2.1 THE JOINT CENTER FOR SATELLITE DATA ASSIMILATION

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1. INTRODUCTION

The Joint Center for Satellite Data Assimilation (JCSDA) was established by NASA, NOAA and DoD in 2001. The goal of the JCSDA is to accelerate the use of observations from earth-orbiting satellites in operational numerical analysis and prediction [*]models for the purpose of improving weather forecasts, improving seasonal to interannual climate forecasts, and increasing the accuracy of climate data sets. Advanced instruments of the current and planned NOAA, NASA, DoD, and international agency satellite missions, do and will increasingly provide large volumes of data related to atmospheric, oceanic, and land surface state. These data will exhibit accuracies and spatial, spectral and temporal resolutions never before achieved. The JCSDA will ensure that the maximum benefit from investment in space is realised from the advanced global observing system. It will also help accelerate the use of satellite data from both operational and experimental spacecraft for weather and climate related activities. To this end the advancement of data assimilation science by JCSDA has included the establishment of the JCSDA Community Radiative Transfer Model (CRTM) and continual upgrades including, the incorporation of AIRS and snow and ice emissivity models for improving the use of microwave sounding data over high latitudes, preparation for use of METOP IASI/AMSU/HSB, DMSP SSMIS and CHAMP GPS data, real-time delivery of EOS-Aqua AMSR-E to NWP centers, and improved physically based SST analyses. Eighteen other research projects are also being supported by the JCSDA (e.g. use of cloudy radiances from advanced satellite instruments) to develop a state of-the-art satellite data assimilation system. The work undertaken by the JCSDA represents a key component of GEOSS. In particular data assimilation, data impact, OSSE, THORPEX and network design studies are key activities of GEOSS.

2. BACKGROUND

There is a continual need for more accurate weather forecasts that extend further into the future. As a result of a growing population, more people living in coastal areas, an expanding economy, and threats to homeland security, the nation is more vulnerable than ever to weather phenomena and requires more precise forecasts. More accurate and longer range weather forecasts directly affect the ability of the populace to prepare for severe weather, allowing protective action to be taken to mitigate the effects of hurricanes, tornadoes, floods, etc. on people and commerce. In addition, more accurate forecasts increase the safety and effectiveness of our defense forces throughout the world and better protect the home front in relation to the release of chemical, biological, or radioactive agents into the atmosphere.

Remotely sensed data from the atmosphere, land, and oceans can provide critically important information to better understand and predict the effects of both weather and climate and are now key components of the environmental observing system. Through data assimilation, diverse atmospheric and oceanic data, sampled at different times, intervals, and locations, can be combined into a unified and consistent description of the state of the atmosphere. Analyses are produced from scattered observations and a prior knowledge of the evolving atmospheric state given by a model. The analyses should be a mathematically optimal fit to the observations, an atmospheric model and the prior knowledge of the atmospheric state, and should represent the most likely state of the atmosphere, ocean, or land surface. Without data assimilation, skillful Numerical Weather Prediction (NWP) is impossible.

Current methods of data assimilation in use at leading numerical weather analysis centers have evolved through more than fifty years of research. Optimal interpolation was the method used by many centers until the early 1990s. Research today concentrates on extending global analysis systems to four dimensions and the inclusion of new data types. By far, the greatest volume of data ingested into these numerical models is from satellites. Also, the assimilation of satellite data has contributed to a substantially improved accuracy of the forecasts over the last twenty years.

Much progress has been made in the utilization of satellite data in the NWP model since the first meteorological satellite was launched in April 1960 and is related to improvement in the satellite instrumentation, continued increase in computational power and improvements in numerical models and data assimilation techniques. During the 1960's and 1970's, a rapid advancement in satellite instruments

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preceded the computing capacity and the complex assimilation techniques required to use these data effectively. Since that time, the horizontal resolution of global models has increased, in the US case from 381 km in 1960 to 55 km today. The vertical resolution has also increased markedly from 1 layer in 1960 to 64 layers in 2004. The computer power, measured in floating point operations per second (flops), has increased from 20 Kflops in 1960 to over 30 Gflops today. During this period, the 36-hr mean sea level pressure forecasts over North America went from having little skill in 1960 (i.e., being of similar skill to a forecast based on climatology), to being skillful 72% of the time in 1995 with the direct inclusion of TOVS radiances (starting in 1995) in concert with the use of more sophisticated models on more powerful computers.

A measure of the impact of satellite data on improving operational numerical weather forecasts is given in Fig. 1, which shows the anomaly correlation coefficient (ACC) for 500mb height calculated for the NCEP 5-day forecast as a function of time. The correlation is between the observed and predicted deviations from the climatological 500mb height field. Neglecting interannual variability, a steady improvement in the ACC is evident, with a larger rate of improvement for the Southern Hemisphere. The noticeable improvements in the late nineties are due, to a significant degree to direct radiance assimilation and instruments such as the Advanced Microwave Sounding Unit (AMSU).

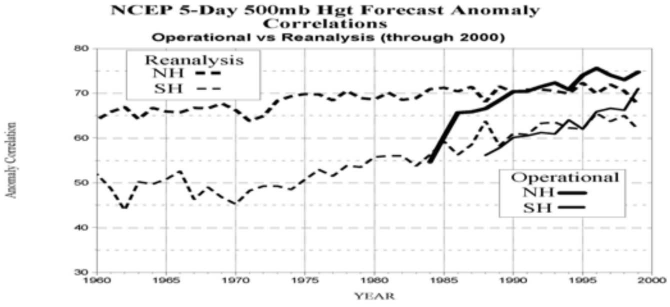

Figure 1. Anomaly correlation coefficient (ACC) for 500mb height for the NCEP 5-day forecast as a function of time. Dashed (solid) lines refer to fixed (evolving) model and assimilation system. Bold (thin) lines refer to the Northern (Southern) Hemisphere.

In addition to operational satellites, research satellites have also demonstrated beneficial impact on weather forecast models. An example of a research instrument that has shown significant operational impact is the scatterometer, which measures wind speed and direction over the global oceans. First flown on ERS-1 in 1991, this instrument presently flies on Quikscat, launched in 1999. The impact of scatterometer data on hurricane forecasts for example is recorded in Isaksen and Stoffelen, (2000). At NCEP, Quikscat data were tested for several numerical forecasts of hurricanes over the Atlantic Ocean in the late 90’s and early this millennium. For Hurricane Cindy in August 1999, the inclusion of Quikscat data reduced intensity errors by nearly 50%, and displacement errors by up to 80%, over a 72-hr forecast (Fig. 2). Improvements of this order are important in reducing the uncertainty in hurricane track and intensity forecasts needed to allow emergency managers to make informed decisions.

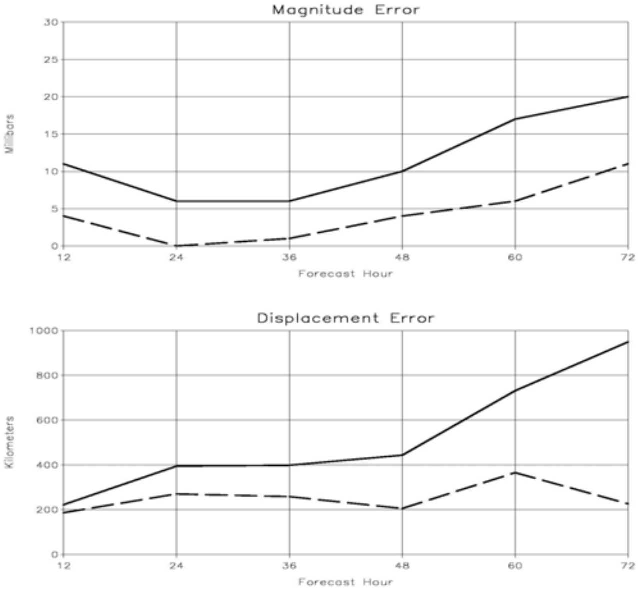

Figure 2. Forecast errors in terms of (a) intensity and (b) position for Hurricane Cindy with (dashed) and without (solid) assimilation of Quickscat data. Units are mb in (a), km in (b).

Despite recent improvements in forecast skills, there is remains room for substantial improvement, in particular toward decreasing the frequency of larger than normal forecast errors, or “busts”. It is also clear that assimilation of satellite observations will contribute to that improvement, given the future growth and improvement of the global observing system expected in the area of space-borne observing systems. As a result there is a need for increasing the emphasis on satellite data usage in the data assimilation community, both in terms of introducing new and additional satellite data, and refining the assimilation methodologies for both current observations and those from future platforms.

Over the coming years, operational instruments such as the current experimental Advanced Infrared Sounder (AIRS) will be launched. These instruments will provide data at spatial, spectral and temporal resolutions vastly exceeding those of earlier instruments. This provides the NWP and data assimilation communities with new possibilities and new challenges. New possibilities arise, for example, because of the unprecedented vertical resolution provided by these instruments. New challenges because of the sheer volumes of data they will provide and because of many scientific questions that need to be answered in order to make optimal use of these observations.

3. A CHALLENGE

Establishing Satellite data assimilation systems involves the transition from research and development (R&D) to operations, which is complex and been discussed in a number of reports. The National Research Council report (NRC, 2000) discusses this issue vividly and refers to the term “Crossing the Valley of Death” to describe this fundamental challenge for R&D programs. Moreover, this report states that “For technology investments, the transitions from development to implementation are frequently difficult, and, if done improperly, these transitions…. can seriously inhibit the implementation of good research leading to useful societal benefits.”

The situation is particularly serious for satellite data utilization. Although satellite data account for greater than 80% of the data assimilated in the NCEP models today, these data only correspond to roughly 14% of the available satellite data from operational lower-Earth orbiting systems. Most data are thinned upon receipt to minimize the effect of cross-correlation errors and to ease data management problems. Furthermore, significant amounts of radiance data collected over land, cloud and in high latitudes and polar regions are often not used directly because of the difficulties in modeling surface effects such as the varying emissivity associated with surface snow and sea ice, and also the effect of cloud. The problem is also compounded by the *five-orders of magnitude* increase in satellite data expected in the next ten years. Figure 3 shows the number of individual daily upper air observations used by the NCEP operational models as a function of time, and an estimate of the data volume by 2010.

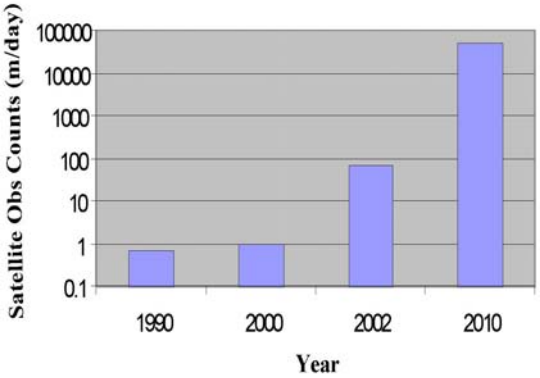

Figure 3. Current and expected number (in millions) of daily upper air observations used by NCEP models as a function of time.

As a result of these volumes and extant resources there has been on occasion a gap of many years before data were fully used operationally. We are now, however, better placed to capitalize more effectively on the investment the U.S. makes on its satellite observing network.

4. THE JOINT CENTER FOR SATELLITE DATA ASSIMILATION

In April 2000, a small team of senior NASA and NOAA science managers released a white paper containing plans to improve and increase the use of satellite data for NWP and climate purposes. The white paper provided a specific recommendation to establish a Joint Center for Satellite Data Assimilation (JCSDA). This white paper came in response to a growing urgency for more accurate and improved weather and climate analyses and forecasts. These improvements could only be made possible by the development of improved models and data assimilation techniques, which will allow models to utilize more and better quality data. In 2001 the Joint Center was established and in 2002, the JCSDA expanded its partnerships to include U.S. Navy and Air Force.

The cooperative agreement allows the Center partners to take advantage of the science and technology resources of NOAA, NASA and the Department of Defense (DoD) in order to accelerate the use of existing and new satellite data. The JCSDA also provides a focal point for the development of common models and infrastructure among the DoD, NOAA, and NASA partners. This shared approach to research and development activities will eliminate the need for redundant resources and will reduce the need for duplicated efforts within the various government agencies.

NOAA has provided a centralized location for JCSDA administrative and information technology (IT) resources. Geographically distributed JCSDA components will be located in various JCSDA member organizations. Projects may be located at universities and other facilities.

The JCSDA consists of an Oversight Board, Director, Deputy Directors, Scientific Staff and Technical Liaisons who represent participating members of the distributed JCSDA. An Advisory Board and the Science Steering Committee provide external advice and review.

All planning efforts have been a collaborative effort among NASA, NOAA and DoD, defining a process that ensures teamwork is a continuing attribute of the JCSDA. Initial efforts have focused on defining a life-cycle approach to data assimilation projects. To date, several critical elements have been defined: Firstly an end-to-end process that begins with defining an instrument, then moves to characterizing that instrument’s in-flight performance, to developing algorithms and testing forward models for data assimilation, to testing the impact of synthetic data, integrating the data into operational systems, and finally to assessing the data's impact on analyses and forecasts. Secondly, a scientific review process by JCSDA personnel and the JCSDA Science Steering Committee, which provides feedback on each scientific project and determines if new systems are ready for implementation into operations. Thirdly, a transition-to-operations plan to ensure that new systems developed at the JCSDA are transitioned smoothly and JCSDA scientists participate in the overall implementation process to the extent needed.

The prime benefit of the JCSDA will be improved weather and climate analyses, forecasts and warnings and an extension of the time range of weather and climate forecasts, resulting in reduced losses of life and property. There will also be considerable productivity increases by reducing the average time for operational implementation of data from new satellite technology from two years to one year. With average satellite lifetimes of five years, this represents a 20 percent productivity increase per satellite. Enhancements to the current satellite data assimilation process are also being developed.

5. JCSDA MISSION, GOALS AND SCIENCE PRIORITIES

The mission of the Joint Center for Satellite Data Assimilation is to accelerate and improve the quantitative use of research and operational satellite data in weather and climate analysis and prediction models.

Three goals support this mission. The first is to reduce from two years to one year the average time for operational implementation of new satellite technology. The second is to increase the use of current satellite data in NWP models and the third is to assess the impacts of data from advanced satellite sensors on weather and climate predictions.

The first goal will result in an increase of 20% in productivity. In the second goal we emphasize the uses of current satellite data because for example fundamental information from satellites associated with clouds and precipitation has not yet been optimally assimilated and the benefits of the current sensors to weather and climate predictions have not been maximized.

To achieve its goals, the JCSDA has *initially* set the five scientific priorities discussed in the following sections.

5.1 Improve Radiative Transfer Models

5.1.1 Atmospheric Radiative Transfer Modeling – The Community Radiative Transfer Model (CRTM)

Satellite radiances are not components of the atmospheric state vectors predicted by NWP models. In order for radiances to be assimilated by NWP models, a relationship between the model state vectors and the observed radiances is required. This is provided by forward radiative transfer models with the state vectors as input (see Fig. 4).

In addition, the Jacobian vectors (or the derivative of radiance relative to the state vectors) are also needed for satellite data assimilation systems. Radiative transfer modeling uses atmospheric transmittance as the key input. The transmittance varies with the atmospheric conditions in a complicated way and is often computed through the line-by-line (LBL) models. Although LBL models are accurate, they take considerable time to calculate transmittances for just a few atmospheres. To provide accurate transmittances in a timely fashion, the JCSDA has generated and uses fast approximations commonly known as fast forward models for specific channels. Current fast models are discussed in Kleespies et al., 2004.

The JCSDA must be state of the art in this area and for operations incorporate any advances made in-house or by other groups. The JCSDA must remain active in the radiative transfer science for the following reasons: Radiative transfer process need to take into account the instrument filter response functions, as each new instrument flown on the new spacecraft has its own specifications. Appropriate changes need be made to the LBL models to regenerate the new coefficients for the fast transmittance models for new instruments. In the past, JCSDA partners such as NESDIS have relied on the University of Wisconsin and/or University of Maryland, Baltimore County (UMBC) to assist to perform these calculations. As the frequency of the need for these calculations increases, JCSDA capability to perform these calculations must increase. Development of these models both inside the JCSDA and by collaborators outside now contributes to the community radiative transfer model (CRTM) in a well-ordered fashion.

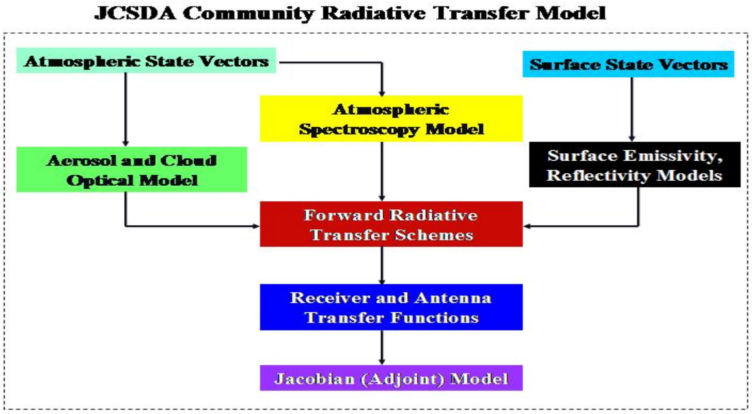

Figure 4. Components of JCSDA community radiative transfer model (CRTM).

Transmittance models now need consider more minor gases such as carbon dioxide, methane, and carbon monoxide because the forecast models are making more use of satellite measurements that are sensitive to them. Presently, transmittance models usually only include a number of “fixed” gases, water vapor, and ozone. Assimilating these measurements into forecasting models and predicting their distributions require transmittance models that include variations in these gases. As the transmittance models become more accurate, the variations in retrieved temperature due to changes in minor gases become significant when they are ignored. For these reasons, future fast models must include the effects of these minor gases. In the short wavelength regions near four microns, aerosols begin to have a minor but significant effect. Volcanic gases and aerosols can also affect the radiation at other wavelenghts as well, and must be included in transmittance calculations.

To fully utilize the information of satellite measurements under all weather conditions for NWP, forward modeling capability needs to be enhanced to include both scattering and polarization processes (Fig. 4). Cloud affected satellite radiances have not generally been assimilated into operational forecasting models although the measurements contain considerable information pertinent to the atmospheric hydrological cycle. In the next decade, many advanced infrared microwave sensors will be deployed in space and their sensitivity to various atmospheric and surface parameters is significant. *The uses of cloudy radiances in NWP models will ultimately enhance the impacts that have been demonstrated presently through clear radiance assimilation and add to our knowledge of clouds, the surface and the hydrological cycle*.

5.1.2 Surface Emissivity Modeling

Satellite observations obtained in and around the window regions of absorption spectra are affected by surface emissivity. Without a surface emissivity model, measurements from current and future advanced sounders may not be effectively assimilated into NWP models. As a critical part of a radiative transfer model (see Fig. 4), surface emissivity modeling should explain the variability of both emissivity and reflectivity. The JCSDA is supporting theoretical and technology advances in quantifying the emissivity spectrum for various sensors covering the global environment.

The JCSDA has developed a microwave land emissivity scheme (Weng et al, 2001) which has undergone operational trials. This model uses volumetric scattering theory to compute the optical parameters of snow, deserts and canopy leaves. In addition, radiative transfer theory has been extended to compute the bulk-emitted radiation from surfaces. The surface emission and scattering models also include the roughness effects approximated by the perturbation theory. The model has recently been extended to include ice and snow emissivity and recent trials of this system have shown improvement in high latitude forecasts using NCEP’s Global Forecast System. Currently testing is also underway for a new polarimetric emissivity model for assimilating advanced instrument data such as that from WindSat/Coriolis which was successfully launched in November 2002 by the U.S. Navy. Data from this satellite are now being used in a risk reduction study for the future NPOESS Conical scanning Microwave Imager and Sounder (CMIS).

5.2 Prepare for Advanced Operational Instruments

A key activity of the JCSDA is the development of the methodologies and associated software and hardware tools for assimilating data from the next generation of advanced satellite instruments. These instruments will be flying on NOAA, NASA and DoD satellites, as well as other international spacecraft. Table 1 lists some current and planned satellite instruments, and their characteristics that JCSDA will use. The large number of advanced sensors will provide environmental data at spatial, temporal, and spectral resolutions never before achieved.

A key performance measure for the JCSDA will be a decrease in the time required to develop and transfer assimilation systems to NOAA, NASA and the DoD for operational use, for each new instrument. The development process will have pre-launch and post-launch phases. Current development times range from two to seven years. Shorter development times will allow the new instruments to come on-line earlier, lengthening the useful life of each new instrument, and speeding up the rate of forecast improvement.

As the number of channels from the new instruments increases by many orders of magnitude (e.g., from the High resolution Infrared Radiation Sounder (HIRS) of 20 channels, to the Atmospheric Infrared Sounder (AIRS) of 2378 channels) there are growing challenges in data handling and radiative transfer modeling. Approaches must take into account ways of selecting or combining the channels so that the observations can be optimally utilized without compromising their information content.

5.3 Assimilating of Observations of Clouds and Precipitation

5.3.1 Assimilating Observations of Clouds and Precipitation for Model Validation

Observations of cloud properties such as coverage, heights, condensate amounts and surface precipitation are vital for evaluation of the cloud schemes used in NWP models. However, in using these products, we must fully understand their strength and weakness. It is well known however that the cloud properties “seen” by visible sensors are not necessarily those detected by microwave sensors. The global cloud fraction inferred by visible and infrared sensors is normally higher (60-70%) than that from microwave sensors (20-30%). Improvements in the precision in the specification of cloud characteristics will however result from use of observations from the ultra spectral sounders. Cloud condensate contents estimated from the visible and infrared sensors over deep convective areas can also differ greatly from those estimated from microwave sensors (Weng et al., 1997). As a result, the best estimates of cloud condensates is done using observations from various sensors.

The availability and accuracy of satellite cloud products are also different over various surfaces. Over oceans, both SSM/I and AMSU have been used to produce operational cloud liquid water in raining and non-raining cloudy conditions. The SSM/I cloud liquid water product and has been operationally available since 1987 (Weng and Grody, 1994) and cloud ice water retrieved from the AMSU and has been operational since 1998 (Weng et al., 2003). Over land, however, the retrievals of cloud liquid water must rely on visible and infrared measurements, since large variations of land emissivity limit microwave retrievals. NESDIS has such an algorithm using AVHRR measurements (Heidinger and Liu, 2001). The AVHRR retrieval is also sensitive to clouds having lower liquid water amounts. With its smaller footprint, AVHRR data is also able to provide information on the distribution of cloud liquid water within the AMSU field of view. It is planned to use this information lead to better estimates of the AMSU retrieval errors and serve as additional information for validation of the NWP cloud scheme.

5.3.2 Assimilation of Precipitation Products

Satellite precipitation estimates have two key strengths for data assimilation. Firstly, they have a wide area of coverage, especially over the data sparse oceans. Secondly, they provide a means for adjusting the vertical profile of latent heating in the atmosphere, which is a quantity that typically cannot be obtained using current in situ coverage. This adjustment is usually accomplished by inverting the convective parameterization scheme of the model and adjusting the vertical profiles of latent heating and, consequently, of temperature and moisture (Krishnamurti et al., 1983; Hou et al., 2000). This process will increase the consistency between the model precipitation and the observed precipitation during a dynamic assimilation period. Similar adjustments can be made to vertical profiles of moisture for grid-scale precipitation.

A number of issues remain to be resolved, however, in order to make optimal use of precipitation data in NWP models, including, the current accuracy of precipitation estimates from satellite data; the lack of error characteristics of satellite precipitation estimates at model scales in a form that can be used to develop appropriate weighting for assimilating the data; convective schemes still do not accurately depict the relationship between latent heating and precipitation; and a single value (precipitation rate) cannot by itself adequately constrain and adjust vertical profiles of latent heating (and thus temperature and moisture).

5.3.3 *Direct Assimilation of Radiances in Cloudy and Precipitation Conditions*

Direct radiance assimilation under cloudy and precipitating conditions may be improved by detailed information on the profiles of cloud microphysical variables that can be explicitly simulated by the NWP models. Cloud schemes based on Zhao and Carr (1997) and Ferrier et al. (2002) have been implemented into NCEP global and regional (Eta) forecast models, respectively. These schemes run slightly different physical packages but predict water mixing ratios associated with various condensates within the model grids. In principle, these cloud schemes can resolve all cloud condensates only when the model resolution is increased to less than a few kilometers. At larger resolutions, the forecast model must use the cumulus parameterization scheme to determine the clouds and precipitation associated with convective motion.

To estimate the quality of the model predicted cloud condensates, observational data sets are required to characterize the errors of the forecast model cloud water/ice content. Retrievals from satellite passive sensors may be used for assessments of model errors in the column-integrated water (Weng et al., 1997), however, it remains difficult to characterize the errors in the profiles of cloud condensates predicted by forecasting models before the data from satellite active sensors such as Cloudsat (Stephens et al., 2002) become available.

The errors of forward radiative transfer models in cloudy conditions also need to be characterized. At microwave frequencies less than 60 GHz, the cloud optical parameters are not sensitive to the particle size and the errors of the forward model may be characterized. However, in microwave window channels, the simulations of cloudy radiances are complicated by the variability in surface emissivity.

Understanding the error characteristics at higher microwave frequencies, and visible/infrared wavelengths remains a challenge since the radiative transfer processes are more sensitive to particle size distribution, shape, bulk volume density and phase (Evans and Stephens, 1995; Weng and Grody, 2000). The simulations are also affected by the vertical structure of clouds in various phases. It is necessary that the detailed observational data of cloud microphysical parameters be available in order to quantify the forward model errors.

5.4 Assimilation of Land Surface Observations from Satellites

NWP models can use satellite based operations to provide model lower boundary conditions in two ways: In the specification of surface boundary conditions and as forcing in uncoupled model surface physics schemes. Lower boundary conditions for NWP models over land surfaces include most of the properties of vegetation, soil, and snow/ice cover. Quantities such as green vegetation fraction, leaf area index, vegetation class, soil albedo, surface emissivity, and snow cover and snowpack parameters (snow water content, snow depth) can be estimated from satellite measurements. Because some of these characteristics change on time scales of hours to days, real-time estimates from satellite observations are required. Satellite estimates of components of the surface radiative fluxes and precipitation may be used to force uncoupled land data assimilation systems (e.g. LDAS). Near real-time estimates of insulation, downward longwave and surface temperatures (the latter for surface physics validation, and later for assimilation into the surface model) are required.

Some of the satellite-derived information mentioned above is yet to be utilized in NWP models. There are several reasons for this. One is the difficulty in deriving physical quantities that can be used in land surface physics packages from common remote sensing quantities. *Examples of physical quantities now used in land surface physics packages are the leaf area index or vegetation fraction from Normalized Difference Vegetation Index (NDVI) or basic window channel reflectance, the estimation of snow fraction and snow albedo from satellite brightness measurements, and the, estimation of surface thermal emissivity from multi-spectral window channel data*.

Another difficulty is the complexity of assimilation of satellite window observations into complex surface models. Forward models and adjoint formulations are very difficult in the atmospheric window regions of the spectrum. Work to extend the use of surface observations from space in the assimilation process remains a priority at JCSDA.

Land surface states are also critical to the initialization of seasonal climate forecasts, especially the memory in the system associated with soil moisture and snow. Global retrievals of snow mass, snow cover and soil moisture are available from various research satellite sensors, including AMSR-E and MODIS on the Aqua satellite. NASA GMAO has developed a system to assimilate these data into the GMAO catchment land surface model using an Ensemble Kalman Filter and are in the early stages of incorporating the system into the GMAO coupled seasonal forecast system. As with other data types, an issue to be addressed is the observational error characterization and biases between different data sources and models (e.g., Reichle et al., 2004; Reichle and Koster, 2004).

5.4 Assimilation of Satellite Oceanic Observations

Satellite-derived ocean observations/products are increasingly being used in data assimilation systems. The wind vectors over oceans are retrieved directly from QuikSCAT data and are being operationally assimilated into the GDAS. Oceanic wind speeds derived from DMSP SSM/I and are also assimilated into the GDAS. Outstanding issues still remain. Satellite observations are currently being utilized at a degraded resolution. For QuikSCAT, NCEP has completed a study using the data at near half-degree resolution and have shown forecasting skills are improved at this increased resolution. Further efforts will focus on utilizing the data in higher resolution models such as the future WRF models.

Recently at JCSDA, Derber and Li (private communication) have developed an assimilation methodology for deriving accurate SSTs from clear radiances. In the longer term this will allow sea surface temperatures to be consistent with atmospheric and skin temperatures derived from multispectral radiance observation.

Several other oceanic data assimilation projects are underway and may be viewed on the JCSDA website (www.jcsda.noaa.gov).). In particular, NCEP and NASA GMAO have developed ocean data assimilation systems to initialize the ocean as part of their coupled seasonal forecast systems. Although the TAO/TRITON mooring array has had a substantial impact on the forecast skill of equatorial Pacific sea surface temperature, the array is sparse and even with other in situ data provide inadequate coverage outside the equatorial Pacific. Hence the near-global information provided by satellite surface altimetry, along with the ocean surface winds, is a critical source of information on ocean variability. Even so, the use of this surface information to infer the subsurface ocean variability that contains the memory of the climate system is not without difficulty, particularly with inadequate information of the geoid. The developments at NCEP and NASA and in the external contributions to the JCSDA are focused on how to make best use of this data source and how to characterize the observational errors in sea surface height in terms of representativeness for the climate system (e.g., Kaplan et al., 2004). The NCEP Global Ocean Data Assimilation System (GODAS) is a three-dimensional variational (3DVAR) method that is an extension of the work of Derber and Rosati (1989) (e.g, Behringer et al., 1998). At NASA GMAO, multivariate forecast error statistics are derived from an Ensemble Kalman Filter to project the information from the surface data to the subsurface ocean (e.g., Keppenne and Rienecker, 2002, 2003). Related developments are focused on the improvement of the assimilation systems to take into account systematic errors in the forecast models, using techniques following Dee and Da Silva (1998).

6. EARLY SUCCESSES

6.1 The Community Radiative Transfer Model (CRTM)

The JCSDA has made significant advances in formulating a Community Radiative Transfer Model (CRTM). For atmospheric transmittance calculations, the gas absorption coefficients are predicted with the atmospheric parameters and the polynomial expansions of the absorber amount (Kleepies et al., 2004). This approach significantly reduces the coefficients which reside in computer memory and preserves the accuracy. Now, only 70 coefficients instead of 1800 are needed to compute the transmittance at each channel. The transmittance is calculated with a correction term to account for the average strengths of gaseous absorption within the instrument band width. In addition, new predictors are added to improve the ozone absorption. Figure 5 displays the performance of a recent fast transmittance model (OPTRAN-V7) and compares it with the recent operational model for the 20 HIRS channels.

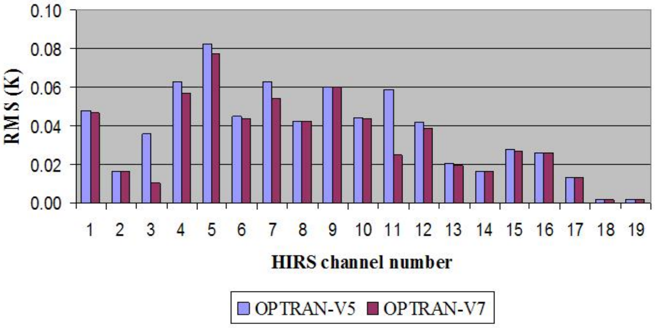

Figure 5. Latest optical path of gaseous transmittance model performed at 19 HIRS channels.

Studies have also been completed to develop a fast radiative transfer model which includes scattering and polarization of clouds, precipitation and aerosols (Liu and Weng, 2002) and (Weng and Liou, 2003). Using a two-stream approximation, the integration of the phase matrix over azimuth angle is derived analytically and can be directly utilized for the general radiative transfer scheme. Each Stokes radiance component is expressed as an analytical function of atmospheric and surface optical parameters. This model is applicable for spherical and randomly oriented nonspherical scatters. The differences in brightness temperatures between the polarimetric two-stream model and the matrix operator method are less than 2 K for various frequencies. It is expected to implement this model for microwave radiance simulations (see Figure 6) in the near future. In data assimilation systems, the Jacobian matrix computation is very important. A proper formulation of the forward scheme will lead to a high accuracy and fast speed in deriving the Jacobian matrix. It has been demonstrated that the discrete-ordinate method can lead to the analytic expressions of Jacobians with respect to a variety of cloud and precipitation parameters (Weng and Liu, 2003).

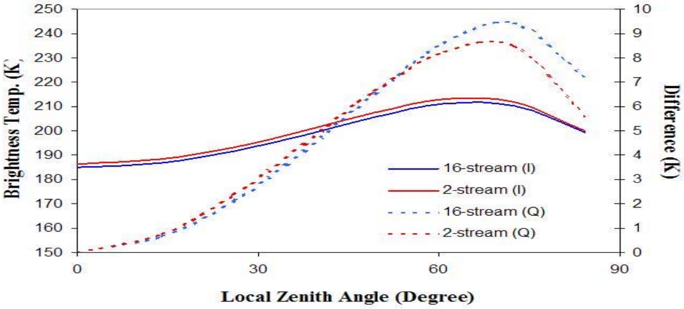

Figure 6. Comparison of the intensity (solid lines) and polarization difference (dashed lines) calculated by sixteen-stream model (blue lines), polarimetric two-stream model (red lines).

In radiative transfer calculations, both radiance and Jacobian computations require knowledge of surface emissivity and reflectivity. Presently, these quantities are simulated at selected frequencies and under specific surface conditions. At microwave frequencies, a model for simulating the land emissivity over various surface conditions has also been developed (Weng et al, 2001).

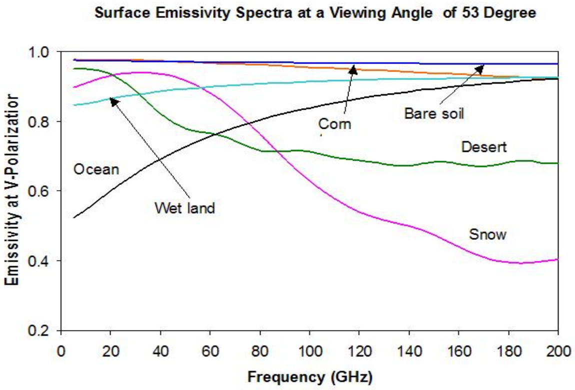

Figure 7. Microwave emissivity spectra for various surfaces at vertical polarization.

For surfaces such as snow, desert and vegetation, volumetric scattering is calculated using a two-stream radiative transfer approximation. In the case of vegetation, geometrical optics has been used since the leaf size is typically larger than the wavelength. For snow and deserts, a dense medium theory has been adopted to take into account the coherent scattering by closely-spaced particles.

Figure 7 displays the emissivity spectra obtained from the land emissivity model. The emissivity of ocean surface is also shown for a comparison. The emissivity of snow decreases as frequency increases due to the scattering from snow particles. It is found that the uncertainty in simulating land emissivity is the largest over snow-covered and desert regions where an assessment of the dense medium scattering needs refining. Recent work has addressed the modeling of ice and snow emissivity, and trials have shown improvement in high latitude forecasts using NCEP's Global Forecast System. Fig.8 provides some results from the trials, showing an increased anomaly correlation at 850hPa for the global forecast system using the new emissivity model, compared to the control (Operations).

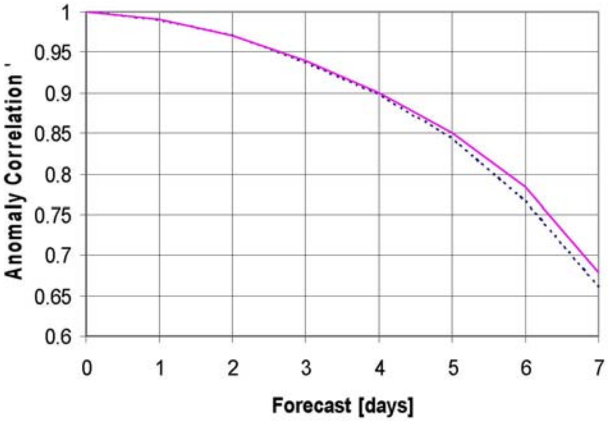

Figure 8. The impact of sea ice and snow emissivity models on the Global Forecast System (GFS) 24 hour forecast at 850hPa. (1 January 2004 – 15 February 2004; the curve with pink cover shows ACC with new snow and sea ice emissivity models).

6.2 AQUA Applications: AIRS Data Thinning and Distribution/MODIS Winds

The JCSDA has successfully distributed AIRS data to the world's major NWP centers. An initial constraint in providing AIRS radiances in near real-time to the main NWP centers is data volume size. AIRS/AMSU/HSB level 1b data is about 2.5 Gigabytes for a 100 minute orbit in comparison to the approximately 14 megabytes per orbit from ATOVS (HIRS ~4.5 megabytes, AMSU-A ~2 megabytes, AMSU-B ~7.5 megabytes). Each six-minute granule consists of 90 AIRS and HSB field of views (fov) per scanline and 30 AMSU-A fovs per scanline. There are 135 AIRS and HSB scanlines per granule, and 45 AMSU-A scanlines per granule (Goldberg et al., 2003; Aumann et al., 2003). A simple solution to the relatively high volume of AIRS/AMSU/HSB is to increase available communication bandwidth. But that option is costly and at present most NWP centers cannot assimilate all the data due to computational costs and limitations in storing the data. The AIRS/AMSU/HSB data are thinned into several sub-datasets Visually, each AMSU-A fov, which has a spatial resolution of approximately 42 km on the Earth near the nadir view position, contains a 3 x 3 array of AIRS and HSB fovs, each with a spatial resolution of approximately 14 km. The AIRS and HSB fovs are spatially coincident. The data are thinned by subsampling fovs and channels. A subset of about 324 channels (see Figure 9) is extracted from the center AIRS fov of the 3 x 3 array, as well as all 15 AMSU-A channels and the 4 HSB channels from the center HSB fov. Each granule has two files, each containing data from alternate center fovs.

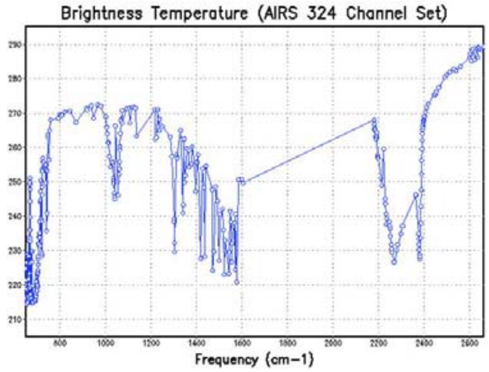

Figure 9. Spectral locations for 324 AIRS thinned channel data distributed to NWP centers.

The size of each file is about 0.5 megabyte. An orbit of data is about 16 megabytes which is only about 15% greater than the full ATOVS data. The method of channel selection is described in (Suskind et al., 2003). The single fov thinned radiance dataset is the core data that is used by most NWP centers assimilating AIRS radiances. The files are available in BUFR and HDF formats. The result of this distribution is that several key Centers have documented their utility for NWP, and included the radiances in their operational data stream.

A number of studies have also been completed in relation to the use of data from the MODIS instrument on AQUA. Winds generated using sequential MODIS images over polar regions (Daniels et al., 2004) have been used in a series of impact studies using NCEPs operational global model (Le Marshal et al., 2004). Impacts in both northern and southern high latitudes were positive (see for example Fig. 10) even though winds were only assimilated up to the second last analysis, to simulate existing operational data availability. These data will become part of the operational suite at NCEP after the next system upgrade.

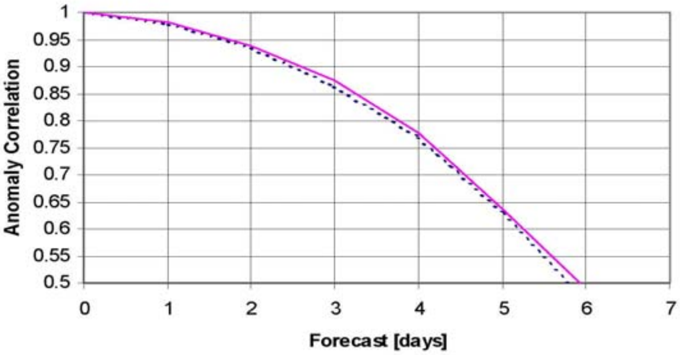

Figure 10. The impact of MODIS AMVs on the operational GFS FORECASTS AT 500hPa (60°S - 90°S). (1 January 2004 – 15 February 2004; the pink (dashed) curve shows the ACC with (without) MODIS wind assimilated)

6.3 Precipitation and Cloud Data Assimilation

Satellite precipitation products are assimilated at JCSDA member institutes. At EMC, the global data assimilation system (GDAS) makes use of instantaneous rain rates derived from SSM/I and TMI brightness temperatures. The Eta model data assimilation system (EDAS) uses these observations as available over its North American domain plus total column water vapor (TCWV) from GOES (over land) and SSM/I (over water). The GDAS assimilates 1° superobs of SSM/I and TMI instantaneous rain rates (Treadon et al., 2002). The forward model used to simulate rain rates includes convective precipitation generated from Arakawa-Schubert cumulus parameterization and grid scale precipitation from the explicit cloud scheme. The total model rain is the sum of convective and grid scale contributions using a fractional stepping approach. The assimilated precipitation observation is actually the natural logarithm of the rain rate plus one. This formulation follows work done by Koizumi (2001) and Bauer *et al.* (2002) who suggests more tractable error specifications when dealing with a logarithmic transform. TMI observation errors were estimated by comparing coincident TMI and TRMM precipitation radar rain rates for July 2001. A similar approach was taken for SSM/I rain rates with the ground “truth” rain rates over the continental United States for the period April-October 2001. The rain rates near 0.1 mm h^{-1} are not assimilated because relative errors are too large. Other quality control techniques are discussed in detail (Treadon et al., 2002). Overall, the greatest effect of rain rate assimilation is the reduction of excessive precipitation. Increases in the simulated rain rates are less pronounced.

At NASA GMAO, Hou et al. (2000) has also assimilated the TMI derived surface rainfall and total precipitable water (TPW) into the Goddard Earth Observing System (GEOS) global analysis. A unique feature of the GEOS data assimilation system is that it uses the incremental analysis update (IAU) developed by Bloom et al. (1996), which virtually eliminates the spinup problem. The control variables are analysis increments of moisture and temperature, within the IAU framework. The procedure minimizes the least squares differences between the TMI observations and the corresponding values generated by the column model averaged over the 6-h analysis window. The minimization procedure is one-dimensional, but the evaluation of the cost function involves a 6-h time integration of the time-averaged rainfall and TPW.

To prepare for the use of satellite cloudy radiances in NWP models, there is a need to understand the quality of various cloud variables predicted or diagnosed from the model, especially for cloud condensates because they are fundamentally related to the forward radiative transfer in data assimilation scheme. At the JCSDA, the SSM/I derived cloud liquid water has been used to validate the cloud prognostic scheme. Since 1998, the cloud liquid/ice water paths have been operational products retrieved from the AMSU (Weng et al., 2003). These products are being used to compare against the global model outputs (Treadon et al., 2002). In the NCEP global forecast system (GFS) model (formerly the medium range forecast MRF model), cloud condensate was added as an additional history variable in May 2001. The convective and grid-scale condensation processes, condensate sinks due to precipitation and evaporation and horizontal and vertical diffusion, are all included in the prognostic equations. As formulated in the GFS, cloud condensate can be liquid water, mixed phase, or ice depending on the local temperature.

Grid-scale condensation is based on Zhao and Carr (1997) with modifications taken from Sundqvist *et al.* (1989). Evaporation of cloud condensate is taken from Zhao and Carr (1997). The precipitation rate for ice follows the parameterization of Zhao and Carr (1997), while that for the liquid phase follows Sundqvist *et al.* (1989). There is no storage for the atmospheric precipitation. As a result, the most of cloud droplets suspended in the air are associated with non-raining clouds.

The GFS mass-flux cumulus parameterization is a Simplified Arakawa-Schubert’s scheme (SAS) and allows a detrainment process of condensate from the convective cloud top. The convective cloud top is randomly chosen to be a level between the level of neutral buoyancy and that of minimum moist static energy. The entrainment rate is then re-computed to ensure that the parcel becomes neutrally buoyant at the selected cloud top. Importantly the model also has cumulus momentum mixing. The momentum exchange is calculated through the mass flux formulation in a manner similar to that for heat and moisture.

It should be mentioned that the liquid phase condensates are currently only produced in the grid-scale cloud/precipitation scheme. The cumulus parameterization does not explicitly modify the mixing ratios of cloud condensates. As a result, the GFS cloud liquid water path in the tropics is low because the grid-scale cloud scheme, according to its physical definition, may only capture about 40% of the cloud condensates associated with the stratiform precipitation. When the GFS cloud liquid water is compared with the AMSU retrieval, a discrepancy is found over the tropical western Pacific where deep convective clouds prevail. However, in the middle to high latitudes where stratiform precipitation dominates, the GFS cloud water agrees with the AMSU retrieval very well.

The NCEP GFS model relationship between cloud liquid water and ice phase has been compared to observations from satellites (See Figure 11). Some of the difference seen may be due to the inability of directly predicting the cloud condensates from the convective scheme at a relatively large spatial resolution. In Fig. 11, the GFS exhibits a smaller dynamic range of cloud liquid water, compared to the AMSU estimates. However, the model did produce an appreciable amount of cloud ice water which may arise from convective detainments and stratiform precipitation. In this analysis, the cloud liquid/ice water paths are derived using the AMSU liquid water algorithm (Weng et al., 2003).

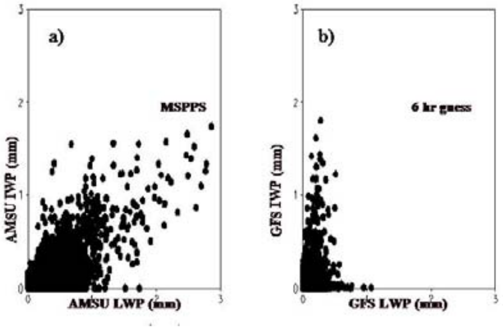

Figure 11. The correlation between cloud liquid and ice water paths from: a) AMSU retrievals and b) the GFS 6-hour guess.

7. THE FUTURE

JCSDA activities are divided into directed R&D/infrastructure activities and proposal-driven projects. Initially, infrastructure activity will maintain focus on the development and maintenance of a scientific backbone for the JCSDA community fast radiative transfer model, a community emissivity model, and an infrastructure for performing assimilation experiments with real and simulated observations from new and future instruments. Proposal-driven scientific projects will be an important mechanism used to accelerate the transition of research and technological advances in satellite data assimilation by planned incorporation of new code into the NASA/NOAA/DoD operational data assimilation systems and by performance of preliminary testing with these systems. Initial JCSDA projects in the past few years have solidified NOAA, NASA and DoD collaborations on AIRS, QuikSCAT, TRMM, and the NPOESS Preparatory missions. Furthermore, the JCSDA will facilitate further collaborations in areas deemed potentially important for improving climate and weather prediction, such as in the utilization of GIFTS, IASI, CrIS/ATMS GIFTS and GPS radio-occultation data and support an examination of the utility of geostationary microwave observations.

A primary goal of the JCSDA in next few years will be to lay the groundwork for and to establish a common data assimilation infrastructure for assessing new satellite data and optimizing the utilization of these data in operational models. An important step is to establish, and make accessible to the community, parallel versions of the EMC, GMAO and DoD partners global/regional data assimilation systems on JCSDA computer systems. This will include establishment of real-time communications to JCSDA computers and real-time data bases and observation handling algorithms for continued assessment of new instruments.

A most important activity for the Center is planning in relation to the form of the next generation assimilation system to be used by the partners.

Strategic planning activity is already underway detailing the optimal form of the infrastructure, for the next model and assimilation system. Planning involves the use of the 4DVar and Ensemble Kalman Filter Approaches.

In summary JCSDA deliverables by 2007 will include the development of a community forecast and data assimilation system for both global and regional scale applications. The system will be linked to the research community through the USWRP and will serve as the primary mechanism for infusing research and operational satellite data into NCEP, GMAO and DoD operations.

The scientific tasks of the JCSDA in next five years will include:

- Continue refining the rapid transmittance model for current and many future sensors, including rapid transmittance coefficients for the new instruments such as IASI and GIFTS; and the corresponding Jacobian code when changes are required,
- Update rapid transmittance coefficients as instrumental parameters, spectral knowledge, or requirements change. This includes the running of the LBL code if required, the integration of the LBL transmittances with the instrumental response functions and the generation of new fast model coefficients,
- Develop and improve radiative transfer models to include scattering, polarization and polarimetry for assimilating the cloudy and precipitation radiances,

- Improve the performance of the emissivity models over snow conditions, which will lead to better use of sounding data over polar region,
- Develop and implement land emissivity models for advanced infrared sounders,
- Develop more comprehensive models to simulate the emissivity for new, second and multiyear sea ice,
- Improve the performance of the current microwave emissivity model at higher frequencies,
- Develop a full polarimetric emissivity model for WindSat and CMIS,
- Perform data thinning and information content analysis for IASI, CrIS, GIFTS, ABS, ABI, and HES. Assimilate these data as they become available,
- Develop a new generation data assimilation system and related infrastructure to specifically handle the fourth dimension
- Develop timely retrieval of snowpack and vegetation properties from satellite observations including snow fraction, snow albedo, snow depth, snow water content, snow cover temperature, green vegetation fraction, leaf area index, canopy temperature, soil surface temperature, and canopy roughness,
- Develop forward models for radiation from atmospheric window bands should include bidirectional properties of the land surface in both reflectance and thermal bands,
- Develop and demonstrate the variational land data assimilation using adjoint models of land physics models and develop treatment for background error covariances,
- Intercompare land assimilation techniques such as adjoint models/variational methods, Kalman filters, neural networks, nudging, and direct insertion,
- Improve observational error characterization for land surface data assimilation,
- Develop techniques to address observational as well as forecast model biases in land surface parameters,
- Assimilate the wind products from WindSat, the first spaceborne radiometer system designed to retrieve the surface wind vectors,
- Assimilate the wind products from ASCAT/METOP,
- Improve surface fluxes from NWP models for use by ocean and land surface models,

- Improve the capability to assimilate ocean surface altimeter data for seasonal climate forecasts,
- Develop the capability to assimilate the satellite-derived surface salinity observations anticipated from SMOS, Aquarius, and HYDROS.

In conclusion, a strong start has been made by the JCSDA. The strength of satellite data assimilation in the Center is central to the quality of future operational climate and weather analysis and forecasting in the US. As a result every effort is being made by the partner organizations to work effectively together for the common good.

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Table 1. Current and Planned Satellite Instruments and Their Characteristics

			Wavelength				Primary Information Content							
Platform	Instrument (Used in NWP*)	Status	UV	Visible	IR	Microwave	Temperature	Humidity	Cloud	Precipitation	Wind	Ozone	Land Surface	Ocean Surface
DMSP	SSM/I *	Current				*		X	X	X	X		X	X
	SSM/T					*	X							
	SSM/T-2					*		X		X				
	OLS			*	*				X				X	X
NOAA	AMSU-A *	Current				*	X	X	X	X			X	X
	AMSU-B *					*		X		X				
	HIRS/3 *				*		X	X	X			X	X	X
	AVHRR *			*	*				X				X	X
	SBUV *		*									X		
GOES	Imager *	Current		*	*			X	X		X		X	X
	Sounder *			*	*		X	X	X				X	X
Meteosat	Imager *	Current		*	*			X	X		X		X	X
GMS	Imager *	Current		*	*			X	X		X		X	X
Terra	MODIS	Current		*	*		X	X	X				X	X
TRMM	TMI	Current				*		X	X	X			X	X
	VIRS			*	*				X				X	X
	PR *					*				X				
QuikSCAT	Scatterometer *	Current				*					X			
TOPEX	Altimeter *	Current				*								X
JASON-1	Altimeter	Current				*								X
Aqua	AMSR-E	Current		X	X	X		X	X	X			X	X
	AMSU						X	X	X	X			X	X
	HSB							X		X				
	AIRS						X	X	X			X	X	X
	MODIS						X	X	X				X	X
Envisat	Altimeter	Current				X								
ADEOS-II	AMSR	Current		X	X	X		X	X	X			X	X
	GLI							X	X				X	X
	SeaWinds										X			
Windsat	Polarimetric radiometer	Current				X					X			
DMSP	SSMIS	2003				X	X	X	X	X	X		X	X
	OLS			X	X				X				X	X

			Wavelength				Primary Information Content							
Platform	Instrument (Used in NWP*)	Status	UV	Visible	IR	Microwave	Temperature	Humidity	Cloud	Precipitation	Wind	Ozone	Land Surface	Ocean Surface
METOP	IASI	2005			X		X	X	X			X	X	X
	ASCAT					X					X			
	GRAS					X	X	X						
	AVHRR			X	X				X				X	X
NPP	VIIRS	2005		X	X				X				X	X
	CRIS				X		X	X	X			X	X	X
	ATMS					X	X	X	X	X			X	X
IGLAB	GIFTS	2006			X		X	X	X		X	X	X	X
COSMIC	GPS	2005				X	X	X						
NPOESS	VIIRS	2009		X	X				X				X	X
	CRIS				X		X	X	X			X	X	X
	ATMS					X	X	X	X	X			X	X
	CMIS					X	X	X	X	X	X		X	X
	GPSOS					X	X	X						
	OMPS		X									X		
GOES R	ABI	2101		X	X				X		X		X	X
	HES				X		X	X	X			X	X	X