derive expressions for the variances of subparts of the background and observation cost functions at the minimum, in the Gaussian case. It is possible to use these expressions for variance tuning, as illustrated first in a simplified variational scheme in a one-dimensional context. We then will prove that background and observation cost functions at the minimum are statistically weakly but positively correlated. Subparts of observation cost functions with uncorrelated observations errors are uncorrelated. This result might serve as a basis for testing for observation error correlations, a recurrent problem for satellite observations.

The expressions for the covariances of subparts of the cost functions at the minimum involve computing the trace of large (and unavailable) matrices, which can be computed using a randomized trace estimate. We will show how to compute them in the ensemble of variational assimilations with perturbed observations implemented operationally at Météo-France [1]. The Gaussian hypothesis will also be discussed, by applying univariate normality tests to an experiment designed with a larger number of assimilations.

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Operational Ensemble Kalman Filter Forecasts For Use in Wind Power Forecasting

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Regional electrical balancing authorities and independent wind farm operators rely on wind power forecasts to estimate the amount of wind energy generation during the current and next operating day. Because power generation is related to the wind speed cubed, small changes in wind speeds can cause large changes in power production. Large increases or decreases in wind power production, also known as ramp events, can impact the balancing of generation and demand, often requiring system operators to dispatch reserve resources. Ramp events can be triggered by a number of meteorological phenomenon including cold fronts, low level jets, thunderstorm outflow boundaries and changes in vertical stability. Grid and wind farm operators require both accurate short term and day-ahead forecasts of power production to determine how much wind generation is available to meet current and forecasted system demand.

In this study, an ensemble forecast system is used to produce wind power forecasts for several regions in North America. Information from the ensemble mean, spread, and the member closest to the ensemble mean are used generate probabilistic and deterministic real-time forecasts. The ensemble, composed of 24 Weather and Research Forecasting members, is run with two nested domains of 51 and 17 km twice a day for 84 hours. The outer domain extends 12,000 km covering most of North America, with the inner domain covering the lower 48 states, southern Canada and northern Mexico. Perturbed Global Forecast Systems (GFS) forecasts are used as boundary conditions for each of the individual ensemble members. Data assimilation is applied to each member by using the Data Assimilation Research Tested (DART) Ensemble Kalman Filter (EnKF) [1] to create an updated set of initial conditions for each ensemble member. This configuration of the EnKF assimilates land surface, buoy, ship, satellite winds, radiosondes, and profiler observations.

The ensemble assimilation performance can be examined by plotting the ensemble spread, analysis increment, and covariance inflation. Additionally, deterministic forecast performance at each wind farm location can be monitored by comparing the ensemble power generation forecast to the observed power generation. Probabilistic forecasts will also be generated using model variables from the ensemble mean or member closest to the mean as well as the ensemble spread. The performance of probabilistic and deterministic forecasts during several high impact ramp events will be detailed. Additionally, the sensitivity of the forecast performance to regional profiler observations will be examined through the use of an ensemble sensitivity analysis (ESA) [2]. To validate the ESA methodology, profiler observations in the regions of high forecast sensitivity will be assimilated and the improvement in forecast performance will be calculated. The conference presentation will highlight the deterministic and probabilistic forecast results during the ramp events.

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Investigating Sources of Error in Numerical Weather Forecasting with an Observing System Simulation Experiment

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It is difficult to evaluate the quality of background, analysis, and short-range forecast errors in numerical weather prediction models due to a lack of independent data for verification. A tool that can potentially be used for examination of these errors is an Observing System Simulation Experiment (OSSE), where the real atmosphere is replaced by a simulation in which the true state of the entire atmosphere is known. In the OSSE framework, errors in the data assimilation process and forecasts can be explicitly calculated, allowing examination of sources of error in a sophisticated modeling system.

An OSSE framework has been developed at the National Aeronautics and Space Administration Global Modeling and Assimilation Office (NASA/GMAO). The performance of the GMAO OSSE has been extensively validated against real observational data to ensure that the behavior of the OSSE is similar to reality in terms of the statistics of observation innovations, analysis increments, forecast skill, and adjoint-estimated observation impacts.

In the simulated reality of the OSSE, aspects of the data assimilation and modeling systems that are hard to modify in the real world may be easily altered in highly controlled or idealized scenarios. A series of experiments is performed in order to examine the relative impacts of observation error, model error, and initial condition error on the evolution of forecast error and on the effectiveness of the data assimilation system. The magnitude of observation errors is varied from low to high, and the global observing network is tested both in a standard realistic configuration and in an idealized global network of high-quality sounding observations. An 'identical twin' case employing a perfect model scenario was also developed to explore the case of no model error.

Observation errors are found to have significant impact on the variance of analysis increments, and can contribute to a degradation of the analysis quality in comparison to the background state if there is a mismatch between the actual error variances and those assumed by the data assimilation system. The smallest analysis errors are achieved in the case of the idealized observing network. The case of the idealized observing network also features the largest total amount of 'work' done by observations during cycling of the data assimilation system.

It is found that model error is a major contributor to the evolution of forecast skill. The forecast skill in cases with no model error showed an improvement in skill compared to cases with model error equivalent to a decrease in forecast lead time of two days in the extratropics and four days in the tropics. In comparison, when the initial condition error is greatly reduced but with model error included, the forecast error increases rapidly during the first 24-36 hours of integration, and the improvement in forecast skill is only equivalent to a reduction in forecast lead time of one day in the extratropics and two days in the tropics.

Sensitivity Experiments with a LETKF Data Assimilation Scheme Employing the WRF Model

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Abstract

In this work the Local Ensemble Transform Kalman Filter [1] (LETKF) implemented in the Weather Research and Forecasting model (WRF) [2] is used to study the sensitivity of this algorithm to different error sources. The domain covers South America and its adjacent oceans. Our approach consists in performing different OSSE experiments where the truth is generated using the WRF model, forced with the FNL analysis. A set of observations is generated taking randomly perturbed values from this true state. LETKF analysis cycle experiments using 40 ensemble members and adaptive covariance inflation [3] were performed using these observations. The following experiments have been performed:

- Perfect model with perfect boundary conditions
- Imperfect model with perfect boundary conditions
- Perfect model with imperfect boundary conditions
- Imperfect model with imperfect boundary conditions

Where Perfect model / Perfect boundary refer to the same version of WRF and boundary conditions used to generate the "true state", while imperfect model includes changes in WRF cumulus and planetary boundary layer parameterizations and imperfect boundary conditions correspond to the utilization of the Reanalysis I dataset to force the model.

Each of these experiments employs the same boundary conditions for all the ensemble members, regardless whether they are perfect or not. The evolution of the ensemble spread under this constrain is analyzed. Results show that the errors in boundary conditions are particularly important in data assimilation problems with limited area domains. Moreover, they indicate that there is a need to perturb the boundary conditions in order to prevent the ensemble spread from collapsing. Nevertheless, adaptive inflation makes a good job in adjusting the ensemble spread in each of the experiments and helps in maintaining the spread under the constraint imposed by the boundary conditions.

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Second and Third order Adjoint Methods for Sensitivity Analysis in Pollution Models

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Understanding the impact changes in pollutant emission from a foreign region on a target region of is a key factor for taking appropriate actions against the pollution and its drawbacks. This can be carried out by the sensitivity analysis of a response function with respect to the source of pollutant. The basic approach determines the sensitivity by carrying out multiple simulations with variation of source parameters. A systematic approach uses the first order adjoint formualtion. Both approaches assume that the transport velocity and the initial distribution of the pollutant are known. However, they are given by the solution of a Data Assimilation problem whose ingredients include, but are not limited to, the pollutant source, the mathematical model and physical measurements. As a consequence, the sensitivity analysis should be carried out on the optimality system of the Data Assimilation problem. It leads to a non standard problem on a second order adjoint system whose the solution requires the third order adjoint.

We present the mathematical derivation of the third order adjoint method for the sensitivity analysis, along with some numerical experiments and a comparison with the first order adjoint approach.

A Comparison of Impacts of Radiosonde and AMSU Radiance Observations In GSI-based Hybrid and 3DVar Data Assimilation Systems for NCEP GFS

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The impact of observations can be dependent on many factors in a data assimilation (DA) system including data quality control, preprocessing, skill of the model and the DA algorithm. The present study focuses on exploring the difference of the impacts of observations assimilated by two different DA algorithms. A 3DVar-based ensemble-variational (3DEnsVar) hybrid data assimilation system was recently developed based on the Gridpoint Statistical Interpolation (GSI) data assimilation system and was implemented operationally for the GFS. One interesting question is if and how the impacts of observations differ when assimilated by the GSI 3DVar and 3DEnsVar. Experiments were conducted over a 6-week period during Northern Hemisphere winter season at a reduced resolution of T190L64 following the configuration of [1]. The control runs assimilated all operational conventional and satellite observations. The impacts of AMSU and Radiosonde observations were studied through data denial experiments. These platforms were selected based on the significance shown by these two data sets in the previous studies. The impacts of AMSU and Radiosonde assimilated by 3DEnsVar were compared with those assimilated by GSI 3DVar. For both the control and data denial experiments, the forecasts produced by the 3DEnsVar are more accurate than the GSI3DVar experiments. The AMSU and Radiosonde, showed positive impact assimilated by both DA schemes in general. In the GSI3DVar, the errors of global wind and temperature forecasts were increased more by denying Radiosonde than denying AMSU observations. In the 3DEnsVar,such impacts of the AMSU and Radiosonde are similar. For the humidity forecasts, the AMSU has larger impact than Radiosonde in both the GSI3DVar and the 3DEnsVar. For the GSI3DVar, the Radiosonde and AMSU observations show similar impact in both magnitude and spatial distribution in the Southern extra-tropics (SH). For the Northern extra-tropics (NH), Radiosonde shows larger and more extensive impact than AMSU. The largest difference of the degradation of the forecast between the 3DEnsVar and GSI3DVar was seen in the SH when Radiosonde was denied, where the forecast was degraded much less in the 3DEnsVar than in the GSI3DVar. The percentage degradation of the forecast skill after denying Radiosonde and AMSU observations is less in the 3DEnsVar than the GSI3DVar. The anomaly correlation of forecasts up to 5-day forecast lead time indicates that the impact of AMSU and Radiosonde observations increases with increasing forecast lead time in both DA systems. The AMSU radiance biases estimated by the GSI 3DVar and the 3DEnsVar show similar values.

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Flow dependency of the global forecast errors: a comparison between a perfect-model experiment and an NWP system

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This study applies the normal-mode function framework to the representation of time-averaged and time-dependent structure of forecast errors.
The applied methodology provides an attractive way to measure the balance by splitting forecast-error variances into parts projecting on the balanced and inertio-gravity (IG) circulations; the approach is particularly suitable for the tropics where the IG circulation dominates on all scales.
The of the modal analysis of the ECMWF ensemble of 4D-Var analyses show that little over 50% of the global forecast-error variance in short-range is balanced. The variance growth between 3-hr and 12-hr range is substantially different in the balanced, eastward and westward IG modes. The balanced mid-latitude variance growth dominates while the variance growth in the IG modes is most significant in the large-scale equatorial Kelvin waves.
Results from the ECMWF ensemble are compared with outputs from a perfect-model ensemble data assimilation experiment which assimilated globally homogeneous observations of dynamical variables by using the ensemble adjustment Kalman filter in the Community Atmosphere Model (DART/CAM).

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Ensemble Transform Adjoint Method for Adaptive Observation

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Adaptive observations provide flexibility and opportunity of much needed observations for High Impact Weather (HIW) due to the limited coverage of existing observation systems, especially over remote areas. Optimal deployment of these adaptive observations might make significant difference impacting forecast accuracy. Ensemble Transformation method (ET) has been shown a useful tool for adaptive observation deployment. In this paper, a new adjoin method is proposed for improving the ET method in efficiency and accuracy. It is named as Ensemble Transformation Adjoint (ETA). ETA improves ET in aspects, 1) ETA reflects variance impact in more meteorologically and statistically meaningful manner since its signal is proportional to the analysis error variance., i.e., areas with larger analysis error variance are more likely identified as sensitive regions; 2) ETA calculates its sensitive regions without loop over all the possible observational resource compared to ET. ETA and ET are applied to a real hurricane case: 2011 Irene. The results confirm the improvements.

Evaluation of the Relative Contribution of Observing Systems in Reanalyses: Aircraft Temperature Bias and Analysis Innovations

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Reanalyses have become important sources of data in weather and climate research. While observations are the most crucial component of the systems, few research projects consider carefully the multitudes of assimilated observations and their impact on the results. This is partly due to the diversity of observations and their individual complexity, but also due to the unfriendly nature of the data formats. Here, we discuss the NASA Modern-Era Retrospective analysis for Research and Applications (MERRA) and a companion dataset, the Gridded Innovations and Observations (GIO). GIO is simply a post-processing of the assimilated observations and their innovations (forecast error and analysis error) to a common spatio-temporal grid, following that of the MERRA analysis fields. The data includes insitu, retrieved and radiance observations that are assimilated and used in the reanalysis. While all these disparate observations and statistics are in a uniform easily accessible format, there are some limitations. Similar observations are binned to the grid, so that multiple observations are combined in the gridding process. The data are then implicitly thinned. Some details in the meta data may also be lost (e.g. aircraft or station ID). Nonetheless, the gridded observations should provide simplified access to all the observations input to the reanalysis.

To provide an example of the GIO data, a case study evaluating observing systems over the United States and statistics is presented, and demonstrates the evaluation of the observations and the data assimilation. The GIO data are used to collocate Radiosonde and Aircraft temperature measurements from 1979-2012. Using the observed residuals from the MERRA data assimilation, we statistically infer the contextual bias and effective gain for various observing systems.

A known warm bias of the aircraft measurements is apparent compared to the radiosonde data forecast departures. However, when larger quantities of aircraft data are available, they dominate the analysis and the radiosonde data become biased against the forecast. When AMSU radiances become available the radiosonde and aircraft analysis and forecast residuals take on an annual cycle. While this supports results of previous work that recommend bias corrections for the aircraft measurements, the interactions with AMSU radiances will also require further investigation. This also provides an example for reanalysis users in examining the available observations and their impact on the analysis. GIO data is presently available alongside the MERRA reanalysis.

Evaluation of Observing Systems variations on Central US Water Cycle

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NASA's latest reanalysis, the Modern-Era Retrospective analysis for Research and Applications (MERRA), has shown significant improvement over previous reanalyses in terms of global, continental and basin scale climatological precipitation. However, details of regional water cycles still exhibit biases that result from model physics uncertainties interacting with an observation suite that varies in space and time. This paper investigates biases at the regional scale to provide understanding of the data assimilation, assimilated observations and forecast water cycle terms.

The extent of regional biases can be deduced from the magnitude and behavior of the non-physical increment terms of the conservation equations which provide a wealth of information as to the biases in model physics as well as the utility and veracity of the observations being assimilated. A new data set just now being released is called the MERRA Gridded Innovations and Observations (GIO). MERRA-GIO includes not only the observations assimilated in MERRA, but also the forecast and analysis departures compared to each observing system, in a straightforward data format. Using this data, we can ascertain the degree to which the reanalysis agrees with each observing system and how the observations influence the increments. Ultimately, we can identify the major observing system controls on the moisture, heat and radiative fluxes and transports.

This paper focuses on North America, where a strong dipole structure in the vertically-integrated moisture increments during the warm season signifies a discrepancy between E-P from the model physics compared to that derived by moisture transport. In this conventional data rich region, we will use the MERRA-GIO data set to determine the relative constraining roles of various observations and to examine the systematic forcing from model physics (or lack thereof) that requires correction. While the water vapor increments are significant in the region, and comparable to the moisture flux divergence, significant changes in the numbers of aircraft and profiler measurements of wind occur through the period.

A Quality Control Study of NOAA MIRS Cloudy Retrievals during Hurricane Sandy

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Cloudy radiancies present a difficult challenge to data assimilation (DA) systems, through both the non-linear radiative transfer behaviors as well the complex hydrometer interactions required to resolve the clouds and precipitation. In most DA systems the hydrometers are not control variables due to many limitations.

The National Oceanic and Atmospheric Administration's (NOAA) Microwave Integrated Retrieval System (MIRS) is producing products from the Suomi-NPP ATMS satellite sensor when the scene is cloud and precipitation affected. We present a test case from Hurricane Sandy in October 2012.

As a quality control study we compare the retrieved water vapor content with the first guess and the analysis from the NOAA Gridpoint Statistical Interpolation (GSI) system during the lifetime of Hurricane Sandy. The assessment involves the gross error check system against the first guess with different values for the observational error's variance to see if the difference is within three standard deviations. We also compare against the final analysis at the relevant cycles to see if the products which have been retrieved through a cloudy radiance are similar, given that the GSI system does not assimilate cloudy radiances yet.

A Non-linear Method for IASI Channel Selection

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The IASI instrument measures top of the atmosphere (TOA) radiances in 8641 channels. In many cases it is difficult to transmit, store and assimilate such a large amount of data [1]. A practical solution is to select a few hundred channels based on those with the highest information content.

Mutual Information (MI) measures information content as the change in entropy when the observations are assimilated. When the observation operator is linearized and the error distributions are all Gaussian, MI has a known analytical form. This linear approximation to MI has been used in previous studies of channel selection (e.g. [2]). However, if we wish to allow for the non-linear relationship between the state vector (profiles of temperature and humidity) and the TOA radiances then no analytical form for MI can be given.

We present a sampling method to calculate MI which is free from assumptions about the linearity of the observation operator and the structure of the posterior distribution, as such providing a more accurate estimate of the information content. This approximation of MI is seen to lead to very different estimates of the information content compared to the linear approximation for some individual channels. Furthermore differences are also seen in the value of MI for one channel relative to another giving a change in the order of channel selection.

We conclude this study by looking at the efficiency of the non-linear method. This method can be seen to suffer from under-sampling as the channel selection progresses and the region of high posterior probability is focused. Resampling from the posterior distribution after each channel is selected is shown to alleviate this problem.

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Joint OSSE and OSSE at JCSDA

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An international collaborative effort for Observing System Simulation Experiments (OSSE) was developed over the last several years (Andersson and Masutani, 2010). Although a large initial investment is required for OSSE, using an OSSE is the most reliable strategy today to assess the quantitative impact from prospective observing systems. The 13 month long (From May 2005-May2006)Joint OSSE Nature Run was produced by the European Center for Medium-Range Weather Forecasts (ECMWF) and shared with the internationally collaborative Joint OSSE community. A simulation of observations over the Nature Run period for control experiments, based on the observations available during the period, was completed by the National Centers for Environmental Prediction (NCEP) and Joint Center for Satellite and Data Assimilation (JCSDA) and shared with the Joint OSSE community. Initial conditions for NCEP global model are also provided.

In order to conduct OSSEs with more recent observations, observations from instruments such as CrIs, ATMS, IASI, SSMIS, and Seviri; from satellites such as Metop, NOAA18 and NOAA19; and from GPSRO and other observational data available in 2012 have been simulated for July, August,January and February. Further simulated observation used for OSSE experiments may become available.

JCSDA has conducted OSSE to assess data impact of DWL(Riishojgaard et al.) and additional satellites in Early-Morning Orbits. in various configurations have been conducted. Further OSSE to evaluate additional GPSRO and Arctic Observation are planned. JCSDA is acquiring a new higher resolution Nature run to conduct OSSE for hurricane forecasts.

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Quantifying uncertainty in Transient Climate sensitivity subject to uncertainty in forcing and natural variability using a non-Gaussian filter

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Uncertainty in future climate change presents a key challenge for various socio-economic policies and planning decisions. Estimates of climate sensitivity are typically characterized by highly asymmetric probability density functions (pdfs). The reasons are well known, but the situation leaves open an uncomfortably large possibility that climate sensitivity might exceed the current estimates of uncertainty. We address the importance of considering non-Gaussian distributions in quantifying uncertainty on estimates of transient climate sensitivity (TCS) of the globally averaged surface temperature, including both uncertainty in past forcing and internal variability in the climate record using a nonlinear particle filter. We extend previously done analysis of this uncertainty to non-Gaussian systems and discuss the implications of important effects such as intermittency and granularity of the climate system. We make these estimates using a nonlinear particle filter coupled to a stochastic, global energy balance model, using the filter and observations to constrain the model parameters. We compare these uncertainties to those obtained from a Gaussian analyses based ensemble Kalman filter estimates. We verify that model and filters are able to emulate the evolution of the global mean temperature derived from comprehensive, state-of-the-art atmosphere-ocean general circulation models and to accurately predict the TCS of the model, and then apply the methodology to observed temperature and forcing records of the 20th century.