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Observing System Simulation Experiments at NCEP

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1. INTRODUCTION

Building and maintaining observing systems with new instruments is extremely costly, particularly when satellites are involved. Any objective method that can evaluate improvement in forecast skill due to the selection of instruments and instrument configurations has been sought after. For future instruments, the forecast skill evaluation needs to be performed using simulation experiments. These experiments are known as Observing System Simulation Experiments (OSSEs). Although an OSSE itself is a very expensive project, the cost of OSSEs is a small fraction of the cost of actual observing systems when satellites are involved. Besides, by using OSSEs current operational data assimilation systems can be prepared to handle new data and the operational use of data from future instruments and observing systems can be accelerated. Through the NPOESS OSSE project, future observing systems will be designed to optimize the use of data assimilation systems (DA) and forecast systems to improve weather forecasts for the maximum societal and economic impact (Arnold and Dey 1986, Lord et al 1997, Atlas 1997). Data assessments using simulation experiments will allow the quantitative evaluation of future observing systems and instruments.

Preparations for new observing systems include handling the volume of future data and the development of database, data processing (including formatting), and quality control systems. Furthermore recent OSSEs showed that some basic tuning strategies can be developed through OSSEs before the actual data become available. All of this development will accelerate the operational use of the data.

An OSSE requires a Nature Run (NR) which is generated from a numerical model and serves as the truth of the OSSE. In OSSEs, it is very important that different models be used to generate the NR and DA. When the same model is used for the NR and DA, it is called the identical twin problem. When similar models are used, such as different versions of the same model, it is called the fraternal twin problem. Many early OSSEs had both the identical twin and fraternal twin problems, possibly due to the lack of good models to be used for the NR and DA. If the model used for the NR and model used for the DA are too similar, there is no model error to be dealt with in DA. The difference between the atmosphere, which is the real atmosphere or NR, and model is one of the major components to be handled by DA. In OSSEs at the National Centers for Environmental Prediction (NCEP) the identical twin problem is avoided. The forecast model at the European Centers for Medium Weather Forecasts (ECMWF) was used to generate the NR and the NCEP model was used for DA. These two models have contrasting physics parameterizations. Traditionally, free forecast runs were used as the NR. The ECMWF analysis was used by Keil (2004) and Lahoz et al. (2005) to evaluate the SWIFT instrument in the stratosphere. Using this analysis causes an unrealistic discontinuity in the nature run which will be much more serious in the troposphere.

The basic concept of OSSEs is presented in Fig.1.

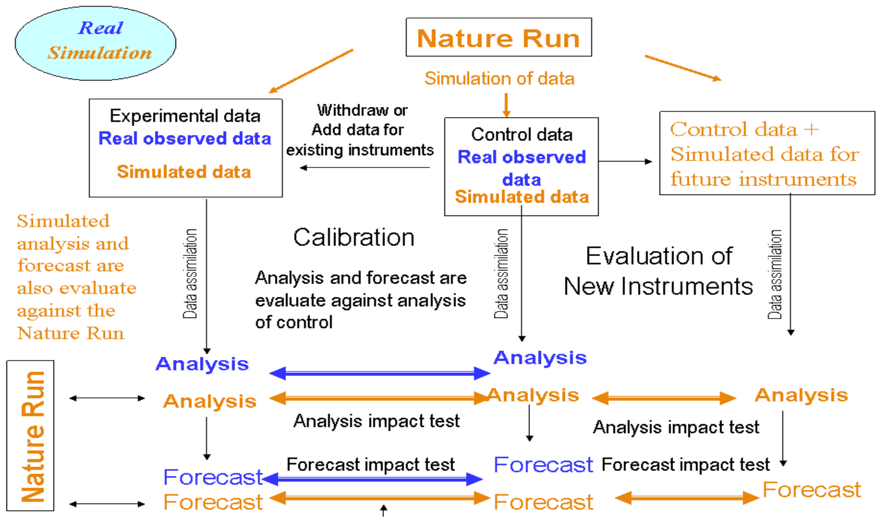


Fig.1 Schematic diagram of OSSE. Orange indicate simulations; blue indicates actual.

At NCEP in particular, the Doppler Wind Lidar (DWL) OSSE was conducted in collaboration with NESDIS, Simpson Weather Associates (SWA), and NASA. DWL was selected because it is the most costly instrument and would justify the expense of an OSSE.

OSSEs to evaluate DWL have been attempted before (Arnold and Dey 1986). One of the comprehensive OSSEs to evaluate DWL was done by Rohaly and Krishnamurti (1993) to evaluate the Laser Atmospheric Wind Sounder. The ECMWF model was used as the NR while the model used for forecasts was developed at Florida State university from ECMWF model, which is considered to a fraternal twin to the NR. Various types of OSSEs were performed over the last decade. An OSSE using the same NR that was used in this paper was performed by Cardinali et al. (1998) and Marseille et al. (2001) to evaluate the impact of the non scan DWL used in the Atmospheric Dynamic Mission (ADM, Stoffelen et al., 2005). Since different versions of the ECMWF model were used for both the NR and DA, these OSSEs are considered to have fraternal twin problems. Satellite radiance data were not used. Without radiance data, the large impact on Southern Hemisphere (SH) and ocean results cannot be verified as an impact of DWL. Wergen and Wetterdienst (2000) performed an observation simulation replacement experiment (OSRE) to evaluate the ADM mission. In OSRE, the data from ADM is simulated from analyses and assimilated with real data. Tan and Andersson (2004 and 2005) and Tan etal. (2006) performed the simulations using an ensemble system at ECMWF. The data impact was evaluated as a reduction in ensemble spread. It was pointed out that the OSRE has a similar limitation as identical twin OSSEs (Lahoz et al. 2005). Atlas et al. (2003) conducted an OSSE using an NR from the finite volume General Circulation Model (FvGCM4). OSSEs were conducted for the summer time and impacts of DWL were assessed for hurricane track forecasts. An OSSE for the limited area mesoscale model was conducted by Weygandt et al. (2004). The assimilation and forecast mentioned in this paper were used as the boundary condition.

In this paper DWL is simulated as line of sight wind (LOS) and TOVS level 1B data were simulated and assimilated using different radiative transfer models (RTM). Other OSSEs use horizontal vector winds instead of LOS. Atlas et al. (2003) also conducted OSSEs for DWL. Vector winds were simulated at the data location and temperature was simulated at the satellite radiance sounding location. The interpretation of the results may be difficult due to these simplifications.

Another important aspect of OSSE is calibration experiments. Through calibration experiments the impact of existing data are evaluated for real and simulated data. The data impact should be similar between real and simulated experiments. The results from calibration experiments will provide guidelines for interpreting OSSE results in the real world. Calibrations were performed in the OSSEs at NCEP; however, calibration experiments were not performed in most of these OSSEs.

Section 2 provides a description of the NR and the evaluation and adjustment of the NR. An overview of the NCEP DA system used for OSSEs is given in Section 3. Procedures for the simulation of observed data are described in Section 4. The results from calibration experiments are presented in Section 5. The results from experiments to assess the impact of DWL are presented in Section 6. The importance of scanning, impact dependence on large scale error and resolution dependencies are discussed in Section 6. Future plans and strategies for OSSEs are discussed in Section 7.

2. EVALUATION AND ADJUSTMENT OF THE NATURE RUN

The NR, which serves as a true atmosphere for OSSEs, needs to be sufficiently representative of the real atmosphere and different from the model used for data assimilation. In the calibration phase (Section 3), the observational data for existing instruments is simulated from the NR and forecast and analysis skill for real and simulated data are compared.

A free forecast from the analysis is used as the NR for this study. Analysis fields are forced by existing observations and also affected by background error covariance in the data assimilation systems. Since many observation are inserted every six hour, the analysis will not be smooth in time. Although NR has to serve as truth in OSSEs, it does not have to be same as the actual atmosphere. However it is important to have dynamical consistency within the Nature Runs. Analysis fields evolve with the real atmosphere but they do not have dynamical consistency. Therefore, it is important to use free forecasts for the Nature Run. However, SST and sea ice are prescribed for the Nature Run. The effect of prescribed SST and sea ice need to be considered when the results are analyzed.

For this project, the NR was provided by ECMWF. The description and evaluation of the nature run is provided by Becker et al. (1996). A one month model run was made at resolution T213 and 31 levels starting on 5 February 1993. The version of the model used for the nature run is the same as in the ECMWF 15 year reanalysis, containing Tiedtke's mass flux convection scheme (Tiedtke 1989) and prognostic cloud scheme (Tiedtke 1993). The 6 hourly data, from 06Z 5 February through 00Z 7 March 1993, were provided by ECMWF as either T213 spectral coefficients or reduced gaussian grid data at a resolution of approximately 60km. The NR period was found to be relatively neutral as an ENSO event, and the tropical intraseasonal oscillation was decaying during the NR period. A comparison of cyclone activities between the NR and the ECMWF reanalysis was performed by NASA DAO. The number of cyclones in the ECMWF analysis is about 10% higher than in the NR run, which is within the natural variability. The distribution of cyclone tracks is very realistic.

Sea surface temperatures (SST) are fixed using SSTs from February 5th, 00Z throughout the entire NR period. The effect of constant SST on the data has been evaluated. It is shown that an OSSE with a constant SST will give a valid data impact if SST variability is small in reality.

Cloud evaluation is particularly important for the assessment of DWL. DWL data can be retrieved only if the DWL shots hit the target. Clouds are important targets for a DWL and they also interfere with the DWL shots for lower levels. Therefore, large differences in the NR cloud amount will affect the sampling of simulated data. Realistic clouds are also necessary for generating realistic cloud track winds from geostationary platforms. The cloud distribution also affects the simulation of radiance data.

All over the globe, the High level Cloud Cover (HCC) amount looked larger than the satellite observed estimate. The amount of Low level Cloud Cover (LCC) over the ocean is less than observed and the amount of LCC over snow is too high (Fig.2). Fig.3 showed an observed estimate for total cloud cover (TCC) based on three different sources (Masutani et al. 1999). In general, the NR total cloud agrees with observational estimates except over the North and South poles. After careful investigation, we found that, due to the lack of reliable observations, there is no strong evidence for an over-estimation of HCC and polar cloud by the NR. However, the under-estimation of low level stratocumulus over the oceans and their over estimation over snow are clearly identifiable problems, and adjustments were consequently applied. (Masutani et al., 1999).

Since satellite-based estimates have difficulty in sensing LCC, the Warren ground-based climatology for stratus and stratocumulus (Hahn et al., 1996) and NR vertical velocity are used for adjustments. At lower levels, Warren cloud climatology (Warren 1988) is added if there is rising motion. The LCC is divided by 1.5 where there is snow cover over land. This adjustment made the cloud distribution much more realistic. After the adjustment, Fig.5 shows that the LCC free area is much smaller and areas with moderate cloud cover have increased over the oceans. This U-shaped distribution agrees with results from ground based observations.

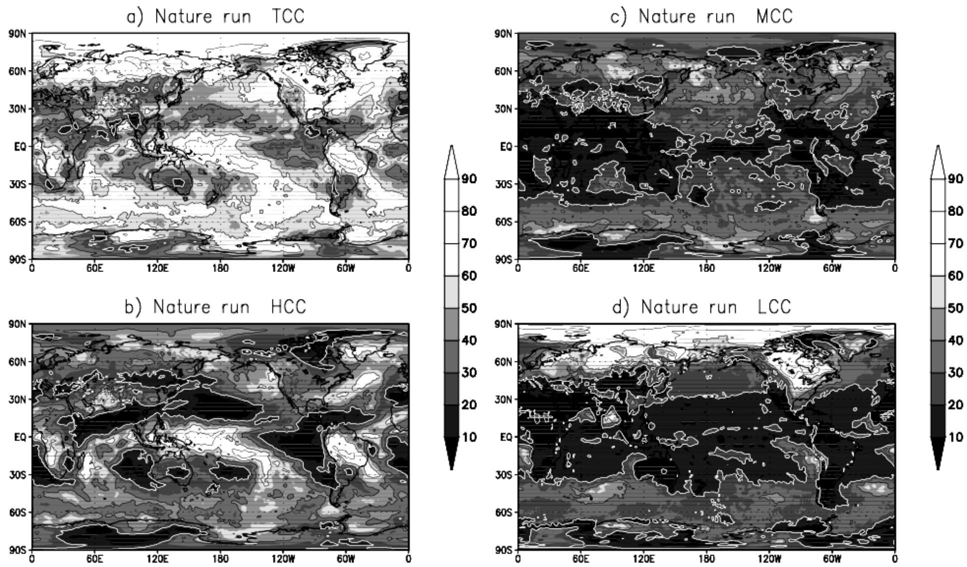


Fig.2 Cloud cover for NR. Time averaged through the NR period

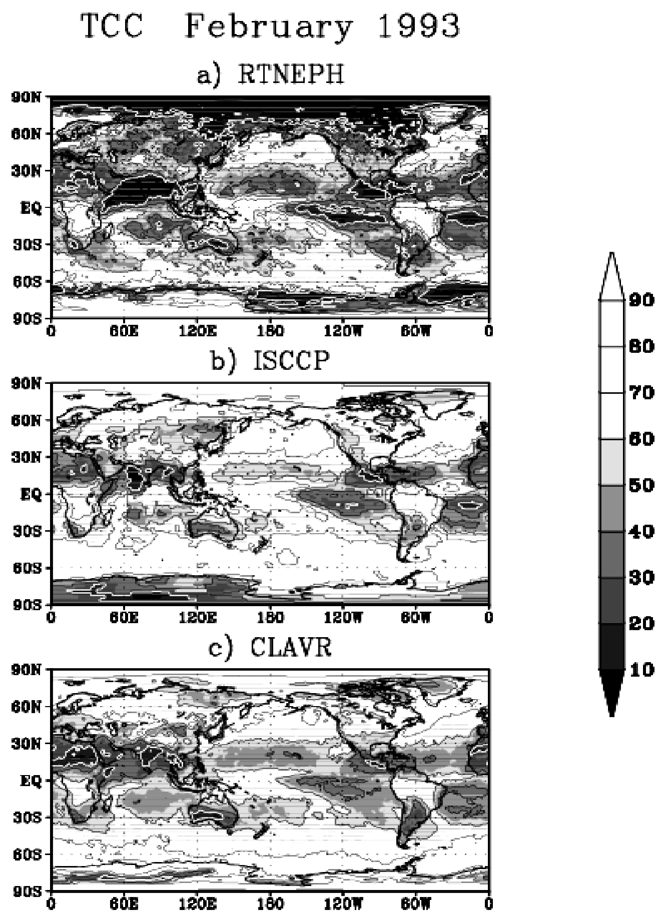


Fig.3 Total cloud cover for February 1993 estimated from three different sources: a) U.S.A.F. Real-Time Nephanalyses (RTNEPH, Hamill, 1992); b) The International Satellite Cloud Climatology Project (ISCCP), stage D2; c) The NESDIS experimental product, "Clouds from Advanced Very High Resolution Radiometer" data (CLAVR-phase 1).

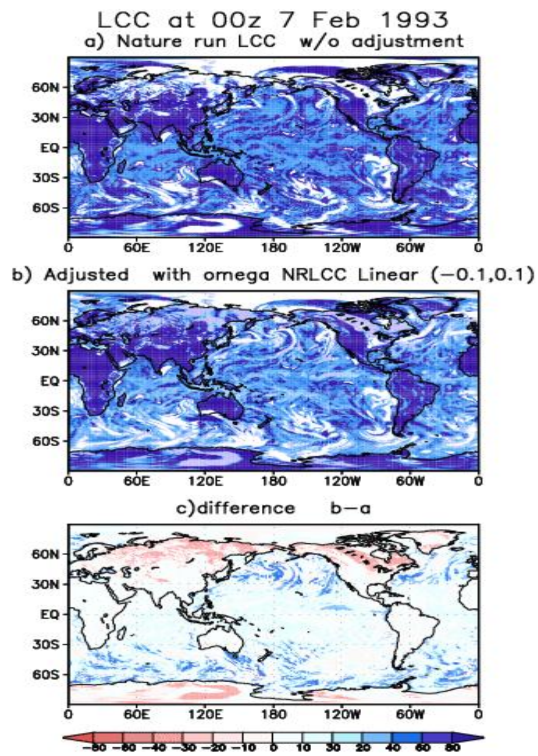


Fig.4. Low level cloud cover: a) NR LCC at 00z 7th February 1993. b) adjusted LCC. c) The adjustment added.

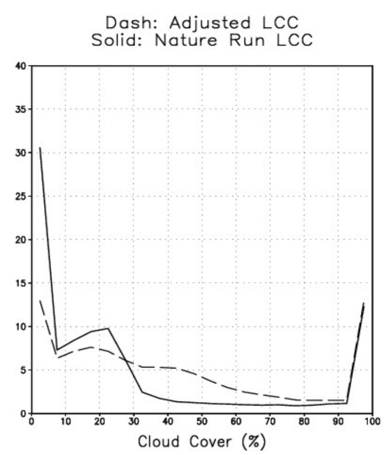


Fig.5 Frequency distribution (in %) for ocean areas containing low level cloud cover in 20 5%- band categories.

Solid line: NR cloud cover without adjustment. Dashed line: with adjustment

3. The elements of OSSEs at NCEP

From the NR provided by ECMWF, conventional observations are simulated at the same locations as in the 1993 distribution. Satellite radiance data are simulated for

NOAA 11 and NOAA 12. These simulated data for the NR period were used for the OSSE calibration. The data impacts of the simulated data were compared with those of real data as of 1993. Satisfactory agreement was reported by Lord et al. (2001) and Errico et al. (2005, 2006). Many OSSEs for DWL were performed with this system and the results are presented in Masutani et al., (2004a, 2004b).

3.1 Data assimilation system

The global data assimilation system at NCEP is based on the Spectral Statistical Interpolation (SSI) of Parrish and Derber (1992), which is a three-dimensional variational analysis (3-DVAR) scheme. TOVS 1B radiance data are used (McNally et al., 2000, Derber and Wu,1998). The March 1999 version of NCEP's operational Medium Range Forecast (MRF) model and data assimilation system were used for these data impact tests. Line of Sight (LOS) winds from instruments such as DWL are directly used instead of wind retrievals. Note that some data assimilation systems use preprocessed retrieved temperatures estimated from satellite radiances and horizontal winds directly from the DWL data. Processing horizontal winds from a DWL LOS wind measurement requires the design of satellite systems capable of taking measurements from at least two different directions at approximately the same time. Data from the DWL-nonscan cannot be used without LOS in data assimilation.

The inclusion of new instruments requires a major revision in the SSI to accommodate large amounts of data and the increased spectral resolution of the new sounding instruments. Coefficients used in the radiative transfer model need to be reevaluated as the new version of the model is introduced. OSSEs will be continued using this new system. AIRS data evaluation and other work will need to be conducted with the 2002 operational data assimilation system. Selected calibrations and impact tests need to be repeated. In the future, the NCEP data assimilation will be upgraded to include a cloud analysis.

The OSSE DA was upgraded to the 2003 operational system and experiments with T170 and T62 resolution were performed to study the impact of model resolution (Parrish and Derber, 1992; Derber and Wu, 1998; McNally et al., 2000). More details of the forecast model, SSI and the upgrade are describer by Global Climate and Weather Modeling Branch (2003, 2004).

A major upgrade to NCEP's operational system that occurred in late 2002 includes:

● A new version of the radiative transfer model to accommodate high resolution radiance data;
● Improved treatment of the bias correction for radiance data;
● Ability to accommodate more recent instruments (AIRS, DWL);

● Addition of LOS as an observed variable;
● Inclusion of precipitation assimilation;
● Adjustment for higher resolution models;
● A comprehensive diagnostic tool for radiance assimilation.

This version is being converted to the OSSE system and will be used for assimilating advanced sounder data (from AIRS, CrIS, etc). The January 2004 data assimilation system was used for experiments described in Section 6.8 which involve the T170 resolution 42 level model. For other experiments the 1999 version of the model were used.

4. Simulation of observations

4.1 *Simulation of conventional data*

The initial simulation of conventional data done by NASA/GSFC uses the real observational data distributions available in February 1993, including ACARS (automated aircraft) and cloud motion vectors (CMV Velden et al. 1997). In the initial simulation by NASA/GSFC, random error was added and the NR surface height used to simulate the surface data. As a result, these surface data may have an exaggerated positive impact on the results. Furthermore, the use of random error alone has been known to cause a positive impact on forecast skill due to a lack of systematic error (bias).

Simulations using real orography and a formulation of systematic error have been conducted by NCEP with more realistic results. The difference between Observation and Analysis (O-A) for each observation was computed from the real analysis at each observation time. These O-A values were added to the simulated data for that time. The O-A value from the real analysis includes representativeness errors (REs) that come from subgrid-scale structures. These REs were already removed from the NR data, since it was from a model integration. Since the NR is a model it does not include errors on scales smaller than the NR resolution, which is about 50Km. Real data have small scale errors due to subgrid-scale structures. The effects of large scale errors are discussed further in Sections 5.4 and 6.7.

This lack of RE in simulated data is particularly serious for surface data. In the NR envelope orography is used, which is higher than real orography on average and much smoother. Data between the real orography and NR orography are missing and these data are main source of RE in the real world. The lack of RE will increase the influence of surface data and make a better analysis with conventional data only. This will cause less room for an additional impact from future instruments.

4.2 *Simulation of DWL data*

The simulation of DWL data includes efforts using DWL performance models, atmospheric circulation models and atmospheric optical models (Emmitt 1999, Emmitt et al., 2000b). The instrument parameters were provided by the engineering community. Scanning and sampling requirements were provided by the science community and define various instrument scenarios. These scenarios were initially tested by examining the sensitivity of the analyses to the various scenarios. A candidate DWL concept is then chosen for a full OSSE and an impact study is conducted and evaluated by a technology-neutral group such as NCEP.

Bracketing OSSEs are being performed for various DWL concepts to bound the potential impact. Future OSSEs will be performed for more specific instruments. The following "technology-neutral" observation coverage and measurement error characterizations will be explored: a DWL which senses PBL and clouds (**DWL-PBL**); an instrument that is sensitive to upper tropospheric clouds (**DWL_upper**); a combination of the previous instruments **(best_DWL**); scan and non-scan versions **(non_scan_DWL**). The quality of sampling also affects the performance of DWL. DWL data is provided by averaging shots within a 200km square. Low quality sampling (LQ) is done without the area averaging. When there are no LQ marks, area averaged data are used.

4.3 Simulation of TOVS and AIRS radiances

TOVS level 1B radiance data (TOVS) were simulated by NOAA/NESDIS, and the strategies for including correlated error in the TOVS simulation were presented by Kleespies and Crosby (2001). The radiative transfer model used in the simulation was RTTOV-6 (Saunders et al., 1999), which is different than the OPTRAN used in the data assimilation (Kleespies et al., 2004).

AIRS radiances, along with those from AMSU and HSB, have been simulated for the NR period. Thus, the capability to simulate data from the next generation of advanced sounders has been achieved. The AIRS simulation package used was originally developed by Dr. Evan Fishbein of JPL (Fishbein et al., 2001). This simulation (i.e., forward calculation) is based on radiative transfer code developed by Dr. Larrabee Strow (Strow et al., 1998). The package was modified to generate thinned radiance data sets in BUFR format. Further details of this simulation are described in Kleespies et al. (2003).

4.4 *Simulation of Cloud Motion Vectors*

For the DWL calibration and initial OSSEs, cloud motion vectors (CMVs) are simulated at the observed data locations (based on observed cloud cover and satellite data from1993). For a more realistic evaluation, the present density of CMVs at the NR cloud location is being simulated by SWA (O'Handley et al., 2001) and NASA/GSFC. Satellite view cloud fractions of 5% to 25 % are assumed to be a potential tracer. Slow bias and image registration errors will be included. Error statistics will be obtained from the NOAA/NESDIS Office of Research and Applications Forecast Products Development Team (NESDIS, 2002).

5. Calibration for OSSE

5.1 Procedure

Calibrations for OSSEs were performed on existing instruments. Denial of RAOB wind, RAOB temperature, and TOVS radiance in various combinations were tested. The period from January 1, 1993 to February 5 1993 was used to spin-up from the reanalysis to the 1999 data assimilation system. The period between February 5 and February 13 was used to spin-up from the real data analysis to the simulated analysis for control experiments. Other data are added or denied at 00Z 13 February, 1993.

5.2 . *Geographical Distribution*

First, the impact was measured as a geographical distribution of time averaged root mean square error (RMSE) between the analysis and forecast fields (Lord et al., 2001). The results show generally satisfactory agreement between real and simulated impacts. In the Northern Hemisphere (NH), the impact of RAOB winds is slightly weaker in the simulation and the impact of RAOB temperature is slightly stronger. In the tropics in particular, there is a large impact from RAOB temperatures in the analysis which does not increase with forecast hour. The impact of TOVS is slightly larger in the simulation. In the NH, TOVS has little impact over Europe and Asia but has an impact over the Pacific in both the real and simulated analyses. The magnitudes are slightly larger in the simulation but the patterns are similar. In the 72 hour forecast, the impact of TOVS spreads out over the NH and shows a similar magnitude of impact when compared to RAOB temperature. In the SH TOVS dominates. However, even with TOVS, RAOB data exhibit some impact and their impacts are similar in the simulated and real analyses. Further detailed evaluation and consequences for the data impact in simulation experiments are discussed in Errico et al. (2006).

The larger impact of TOVS in the simulation is expected because of the lack of measurement error in the simulated data. Under-estimation of the cloud effect in the simulation is another possible reason for the large impact. However, over the SH oceans there is more impact with the real TOVS. This will be discussed in Section 5.3. The large analysis impact in the tropical temperatures may be related to the bias between the NCEP model and the Nature Run.

5.3. *Impact on forecast Skill*

Anomaly correlations (AC) skill in the 72 hour forecast 500hPa height fields are evaluated using a correlation to the analysis of control experiments. The analysis of the control experiments (CTL) includes conventional observations and TOVS. The comparison of anomaly correlations between real and simulated experiments are presented in Fig. 6. More detailed discussion is in Masutani et al. (2001). The experiment without TOVS (NTV), experiments with TOVS but without RAOB winds (NWIN), and experiments with TOVS but without RAOB temperatures (NTMP) are studied. Forecast skill is verified against experiments with all the data (CTL). In both real and simulated experiments NWIN shows the least skill in the NH and less skill globally compared to NTMP. Therefore, RAOB winds have more impact compared to RAOB temperatures in both simulated and real cases and in both the NH and SH.

The simulated TOVS data are supposed to be of better quality than the real TOVS because various systematic errors and correlated large scale errors have not been added to the simulation. Therefore, it is expected that denial of the simulated TOVS would result in more skill reduction than denial of the real TOVS. However, in the SH, the impact of real TOVS is much larger than the simulation. Variable SST was used in the assimilation with real data and constant SST in the simulation. The consistency in response to two different SSTs between the simulated and real atmosphere was confirmed (Masutani, 2005) These results suggest that if SST has a large variability, the impact of TOVS becomes more important. With this NR, the data impact of slowly varying SST in SH can be tested.

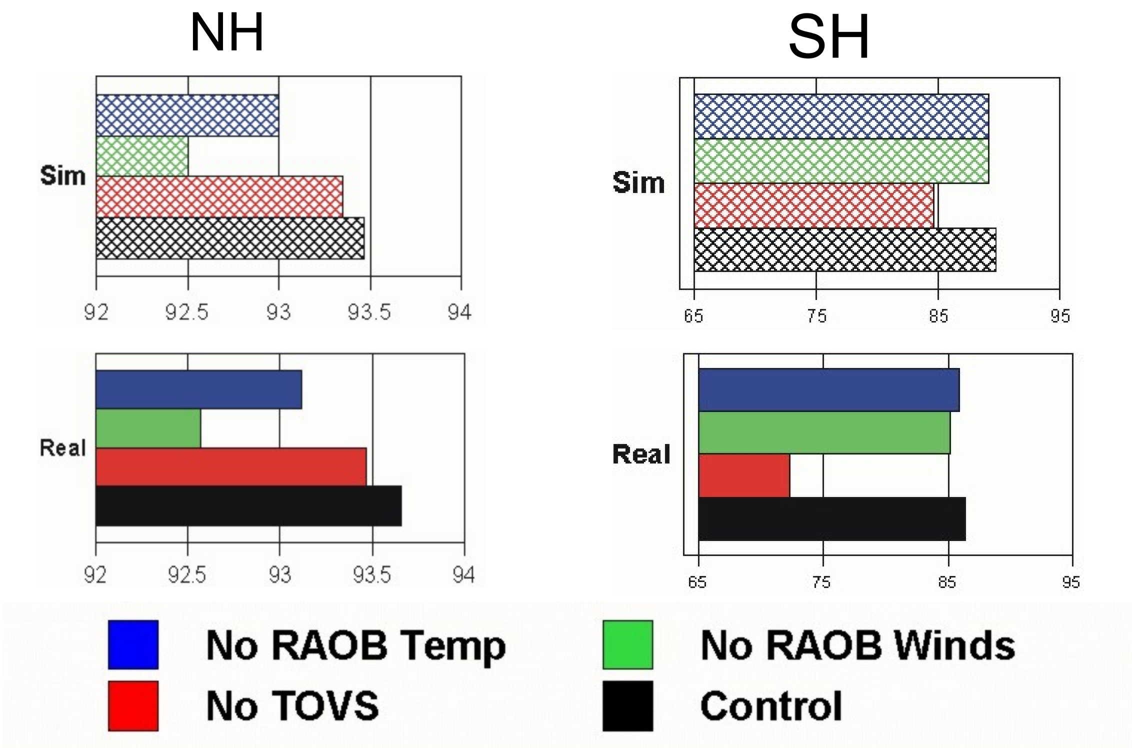


Fig.6 500hPa height anomaly correlation time averaged between February 13 and 28. 72 hour forecast fields are verified against the control analysis. Control runs include all conventional data and TOVS radiances. For each run RAOB winds, RAOB temperatures and TOVS radiance are withdrawn in turn (NWIN, NTMP,NTV, respectively). The left two panels are for the Northern Hemisphere and right two panels for SH. The top two panels are for simulation experiments and bottom two are real.

5.4 Adjustment of Error for the simulated data

The problems in the original simulated data were noted in Section 3.1. In order to improve the simulated data, simulations using real orography and the formation of systematic error were conducted by NCEP.

In order to test the effect of the systematic error, an O-A for each observation was computed from the real analysis at each observation time and added to the errorless simulated data for that time. The O-A value from the real analysis includes an RE that comes from subgrid-scale structures. REs were already removed from the NR data as it came from a model integration. The O-A also adds a large-scale correlated error.

With the O-A error, the rejection statistics of the simulated experiments become closer to those from real data. With random error, too few data are rejected by the quality control. The coefficient for O-A is evaluated through the impact of surface data. The optimum coefficient for O-A is between 1.0 and 2.0. Further improvement in systematic error will be conducted throughout the project and some results will be presented in Section 6.7.

5.5 Summary

Results show that the simulations reproduced major features of the impacts seen in the real data. Error assignment requires further investigation. The data impact is also expected to change when new features are added to the data assimilation system. CMV and AIRS need to be included to demonstrate their impact on a future observing system and the impact of the future observing system needs to be evaluated with CMV and AIRS. Since there was no real AIRS in 1993, the data impact of simulated AIRS data has to be compared with that of the current real data.

6. Assessment of doppler wind lidar (DWL) impact

6.1 *Evaluation of scanning*

Many experiments have been done to illustrate the impact of conventional and DWL data over the first few days. Then selected sets of experiments were extended to the whole NR period, with forecasts also being performed. The impact of DWL was assessed by using AC with the NR at various space scales and by a synoptic analysis of case studies. Time averaged geographical distributions and a time series of RMS error were also studied. Consensus among the different measures of skill were examined for the assessment.

In the NH, skill on the global scale is mostly achieved by existing (conventional and TOVS) data. Therefore, the impact of DWL at synoptic scales is the most important. The skill for zonal wind (U) and temperature (T) are mainly from planetary scale events, while the skill for meridional wind (V) is from the synoptic scale. Therefore, the impact of DWL is much clearer for V than U or T on the synoptic scale. The advantage of scanning was clear (Fig.7) . For the NH in particular, it is very problematic to expect a significant impact without scanning. At 850hPa, the skill of DWL-PBL was better than the DWL-upper analysis. However, after 48-72 hours the forecast with DWL-upper becomes better. This is observed for various values and at various latitudes. This indicates that upper level data are much more important than low level data beyond 48 hours.

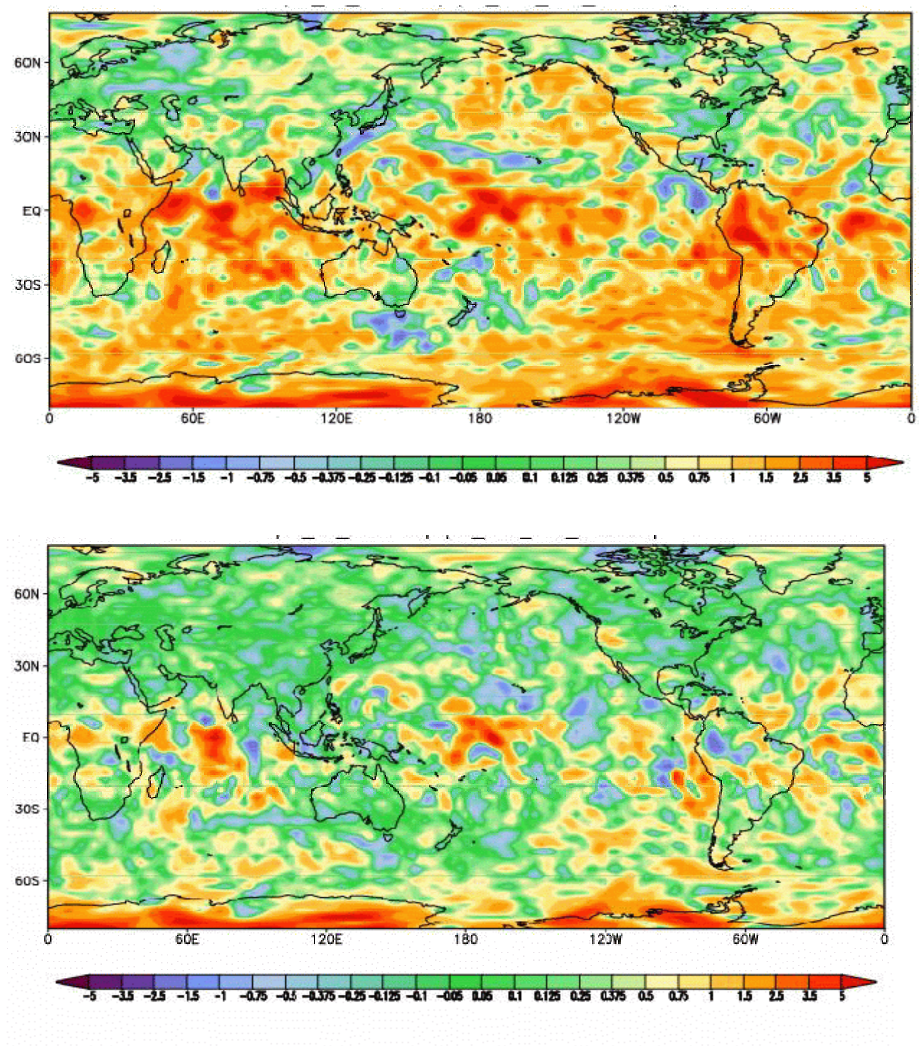


Fig.7
RMSE(CTL-NR)-RMSE(CTL-EXP) for 500hPa wind fields. Times were averaged beween February 13 and March 6th. Warm colors indicate a positive impact. Green indicates a neutral impact. Blue indicates a negative impact. On top is the experiment with CTL+ best_DWL. Best_DWL is DWL with scanning. On the bottom is the experiment with CTL+(no_scan_DWL).
RMSE(CTL-NR):RMSE between analysis of CTL run and NR
RMSE(EXP-CTL): RMSE between analysis of experiment and NR.
CTL: analysis with conventional data and TOVS level 1B radiance.

Fig. 8 shows the anomaly correlation (AC) to the Nature Run. NTV, CTL, CTL+best_DWL, and CTL + non-scan_DWL are presented. Low and high quality DWL data were also tested in Masutani et al (2002b.) Low quality data involves less shots for each measurement and a representativeness error of 7 m/s was assigned. The details of the quality of the data is discussed in Masutani et al (2002b.) A representativeness error of 1 m/s was assigned to the high quality DWL data. Non_scan_DWL adds very little skill to CTL+TOVS in both the NH and SH. However, in the SH without TOVS, low quality non_scan_DWL recovers the skill lost by TOVS. Therefore, the magnitude of the impact of low quality non_scan_DWL can be considered to be similar to TOVS radiance in the SH. In the NH, only the best DWL can add a significant impact in addition to TOVS radiance. In the tropics, scanning is the most important in the upper atmosphere and the quality of the data does not make much of a difference. On the other hand, at lower levels the quality of the DWL data makes a significant difference. For the rest of this paper only high quality DWL data will be used.

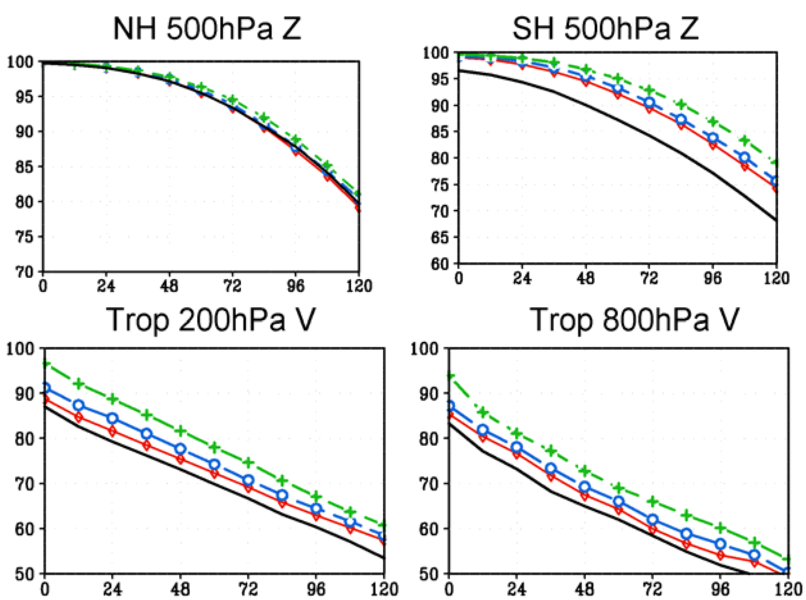


Fig.8 AC to NR.
Top left: NH (20N-80N) 500hPa geopotential height (Z).
Top right: SH (80S-20S) 500hPa geopotential height (Z).
Bottom left: Tropics (20S-20N) 200hPa meridional wind (V).
Bottom right: Tropics (20S-20N) 850hPa meridional wind (V).

Black solid line with no mark:s: Conventional data only (NTV).
Red solid line with diamonds: NTV+ TOVS (CTL).
Green dashed line with solid circles: CTL+best-DWL.
Blue dashed line with open circles: CTL+ non-scan-DWL.

6.2 *Scale dependence*

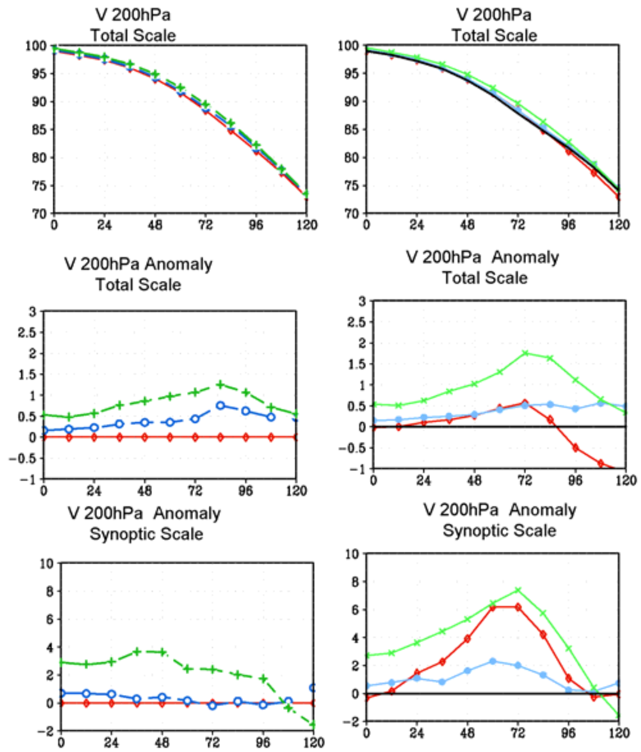
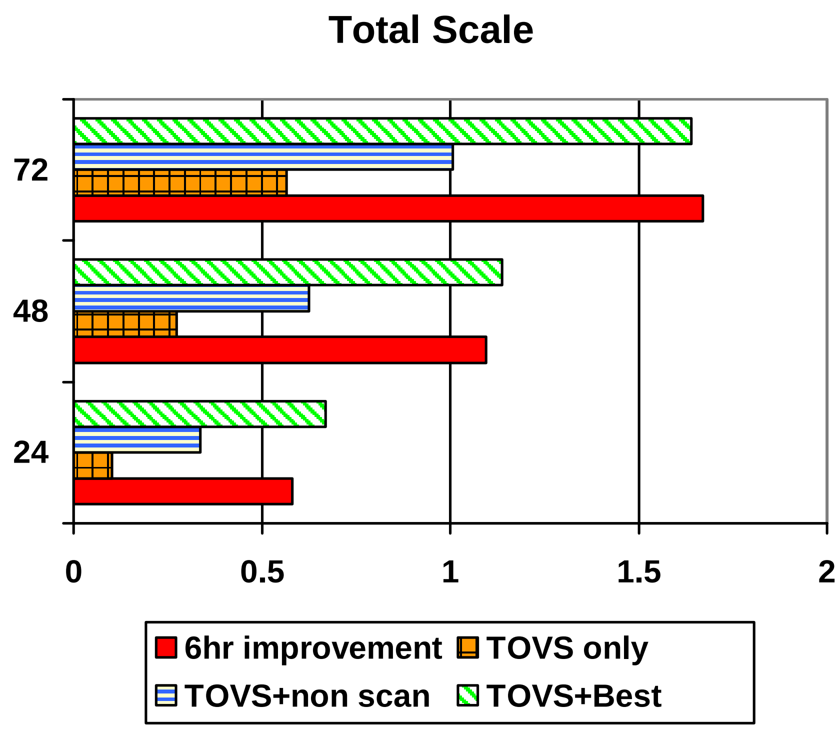


Fig.9 AC with NR. ACs for NH 200hPa V are plotted.
Top row: Total anomaly correlation at the total atmosphere scale.
Middle row: Differences at the total scale
Bottom row: Differences at the synoptic scale
Left: column: Experiments with TOVS.
Green dashed line with x'es: CTL+best-DWL.
Blue dashed line with open circles: CTL+ non-scan-DWL.
Red solid line with diamonds: NTV+ TOVS (CTL).

Right column: Experiments without TOVS.
Black solid line with no marks: Conventional data only (NTV).
Green solid line with x'es: NTV+best-DWL.
Light Blue solid line with closed circles: NTV+ non-scan-DWL.
Red solid line with diamonds: NTV+ TOVS (CTL).

The improvement in AC is much less than 1% in the NH, even with the best_DWL. However, we need to be aware that most of the ACs are computed from long planetary scale waves and we are expecting more impact from DWL at smaller and shorter scales. Fig. 9 shows the improvement in AC for the total atmosphere scale and at wave numbers 10-20, which is the scale of synoptic events. At the synoptic scale, DWL improves the AC nearly 8% and the maximum improvements are observed in the 48 hour forecast. 200 hPa meridional wind (V) depicts the waves responsible for meridional transports of momentum and heat.

6.3 *Time evolution of the forecast skill*



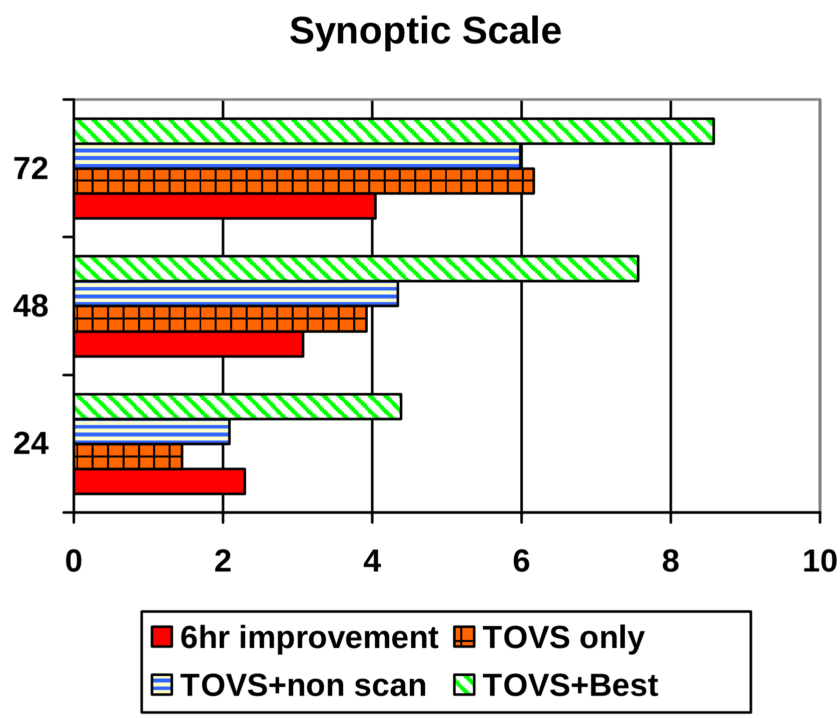


Fig.10 The time evolution of AC (%) skill in 200hPa V as the differences from CTL. Here the CTL includes conventional data only. Top panel show the AC for total scale and bottom panel show the AC for synoptic scale. Improvement in AC in forecast time of 6 hour for CTL+TOVS is plotted as reference.

Figure 10 shows the time evolution of data impacts compared with TOVS radiance. The difference in the anomaly correlation of meridional wind (V) for synoptic scale (wave numbers 10-20) and total scale (wave number 1-20) at 200hPa are presented. For 24 hour forecasts wind data add about 12 hour fcst skill to the radiance data in synoptic scale but by the 72 hour forecast radiance data become important as well. DWL consistently add skill to TOVS in total scale but improvement in skill in total scale is no more than 6 hours.

6.4 *Results for upper versus lower level data*

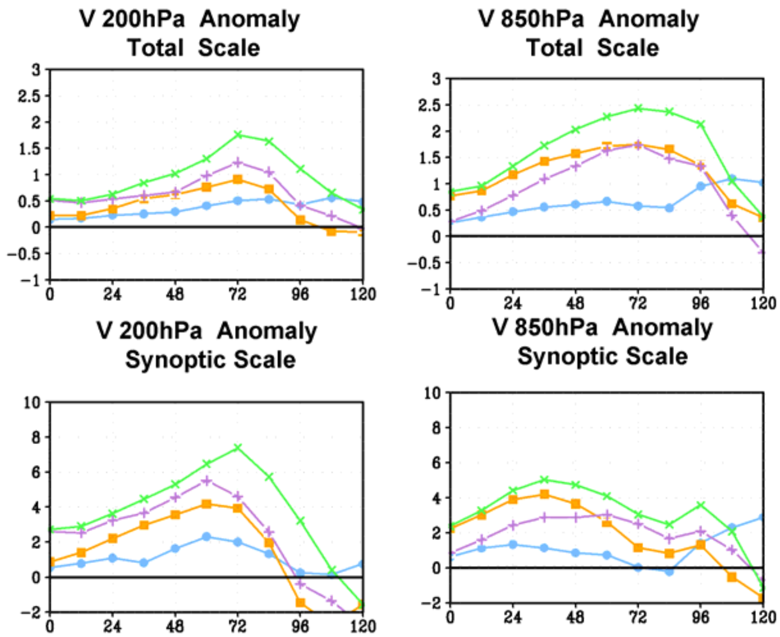


Fig.11 Time averaged anomaly correlations between the forecast and NR for meridional wind (V) fields at (a) 200hPa and (b) 850 hPa. Anomaly correlations are computed for zonal wave numbers with 10 to 20 components. Differences from the anomaly correlation for the control run (conventional data only) are plotted. Green x'es are best DWL,purple +'s are upper DWL, orange solid circles are Lower DWl, blue solid circles are non scan DWL.

If DWL lower level is added, the analysis improves at lower levels and upper level data improve the upper level analysis. However, Fig.11 shows that in the forecast of 850hPa, after 48 hours the upper level data become more important than lower level data.

6.5 *Results in the tropics*

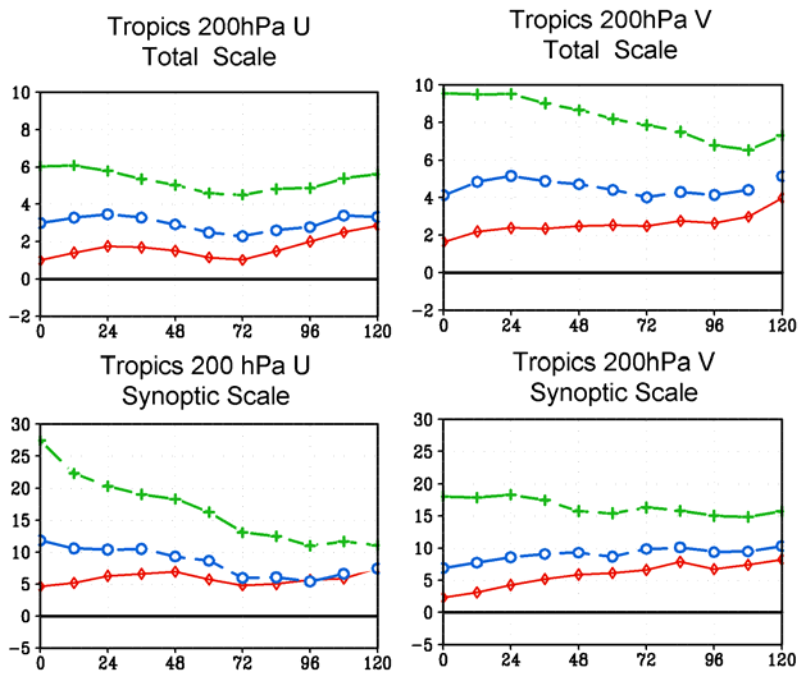


Fig.12 Wave number 10-20 component of anomaly correlation over the tropics (20S-20N). Colors as the same as Fig.10. The difference from the AC using conventional data only are plottted. Green dashed line with x'es is Best DWL+ TOVS+ conv; blue dashed line with open circles is non scan DWL + TOVS+ conv; red solid line with diamonds is TOVS + conv.

Fig. 12 shows that DWL improves the analysis significantly in the tropics. However, the improvement is not maintained well in the forecast fields. The NCEP model and ECMWF model present different problems in the tropics but both show similar forecast skill there. Therefore, these results require careful interpretation. In the tropics DWL definitely helps in improving the analysis but the model needs to be improved to gain the maximum benefit from DWL data in the forecast. This is most evident in zonal wind fields where large scale phenomena are captured. The improvement in synoptic scale V is maintained better.

6.6 *Combined impact with radiance data*

Masutani et al (2004a) demonstrates the impact on a particular synoptic event in terms of difference from the NR. It showed that the improvement in the analysis is not that significant, but it becomes much more significant in the 48 hour forecast. TOVS 1B data itself does not show much improvement in the forecast, and neither does non-scan DWL. Differences from the NR are similar to a forecast using conventional data only. However, when both TOVS and non-scan-DWL are used, the forecast improvement is as much as with the best DWL. A longer NR will provide better examples to demonstrate the various impacts.

In the tropics, DWL shows a large positive impact in most of the configurations tested. Even the non-scan DWL has more impact than TOVS. The positive impact is reduced with forecast time; the large positive impact in the analysis from the best DWL decreases by half beyond the 72 hour forecast. In the SH any DWL has more impact than TOVS. With TOVS and DWL together, the impact is larger than with TOVS alone.

6.7 *Role of systematic error*

The impact of DWL also depends on the error in the data used in CTL runs. Experiments with conventional data with and without O-A error were conducted along with either best-DWL or non-scan-DWL. The results are presented for the upper troposphere (200hPa) and lower troposphere (850hPa) at the all atmosphere scale (wave numbers 1-20) and the synoptic scale (wave numbers 10-20).

In Fig 14 the results show that the systematic errors, such as O-A, significantly increase the forecast impact at the large scale. At synoptic scales where the impact is already significant without O-A, changes in impact due to additional systematic error are rather small. However, even with the O-A error in the CTL the impact of non-scan DWL is much smaller than that of best-DWL.

The sensitivity to the DWL representativeness error (RE) (RE-DWL) has been tested. Ideally, RE-DWL should be a function of various parameters such as height, latitude, and the number of shots per one measurement. However, in this evaluation the effect of RE-DWL is kept the same for all LOS. The results showed that the analysis with DWL was the closest to the NR, if RE-DWL is between 1.0 and 2.0. If RE-DWL is too small, the DWL data forces the analysis away from the NR. The RE for TOVS was also tested. The analysis seems to improve when RE is increased compared to what is used in operations. A further investigation of random error will be made, and the balance in weight within the data assimilation will be tested with the development of DA systems. These results will provide a valuable evaluation of real data assimilation.

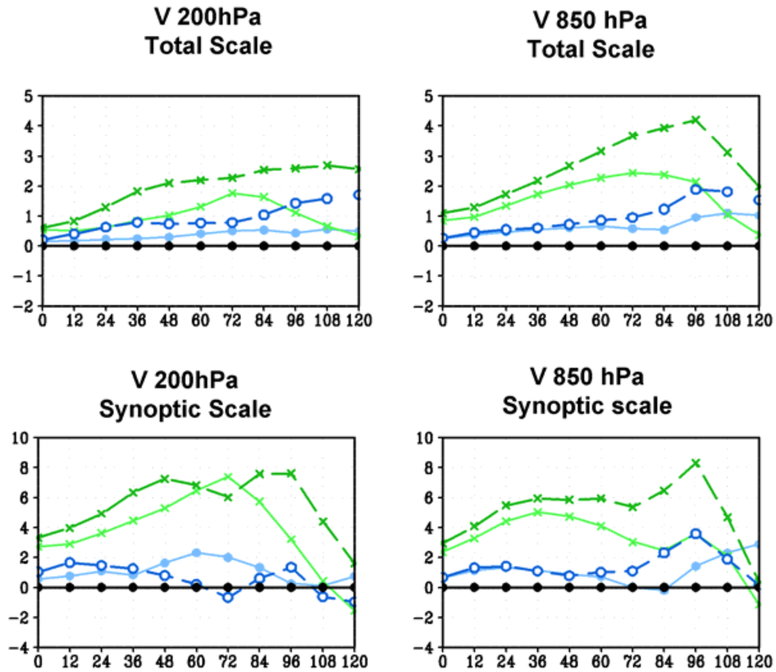


Fig 14. Differences in AC from the control (CTL) for 200hPa and 850hPa meridional wind. AC differences between forecasts and the NR are computed. In the control experiments conventional data are assimilated. ACs are averaged over the NH (20N-80N) and ACs for forecasts with DWL minus ACs for the CTL are presented. Solid lines with solid symbols are for the experiments with conventional data and no error added. Dashed lines with open symbols are for experiments with conventional data and (obs-anal) added as an error. Circles indicate the best_DWL, squares indicate experiments with non-scan-DWL. The top two panels are for ACs computed using zonal wave numbers 1-20. The bottom two panels show ACs using only zonal wave numbers 10-20, to capture synoptic events. Green solid line with x'es is NTV+Best DWL; blue solid line with closed circles is NTV+non scan DWL; green dashed line with x'es is NTV+Best DWL with O-A added to conventional data; blue dashed line closed circles is NTV+non scan DWL with O-A added to conventional data.

6.8 *Data impact and model resolution*

In the previous section DWL was evaluated using a T62 resolution model. However, there are many reasons to expect that data impacts using a higher resolution model could be different. The data impact may be reduced with higher resolution models (or better forecast models) because they can provide much better background fields and there is less room for data to improve the analysis. On the other hand, a higher resolution model will be able to utilize data in finer detail efficiently and that may lead to more data impact.

A comparison of the data impact between T62 and T170 model resolutions was performed without radiance data. The data impact is presented for 200mb meridional wind fields (V200). The results shows that a synoptic wave formed over a midlatitude jet, which is one of the important components of momentum and temperature flux that control global circulations. The impacts are discussed for total atmosphere scale waves (wave numbers 1-20) and synoptic scale waves (wave numbers 10-20).

Best-DWL and non-scan-DWL were tested with T62 and T170 resolution forecast models. Apparent data impacts are reduced in the T170 model (Fig. 15, Fig.16) because the forcast fields from the T170 model is already good and leaves less space of improvement. On the other hands, the data impact in the T62 experiments shows an erroneous impact near the North Pole and this erroneous impact is reduced in the T170 model experiments and the 48 hour forecast fields. The data impact in the 48 hour forecasts are slightly larger with the T170 model. If the model is poor it easily produces a large analysis impact due to the poor guess fields, but the large analysis impact rapidly decreases with forecast time. If the model is sufficiently good, small analysis impacts will grow with forecast time.

The impact of increasing the model resolution to T170 is comparable to the hybrid DWL impact for the total atmosphere scale. However, at synoptic scales the impact of DWL exceeded that from the improvement due to T170 resolution (Fig. 17). The model improvement seems to be more important in improving the forecast of planetary scale waves. However, any improvement in synoptic scale wave model forecasts requires better data to become more important.

These results are affected by the way DWL data are prepared. DWL data are prepared as an area average with a 200km radius or a 200km uncertainty in position. In order to reduce the observational error in DWL data, averaging needs to be performed. If DWL can produce higher resolution data, the advantage from a high resolution model may increase.

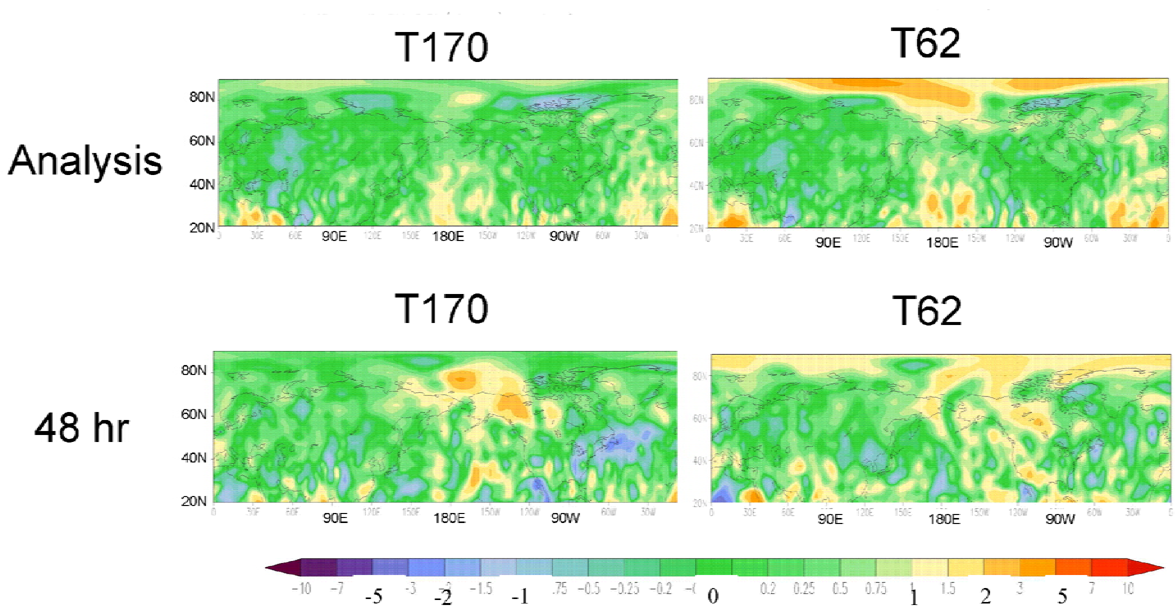


Fig.15 Impact of best-DWL in V200 fields. Differences in RMSE between experiments and the CTL are plotted. The CTL includes only conventional data. Warm colors indicate positive impacts from DWL. In the left two panels a T170 forecast model is used and in the right two panels T62 forecast models are used.

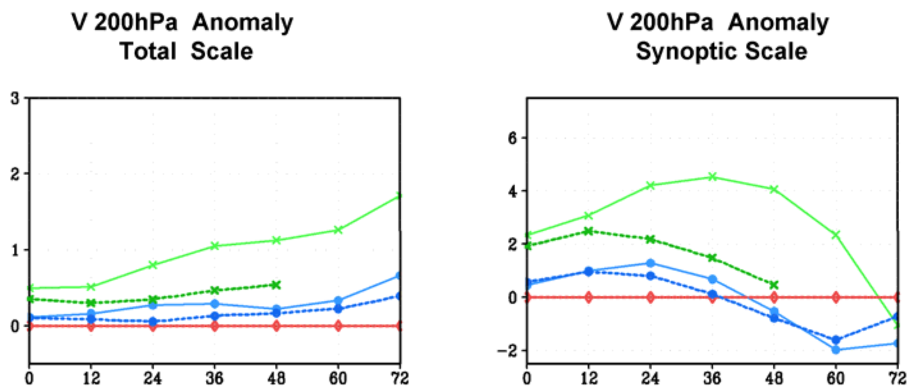


Fig.16. AC with Nature Run for 200mb V. The difference in AC from the CTL (red solid line with ◊ for both T62 and T170) shows the forecast impact of DWL with scanning (x) and non-scanning (●). CTL experiments (◊) include only conventional data. The left panel includes all waves; the right panel includes wave numbers 10-20 only (synoptic scale). Period used is February 13-20. Solid lines are for T62 experiments; dashed lines are for T170 experiments.

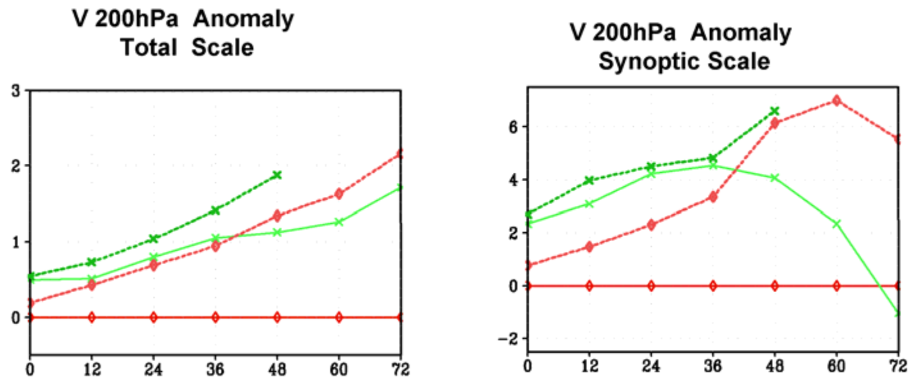


Fig.17. AC with Nature Run for 200mb meridional wind. The difference in AC from the T62 CTL (solid line with ◊) shows the forecast impact of the T170 CTL (red dashed line with ◊) and DWL with scanning (x). CTL experiments (◊) include only conventional data. The left panel includes all waves; the right panel includes wave numbers 10-20 only (synoptic scale). Period used is Feb 13-20. Solid lines are for T62 experiments; dashed lines are for T170 experiments.

6.9 *Impact of Non Scan DWL*

The impact of non-scan-DWL is much less than best-DWL with scanning. However, scanning is extremely challenging for a sensitive instrument like DWL. Evaluation of non-scan-DWL is of great interest because it is used in the ADM mission. OSSEs to evaluate the impact of the ADM mission have been done previously as mentioned in Section 1. The non-scan-DWL tested in this paper has a more general design, with profiles from all levels and a 100% duty cycle. It will provide information for LOS only. If u and v are used for a non-scan lidar, such as in OSSEs by Atlas (2003), the DWL data will represent the impact of a two way scan or of two satellites with non-scan DWLs.

The experiments were conducted comparing the impact among experiments using all conventional data (CTL), removing RAOB winds from the control (CTL-RAOB), adding non scan lidar to CTL-RAOB (CTL-RAOB+DWL), and including both RAOB and DWL (CTL+DWL). Fig 18 showed the results with a T170 model with analysis and 48 hour forecast fields. The difference in RMSE error is between (RAOB+CTL) and (DWL+RAOB+CTL). It is noted the impact of non scan lidar does not provide significant incremental improvement to forecasts beyond that provided by the RAOBs. However, there is improvement for DWL+CTL-RAOB when compared with CTL. The result showed that over the land RAOB data are more important than non-scan DWL, but non-scan DWL can still show a significant impact over the ocean. Note that TOVS radiance was not added to these experiments.

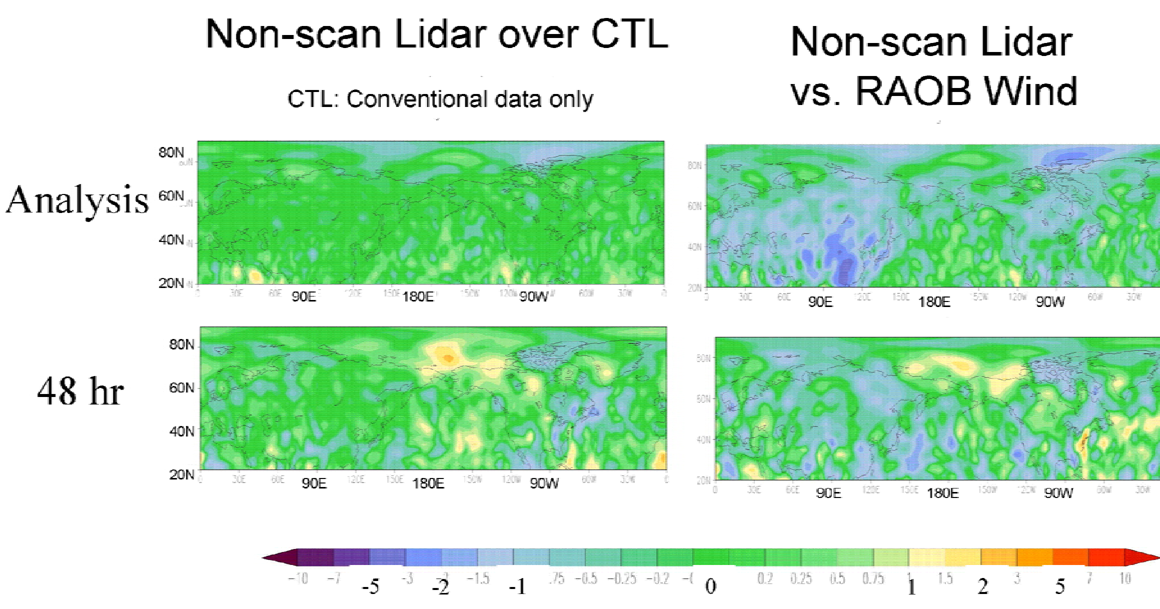


Fig.18 Comparison between the impact of non-scan-DWL in 200hPa V-component fields. Differences in RMSE between two experiments are plotted. The CTL includes only conventional data. In the left panels non-scan DWL added to CTL is compared to the CTL. Warm colors indicate additional impact from non-scan-DWL added to conventional data. In the right panels non-scan-DWL without RAOB winds are compated to the CTL. Warm colors indicate more impact from the non-scan DWL compared to RAOB wind. Blue colors indicate more impact from RAOB wind than from non-scan DWL.

7. Summary and Discussion

7.1 *Summary*

It is a challenging task to evaluate the realism of impacts from OSSEs. Due to uncertainties in OSSE; the differences between the NR and real atmosphere, the process of simulating data, and the estimation of observational errors all affect the results. Evaluation metrics also affect the conclusion. Consistency in results is important. Some results may be optimistic and some are pessimistic. However, it is important to be able to evaluate the source of errors and uncertainties. As more information is gathered we can perform more credible OSSEs. If the results are inconsistent, the cause of inconsistency needs to be investigated carefully. If the inconsistencies are not explained, interpretation of the results becomes difficult.

NCEP's OSSE has demonstrated that carefully conducted OSSEs are able to provide useful recommendations which influence the design of future observing systems. OSSEs for DWL and for TOVS and AIRS radiance showed that OSSEs can provide an evaluation of:

- whether scanning significantly improves the data, particularly in the upper atmosphere;
- the relative importance of upper or lower atmospheric data;
- the evolution of data impact with forecasts;
- the balance between model improvement and data improvement;
- the combined impacts of radiance data and wind data;
- the development of bias correction strategies.

Much research has showed that wind information has a much stronger impact on weather forecasts as compared to temperature (Arnold and Dey, 1986; Halem and Dlouhy, 1984). The results from NCEP OSSEs support these results in many ways. If DWL provides three dimensional wind data, it would cause a fundamental advance in the prediction of weather (Baker et al., 1995). Another advantage of DWL is its ability to take direct measurements of the wind, while extracting temperature information from radiance data involves radiative transfer models and many other complicated processes. Since space based DWL is a costly instrument, careful evaluation through OSSEs is extremely important before the investment at a large amount of resources.

As models improve, improvement in the forecast due to data becomes less. Sometimes the improvement in forecasts due to model improvements is much more than the data improvement. However, even in the NH, forecasts for sub-synoptic scales require much better data. In the tropics, models need to be improved to retain the analysis improvement for more than a few days of forecasts.

AIRS data have already been simulated by NESDIS (Kleespies et al., 2003) and the simulation of Cross Track Infrared Sounder (CrIS) data has been started. Experience with OSSEs for AIRS data showed that OSSEs will be very important in developing various tuning systems for the new satellite data. The experience demonstrated that if OSSEs are conducted years before the actual launch of the instruments, the operational use of the data will be accelerated.

7.2 *Seeking the next Nature Run*

It is evident that the OSSE with its current Nature Run is limited. The new data need to be tested with at least a T170 model resolution, but the T213 NR produced by ECMWF is too coarse to be used in OSSEs with the higher resolution assimilation model.

We found that the preparation of the NR and the simulation of data consumes significant resources. It is desirable to have one or two good NRs and have the data to be simulated created by one or two institutes. NRs and simulated data must be shared with many different institutes and OSSEs. OSSEs with different NRs are difficult to compare but OSSEs using different DAs but the same NR produce a valuable evaluation of data impact.

The basic features of this proposed NR are:

a. Cover a long period to allow selection of the most interesting periods;
b. Use a temporal resolution higher than the analysis cycle;
c. Use daily SSTs;
d. Use a high special and/or temporal resolution NR for the selected periods;
e. Include user-friendly archiving.

7.3 *Role of OSSEs in future observing systems*

The Joint Center for Satellite Data Assimilation (JCSDA) recognized OSSEs as a key program element for the center. The goal is that all new instruments will be tested by OSSEs before they are built.

NCEP needs to develop a system to assimilate these data in order to conduct the OSSEs. NCEP will collaborate with JCSDA to conduct OSSEs for advanced satellite sensors that will be used for weather and climate analysis and prediction. International collaboration will also be expanded through the THORPEX project.

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Throughout this project NOAA/NWS/NCEP, NASA/GSFC, NOAA/NESDIS and ECMWF staffs contributed to this project. Especially, we would like to acknowledge contribution from J. Derber, W. Yang,Y. Song, Z. Toth, W. Baker of NCEP, R. Atlas, G. Brin, S. Bloom of NASA/GSFC, and V. Kapoor, P. Li, W. Wolf, M. Goldberg of NOAA/NESDIS. We appreciate the constructive comments from members of the OSSE Review Panel. Finally we appreciate efficient technical support of M. Hart in preparation of the manuscript.

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