Tests of a Procedure for Inserting Satellite Radiance Measurements into a Numerical Circulation Model

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18 April 1972

A number of iterative techniques have been developed in recent years for retrieving vertical temperature profiles from satellite radiance measurements (e.g., Smith, 1968; Chahine, 1968; Conrath, 1969). Although these methods differ in details, all require the specification of an initial guess of the temperature distribution. This guess is inserted into the radiative transfer equation to calculate a set of radiances which is compared with the set of measured radiances. Based on this comparison, a correction is made to the "initial-guess" temperature profile.

We have developed an iterative technique for solving the integral equation of radiative transfer, similar to the one developed by Chahine (1968), but incorporating a modification suggested by Smith (1970). Chahine's method retrieved temperatures at a number of pressure levels equal to the number of channels in which radiance measurements are made, with temperatures at intermediate levels being obtained by interpolation. Smith modified this approach to allow direct solution for the temperature at any desired number of pressure levels. Also, Smith considered the difference between observed and calculated radiances as an indication of the correction to be applied to the temperature, while Chahine used the ratio of these radiances.

Like Chahine (1970) we use an iterative equation of the form

$$T^{n+1}(p_j)=c_2\nu_j \Big/ \ln\left\{1+\frac{I_{\nu_j}{}^n}{I_{\nu_j}{}'}\{\exp[c_2\nu_j/T^n(p_j)]-1\}\right\},$$

where $T^{n+1}(p_j)$ and $T^n(p_j)$ are the nth and $(n+1)$st estimates of the temperature at pressure level p_j, based on the measured radiance $I_{\nu_j}{}'$ in the jth channel, $I_{\nu_j}{}^n$ is the nth approximation to $I_{\nu_j}{}'$, calculated from the nth estimate of the temperature profile, ν_j is the central frequency of the jth channel, and c_2 is the second radiation constant.

Like Smith (1970) we obtain an $(n+1)$st estimate of the temperature at any pressure p, by weighting the j values $T^{n+1}(p_j)$ using the equation

$$T^{n+1}(p)=\sum_{i=1}^{j} T^{n+1}(p_i)W_i(p)/\sum_{i=1}^{j} W_i(p),$$

where $W_j(p)$ is the weighting function of the jth channel, evaluated at the desired pressure. A complete description of the present technique is being prepared for publication.

The present note reports on experiments designed to test the sensitivity of our retrieval method to the initial guess. We are particularly interested in initial guesses of the kind that would be provided by a numerical model of the atmospheric circulation, the objective being to develop a procedure for direct use of satellite radiation measurements as input to a numerical forecasting scheme. We have also used our method to simulate the complete procedure for inserting satellite radiance data into a circulation model to generate temperatures, pressures and winds. The simulation was based on the scan pattern and field of view of the VTPR sounder, scheduled for flight on the polar-orbiting ITOS-D satellite in 1972.

The tests were performed for a clear dry atmosphere, to avoid the complicating effects of water vapor and clouds. Weighting functions were computed in the 15 μ CO_2 band from the line data of Drayson and Young (1967), adopting a constant line half-width of 0.08 cm^{-1} at STP, and assuming a Lorentz line profile. The weighting functions were calculated for an isothermal atmosphere at 250K, in seven 5 cm^{-1} wide spectral channels, centered on wavenumbers 668.7, 679.8, 692.0, 701.0, 709.0, 734.0 and 750.0. The temperature dependence of the weighting functions was neglected in carrying out the experiments described here. Our procedure was to (i) specify a "correct" temperature profile, (ii) compute the corresponding radiances, and assume these to be the measurements yielded by the satellite-borne instrument, and (iii) invert the set of "measured" radiances, starting from a "guessed" temperature profile, different from the "correct" one.

Our experiments indicate that, in general, accurate retrievals are obtained for cases in which the initial guess is smooth and its shape bears some resemblance to the shape of the "correct" profile. We find that the particular case of the isothermal guess, although its shape does not resemble the correct shape, also produces good retrievals, which are insensitive to the isothermal

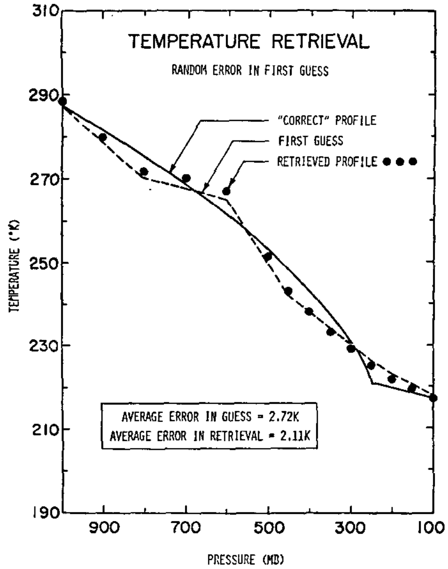

FIG. 1. "Correct," first guess, and retrieved profiles, for a case in which the guess contains random errors only.

value. Similar results were found by Smith (1968) and Chahine (1968).

However, these types of tests, using a smooth "guess", are not realistic for the case in which the retrieval method is to be combined with the use of a numerical circulation model. In that case, the initial guess is likely to have a "zig-zag" appearance because of the limited vertical resolution of the model. We have carried out tests with a "zig-zag" initial guess, and find that the retrieval method does not eliminate the "zig-zag" variations in the profile. For this guess the final result has a substantial error roughly equal to the average scatter of the points in the initial guess.

The explanation for the relatively poor result of the retrieval method in this case lies in the fact that the vertical resolution of the temperature profiles obtainable from infrared sounders is limited by both the considerable half-width and the extensive overlap of the atmospheric weighting functions. Due to these factors, the radiance measurements contain an inherent redundancy, and do not provide as many independent pieces of information as the number of measurements (spectral channels) would imply. As a result, only a few independent pieces of information on the temperature profile in the troposphere can be recovered from infrared radiance measurements. If a guessed profile contains features which cannot be resolved by the atmospheric weighting functions, such as the "zig-zags" mentioned above, these features will persist throughout the inversion procedure, eventually appearing in the retrieved profile.

This effect is illustrated in Fig. 1. In the experiment to which this figure corresponds, a "zig-zag" temperature distribution straddling the "correct" profile (Standard Atmosphere), with a maximum departure of about 5K, was used as the initial guess. Such a guess simulates an operational situation in which a guessed profile generated by the circulation model is similar to the "correct" profile, except for the presence of scatter in the model profile used as the guess. In this case, the retrieved profile is actually less accurate at some levels than the guessed profile.

In general, the guess provided by the general circulation model will have both systematic and random departures from the "correct" profile. To simulate this case, a "zig-zag" profile colder on the average by about 5K than the "correct" profile (Standard Atmosphere) was used as the guess. Although the systematic error of 5K in this guess is removed by the retrieval procedure, the random departures persist as in the previous case, so that the retrieved profile has the same "zig-zag" appearance as the guess, and, as a result, has a substantial mean error (Fig. 2).

The failure of the retrieval procedure to remove random errors from the guessed profile must be taken into account in the application of satellite radiance measurements to numerical forecasting. Although the natural source for the first guess in such applications is the numerical model itself, direct use of the model temperature profile as a guess can lead to substantial errors in the retrieved temperatures.

However, a considerable gain in retrieval accuracy can be achieved by smoothing the model-generated guess before it is used in the inversion procedure. In the experiment to which Fig. 3 corresponds, a smooth curve of the form $T=ap^b$ was fitted by least-squares to the segment of the "zig-zag" profile below the 300-mb level, that was used as a guess in the case depicted in Fig. 2. The smoothed curve was then used as the first guess. For this guess, the retrieved temperatures are found to be close to the "correct" temperatures at all levels.

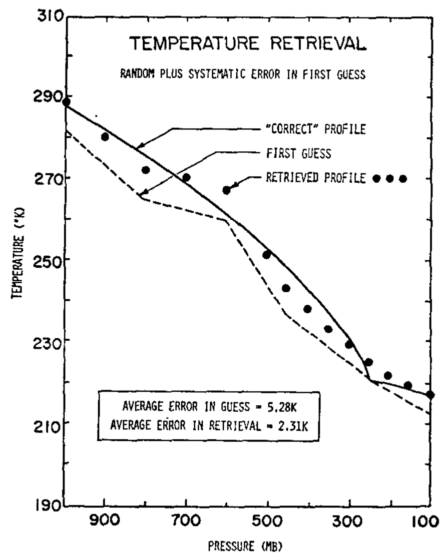

FIG. 2. "Correct," first guess, and retrieved profiles, for a case in which the guess contains both random and systematic errors.

The present retrieval method, including the smoothing technique, has also been applied to a complete simulation of the procedure for using VTPR soundings from the ITOS-D satellite in a general circulation model. In this study, the scheme was used in conjunction with a 5-level circulation model modified from the UCLA 2-level model (Mintz *et al.*, 1968). The horizontal resolution of the model was 400 km. The model was run out for a number of days from an available initial condition to generate a sequence of states assumed to describe the "real" atmosphere. For these "real" states, outgoing radiances were calculated globally, at 12-hr intervals, to simulate the coverage provided by the VTPR sounder. Jastrow and Halem[1] have verified that the synoptic insertion of temperature data has the same effect as asynotpic insertion, provided the same volume of data per day are inserted in both cases. The simulated sounder was assumed to have the field of view and scan pattern of the VTPR. However, the radiance measurements were made in the seven channels defined above, which differ somewhat from the VTPR channels. Random errors of a magnitude obtainable by the averaging of independent areal measurements made by the VTPR were included for each channel. It was assumed that the basic noise level of the instrument was 0.25 erg cm^{-2} sec^{-1} $ster^{-1}$ cm^{-1} for each independent measurement, that 50 soundings would be made every 12 hr within each 400 km$\times$400 km grid area of the dynamical model, and that 10 of the 50 soundings would be free of clouds, reducing the noise level after averaging the clear-column radiances to 0.075 erg cm^{-2} sec^{-1} $ster^{-1}$ cm^{-1}.

Temperatures were retrieved from the simulated radiances at 12-hr intervals, using smoothed temperature profiles generated by the model as initial guesses. These temperatures were inserted into the dynamical model at 12-hr intervals. Also, following a technique developed by Jastrow and Halem (private communication), temperature fields linearly intepolated from the observed fields were inserted at 3-hr intervals to obtain better control of error growth in the model. The procedure for carrying out the remainder of the simulation study was as described by Jastrow and Halem (1970).

The wind errors produced by the insertion of retrieved temperatures into the circulation model are shown in Curve A of Fig. 4. These wind errors correspond to means of the global rms zonal and meridional wind errors. The mean wind error for this case, averaged vertically, is 3.1 m sec^{-1}. The average error in pressure resulting from the same retrieved temperature insertion is 2.3 mb. Curve B shows the result obtained by inserting exact temperatures into the model, with the remainder of the procedure unchanged. The vertically averaged wind error in this case is 2.5 m sec^{-1}, with a mean error in pressure of 2.2 mb. The difference between curves A and B shows the combined effect of the simulated errors in the radiance measurements and the basic inaccuracy of the retrieval method which arises from the half-width and overlap of the weighting functions.

[1] Paper presented at the 1971 Princeton Conference on Four-Dimensional Data Assimilation.

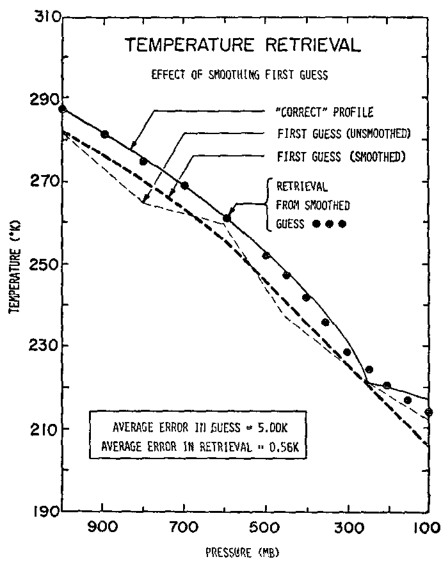

Fig. 3. "Correct," first guess, and retrieved profiles, for a case in which random errors are removed by smoothing.

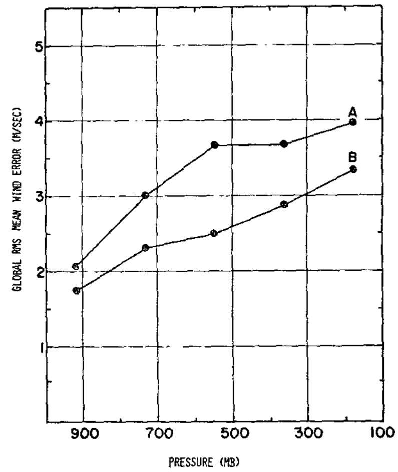

Fig. 4. Profiles of global rms mean wind errors produced by insertion of temperature data. The values shown were obtained by averaging zonal and meridional rms wind errors. Curve A indicates wind errors obtained by inserting simulated temperature data from the VTPR observations. Curve B indicates wind errors obtained by inserting exact temperature data.

REFERENCES

Chahine, M. T., 1968: Determination of the temperature profile in an atmosphere from its outgoing radiance. *J. Opt. Soc. Amer.*, **58**, 1634–1637.

——, 1970: Inverse problems in radiative transfer: Determination of atmospheric parameters. *J. Atmos. Sci.*, **27**, 960–967.

Conrath, B., 1969: On the estimation of relative humidity profiles from medium resolution infrared spectra obtained from a satellite. *J. Geophys. Res.*, **74**, 3347–3361.

Drayson, S. R., and C. Young, 1967: The frequencies and intensities of carbon dioxide absorption lines between 12 and 18 microns. Rept. 08183-1-1, High Altitude Engineering Laboratory, University of Michigan.

Jastrow, R., and M. Halem, 1970. Simulation studies related to GARP. *Bull. Amer. Meteor. Soc.*, **51**, 490–513.

Mintz, Y., A. Arakawa and A. Katayama, 1968: Numerical simulation of the general circulation of the atmosphere. *Proc. WMO/IUGG Symp. Numerical Weather Prediction*, Tokyo, IU-7-IV, 8–12.

Smith, W., 1968: An improved method for calculating tropospheric temperature and moisture from satellite radiometer measurements. *Mon. Wea. Rev.*, **96**, 387–396.

——, 1970: Iterative solution of the radiative transfer equation for the temperature and absorbing gas profile of an atmosphere. *Appl. Opt.*, **9**, 1993–1999.