NOTES

Limb Effects in Satellite Temperature Sounding

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ABSTRACT

To date, operational satellite temperature retrievals from the TIROS-N/NOAA A–G series of satellites and a large percentage of those produced for research purposes have used statistical techniques to estimate limb effects in satellite-observed radiances. In this study, temperature profiles were derived using the radiative transfer equation in a form which properly takes into account the angle of observation. These temperature profiles were then compared to those derived using the radiative transfer equation with "nadir radiances" produced by a statistical limb correction technique similar to those now used operationally. This comparison revealed significant differences in the derived temperature profiles at large viewing angles, particularly in the case of strong meridional temperature gradients. Overall, the results suggest that for the calculation of temperature profiles from nonnadir observations, the more proper physical solution is the preferred procedure for deriving temperature fields.

1. Introduction

During the First International TOVS Study Conference at Igls, Austria in 1983, stress was put on the use of physically-based rather than empirical algorithms in future temperature retrieval procedures (Menzel and Lynch, 1983). In this spirit and also because of the widespread operational use of statistically limb-corrected data (e.g., Smith *et al.*, 1979; Kelly *et al.*, 1983), a study was undertaken to gauge the differences between temperature soundings generated from a full physical solution of the radiative transfer equation taking into account slant path (e.g., Smith *et al.*, 1983; Susskind *et al.*, 1984), and those derived using a statistical correction to the slant path radiances followed by a physical solution of a nadir form of the radiative transfer equation.

Two adjacent orbits starting at 1200 and 1340 GMT on 4 March 1982 were used for the study. These were chosen because they had been extensively studied at the First International TOVS Study Conference, they overlaid an area with a good conventional data base and, most importantly, they exhibited a strong meridional temperature gradient. This strong gradient provided a means of examining any loss of information as a result of the limb modeling procedures.

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2. The retrieval technique

The retrieval technique used with both the statistically limb-corrected and nonlimb-corrected data produces temperature, moisture and ozone profiles which are a full solution of the radiative transfer equation,

$$R(\nu_j, \vartheta) = B(\nu_j, T_S)\tau(\nu_j, p_s, \vartheta) - \int_0^{p_s} B(\nu_j, T)\frac{\partial\tau(\nu_j, p, \vartheta)}{\partial \ln p}\frac{dp}{p},$$

where R is the mean spectral radiance measured in a channel whose mean effective wavenumber is ν_j and the local zenith angle of the observation is ϑ, B is the Planck radiance associated with temperature T, τ is the transmittance of the atmosphere above pressure level p, and the s subscript denotes the surface. The solution methodology is described in detail in Smith *et al.* (1983). Briefly, the physical retrieval algorithm solves for a departure of the true atmospheric temperature, moisture, and ozone profile from a "guess" condition, as a function of the departure of observed radiances from those calculated for the guess profile. In this study a climatological first guess was used. Surface air temperature and a surface pressure derived from conventional surface data were used to constrain the lowest levels of the soundings.

3. The limb correction techniques

a. Statistical

The statistical limb correction technique is similar to that used operationally (Werbowetski, 1981) and was of the form used in the First TOVS Export Package. The statistical limb correction coefficients, which are applied to non-nadir radiance observations to give nadir radiances, were generated using synthetic radiance data in a manner described by Smith *et al.* (1974). A global representation of 100 temperature and water vapor mixing ratio profiles was used to generate synthetic radiances and brightness temperatures at nadir and non-nadir angles. In the case of High-resolution Infra-Red Sounder (HIRS) observations, each profile was used with a variety of cloud heights and amounts to produce the radiances. For the Microwave Sounding Unit (MSU) data, although land and water surfaces are treated separately, hybrid samples were used for every fifth profile and one in ten soundings over land had randomly introduced precipitating clouds. In addition, the effect of sidelobes and emissivity was removed from the nadir MSU radiances. Limb brightness temperature correction coefficients were then computed using stepwise multiple linear regression, with the differences between the vertical path and slant path synthetic data being predictands and the product of the synthetic non-nadir channel brightness temperature and secant of

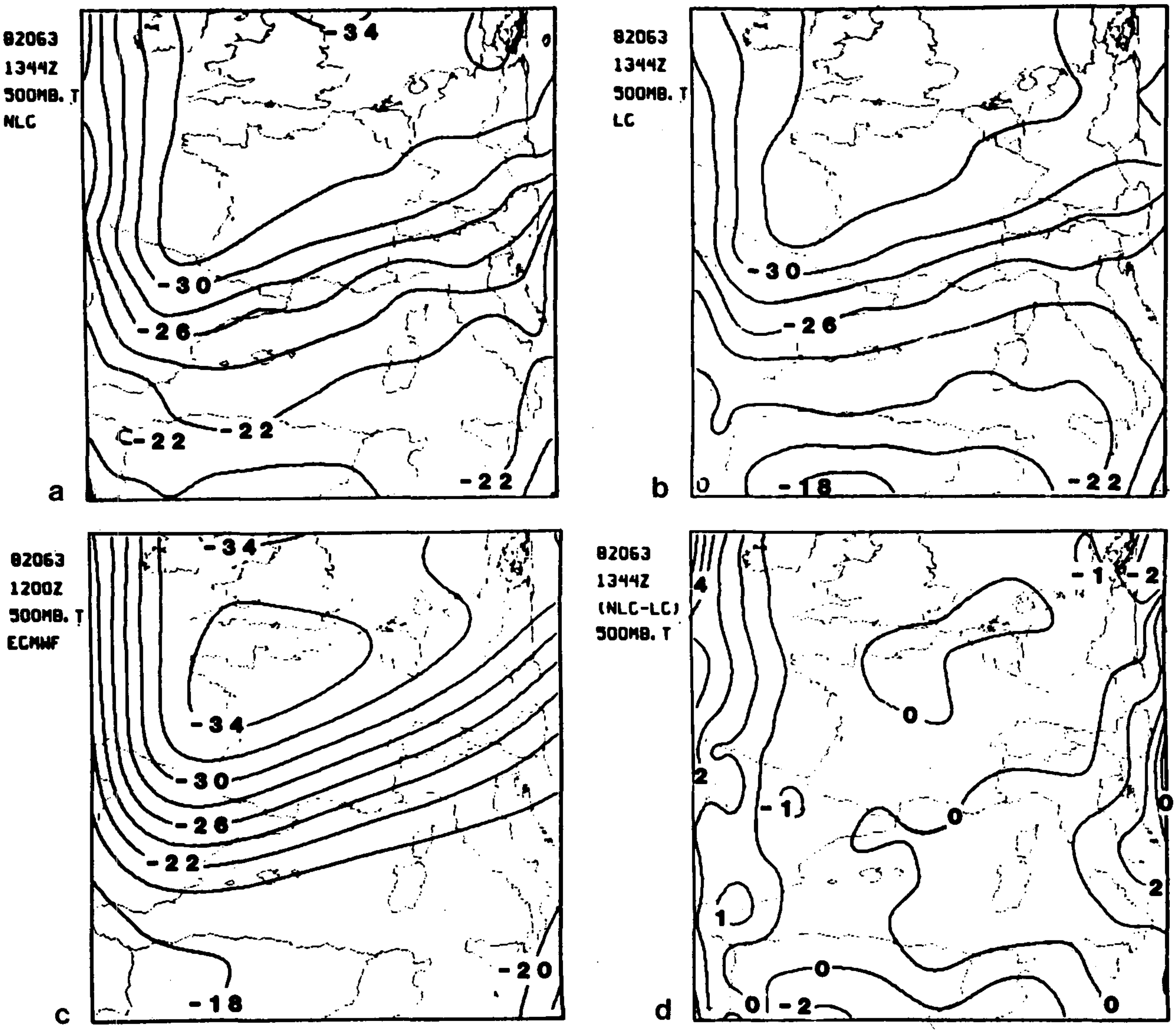

FIG. 1. 500 mb temperature analysis at 1344 GMT 4 March 1982 derived using: (a) observed radiances (NLC) and the full physical retrieval technique; (b) using statistically limb-corrected radiances (LC). (c) 500 mb temperature analysis from ECMWF for 1200 GMT 4 March 1982. (d) Differences in 500 mb temperature between nonlimb-corrected (NLC) and statistically limb-corrected (LC) retrievals.

the local zenith angle as well as the secant itself being predictors.

b. Physical

The radiative transfer equation was used with nonlimb-corrected data to generate temperature profiles by utilizing a computationally efficient transmittance model which provided transmittances appropriate for the atmospheric path at the angle of observation. The model algorithm is similar to that described by McMillin and Fleming (1976). For the MSU transmittances, the effects of side lobes on the transmittances were computed by a regression technique rather than by using the costly computational process of convoluting the antenna gain pattern with transmittances for a number of angles (Smith *et al.*, 1983).

4. The retrievals

As previously described, the test orbits were processed using statistically limb-corrected radiances and nonnadir radiances in conjunction with transmittances appropriate to a slant path. The temperatures were then analyzed at standard levels using the Barnes analysis scheme (Barnes, 1973). The analyzed 500 mb temperature fields, their differences and the corresponding archived field from the European Center for Medium Range Weather Forecasts (ECMWF) are shown in Fig. 1. It can be seen that the thermal gradients in the satellite only and ECMWF analyses show good agreement, although a bias of 1.5 degrees at 500 mb is evident for these orbits (Smith *et al.*, 1983). An examination of the western edge of the 1340 GMT orbit reveals that the strong thermal gradient region has been best depicted by the full physical scheme. The differences between the two satellite analyses show little deviation in the center and become quite significant at larger angles. The differences at 700 and 250 mb are shown in Fig. 2. Again, the differences increase at the edge and the large differences appear more frequently as one moves from 250 to 700 mb. The satellite analyses also show a difference over northern Africa where we believe the statistical limb correction to be less reliable because of extreme surface conditions. The distribution of differences was found to be similar for the eastern orbit.

The analyzed temperature fields were compared to the 1200 GMT radiosonde data. The differences in the root-mean-square error and the standard error between the statistically limb-corrected (LC) and nonlimb-corrected (NLC) fields (LC − NLC) are shown in Fig. 3. In general, both the rms error and standard error are reduced by using the full physical scheme. At the lowest levels the differences are small, partially as a result of surface temperature and pressure constraints on the solution at those levels, while for the rest of the levels a positive impact is the result of the full physical retrieval scheme.

5. Conclusions

It has been shown in this study that there appear to be systematic differences between soundings generated from the statistically limb-corrected data using a scheme similar to that now used operationally and those generated using transmittance functions appropriate to the angle of view. These differences can be significant at larger viewing angles. It appears from the sample examined that physical retrievals that account for the angle of view explicitly are more realistic and appear to better maintain temperature gradients in the limb. Overall, it would appear that

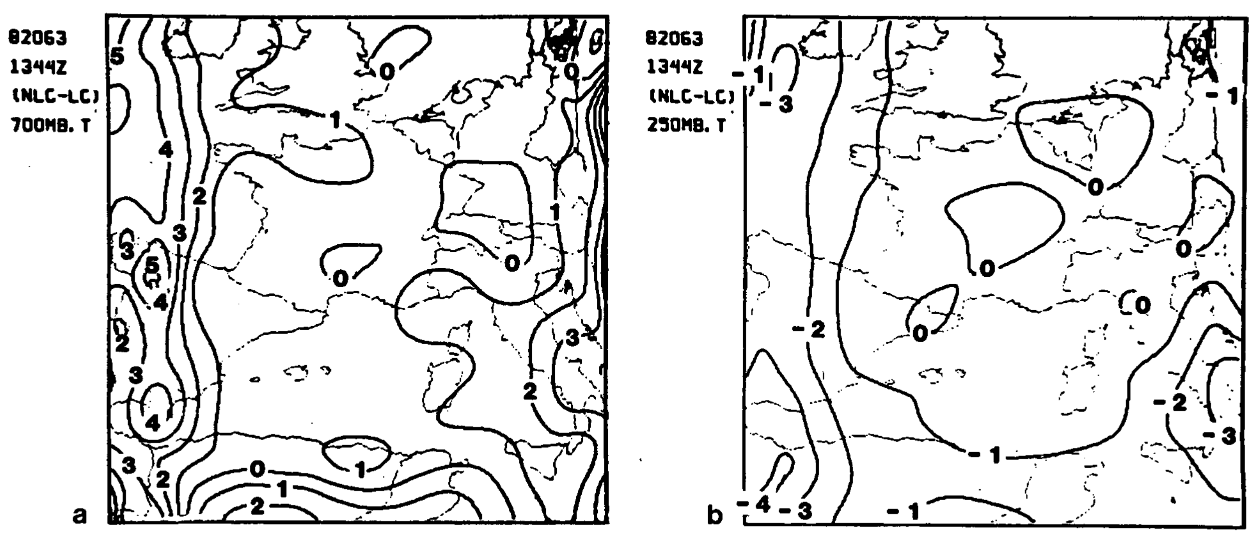

FIG. 2. Differences (a) in 700 and in (b) 250 mb temperature between nonlimb-corrected (NLC) and statistically limb-corrected (LC) retrievals.

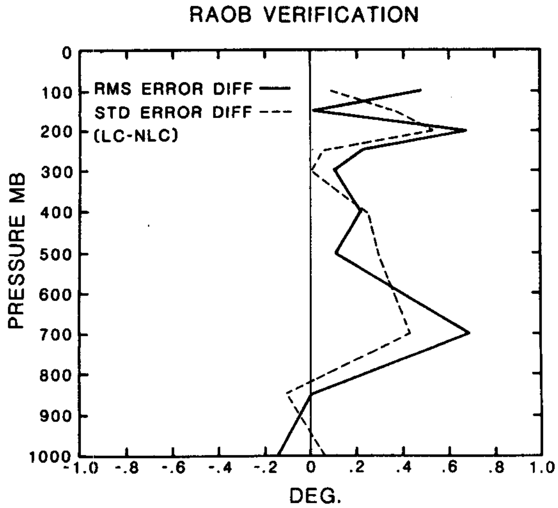

FIG. 3. Differences in rms and standard error compared to radiosondes between statistically limb-corrected (LC) and nonlimb-corrected (NLC) retrievals.

the physical modeling of limb effects in the transmittance terms of the radiative transfer equation is the preferred method for temperature retrieval. Some of the weaknesses in using the common statistical correction scheme in conjunction with a statistical retrieval technique may be ameliorated by removing the effects of cloud before limb correction and by applying a smaller limb correction to a number of different viewing angles at which statistical retrievals are performed.

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REFERENCES

Barnes, S. L., 1973: Mesoscale objective analysis using weighted time series observations. NOAA Tech. ERL NSSL-62, 60 pp.

Kelly, G. A., B. W. Forgan, P. E. Powers, J. F. LeMarshall, M. Hassett and B. O'Connor; 1983: A satellite based operational system for upper air analysis in the Australian Region. *Remote Sens. Environ.* **13,** 369–390.

McMillin, L. M., and H. E. Fleming, 1976: Atmospheric transmittance of an absorbing gas: A computationally fast and accurate transmittance model for gases with constant mixing ratios in homogeneous atmospheres. *Appl. Opt.,* **15,** 358–363.

Menzel, W. P., and M. J. Lynch, Eds., 1983: A Report on The First International TOVS Study Conference, The Cooperative Institute for Meteorological Satellite Studies, Madison, 32 pp.

Smith, W. L., H. M. Woolf, P. G. Abel, C. M. Hayden, M. Chalfant and N. Grody, 1974: Nimbus-5 sounder data processing system Part I: Measurement characteristics and data reduction procedures. Final Rep. GARP Project Office, NASA Contract S-70249-AG, NOAA Tech. Memo. NESS 57, 99 pp.

——, ——, C. M. Hayden, D. Wark and L. M. McMillan, 1979: The TIROS-N operational vertical sounder. *Bull. Amer. Meteor. Soc.,* **60,** 1177–1187.

——, ——, ——, A. J. Schreiner and J. F. Le Marshall, 1983: The physical retrieval TOVS export package. *Tech. Proc. First International TOVS Study Conference,* Igls, Austria, The Cooperative Institute for Meteorological Satellite Studies. 352 pp.

Susskind, J., J. Rosenfield, D. Reuter and M. T. Chahine, 1984: Remote sensing of weather and climate parameters from HIRS2/MSU on TIROS-N. *J. Geophys. Res.,* **89D,** 4657–4676.

Werbowetski, A., Ed., 1981: Atmospheric sounding users guide. NOAA Tech. Rep. NESS 83, 82 pp.