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MARSHALL GRAW

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**An Investigation of the Role of Current and Future Remote Sensing
Data Systems in Numerical Meteorology**

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Final Report on

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The Cooperative Institute For Meteorological Satellite Studies (CIMSS)
Space Science and Engineering Center
University of Wisconsin-Madison
1225 West Dayton St. Madison, WI 53706

Investigators

George R. Diak
William L. Smith

Prepared by

George R. Diak

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1. Introduction

The focus of this research has been to develop a flexible system for the evaluation of the information content of satellite remote sensing systems in numerical meteorology. For the past three years, most of the efforts have been concentrated on pre-flight evaluations of the Advanced Microwave Sounding Unit (AMSU), a twenty-channel microwave system which is planned for launch in 1994 and which will replace the Microwave Sounding Unit (MSU) on board NOAA polar orbiting satellite beginning with NOAA-K. The AMSU is actually composed of two separate radiometers, the AMSU-A, primarily a temperature sounding instrument and the microwave humidity sounder (MHS, formerly the AMSU-B), whose primary function is the profiling of atmospheric water vapor. Both instruments will provide information on such elements as cloud and precipitation water, surface emissivity and other surface characteristics. The High Resolution Infrared Sounder (HIRS) will remain the companion infrared instrument on NOAA satellites until the late 1990s, when it will be replaced by the Advanced Medium Resolution Imaging Radiometer (AMRIR).

The work we have accomplished during the course of this project will have many applications across the range of time and space scales of numerical weather prediction (NWP). A convenient framework for the discussion of this research is that of the so-called observing system simulation experiment (OSSE) shown in Fig. 1. In a typical OSSE, a forecast model run at a high horizontal and vertical resolution with the most sophisticated physics parameterizations available is used to generate surrogate atmospheric three-dimensional fields which are taken to be the truth in the experiments. Subsequently, synthetic raw data is made from these fields appropriate to the sensor or observing system being represented in the OSSE. In the case of our AMSU/HIRS experiments, these "data" are channel radiances computed using the three dimensional fields of atmospheric state and clouds from the model output combined with appropriate forward models of radiative transfer.

The high-resolution truth fields of atmospheric variables are interpolated to a coarser grid for the subsequent analysis and forecast experiments (A1). This step is in recognition that the "truth" always will contain detailed high-resolution features which it will not be possible to duplicate in forecast models. From A1, a control forecast (F1) is made to represent a "perfect" forecast made from the truth fields. A second analysis (A2) is made with errors added to the truth fields which recognize that prior to a data analysis procedure, our knowledge of the atmospheric state is generally imperfect (usually derived from an atmospheric forecast valid at the data time).

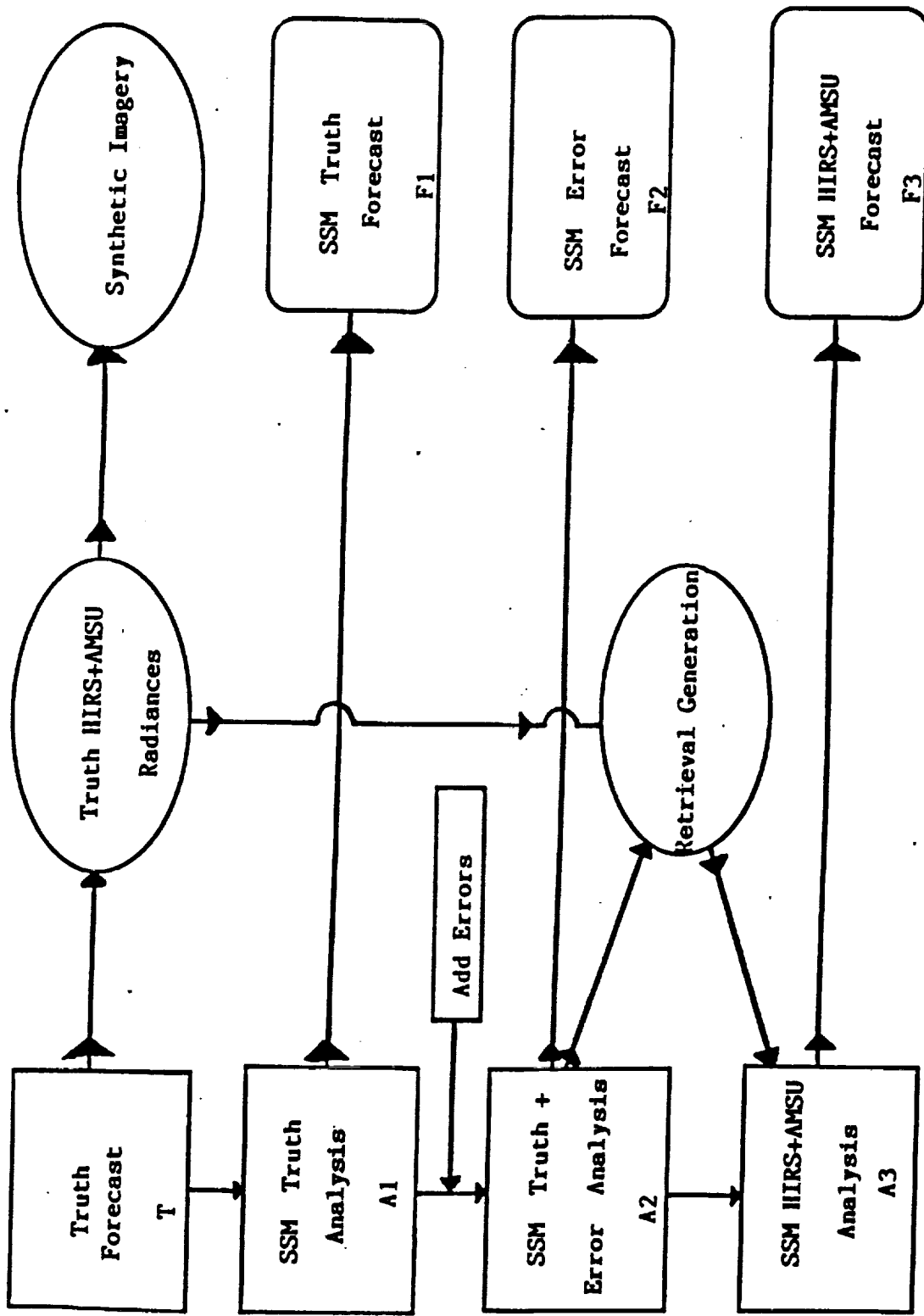


Figure 1 OSSE Logistics

It will be the function of the data to try and correct such errors. An "error" forecast (F2) evaluates the forecast impact of these errors if they were to go uncorrected.

Subsequently, derived-product data (in our case atmospheric soundings) are generated using the raw radiances made from the truth atmosphere and guess profiles of atmospheric variables from A2. If the observing system and retrieval methodology were both perfect, we would see a retrieval correction in the guess profiles back to exactly match those from the truth atmosphere. In reality, it is usually the case that a fraction of the error in A2 is corrected, the amount depending on the inherent information content of the observing system and the quality of the retrieval system. These data are analyzed to the model grid (analysis A3), using the error analysis A2 as a guess for the procedure. A subsequent forecast (F3) evaluates both the quality of the data and how well the analysis procedure has been able to capture the inherent information in the derived data. Ideally, we would like to see F3 identical to the error-free forecast F1. Again, this is never the case and we judge the observing system to make a positive contribution if the differences between F3 and F1 are smaller than those between F2 (the error forecast) and F1.

For observing system simulation experiments involving satellite radiances, it is most rigorous and informative if the OSSE sequence is complete from the generation of synthetic atmospheres and radiances through the retrieval production and the analysis/forecast impact stage. By starting at the most basic level, instead of just assuming that the derived sounding data will have certain error characteristics, a more complete understanding of the observing system is possible. In this research, considerable effort has gone into making the OSSE sequence complete and representative of a real data/analysis/forecast environment. In subsequent sections we will discuss the contributions of this research to the various components of the OSSE sequence detailed in Fig. 1.

2. Research Accomplishments

A. The Application and Development of Atmospheric Models to Generate "Truth" Atmospheric States

The "surrogate" or "truth" atmospheric representations shown in Fig. 1 come from atmospheric forecasts run at high resolution with as complete physical parameterizations as are available to us. Two such models have been used in this work, the Limited-Area Mesoscale Prediction System (LAMPS), run at the MSFC and the Subsynoptic Scale Model (SSM), run at the CIMSS. The SSM has been the model most used to generate surrogate atmospheres for these OSSEs because of the convenience of running it locally. This has required upgrading of the

original physics parameterizations in the model. Part of the capabilities of the AMSU will be measuring cloud liquid water (CLW) amounts as well as the radiance signatures of other atmospheric condensed water forms. Thus to perform OSSEs, it is necessary that these water forms be included in the forecast model representation of the "truth" state. Part of the work of this project has been to upgrade the SSM precipitation microphysics to the so-called "explicit" type, which currently includes prognostic equations for the time-development of cloud and ice water and various precipitation forms. Further upgrades are in progress, under continuing NASA support, which will increase the number of hydrometeor forms explicitly included in the parameterization and the realism of the simulations. At this writing, we are also bringing on line the UW-RAMS (Tripoli, 1992) a non-hydrostatic model with very sophisticated microphysics, for use in generating surrogate atmospheres and for comparisons with the SSM and LAMPS.

Partially under support from this project, the SSM has been converted to a format suitable for running on a suite of IBM-RISC workstations recently added to the CIMSS. This has given us the computing capability to run forecasts in a real time, operational mode. Currently, we are running two 80-km resolution, 20-level, 36-hour duration forecasts twice a day (based at the synoptic times) for an area the size of the continental United States. From these forecasts, we have gained a considerable amount of experience, especially on the character of the "explicit" microphysical parameterizations previously described. The model has been linked to the McIDAS system and information data base so that in the future improved satellite verification tools for cloud and precipitation forecasts may be developed and exploited. The model has also been coupled to the VIS-5D visualization system, so that improved diagnostic feedbacks are available.

Goals for future work are to increase the detail in the microphysical parameterizations in the SSM and to experiment with finer horizontal and vertical resolution in the model to also increase the realism of the surrogate atmospheres and the general quality of forecasts.

B. Forward Radiances

The forward model of radiative transfer used to calculate AMSU channel radiances is from Eyre and Woolf (1988), which we have adapted to include a suitable parameterization for radiative transfer including the cloud liquid water fields generated by the SSM and LAMPS. A convenient "synthetic image" format has been developed for displaying and analyzing these channel radiances, both for the AMSU and HIRS, which has proven to be a valuable diagnostic tool for evaluating these forward radiances. We expect that these synthetic images will be of increasing value when real AMSU imagery is available for comparison. At this writing, we have obtained some radiance data sets from the SSM/T-2 instrument, which has several channels corresponding to those on the

AMSU. We will be using this data sets for evaluation and improvement of forward radiance models.

C. Retrievals from AMSU/HIRS Data

The retrieval scheme is a non-linear "maximum likelihood " type developed for the HIRS/MSU system by John Eyre (current affiliation, ECMWF) while he was a visiting scientist at the CIMSS and adapted for use with HIRS/AMSU data (Eyre, 1990; Diak et. al 1990). A unique feature of the scheme is that it simultaneously retrieves the atmospheric profiles of temperature and moisture, as well as the surface emissivity in the microwave and the infrared cloud top and "effective" fraction (from HIRS infrared data) and the total-column cloud liquid water content (from AMSU microwave radiances).

The quality of retrievals of atmospheric structure depends on many elements besides the inherent information content of the satellite radiances. In general, satellite retrieval problems are "ill conditioned" in the sense that there are many atmospheric states which can produce the measured top-of-atmosphere radiances and we must rely in some way on a priori information to limit the retrieval solution set. In physical retrieval schemes, usually a atmospheric forecast valid close to the data time serves as a "guess" and the quality of the retrievals are closely linked to the quality of the guess. For numerical weather prediction purposes, the usefulness of satellite soundings is not linked to the basic RMS accuracy of the soundings, but rather to how much improvement they provide over the a priori information. If they do not provide an improvement over this forecast information, there is no sense incorporating them into a subsequent analysis/forecast cycle.

The quality of an NWP "guess" for retrievals depends on many factors, important among which are the availability of conventional data sources in the region to the NWP system and the resolution and sophistication of the forecast model used to provide the guess. Traditionally, satellite soundings have not been able to provide much information to the sophisticated mesoscale NWP systems in use in conventional data-rich areas such as the continental United States. The soundings have, however, been more useful in oceanic regions and also in the southern hemisphere, where conventional data is sparse and forecast models in general are of coarser resolution.

Thus, in evaluating a satellite sounding system via OSSE methodologies, it is important to be able to accurately estimate the characteristics of the atmospheric "guess" fields to be able to say where the satellite information can make a contribution. In this work we have developed sophisticated procedures to generate guess fields whose characteristics can be adjusted to represent different NWP regimes (see Diak et al., 1990). The procedures generate guess fields with specified RMS magnitudes of simulated forecast error as well as the appropriate horizontal and vertical

covariances of error which are representative of the regime and the forecast model environment. For a satellite retrieval system, the accurate representation of vertical structure of guess field error is especially important, since the measured radiances in any sounding channel represent the atmospheric state over a depth of several hundred millibars. Satellite retrievals are thus more likely to be able to correct guess errors which span larger atmospheric depths than those with lesser vertical length scales.

Results of simulation work (see Diak et al., 1992) suggest that the HIRS/AMSU data will be able to make a slight improvement on our forecast knowledge of the atmospheric temperature and moisture state, even in a data-dense region such as the continental United States. There will be a small general improvement in sounding quality over the current HIRS/MSU systems. This will be most evident under cloudy circumstances (when the HIRS information cannot be used below cloud top and the improvements of the AMSU over the MSU will be most apparent). Retrievals of the infrared cloud top via this retrieval methodology show a RMS accuracy of about 50 mb, close to that of the so-called "CO₂ slicing" methods used for similar purposes.

In the last year of this program, we have concentrated on the retrieval of cloud liquid water from AMSU data. Our simulations show that it will be possible to estimate total-column CLW with an accuracy of about 100-200 g-m⁻² (0.10-0.20 mm). Cloud liquid water is a fundamental quantity in the transfer of visible, infrared and microwave radiation and we expect that the results of this CLW retrieval will be very valuable to scientists working to develop radiation parameterizations for NWP models across all time and space scales and also may have some benefit for initializing the physics parameterizations in short-term NWP models to reduce the "spin up" time to generate precipitation. At this writing, we have just completed a preliminary investigation to evaluate whether there is a possibility of obtaining more than one vertical level of CLW information from AMSU radiances (Huang et al., 1992) using an information theory technique developed by Purser and Huang (1992). This investigation demonstrated that perhaps two vertical levels of information on cloud water are obtainable using AMSU data. The results, however, are very variable for different cloud situations and also depend strongly on the surface type (emissivity), as is generally the case using microwave radiation to detect and quantify cloud and rain water amounts. Further investigation should indicate whether it will be beneficial to modify our atmospheric/CLW retrieval system to include more than one level of cloud water.

Goals for future research are to better-understand cloud liquid water and the retrieval of this quantity from AMSU data and to investigate more closely the cloudy situations where the AMSU is likely to offer the most improvement over the MSU. We anticipate that the details of the retrieval of the surface emissivity will also require a good deal of attention when real AMSU data becomes available.

D. Forecast/Impact Studies

During the course of this research we have run a number of analysis/forecast experiments using atmospheric soundings retrieved from the synthetic HIRS and AMSU radiance data described previously. Results from these experiments are summarized in Diak et al. (1992). For atmospheric temperature, the impact of HIRS/AMSU data in a data-rich area such as the continental United States is small, although positive. The improvements of HIRS/AMSU soundings over the guess for retrieval averages between a few tenths and half of one degree, depending on the atmospheric situation and vertical level. There is clearly a problem in maintaining these small increments of improvement through an analysis/forecast cycle. The results for atmospheric moisture, however, are significantly better since numerical prediction for atmospheric water vapor is less certain than for temperature and the additional contribution of the new AMSU water-vapor-sensitive channels is significant.

In the last year of this program, we have begun to investigate incorporating other retrieval products from the HIRS/AMSU data into numerical predictions. As discussed earlier, precipitation schemes in numerical models which incorporate explicit cloud and precipitation forms have natural advantages over older diagnostic formulations. A drawback, however, is that cloud water is a "reservoir" which must be filled before precipitation can begin and thus there is an inherent lag or "spin up" in these schemes before precipitation can commence after a forecast is initialized. We have been investigating both the initialization of cloud liquid water in these forecasts and also latent heating amounts, these via a "diabatic" type vertical mode initialization scheme (the limited-area model equivalent to the "normal mode" initialization schemes used in global spectral models). The impact on rainfall amounts and patterns in the first several hours of a forecast period of these initializations is positive and significant.

E. Other Contributions

We have added new surface shortwave and longwave radiation packages to the SSM which take advantage of the availability of cloud and ice water in the predictions. The shortwave results especially show realistic small-scale detail not present in the prior "bulk" cloud parameterization. Future goals are to improve these parameterizations and add others to the forecast model for atmospheric shortwave and longwave heating/cooling.

A "microwave slicing" algorithm (Huang and Diak, 1992) has been developed to be used with AMSU data for determining the height and effective fraction of non-precipitating cloud. We

are investigating uses for this algorithm, including the possibilities of incorporating it as a preprocessing step for a full atmospheric/cloud retrieval scheme to provide an improved first guess for clouds in the microwave.

A preliminary investigation of a combined AIRS/AMSU retrieval system has also been accomplished (Huang et al., 1991) under the support of this grant.

3. Conclusions

In this research we have developed a flexible system for performing observing system simulation experiments which has made contributions to meteorology across all elements of the OSSE components shown in Fig. 1. Future work will seek better understanding of the links between satellite-measured radiation and radiative transfer in the clear, cloudy and precipitating atmosphere and investigate how that understanding might be applied to improve the depiction of the initial state and the treatment of physical processes in forecast models of the atmosphere.

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