Production and Use of Satellite Soundings with an Interactive Analysis/Forecast/Retrieval/System

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ABSTRACT

The National Meteorological Center (NMC) has initiated a comprehensive effort to improve the use of satellite data in the global data assimilation system (GDAS) including a comprehensive quality control system and a new interactive retrieval system. This article describes the present system and the various research activities that are related to this effort.

1. INTRODUCTION

The accuracy of operational numerical weather forecasts has steadily increased through the 1980's to the point where it is becoming difficult to routinely expect operational satellite temperature soundings to have a positive impact on the forecasts over the Northern Hemisphere. In fact, the European Centre for Medium Range Weather Forecasts (ECMWF) has recently obtained a substantial negative impact from satellite soundings on Northern Hemisphere forecasts (A. Hollingsworth, personal communication).

The realization of the importance of the satellite retrieval problem to numerical weather prediction (NWP) culminated recently in the formation of an Interagency Satellite Retrieval Working Group in the United States which includes satellite retrieval and NWP experts from the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). The charge to this Working Group (see Appendix) is to develop as soon as possible a state-of-the-art satellite retrieval system for numerical weather forecasting. This system will take

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advantage of the best components of the operational system at NESDIS and those from experimental approaches at NESDIS and at NASA.

There was also a strong consensus among the Working Group members, that, over most of the globe, the present-day accuracy of the model 6 hour forecast during the data assimilation should be beneficial to the retrieval process. The approach of producing and using the satellite soundings "interactively" then naturally follows, where the assimilation model forecast is used as a first guess by the retrieval scheme (the model forecast has also been used with a variational approach to analyze radiances directly for numerical prediction (e.g., Eyre and Lorenc, 1989)). The resulting retrievals are then analyzed in conjunction with other available data to produce initial conditions for the subsequent forecast by the assimilating model. Such an approach developed and used extensively in a research mode by J. Susskind and collaborators at the NASA Goddard Space Flight Center, has been shown to have a beneficial effect on both the accuracy of the 6 hour assimilation model forecast and that of the retrievals (Susskind and Pfaendtner, 1989). More importantly, the negative impacts on medium range forecasts over the Northern Hemisphere are, for the most part, eliminated. In addition to temperature profiles and thick-layer precipitable water estimates, a wide range of geophysical parameters (e.g., land and sea surface temperature, ice and snow extent, cloud top pressure and amount, and estimates of outgoing long wave radiation, soil moisture, total ozone, precipitation, and a vegetation index) can also be produced. A particularly strong point with the interactive approach is that the above parameters are obtained in a way which is consistent with the mass and wind fields in the assimilation because the 6 hour forecast from the assimilation is used as the first guess for the retrievals.

Preliminary results using the model 6 h forecast as the first guess for the retrievals are discussed in Section 4 following a summary of the present treatment of satellite data in the NMC GDAS and some current problems with satellite data, in Sections 2 and 3, respectively. The specific findings of the Interagency Satellite Retrieval Working Group resulting from a meeting at NMC on July 6-7, 1989 and the plans for developing a state-of-the-art retrieval system are outlined in Section 5.

2. PRESENT TREATMENT OF SATELLITE DATA AT NMC

Here, we describe the way we are currently processing satellite data in the global data assimilation system at NMC and include results comparing physical and statistical retrievals. Our current restrictions in the use of satellite data with respect to coverage and vertical extent are summarized as follows:

1. All microwave retrievals between 20N and 20S are not used by the analysis.

2. No moisture retrievals are used anywhere in the analysis.

3. Overland retrievals at and below 100 hPa are not used by the analysis.

4. For satellite sounding pairs which are within 100 km of each other, the one whose observation time differs most from the time of the analysis is excluded from the analysis. This effects overlapping swaths near the poles.

The quality control of SATEMS is not adequate and is a serious deficiency in the NMC system. A major effort is now underway to revise the entire quality control system at NMC incorporating the ideas of Gandin (1988) on complex quality control.

2.1 Gross Toss Limits

The standard deviations of observation-first guess (6 h forecast) differences used in computing gross toss limits are listed in Table 1.

For SATEMS, values of 5 * Z-values (left column) are used. For all others the observational increment (data-first guess) $< n\sigma$ is checked, where n is a function of the quality mark (QM).

	QM	n
keep	0	∞
passed	1	7
unchecked	2	5
suspect	3	3

The other exception to the above table is for SATOBs, where n is divided by 2, if the observed speed is less than the guess speed. In the future, we plan to test replacing the SATOB speed with the guess speed for high-level, strong winds.

Table 1 Standard deviation of observation minus 6 hour forecast differences for z (top) in m, u (middle) in ms-1, and v (bottom) in ms-1.

P	-90 to -10	-10 to 10	10 to 30	30 to 50	50 to 90
1000	25.4	14.7	19.4	19.7	21.6
850	25.4	15.5	16.7	19.6	19.4
700	26.8	19.3	18.7	19.7	20.8
500	33.5	25.4	25.6	23.2	25.8
400	39.2	29.6	32.4	27.2	29.9
300	47.0	40.1	42.3	34.1	36.5
250	50.6	49.4	47.3	37.4	39.2
200	53.5	55.3	56.3	41.6	42.0
150	57.3	61.4	67.4	46.7	48.3
100	69.8	78.0	80.0	55.2	59.4
70	77.7	80.0	80.0	64.2	71.8
50	90.1	80.0	80.0	78.3	88.1

P	-90 to -10	-10 to 10	10 to 30	30 to 50	50 to 90
1000	4.24	3.48	4.11	4.59	4.36
850	3.88	3.18	3.71	4.12	3.58
700	4.18	3.56	4.10	4.19	3.56
500	4.79	4.25	4.81	4.79	4.41
400	5.47	4.05	5.34	5.63	5.25
300	6.59	5.76	6.53	7.11	5.66
250	9.52	5.78	7.33	6.65	5.45
200	7.29	7.81	7.61	6.72	4.38
150	6.53	8.24	7.30	5.89	3.72
100	6.96	8.77	7.73	5.07	3.67
70	6.56	7.71	5.56	7.10	5.48
50	8.29	9.85	8.66	8.22	7.61

P	-90 to -10	-10 to 10	10 to 30	30 to 50	50 to 90
1000	4.12	3.30	3.92	4.87	4.33
850	3.69	2.76	3.43	4.29	3.59
700	4.10	3.27	3.62	3.79	3.57
500	4.61	3.52	4.20	4.57	4.41
400	5.66	4.04	4.95	5.26	5.03
300	6.83	5.26	6.05	6.39	5.50
250	7.34	5.24	6.89	6.62	5.31
200	7.02	5.77	7.64	6.21	4.28
150	6.71	5.68	7.15	4.89	3.71
100	6.37	7.07	6.23	4.07	3.58
70	5.46	4.82	5.32	4.89	5.14
50	8.00	8.26	8.63	6.71	7.41

2.2 Description of the Buddy Check

In February 1987, a modified version of the "buddy" check was implemented in the regional analysis. This version was incorporated in the global data assimilation system in May 1988. The principal change from the previous scheme is in the final decision making procedure. The approach involves adding all of the flags for agreement (KEEP) and disagreement (TOSS) and keeping those obs with at least 2 KEEPs and excluding obs with fewer than 2 KEEPs which have more than 2 TOSSes. In the original scheme flags were set to an integer 1 when agreement or disagreement occurred. The new procedure sets the flag value equal to the forecast error correlation value (height-height autocorrelation) which is nearly 1.0 for observations close to each other and nearly 0.0 if two observations are far apart. Thus, the new procedure gives much more weight in the final decision to pairs which are close together than to those pairs which are far apart.

Other changes were incorporated to be more "heavy handed" with the satellite sounding data. In order for a satellite report to be accepted, it must have a sum of 3.0 agreement flags (KEEPs). In addition, agreement flags are not set for pairs which are of the same retrieval path because their values are assumed to be correlated and not sufficiently independent. This makes it more difficult for satellite soundings to achieve the requisite number of KEEPs.

Finally, if any type of error is encountered with a satellite sounding, all of the levels of the sounding are deleted. Table 2 contains some recent statistics on the number of SATEMS used or tossed by the analysis.

Table 2 Number of SATEMS used or tossed by the analysis.

Date		Received	Used	Tossed	%
1/7/89	12Z	1809	1631	178	9.8
1/7/89	18Z	2047	1924	123	6.0
1/8/89	00Z	2391	2165	226	9.5
1/8/89	06Z	1972	1811	161	8.2

In the future, we plan to either give less weight to swath edge profiles or delete them, and use satellite thickness data in the analysis rather than heights.

2.3 Recent Analysis Changes

Several analysis changes in the global data assimilation system (GDAS) were evaluated during the summer of 1988. Some of the changes were designed to improve the efficiency and structure of the computer codes. Other changes were made to update and improve the statistical quantities that are used in the optimum interpolation analysis. Forecasts from the global model have improved over the past few years due to improved physical parameterizations and increased resolution. For this reason, the observation and forecast errors that are used during the assimilation have been updated to reflect the current forecast skill of the T80 global spectral model.

The following list of modifications to the GDAS were tested and evaluated in the NMC Development Division parallel system. The complete package of changes including those to the model (see Campana et al., 1989) were placed into the operational job stream on November 30, 1988 at 1200 UTC.

2.3.1 Treatment of Satellite Profiles

In the operational system prior to November 30, 1988, satellite profiles of geopotential height over water were anchored at 1000 mb and those over land at 100 mb. No satellite observations were used for either anchoring analysis. This procedure produced large gradients in the analysis increments and the resulting analysis near coast lines at levels above 100 mb whenever a mismatch occurred between profiles over water and those over land. This effect has been reduced by using the anchored satellite observations over water during the anchoring analysis for those over land. In addition, satellite geopotential observations are no longer used during the analysis at or below the anchoring level as was done previously.

A deficiency in the NMC processing of NESDIS satellite derived heights, which had produced a systematic warming of the layer between 300 and 100 mb in areas covered mainly by satellite observations, has been corrected. A gradient of height errors had developed normal to the continental coasts in regions where the satellite data were adjacent to radiosonde reports. NESDIS provides NMC with heights at selected constant pressure levels throughout the depth of the atmosphere. However, not all mandatory pressure levels are included. To provide data at all of the mandatory levels for the analysis, NMC interpolates data to the "missing" levels. The interpolation process was biased and did not preserve the total thickness of the column between reported levels.

To alleviate this problem, the height calculation technique has been modified so that the thickness values in the deeper layers are used directly as reported by NESDIS. The thickness values at the "missing" layers are then obtained using the relative values calculated previously, but constrained to the reported total value. The modified procedure does preserve the mean thickness of the column and is, therefore, unbiased. This change alone resulted in significant improvements in both the first guess and the longer forecasts.

2.3.2 Updated Forecast and Observation Errors

Forecast errors in the GDAS are based upon prescribed forecast error growth rates and the normalized analysis error resulting from each analysis. Since the implementation of the T80 global spectral model, forecast errors in most NMC global products have been reduced. For this reason, the forecast error growth rates that are used in the GDAS to model forecast errors have been reduced. In addition, the capability to use different growth rates in the northern and southern hemispheres and in the tropical regions has been added to the new system. The current operational and old values are shown in Table 3.

New observation errors have been constructed by some objective criteria and statistics, and by a certain amount of subjective judgment. The latter is based upon the performance of the current GDAS and the observation errors carried presently by the United Kingdom Meteorological Office (UKMO) and by ECMWF. The current operational and new values of observation error are shown in Table 4.

The estimates of radiosonde geopotential height and wind observation errors have been constructed from a study of observation minus 6-hour forecast values for radiosonde stations during the winter of 1986-87. These quantities represent the total forecast error variance including the true error of the forecast model and the errors associated with the observations. Therefore, the minimum value of the total forecast error variance represents an upper bound on the observation error estimate. An examination of these minimum values reveals a latitude dependence for both height and wind components. However, since the present scheme does not permit latitude or station-dependent observation errors, the table has been constructed by averaging the minimum values over latitude. This number is quite close to the values carried by ECMWF, particularly for the wind components (Thiebaux, personal communication).

TABLE 3 Extratropical height forecast error growth rates (top) in m and tropical values of height$_1$ (m) and wind forecast error (bottom) in ms^{-1}.

LEVEL	GROWTH RATE NH OLD	GROWTH RATE NH NEW	GROWTH RATE SH NEW	MAXIMUM VALUE OLD	MAXIMUM VALUE NEW
1000	5.0	3.6	4.3	40	42
850	6.3	3.8	6.2	46	38
700	8.8	4.0	6.5	54	39
500	12.5	5.5	9.3	73	50
400	16.3	6.4	12.0	87	62
300	20.0	9.5	13.1	104	72
250	22.5	10.5	12.8	116	72
200	25.0	10.5	12.9	123	68
150	27.5	10.5	14.0	111	62
100	30.0	11.5	16.2	93	67
70	31.3	12.0	18.1	90	71
50	31.3	13.0	20.0	90	82

FORECAST ERRORS (TROPICS)

LEVEL	GEOPOTENTIAL HEIGHT	U AND V COMPONENT OLD	U AND V COMPONENT NEW
1000	14	4.0	1.9
850	15	4.0	2.9
700	17	4.5	3.2
500	22	6.5	3.7
400	27	8.0	4.5
300	30	8.0	4.5
250	32	9.0	4.3
200	32	10.0	4.0
150	35	13.0	3.6
100	38	13.0	3.3
70	41	11.0	3.5
50	48	8.0	3.6

TABLE 4 Revised observation errors in units of m for geopotential height Z and ms^{-1} for the wind components U and V.

LEVEL	RAWINSONDE, PIBAL, DROPSONDE			
	GEOPOTENTIAL		U,V	
	OLD	NEW	OLD	NEW
1000	7.0	7.0	1.8	1.4
850	8.0	7.5	1.8	2.2
700	8.6	8.5	2.4	2.4
500	12.1	11.0	3.8	2.8
400	14.9	13.7	4.7	3.4
300	18.8	15.2	5.9	3.4
250	25.4	16.0	5.9	3.2
200	27.7	16.1	5.9	3.0
150	32.4	17.5	5.5	2.7
100	39.4	19.1	4.9	2.5
70	50.3	20.5	4.9	2.5
50	59.3	24.0	3.9	2.7

	POLAR ORBITER SOUNDINGS		
	CLEAR	PARTLY CLOUDY	CLOUDY
1000	10.0	10.0	20.0
850	12.5	12.5	21.0
700	20.0	20.0	38.3
500	25.0	25.0	45.3
400	25.0	25.0	44.8
300	27.5	27.5	42.0
250	36.5	36.5	42.6
200	44.5	44.5	43.2
150	44.7	44.7	46.5
100	45.0	45.0	50.9
70	45.0	45.0	53.0
50	45.0	45.0	55.0

		OLD	NEW
CLOUD DRIFT WINDS			
HIGH LEVEL	(U,V)	6.1-8.4	6.1
LOW LEVEL	(U,V)	3.9-7.2	3.9
AIRCRAFT	(U,V)	6.0	4.5
ASDAR/ACAR	(U,V)	4.9	3.2
SFC BOGUS	(Z)	7.0	32.0
SHIPS	(Z)	7.0	7.0
	(U,V)	2.5	2.5
BUOYS	(Z)	7.0	7.0
	(U,V)	2.5	2.5

For the aircraft wind entries, the values were based upon collocation studies and the somewhat subjective conclusion that inertial-based winds from aircraft are at least as accurate as rawinsonde winds. The entries for satellite cloud motion vectors are based on the assumption that statistics of observation minus forecast values do not show any significant variation by producer. Recent evidence suggests that this assumption may no longer be valid. However, a problem common to all cloud motion vectors is the consistent speed bias shown at high levels.

The value of observation error for surface pressure bogus observations was increased significantly. The assumed observation error for buoys and ships remains the same. This change is entirely subjective and will be re-evaluated at some future time.

The values of the satellite temperature sounding errors were left as above. We plan to improve those estimates as well as the method of assimilation during 1989.

2.3.3 Modified Quality Control

Presently, each observation is subjected to two gross limit quality control checks in addition to those performed during preprocessing. First, the observational increment (data - first guess) is compared to a gross toss limit and dropped from the data base if the gross limit is exceeded. Second, the increment is compared to another limit and flagged as large if this limit is exceeded. After the gross limit checks are completed, a nearest neighbor (buddy check) is performed (see Section 2.2). During the buddy check an isolated observation is dropped from the data base if it has been flagged as large during the gross check, otherwise it is kept. The current limit denoting large isolated residuals has been increased in the new version of the GDAS. The major impact of this change will occur in the southern hemisphere data sparse regions causing more observations to be retained by the assimilation system.

In the current system, tropical high-level geopotential residuals between 20N and 20S and above 400 mb are required to be within 1 standard deviation (see Table 1) regardless of the quality mark. A minor modification was made to remove the abrupt change in criterion by using a linear blend of the tropical value and the quality dependent extratropical value in the region between 20 and 30 degrees latitude in both hemispheres.

2.3.4 Interactive Clouds

Satellite-derived clouds have also been used in the evaluation of interactive clouds in the global spectral model. The clouds in the present model are computed only to modify the radiative fluxes, through the processes of reflection, scattering, absorption, and emission. Since the current model carries no liquid or frozen water, clouds must either be pre-specified or else be diagnosed from model-predicted variables. Prior to November 30, 1988, cloud amounts and heights were obtained from a zonally-averaged climatology, which changed only seasonally. Since the clouds were fixed functions of height and latitude, they could neither respond to different initial conditions, nor properly evolve during the forecast. The new clouds, however, are diagnosed from model variables and recalculated before each call to the radiation package.

The diagnosis of the clouds - both stratiform and convective - is done by techniques similar to those developed by Slingo (1987). The stratiform clouds exist in three domains (high, middle, and low). Within each of the three domains, the cloud top for each domain is taken to be coincident with the cloudiest layer within that domain. Usually the cloud is allowed to be only one layer thick, except that close to the surface, where model layers are thinnest, the clouds are required to be at least 90 mb thick. For low clouds to exist, there is an additional requirement that vertical motion be either upward or only slightly downward (less than 0.5 cm/sec.).

For convective clouds, bases and tops are calculated in the model's Kuo convective routine. The cloud cover, determined as a logarithmic function of the model's convective precipitation rate at a grid point, can extend through all three domains. For sufficiently strong and deep convection, the scheme can produce a dense anvil. Use of this parameterization is seen to give a reasonable approximation to the observed cloud field (now shown).

2.3.5 Results of a Parallel Test

The modifications to the analysis and to the assimilating model, described in the previous section and in Campana _et al._ (1989), were placed into the NMC/Development Division parallel GDAS on October 20, 1988. A sample consisting of the first 20 days in November was chosen to compare the differences between the parallel and operational systems. Table 5 shows the rms and mean differences between the proposed and operational systems for this 20 day period. As shown in the table, the major impact of these modifications has occurred at 100 mb. At this level, heights are much lower in the parallel system and temperatures are colder in

TABLE 5 Analysis differences parallel system minus operational system for November 1 to 20, 1988.

GEOPOTENTIAL HEIGHT (m)

LEVEL	NH		SH		TROPICAL	
	MEAN	RMS	MEAN	RMS	MEAN	RMS
1000	0.5	3.8	1.4	4.5	-1.1	2.7
850	0.0	3.4	0.6	3.1	-0.8	2.1
500	-0.3	1.7	0.4	3.2	-1.5	2.8
250	-1.3	2.3	-4.1	5.3	-3.3	4.2
100	-9.1	14.8	-18.0	19.9	-25.6	28.7

TEMPERATURE (K)

LEVEL	NH		SH		TROPICAL	
	MEAN	RMS	MEAN	RMS	MEAN	RMS
1000	-0.2	0.5	-0.3	0.7	0.1	0.5
850	0.0	0.2	-0.1	0.3	0.1	0.2
500	0.0	0.1	0.0	0.1	0.0	0.1
250	-0.2	0.3	-0.8	0.8	-0.4	0.4
100	-0.2	0.4	-0.2	0.3	-0.6	0.7

TABLE 6 Parallel and operational systems compared to radiosonde observations using the NH102 network.

	MEAN VALUES ANALYSIS		RMS VALUES ANALYSIS		MEAN VALUES GUESS		RMS VALUES GUESS	
	OPL	PAR	OPL	PAR	OPL	PAR	OPL	PAR
				850 MB				
Z	0.5	0.5	7.3	8.0	2.9	1.0	13.2	13.7
T	0.5	0.5	2.0	2.1	-0.2	-0.1	4.1	4.5
SPD	-0.5	-0.5	2.6	2.9	-0.4	-0.3	3.4	3.4
VECT	3.0	3.0	3.6	3.9	4.1	4.1	4.7	4.8
				500 MB				
Z	0.4	0.0	10.1	10.6	-1.2	-1.9	17.4	17.1
T	0.2	0.2	1.2	1.2	-0.1	-0.2	1.4	1.4
SPD	-0.4	-0.5	3.1	3.1	-0.7	-0.7	4.0	4.0
VECT	3.4	3.5	4.1	4.1	4.7	4.6	5.5	5.4
				250 MB				
Z	1.8	0.9	18.7	18.9	2.7	0.3	28.3	27.9
T	0.3	0.3	1.5	1.4	0.8	0.5	2.1	1.9
SPD	-0.5	-0.5	3.6	3.5	-1.0	-1.0	4.9	4.9
VECT	4.0	3.9	4.7	4.6	5.6	5.5	6.6	6.6
				100 MB				
Z	4.6	0.9	32.8	31.4	6.6	-1.3	45.3	44.5
T	0.3	0.2	1.7	1.6	0.8	0.6	2.5	2.3
SPD	0.1	0.0	2.3	2.2	0.6	0.2	4.0	3.7
VECT	2.6	2.5	3.1	3.0	4.6	4.2	5.5	5.0

all upper level regions, with the tropical area showing the most impact. The parallel system is colder at upper levels in regions where rawinsonde observations are sparse because the warm bias has been reduced in the satellite temperature profiles.

Table 6 shows the difference between the two systems when compared to rawinsonde observations. Values are listed for the operational (before December 1988) and parallel system analysis and first guess fields. In most cases, the bias is closer to zero in the parallel system. However, the rms values indicate that the operational analysis "fits" the radiosonde observations better than the parallel while the six hour first guess fits the observations slightly closer in the parallel system. Evidently, the new ratio of observation errors to forecast errors has instructed the optimal interpolation analysis in the new system to rely more on the first guess values than was the case in the operational system.

The impact of these changes on the MRF forecasts is described in Campana et al. (1989). These changes plus those made to the numerical model have in most cases slightly improved the skill scores for medium range forecasts. However, the major improvement has occurred in the temperature and height field biases which are significantly reduced.

2.4 Comparison of Physical and Statistical Retrievals

The retrieval process in use for many years at NESDIS was based on a statistical comparison of a large number of radiosonde reports with collocated TIROS Operational Vertical Sounder (TOVS) radiance measurements. Temperature profiles produced in this manner were, therefore, referred to as statistical retrievals. This technique served the meteorological community well over the years. However, this approach had the deficiency that it tended to not depart from mean conditions very far. The resulting retrievals generally underestimated gradients. In an attempt to alleviate this deficiency, NESDIS has recently developed an alternative technique -- the NESDIS TOVS Physical Retrieval System -- which utilizes a priori physical knowledge of the atmosphere and thereby substantially reduces the number of radiosonde reports needed for a statistical comparison. The temperature profiles produced by this procedure are referred to as physical retrievals.

The data impact studies described here were performed by first insuring that the parallel GDAS system exactly reproduced the operational GDAS results, then admitting the physical retrievals to the parallel GDAS analyses, while the statistical retrievals continued to be used in the operational GDAS. As a time saving measure, the parallel MRF forecasts were integrated only to 5 days instead of the operational length of 10.

The first experiment began at 0000 UTC on September 11, 1987, and ended at 1800 UTC on October 1, 1987, for a total of 21 days, with each system producing its own analyses and forecasts from different first guesses. During the experiment, the number of non-TOVS observations available to the operational and parallel analyses was closely monitored and found to be identical at every individual analysis time during the 21 days.

The first impact study showed that the physical retrieval system performed generally better in the southern hemisphere, but slightly worse in the northern hemisphere, as illustrated in Table 7. In addition, the path C physical retrievals were found to have a significant cold bias. These results led us to conclude that the physical retrievals should not be used operationally at that time. Thereafter, a period of over 6 months ensued, during which NESDIS made various improvements to the physical retrieval system, after which a second data impact study was performed. During this 6-month period, several changes were made to the operational GDAS system as well. A second data impact study began at 0000 GMT on April 6, 1988 and ended at 1800 GMT on April 18, 1988. In this study, the physical retrieval system performed better in both hemispheres (Table 8), although there was less improvement in the southern hemisphere than in the first study. This may be due to the physical retrieval system performing relatively better in the winter hemisphere. The cold bias in the path C physical retrievals remained, although it was reduced in the northern hemisphere. The results of the second data impact study were sufficiently encouraging to justify operational use of temperature retrievals produced by the new method. This occurred on September 20, 1988.

3. CURRENT PROBLEMS WITH SATELLITE DATA

Clearly, the way that satellite data are being utilized in the GDAS is much less than optimal. For example, the accuracy of the 6 hour forecast is of the order of 1 K in the lower troposphere, while that of the satellite temperatures produced operationally is typically 3 to 4 K. Regional biases during the winter over the oceans east of the northern hemisphere continents are even larger (A. Hollingsworth, personal communication). Under these circumstances the best that can be hoped for is that the quality control system is sophisticated enough to delete the poor quality satellite data in order to avoid negative forecast impacts in the northern hemisphere. A few examples of negative impacts from satellite temperatures have even

Table 7 Verification of 3 Day Forecasts from the first data impact study, September 11, 1987 - October 1, 1987

102 Northern Hemisphere Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	- 0.1	- 0.5	34.3	35.0	7.3	7.3
500 hPa	-17.8	-18.5	44.8	44.8	8.8	8.8
250 hPa	-14.5	-16.0	64.2	64.0	13.5	13.7
100 hPa	-46.3	-47.4	55.4	56.4	6.6	6.7

110 North American Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	- 6.0	- 7.0	26.2	26.4	6.5	6.5
500 hPa	-27.8	-29.0	35.9	36.6	8.3	8.4
250 hPa	-27.3	-28.2	58.3	59.5	14.9	15.0
100 hPa	-42.1	-42.5	41.8	43.5	7.6	7.8

31 Southern Hemisphere Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	- 8.0	- 4.0	36.9	36.3	8.9	9.0
500 hPa	-24.3	-20.9	52.0	51.3	11.0	11.1
250 hPa	-10.4	- 3.4	71.7	70.6	16.3	16.3
100 hPa	-31.1	-23.4	66.0	64.6	10.5	10.3

Table 8 Verification of 3 Day Forecasts from the second data impact study, April 6, 1988 - April 18, 1988

102 Northern Hemisphere Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	- 1.1	- 1.3	43.8	43.2	8.5	8.4
500 hPa	-24.2	-24.2	58.2	57.0	11.1	11.0
250 hPa	-24.0	-23.1	77.2	75.8	14.4	14.2
100 hPa	-49.3	-49.4	66.3	66.7	8.0	8.0

110 North American Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	3.9	4.3	34.3	34.0	7.7	7.6
500 hPa	-22.1	-21.4	51.2	49.4	11.1	10.8
250 hPa	-14.8	-11.8	73.6	70.7	16.1	15.5
100 hPa	-35.9	-33.7	48.4	48.0	8.1	8.0

31 Southern Hemisphere Stations

	Mean Hgt. Error		Standard Deviation of Hgt. Error		RMS Vector Wind Error	
	Stat.	Phys.	Stat.	Phys.	Stat.	Phys.
850 hPa	- 0.4	- 1.3	29.1	28.1	7.5	7.6
500 hPa	-14.4	-15.8	38.8	40.7	9.7	9.5
250 hPa	- 4.1	- 5.6	58.7	59.3	16.4	15.6
100 hPa	- 0.0	1.6	53.0	51.1	10.1	9.8

recently been noted in the southern hemisphere (J. Alpert, personal communication). While the above situation is probably the most serious, other problems are also contributing to the less-than-optimal utilization of the satellite data. These are briefly discussed here and include:

1) The analysis of satellite height needs to be replaced with an analysis of thickness. Originally, analyzing satellite heights seemed to be an advantage because of the oscillation in the vertical between warm and cold biases which permitted some cancellation in the mid and upper troposphere. However, as the accuracy of the model 6 hour forecast has continued to improve, the lower tropospheric satellite temperature error has become a significant source of error in the mid and upper troposphere through the integration to produce height profiles. Anchoring the satellite height profiles in a consistent manner between land and ocean is also a problem. In the near future, we plan to develop an analysis of satellite thickness once the development of a model-level-based analysis is completed (currently the analysis is performed on mandatory pressure levels).

2) The sat-sat error correlation statistics are outdated. The present sat-sat correlation statistics used in the optimum interpolation analysis are based on a study by Schlatter (1981) which were appropriate for the polar orbiting satellites in the early 1980's in which statistical regression was used to produce the retrievals (Smith and Woolf, 1976). More recently, with the implementation of a physical retrieval scheme (Fleming et al., 1986, 1988) at NESDIS, the sat-sat correlation statistics need to be revised. For this purpose, a collaborative effort between NESDIS and NMC is underway using currently produced sounding data.

3) The quality control of SATEMS is not adequate. As mentioned earlier, this is a serious deficiency in the NMC system, particularly with respect to the occasional negative forecast impacts obtained from satellite data. It should be noted that other centers have also obtained negative forecasts impacts from satellite data as well (e.g., ECMWF, GLA). A major effort is now underway to revise the entire quality control system at NMC incorporating the ideas of Gandin (1988) on complex quality control. With this approach, several checks, which are observing-system-dependent, will be made in parallel, rather than serially. The final decision of whether to accept or reject a particular piece of data will be based on all of the available information.

4) The negative bias in the high-level cloud-track winds (CTW's) is particularly serious in strong wind situations in the northern hemisphere (i.e. in the subtropical jet). There are undoubtedly several sources for this error. In the near term, we plan to conduct an experiment in which the wind direction from the CTW's is combined with the wind speed from the 6 hour forecast for those situations in which the wind speed of the model forecast is significantly stronger than that of the nearby CTW's.

In the longer-term the CO_2 slicing technique (Merrill, 1989), seems promising. An evaluation of data produced at NESDIS using that approach is planned, as well as tests with 15 min data (e.g., Peslen, 1980) compared to the presently operational 30 min data. In addition, in order to improve the quality of the data in the southern hemisphere, NMC has begun providing to NESDIS 12 h forecasts for use in CTW production and height assignment. Previously, NESDIS has used a climatological height assignment for the high-level winds in the southern hemisphere (T. Stewart, personal communication).

4. PRELIMINARY RESULTS FROM USING THE NMC 6 HOUR FORECAST WITH THE NESDIS RETRIEVAL SCHEME

A joint NESDIS/NMC effort was initiated in early 1989 to develop an interactive retrieval system. Preliminary results have been obtained for two time periods. For the 24 hour period for April 30, 1989, the retrievals were produced using the NMC global 6 hour forecast as the first guess for the retrievals, but off-line from the assimilation or "non-interactively". Subsequently, during the 12 hour period beginning on 0000 GMT 27 January 1989, retrievals were produced interactively.

The top panel of Fig. 1 compares the accuracy as measured against rawinsondes of the NESDIS operational retrievals (Fleming et al., 1986b, 1988) and those produced using the NMC 6 hour forecast as the first guess for the non-interactive test. At the bottom of Fig. 1, the accuracy of the latter set of retrievals is compared with that of the 6 hour forecast. The results are quite encouraging considering the fact that only the guess and the solution covariance matrix were changed in the retrieval system. The improvement in the accuracy of the retrievals using the 6 hour forecast over that of the operational retrievals is substantial in the 700 mb to 250 mb layer and near the surface.

The top panel of Fig. 2 compares the accuracy as measured against rawinsondes of the operational path A (clear) retrievals produced interactively for the second time period. The results for the path C (cloudy) retrievals are shown at the bottom of Fig. 2. As may be seen for the clear retrievals, the interactive approach has resulted in a small improvement through the troposphere (1000 mb to 200 mb). The accuracy of the interactive retrievals is significantly poorer in the stratosphere than that for the operational soundings, however. This result is not surprising considering the poorer quality mandatory level stratospheric analysis (top level at 50 mb) relative to that in the troposphere for the current operational system. In the near future, NMC plans to implement operationally an 18 level analysis (top level at 10 mb) on the model sigma levels.

For the cloudy retrievals (bottom of Fig. 2), there is a significant improvement through the troposphere (up to 1000 mb) with the interactive retrievals, with the improvement in the 1000 mb to 700 mb and the 400 mb to 300 mb layers being 1 K or larger. As in the case of the clear stratospheric interactive retrievals, the accuracy of the cloudy interactive retrievals is significantly poorer than that of the cloud operational retrievals. It should also be noted that the magnitude of the collocation errors shown in Figs. 1 and 2 are larger than otherwise expected because a large collocation window was used (300 km, ±3 hours) as a result of the small sample size.

5. PLANS FOR DEVELOPMENT OF AN OPTIMAL RETRIEVAL SYSTEM

As mentioned in the Introduction, the Interagency Satellite Retrieval Working Group has developed plans to assemble a state-of-the-art retrieval system for numerical weather forecasting, as outlined below.

There was a general agreement among the Working Group participants that the various sophisticated inversion methods (e.g., the NESDIS operational system (Fleming, et al., 1986b, 1988); the NASA research scheme (Susskind, et al., 1984)) should have about the same accuracy, given the same radiances. There was also a strong consensus that the most accurate first guess possible should be used for the inversion problem. Over most areas of the globe that is most likely a forecast provided by a general circulation model during the data assimilation. In areas where the model forecast might be poor as determined by comparing observed (satellite) and computed (model) radiances from the forward problem, a classification approach (i.e., McMillin, 1986b) blended with the model first guess, seems promising.

The Working Group participants strongly agreed that the most important remaining weakness (assuming the use of a forecast first guess) in the NESDIS operational system was in the approach used for cloud-clearing, where an angle correction (to nadir) is performed before cloud-clearing, and hence, the angle correction procedure must also simultaneously account for clouds. All the participants agreed that the most accurate off-nadir retrievals are produced if the off-nadir radiances are cloud-cleared at the same angle that the satellite views the atmosphere (as in the NASA scheme). In addition, the NASA scheme also uses the forecast temperature information in the cloud-clearing, while the NESDIS scheme does not use this information. On the other hand, a weakness identified in the NASA retrieval scheme was in not utilizing the SSU data for the stratospheric sounding problem, as is done in the NESDIS system.

With the above considerations in mind, the Working Group decided on the following plan which combines the strengths of the different approaches:

1. NESDIS and NASA will exchange retrieval software.
2. Both retrieval systems will be implemented on the NMC vector machine for experimentation.
3. The NASA approach for cloud-clearing (producing cloud-cleared radiances at the angles of observation) will be tested by NESDIS (but without iteration as in the NASA system).
4. NASA will provide NESDIS cloud-cleared radiances; NESDIS will produce retrievals; NMC will evaluate the analysis/forecast impact.
5. NESDIS will implement a bias correction (on observed radiances during the forward problem) in the NASA code. This will be compared with the NASA approach.
6. Other aspects of the retrieval problem will also be evaluated, such as the ability to retain an accurate first guess and improve a poor one.

6. ACKNOWLEDGEMENTS

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8. APPENDIX

The members of the Interagency Satellite Retrieval Working Group include:

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W. Baker	NOAA/NWS/NMC
R. Bates	NASA/GSFC
D. Birkenheuer	NOAA/ERL/FSL
E. Burdsall	NOAA/NESDIS
M. Chahine	NASA/JPL
D. Chesters	NASA/GSFC
D. Crosby	NOAA/NESDIS
J. Daniels	Under contract through NOAA/NESDIS with ST Systems Corp. (STX)
D. Deaven	NOAA/NWS/NMC
J. Derber	NOAA/NWS/NMC
H. Fleming	NOAA/NESDIS
L. Gandin	NOAA/NWS/NMC and UCAR
M. Goldberg	Under contract through NOAA/NESDIS with ST Systems Corp. (STX)
K. Hayden	NOAA/NESDIS
R. Kakar	NASA/Headquarters
E. Kalnay	NOAA/NWS/NMC
B. Katz	Under contract through NOAA/NWS/NMC with Centel Federal Services Corp.
D. Keyser	NOAA/NWS/NMC
S.-Y. Lee	Under contract through NASA/GSFC with Centel Federal Services Corp.
L. McMillin	NOAA/NESDIS
D. Miller	NOAA/NESDIS
G. Ohring	NOAA/NESDIS
R. Petersen	NOAA/NWS/NMC
J. Pfaendtner	NASA/GSFC
W. Planet	NOAA/NESDIS
W. Smith	Univ. of Wisconsin/Space Science and Engineering Center
J. Susskind	NASA/GSFC
J. Theon	NASA/Headquarters
D. Wark	NOAA/NESDIS

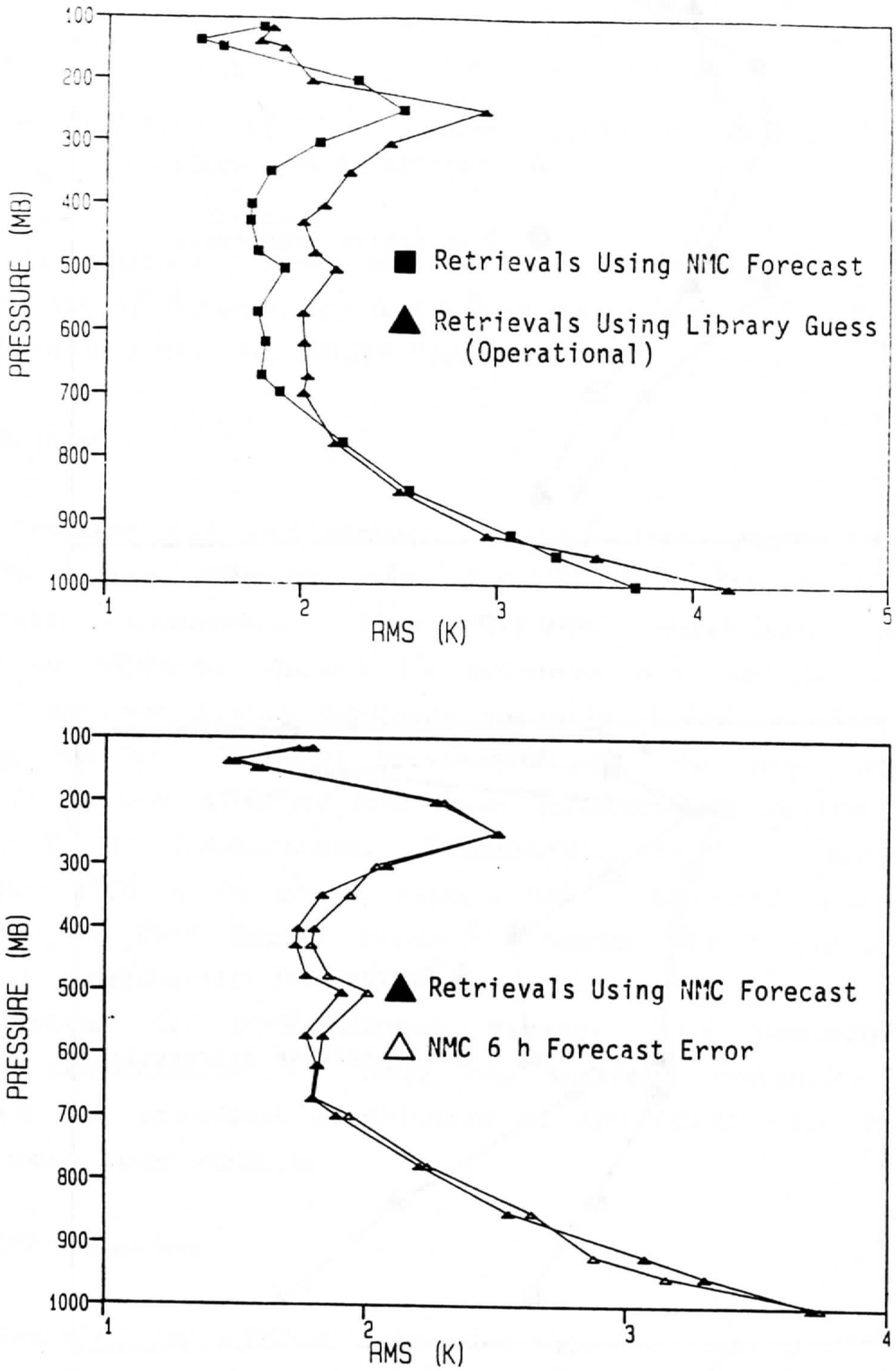
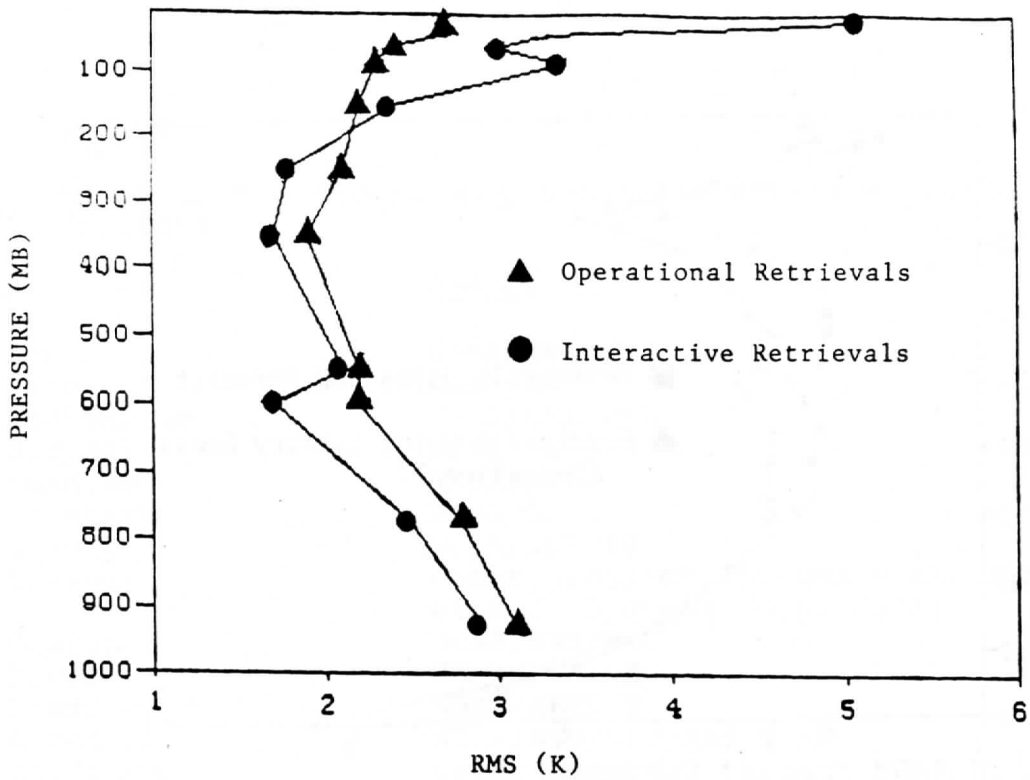


Fig. 1. Rms difference between rawinsondes and collocated retrievals (top) and between rawinsondes and retrievals or rawinsondes and the 6 hour forecast (bottom) for a sample size of 273 from the 24 hour period for April 30, 1989.



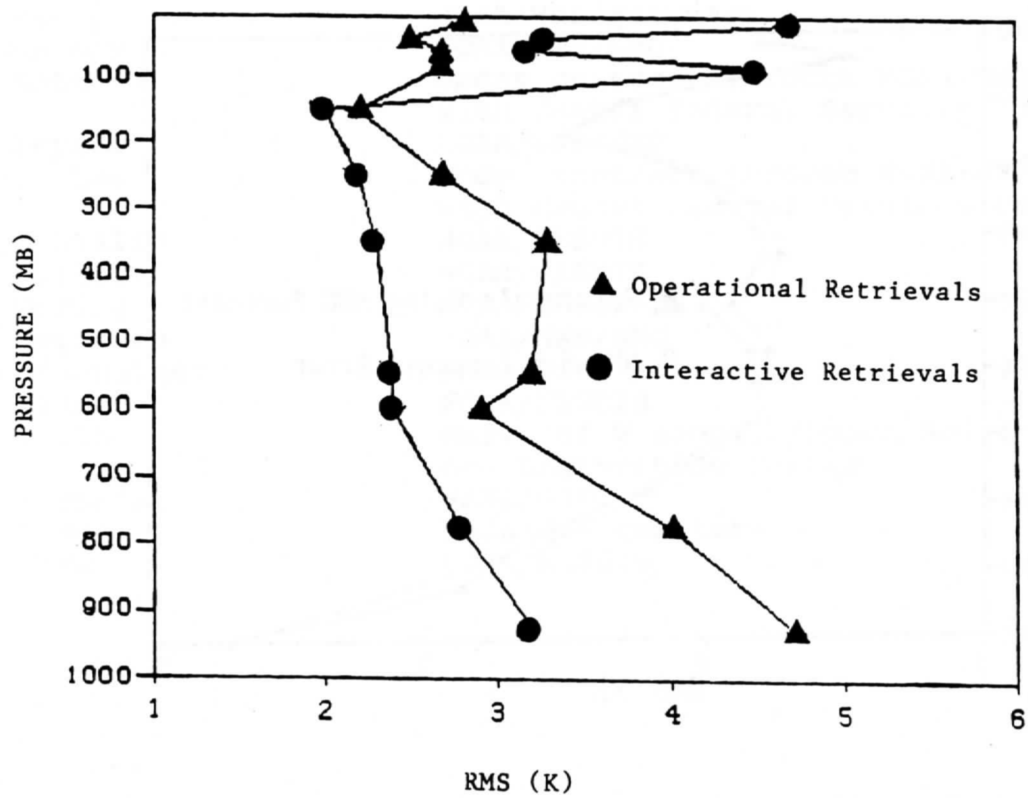


Fig. 2. Rms difference between rawinsondes and collocated clear (path A) retrievals (top) and for rawinsondes and cloudy (path C) retrievals (bottom) for a sample size of a few hundred from the 12 hour period beginning 0000 GMT 27 January 1989.

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