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NOAA OPERATIONAL SOUNDING PRODUCTS FOR ADVANCED-TOVS: 2002

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service (NESDIS) operates a fleet of civilian, polar orbiting environmental satellites which provides users and researchers with a suite of operational atmospheric and environmental data. On May 13, 1998, the Advanced TIROS Operational Vertical Sounder (ATOVS) instrument configuration (Goodrum et al., 2000) onboard NOAA-15 was successfully deployed into a morning orbit, followed by NOAA-16 into an afternoon orbit, on September 21, 2000. The ATOVS sounders consist of the 15-channel Advanced Microwave Sounding Unit-A (AMSU-A), the 5-channel AMSU-B, the 20-channel High-resolution Infrared Radiation Sounder (HIRS/3), and the 6-channel Advanced Very High Resolution Radiometer (AVHRR/3).

The following report summarizes the Phase-1and Phase-2 series of modifications for operational ATOVS[1] sounding products implemented in October 2001 and March 2002 and presents results. The report also addresses the requirement for ground truth radiosonde observations in support of satellite operations, the potential benefits of designated radiosonde launches concurrent with satellite overpass, and future ATOVS plans to better accommodate the expanding requirements of users.

2. BACKGROUND

Scientific procedures for processing NESDIS operational sounding, cloud (experimental), radiation and ozone products for ATOVS are briefly summarized below. These are divided into **Orbital** and **Offline** processing systems; for a more detailed discussion see Reale, 2001. A complete listing of ATOVS operational (and experimental) sounding products is given in Appendix A1.

The **Orbital** processing system provides:

- Pre-processing,
- Contamination detection,
- First guess and retrieval for soundings, and
- Cloud, Radiation, and Total Ozone products.

Pre-processing steps include instrument calibration, quality control (QC) of the sounder measurements, attachment of ancillary data such as terrain designation, Sea Surface Temperature and Numerical Weather prediction (NWP), the spatial interpolation of the AMSU-A measurements to the HIRS/3 field-of-view (FOV), and radiance temperature adjustments such as limb correction (Allegrino, 1999).

Contamination detection consists of the identification of effects due to precipitation for the AMSU measurements, and clouds for the HIRS/3 measurements. Global cloud detection (Ferguson and Reale, 2000) and the resulting cloud-mask constrains the use of HIRS in subsequent first guess and retrieval steps.

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[1] Does not include AMSU-B (see Chalfant et al., 1999).

The **first guess** is uniquely determined for each sounding using a library search technique (Goldberg et al., 1988). The libraries consist of segregated samples of collocated radiosonde and satellite measurements (Tilley et al., 2000) as described later in Section 4 (and table 2) which are directly accessed during orbital processing.

The first guess is obtained by minimizing equation (1):

$$D = (R - R_k)^t B^{-1} (R - R_k) \qquad (1)$$

where the superscript t indicates the matrix transpose, -1 the inverse, and

- D : scalar closeness parameter,
- B : sounding channel radiance covariance matrix; dimension (35 x 35),
- R : adjusted, observed radiance temperature vector; dimension ($N_{A,i}$), and
- R_k : adjusted, library radiance temperature vector; dimension ($N_{A,i}$).

The dimension "35" for the B matrix in Equation (1) denotes the total number of sounder channels available from ATOVS; not all are used. The dimension ($N_{A,i}$) denotes the specific channel combination used to compute D, and the subscript "k" denotes the collocations searched. The channel combination for a given sounding varies depending on whether the sounding type is clear or cloudy, and sea or non-sea. The actual first guess temperature, moisture and radiance temperature profiles for a given sounding are computed by averaging the 10 closest collocations with the smallest D. The B-matrix is pre-computed Offline, and updated weekly.

The **retrieval** is done using a Minimum Variance Simultaneous solution (Fleming et al., 1986), which is given by equation (2):

$$T - T_g = S A^t (A S A^t + N)^{-1} (R - R_g) \qquad (2)$$

where the subscript t indicates the matrix transpose, -1 the inverse, and:

- T: final soundings products vector, (133),
- T_g: first guess products vector, (133)
- S: first guess covariance matrix, (133 x 133),
- A: sounder channel weighting matrix, (35 x 133),
- N: measurement uncertainty matrix, (35 x 35),
- R: observed radiance temperature vector, ($M_{A,j}$), and
- R_g : first guess radiance temperature vector, ($M_{A,j}$).

The product vector (T) includes 100 levels of atmospheric temperature (1000mb to .1mb), 32 levels of moisture (1000mb to 200mb), and the surface temperature (level 101). The dimension 35 for the A and N matrices denotes the available ATOVS channels; not all are used. The dimension ($M_{A,j}$) denotes the specific channel combination used to compute retrievals, depending on the sounding type. The S, A, and N matrices of the retrieval operator are pre-computed offline and updated weekly, with nine unique sets of matrices combined depending on the sounding type and latitude.

Derived **cloud products** (Chalfant and Allegrino, 2001) consist of the following parameters:

- Effective Cloud Amount (ECA) (%),
- Cloud Top Pressure (CTP), and
- Cloud Top Temperature (CTT).

Cloud products are available for each of the HIRS/3 Fields-of-View (FOV), for each sounding, and on 1-degree global "Grid" fields. The Grid data are also used to process ECA summary tables (Section 3, Table 1).

The cloud products are computed using the CO_2 Slicing algorithm, which is a slope-radiance technique for deriving the cloud parameters, based on the assumption that the observed radiance for any channel is a linear function of the ECA, and falls on a line between the totally clear and the cloudy radiance (Yang et al., 1996). The algorithm uses a triple pass approach (McMillin et al., 1994) to calculate the cloud products. The first and second iterations calculate these products based on HIRS channels 7 and 8[2], with the third iteration using a HIRS channel pair based on the CTP. The computed CTT temperature and adjacent ATOVS sounding (computed earlier) are used to determine the CTP for each iteration, with effects due to CO_2 attenuation above the cloud accounted for in the second and third iterations.

Regression coefficients are used in the cloud products algorithm to predict clear sky measurements at the cloud top (and ultimately the CTT). These coefficients are derived offline, using clear-sky samples of HIRS and AMSU-A tropospheric channels (Chalfant and Allegrino, 2001). Coefficients are produced for five (5) latitude zones, with linear interpolation near latitude boundaries, and updated weekly.

NESDIS also has a long history of providing **Outgoing Longwave Radiation** (OLR), clear-sky **Layer Cooling Rates** (LCR), and **Total Ozone** products from its polar orbiting satellites.

ATOVS OLR and LCR products are derived at each of the HIRS/3 FOV and on Grid, and consist of:

- All Sky and Clear Sky OLR,
- Clear Sky LCR1 (1000mb to 700mb),
- Clear Sky LCR2 (700mb to 500mb),
- Clear Sky LCR3 (500mb to 240mb), and
- Clear Sky LCR4 (240mb to 10mb)

OLR and LCR parameters are computed using a fixed set of regression coefficients as described in Ellingson et al., 1994a and 1994b.

ATOVS Total Ozone is derived at each sounding location, except for cases of very thick (and cold) clouds, using a two-layer, transmittance-radiation model (Neuendorffer 1996).

The **Offline** processing system compiles and updates the respective data sets of sounder FOV, and the collocated satellite and radiosonde observations used to derive coefficients.

The sounder FOV for "clear" HIRS/3 observations are used to update the respective cloud detection and cloud product coefficients for each operational satellite. Samples are global, typically span the most recent 30 to 60 days and are updated daily. Coefficients are updated weekly.

Collocated radiosonde and satellite observations are compiled daily for each satellite and are used in orbital processing to provide first guess information, and on a weekly basis to compute the retrieval coefficients and product accuracy statistics (Tilley et al., 2000). Their use in product processing, referred to as "Tuning," attempts to compensate for the systematic differences among the scientific algorithms, ground truth, and satellite measurements, including seasonal changes and instrument drift. The primary data set of collocations used for these purposes is referred to as the Matchup Data Base (MDB) which is discussed later in Section 5.

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[2] The ATOVS cloud mask is used to initially identify cloudy FOV over land, and for which a regressed estimate for HIRS-8 (Ferguson and Reale, 2000) may be substituted.

3. ATOVS MODIFICATIONS

ATOVS science and system upgrades over the past 18 months were separated into two series of changes, Phase-1, which was implemented into Operations during October 2001, and Phase-2, which was implemented in March 2002. The following sections describe these changes for the orbital and offline systems, respectively.

3.1 Orbital Processing System

The **Phase-1** series of scientific upgrades implemented during October 2001 included:

- HIRS/3 scan misalignment correction,
- automatic AMSU-A only processing mode if HIRS fails,
- removal of cloud mask inconsistencies in vicinity of coastlines, and
- median filter (for precipitation detection of AMSU-A) expansion.

The **Phase-2** series of upgrades implemented during March 2002 included:

- more consistent terrain designation (i.e., sea, coast, land),
- selection of "Sounding" fields-of-view (FOV) based on AMSU-A Ch.2 instead of HIRS Ch. 8
- expanded tests for cloud detection (restoral and land surface),
- introduction of secondary retrieval channel combinations for very high terrain (Antarctica), and
- cloud product, OLR and LCR improvements.

A primary goal for the Phase-1 series of changes was to deploy a generic set of software procedures which could handle both the NOAA-16 HIRS/3 scan mirror misalignment problem (Reale et al., 2001), and in the event of HIRS/3 failure[3] could process AMSU-A only sounding products with a minimal disruption of service. This included procedures which could omit individual channels of the HIRS/3 or AMSU-A radiometers in the event of single-channel failure(s). The NOAA-15 satellite has offered ample opportunities to validate these procedures, given the intermittent problems with the HIRS/3 due to filter wheel heating, and the failures of AMSU-A channels 14 (October 2000) and 11 (March 2002).

NESDIS internal monitoring had also identified inconsistencies between the global cloud-mask and several of the individual cloud tests (Ferguson and Reale, 2000) which were occurring on an intermittent basis in the vicinity of coastlines. Although a relatively minor problem from the perspective of the orbital products, its potential impact when compiling collocations with radiosondes (many of which occur along coasts) was a concern; the inconsistencies were corrected.

The final science change for Phase-1 affected the median filter technique (Reale 2001) which is used to help identify AMSU-A FOV over land and in the extra-tropics that are contaminated by precipitation. This technique, originally designed for the old Microwave Sounding Unit (Kidwell 1998), was using a 3x3 array of AMSU-A FOV, which at the nominal 50km horizontal resolution was too small to identify precipitating cells. Expansion to an array size of 7x7 AMSU-A FOV resulted in an up to 25% increase in the contaminated FOV identified, mainly in the vicinity of mid-latitude frontal zones.

[3] NESDIS considers AMSU-A-only temperature retrievals acceptable for operational distribution.

The goals of the Phase-2 upgrades were to deploy the numerous changes that had been developed and validated since the year 2000, but had not yet been implemented. A synopsis of the scientific changes that were implemented is given below.

The scientific monitoring of ATOVS products had revealed numerous cases where the land, sea, and coastal designation of the soundings appeared to depart from known geographical landmarks, beyond the expected tolerance given the horizontal resolution of the HIRS/3. A review of procedures indicated that inconsistencies were being introduced in two ways: first, during initial access from the baseline topographic map[4], and second, during the selection of the sounding location among the 2x2 HIRS/3 FOV array. In the first case, procedures were modified to insure that the HIRS FOV was "assigned" the proper geographic designation (land, sea, or coast) consistent with the "closest" grid point. In the second case, procedures were modified to insure that the sounding location selected among the 2x2 array of HIRS retained the "assigned" geographic designation.

During the above investigation, it was also observed that the FOV selected for soundings were not always consistent with design. For example, if a 2x2 occurred near a coastline, but the four candidate FOV were designated as sea, the scene closest to land, and therefore the most likely to be contaminated by land, was typically selected (it would have been preferable to select the sea scene furthest from the coast). This occurred because the discriminator for selecting the scene was the warmest HIRS/3 channel 8 value, which tended to occur closer to land (during daytime). Modifications were installed to discriminate using the AMSU-A channel 2 instead of HIRS/3 channel 8, and to discriminate for non-sea soundings based on the warmest value, and for sea soundings based on the coldest value, respectively. These changes also had a significant impact on the distribution of collocated radiosonde and satellite observations in coastal zones, reducing the number of false-sea collocations along coastlines.

Cloud mask and cloud detection test performances are continuously monitored at NESDIS, with the respective test thresholds (Ferguson and Reale, 2000) requiring seasonal adjustments to maintain a global consistency. One of the more difficult areas to maintain performance is over land, where in many cases the same test threshold is used in polar and tropical regions. Two sets of test modifications were implemented to help alleviate these constraints. The first was to modify the land, surface temperature tests to have separate thresholds pole-ward and equator-ward of a specified latitude. The second affected the Restoral test, that is, the test that restores a clear designation if the estimated surface temperature is high enough, which was modified to have separate temperature limits for day and night scenes. The net results were positive, particularly over South America and Africa.

Retrieval techniques over high terrain, with particular attention for products over Antarctica, were reviewed and modified during Phase-2. Current software, although not very flexible with respect to the sounder channels used in the first guess step, is quite flexible concerning the channels used in the retrieval step. Subsequently, tests were done for a variety of retrieval channel combinations as a function of terrain height and latitude. Results indicated that removing AMSU-A channel 5 from the retrieval step for locations above 1500m that were pole-ward of 60 degrees latitude, and channels 5 and 6 for all locations above 2000 m, tended to minimize discontinuities in temperature fields (above 500mb) across mountainous regions. Our interpretation of this result was that it was related to whether radiosonde and satellite collocations were routinely available from the respective regions, which tended not to be the case poleward of 60 latitude. Although still problematic, soundings over high terrain are becoming more consistent, particularly in the middle troposphere and upwards, an important trend given the increasing user interest in land products, for example, over Antarctica.

[4] A 1/8th grid mesh derived from an SSM/I based 1km Air Force grid.

A number of cloud product, OLR, and LCR upgrades were also installed as part of the Phase 2 upgrades. Cloud product upgrades included the application of cloud product coefficients poleward of 60 S, the interpolation of cloud coefficients between latitude bands, the limiting of tests for Restrahlen effect to land areas, and several enhancements concerning the QC and monitoring of the cloud products. These are discussed in Section 3. LCR changes primarily affected the screening of clear sky layer cooling rates, reducing the number of clear sky scenes removed.

The ATOVS Total Ozone algorithm was also modified to provide improved coverage over cold land, with significant improvements in coverage over Siberia and Antarctica.

3.2 Offline Processing System

Phase-2 included several modifications to the Offline support systems which compile the data sets of collocated radiosonde and satellite observations (Tilley et al., 2000) for each operational satellite. These actions primarily affected the QC procedures for compiling collocations, particularly for radiosonde moisture, addressing:

- moisture profile extension through gaps and aloft,
- missing moisture for temperatures below -40C,
- "spikes" in observed dew-point depression profiles,
- processing of reports with over 50 significant levels, and
- the need for better diagnostics.

The radiosonde moisture upgrades were significant, since up to 30% of the radiosonde reports from the upper latitudes were being screened due to incomplete moisture profiles, even though the accompanying temperature data was complete into the stratosphere. Internal investigations indicated that in many cases there was enough moisture information to provide a reasonable interpolation and/or extrapolation of the radiosonde moisture profile to 200mb as required for the ATOVS sounding products. For example, groups of radiosondes did not report moisture if the atmospheric temperature was below -40C.

However, it was also noted that the technique for extrapolating moisture profiles to 200mb was using a "constant Dew-point Depression" approach which was not suitable in polar regions where the tropopause can be well below 200mb. A new extrapolation technique was developed to use a "constant dew point temperature lapse rate," uniquely derived based on the uppermost levels of the moisture report.

QC changes were also developed to screen radiosonde data exhibiting "spikes" in the dew-point depression profile, with a spike defined as a difference exceeding 15K between three successive levels[5]. This action, combined with new procedures to not use "Significant" level data (below 100mb) that were within 10mb of another level, successfully reduced the occurrences of excessive spikes in radiosonde moisture reports.

Procedures were also installed to sub-sample over the entire range of reported significant levels if their number exceeded 50, instead of simply taking the first 50 levels.

NESDIS also deployed several enhancements for monitoring the collocated radiosonde and satellite observations which play such a key role in the processing and validation of the satellite data. A number of these are illustrated later in Section 5.

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[5] The difference must change sign over the three levels.

4. RESULTS

The following sections present results illustrating the meteorological information content of the derived ATOVS products.

4.1 NWP Comparison

The motivation for all scientific upgrades developed by NESDIS is to enhance the information content of the derived products in the context of NWP and Climate applications. Upgrades typically result in improved consistency in products relative to the sounder measurements and ground truth, and product expansion such as the global cloud products which are now available experimentally. Selected results from NESDIS operational product systems are discussed below, as provided through the Environmental Data Graphical Evaluation (EDGE) system, developed at NESDIS in support of operational products (Brown et al., 1992).

The panels in Figure 1 illustrate the information content of the NOAA operational sounding products from ATOVS in the context of NOAA, Environmental Modeling Center (EMC) NWP data. The upper two panels illustrate difference fields for **SAT**ellite (NOAA-16) operational soundings minus EMC**, NWP** (6-hour "Aviation" forecasts) for the (500 to 300mb) layer mean virtual temperature, with the SAT-NWP time differences constrained to be within 2 hours. The middle two panels show EMC 400mb wind fields (m/s) corresponding to the same periods, and the lower panels illustrate concurrent AMSU-A channel 5 radiance temperature measurements (K), which are sensitive to middle tropospheric temperature. The region displayed is the remote South Indian Ocean region (see EMC panels for latitude and longitude boundaries), on March 23, 2002 (left) and 48 hours later on March 25 (right).

As can be seen, there is a very high correlation among the SAT-NWP difference pattern, the location of the 400mb maximum wind (jet-stream), and the satellite measurement patterns, each denoting the frontal zone. The reliability of the derived satellite soundings is not susceptible in weather transition zones, compared to NWP which becomes less reliable in changing weather (particularly in remote regions). The persistence of the SAT-NWP pattern in the frontal zone illustrates the additional information content of derived soundings in the context of NWP forecasts, information which may be compromised in conventional NWP systems which assimilate radiance data based on a NWP first guess (Derber and Wu, 1998). Such cases warrant further study to better understand the implications of these signature SAT-NWP patterns, and the potential value of NWP-independent derived sounding products to assist forecasters in identifying developing storm systems (also see Reale 1995 and 2001).

Arguments have also been suggested that these patterns are not an indication of information relevant to NWP, but instead the result of analytical error. For example, one contention is that the patterns are artifacts of the SAT minus NWP time differences. This can be refuted in several ways, but perhaps the best is to realize that the wave speed in Figure 1 is approximately 20 kph, which given the less than 2-hour time difference and approximately 40km horizontal resolution of the satellite data is insufficient to account for such a pattern. Another argument is that the difference patterns are due to the fact that the 6-hour NWP has not yet assimilated the (current) satellite data, which suggests that the pattern would disappear if the ensuing Analysis was used. However, internal results comparing initial 6-hour forecast and analysis indicate that they are typically similar and uncorrelated with observed SAT-NWP patterns.

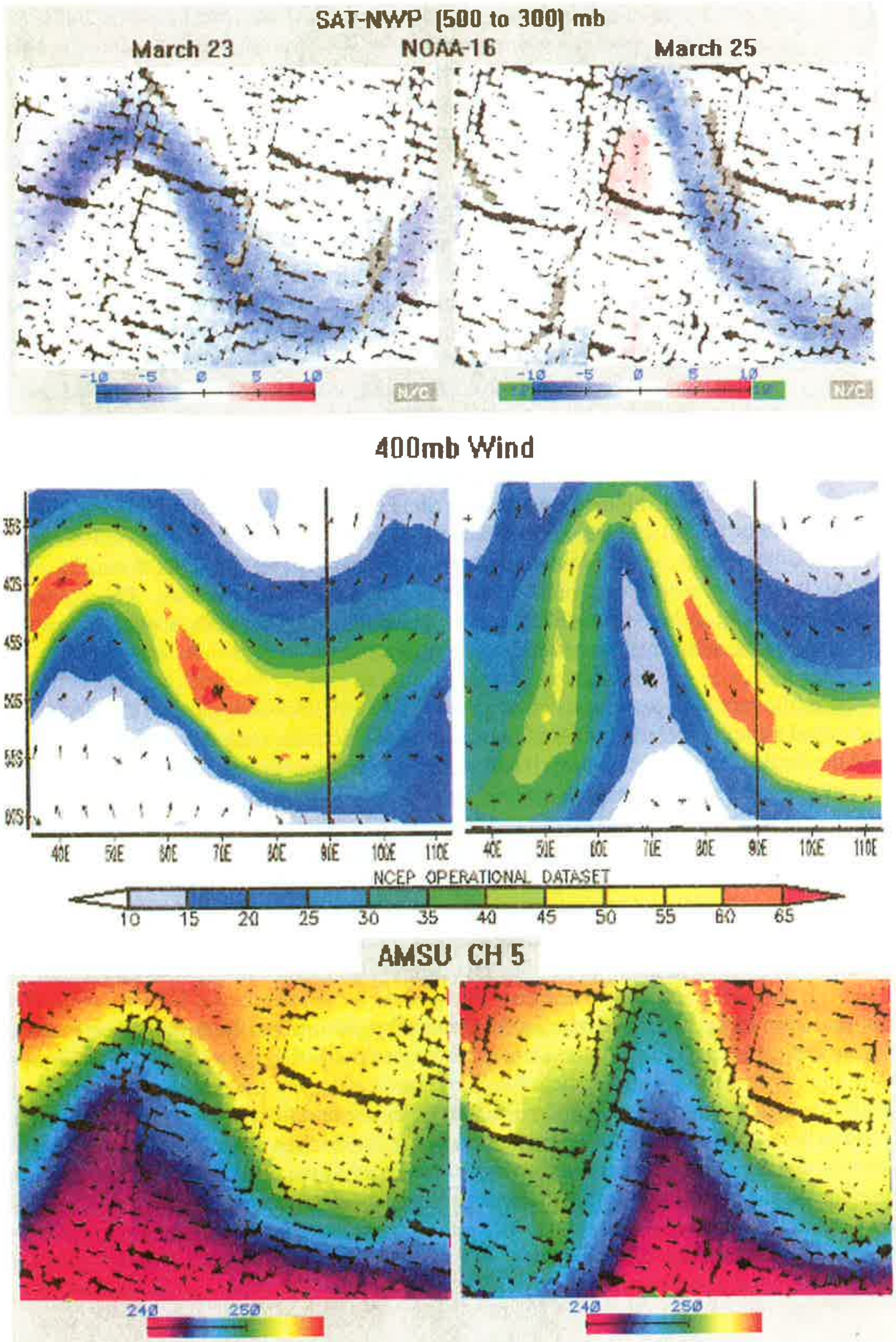

Figure 1: (SAT-NWP) differences (K) for the 500 to 300mb layer (upper), NOAA/NWP Wind (m/s) Analysis at 400mb (middle), and AMSU-A channel 5 (K) data (lower) over the Indian Ocean on March 23, 2002 (left) and 48 hours later on March 25 (right).

4.2 Antarctica

Over the past few years, a number of users have indicated an increasing interest in Southern Hemisphere sounding products, including those over Antarctica. Given its high terrain and global isolation, generating products over Antarctica is very challenging and requires some special considerations. For example, the use of infrared observations and lower peaking microwave sounding channels in this region has been found to be prohibitive, and the sparsity of collocations (radiosondes are mainly limited to coastal regions) makes it difficult to operate and validate the NESDIS algorithms over inland Antarctica. Recent changes to further constrain the use of sounder data from Antarctica, along with increased monitoring of this region by NESDIS has significantly improved the product performance in Antarctica, particularly above the 500mb level.

An example of the improved southern hemisphere sounding products in polar regions is shown in the three panels of Figure 2, which illustrates AMSU-A channel 8, which is sensitive in the vicinity of 200mb (upper left), the NESDIS, derived 200mb temperature data from NOAA-16, and the corresponding terrain designation for the Antarctic region. The derived soundings and measurements show quite good agreement[6], with a relatively smooth transition across the sea, ice and land boundaries[7]. Users are encouraged to further consider the use of these data and to provide feedback to NESDIS on performance.

4.3 Upper Stratosphere

The failures of AMSU-A channels 11 (sensitive around 30mb) and 14 (sensitive around 2mb) onboard NOAA-15, has provided an opportunity to study the impact of losing these upper stratospheric measurements on the derived sounding products. Generally, the loss of channel 11 had a minimum impact on derived soundings, mainly due to the relatively linear vertical temperature structures and the overlap of neighboring AMSU-A channels 10 and 12. However, the loss of channel 14, the highest peaking AMSU-A channel, was quite a bit more noticeable, particularly above 2mb. This is demonstrated in the 5 panels of Figure 3, with the two upper panels illustrating AMSU-A channels 13 (left) and 14 (right) from NOAA-16, the two middle panels the derived 1mb temperatures for NOAA-15 (left) and NOAA-16 (right), and the bottom panel the NOAA-16 minus NOAA-15 temperature differences at 1mb. The illustrated region covers a large portion of the eastern hemisphere from about 70N to 60S. Spectral color scales (K) are shown below each of the upper 4 panels, with identical scales used for the satellite data at 1mb, allowing a direct color comparison. A red, white, and blue color scale (K) is used for the NOAA-16 minus NOAA-15 differences, with differences greater than 0.5K in red, those between +/-0.5K in white, and differences less than -0.5K in blue; differences exceeding Absolute 5K are shown as bright green.

As can be seen in the lower panel of Figure 3, the NOAA-16 minus NOAA-15 differences at 1mb are well correlated with features in AMSU-A channel 14 that are not observed in the AMSU-A channel 13, with differences exceeding absolute 5K (green) over a sizeable portion of the southern hemisphere [8]. Such differences must be accounted for when considering the data from both satellites at these levels; that is, the data from NOAA-15 must receive a lower weight.

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[6] Measurement and derived temperatures exhibit different dynamic ranges making direct color comparisons difficult.

[7] NESDIS products in the past have typically exhibited sharp discontinuities across the south polar sea, ice and Antarctic coastal boundaries.

[8] The maximum absolute difference is 8K.

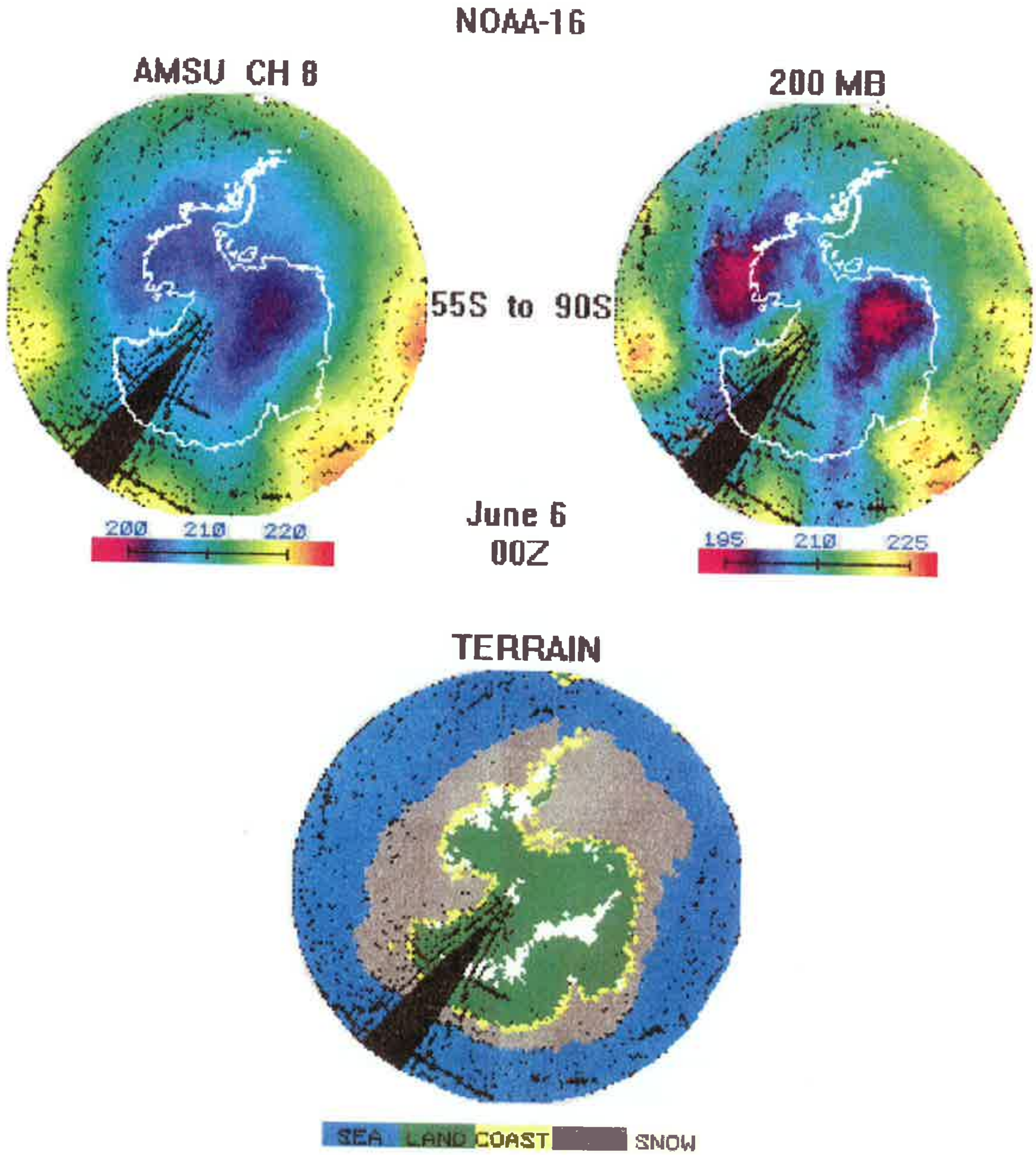

Figure 2: The upper left and right side panels show AMSU-A channel 8 radiance temperature measurements (K) and the associated derived 200mb temperature (K) fields for NOAA-16, with the corresponding terrain map (lower) across the south polar ocean, sea-ice and Antarctic region (lower).

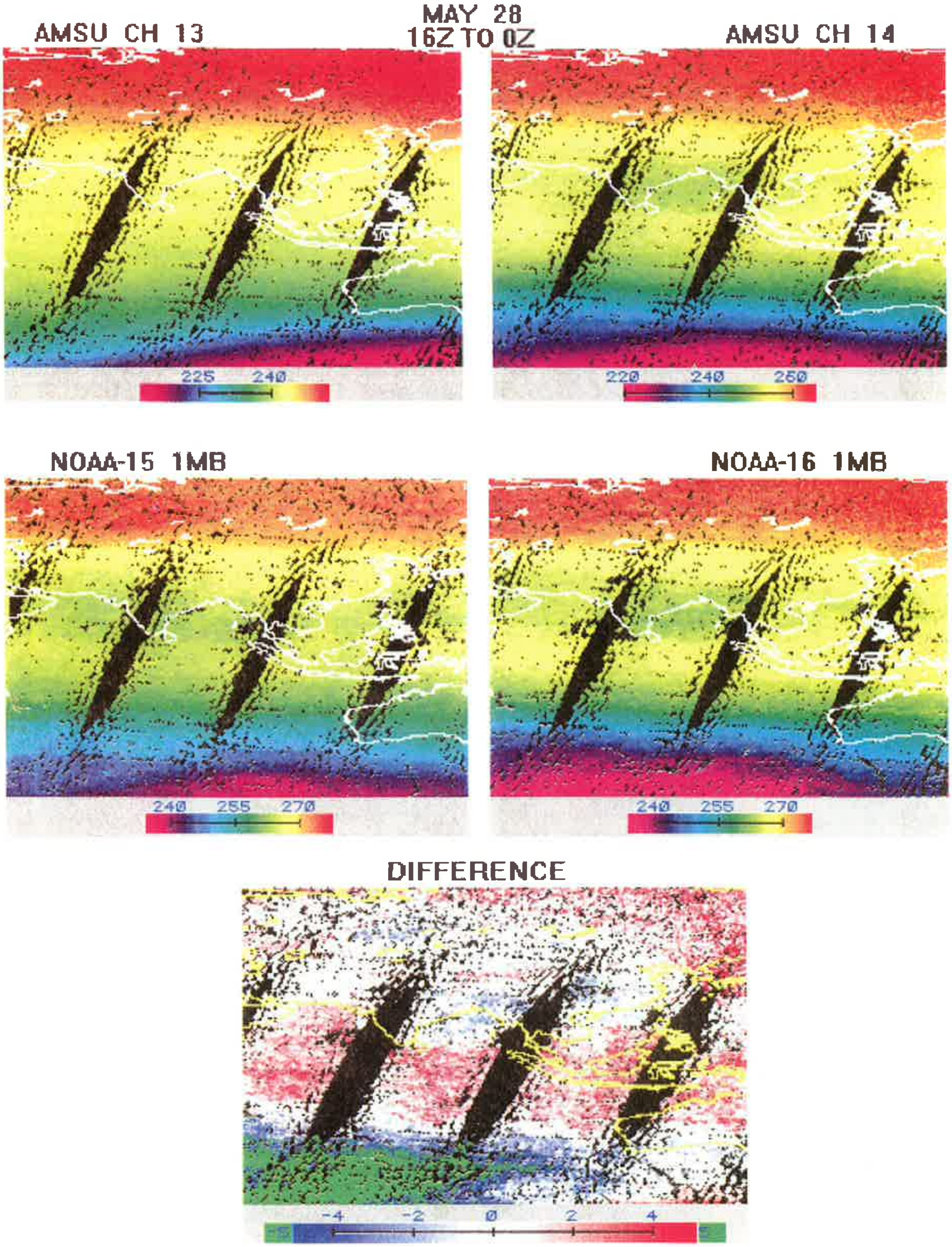

Figure 3: The upper left and right panels illustrate AMSU-A channels 13 and 14 radiance temperature measurements (K) from NOAA-16, the middle left and right panels show the associated 1mb derived temperatures (K) from NOAA-15 (left) and NOAA-16 (right), with the NOAA-16 minus NOAA-15 differences (K) at 1mb on the bottom.

4.4 Cloud and Radiation Products

A portion of the Phase-2 upgrades addressed the ATOVS experimental Cloud and Radiation products. Together these products represent a unique source of global cloud and atmospheric radiation information, providing a forefront research data set which can significantly impact future NWP and climate applications.

Of particular interest are the global, Grid data-sets for Clouds, which were created to facilitate comparisons with other sources of cloud products (i.e., Menzel et al., 2001). Grid data sets are provided daily, per satellite, and for the ascending and descending orbital node data, respectively. After sorting the products by CTP into High, Medium and Low cloud heights, the values in each grid cell are computed as a weighted average with respect to the ECA. The Cloud Height Categories are:

- **ALL:** High, Medium and Low,
- **HIGH:** above 440mb,
- **MEDIUM:** from 440mb to 680mb, and
- **LOW:** below 680mb.

Figure 4 shows examples of Grid data for the experimental Cloud and Radiation products, illustrating (clockwise beginning upper left) the derived CTP, CTT, High-CTT[9], Clear-Sky LCR for the 1000mb to 700mb layer, OLR, and AVHRR channel 4. Very good agreement is observed. For example, the locations of high cloud correspond with lower CTP, CTT and AVHRR measurement values.

NESDIS also provides ECA summary tables (consistent with Menzel et al., 2001) on a daily basis which are generated from the Grid data. The ECA summary tables report the equal-area equivalent cloud percentage (%) for a given latitude band, averaged over all the grids for each Cloud Height category (see above), and the following ECA categories:

- **ALL:** Opaque, Thick, and Thin,
- **OPAQUE:** ECA greater than 90%,
- **THICK:** ECA 50% to 90%, and
- **THIN:** ECA less than 50%.

Separate ECA tables are provided for:

- 6 pre-defined latitude bands,
- two additional areas covering the continental U.S.,
- ascending and descending orbital nodes, and
- each operational satellite.

Table 1 provides examples of ECA summary tables for the 60N to 30N (upper) and 30N to the Equator (lower) latitude bands, respectfully, each a sub-sample of the region illustrated in Figure 4. The values in Table 1 are the daily average ECA for a given latitude band, cloud-height and thickness category. For example, on average, a given grid cell in the 60N to 30N band was 34.7% cloudy, with 18.8% covered by High clouds, 11.7% by Opaque clouds, and 8.0% by High, Opaque clouds on the given day.

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[9] Black areas (other than orbit gaps) denote areas of Medium and Low Clouds.

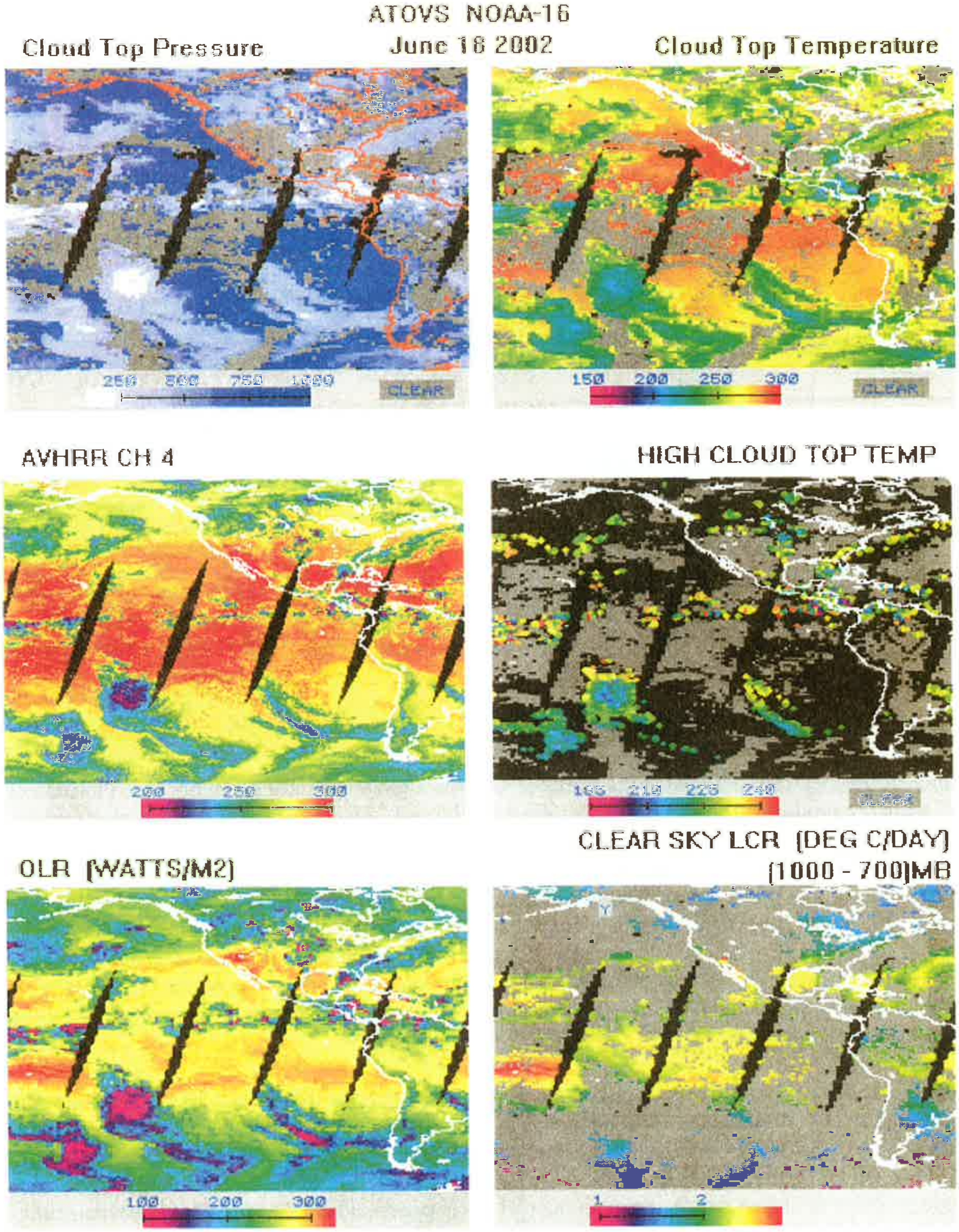

Figure 4: Experimental Cloud and Radiation Grid Products for NOAA-16, illustrating (clockwise beginning upper left) the derived CTP (mb), CTT (K), High-CTT (K), Clear Sky Layer Cooling Rate (LCR) for the 1000mb to 700mb layer, Outgoing Longwave Radiation (OLR), and AVHRR channel 4 radiance temperature (K) measurements.

ECA PERCENTAGES FOR (60N - 30N)

	ALL	HIGH	MED	LOW
ALL	34.7	18.8	6.2	9.7
OPAQUE	11.7	8.0	0.4	3.3
THICK	15.6	8.0	3.8	3.8
THIN	7.4	2.8	2.0	2.6

ECA PERCENTAGES FOR (30N - EQUATOR)

	ALL	HIGH	MED	LOW
ALL	36.0	30.0	2.8	3.2
OPAQUE	11.5	10.4	0.2	0.9
THICK	16.1	13.6	1.1	1.4
THIN	8.4	6.0	1.5	0.9

Table 1: **Examples of daily, Effective Cloud Amount (ECA) summary tables for the 60N to 30N (upper) and 30N to Equator (lower) regions showing the ECA for ALL, OPAQUE, THICK and THIN clouds distributed over ALL, HIGH, MEDIUM and LOW Clouds.**

4.5 Upper Level Moisture

An example of the impact of changes in the "Offline" extrapolation procedures for radiosonde moisture on "Orbital" moisture products is shown in the six panels of Figure 5. The upper four panels display (clockwise beginning upper left) AMSU-B channel 3 and HIRS/3 channel 12 radiance temperature measurements (K), both sensitive to upper tropospheric moisture, and corresponding 200mb derived moisture (g/kg) fields from NOAA-16 using the "New" and "Old" approaches for the upward extrapolation of radiosonde moisture. The spectral color scales below each panel denote the data ranges, notice that the 200mb moisture scales are identical and range from 0 to .25 (g/kg). The two lower panels of Figure 5 show examples of radiosonde significant level (Red) data for dew-point temperature (dashed) and temperature (solid), and the constructed radiosonde profiles (Blue) using the Old-constant dew-point depression (Left), and New-constant dew-point temperature (Right) for extrapolating upper level moisture.

As seen in Figure 5, the "New"approach retains the northerly decrease in the derived 200mb moisture across the mid-latitude and polar regions (as also supported by the corresponding sounder measurements displayed in the upper panels), compared to the increase in upper level moisture (progressing northward) using the "Old" method. This "orbital" difference is directly due to the "offline" revision of the method for extrapolating radiosonde moisture to 200mb, as illustrated in the two lower panels, where the "New" (Right) moisture profile shows a continued decrease in the upper level moisture, compared to the "Old" (Left) profile which shows increasing moisture aloft.

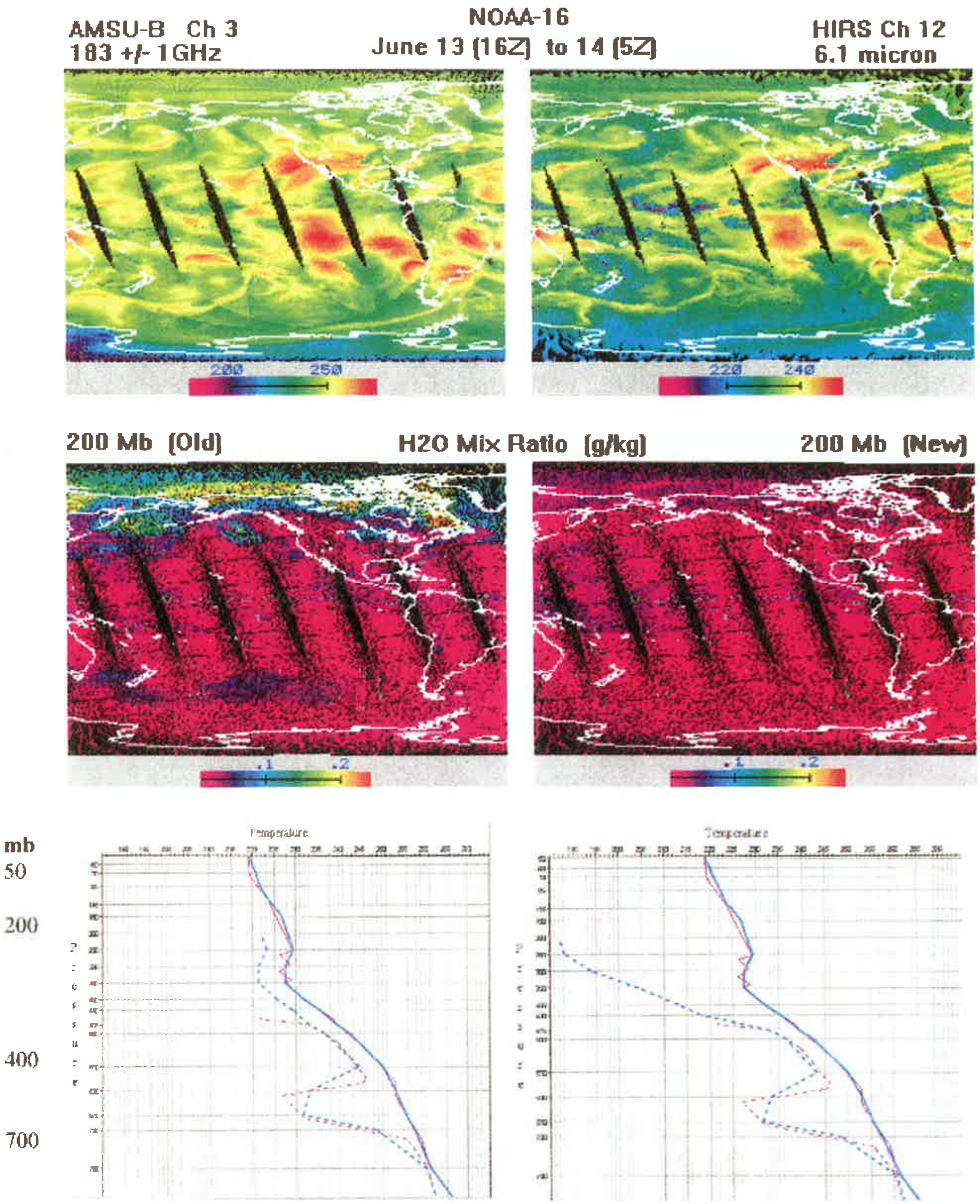

Figure 5: **AMSU-B (upper left) and HIRS (upper right) measurements (K) sensitive to upper tropospheric moisture, derived ATOVS water vapor mixing ratio (g/kg) at 200mb using the Old (middle left) and New (middle right) radiosonde extrapolation methods, and constructed (blue) radiosonde moisture (dashed) from significant level data (red) using the Old (lower left) New (lower right) extrapolation methods.**

5. THE GROUND TRUTH PROBLEM

Ever since the advent of NOAA polar satellite operational product and distribution systems in 1979, NESDIS has relied on collocated radiosonde and satellite observations for derived products validation. This has resulted in the continuous compilation of collocations on a daily basis, and the subsequent use of these data not only to validate products, but also as a source of information for deriving products and monitoring sounder performance.

The expanding use of satellite products in real-time weather and climate applications has also led to an expanding need to validate associated physical models used to interpret the satellite data, for example, atmospheric radiative transfer (Uddstrom and McMillin,1994a and 1994b), and to quantify inter-satellite measurement bias that may be contaminating the long-term record needed for climate (Chen et al., 2002). Unfortunately, and as discussed in the following sections, the deployment of reliable ground truth programs in support of polar satellite data platforms has not kept up with our growing use of these data for environmental monitoring, which appears to be compromising our ability to optimize their unique information content.

5.1 Collocated Radiosonde and Satellite Observation

Ground truth data, consisting of collocated radiosonde and satellite observations, are routinely compiled in support of the NESDIS sounding product systems, and play a critical role in the processing algorithms and validation for the operational products distributed by NESDIS (Reale, 2001, Tilley et al., 2000). One of the basic problems confronting NESDIS, which currently operates two polar satellites with a six-hour orbital separation, is to maintain consistent databases of collocations in support of each satellite. Unfortunately, since a majority of the radiosondes are taken at the 0Z and 12Z synoptic times, the collocation samples for each satellite tend to be mutually exclusive (particularly over land), a manifestation of the local overpass time and time windows[10] used for compiling collocations for each satellite.

The exclusive nature of the collocation samples for each satellite are illustrated in the three panels of Figure 6, which show 24-hour global distributions of collocations with NOAA-15 (Upper) and NOAA-16 (Lower), and the corresponding radiosonde observations that were available (Middle). Notice the differences in the spatial distributions for each satellite, particularly over land, where NOAA-16 samples are mainly from Western Europe and the U.S. West Coast, whereas NOAA-15 samples China and the U.S. East Coast. This underscores a basic need for considering at least a partial rededication of the radiosonde network to provide more consistent ground truth on a global scale in support of each operational satellite. Otherwise, the use of collocated radiosonde and satellite data for monitoring and validation can lead to satellite dependent bias.

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[10] Up to 3-hours over land and 4-hours over sea as specified later in Table 2.

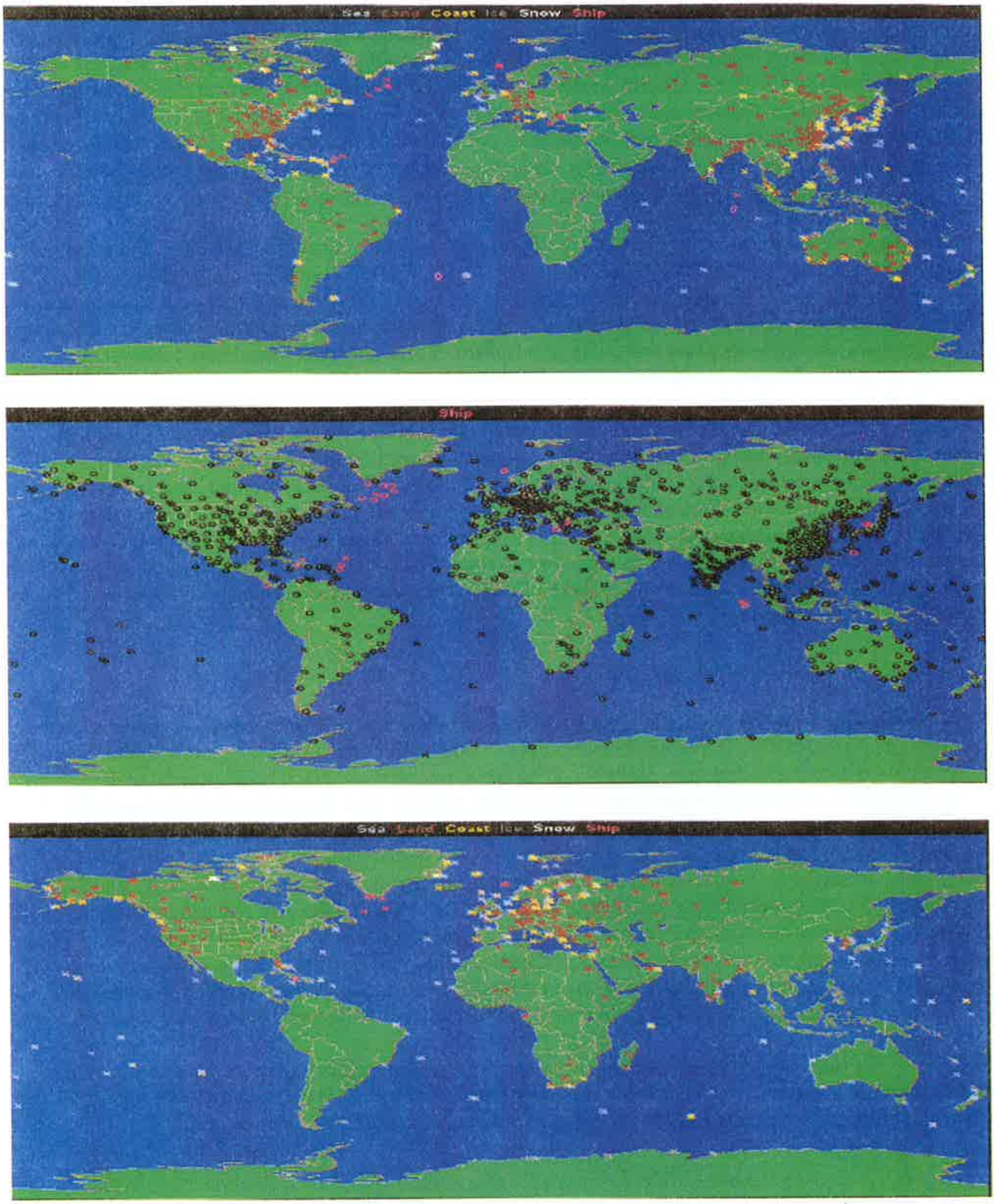

Figure 6: Daily distributions of MDB collocations for NOAA-15 (upper) and NOAA-16 (lower), and available Radiosondes (middle) as observed on July 28 and 29, 2002, with collocations color coded based on the sounding type (Blue, sea; Brown, land; Yellow, coast; Grey, ice; and White, snow), with Ship data in red.

5.2 Collocation Sampling Bias

The potential for satellite dependent bias using collocated radiosonde and satellite observations are seen through the two panels of Figure 7, which illustrate the use of the collocation data to compile accuracy statistics for NOAA-15 (left) and NOAA-16 (right) sounding products. Each panel shows vertical plots of the Mean and Standard Deviation of the Satellite minus Radiosonde differences for the satellite derived first guess (light) and final sounding (**heavy**) temperatures, with atmospheric pressure and sample size indicated on the left and right vertical axes, respectively. The collocations for computing each set of curves are from the 60N to 60S regions, for combined clear and cloudy satellite soundings over all terrains, covering a 7-day period in June 2002.

As can be seen, the curves shown in Figure 6 are very useful for estimating product accuracy, and also illustrate the convergent nature of the NESDIS retrieval approach, that is, the final soundings curves (heavy) show improved accuracy compared to the first guess. However the curves also suggest differences in the accuracy of NOAA-16 products versus NOAA-15, for example, a relatively warm bias for NOAA-15 near the surface, with other differences near the tropopause and in the stratosphere. These are much more likely a measure of sampling differences than any actual differences in accuracy.

It is the opinion of the authors that the lack of a dedicated global program to provide ground truth data in support of NOAA operational polar satellites has contributed (is contributing) a sizeable portion of the problems which have inhibited the validation (real-time and long-term) of polar satellite data, and ultimately their use in NWP and climate applications. Until such programs are in place, the NESDIS approach to utilize radiosonde data in its operational satellite systems is to minimize the impact of regional (spatial) and temporal (synoptic) discrepancies in the radiosonde sample when compiling collocations with each satellite. Some of the sampling and monitoring strategies employed by NESDIS to maintain balanced global samples of collocations for each satellite are discussed below.

5.3 Collocation Sampling Strategies

The collection of collocations maintained in support of each operational ATOVS system is referred to as the Matchup Data Base (MDB). The MDB contains about 15,000 collocations which are stratified into 23 geographical categories for clear and cloudy sounding types, respectively. Each MDB is updated daily, with approximately 75% overlap in samples from week to week, with the most recent data stored being about 12 hours old, and the oldest up to104 days old. The MDB is archived by the National Climatic Data Center.

Table 2 summarizes the collocation sampling parameters consisting of the 23 geographical (LAT and TERR) categories (CAT), the corresponding sample size allocations (SAMP), and the time (hr) and distance (km) windows for compiling the MDB collocations. As can be seen, separate sets of parameter values are defined for the clear and cloudy soundings from each operational satellite, respectively. As expected, the sample size allocations (SAMP), that is, the target sample size retained for each CAT[11], vary in proportion to the density of available radiosonde observations, with the radiosonde-dense categories having the smallest distance windows.

The time periods (Δt) spanned by the collocation sample (or age of the oldest collocation retained) in each category are also monitored. Notice that the corresponding differences in Δt across the 23 categories (and for each satellite) are more uniform than the sample sizes, which as discussed below is by design.

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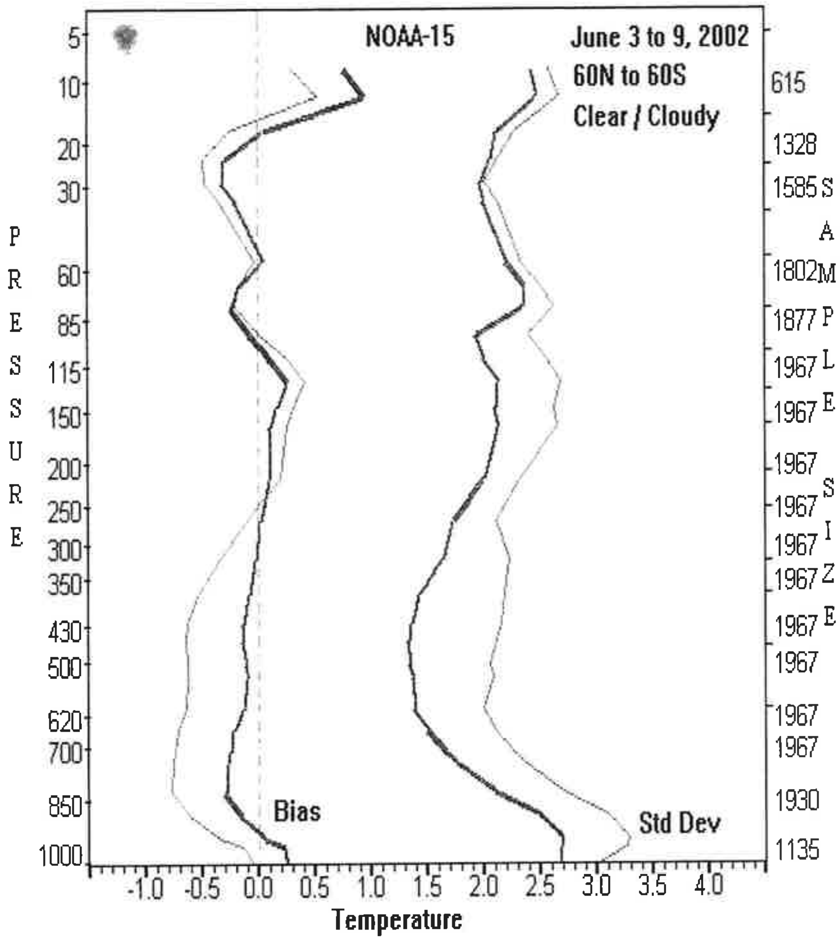
[11] The actual sample size for a given category equals SAMP unless Δt is 104 days, in which case the actual sample size is less than SAMP (as indicated in parenthesis).



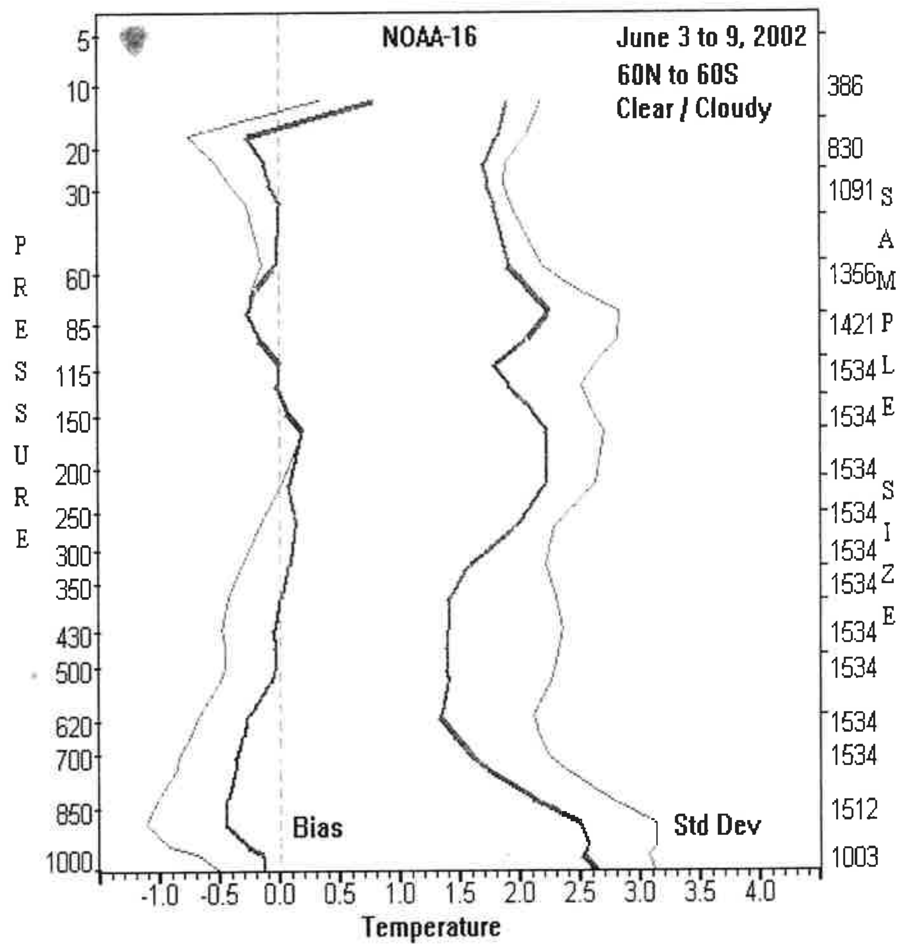


Figure 7: **Vertical accuracy statistics displaying the Mean Bias and Standard Deviation of ATOVS minus Radiosonde Temperature (K) profiles for NOAA-15 (left) and NOAA-16 (right) First Guess** (light) **and Sounding (dark), for combined Clear and Cloudy atmospheres, for the 60N to 60S latitude band over the period July 3-9, 2002, with pressure shown on the left axis and the sample size for each satellite on the right axis.**

CAT	LAT	TERR	NOAA-15 SAMP	NOAA-15 Clear (km)	NOAA-15 Clear (hr)	NOAA-15 Clear Δt	NOAA-15 Cloudy (km)	NOAA-15 Cloudy (hr)	NOAA-15 Cloudy Δt	NOAA-16 SAMP	NOAA-16 Clear (km)	NOAA-16 Clear (hr)	NOAA-16 Clear Δt	NOAA-16 Cloudy (km)	NOAA-16 Cloudy (hr)	NOAA-16 Cloudy Δt
	(Ascending, Descending)															
1	N	Ice/Coast	350	125	3	104 (200)	70	3	60	425	100	3	75	70	3	50
2	Ice-45N	Sea	650	80	4	40	80	4	55	600	70	4	40	70	4	35
3	45-30N	Sea	650	70	5	50	80	5	35	625	70	5	70	80	5	35
4	30-15N	Sea	650	80	5	70	90	5	55	525	80	5	60	90	5	35
5	15N-15S	All	650	50	3	40	50	3	35	550	90	3	55	60	3	35
6	15-30S	Sea	300	80	5	40	120	5	75	400	90	5	40	100	5	55
7	30-45S	Sea	300	110	5	60	110	5	70	300	100	5	70	100	5	70
8	45S-Ice	All	200	100	3	70	80	3	40	250	120	3	90	100	3	55
9	S	Ice/Coast	200	125	3	104 (10)	90	3	50	250	125	3	- (0)	80	3	50
	(Ascending)															
10	90-60N	Non-Sea	225	125	3	104 (210)	60	2	35	400	90	3	45	40	2	30
11	60-45N	Non-Sea	500	80	2	50	50	2	35	500	50	2	35	40	2	35
12	45-30N	Non-Sea	550	40	2	30	40	2	40	450	70	2	35	70	2	45
13	30-15N	Non-Sea	400	50	3	35	50	3	30	400	70	3	35	100	3	50
14	15-30S	Non-Sea	200	50	3	25	90	3	45	150	100	3	65	125	3	104 (110)
15	30-45S	Non-Sea	200	60	3	25	100	3	40	150	110	3	90	125	3	104 (120)
16	60-90S	Non-Sea	25	125	3	- (0)	125	2	- (0)	25	125	3	- (0)	125	2	- (0)
	(Descending)															
17	90-60N	Non-Sea	225	125	3	95	70	2	30	375	90	3	50	90	2	75
18	60-45N	Non-Sea	500	70	2	45	40	2	40	500	50	2	35	40	2	35
19	45-30N	Non-Sea	550	40	2	25	40	2	40	450	60	2	35	50	2	40
20	30-15N	Non-Sea	350	60	3	25	50	3	30	350	100	3	40	90	3	50
21	15-30S	Non-Sea	150	90	3	35	120	3	70	150	120	3	104 (90)	125	3	104 (75)
22	30-45S	Non-Sea	150	90	3	25	100	3	40	150	120	3	104 (100)	125	3	104 (80)
23	60-90S	Non-Sea	25	125	3	- (0)	125	2	- (0)	25	125	3	- (0)	125	2	- (0)

Table 2: **Sampling characteristics of the ATOVS Matchup Data Base (MDB) showing the geographical category (CAT) definitions (LAT and TERR), and the corresponding sample size allocations (SAMP), time (hr) and distance (km) windows, and the time periods (Δt) spanned by the collocation sample within each category. Data are segregated for each operational satellite (NOAA-15 and NOAA-16) and sounding type (Clear and Cloudy), and are a snapshot as observed in July 2002 (numbers in parentheses indicate actual sample size if different from "SAMP").**

Given that the global distribution of the collocation samples for each satellite (Figure 6) is exclusively pre-determined[12], particularly over land[13], sampling differences between corresponding CATegories for each satellite can be significant even though the sample sizes are the same. For example, Table 2 shows that the sample size per satellite for CAT-13 cloudy soundings is 400 collocations, however it only takes about 30 days to collect this sample for NOAA-15, whereas for NOAA-16 it takes 50 days, and this despite the fact that the distance window for NOAA-16 is larger. Subsequently, an evolving strategy at NESDIS for maintaining a balanced distribution of collocations is to try and minimize differences in "Δt," not only across the individual categories for a given satellite, but also between (among) corresponding categories for each satellite. This is achieved through the routine monitoring of "Δt" and the iterative adjustment of distance windows as required.

Figure 8 displays a diagnostic tool designed for monitoring seasonal changes in "Δt." The example shown is a 90-day trend plot (March through May 2002) of "Δt" for collocated radiosonde and NOAA-16 cloudy soundings from geographical categories 1 through 9. As can be seen, the drift in "Δt" over time for each category is variable, for example, in CAT-3 it varies from 55 to 90 days[14], whereas in CAT-1 it is relatively constant at about 40 days. Trend plots such as these are routinely monitored for operational satellites, and provide criteria for adjusting the sample size allocations and distance windows.

5.4 Recommendations

International coordination is needed to formally recognize and promote the very basic requirement for reliable ground truth observations in support of operational polar satellite data platforms. As a first step, it must be acknowledged that the optimal use of radiosondes is shifting (has shifted) from an initial requirement to provide "synoptic" observations primarily in support of NWP, to a more modern requirement to provide ground truth for validating the satellite data (and associated physical models) which are now providing a major component of the observations for NWP and climate applications. Such actions must be taken carefully, and in full consideration of ongoing, long-term climate records and lingering requirements for regional and local weather forecasts.

Several actions are also needed to improve the scientific integrity of the radiosonde data, for example with respect to moisture, and also the consistency of radiosonde reporting and transmission protocols across the global community. Although these issues have been addressed in the past, more work is needed to consolidate the identified problem areas and to take action.

NOAA can also pave the way toward harvesting the significant benefits of a coordinated effort to provide ground truth data for satellite observations over the vast ocean regions of the earth. The NOAA flagship scientific vessel, RONALD H BROWN (RHB), which typically operates for over 250 days a year, provides both a radiosonde launch and polar satellite data reception capabilities, along with other in-situ measurements (i.e., for clouds, SST, etc). The RHB represents a cost-effective and potentially valuable resource for remote ocean sensing, which could provide valuable real-time weather and climate research data, and greatly enhance our understanding of ocean-atmosphere interactions as portrayed by remote satellite observations.

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[12] As seen in Table 2, the time windows for collocations are the same for all satellites.

[13] Aside from regional and diurnal differences in cloudiness.

[14] Table 1 indicates the Δt reduces to about 35 days in July.

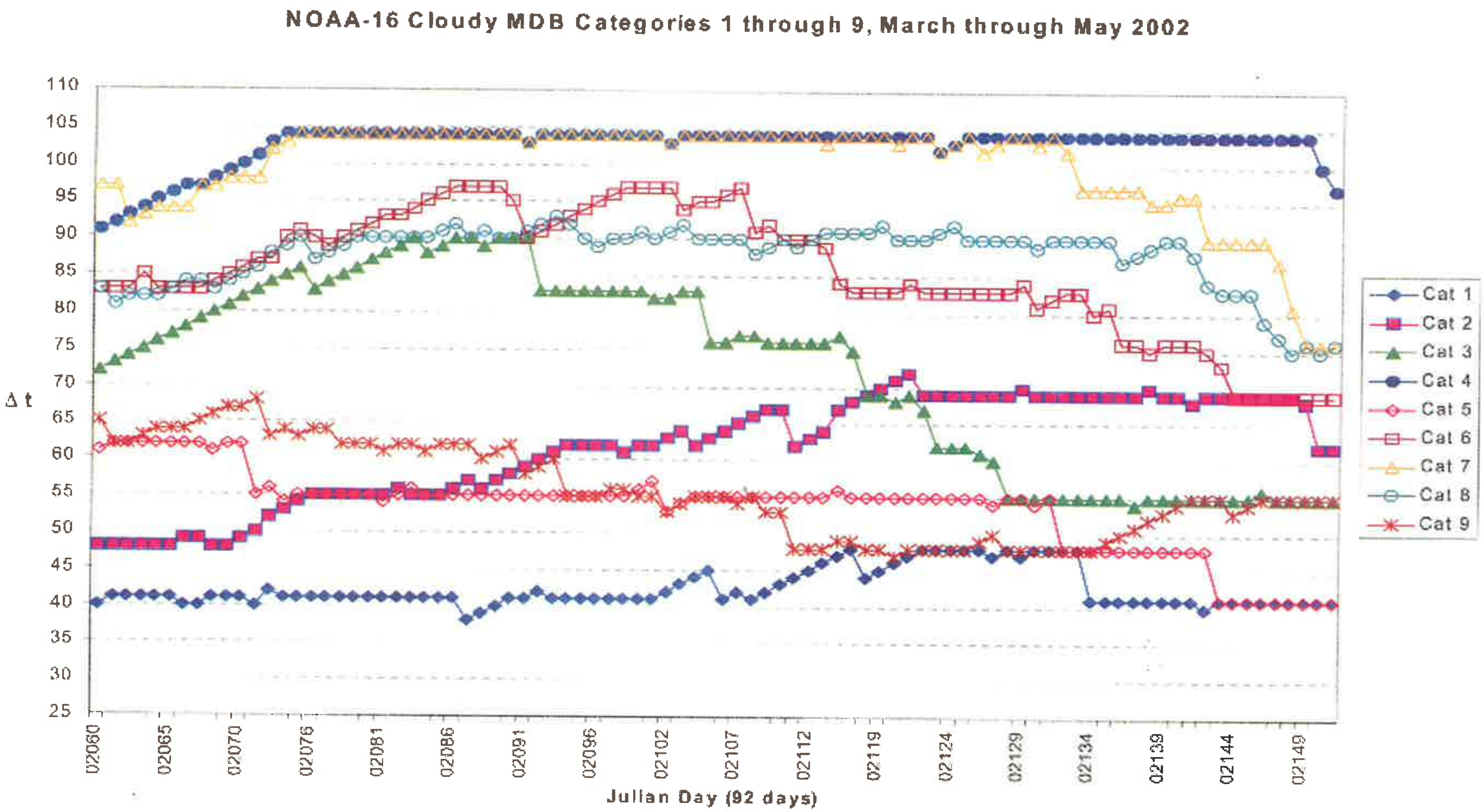

Figure 8: Trend plots (March through May 2002) of the time periods (Δt) spanned by the collocations in Categories (CAT) 1 through 9, for NOAA-16 cloudy soundings.

6. FUTURE PLANS

A new series of scientific upgrades for NESDIS derived sounding products are planned for ATOVS over the next 2 years. The ultimate goal of these upgrades is to provide sounding products that have error characteristics that can be more easily defined by potential NWP users, while remaining independent of any particular NWP model.

The new upgrades planned by NESDIS for ATOVS derived sounding products include:

- use of AMSU-B measurements for the simultaneous retrieval of temperature and moisture soundings,
- replacement of the library search technique for computing the first guess with an AMSU based statistical regression approach (Goldberg 1999),
- more direct use of radiative transfer (McMillin et al., 1995) methods to compute each sounding,
- the (radiance) bias adjustment of sounder measurements,
- a convergence of "common" technique's resident in NESDIS atmospheric and microwave surface product programs (Grody et al., 2001), and
- improved diagnostic capabilities to compile and evaluate collocations of Satellite, NWP and Radiosonde observations, including observed versus calculated sounder measurement statistics.

NESDIS will also be involved with the operational implementation of ATOVS products from NOAA-17 and the efforts to prepare for the METOP and NPOESS programs planned for 2005 and beyond.

7. SUMMARY

NESDIS provides routine sounding products from the ATOVS sounder data onboard the current NOAA-15 and NOAA-16 operational polar satellites. This report addresses the current scientific status and latest series of upgrades for the temperature and moisture soundings, and associated cloud, radiation, and ozone products which were deployed during 2001 and 2002. Results are presented which illustrate the scientific integrity of NESDIS weather products for analyzing global and regional scale weather systems, and their information content in the context of NWP. The report also discusses the requirement for ground truth radiosondes collocated with polar satellite observations to monitor, the use for monitoring and maintaining product (and instrument) performance, and problems using the current global radiosonde network to meet these requirements. The report concludes with future plans, consisting of the pending operational implementation of the NOAA-M satellite (successfully launched on June 24, 2002), and a new series of ATOVS upgrades to utilize AMSU-B data, replace the first guess approach, and more directly utilize radiative transfer models in the final retrieval step. A complete listing of ATOVS operational (and experimental) sounding products is given in Appendix A1.

8. ACKNOWLEDGMENTS

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APPENDIX A1

Appendix A1 provides a summary table of the current suite of ATOVS derived products operationally available from NESDIS. The Table A1 lists each of the **ATOVS Product** types in column 1, beginning with the radiometer/sounder measurements for each **AMSU-A, HIRS/3, AVHRR/3** and **AMSU-B**[15] channel, followed by the derived **Temperature** and **Moisture** soundings, **Outgoing Longwave Radiation (OLR)** and **Layer Cooling Rates (LCR)**, experimental **Cloud** products and **Total Ozone**. The **Units** of measurement, product **Levels (or Layers)**, the nominal (at nadir) **Horizontal Resolution** and additional **Comments** are tabulated for each Product.

Several items in Table A1 warrant further clarification. Although the sounder measurements are strictly speaking not considered a derived product, the **Calibrated** measurements, the series of radiometric **Adjustments**, and the **First Guess** measurement profiles computed in the NESDIS scientific algorithm have become a focal point of user interest over the past few years, along with the First Guess profiles from which the soundings are derived.

AVHRR channel measurements are available on selected operational files, comprised of the 17 Global Area Coverage (Goodrum et al., 2000) pixels corresponding to the HIRS/3 FOV.

Many users receive and utilize secondary derived products, that is, products derived from the temperature and moisture soundings. The secondary products routinely distributed by NESDIS include the **Geopotential** height, Layer Mean **Virtual** temperature and the Total and Layer Precipitable Water (**TPW** and **LPW**). Secondary sounding products are typically computed for the standard mandatory pressure levels.

Horizontal Resolution is a difficult parameter to define, particularly for the ATOVS sounders which are cross-track scanners with variable resolution from one side of the orbit to the other. In addition, the scientific processing techniques typically involve spatial interpolations of the sounder measurements (i.e., for ATOVS all measurements are interpolated to the HIRS). The values listed for the horizontal resolution represent estimates of nominal values (at nadir), typically **17km** for the HIRS, **50km** for the AMSU-A FOV (**15km** for AMSU-B), and **35km** for derived soundings.

1 x 1 Degree gridded **(GRID)** data sets are processed for several of the Radiation and Cloud products. Equal-area, cloud-amount summary tables are also generated from the Cloud GRID data.

All **Cloud** products are currently **Experimental** and under evaluation for pending operational approval. Grid data sets are also segregated by cloud Height (Low, Med., High).

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[15] AMSU-B measurements and derived sounding products are currently not available as part of the ATOVS product suites, but are available separately from NESDIS, with pending work underway to integrate these measurements into ATOVS.

ATOVS PRODUCT	UNIT	LEVELS (LAYERS)	HORIZONTAL RESOLUTION	COMMENTS
AMSU-A	K	15 Channels	50km	Calibrated, Adjusted, and First Guess
HIRS/3	K	20 Channels	17km	Calibrated, Adjusted, and First Guess
AVHRR/3	K	6 Channels	2.5km	17 pixels @ HIRS/3
AMSU-B	K	5 Channels	15km	(See footnote 15)
TEMPERATURE **Geopotential** **Virtual**	K m K	40 @ 1000 to .1mb (18 @ 1000 to .1mb) (18 @ 1000 to .1mb)	35km	Includes First Guess Secondary Secondary
MOISTURE: **ATOVS** **AMSU-B** **TPW** **LPW**	g/kg mm mm	 17@ 1000 to 200mb 15@ 1000 to 300mb (Total) (1000 to 700mb) (700 to 500mb) (500 to 300mb)	 35km 15km	Includes First Guess (See footnote 15) Secondary Secondary
OLR: **ALL SKY** **CLEAR SKY**	Watts / m2		17km, GRID	
CLEAR SKY LCR	K/day	(1000 to 700mb) (700 to 500mb) (500 to 300mb) (300 to 100mb)	17km, GRID	
CLOUD TOP: **PRESSURE** **TEMPERATURE** **CLOUD AMOUNT**	 mb K %	Low, > 680mb, Med, 440 to 680mb, High, < 440mb	 17km, 35km, and GRID	Experimental Opaque, > 90% Thick, 50 to 90% Thin, < 50%
OZONE	DOBSON	(TOTAL)	35km	

Table A1: NESDIS Operational (and Experimental) ATOVS Products.

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