OSSES WITH THE AFGL GLOBAL DATA ASSIMILATION SYSTEM

R.N. Hoffman, R. Isaacs, J.-F. Louis, T. Nehrkorn and C. Grassotti
Atmospheric and Environmental Research, Inc.
Cambridge, MA, USA

Summary: We have conducted a series of realistic Observing System Simulation Experiments (OSSEs) to assess the impact of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave (SSM) T-1 and T-2, temperature and humidity profiles and a Doppler wind lidar (DWL) sounder. The addition of DWL profiles significantly improved the initial state specification, especially in the Southern Hemisphere extratropics relative to our control experiment. The addition of the SSM data significantly improved the moisture analyses in the tropics and Southern Hemisphere extratropics.

1. INTRODUCTION

Observing system simulation experiments (OSSEs) are often used to estimate the impact of proposed advanced observing systems and as an aid in their design by examining various implementation scenarios. In the present study we examined the impact of the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave (SSM) T-1 and T-2 instruments and the proposed Doppler wind lidar (DWL) instrument. In all, five OSSEs were performed. These are listed along with an indication of which data sources were used in each experiment in Table 1. In addition to the DWL and SSM data, the data sources include the conventional ground based data (radiosondes, aircraft reports, etc.), cloud drift winds (CDW) and civilian satellite profiles (TOVs). Detailed descriptions of these experiments may be found in Hoffman et al. (1989) and Grassotti et al. (1989).

Table 1. OSSE data sources summary

OSSE	Ground-based	CDW	TOVS	SSM	DWL
STATSAT	X	X	X		
NOSAT	X				
SSMSAT	X	X		X	
SSM+TOVS	X	X	X	X	
WINDSAT	X	X	X		X

There are four components common to any OSSE: (1) A four dimensional reference atmosphere, often called the nature run. This is considered to be the "TRUTH". (2) A sampling procedure to obtain observations. (3) A data assimilation system, composed of a forecast model and analysis procedure. (4) A quantitative verification procedure. These components will be detailed in succeeding sections.

Usually, the nature run is simply a long forecast made by an advanced numerical weather prediction (NWP) model or Global Circulation Model. The more sophisticated the nature model, the better. Remotely sensed data are influenced by many geophysical parameters, including sea surface temperature, atmospheric aerosol, clouds, etc, which should be included in the nature run to the extent possible. For example, SSM/T should provide less accurate retrieval of atmospheric boundary layer humidity when wind speeds are high since in this case surface emission dominates the atmospheric emission.

From the point of view of NWP, the most important characteristics of any proposed remote sensing system are its geographical coverage, horizontal and vertical resolution and its error characteristics. In a simulation study these characteristics must be properly accounted for. The procedures for simulating data from the nature run should consider the following items: (1) representational errors; (2) sampling; (3) geophysical local bias; (4) random error, which might contain vertical and horizontal correlations; and (5) sensor filtering. When a sensor uses a statistical retrieval method, all its observations should be filtered by projecting onto the vertical basis functions which are used in the retrieval. This is also true for so-called physical retrieval methods. Note that (2)-(5) above can be achieved by simulating the sensor and its retrieval scheme (e.g. Atlas et al., 1985). This is costly and, in our study, we have, instead, performed selected sensor simulation/retrieval studies described below to define the error characteristics.

By representational errors we mean that it is not just accuracy of the measurement which is important, the measurement must be representative as well. NWP is really concerned with the spatially and temporally smoothed behavior of the atmosphere. Variations on scales up to kilometers and minutes are generally considered to be averaged over and are parameterized within the model. Consequently, that part of the measured signal attributable to these scales is considered to be noise from the NWP point of view. This source of error can in some cases be predominant as, for example, in radiosonde observations. One implication of this is that as models improve in resolution, this source of error decreases. No existing global model has fine enough resolution to represent all scales of motion which exist in nature. In fact the smallest scales represented by models are usually severely damped for computational reasons. A method to unfilter the nature run was suggested by Hoffman (1988), but not used here.

Verification of OSSE results is easy because we have total knowledge of the "TRUTH". In these experiments we may legitimately use the word error instead of difference when we compare an experiment to the nature run. Interpretation of these results, however, is not so easy. For these reasons it is desirable to calibrate the OSSE results to Observing System Experiment (OSE) results. In the present case we conduct two OSSEs, NOSAT and STATSAT, for which we have previously conducted analogous OSEs. We use only a very simple calibration procedure in Section 5.3. Basically we assume OSSE impacts relative to STATSAT are proportional to corresponding OSE impacts in deriving our estimates of actual SSM/T-1,2 and WINDSAT impacts.

2. NATURE RUN

It would be possible to use a series of real analyses for the reference atmosphere, but the results of such experiments would be even more difficult to interpret for the following reasons. In this situation the "TRUTH" is the actual atmosphere, not the reference atmosphere. Therefore, in data rich areas, the reference atmosphere would agree well with the "TRUTH" while in data voids it would not. Consequently, simulated observations in data rich areas would add correct information, but have little impact because of the concentration of other observations already available, while simulated observations in data poor areas would add erroneous information, which would be carried by the model during the data assimilation cycle to other areas. If the results are then verified in data rich areas we might obtain a negative impact by adding a new observing system. Greater accuracy in the simulated observing system would not avoid adding erroneous data in data poor areas. For these reasons it is more advantageous to use a long range forecast for the nature run.

ECMWF generated the nature run used in this study. The nature run is simply a 20 day forecast from the FGGE IIIb analysis produced at ECMWF at 00 GMT 10 November 1979 (Bengtsson et al., 1982). The model used in the nature run forecast was a version of the 15 layer, 1.875 degree grid point model (Hollingsworth et al., 1980). This model included fairly complete physics (Tiedtke et al., 1979) with a diurnal cycle.

3. SIMULATED OBSERVATIONS

NMC simulated the FGGE Level IIb and WINDSAT data for the period, in the NMC (Office Note 29) format from the ECMWF nature run (Dey et al., 1985). Almost all Level IIb data were simulated. Later GLA converted the NMC data to the standard FGGE format (WMO, 1986). All this work was completed by early 1984. We received copies of the nature run and FGGE format Level IIb data from GLA, courtesy of R. Atlas. We simulated the SSM/T-1 and SSM/T-2 data based on careful simulation studies of the operational retrieval methodology.

3.1 Conventional data

The simulated standard FGGE Level IIb data were created by replacing all the observed atmospheric variables in the real FGGE Level IIb data with values interpolated from the nature run, corrupted by adding a simulated observing error. Therefore if a particular radiosonde report is missing in the real data, it is missing in the simulated data, if it is present in the real data, it is present in the simulated data and has the same quality control marks and missing data flags as the real observation. The simulated observational error which is added to the value of the nature run at the observing location is composed of a random Gaussian error which is not correlated with anything else and in the case of the TOVS data a bias depending on the diagnosed cloud cover. The size of the random error, or observing error standard deviation (OESD) is appropriate for the particular observation.

3.2 WINDSAT data

The basis of DWL is the measurement of the Doppler shift of a laser pulse backscattered by aerosols and other particles in suspension in the atmosphere. Two measurements of the same atmospheric volume from two different angles provide an unambiguous wind determination, with the reasonable assumption that the vertical velocity can be neglected.

The simulated WINDSAT data are created at all TIROS reporting locations in a manner similar to that described above for the other data types. At each TIROS location for which NESDIS performed a retrieval, a WINDSAT profile is produced. This profile extends from 10 mb down to the surface in relatively clear conditions or down to cloud top in cloudy conditions. Typically there are 2000 to 4000 WINDSAT profiles per six hour time period. We note that error levels assigned to the lidar winds are approximately half that of the RAOB winds. This characteristic combined with the full TIROS coverage and uncorrelated error structure are expected to greatly improve the analyses and forecasts.

3.3 <u>SSM/T data</u>

The SSM/T-2 retrieves moisture profiles using 5 microwave channels near the 183.31 Ghz water vapor resonance line. The main advantage of millimeter wavelengths over infrared retrievals is the low emissivity of the ocean surface, making possible the retrieval of low layer moisture. Another advantage is that clouds are not opaque to millimeter waves. However, the effect of clouds on the transmission of these waves cannot be neglected and is a field of continuing research. In particular, the role of ice clouds as attenuators may have been underestimated. For measurements taken over the oceans the main difficulty is estimating the effect of high winds on the surface emissivity. Over land, the variable, and in general higher surface emissivity makes millimeter wave retrieval of moisture less attractive. For a thorough review of millimeter wave moisture retrievals see Isaacs (1987).

We simulated SSM retrievals over oceans only because of the expected poor performance over land. The most accurate way to simulate an observing system such as the SSM is to use the nature run to generate the radiances (or brightness temperatures) that would be observed, add appropriate measurement errors and simulate the retrieval of temperature and moisture profiles. It would be very expensive to do this for every data point. Instead, we characterized the errors of the SSM instruments and the associated operational retrieval system. To do this, we solved the forward problem, i.e. the brightness temperature computation, only for two subsets of the data. The first subset was used to derive regression equations between nature run temperature and moisture profiles and computed brightness temperatures. The coefficients of these equations form the so-called D matrix. Several D matrices were derived, depending on whether the ocean was ice covered or not, and whether the sky was clear or cloudy.

These D matrices were then used to simulate statistical retrieval on the second subset of data. This procedure enabled us to derive a set of retrieval error statistics. These error statistics were stratified according to geophysical criteria, which included the latitude and strength of the wind in addition to cloudiness and the presence of ice. In the OSSE, then, we used these error statistics to modify the nature run profiles and create pseudo-retrievals. This work is described in detail by Grassotti et al. (1989).

In the SSM/T OSSEs we do not directly use the statistical properties which were used to simulate the data. Instead we saved the actual errors used in simulating the data and used them to develop global models of the observing errors for use in the analysis. Our first motivation for this is to estimate horizontal correlations. Secondly, the models of the observing errors used in our sensor simulation study are considerably more complex than those used by ASAP and we did not wish to make major modifications to the analysis procedure. Basically we found that:

1) The vertical height error correlations were fairly well fit by a simple function,

$$\nu = 1/(1 + k(\Delta(\ell n\ p))^2)$$

where we found k to be .3744 by a least squares fit. The corresponding relative humidity correlations were all small and deemed not significantly different from zero.

2) The horizontal height error correlation are close to zero. The relative humidity horizontal error correlations are also very small except at 300 and 400 mb where they remain above .2 out to 3000 km. In both cases we modeled the horizontal error correlations by

$$\mu = \exp(-(d/d_0)^{\frac{1}{2}})$$

where we choose d_0 as 83 km for height and 198 km for relative humidity.

3) No significant biases were found and the rms errors were of the expected size (see Table 2).

The statistical models used in the OI make use of these findings.

Table 2. OESDs used in data assimilation experiments

p(mb)	Z(m)	RH(%)	p(mb)	Z(m)
1000	7.98	7.91	250	27.01
850	7.98	18.35	200	28.38
700	14.01	14.45	150	32.15
500	21.71	15.12	100	38.37
400	25.08	15.17	70	39.40
300	26.57	19.35	50	41.85

4. EXPERIMENTAL DESIGN

The series of four dimensional data assimilation experiments described here make use of the AFGL Global Data Assimilation System. The assimilation cycle consists of a sequence of three major steps: analysis, normal mode initialization, and forward integration of the initialized state to the next analysis time. Some pre-/post-processing of the data may occur between the major steps. An entire assimilation run is a repetition of this sequence until an initialized analysis is obtained at the ending time.

Optimal interpolation (OI) provides the mechanism for obtaining regularly gridded initial conditions, i.e., analyses, from incomplete, irregularly spaced data. The AFGL Statistical Analysis Program (ASAP) Norquist (1986, 1988) is based on the NMC assimilation system, as reported in the literature and in personal communications. The ASAP OI is a multivariate analysis of height and wind components and a univariate analysis of relative humidity. The equations for the weights assigned to the data, as well as the computation of the horizontal and vertical correlation functions, follow Bergman (1979). The analysis error evolves according to simple rules (Norquist, 1986). The great circle distance method for correlation functions equatorward of 70° latitude is included as described by Dey and Morone (1985) without changing the Bergman formulation (including map factor) for latitudes poleward of 70° latitude. An important characteristic of the ASAP OI is that it is done on the sigma vertical coordinate system of the forecast model.

Data used by the height-wind analysis include Type 1 observations (radiosondes, pibals, etc.), Type 2 observations (aircraft), Type 4 observations (satellite-retrieved temperatures or thicknesses) and Type 6 observations (cloud drift winds (CDWs)). The Type 3 surface observations are not used at all. Earlier versions of ASAP included the use of surface reports in a preliminary surface pressure analysis. However, it was found that the surface pressure analysis was noisy and tended to destabilize the entire assimilation procedure. Consequently, it was decided to eliminate the surface pressure analysis. In retrospect, it might have been better to retain a surface pressure analysis, but only to anchor the satellite height retrievals.

The normal mode initialization (NMI) is a part of the forecasting system which adjusts the initial data in such a way that undesirable gravity waves do not grow in the forecast. The AFGL NMI is based on the NMC NMI described by Ballish (1980). The AFGL global spectral model (GSM) is based on the NMC GSM designed by Sela (1980). For the version used here, the physics routines are taken almost intact from NMC (circa 1983). The hydrodynamics, i.e., the nonadiabatic, inviscid dynamics including vertical and horizontal advection, time stepping, and transformations between spectral and physical space, were completely redesigned, as documented by Brenner et al. (1982, 1984).

There are a number of parameters in the assimilation cycle codes that can be adjusted. Typically, the parameters have the same values as used by Brenner et al. (1984) and Halberstam et al. (1984). Briefly, the spectral resolution of the forecast model is relative humidity rhomboidal 30. The Gaussian grid of the forecast model (analysis) contains 76 x 96 (62 x 61) latitude longitude points. There are 12 layers, the first (top) 5 of which have no moisture. Except for the GSM experiment, the sigma interfaces are at 0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.375, 0.50, 0.65, 0.80, 0.925, and 1.00, the time scheme used is centered semi-implicit with a time step of 17.25 minutes and a Robert time filter is applied with a constant of 0.04. A spectral diffusion coefficient of 6×10^{15} $m^{-4}s^{-1}$ is applied during the forecasts to all prognostic variables except for moisture. In the NMI, two Machenhauer iterations are applied to modes for the four largest equivalent depths which have periods less than or equal to 48 hours.

For the experiment to be realistic, we must start the first assimilation cycle with a state reasonably far away from the nature run. Otherwise the baseline analyses would be too good, and any impact of a new observing system hard to detect. We started by running a four day forecast from the state given by the nature run for 00 GMT, 11 November 1979. The error growth was relatively slow but, after four days, the level of error was at least as large as that inferred for the analyses of our real data experiments. We then performed an additional three day spin-up assimilation run, using the STATSAT data configuration. The resulting fields, at 00 GMT on 18 November, where then used as the starting point for all assimilation experiments.

Each OSSE runs from 00 GMT 18 November through 00 GMT 25 November. For each OSSE 96 hour forecasts are made from 00 GMT 21, 23 and 25 November. The OSSEs described make use of all the Level II data which were simulated by NMC as described in Section 3.1, except that surface observations are not used and satellite temperature soundings over land are not used. In NOSAT the satellite temperature soundings and CDW observations are excluded, in WINDSAT, the Doppler wind lidar observations described in Section 3.2 are added, in SSM+TOVS the SSM data described in Section 3.3 are added and in SSMSAT the SSM data replace the TOVS data. (Refer to Table 1.)

5. RESULTS

There are some important caveats that apply to the results reported here. As is the case with all OSSEs and OSEs, the measured impacts apply to the particular data assimilation system used here. While the assimilation system is reasonably "state of the art", some aspects, in particular the anchoring of the satellite thicknesses and the limitations of data selection, may limit the extent to which our conclusions are generally valid. Since we used simulated data in our experiments, the realism of our OSSE results depends on how realistic the simulated observation errors were. We took particular care that they were of sufficient size and had the appropriate error correlation structure. Finally, the calibration of our OSSE results with OSE RAOB statistics suffers from the usual problems of the uneven distribution of radiosondes, particularly the bias toward land areas (where no satellite data were used), and the small sample sizes over the Southern Hemisphere.

5.1 Synoptic evaluation

In this section we summarize the results of our synoptic evaluation. The OSSE analyses are all found to be noisier than the corresponding nature data. The Northern Hemisphere WINDSAT analyses of 500 mb height have errors smaller roughly by half than the corresponding STATSAT analyses. The SSMSAT and SSM+TOVS analyses in the Northern Hemisphere tend to be more like STATSAT. In the Southern Hemisphere, on the other hand, it is possible to differentiate between the different satellite based observing systems. Also in the Southern Hemisphere, we see that NOSAT is quite poor.

In a number of cases, synoptic features are better analyzed by SSMSAT than by SSM+TOVS. The somewhat surprising result that adding TOVS data leads to a degradation of the analyses is caused by a combination of factors, some of which are related to the anchoring of satellite thicknesses, others to data selection and quality control procedures.

Moisture analyses, either in terms of relative humidity or cloud cover, are noticeably improved by the addition of SSM data. It is quite clear that the moisture analyses created with the SSM retrievals are much improved over the STATSAT analyses. In addition, the humidity analyses for SSMSAT and SSM+TOVS are very similar with only minor differences seen between the two experiments. It seems that the presence or absence of TOVS retrievals has only a small impact upon the humidity analysis and that nearly all the improvement stems from inclusion of the additional SSM data. Improvement is most dramatic over southern hemisphere ocean areas where conventional moisture data is practically nonexistent. Smaller, but equally clear improvements are seen in the northern hemisphere as well. Also noteworthy is the fact that the analyses are improved over some land areas even though SSM retrievals were confined to the oceans.

In terms of forecast error, the Northern Hemisphere 500 mb height field is better forecast by WINDSAT relative to STATSAT by roughly 24 hours. Interestingly, although the analysis error patterns of WINDSAT and STATSAT are quite different, the forecast error patterns tend to have the same shape. This suggests that model errors are significant in these experiments. The quality of the three sounder based forecasts are all similar; in some cases one is better, but in other cases the roles might be reversed.

5.2 Statistical evaluation

The conclusions of the previous section are summarized by the objective statistical measures we have examined. Fig. 1 shows the global 500 mb rms height error of the NOSAT, STATSAT, SSMSAT and WINDSAT analyses and forecasts. The NOSAT analysis errors increase from the 35 m typical for the STATSAT analysis to 50 m by day 4 of the assimilation, whereas the STATSAT analysis errors decrease by 1-2 m over the assimilation period. This is an indication of how well the spin-up process has performed. The forecast error growth is more rapid in STATSAT, but errors remain smaller than those of the NOSAT forecast for the length of the forecasts. The SSMSAT analysis errors are consistently smaller than those of STATSAT, but by only 2-3 m. SSM+TOVS (not shown) is quite similar to STATSAT. The WINDSAT data have a definite and dramatic impact on the analysis error; by 24 hours the error has dropped to 20 m and continues to slowly decline thereafter. The WINDSAT forecast errors, since they start from such good initial conditions are the smallest of all the experiments. Results at other levels largely mirror those at 500 mb.

Considering the 850 mb relative humidity field (Fig. 2), we see that SSMSAT provides the best analyses yet the best forecasts are obtained from WINDSAT. This is more so in the extratropics than the tropics; presumably the relative humidity forecasts are determined largely by the large scale fields of temperature and winds in the extratropics and the WINDSAT analyses of these are superior. SSMSAT is always better than NOSAT which in turn is somewhat better than STATSAT. With regard to relative humidity SSM + TOVS is very similar to SSMSAT. The particularly low growth rate of relative humidity errors for STATSAT is an indication that the errors have already saturated and that the STATSAT humidity analyses are nearly worthless.

We examined zonal cross sections of u and v wind components, temperature and relative humidity at individual synoptic times and averaged over the last five 0000 GMT analyses of the experiments. Generally good agreement with the GFDL (Lau, 1984) time and zonal averaged cross sections for November, 1979 was obtained. Considering the amount of high quality wind data available to WINDSAT, the small improvements to the zonally averaged wind fields are disappointing.

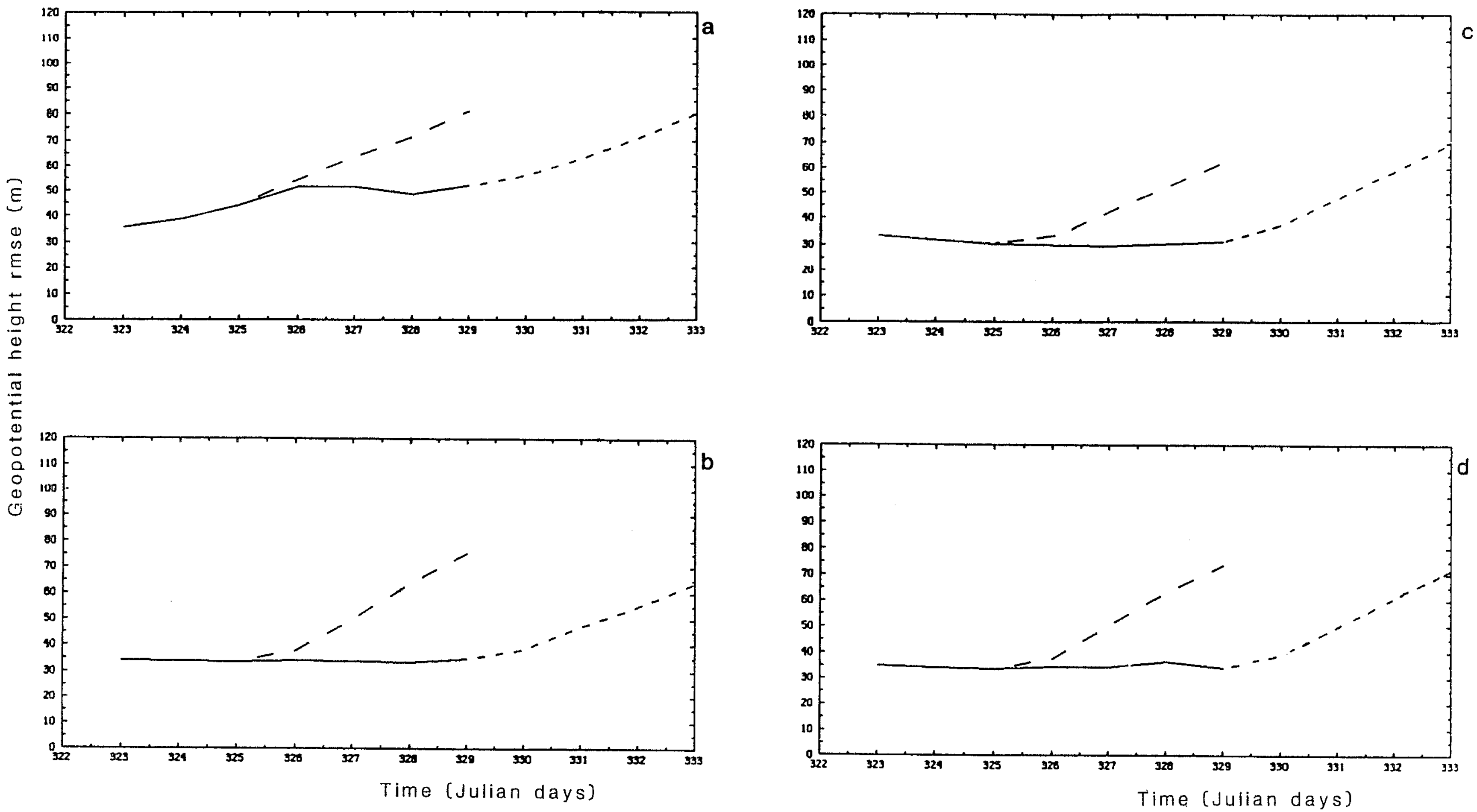

Fig. 1 *Rms height errors at 500 mb. (a) NOSAT, (b) STATSAT, (c) SSM, (d) WINDSAT. Analysis errors are shown in solid curves, forecast errors in dashed curves. Julian day 322 corresponds to 00 GMT 18 November.*

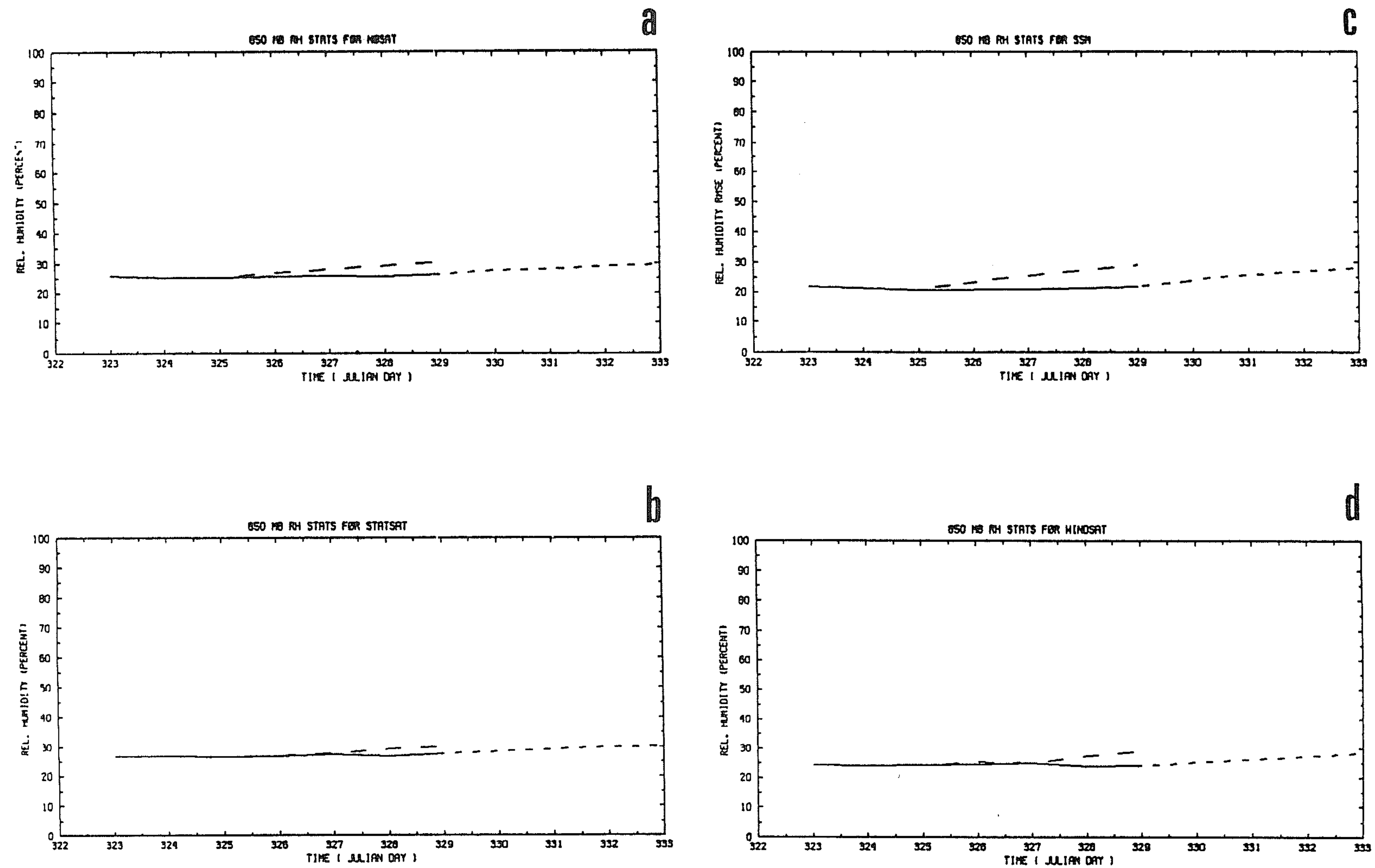

Fig. 2 Global rms analysis/forecast errors for 850 mb relative humidity. (a) NOSAT, (b) STATSAT, (c) SSM, (d) WINDSAT. Solid curves denote analysis, broken curves are forecasts.

Time mean zonally averaged relative humidity errors are relatively large in all assimilations. Generally, the boundary layer is too cold and too dry and the tropical free atmosphere is too moist. We may contrast nature with the cross sections for STATSAT and SSMSAT (Fig. 3). In STATSAT the low level averaged relative humidity analysis below 850 mb is consistently too dry while at higher levels relative humidity is too high in the tropics and too dry near the poles. As a result the northern and southern hemisphere mid-level minima are greatly increased in magnitude in STATSAT. Additionally, the asymmetry seen in the nature run with respect to height is gone and both features now occur at 650 mb. In SSMSAT the averaged relative humidity analysis is improved almost everywhere. As in STATSAT, the averaged SSMSAT analysis does not retain the asymmetry in the moisture field which is seen in averaged nature data, although the magnitudes of the minima are better analyzed. In short, as determined from differences in averaged analyses, SSMSAT relative humidity analyses are closer to nature at most latitudes and at all vertical levels. However, in general, the polar regions and boundary layer are too dry and the mid-latitude and tropical atmosphere above the boundary layer is too moist.

In general the biases during the forecast are small compared to the rms differences. However, in many cases the biases grow very steadily with time indicating that the AFGL model is warming and drying relative to the ECMWF nature. For example, Fig. 4 shows the evolution of bias for the 500 mb height in the OSSEs.

5.3 Calibration of forecast impacts to OSE results

Forecasts made within OSSEs are often much better than any real forecast. There are two principle reasons for this behavior: First, the model used to produce the nature run is inevitably more similar than the true atmosphere to the forecast model. Second, the errors used in many simulation experiments are easy for the analysis system to handle.

For these reasons it is desirable to calibrate the OSSE results. In order to have a closer correspondence with the real world and to simplify our calibration procedure we have calculated rms difference between the forecasts and the simulated radiosondes for different regions and for several variables at each layer in the atmosphere. The variables examined include geopotential height, temperature, vector wind, relative humidity, and cloud cover. We then developed a procedure to calibrate these differences

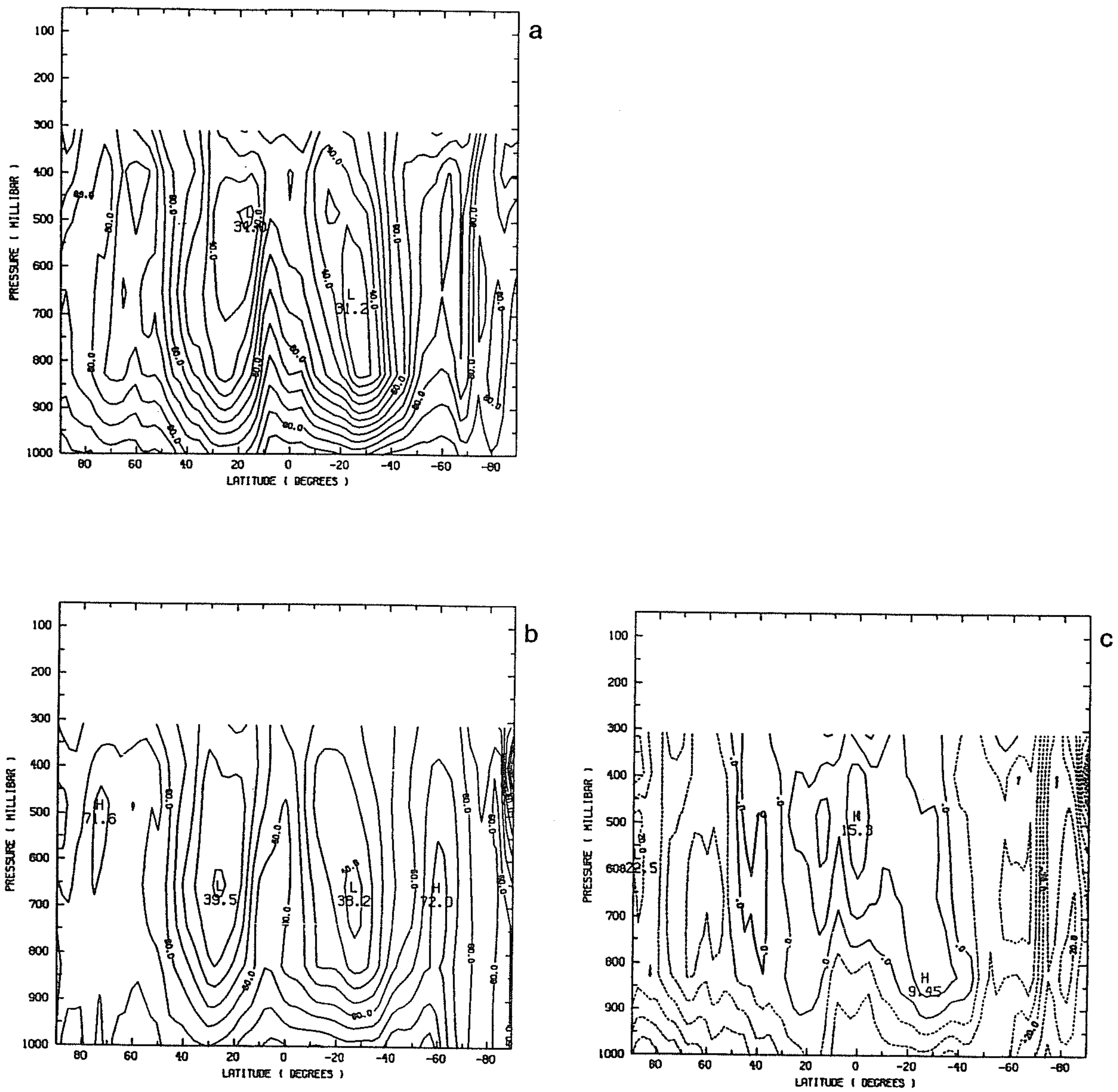

Fig. 3 Zonal time averaged relative humidity. (a) The nature run, (b) STATSAT, (c) STATSAT - the nature run, (d) WINDSAT, (e) WINDSAT - the nature run, (f) SSM, (g) SSM - the nature run. Contour interval is 5 percent, negative values are dashed.

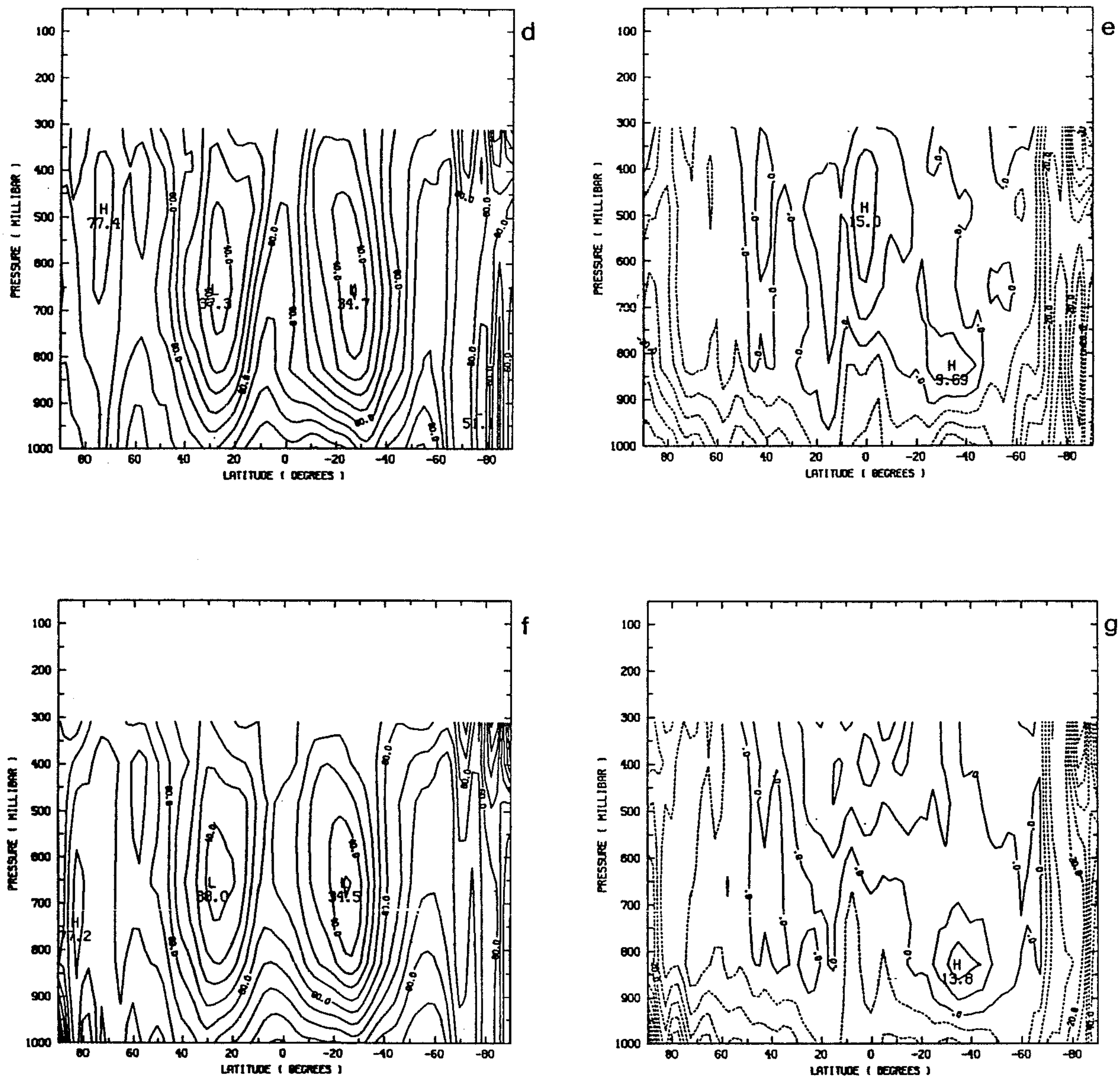

Fig. 3 (con'd)

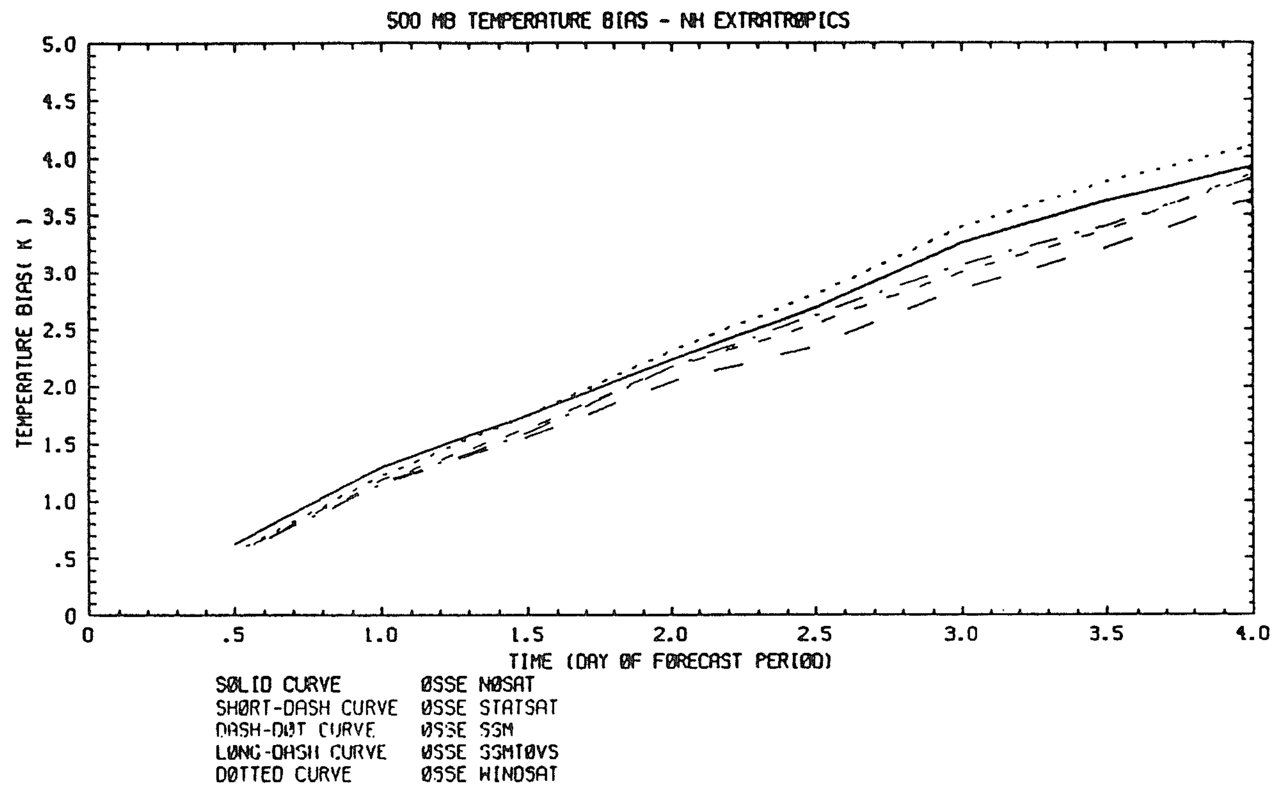

Fig. 4 Forecast 500 mb temperature bias for northern hemisphere extratropics.

using the NOSAT - STATSAT impact observed in the OSEs conducted by Louis et al. (1989) as a yardstick. However, for the present experiments we find that the OSSE impacts are fairly similar to the OSE impacts and the calibration procedure does not greatly alter the conclusions one might draw from the OSSE results directly. We also calculated rms difference in cloud cover layer by layer. Invariably, the corresponding relative humidity and cloud cover plots look very similar.

Our principal calibration assumption is that the OSE impact of adding or removing an observing system is proportional to the corresponding OSSE impact. In our calibrations we always take STATSAT to be our standard. We use the NOSAT - STATSAT difference to determine the constant of proportionality. However, in the Northern Hemisphere, STATSAT and NOSAT OSSE results are often so nearly equivalent that impacts expected from advanced observing systems cannot be calibrated. We measure impact in terms of predictability time, i.e. we define impact to be the change in the useful length of the forecast. We then took advantage of the observation that our rms difference curves grow nearly linearly, at least during the forecast period from 12 to 48 hours, to fit these data with a series of straight lines having a common slope. In the Northern Hemisphere these fits were very good. They are less reliable in the Southern Hemisphere and tropics, presumably because the number of radiosondes in these regions is small.

The impact of the SSM and DWL data was found to be generally small in the Northern Hemisphere, but quite substantial in the Southern Hemisphere. This result is in agreement with numerous previously conducted OSSEs and OSEs which measured the impact of satellite data. Consider the rms difference for 500 mb geopotential. Figure 5 shows the uncalibrated forecast error growth curves. In the Southern Hemisphere, WINDSAT is 36 hours better than STATSAT, which is in turn more than 36 hours better than the NOSAT forecasts. The three sounder based systems are roughly equivalent with SSM and SSM+TOVS better than STATSAT by 12 and 8 hours respectively. At 200 mb compared to STATSAT, WINDSAT provides 1, 2 and 2.75 day improvements in rms wind vector forecast skill in the Northern Hemisphere, tropics and Southern Hemisphere, respectively. In the Southern Hemisphere, the rms difference curves sometimes exhibit a sawtooth pattern due to sampling problems; there are usually about 60 RAOBs at 00 GMT and only about 40 at 12 GMT in the Southern Hemisphere. Most of the non-reporting RAOBs are in the Australian sector.

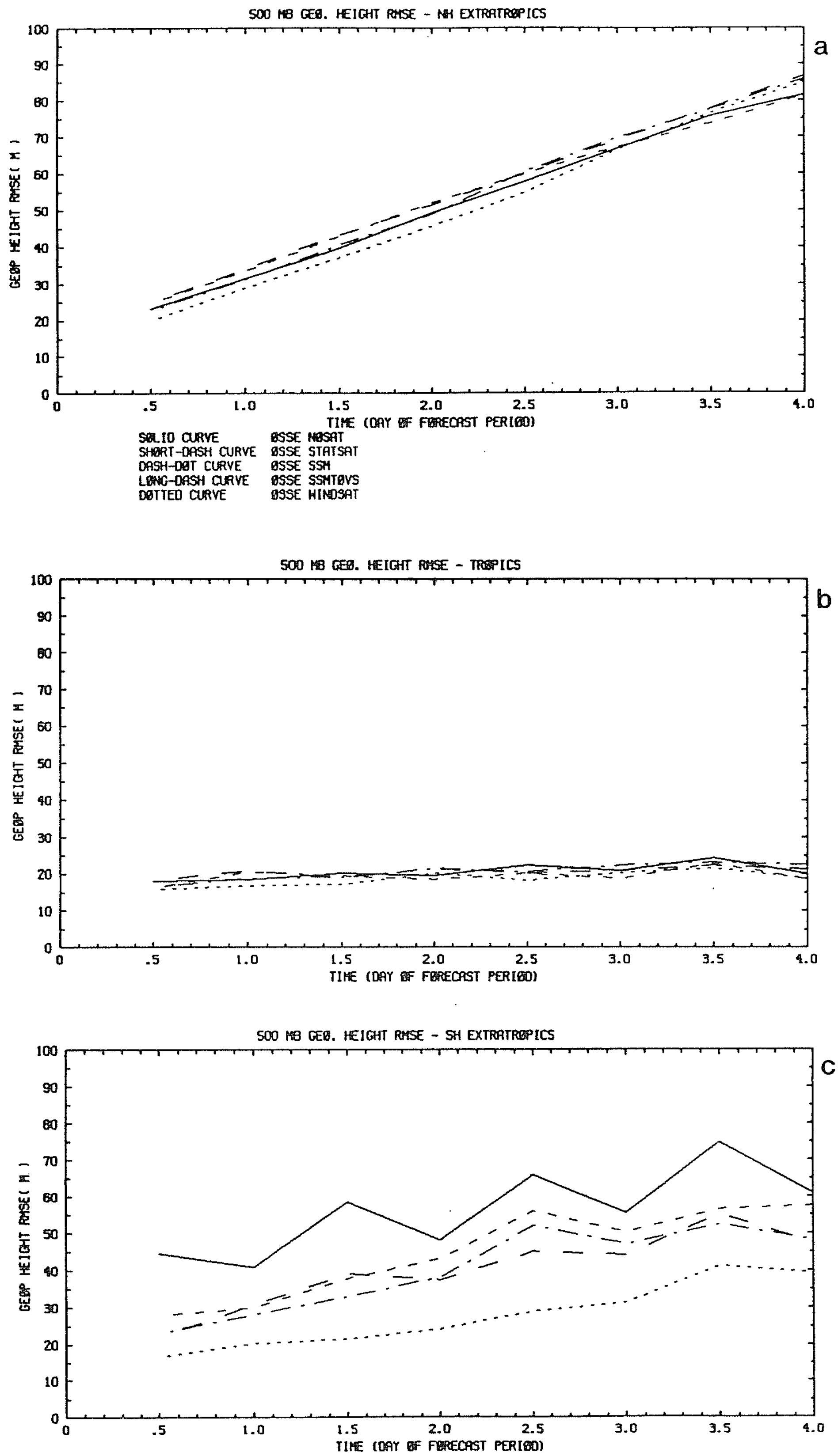

Fig. 5 Forecast rms error growth, 500 mb height. (a) Northern hemisphere extratropics, (b) Tropics, (c) Southern hemisphere extratropics.

The relative humidity forecast errors were not appreciably affected in the Northern Hemisphere extratropics, but a marked improvement could be seen in the tropics and the Southern Hemisphere extratropics (Fig. 6). Interestingly, though, WINDSAT moisture forecasts were superior to SSMSAT in the extratropics, even though only RAOB moisture data were used in WINDSAT, reflecting the dominant role of the mass and wind fields in forcing the moisture field in the extratropics. Overall the ranking is WINDSAT, SSM, NOSAT, SSM+TOVS and STATSAT. It appears that using TOVS degrades the moisture analysis.

6. SUMMARY AND CONCLUDING REMARKS

We have conducted a series of realistic observing system simulation experiments (OSSEs) to assess the impact of a Doppler Wind Lidar (DWL) sounder and the SSM/T-1,2 microwave and millimeter wave temperature and humidity profiles. These experiments are summarized in Table 1. The addition of DLW profiles in our WINDSAT experiment significantly improved the initial state specification, especially in the Southern Hemisphere extratropics relative to our control STATSAT experiment. The addition of the SSM data significantly improved the moisture analyses in the tropics and Southern Hemisphere extratropics.

In all the forecasts the AFGL model has a tendency to warm and dry out relative to the ECMWF nature model. We note that the version of the AFGL model which we used has no radiation parameterization. The results of our WINDSAT experiment are consistent with previous studies. However, it should be noted that the error characteristics chosen for the simulated DWL seem optimistic.

WINDSAT improvements in forecasting ability were quite large in the Southern Hemisphere. These differences are expected to increase the length of the useful forecast by 36 hours in the height field at 500 mb and by 48 hours in the wind field at 200 mb. Details of the analyzed tropical wind field using WINDSAT were somewhat disappointing. Improvements to the assimilation procedures might enable the WINDSAT data to have greater impacts in the tropics. In the Southern Hemisphere, SSM data improved the 500 mb height forecasts by 8-12 hours.

Moisture analyses were substantially improved in the SSM OSSEs. Typical rms errors were decreased by 1/5 from 27% to 22%. Cloud cover estimates

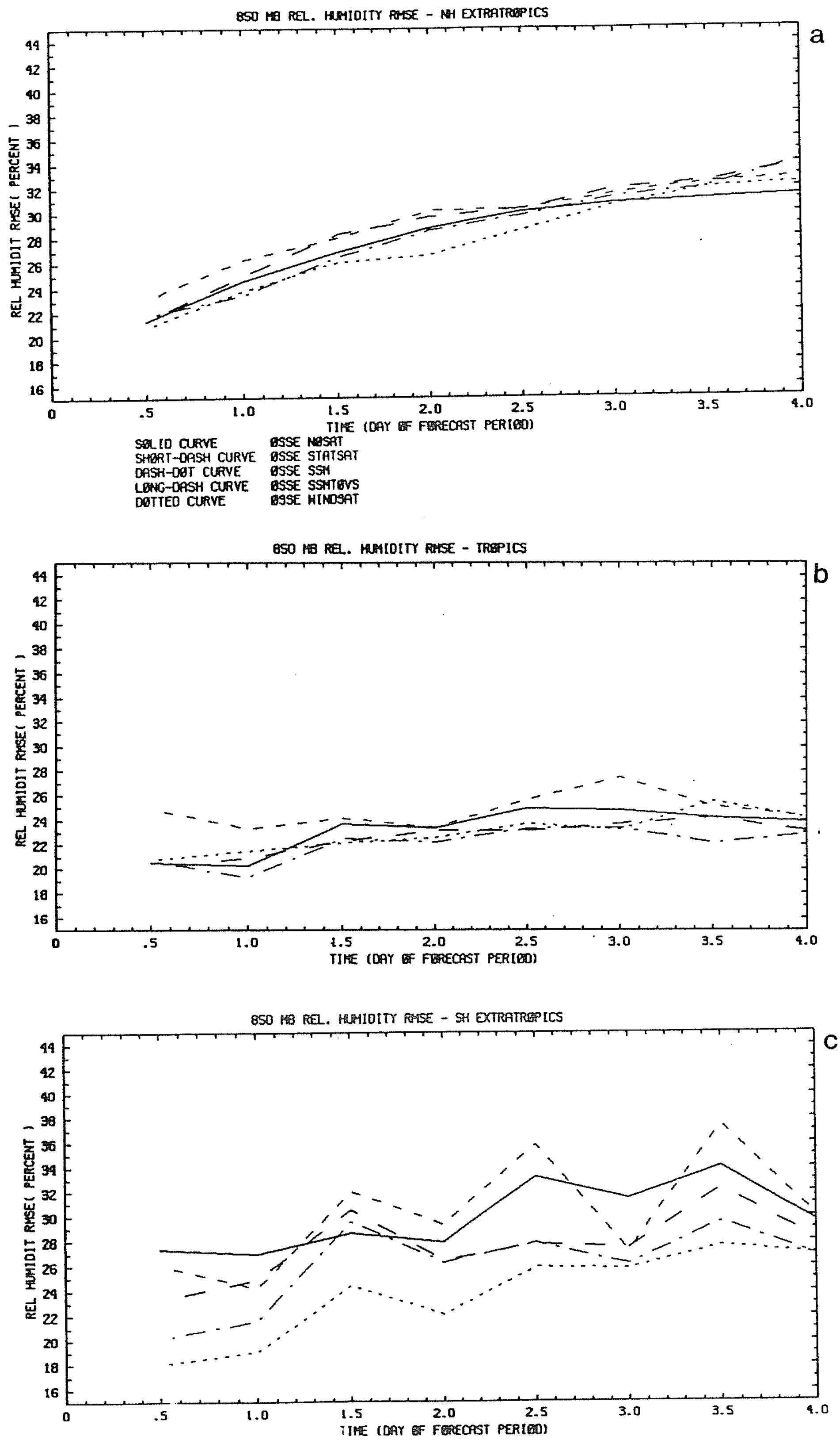

Fig. 6 Forecast rms error growth, 850 mb relative humidity. (a) Northern hemisphere extratropics, (b) Tropics, (c) Southern hemisphere extratropics.

derived from the relative humidity fields are too high. Either the model is too moist or the relative humidity to cloud cover algorithm needs to be tuned. The forecasts of relative humidity were also significantly improved. The comparisons of rms difference of cloudiness yield the same results as comparisons of rms difference of relative humidity. However we note that improved wind data also improved the analyzed and forecast moisture and cloudiness fields. Relative humidity forecasts are best in WINDSAT although SSM had better relative humidity analyses. This is to be expected since the relative humidity field adjusts to the large scale mass-motion fields, which are better analyzed and forecast in WINDSAT.

We developed a calibration procedure to translate our simulation results into realistic estimates of forecast impact. The calibration indicates that the improvements seen in the OSSEs in the Southern Hemisphere and tropics are realistic, but in the Northern Hemisphere extratropics, the fact that satellite data has little impact as seen in our NOSAT versus STATSAT comparisons implies that any novel observing system will have limited impact.

There is considerable opportunity to improve and refine the experiments reported here. Such efforts would allow the quantification of the relative impact of proposed advanced temperature and moisture sounders and DWLs. In addition cost benefit analyses of observational accuracies could be supported by such studies. In future studies it will be important to carefully simulate the geographical coverage and error characteristics of proposed instruments. In particular, natural phenomena which give rise to correlated observational errors should be included to the extent possible.

7. ACKNOWLEDGEMENTS

This study was supported by Air Force Geophysics Laboratory Air Force Systems Command contract F19628-86-C-0141. We thank R. Atlas who provided the nature data and simulated FGGE Level II data. We also thank M. Mickelson who ran the experiments, D. Coombes who produced the plots, and E. Stenhouse and L. Struz for expert typing.

8. REFERENCES

Atlas, R., E. Kalnay, W.E. Baker, J. Susskind, D. Reuter, and M. Halem, 1985: Simulation studies of the impact of future observing systems on weather prediction. In Preprint volume. Seventh Conference on Numerical Weather Prediction. American Meteorological Society, Boston, MA, pp. 145-151.

Ballish, B., 1980: Initialization, theory and application to the NMC spectral model. Ph.D. Thesis, Dept. of Meteorology, University of Maryland, College Park, MD, 151 pp.

Bengtsson, L., M. Kanamitsu, P. Kåallberg and S. Uppala, 1982: FGGE 4-dimensional data assimilation at ECMWF. Bull. Amer. Met. Soc., 63, 29-43.

Bergman, K. H., 1979: Multivariate analysis of temperature and winds using optimum interpolation. Mon. Weather Rev., 107, 1423-1444.

Brenner, S., C.-H. Yang, and S.Y.K. Yee, 1982: The AFGL spectral model of the moist global atmosphere: Documentation of the baseline version. AFGL-TR-82-0393, AFGL, Hanscom AFB, MA, 65 pp. [NTIS AD A129283]

Brenner, S., C.-H. Yang, and K. Mitchell, 1984: The AFGL global spectral model: Expanded resolution baseline version. AFGL-TR-84-0308, AFGL, Hanscom AFB, MA 80 pp. [NTIS ADA 160370]

Dey, C.H., and L.L. Morone, 1985: Evolution of the National Meteorological Center Global Data Assimilation System: January 1982-December 1983. Mon. Weather Rev., 113, 304-318.

Dey, C., C.P. Arnold, and W. Bostelman, 1985: Design of a windsat observing system simulation experiment. In Global Wind Measurements, W. E. Baker and R. J. Curran (Eds.), A. Deepak Publishing, Hampton, VA, pp. 73-79.

Grassotti, C., R. Isaacs, R.N. Hoffman, J.-F. Louis, T. Nehrkorn and M. Mickelson, 1989: A study of the impact of 183 GHZ water vapor retrievals on numerical weather prediction. AFGL-TR-89-0093, AFGL, Hanscom AFB, MA, 181 pp.

Halbertstam, I., C. Johnson, D.C. Norquist, and S.-L. Tung, 1984: Two methods of global data assimilation. AFGL-TR-84-0260, AFGL, Hanscom AFB, MA., 91 pp. [NTIS ADA155981].

Hoffman, R., 1988: Sampling data for OSSEs. In Preprints, Eighth Conference on Numerical Weather Prediction, February 22-26, 1988, Baltimore, MD, American Meteorological Society, Boston, MA, pp. 831-833.

Hoffman, R.N., M. Mickelson, and T. Nehrkorn, 1988: Enhancements to the AFGL Statistical Analysis Program (ASAP) for the global multivariate analysis of heights and winds. AFGL-TR-88-0279, AFGL, Hanscom AFB, MA, 110 pp.

Hoffman, R.N., J.-F. Louis, T. Nehrkorn, M. Mickelson and R. Isaacs, 1989: A study of the impact of simulated satellite lidar wind observations. AFGL-TR-89-0094, AFGL, Hanscom AFB, MA, 41 pp.

Hollingsworth, A., K. Arpe, M. Tiedtke, M. Capaldo and H. Savijärvi, 1980: The performance of a medium range forecast model in winter - impact of physical parameterization. Mon. Wea. Rev., 108, 1736-1773.

Isaacs, R.G., 1987: Review of 183 GHz moisture profile retrieval studies. AFGL-TR-87-0127, Air Force Geophysics Laboratory, Hanscom AFB, MA, 45 pp.

Lau, N.-C., 1984: Circulation statistics based on FGGE Level III-b analyses. NOAA Data Report ERL GFDL-5, NOAA, Washington DC, 427 pp.

Louis, J.-F., R.N. Hoffman, T. Nehrkorn, and D. Norquist, 1989: Observing systems experiments using the AFGL four-dimensional data assimilation system. Mon. Weather Rev., submitted.

Norquist, D.C., 1986: Alternative forms of moisture information in 4-D data assimilation. AFGL-TR-86-0194, AFGL, Hanscom AFB, MA, 144 pp.

Norquist, D.C., 1988: Alternate forms of humidity information in global data assimilation. Mon. Wea. Rev., 116, 452-471.

Sela, J.G., 1980: Spectral modeling at the National Meteorological Center. Mon. Weather Rev., 108, 1279-1292.

Tiedtke, M., J.-F. Geleyn, A. Hollingsworth and J.-F. Louis, 1979: ECMWF model parameterisation of subgrid scale processes. ECMWF Tech. Rep. No. 10. Reading, Berkshire, U.K.

WMO, 1986: Formats for International Exchange of FGGE Level II Data Sets, International Council of Scientific Unions/World Meteorological Organization, The World Climate Research Programme, WMO/TD-No. 100, WMO, Geneva, 86 pp.