NASA-CR-203714

IN-47-CR
9c/T.
027480

Final Report

An Investigation of Current and Future Data Systems in Numerical Meteorology

NASA GRANT
NAG8-927

Principal Investigator

George R. Diak

Cooperative Institute for Meteorological Satellite Studies (CIMSS)
Space Science and Engineering Center
University of Wisconsin-Madison

Prepared by

George R. Diak
Barbara A. Burns
Xiangqian Wu

December, 1996

Table of Contents

I. Introduction

The Advanced Microwave Sounding Unit (AMSU) and the Microwave Humidity Sounder (MHS) constitute the advanced microwave sounding system to be flown on the EOS-PM platform. Similar instruments (the AMSU-A corresponding to the AMSU and the AMSU-B corresponding to the MHS) are scheduled to become operational on the NOAA polar orbiting satellites beginning with NOAA-K. The unique characteristics of the AMSU-MHS instruments, as compared to the capabilities of their infrared and microwave predecessors, introduce new opportunities --- and challenges --- for operational retrievals of atmospheric structure. Not only will these new data improve present capabilities for the retrieval of atmospheric profiles of temperature and moisture, but they will provide the only opportunity for successfully retrieving atmospheric temperature and humidity profiles in the presence of modest amounts of cloud and precipitation. A complementary opportunity is presented by the potential of the AMSU-MHS to obtain information about the structure of clouds and precipitation. The data sets obtained will contribute to the current knowledge of global water and energy budgets, and provide critical information on the horizontal and vertical distribution of tropospheric water vapor, the spatial and temporal distribution of rain, and the relationship of cloud formation and dissipation to atmospheric dynamics and thermodynamics.

The AMSU and MHS combined have a total of 20 channels in the microwave region of the spectrum. Each channel receives a single linear polarization which changes orientation with scan angle. Of the 15 AMSU channels, the 12 channels in the 50-60 GHz oxygen absorption region are primarily intended for atmospheric temperature sounding. The three remaining channels at 23.8, 31.4 and 89 GHz are used to obtain estimates of total column water vapor and cloud liquid water as well as rain amounts, and to supply information on surface conditions. The MHS also has an 89 GHz channel, but with a factor of three smaller field-of-view (FOV) than its counterpart on the AMSU. The other four MHS channels are on the wings of the 183.3 GHz water vapor absorption line, and are used together with the moisture channels of the AMSU to retrieve profiles of tropospheric water vapor.

Data from these microwave sounders will be complemented by visible and infrared data from companion instruments on the same platforms. These companion instruments are the Atmospheric Infrared Sounder (AIRS) and the MODerate-resolution Imaging Spectroradiometer (MODIS) on the EOS platform, and the High-resolution Infrared Radiation Sounder (HIRS) and the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar orbiting satellites. This unique combination of instruments on both NASA and NOAA platforms will also provide challenging opportunities for merging complementary data with different resolutions and sampling characteristics to produce products which combine the individual strengths of each component observing system.

The greatest challenge to using these data sets for the study and modeling of climate, and of the Earth's water and heat exchanges, is the development of robust methods capable of retrieving atmospheric humidity and temperature profiles at optimal accuracy for a given set of atmospheric conditions. In work to date with the Marshall Space Flight Center (MSFC), the Cooperative Institute for Meteorological Satellite Studies (CIMSS) has set up a flexible framework for the investigation of future satellite data systems in quantitative analysis and atmospheric numerical prediction. The work has covered a wide range of related topics within the general guidelines of observing system simulation experiments (OSSEs). The topics have included: 1) synthesis of raw data for current and future satellite sensors using surrogate atmospheres from forecast models; 2) the development of synthetic radiance images for forecast and radiation model diagnostic purposes; 3) the generation of atmospheric retrievals and other derived products from the synthetic data; 4) the application of these derived products to numerical models of the atmosphere; and 5) the investigation of real data from the SSM/T2 instrument for the purposes of atmospheric water vapor profiling, cloud discrimination and the estimation of column cloud water amounts.

II. Accomplishments

Much of the work to date can be conveniently discussed within the various components of observing system simulation experiments. Fig. 1 (Wu et al. 1995) shows a diagram of a typical so-called "fraternal twin" OSSE, where a different forecast model is used to generate the surrogate atmosphere and synthetic data than is used to run the data impact evaluations. A high-resolution physical model of the atmosphere is used to generate a surrogate "truth" of "nature" state which, similar to the real atmosphere, contains high spatial and temporal resolution features of dynamical and physical consistency. From this model atmosphere, radiance sets can be constructed for the channel complement of existing or planned satellite instruments using forward radiative transfer models and adding realistic instrument errors

Subsequently, retrievals of atmospheric profiles or other variables are made from these radiances using a background atmosphere for the retrieval, consisting of the "truth" plus realistic error fields. The sum of truth plus error is designed to mimic the usual forecast information available to an operational retrieval system. Finally, the retrieval data are used in a data assimilation (analysis/forecast) system to estimate how much the "errors" can be corrected (e.g., via the assimilation, how much can the "truth"+error state be returned to the "truth" state), and what are the benefits of these corrections in subsequent forecasts. In this OSSE sequence (Fig. 1), experiments using various satellite data forms are depicted "SAT", while other experiments employing either adiabatic or diabatic model initialization procedures are labeled "AI" and "DI", respectively. The various experiments will be detailed in later sections. The work accomplished under this program comprises elements of the observing system simulation overview.

As discussed by Lipton (1988) and others in reviews of OSSE procedures, for simulations involving satellite products it is highly desirable for the experimental sequence to be complete in the sense that the surrogate atmosphere should be used to generate raw satellite radiances from which the atmospheric retrievals or other satellite products are then derived. The simpler route, assuming a priori that the data will have certain error characteristics, is not nearly as realistic and informative. The procedures which we have developed follow this directive, the goal being to make the evaluation of data products from future satellite sensors as rigorous as is possible within a simulation context. Our OSSEs are somewhat unusual in that the synthesis of satellite data, soundings and other satellite data products has been given at least equal emphasis to the testing of data in forecast situations.

A. Radiative Transfer Models and Synthetic Radiance Imagery

1. Synthetic Imagery Generation

The generation of synthetic radiances for future satellite instruments, as depicted in Fig. 1, has proceeded using atmospheric forecast model simulations run at high horizontal and vertical resolution, so that small scale atmospheric features may be captured both in the surrogate atmosphere and the resulting forward radiances. In this work, we first developed and implemented forward models of radiative transfer for the clear air to produce radiances for the AMSU, MHS and HIRS instrument channel suites. Later (Diak et al. 1992; Wu et al., 1995), the models were amended to include the non-scattering effects of cloud liquid water. Most recently, the effects of scattering processes of cloud ice and hydrometeors have been included in synthesizing the microwave brightness temperatures (Burns et al. 1996).

Diak et al. (1992) and Diak and Huang (1994) gave examples of channel radiances made from CIMSS mesoscale model output for the case study day of 25 January 1986 for AMSU-B channel 19 (a 183 GHz water vapor sounding channel) and AMSU-A channel 3 (a 50 GHz O_2 atmospheric sounding channel). Both channel simulations included the non-scattering effects of cloud liquid water (CLW) distributions from CIMSS forecast model output. This day was marked by a strong frontal system dominating the weather of the east coast. For AMSU 19, the differences in brightness temperature caused by the presence of cloud liquid water were as much as 5 degrees K. Cloudy minus clear brightness temperatures for channel 3 were most evident over water surfaces, (as much as 40-50 K), where there is pronounced warming of the scene by clouds due to the low microwave emissivity of water at this frequency. In both of these channels, the structure of the east coast cold front was well-represented, as was information on the location of clouds.

To calculate the clear and cloudy radiances described above, the fast model for microwave transmittance of atmospheric gases developed by Eyre and Woolf (1988), was used, extended to account for the transmittance of cloud liquid water (CLW) using the formulation of Grody (1988). This transmittance formulation, however, does not easily allow scattering effects to be addressed. For this purpose, a radiative transfer model (RTM) has been adapted for this project from Kummerow and Giglio (1994), which uses Mie scattering code to obtain the absorption and scattering coefficients, which are then input to a 2-stream radiative transfer calculation. The forecast models used to produce synthetic data for these cases include both the CIMSS forecast model (80 km resolution in the horizontal, 1 km in the vertical) and the UW-RAMS model (Tripoli, 1992, horizontal resolution of 3.3 km, a vertical resolution of approximately 500 m). In terms of resolution and complexity, the former model is representative of operational models currently in use. The fields from the latter model include six hydrometeor species (cloud water, rain water, graupel, pristine [cloud] ice, snow, and aggregates), which allows detailed examination of the scattering process at the various sensor frequencies. One of the motivating factors for such radiance comparisons was to assess the potential of model-predicted fields of cloud, hydrometeors and resulting forward radiance calculations to serve as guesses for the retrieval of atmospheric profiles and microphysical quantities.

The images shown in Figs 2 and 3 were generated to simulate observations made with the SSM/T-2 sensor on a Defense Meteorological Satellite Program (DMSP) satellite, which has channels similar to those of MHS (AMSU-B) (see Burns et al. 1995 and 1996 for details). Forward brightness temperatures were calculated from CIMSS forecast model output on 9 February 1995, when a convective system was observed over the eastern Pacific Ocean. Calculations were carried out at five frequencies: 91.655 and 150.0 GHz (SSM/T-2 window channels) and 176.31, 180.31, and 182.31 GHz (lower side-bands of the SSM/T-2 water vapor channels).

Fig. 2 presents the synthesized brightness temperatures at 91 GHz for three cases: (1) a "clear" case where the presence of cloud was ignored; (2) a "cloud" case which incorporated the forecast cloud water profile to determine the absorption and transmittance; and (3) a "rain" case calculated with the scattering RTM and including rain water profiles from model output. The effect of including cloud absorption and scattering successively in the radiative transfer calculations can be seen most clearly in this example at 28N and 134 to 130W. The "cloud" case shows significant warming at this frequency compared to the "clear" case. The effect of adding scattering by rain is to reduce the brightness temperatures by up to 5 K. The results for the other frequencies show much smaller absorption and scattering-induced changes. We believe this is due in part to the minimum size set here for scattering hydrometeors.

Fig 3 shows synthetic imagery generated from the same atmospheric fields for 176 GHz (AMSU-B channel 20) and here scattering from smaller cloud droplets and ice particles is also included. The brightness temperature depressions seen along 30N in the "ice" case, but not in the "clear" or "cloud" cases, are associated with the distribution of cloud ice in the forecast model output. The maximum brightness temperature depression in this region in the "cloud" case is only 5 K, compared to 17 K in the "ice" case. The discrepancies decrease for frequencies closer to the center of the 183.3 GHz water vapor line: ice-related depressions are 10 K and 6 K at 180 and 182 GHz (AMSU-B channels 19 and 18), respectively.

2. Comparison With DMSP Data

The images actually obtained by the DMSP F-11 satellite at 91 and 183±7 GHz are shown in the lower right panels of Figs 2 and 3, respectively. Observed and simulated brightness temperatures are further compared in Fig. 4, using transects through the images. The measured brightness temperatures show a much larger range of variation than do the synthetic data. In particular, the low measured brightness temperatures at the core of the system (26N, 13 W) are not seen in the simulated "rain" or "ice" results. This is due not to deficiencies in the radiative transfer model, but rather to the inability of a forecast model of this resolution and level of physical complexity (typical of current operational models) to produce the high localized rain and ice water concentrations which causes the low observed microwave brightness temperatures. The synthetic imagery does indicate scattering in the cloudy region to the north (29.5N), due to a peak in model-predicted cloud ice and rain water. This peak, however, is displaced relative to the column cloud water and a scattering index derived from coincident Special Sensor Microwave Imager (SSM/I) data, both of which show peaks coinciding with the convective core.

Table 1 summarizes the statistics on the difference between simulated and observed SSM/T-2 brightness temperatures. Statistically, the agreement is actually worse when the radiation model includes scattering than when it does not. This is because the forecast model produces broad areas with cloud ice, whereas, in reality for this case, ice occurs in more localized centers. This model therefore predicts lower than observed brightness temperatures in these areas (compare the lower left and lower right panels of Fig. 3). Only for the few locations with high ice content, where the forecast model produces not enough ice and the predicted brightness temperatures are too high (positive differences), does use of the scattering model with the mesoscale model fields represent an improvement in the forward brightness temperature comparisons.

To better understand the causes for the differences between observed and simulated brightness temperatures, the scattering RTM has been applied to high resolution fields for the Hurricane Gilbert event produced by the UW-RAMS model. These simulations showed brightness temperature behavior similar to that seen in the data transects (25N to 29N), where the Tb-frequency relationship for the three water vapor channels is reversed relative to clear air situations. The "cross-over" of brightness temperatures is caused by the presence of precipitating ice, especially snow and aggregates. However, even cloud ice alone can result in substantially reduced brightness temperatures and therefore large deviations from the expected brightness temperature behavior due to water vapor variations. It is thus necessary to screen out such events prior to processing data for water vapor profile retrieval.

The difference Tb(180)-Tb(182) was applied to screen out areas of intense oceanic convection in the study area. Table 1 indicates that this improved agreement by more than a factor of two at 176 GHz, smaller factors for the other two channels which are less affected by ice, and resulted in a loss of less than 20% of the data points. The remaining 5-6 K difference may be attributable to errors in the water vapor absorption model (English et al. 1995), as well as to actual differences in atmospheric moisture between the background and real atmospheres. Such screening had no effect at 91 GHz, indicating that this channel is sensitive to different hydrometeor forms than are the water vapor channels. As indicated by the comparison for nominally clear areas shown in Table 1, the large differences between observed and synthetic imagery is most likely due to inadequacies in the surface description rather than in the atmospheric hydrometeor profiles.

Table 1

		Channel Frequency			
Simulation	**91Ghz**	**178Ghz**	**180Ghz**	**182Ghz**	**#points**
no screening					1606
"cloud"-obs	13.4K	11.2K	8.1K	8.8K	
"rain/ice"-obs	14.6K	11.4K	8.8K	7.1K	
screening					1317
"cloud"-obs	13.8K	4.7K	5.2K	6.1K	
"rain/ice"-obs	15.1K	6.6K	6.5K	8.8K	
clear					522
"cloud"-obs	16.6K	3.9K	3.9K	7.0K	
"rain/ice"-obs	17.0K	4.2K	4.4K	7.3K	

Table 1. RMS differences (simulated minus observed) for channels of the SSM/T2 instrument. "Cloud" and "rain/ice" indicate which forecast model microphysical species were included in the forward radiance calculations. "Screening" indicates that measured Tb(180)-Tb(182) was used to screen precipitation events. "Clear" indicates results for clear areas only.

B. Retrievals: Theory and Synthetic Data

1. Simultaneous Retrieval of Atmospheric Profiles and Cloud Properties

The simultaneous retrieval technique used in this research for the production of AMSU-HIRS atmospheric sounding information and cloud properties is a physical-statistical algorithm from Eyre (1989, 1990), which is a form of the so-called "maximum likelihood" retrieval algorithms used to produce atmospheric soundings from satellite measurements. The form of the retrieval equation is,

$$\mathbf{X} = \mathbf{X}_b + \mathbf{C}\mathbf{K}^T(\mathbf{K}\mathbf{C}\mathbf{K}^T + \mathbf{E})^{-1}(\mathbf{T}_{Bm} - \mathbf{T}_B(\mathbf{X}_b)), \qquad (1)$$

where $\mathbf{X}$ is the retrieval atmospheric and cloud state profile vector; $\mathbf{X}_b$, a background profile vector representing prior knowledge of this atmospheric state; $\mathbf{C}$, the expected vertical covariance of the background error; $\mathbf{E}$, the expected radiometric error plus the error in the radiative transfer forward model; $\mathbf{T}_{Bm}$, the vector of satellite-measured channel radiances or brightness temperatures; $\mathbf{T}_B(\mathbf{X}_b)$, a component of the forward radiative transfer giving the radiances or brightness temperatures corresponding to the background atmospheric state $\mathbf{X}_b$; and $\mathbf{K}$, the gradient of the forward radiative transfer model, that is, the partial derivatives of $\mathbf{T}_B(\mathbf{X}_b)$ with respect to the elements of the atmospheric state vector $\mathbf{X}$. Superscripts T and -1 denote matrix transpose and inverse, respectively.

Within this physical-statistical retrieval approach, certain cloud parameters can be retrieved simultaneously with the atmospheric profiles of temperature and moisture. To date, the profile vector $\mathbf{X}$ includes the variables required for an adequate representation of the cloudy (non-precipitating, water cloud) radiative transfer problem, that is, the atmospheric temperature profile, the humidity profile, the surface air and skin temperatures and the cloud top pressure, "effective" fraction and column cloud liquid water amount. Further details on the application of this algorithm to a synthetic AMSU-HIRS data base for this program can be found in Diak et al. (1992) and Wu et al. (1995).

2. Retrieval of Atmospheric Temperature and Moisture Profiles Using Synthetic Data

Several investigators (e.g., Hayden 1988; Eyre 1989) have indicated that the quality of physically-based satellite retrievals is closely linked to the quality of the background fields used in the retrieval process. Therefore, in generating these atmospheric fields used for the simulated AMSU-HIRS retrievals, it is important to approximate background error statistics and background (forecast) field errors that represent realistic uncertainties, as influenced by conventional data availability, forecast model accuracy and other considerations. In this work, we have applied numerical procedures which are able to generate background field errors with specified RMS magnitudes and defined horizontal and vertical covariances (Diak et al. 1992), so that the quality and effectiveness of the retrieval process may be realistically evaluated.

The quality of the retrieved temperature and moisture profiles and total column cloud liquid water amounts can then be addressed by examining the reduction of the simulated temperature, moisture and cloud water errors, that is, a comparison of the retrieval versus the "truth" values (see Fig. 1). We present here two representative examples of such error reduction using AMSU-HIRS synthetic data in the retrieval algorithm of Eq. 1, differing from one another in that they were made using two independent sets of synthetic error fields. These results are shown in Fig 5 (a-b), illustrating the retrieval performance for both temperature and dewpoint temperature profiles. The statistics are generated from 820 retrievals covering most of the continental United States on one case study day and include both clear and cloudy regions (Wu et al. 1995).

For the temperature retrievals, the first data set (5a) shows that the RMS error for the background (guess) temperature profiles at most levels below 400 hPa is between 1 and 2 K. The temperature retrieval is able to improve upon the background profile by 0.3-1 K. Above 400 hPa, the RMS error for the background temperature is larger than 2 K, and here the retrievals have reduced the error by about 0.5 K. In the second data set (5b), the errors in background temperature profiles at all levels are less than 2 K. For both data sets, the absolute accuracy of the retrieved temperature profiles at most levels below 500 hPa is about 1 K. The profiles of RMS error for the dewpoint temperature in both data sets show that the background errors for the dewpoint temperature at most levels below 400 hPa are 4-5 K and the retrievals have reduced these errors to 3-3.5 K. The results shown here are typical of those obtained in our studies (Diak et al. 1992; Wu et al 1995) and demonstrated in a more theoretical framework by Eyre (1990).

3. Cloud Liquid Water and Cloud Top Pressure Retrievals

The retrieval of cloud liquid water and cloud-top height are accomplished in the retrieval algorithm through the inclusion of synthetic microwave (AMSU) and infrared (HIRS) data, respectively. A simple (non-scattering) transmittance formulation for the effects of cloud water on the AMSU microwave frequencies is used to interpret these measurements to obtain estimates of total column cloud liquid water. Infrared data is input to a simple algorithm (resembling so-called "CO_2 slicing" methods) within the retrieval to estimate a cloud top pressure and "effective" fraction.

Through various sets of simulated retrievals, cloud water was retrieved with an RMS accuracy of about 170 g-m^{-2} (0.170 mm). A range of the "truth" cloud water amounts which were used in the forward radiative transfer calculations to produce the synthetic data was about 50 to 1500 g-m^{-2}. In the simulated retrievals, occasionally cloud liquid water was retrieved at locations where cloud presence was not supported by the truth data set, however, the amounts were very small (less than 50 g-m^{-2}). The RMS error in the estimation of cloud top pressures for the same data sets is about 50 hPa.

C. Observing System Simulation Experiments

1. Overview

Again, Fig. 1 is a flow diagram depicting the series of OSSEs which were carried out using the atmospheric retrievals and estimates of cloud liquid water amounts and cloud top pressures which were described in the previous section. Included in these tests were analyses and forecasts which used only the retrievals. Subsequent experiments then sequentially added: 1) cloud liquid water and cloud top estimates from the synthetic satellite data and 2) a diabatic initialization procedure, in which model-generated latent heating (from precipitation) in the first several hours of the forecast is used in a re-initialization of the model from the initial time to reduce the model spin up time to produce precipitation (see Wu et al. 1995 for details).

2. Forecast Results

Results of experiments employing synthetic AMSU-HIRS soundings, estimated cloud liquid water amounts and cloud top pressures and the diabatic initialization procedures have been detailed in Diak et al. (1992) and Wu et al. (1995) and will only be summarized here. Table 2 gives a summary of forecast errors for a suite of 12-hour model predictions (see Fig. 1), comparing those where satellite retrievals of atmospheric temperature and moisture have been used to correct errors in the model initial state ("SAT") to forecasts with no satellite data input ("NOSAT"). These results are representative of those detailed in Diak et al., 1992 and Wu et al., 1995. As shown, for each forecast time there is a modest but consistent improvement in the model error statistics for both temperatures and dewpoint temperatures with the inclusion of the AMSU-HIRS retrievals.

The inclusion of estimated cloud parameters and the diabatic initialization procedures are targeted at reducing the spin-up time in model forecasts to achieve realistic precipitation amounts and horizontal patterns. In modern atmospheric prediction systems, cloud liquid water is a prognostic variable whose evolution depends on atmospheric humidity and parameterized rate reactions between various precipitation forms and other water states. In these cloud and precipitation parameterizations, cloud water is a "bucket" which must be filled to a certain threshold before precipitation can occur. Thus, any information on the cloud water distribution at the beginning of a forecast can be very beneficial to improving short-term forecasts of precipitation. Similarly, the diabatic initialization procedure developed here (Wu et al. 1995) can use precipitation rates (latent heating) from any source to enforce dynamical consistency between model fields of temperature, wind and moisture and the latent heating fields associated with the precipitation. This information is also beneficial in short-term forecasts of precipitation and cloud.

Fig. 6 shows a typical example of precipitation patterns and amounts for four forecasts. Fig. 6a shows 4-hour precipitation from a control forecast. The objective of the next three experiments shown (b-d) is to see how well various data and initialization procedures can replicate the control forecast precipitation features. Fig. 6b shows the reduction in precipitation in the early stages of a forecast when no satellite data is included and a standard adiabatic (no latent heating feedback) procedure is employed to initialize the forecast model. Fig. 6c shows improvements with the inclusion of the satellite temperature and moisture retrievals and also the cloud quantities estimated from satellite data. The best results, shown in 6d, are achieved when both these satellite data and a diabatic initialization procedure (see Wu et al. 1995) are utilized. In general, the time of maximum impact on the precipitation is at or before this 4-hour forecast time, when models typically exhibit the worst spin-up problems.

Table 2

Time	Initial Data	1000hPa	850hPa	700hPa	500hPa	300hPa
		T / Td	T / Td	T / Td	T / Td	T / Td
0h	NOSAT	1.21/2.25	1.28/3.46	1.37/4.10	1.70/3.90	1.51/4.43
(ANAL)	SAT	1.01/1.85	0.97/2.12	1.06/3.21	1.04/3.33	1.36/4.76
3h	NOSAT	1.36/2.53	1.26/3.71	1.65/3.89	1.69/3.66	1.59/3.71
	SAT	1.07/1.52	1.15/2.64	1.38/3.18	1.12/2.45	1.53/3.73
6h	NOSAT	1.27/2.50	1.40/2.80	1.82/4.04	1.70/4.07	1.59/4.14
	SAT	1.16/1.49	1.03/2.05	1.47/3.62	1.23/3.21	1.50/3.47
12h	NOSAT	1.34/2.23	1.47/2.55	1.36/3.31	1.53/4.71	1.30/4.44
	SAT	1.34/1.36	1.05/2.37	1.17/3.54	1.08/4.67	1.15/4.10

Table 2. Root mean square errors of temperature and dewpoint temperature for 0, 3, 6 and 12-hour forecasts compared to a "truth" forecast (see Fig. 1). "SAT" indicates a forecast which includes satellite-retrieved profiles of atmospheric temperature and moisture, based on simulated AMSU-HIRS data. The "NOSAT" results have no data inputs and thus document the effects of uncorrected errors in the initial state (0h) and the growth of these errors through the subsequent forecast times.

D. Retrieval of Atmospheric Moisture from DMSP data

The variational method described in Section C above has been used to retrieve the 3-dimensional water vapor distribution from actual DMSP observations (Wu et al 1996). The case study presented here is from 9 February 1995, over the eastern Pacific Ocean adjacent to California and Mexico, and is based on the same inputs used in the generation of synthetic data as described in Section A1 above. The measurement vector consisted of brightness temperatures from the four functioning channels of the F11's SSM/T-2: 183±1 GHz, 183±3 GHz, 183±7 GHz, and 91 GHz. No screening of the data for convective events was done prior to retrieval. CIMSS model forecasts of the atmospheric and surface conditions provided the background fields for the retrieval.

The upper, middle, and lower panels of the left column of Fig. 7 show, respectively, the background, the retrieved, and the observed $T_b(180)$ (the brightness temperature for the 183±3 GHz channel). The background and the retrieved T_b's are computed using the background and the retrieved atmospheric states, respectively, and their differences from the observed $T_b(180)$ are shown in the right column of Fig. 7. The sharp frontal zone observed in the measured brightness temperatures near 30°N, separating the dry air to the north (high value of $T_b(180)$) from the moist air to the south, also appears in the background $T_b(180)$, albeit smoother and some 100-150 km further north. In the retrieval, this moisture front is pushed southward closer to its actual position, reducing the magnitude and the width of a belt of error shown in the difference image. The mesoscale features of convection evident along 126°W and 132°W are absent in the background $T_b(180)$, but are remarkably recovered by the retrieved $T_b(180)$. As implied in the previous discussion of simulated data, however, the retrieval failed to reproduce the extremely cold $T_b(180)$ at the core of convective cells. These cold $T_b(180)$ correspond well to the scattering index derived from the concurrent SSM/I observations using the algorithm of Grody (1991), displayed in the lower right panel of Fig. 8.

The results for the other two water vapor channels are similar. For the surface channel $T_b(91)$, however, the error after retrieval, though reduced (except for the convective regions), remains relatively large (Fig. 8). A likely reason for this larger error is the specification of the surface emissivity. While the retrieval algorithm (Eq. 1) can include estimation of the surface microwave emissivity (see Eyre 1989), this has not yet been implemented. In the retrievals, we have specified the mean emissivity of the surface, but have not taken into account modulations which may be caused by variations in temperature and wind speed. The implementation of the emissivity retrieval (Eyre 1990) and/or a more sophisticated emissivity model, such as that of Wilheit (1979). is planned,

Figure 9 shows relative humidity (RH) cross sections along 129°W, from the background (upper panel), the retrieved (middle panel), as well as their difference (lower panel). In the upper and middle troposphere, the retrieval moved the front southward and added mesoscale structure associated with the convective cells south of the front. These RH changes, evaluated using the SSM/T2 T_b measurements (Fig. 7), likely indicate improvements to the background RH fields, although a more definitive conclusion will require additional verification data. In the lower troposphere, the retrieval impact progressively diminishes and the retrieval process shows only a minimal effect on the background RH. The magnitude of the background error estimate in moisture (the diagonal of the C matrix of Eq. 1) is smaller at lower atmospheric levels, and thus the retrieval algorithms considers the background value of water vapor in the lower troposphere to be more reliable (~10% error) than in the upper troposphere (~100% error). As a result, the adjustment of atmospheric moisture in the lower troposphere is more constrained towards the background. This is consistent with Fig. 8, which shows large difference in the retrieved versus measured $T_b(91)$, a channel which is sensitive to lower tropospheric moisture. The diagonal elements of the C matrix (the error variance of background humidity information), has been evaluated using radiosonde data and thus is heavily weighted towards land regions, where errors in predictions are generally lower. It is probable that these error variances should be increased for oceanic locations, so that the retrieval algorithm can make larger adjustments to the moisture profiles at lower tropospheric levels.

Figure 10 shows the total precipitable water (TPW) from using an algorithm by Petty (1994). Using the SSM/I product as a qualitative verification, the SSM/T2 retrieval puts the front in a better position and adds realistic features to the south of the front. Both the background atmosphere and the retrieval, however, overestimate the TPW, compared to the SSM/I estimate. The overestimate by the SSM/T2 retrieval algorithm is due to the relatively small background error variance (the C matrix discussed in the previous paragraph) at lower atmospheric levels. The retrieval is able to add water vapor where the background is unrealistically dry (in the upper and middle troposphere) but is constrained to not allow large adjustments to the RH background fields at lower levels, that is, to remove water vapor in the lower troposphere.

E. Other Accomplishments

First results were also obtained for simultaneously retrieving column cloud liquid water (CLW) and water vapor from the SSM/T2 data using the variational method framework outlined in Section B1. Table 3 summarizes the CLW statistics from the 9

February 1995 case study. Included here are the total CLW amounts derived from the coincident SSM/I data using the algorithm of Bauer and Schluessel (1993). The horizontal patterns of CLW retrieved from the SSM/T2 are encouraging in that they are very similar to those from the SSM/I. The magnitudes are, however, much smaller than the SSM/I-derived CLW. Two factors are involved. First, the spatial resolution of the some of the SSM/I channels used in the CLW estimate from that sensor is about 15 km. The highest-resolution SSM/T2 channel is 45 km. The SSM/I is thus able to resolve spatial detail in the cloud fields below the resolution of the SSM/T2. A second contributing factor is that three out of the four SSM/T2 channels used for the cloud water retrieval are around 183 GHz, where signal saturation occurs for relatively low amounts of CLW (Bauer and Schluessel, 1993). This means that only for relatively thin clouds do the weighting functions for these channels extend below cloud top. Inclusion of the lower frequency channels on the AMSU should improve the retrieval of higher cloud liquid water amounts.

Table 3

	Mean (gm^{-2})	**Maximum (gm^{-2})**
Retrieved	77.9	1400
SSM/I	201.7	4000

Table 3. Cloud water estimates retrieved from SSM/T2 data compared to estimates from SSM/I data.

A simple "minimum residual" (Eyre and Menzel 1989) cloud estimation algorithm, originally developed for use with infrared sounder data, has been adapted to channels of the AMSU and MHS and investigated for the determination of cloud properties in the microwave region of the spectrum (Huang and Diak 1992; Diak 1994). In these studies, it was found that this method, using certain adjacent pairs of sounding channels, could be used to estimate a cloud height and "effective" fraction pertinent to microwave frequencies . The "effective" cloud fraction was found to be well-correlated with column cloud water amount (Diak 1994). The "minimum residual" technique thus can either be useful as simple two-channel means to approximate column cloud water, or as a preprocessing step in the cloud water retrieval component of the simultaneous atmosphere/cloud retrieval algorithm (Eq. 1), to provide a better initial guess of the cloud state.

III. Conclusions and Future Goals

Research over the lifetime of this project has progressed from experiments with simulated AMSU-MHS-HIRS data, investigating the retrieval of atmospheric profiles and cloud water from these data and their applications to numerical forecasts (OSSEs), through to studies using the developed procedures with real data. These real-data studies have examined the retrieval of atmospheric moisture profiles and column cloud water amounts from SSM/T2 data, as well as the effects of scattering on SSM/T2 radiances.

In OSSEs using atmospheric soundings and column cloud liquid water amounts derived from a synthetic data base, there has been a modest but consistent improvement in atmospheric predictions of temperature and moisture with the inclusion of these data. A diabatic initialization procedure, developed under this project, has complemented the satellite data studies and been used to increase the accuracy of short-range forecasts of precipitation coverage and amounts

Brightness temperature simulations of SSM/T2 observations containing a convective storm system have been made by applying two radiative transfer models, one which accounts only for the absorption due to cloud water and the other which also considers scattering from precipitating hydrometeors, to CIMSS forecast model output. The level of complexity of the CIMSS model in the prediction of cloud and rain features is equal to or slightly better than average operational forecast systems. Comparisons show that incorporating forecast information on cloud and rain water profiles produces a significant impact on simulated brightness temperatures. Scattering due to the presence of rain and ice in the forecast model causes decreases of up to 5 K at 91 GHz and up to 17 K for water vapor channels relative to the case where scattering is ignored. This is small, however, compared to scattering depressions of over 80 K seen in SSM/T2 observations of the same event. This suggests that the information on rain supplied by operational forecast models is not sufficiently detailed (not at high enough resolution) to produce the signatures of rain systems observed in the satellite measurements. Therefore, in water vapor retrievals using this forecast model for initialization, increasing the complexity of the forward model to account for scattering effects is not warranted. In this case a pre-processing step will be necessary to detect and exclude precipitation events.

A case study using SSM/T2 data demonstrated how the 3-dimensional water vapor distribution can be physically retrieved using the variational approach first investigated using a synthetic data base. As described, the retrieval is able to produce a more realistic horizontal moisture distribution, relative to the background field, and has significant impact on the RH estimate in the upper and middle troposphere, which seems to be positive, but has little impact on lower tropospheric moisture. With a better surface emissivity model and careful examination of the retrieval constraints, the overall quality of the retrieval should be further improved, particularly in the lower troposphere. Results on the estimation of column cloud liquid water amounts from the same data base, while very preliminary, are encouraging.

Future work will involve a merger of the extensive experience of the University of Wisconsin-Madison in remote temperature and moisture sounding of the atmosphere with the expertise in precipitation retrieval at Purdue University. In new efforts, the retrieval systems developed under the current program will be extended to include more complex atmospheres containing diverse cloud and precipitation features. The research tasks will address four major problems associated with clouds and precipitation:

- the importance of microwave scattering in precipitating cloud;
- significant uncertainties in the theoretical modeling of top of atmosphere brightness temperatures for precipitation structures owing to the sensitivity of radiative transfer calculations to the assumed vertical and horizontal distributions of hydrometeors, as well as particle size, shape and density;

- the highly nonlinear response of many of the AMSU channels to the vertical distribution of cloud and precipitation water, and
- the extreme spatial variability of clouds and precipitation, often on scales much smaller than the footprint of the sensor.

IV. Publications from NAG8-927

A. Refereed

Burns, B. A., X. Wu and G. R. Diak, 1996: Effects of precipitation and cloud ice on brightness temperatures in AMSU moisture channels. Accepted for publication, IEEE Trans. Geosci. Remote Sensing.

Diak, G. R., 1994: A note on the relationship of a microwave "effective cloud fraction" derived from a minimum residual method to the column cloud water amounts for non-precipitating clouds. J. Atm. Ocean Tech., 12, 960-969.

Wu, X., G. R. Diak, C. M. Hayden and J. A. Young, 1995: Short-range precipitation forecasts using assimilation of simulated satellite water vapor profiles and column cloud liquid water amounts. Mon. Wea. Rev., 123, 347-365.

B. Conference

Wu, X, B. B. Burns and G. R. Diak, 1996: Water vapor retrievals using SSM/T2 data. Eighth AMS Conference on Satellite Meteorology and Oceanography, Jan. 28-Feb. 2, 1996, Atlanta, GA.

Burns, B. B., X. Wu and G. R. Diak, 1995: Model-derived brightness temperature in AMSU moisture channels for various precipitation structures: Comparison of two radiative transfer formulations. Proc. 1995 International Geoscience and Remote Sensing Symposium, Florence, Italy 10-14 July, 1995, Vol. II, 876-878..

Diak, G. R., R. M. Aune, D. Santek and R. C. Dengel, 1995: Synthetic GOES infrared images based on the CIMSS regional assimilation model. Reprint volume, AMS 11th International Conference on Interactive Information and Processing Systems (IPS) For Meteorology, Oceanography and Hydrology, Dallas, TX, 15-20 Jan., 1995.

Diak, G. R. and H-L Huang, 1994: A "minimum residual" method for evaluating an effective cloud fraction applied to the estimation of column cloud liquid water amounts using simulated AMSU data. Reprint volume, AMS Eighth Conference on Atmospheric Radiation, January 23-28, 1994, Nashville, Tennessee, 537-538.

Wu, X., G. R. Diak, C. M. Hayden and J. A. Young, 1994: Short-range precipitation forecasts using assimilation of simulated satellite water vapor profiles and cloud liquid water. Reprint Volume, AMS 10th Conference on Numerical Weather Prediction, July 18-22, 1994, Portland, Oregon, pp. 124-127..

Wu, X., J. A. Young, G. R. Diak and C. M. Hayden, 1994: Impacts of diabatic vertical mode initialization for model precipitation forecasts. Reprint Volume, AMS 10th Conference on Numerical Weather Prediction, July 18-22, 1994, Portland, Oregon, pp. 294-297.

C. Theses

Wu, X., 1993: Short-Range Precipitation Forecasts Using Assimilation of Simulated Satellite Water Vapor Profiles and Cloud Liquid Water. Ph.D. Thesis, Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, 182pp.

V. References

Bauer, P. and P. Schluessel, 1993: Rainfall, total water, ice water, and water vapor over sea from polarized microwave simulations and Special Sensor Microwave/Imager data. J. Geophys. Res., 98, 20,737-20,759.

Burns, B. A., X. Wu, and G. R. Diak, 1996: Effects of precipitation and cloud ice on brightness temperatures in AMSU moisture channels. Accepted for publication IEEE Trans. Geosci. Remote Sensing.

Burns, B. A., X. Wu, and G. R. Diak, 1995: Model-derived brightness temperature in AMSU moisture channels for various precipitation structures: Comparison of two radiative transfer formulations. Proc. IGARSS'95, Florence, Italy, 10-14 July, 1995, pp. 876-878.

Diak, G. R., 1994: A note on the relationship of a microwave "effective cloud fraction" derived from a minimum residual method to the column cloud water amounts for non-precipitating clouds. J. Atm. Ocean Tech., 12, 960-969.

Diak, G. R. and H-L Huang, 1994: A "minimum residual" method for evaluating an effective cloud fraction applied to the estimation of column cloud liquid water amounts using simulated AMSU data. Reprint volume, AMS Eighth Conference on Atmospheric Radiation, January 23-28, 1994, Nashville, Tennessee, 537-538.

Diak, G. R., D. Kim, M. S. Whipple and X. Wu, 1992: Preparing for the AMSU. Bull. Amer. Meteor. Soc., 73, 1971-1984.

English, S. J., D. C. Jones, P. J. Rayer, T. J., R. W. Saunders, C. Guillou, C. Prigent, J. Wang, and G. Anderson, 1995: Observations of water vapour absorption using airborne microwave radiometers at 89 and 157 GHz, in Proc. Int. Geoscience Remote Sensing Symp., Firenze, Italy, 10-14 July 1995, pp. 1395-1397.

Eyre, J. R., 1989: Inversion of cloudy satellite sounding radiances by nonlinear optimal estimation. I. Theory and simulation for TOVS. Quart. J. Roy. Meteor. Soc., **115**, 1001-1026.

Eyre, J. R., and H. M. Woolf, 1988: Transmittance of atmospheric gases in the microwave region: a fast model. Appl. Opt., 27, 3244-3249.

Eyre, J. R. and W. P. Menzel, 1989: Retrieval of cloud parameters from satellite sounder data: A simulation study. J. Appl. Meteor., 28, 267-275.

Eyre, J. R., 1990: The information content of data from satellite sounding systems: a simulation study. Quart. J.. Roy. Meteor. Soc., 116, 401-434

Grody, N. C., 1988: Surface identification using satellite microwave radiometers. IEEE Trans. Geosci. Rem. Sens., 26, 850-859.

Grody, N. C., 1991: Classification of snow cover and precipitation using the Special Sensor Microwave Imager. J. Geophys. Res., 96, 7423-7435.

Hayden, K. M., 1988: GOES-VAS simultaneous temperature- moisture retrieval algorithm. J. Climate Appl. Meteor., 6, 705-733.

Huang, H. L. and G. R. Diak, 1992: Retrieval of non-precipitating water cloud parameters from microwave data: A simulation study, J. Atmos. Ocean Tech., 9, 354-363.

Kummerow, C. and L. Giglio, 1994: A passive microwave technique for estimating rainfall and vertical structure information from space, Part I: Algorithm description, J. Appl. Meteor., vol. 33, pp. 3-18.

Lipton, A. E., 1988: Observing system simulation experiments: Their role in meteorology. Air Force Geophysics Laboratory Environmental Research Paper No. 1038. Hanscom AFB, Massachusetts, 15pp.

Petty, G. W., 1994: Physical retrievals of over-ocean rain rate from multichannel microwave imagery. Part II: Algorithm implementation. Meteor. Atmos. Phys., 54, 101-122.

Tripoli, G. J., 1992: A nonhydrostatic mesoscale model designed to simulate scale interaction, Mon. Wea. Rev., vol. 120, pp. 1342-1359.

Wilheit, T. T., 1979: A model for the microwave emissivity of the ocean's surface as a function of wind speed. IEEE Trans. Geosci. Electro., GE-17, 244-249.

Wilheit, T. T., 1990: An algorithm for retrieving water vapor profiles in clear and cloudy atmospheres from 183 GHz radiometric measurements: Simulation studies. J. Appl. Meteor., 29, 508-515.

Wu, X., G. R. Diak, C. M, Hayden, and J. A. Young, 1995: Short-range precipitation forecasts using assimilation of simulated satellite water vapor profiles and column cloud liquid water amounts. Mon. Wea. Rev., 123, 347-365.

Figure Captions

1. A schematic diagram to illustrate satellite data observing system simulation experiments (OSSEs).

2. Brightness temperature maps at 91 GHz from the three simulation cases (clear, cloud and rain) and from SSM/T2 observations.

3. Brightness temperature maps at 183 ± 7 GHz from the three simulation cases (clear, cloud and rain) and from SSM/T2 observations.

4. Transects across convective system: (a) brightness temperatures measured in the three SSM/T2 water vapor channels and the GOES-IR channel; (b) simulated brightness temperatures (both RTM modes for 176 GHz); and (c) quantities derived from coincident SSM/I measurements: column integrated water vapor (wv), cloud liquid water (clw) and scattering index (SI).

5. Profiles of forecast model error in temperature and dewpoint temperature and errors in synthetic AMSU-HIRS retrievals for two case studies.

6. Four-hour precipitation fields: a) control (truth) forecast); b) a forecast with no satellite inputs and an adiabatic initialization; c) a forecast including satellite retrievals of atmospheric profiles of temperature and moisture, column cloud liquid water and utilizing an adiabatic initialization procedure; d) a forecast with identical satellite inputs as (c), only utilizing a diabatic initialization procedure.

7. Left column, top to bottom: Predicted, retrieved and observed radiances at 180 GHz

Right column, top to bottom: Observed minus background radiances and observed minus retrieved radiances at 180 GHz and scattering index.

8. Left column, top to bottom: Background, retrieved and observed radiances at 91 GHz.

Right column, top to bottom: Observed minus background radiances and observed minus retrieved radiances at 91 GHz and Tb(182) minus Tb(180).

9. Cross sections of forecast model relative humidity, retrieved relative humidity and retrieved minus predicted relative humidity.

10. Top to bottom: Model-predicted total precipitable water, retrieved precipitable water and precipitable water observed from SSM/I.