OBSERVATIONS AND THEIR ASSIMILATION IN GLOBAL TO CONVECTIVE SCALE MODELS

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ABSTRACT

The accuracy of NWP model forecasts continues to improve. Important contributions to this are the advances made in data assimilation, coupled with increased computer power, better models, and more extensive observing systems. Global models continue to make use of increasing amounts of satellite data enabled by greater computing power and higher resolutions. The challenge now is to assimilate observations in convective scale models that represent phenomena with much shorter temporal and spatial scales. Novel observation networks are required for these fine scale models as in-situ observations have very limited coverage. New techniques for assimilation of observations of all kinds are now being developed particularly for convective scale models.

1. INTRODUCTION (max 300 words)

This white paper was prepared by contributors to the session on *Observations and Data Assimilation in global to convective scale models* at the WWRP Open Science Symposium held in Montreal in August 2014 and attempts to provide a summary of the current status.

The assimilation of many different kinds of observations from satellite radiances to cloud base observations is now commonplace at most forecast centres. Methods developed and applied with great success in global-scale NWP over the last two decades are now being extended with increasing success down to the convective scale, with the latter providing demonstrated improvement over simply “down-scaling” lower-resolution analyses. However, the application of these methods is far from seamless, requiring careful consideration of the underlying model properties and specific data types. Current global models have horizontal resolutions on the order of 10 km or more, are mostly hydrostatic and include parameterizations for convection and other physical processes. Convective-scale models have resolutions on the order of 1 km, are non-hydrostatic, and resolve scales dominated by highly nonlinear processes. To perform optimally, the data assimilation systems developed for these models must account properly for these characteristics, including differences between the scales present in the model and those present in the observations.

An ongoing challenge is to maintain the coverage of the observing system as satellite instruments fail and are not replaced and surface networks over land and ocean decline. A positive trend is that in recent years more nations are sharing the burden of contributing to the global observation network, both in-situ and satellite, which can provide some redundancy. Use of fine-scale observations in convective scale models is still at an early stage and more work is needed on developing observational networks to cover mesoscale areas but this is an emerging activity.

2. OBSERVATIONS

The global observing system (GOS) is co-ordinated by WMO and includes many diverse types of observation as shown in Figure 1. The OSCAR[1] database maintained by WMO is a good summary of the observational requirements[2] for NWP and current/planned capabilities of the surface and space based observations. These observations are transmitted to NWP centres in near real time (typically within 3 hrs for global NWP) on the global telecommunication system in several different formats although BUFR is being increasingly adopted for all observation types. BUFR allows a more complete description of the observations encoded in a compact format. The suite of observations made of the atmosphere, land and oceans can be divided into four classes, surface in-situ, upper atmosphere in-situ, ocean at depth in situ and satellite remote sensing of the atmosphere and surface which are described briefly below. The observations received at the U.K. Met Office for assimilation in its global NWP model are given in Table 1 together with a summary of their characteristics and the percentage actually assimilated after quality control and thinning.

2.1 In-situ Observations

Surface in-situ observations over land are provided from the global network of Surface Synoptic Observations (SYNOP) stations which provide measurements at least every six hours of temperature, pressure, wind and relative humidity nominally at a height of 1.5-2m (Ingleby, 2014). Over 80,000 observations are received in a day within 3 hrs of the measurement time to be assimilated in NWP models. In addition to the SYNOP network, METARS which are reports of pressure and temperature for aviation purposes, typically at airfields, are now also being used by NWP centres. A relatively new observation type is zenithal total delay (ZTD) from GPS sensors on the ground. ZTD (Yan et. al., 2009) is a measure of the total column water vapour in the atmosphere and is measured under all weather conditions. The measurements are made in most countries but the dissemination of the data to NWP centres is still work in progress. Europe and the U.S. have good networks which provide data in near real time but there is scope for much more data to be made available from other countries. There are initiatives to make use of new sources of data, especially for convective scale models, such as from crowd sourcing sites and utilising mobile phone technology. These should not be seen as a replacement for the conventional observations however, which provide the reference but as a means to improve the coverage.

Upper air observations from the surface come from radiosonde ascents, aircraft profiles, wind profilers, cloud base heights and radar winds and reflectivity to infer precipitation. Assimilation of all but radar reflectivity is mature and widespread. With the move of all observations to be reported in the BUFR format from Nov 2014 this will enable users to be able to access more detailed vertical profile information. Aircraft wind and temperature data are now widely reported and provided to NWP centres but are restricted to the flight paths of commercial airlines with profiles at airports. Aircraft profiles of water vapour concentration are now starting to become available as instrumentation is developed, but currently these are limited to over the U.S. and Europe (Gao et. al. 2012). Wind profilers are used, primarily over Europe, to provide vertical wind profiles up to the tropopause height. The coverage of this network has declined in recent years particularly over N. America. Weather radars are now widely used in NWP models both for defining the wind field and mostly in research mode for defining areas of precipitation.

[1] http://www.wmo-sat.info/oscar/
[2] http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html

Over the ocean the in-situ observations are mainly from the drifting buoy network introduced in the late 1990s supplemented by moored buoys, rigs and ships. Pressure, wind and sea surface temperature are all measured. Funding constraints have led to cutbacks in the moored buoys in the Pacific but efforts are underway to restore the network. In addition, Argo floats have started to provide profiles of temperature and salinity down to 2000m. Marine mammals are being instrumented to provide a new source of three dimensional ocean data primarily in the southern oceans. Underwater gliders are also being developed to sample the ocean at several depths over periods from weeks to months.

2.2 Satellite Observations

Satellites provide a wealth of observations of the atmosphere and surface which in principle provide good global coverage. Typically more than 10^5 measurements for a specific satellite observation type (see Table 1) are received every day at operational centres. However due to difficulties in using the data over land, cloud and sea-ice, and the need to thin the data to reduce horizontal error correlations between measurements, only about 20% of most satellite data are actually assimilated. A key objective is to increase the amount of satellite used in these areas.

The primary measurement of the atmosphere and surface properties from space is from the top of atmosphere radiation emitted by the surface, atmosphere and clouds. The atmosphere is sensed across the electromagnetic spectrum from the microwave to ultra violet wavelengths. The variable spectral absorption of atmospheric gases allows profiles of atmospheric temperature and water vapour to be inferred from the measured radiances. Table 1 lists the radiances received from many sensors in polar and geostationary orbit which are currently assimilated in NWP models. Both advanced infrared sounders with high spectral resolution and radiometers with broader spectral responses are used to modify the NWP fields of temperature and humidity to better fit the observations (see sec. 3.2). Assimilation of radiances over cloud and land surfaces is still an area of research but increasingly the data are being exploited over these surfaces. Although only 10-20% of the data received are assimilated, microwave radiances give a much better global coverage compared to the infrared radiances as they are not affected by non-precipitating cloud. Visible and near infrared radiances are not assimilated at present but work is in hand to enable this. The total column amounts of trace gases (e.g. ozone, nitrous oxide, methane and carbon dioxide) and aerosol optical depths can also be inferred from the radiances which are exploited in atmospheric composition models (e.g. MACC).

Bending angles from GPS radio occultation measurements have become available in near real time to the meteorological community since the early 2000’s and the constellation of satellites has increased to give reasonable global coverage although in recent years it is declining as the original satellites start to come to the end of their life. A new constellation of satellites is being planned. The advantage of these bending angle measurements is that they do not rely on any calibration in contrast to the radiometers, and so can be considered as an absolute reference measurement of upper tropospheric and stratospheric temperature (Eyre, 1994). This makes these measurements attractive for climate monitoring and investigating biases in radiosonde temperature profiles.

Scattering of microwaves from the sea surface measurements provide important information about the sea surface wind strength and provide some information on direction giving several preferred directions which the assimilation system can then select (Figa-Saldaña et. al., 2002). Studies have shown that at least 2 of these active microwave instruments in polar orbit provide significant impacts in NWP forecasts, particularly for tropical cyclone forecasts. Currently there are only operational scatterometers in the morning orbit available to forecasting centres, which is sub-optimal for providing a good daily coverage (note Table 1 includes data from OSCAT before it failed in Feb 2014). These active microwave measurements have also proven useful over land surfaces to infer soil moisture in the upper surface levels and these data are now assimilated in land surface models.

Atmospheric Motion Vectors (AMVs) or cloud motion winds are a product derived from tracking clouds or water vapour features in geostationary image sequences and successive overlapping polar orbiter passes (Soden et. al., 2001). They give good coverage for low and high cloud features but are sparse at mid-levels. Their impact in NWP models has been less than anticipated which may be in part due to inaccurate height assignments of the wind vectors. Various techniques have been developed to allow for this in the assimilation, for instance by reducing the weight in regions of strong vertical wind shear. New AMVs are now being generated from a combination of polar and geostationary satellites with the aim of filling the gap between the latitudes of 55-65N and 55-65S where geostationary and polar AMVs cannot be inferred. In the next few years a satellite doppler wind lidar will provide line of sight winds at all levels in clear skies and be a step forward in 3 dimensional measurements of the atmosphere.

Active microwave rain radars (Benedetti et. al. 2005) are now in space (e.g. TRMM, GPM) but assimilation of the precipitation information has not yet been developed to a stage where it is used in operational systems due to the highly non-linear nature of precipitation and how it is related to the model variables.

2.3 Impact of Observations in NWP systems

Over the past few years tools have been developed to quantify the impact of all observations in NWP systems both for short range forecasts and longer range predictions. For the former as a by-product of the development of four-dimensional variational data assimilation (4D-Var) systems, adjoint-based techniques, often called “Forecast Sensitivity to Observations” (FSO), have been developed (Langland and Baker, 2004; Gelaro et al, 2010; Lorenc and Marriott, 2014). These have enabled the impact of observations in a number of different ways to be assessed for example by looking at the impact of a complete satellite, to the impact of different measurement types as plotted in Figure 2 to individual components of the measurement such as radiances in different channels. This flexible framework can be very valuable in assessing the value of different observations. These adjoint techniques are best for impacts on short-range forecasts, typically 24 hours. The FSO results between different centres have been compared and shown to be broadly consistent giving confidence in the technique. The impact assessments of observations in regional and local area models is still in its infancy and requires some development. There will also be a challenge to provide this capability for the new ensemble data assimilation systems now being implemented.

For longer forecast periods the more traditional Observing System Experiments (OSE) can be run where the full data assimilation is run without one particular observation type included and compared to the control run where all the observations are used e.g. Bouttier and Kelly (2001). This shows the impact of that observation type for the complete forecast period. The drawback is that OSEs are much more expensive to run than FSOs as the latter can be run as an add-on to the operational assimilation system but they do give a more complete picture of the impacts of an observation. Both the FSO and OSE estimates of observation impacts are being used for cost-benefit studies to inform the design of the future global observing system.

OSEs have been further developed to try and assess the impact of new types of observations not yet available (e.g. line of sight doppler winds) and these have been termed OSSEs (Observation System Simulation Experiments) as described in Becker et al (1996) and Masutani et. al. (2002). These OSSEs rely on a 'nature run', typically an extended integration of an NWP model, from which the observations can be simulated using the observation operators. These simulated observations are then assimilated into a different forecast model as an OSE type experiment to assess their impact. The drawback of OSSEs is the continued need for providing updated nature runs from which to generate simulated observations datasets which requires significant resources.

2.4 Adaptive Observations

Adaptive or targeted observations refer to those, in addition of the regular observing network, which can be specifically directed to certain locations with the aim of improving NWP forecasts in particular weather situations. These locations are chosen in order to improve forecasts of high-impact weather events. Examples include dropwindsondes launched from aircraft or balloons, additional rawinsonde ascents, directed remotely sensed observations, and the inclusion of more regular satellite observations (such as radiances or winds) that are normally excluded from the assimilation due to routine thinning or quality control procedures. As a consequence of many field campaigns worldwide during the past two decades, advancements have been made in the development of objective strategies for targeting observations, and in quantitative evaluations of the impact of assimilating these extra observations on numerical weather predictions.

To date, observations have primarily been targeted to improve short-range (1-3 day) forecasts of extratropical and tropical weather. For extratropical systems, the value of targeted data has been found to be mixed and small on average although it is dependent on the flow regime, the numerical model, and the treatment of both routine and targeted observations in the data assimilation scheme. For forecasts of the track of tropical cyclones (TC), targeted observations have been shown to provide statistically significant benefit. A simple sampling strategy of observing uniformly around the TC has been shown to be effective, with most models exhibiting an improvement in their track forecasts. Recent studies have also demonstrated that observations targeted for TCs can improve the skill of forecasts in regions well away from the TC. The mechanisms behind how TC forecasts are improved, and can be improved further, by targeted observations is a subject for continuing research.

3. DATA ASSIMILATION

3.1 Methodology

The steady increase in computing power and availability of diverse, high-quality observational data types have combined to make data assimilation an essential component of numerical weather prediction from global to convective scales. Like the forecast models themselves, the data assimilation systems for global and convective-scale applications have been developed separately, but generally employ similar methodologies including, for example, three- and four-dimensional variational schemes (3D- / 4D-Var) and ensemble Kalman filters (EnKF). Variational algorithms, being well suited to accommodate large numbers and types of satellite radiance observations, remain the cornerstone of most operational data assimilation systems, especially for the global scale. The inclusion of bias correction terms (discussed below) and additional constraints, such as for controlling gravity wave noise, is relatively straightforward in these schemes. The implementation of 4D-Var in particular has provided significant positive impact on forecast performance at several operational centres (..refs..). The major strength of 4D-Var is that it takes into account the dynamics of the forecast model to ensure observations are used in a meteorologically consistent way within the assimilation window (Rabier et al, 2000). It is, however, computationally expensive, requires significant infrastructure development, including tangent linear (TL) and adjoint (AD) versions of the forecast model, and does not propagate flow-dependent information from one assimilation cycle to the next.

On the meso- and convective scales, ensemble methods have been applied with considerable success. In contrast with 4D-Var, development of an ensemble data assimilation scheme typically requires less initial infrastructure development (TL and AD models are not required). Most importantly, ensemble-based background error covariances are fully flow-dependent and their use circumvents the need to develop explicit background error models involving poorly understood balance relations and complex physical processes. While still computationally intensive, especially for increasing ensemble sizes, these algorithms are well suited for implementation on large parallel computers. However, the practical necessity of having to rely on small ensemble sizes (relative to the size of the model state) presents ongoing challenges. Typically, these systems require the incorporation of ad-hoc technical controls to which the system's performance is highly sensitive. These include the use of localization functions to reduce spurious correlations in the sample covariances, as well as inflation of the ensemble to maintain an appropriate level of spread among the members.

Most recently, efforts to combine the recognized strengths of both the variational and ensemble approaches have catalysed the development of 3D- and 4D-hybrid data assimilation schemes (Fig 3). Techniques that have emerged include running an ensemble of variational assimilations to provide flow-dependent parameters to the background error covariance model (e.g., as done at ECMWF and Météo France), as well as direct incorporation of an ensemble-based background term into the variational cost function (e.g., as done at CMC, Met Office, NCEP). Some centres are also developing a variant of the 4D-hybrid system that uses 4D flow-dependent covariances estimated from the ensemble members without the need for the TL and AD models used in traditional 4D-Var. Referred to as 4D-EnsVar, this approach has the advantage of implicitly incorporating the effects of the full suite of model physics within the variational minimization while eliminating the need to run and maintain additional TL and AD codes. It also ameliorates some of the computational limitations of traditional 4D-Var stemming from the inefficient use of large numbers of processors to run relatively low-resolution versions of the TL and AD models within the minimization loop (as compared with the typically higher resolution background forecast model). A key question in 4D-EnsVar is whether a limited ensemble can adequately represent the dynamic effects of the TL and AD models during the minimization process.

While the methodologies used for global and convective-scale data assimilation are similar in origin, their application, and hence the details of the resulting algorithms, can differ significantly. For example, in convective-scale data assimilation, rapid updates are essential and involve novel observation types such as radar reflectivity, radial wind information and lidar backscatter; background error structures can vary significantly depending on whether convection is absent or present; highly nonlinear dynamics often result in non-Gaussian error distributions, while the analysis is designed to produce the best state estimate under Gaussian assumptions. The latter may be especially challenging for the assimilation of cloud and precipitation data where displacement errors can dominate. In an ensemble context, this can lead to situations where the analysed (ensemble mean) position of a given feature may not fit the available observations. To be clear, however, the increasing focus on observation types with non-Gaussian error distributions poses significant challenges in both the variational and ensemble contexts.

Accounting for model error in the assimilation process remains a significant challenge going forward. In the variational context, weak constraint extensions to 4D-Var are, in principle, straightforward. However, estimation of the required model error covariance (that is, characterizing the statistical properties of model error) has so far proven to be very difficult. Reasonable first attempts, such as assuming the model error covariance is simply proportional to the background error covariance, or applying the same statistical model for computing background errors to tendencies instead of analysis increments, have met with limited success. Other approaches include using tendency differences between members of an ensemble as a proxy for samples of model error (Trémolet 2012, personal communication). In the ensemble context, the focus is on replacing additive inflation factors with more physically based approaches such as using multiple physics packages within the ensemble, or stochastically perturbing the physics tendencies (...refs...).

3.2 Use of Satellite Radiances

Modern data assimilation systems make abundant use of satellite observations as described in sec. 2.2. The assimilation of satellite radiances, in particular, has been an area of great progress over the last two decades and a major factor in the improvement of forecast skill, especially in the southern hemisphere. These data currently account for a large majority of the available observations used in operational numerical weather prediction. While some of the improvement in forecast skill comes from improved instruments and the increased number of available observations, most of it comes from our improved ability to use the information in these observations (Derber and Collard, 2012, hereafter DC12). Fig. 4 shows the increase in forecast skill with time from the evolving ECMWF operational forecast system (top panel), as well as from fixed versions of the system used in recent reanalyses (bottom panel). Two points are readily discerned from the figure: 1) forecast skill increases at a considerably faster rate in the operational forecast system, reflecting system improvements in addition to changes in the observing system, and 2) forecast skill in the southern hemisphere improves dramatically beginning in the mid to late 1990's. This period coincides with the implementation of direct assimilation of satellite radiances using 3D- and 4D-Var.

Satellite observations have characteristics that make them unique and especially challenging to use compared with most other observation types. Most of these data are asynoptic, exhibit significant biases due to instrument characteristics and other factors, and provide only indirect measurements (radiances) of the model and analysis variables (e.g., temperature and humidity). Accordingly, much of the progress in the use of satellite data has stemmed from careful consideration of these characteristics in the design of the assimilation system, including quality control procedures, bias correction, and observation error specification.

Key to the assimilation of satellite radiances is the treatment of the forward model that transforms the analysis variables to the form of the observations. In the case of satellite radiances, the forward model involves integration of a fast radiative transfer model whose inputs include model profiles of temperature, humidity and ozone, as well as surface characteristics including skin temperature, emissivity and surface type. For low-peaking channels with strong surface sensitivity, the latter can be a significant source of uncertainty in the radiative transfer calculation. Thus, most of these data go unused in current data assimilation systems. For channels that have a significant moisture signal, the forward model calculation may be weakly nonlinear, while the inclusion of clouds and precipitation can be strongly nonlinear, adding significant complication and expense to minimizing the variational cost function that defines the analysis problem (DC12). For this and other reasons, the vast majority of the data currently assimilated are limited to cloud-free scenes or channels that peak above clouds. However, efforts are underway in many research and operational centres to expand the use of cloud- and rain-affected radiances, sometimes referred to as “all-sky” radiance assimilation. In 4D-Var, the forward model also includes an integration of the TL and adjoint AD forms of the forecast model from the analysis time to the observation time. Use of 4D-Var has proven to be especially effective for extracting information from asynoptic satellite observations as well as other non-conventional data types.

Advances in the detection and removal of observational bias have also been an important part of the progress in assimilating satellite radiances. The bias in a given satellite channel can vary significantly in space and time depending on the atmospheric conditions, errors in the radiative transfer model, and quality and age of the instrument (Rienecker et al., 2011). Currently, most operational centres employ a variational bias correction scheme in which bias parameters for each satellite channel are added to the control vector and updated during the analysis cycle along with all the other analysis variables (Derber and Wu, 1998; Dee and Uppala, 2009). The bias estimates thus adapt in response to natural phenomena, such as volcanic eruptions, or changes in the instrument quality and orbital position of the satellite that can severely affect the radiance measurements (see, for example, Figs. 4 and 5 in Dee and Uppala, 2009). It should be noted that a drawback of this procedure is its inability to distinguish between model and observation bias when no other data are available, potentially making erroneous corrections to the observations due to biases in the forecast model. In particular, it is important that the observing system maintain some threshold level of unbiased observations to “anchor” the bias estimation for satellite radiances. The growth in the number of GPS radio occultation data over the last decade has played an important role in this context, but a possible decline in the number of these data if aging instruments are not replaced, while unfortunate in its own right, could also adversely affect the use of satellite radiances.

Observations from satellites are now enabling the assimilation of new variables such as clouds and precipitation, trace gases and aerosols, and characteristics of the land surface and ocean. DC12 point out that inclusion of additional analysis variables poses several challenges emphasizing the integration of all components of the assimilation system. These include accounting for nonlinearities in the assimilation of clouds and precipitation, and specifying background error covariances so as to use information in the data at the correct scales and make proper adjustments to other variables. Other suggested focus areas for improving satellite data usage include properly accounting for biases in the forecast model, and improving our ability to simulate surface properties such as skin temperature and emissivity.

4. CONCLUSION

A conclusion with no more than 300 words. To be added after inputs from OSC.

Acknowledgements

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Tables and Figures

Observation group	Observation Sub-group	Items used	Daily extracted	% assimilated
Ground-based vertical profiles	TEMP PILOT PROFILER	T, V, RH processed to model layer average As TEMP, but V only As TEMP, but V only	1,300 830 18,000	96, 95, 76 21 17
Satellite-based vertical profiles	METOP-A/B NOAA-15/16/18/19, Aqua AIRS, IASI, HIRS, AMSU-A/B, MHS, ATMS, CrIS. GOES-13/15, Met-10, MTSAT-2. Radio-occultation COSMIC, GRAS AOD MODIS AQUA, MSG	Radiances directly assimilated with channel selection dependent on surface instrument and cloudiness. Profiles of refractive index. Aerosol Optical Depth	ATOVS:4,000,000 IASI: 500,000 AIRS:300,000 ATMS: 320,000 CrIS: 300,000 GOESclr:600,000 SEVERI:400,000 MTSATclr:160,000 GPSRO: 3000 SATAOD: 700,000 MSGAOD: 2,300,000	5 10 13 22 12 2 7 9 80 15 0
Aircraft	*Manual* AIREPS (incl. ADS) *Automated* AMDARS TAMDAR	T, V as reported, with duplicate checking and reject lists	 13,500 380,000 62,000	 77, 62 24, 24 0, 0
Satellite atmospheric motion vectors	GOES 13,15 BUFR Meteosat 7 BUFR Meteosat 10 BUFR MTSAT BUFR Terra/Aqua MODIS NOAA polar AMVs MetOp polar AMVs	IR, WV IR, VIS, WV IR, WV IR, VIS, WV IR, WV, clear sky WV IR IR	190,000 80,000 400,000 240,000 130,000 85,000 110,000	13 20 5 8 8 6 3
Satellite-based surface winds	METOP-A/B ASCAT CORIOLIS WINDSAT OceanSat-2 OSCAT	KNMI retrievals NRL winds KNMI retrievals	1,800,000 1,200,000 400,000	4 1 6
Ground-based surface	Land SYNOP Ship Fixed Buoy + Rigs Drifting Buoy METAR Mobile SYNOP	P (processed to model surface), V, T, RH P, V, T, RH P, V, T P, T P, V, T, RH P, T, RH	80,000 6,000 11,500 11,000 140,000 2,700	88, 86, 90, 91 80, 67, 77, 47 72, 90, 80 87, 8 35, 30, 32, 32 20, 15, 15
Ground-based satellite	GPSIWV	ZTD	450,000	0.3

Table 1. Observations assimilated in the Met Office global NWP model during 2013.

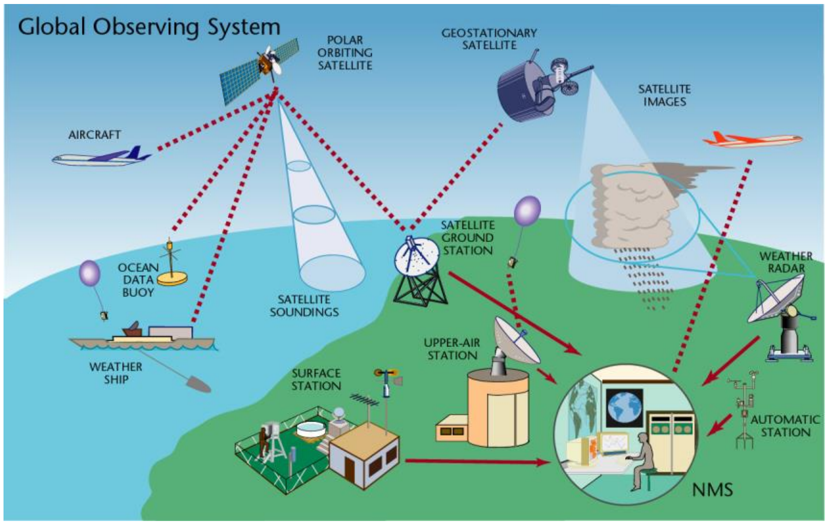

Figure 1. The main components of the global observing system

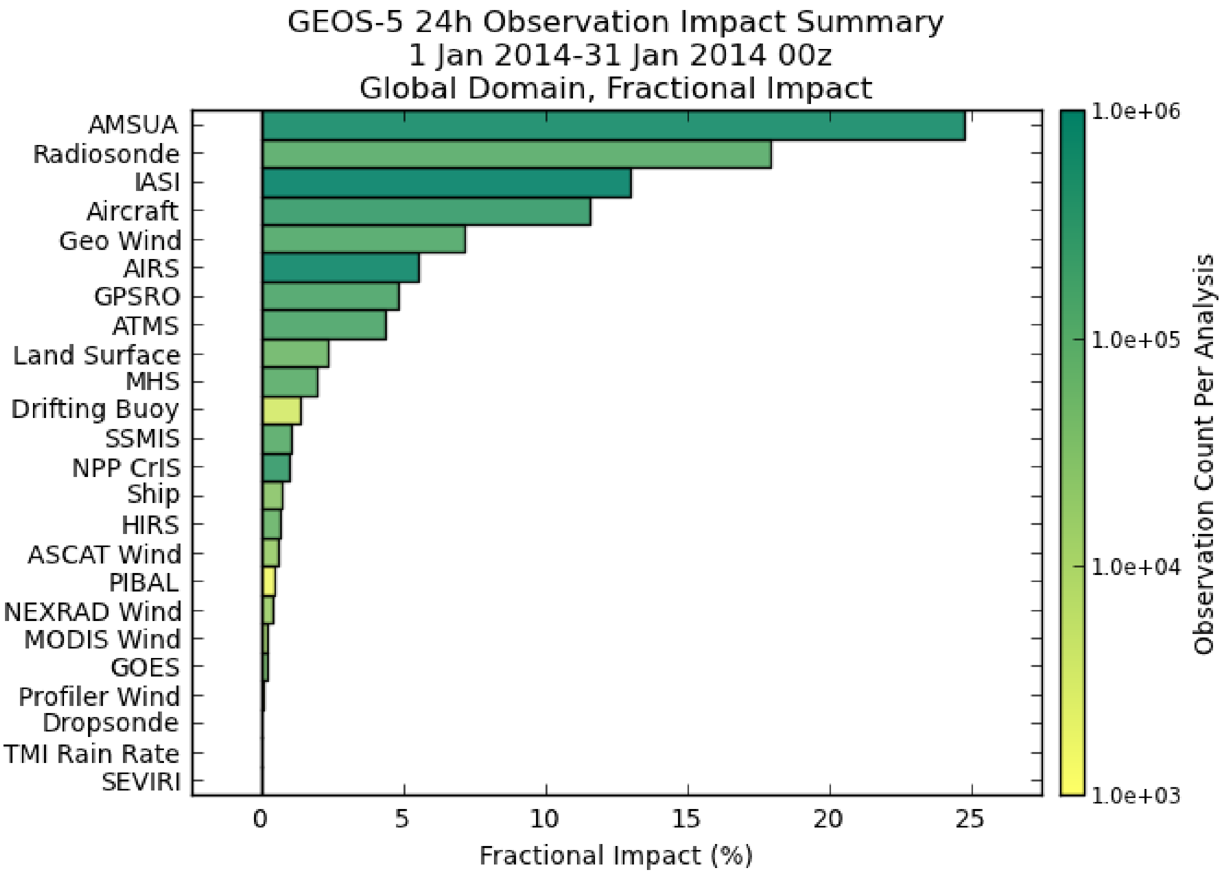

Figure 2. Adjoint-based 24-hr observation impact in the NASA/GMAO data assimilation system for forecasts initialized at 00Z during January 2014. The values for each observation type are plotted as a fraction of the total forecast error reduction based on a moist global energy norm from the surface to 1 hPa. The color shading indicates the average observation counts

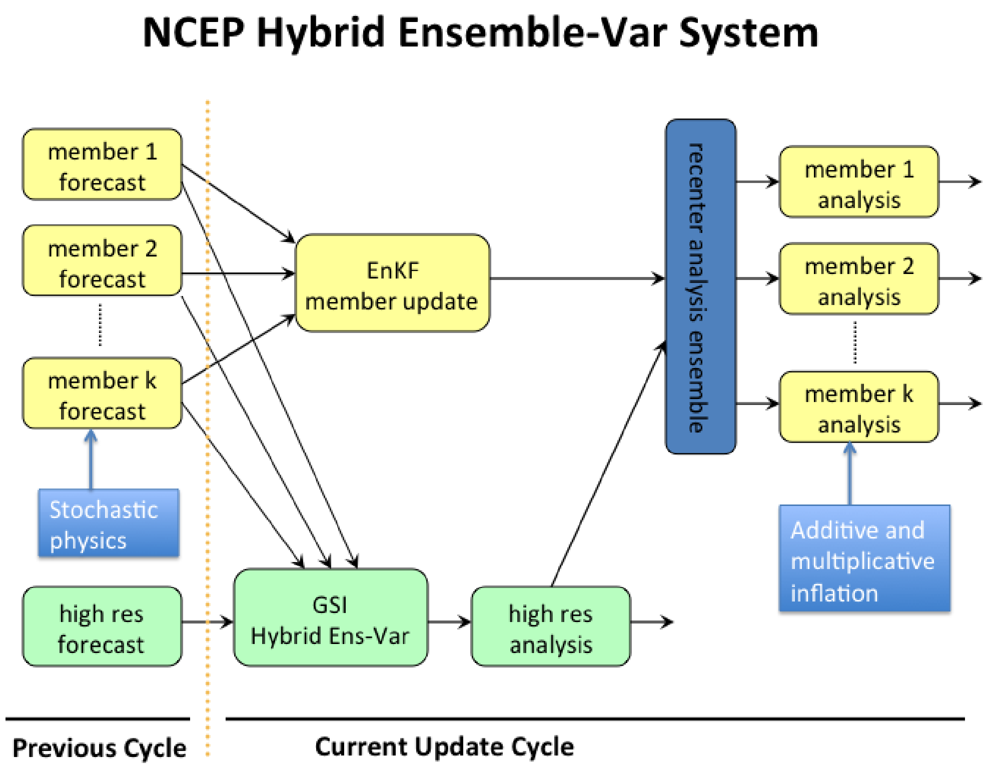

Figure 3. Schematic of the NCEP hybrid data assimilation system. The EnKF provides background error covariance information to the Gridpoint Statistical Interpolation (GSI) analysis scheme which, in turn, provides the updated central analysis to re-center the ensemble for the next assimilation cycle. Figure courtesy of Jeff Whitaker, NOAA/ESRL.

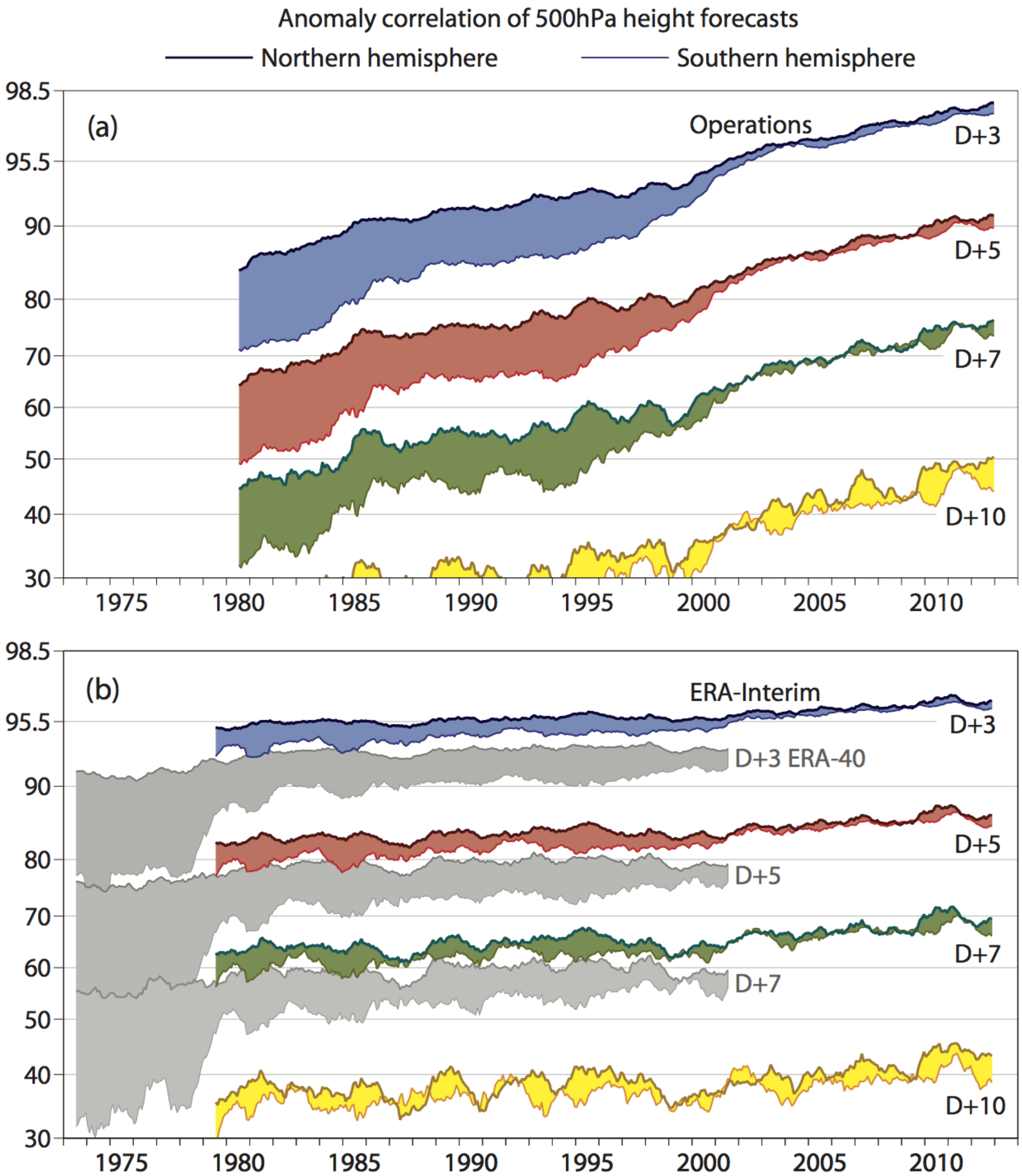

Figure 4. Twelve-month running mean of anomaly correlation of 500 hPa height for various lead times in the ECMWF operational forecast system (top) and in the ERA-40 and ERA-Interim reanalysis systems (bottom). The shading shows the differences in skill between the northern and southern hemispheres. From Dee et al. (2014).