1. **INTRODUCTION**

NOAA's contribution to the NOAA/NASA Pathfinder program (Ohring and Dodge, 1992) is the generation of first guess independent climate products. These products include cloud cleared radiances (McMillin and Dean, 1982), deep layer mean temperatures, relative moisture indicators (McMillin et al., 1995), total ozone (Neudorffer, 1995) and outgoing longwave radiation (Ellingson et al. 1989, 1994). Deep layer mean temperatures are to be generated from MSU only and combined HIRS and MSU measurements. The algorithm for deriving the MSU deep layer means can be found in Goldberg and Fleming (1995). The layer associated with the mean temperature is given by the derived averaging kernel.

A microwave only temperature product is very conducive for long term monitoring of temperature change for three basic reasons. First, the weighting functions are nearly invariant with changes in temperature or moisture; hence the averaging kernel remains relatively stable. Second, the effects of clouds on the signal are generally small. Third, radiance in the microwave region is approximately linear with temperature. It is the third reason that is very important because it results in a product that is independent of a first guess. This is because a temperature profile is not needed to linearize the Planck function within the radiative transfer equation. A study by Thompson and Tripputi, (1994) demonstrated that first guess errors are a) systematic, b) a function of atmospheric type, and c) are not entirely removed by the retrieval process. For long term monitoring the errors need to be random. The problem with systematic errors are that they are usually not known and therefore cannot be removed.

This paper will provide a methodology in which measurements of upwelling infrared radiation in the 15 and 4.6 micron bands by HIRS can be used to produce time series of deep layer mean temperatures. Because there are more infrared channels, the addition of these channels will yield narrower averaging kernels as well as to enable the monitoring of temperature in regions where the MSU is unable to detect. To use the infrared, one needs to 1) select only the channels for which weighting functions are largely invariant with temperature and moisture, 2) cloud clear channels that are affected by clouds, 3) linearize the nonlinear radiances directly and 4) use the linearize radiances to derive deep layer mean temperatures and their corresponding averaging kernels. The third step is needed so that the measurements can be combined without the need to linearize the Planck function, which would require a first guess profile. In other words, without step 3 the products would be first guess dependent. The emphasis of this paper is to develop the methodology and demonstrate the effectiveness of the third step.
2. LINEARIZATION OF THE PLANCK FUNCTION

As was mentioned in the introduction, we need to avoid Planck linearization in order to remove first guess dependency from the deep layer mean temperature product. Planck linearization is a well known stage in the retrieval process and is reviewed here to demonstrate its strong dependency on the first guess. A simplified form of the radiative transfer equation valid for the 15 and 4.6 micron infrared spectral regions is:

\[
R(\lambda) = \int B(\lambda, t(p)) \frac{dT(\lambda, p)}{dp} dp
\] (1)

In (1) \( R \) is the upwelling radiance at wavelength \( \lambda \), \( B \) is the Planck radiance at wavelength \( \lambda \) and temperature \( t \) at pressure \( p \), and \( \tau \) is the atmospheric transmittance for a given \( \lambda \) and \( p \). The term \( \frac{dT(\lambda, p)}{dp} \) is referred to as the Planck weighting function. The limits of integration are from the surface pressure to zero pressure. In (1) the atmosphere is a perfect blackbody (with no scattering or reflection) and the surface term has been omitted. For the purpose of this discussion we will assume that the measurements are governed exactly by (1). To produce a temperature product from measurements at different wavelengths (1) is linearized to the following form:

\[
T(\lambda) = \int I(p) \phi(p) \frac{dT(\lambda, p)}{dp} dp
\] (2)

where \( T \) is now brightness temperature and \( \phi(p) \) is the exact linearization factor which is given by:

\[
\phi(p) = \left[ B(\lambda, t(p))/t(p) \right] \left[ T(\lambda)/R(\lambda) \right]
\] (3)

For the microwave MSU channels, \( \phi(p) \) is essentially equal to 1 and hence can be ignored, however for infrared channels \( \phi(p) \) can differ significantly from unity. The added complication is that \( \phi(p) \) is a function of the atmospheric temperature profile, which is unknown. To illustrate this problem for the infrared, HIRS channels 15 (4.46 \( \mu \)m) and 16 (4.40 \( \mu \)m) Planck weighting functions for tropical (solid) and midlatitude (dashed) atmospheres are shown in plot B of Fig. 1. The temperature profiles are given in plot A. The Planck weighting functions are very similar for the two atmospheres which signify that the temperature and moisture dependence on atmospheric transmittance for these two channels is not an important issue. However, it is the temperature weighting function, i.e. the product of the Planck weighting function and the linearization factor, that is needed for the temperature retrieval. The temperature and Planck weighting functions are identical for the microwave, but can differ significantly for the infrared. In plot C of Fig. 1 the temperature weighting functions for the two channels and airmasses are shown. Clearly, the HIRS 15 and 16 temperature weighting functions are not similar for the two airmasses. They differ greatly because the atmospheric temperature profiles are quite different.
Hence the dependency on the first guess is quite large. Our approach to this problem is to adjust the nonlinear radiances so that the Planck weighting function is the temperature weighting function for the adjusted measurements. To yield a deep layer mean temperature associated with a fixed averaging kernel for all atmospheric conditions, the adjusted measurements need to be associated with a fixed set of Planck weighting functions. The methodology does not require a localized first guess. Details are given in the next section.

3. **LINEARIZING NONLINEAR RADIANCES - ALGORITHM AND RESULTS**

Physical retrieval methods, which explicitly use the radiative transfer equation, require some kind of correction to account for differences between measured and calculated radiances. The calculation of radiances from the radiative transfer equation is commonly referred to as the forward problem. Frequently forward problem calculations have biases because of incorrect or incomplete knowledge of the transmittance functions, or of the physical parameters used in their calculation, or other reasons. On the other hand, the measured radiances and radiance temperatures are subject to observational error, residual cloud contamination, and so forth. An effective method for compensating for these errors has been found to be shrinkage estimation (Fleming et al, 1990). Shrinkage estimation is a modified regression procedure in which the regression coefficient matrix is constrained by the identity matrix.

In this work, the shrinkage estimator is used to adjust calculated nonlinear radiances to "look like" calculated linear radiances for a fixed Planck weighting function. To compute a linear radiance, $\Phi(p)$ in (2) is set to unity and the transmittance is computed from a fixed atmosphere. The nonlinear radiance is computed using (1). Even though omitted in (1) and (2), the computations include the surface temp. The linear radiance is actually a temperature given in units of degrees Kelvin. The nonlinear radiances are converted to an equivalent temperature using the inverse of Planck's equation. From now on these quantities as referred to as linear and nonlinear radiance temperatures. To calculate the coefficient matrix of the shrinkage estimator to account only for the linearization problem, one only needs an a priori ensemble of temperature and moisture that is representative of all atmospheric situations from which linear and nonlinear radiance temperatures are computed. A set of coefficients can also be generated to also take into account the inherent differences, discussed above, between measured and computed radiance temperatures. This is accomplished by using a ensemble of coincidence observed nonlinear radiances and radiosonde data; the radiosonde data is used to calculate the linear radiance temperatures.

A global dataset containing radiosonde profiles for April, 1994 were used to generate shrinkage coefficients for the purpose of adjusting nonlinear calculated radiance temperatures to "look like" linear calculated radiance temperatures for a fixed Planck weighting function. In Fig. 2, the bias between the nonlinear and linear radiance temperatures are shown. As to be expected, the original bias for very
nonlinear channels (HIRS 13-16) is quite large. All of the channels noted in Fig. 2 are used as predictors. Fig. 3 shows the remaining standard error between the adjusted and the true linear radiance temperatures for each channel. The encouraging part is that after the correction is made, the standard error for most of the channels is similar to the 0.3 K noise used in the simulation of the nonlinear radiance temperatures. HIRS channel 7 is the only one with a relatively large standard error, and the reason is due to the dependency it has with water vapor. In other words, this channel is affected by moisture and consequently the use of a fixed weighting function results in a larger error. As a result, the adjusted channel 7 is not used in deriving the deep layer mean temperature. However it is an important predictor for reducing the residual in channel 6.

The adjustment coefficients were applied to an independent ensemble. The scatter between the original nonlinear measured radiance temperatures and calculated linear radiance temperatures for HIRS 16 is given in Fig. 4. The scatter between the adjusted nonlinear measurements and the linear calculated values for HIRS 16 is given in Fig. 5. In Fig. 4, the scatter for HIRS 16 agrees to the findings of Fig. 1a-c. The cluster of points protruding from the best line fit are tropical atmospheres. In Fig. 1c, the nonlinear temperature weighting function for the tropical atmosphere has a very small contribution from the stratosphere, therefore resulting in a much warmer temperature than its linear counterpart, which is based on the Planck weighting function. The adjusted values in Fig. 5 eliminates any sign of the protrusion, and demonstrates the definitude of the adjustment procedure.

4. DEEP LAYER MEAN TEMPERATURES FROM LINEARIZED RADIANCES

Once the nonlinear radiance temperatures have been adjusted to "look like" calculated linear radiance temperatures for a fixed Planck weighting function, the adjusted values can be combined into higher vertical resolution deep layer mean temperatures. The fixed Planck weighting functions for the HIRS 2, 6, 13, 16, and MSU 4 are given in Fig. 6a-b. The algorithm of Goldberg and Fleming (1995) can now be used to combine these weighting functions into narrower averaging kernels. An example of five deep layer mean temperature averaging kernels are given in Fig. 7. The one peaking at 50 mb uses HIRS channels 2 and 3 and MSU channel 4. The other averaging kernels peaks at 500, 700, 850 and 1000 mb and are linear combinations of every channel weighting function in Fig. 6a-b. The channel set used for linearizing the measurements and for deriving the deep layer means are generally the same. The one exception is HIRS channel 7. Channel 7 was used in the linearizing the channels for the tropospheric deep layer means, but was not used directly for determining their averaging kernels. Note that the coefficients derived for combining weighting functions into averaging kernels are applied to the adjusted measurements to yield the deep layer mean temperatures. The seven TOVS Pathfinder MSU averaging kernels from the Goldberg and Fleming paper are shown in Fig. 8 for comparison. To obtain the relatively sharp averaging kernels for the MSU, a linear combination of weighting functions from all view
Fig. 1 Plot A: tropical and mid latitude temperature profiles; Plot B: Planck weighting functions for HIRS channels 15 & 16; Plot C: temperature weighting functions for channels 15 & 16.

Fig. 2 Bias between linear and nonlinear radiance temperatures.

Fig 3. Standard error of adjusted nonlinear radiance temperatures.

Fig. 4 Scatter of the nonlinear and linear HIRS 16 radiance temperatures.

Fig. 5 Scatter of the adjusted nonlinear and linear HIRS 16 radiance temperatures.
Fig. 6a-b Fixed channel weighting functions used for deriving averaging kernels.

Fig. 7 HIRS/MSU deep layer temperature averaging kernels.

Fig. 8 MSU averaging kernels.
angles was necessary. Hence the spatial size of the product from the MSU is quite large. Because HIRS provides many more channels, combining observations from different angles are not needed. Each angle will need its own set of linearization and deep layer mean temperature coefficients, so that the change in shape of a given averaging kernel as a function of angle will be negligible.

The procedures described above to generate linearized radiances and deep layer temperatures from HIRS and MSU radiances will be eventually applied to the entire 1979 - present TOVS archive, from which time series of temperature anomalies will be derived. The above procedures were tested by applying the algorithm to a five year time series of NOAA-10 radiosonde and satellite collocations for the latitude band +− 30 degrees. The 700 mb peaking averaging kernel given in Fig 7. were used to weight the radiosonde temperature profiles to yield simulated radiosonde deep layer means. The observed radiance temperatures were linearized and combined to yield the TOVS deep layer means. Shown in Fig. 9 are the radiosonde and TOVS deep layer mean temperature anomalies for climatological fall, winter, spring and summer. There is general agreement between the two sets of anomalies; the standard error is .10 K. Spencer et al. (1990) using a lower tropospheric MSU averaging kernel conducted a similar comparison. Their standard error for the tropics was .11 K.

5. SUMMARY

A procedure for deriving deep layer temperatures from infrared measurements has been developed. Because temperature and radianc are nonlinear, the infrared measurements need to be linearized before being combined into deep layer temperatures. With the exception of an ensemble of temperature and moisture profiles to compute the linearization coefficients, the algorithm is independent of any other ancillary information. All coefficients remain fixed for each satellite archive. Unlike traditional retrieval algorithms, the algorithm does not require a first guess of the ambient situation. This is a very desirable trait, since first guess errors are not random; it introduces unknown biases in a long time series of temperature change. The addition of infrared channels will provide layer temperatures that are associated with narrower averaging kernels and higher horizontal resolution.

6. REFERENCES


Neundorffer, A.C. 1995: Ozone monitoring with TIROS-N Operational Vertical Sounders (TOVS), accepted by J. Geophysical Review.


Fig. 9 Anomalies for radisonde and observed HIRS/MSU deep layer mean temperature centered at 700 mb for +/- 30 degrees latitude.

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