NOTES

Improvements in the Accuracy of Operational Satellite Soundings

L. M. McMillin, D. G. Gray, H. F. Drahos, M. W. Chalfant and C. S. Novak

National Earth Satellite, Data, and Information Service, Washington, DC 20233

4 January 1983 and 30 June 1983

ABSTRACT

Root-mean-square differences between satellite and radiosondes for the past three years that TIROS-N has been operational are examined. They show a pronounced annual cycle because the statistics are dominated by the Northern Hemisphere. Differences are smaller in the summer and are larger in the winter, but they reflect a change in the effect of location differences as well as retrieval error. In addition to the annual cycle, there is an increase in retrieval accuracy with time. For the partly cloudy retrievals, the increase approaches 1.3 K for some levels.

1. Introduction

Satellite retrievals of temperature are evaluated by comparing the retrievals with radiosondes. Once a month, a summary of all comparisons is made and an rms value of the difference is calculated. These differences have been calculated over a period of three years during which the sounding system has been subjected to a series of changes. The results show a gradual improvement over time.

One factor that must be remembered in a comparison such as this is the role of the radiosonde. The error in the radiosonde as well as errors due to differences in the times and locations of the soundings being compared are a significant portion of the total rms error that is observed and become more of the total as the satellite error is reduced. As a result, the magnitude of a change in retrieval accuracy is not fully represented by the size of the decrease in rms difference from a noisy radiosonde. It is necessary to account for the various factors contributing to radiosonde and space and time errors to estimate the true sounding accuracy.

2. Comparisons with radiosondes

When evaluating satellite retrievals, radiosondes are used as a comparison. The values shown in this study were computed by a program at the National Meteorological Center that was designed by A. Desmarais. Comparisons are calculated from radiosondes within ±3 hours and within 3 degrees of latitude from the satellite observation. These factors introduce an element of uncertainty into the radiosonde observation. In addition, the comparison is representative of the Northern Hemisphere even though the comparisons are global. This bias toward the Northern Hemisphere is the natural result of the large number of radiosondes and, thus, comparisons in that area. The comparisons in this study include both land and water areas. However, radiosondes are more numerous over land, and the land cases dominate.

It should be noted that the method used for these comparisons is different from the one used to generate regression coefficients within the system, which attempts to minimize differences in time and space to a greater degree. Although similar changes could be made in the evaluation program, we would lose the consistency of the comparison for previous times. The main point is that two systems exist.

The number of comparisons varies somewhat with the satellite (i.e., TIROS-N, NOAA-6 or NOAA-7), the length of the period, and the type of retrieval. However, comparisons for a single satellite for a month typically total over 2000 for cloudy soundings, 7000 for partly cloudy soundings, and over 10 000 for clear soundings. Data shown are for TIROS-N or NOAA-7. NOAA-6 was used only during the early summer of 1981 when data were being processed to start NOAA-7. Thus all samples are large enough to provide stable statistics.

3. Radiosonde errors

Estimates of satellite retrieval accuracy are obtained from comparisons with radiosondes. In these evaluations, it is frequently assumed that the major factor in the difference is the satellite error. However, radiosondes are subject to their own errors and there is an additional error due to differences in time and location between the satellite soundings and the "simultaneous" and "coincident" radiosondes that are used as the comparison.

Estimates of radiosonde accuracy are frequently optimistic when used on a global scale to evaluate satellite soundings. Satellite soundings are compared to radiosondes of different designs, from different manufacturers and that are operated by different countries using different procedures. All these differences contribute to the difference between satellite and radiosonde profiles. In contrast, studies of radiosonde accuracy are usually limited to radiosondes from one manufacturer, and frequently one lot, and the data are processed by the same procedures. Even studies of nearly coincident radiosondes in an area like Europe where the studies can include radiosondes from different countries, all the radiosondes taken in a small area at one time are exposed to similar radiation effects. In contrast, satellite soundings are compared to radiosondes taken at all hours of the day in terms of local time and thus all sun angles. In fact, comparisons of radiosondes with a consistent global retrieval system such as TOVS may be the best way to evaluate some biases between different radiosondes at different locations.

Several estimates of radiosonde accuracy are available. Perhaps the most precise for those factors which are considered, and at the same time most conservative, is reported by Hohne (1980). He reported the precision of radiosondes as determined by comparing two radiosondes mounted on a single balloon. In this study, great care was taken to assure uniformity of the radiosondes. The precision as well as the atmospheric standard deviation are shown in Fig. 1. The problem with using this figure as an indication of expected differences between satellites and radiosondes is that a measure of radiosonde precision is not intended to include all the factors which may contribute to the differences beween satellite retrievals and radiosondes.

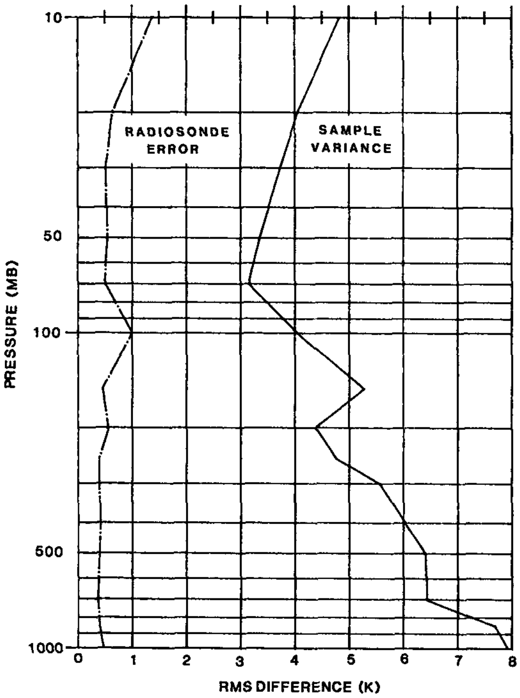

Fig. 1. Radiosonde errors for two radiosondes attached to the same balloon as a function of pressure. The standard deviation of the atmosphere for the data used in the test is shown by the solid line.

Another factor contributing to the satellite versus radiosonde temperature difference is the spatial separation between the area measured by the satellite and the point measured by the radiosonde. In addition, when comparisons are made there is a difference between the location of the satellite measurement and the path followed by the balloon. Bruce *et al.* (1977) compared nearby radiosondes launched at White Sand Missile Range. They obtained estimates of radiosonde errors that ranged from 0.5 K at the ground to 1.0 K at 130 mb for radiosondes at the same location. They also included the location errors and estimated the expected difference between a perfect satellite measurement and a typical radiosonde. When these factors were included, expected differences ranged from 1.4 to 1.7 K.

These values agree well with the value of about 1.5 K reported by Bengtsson and Morel (1974). Their study compared radiosonde reports at locations which differed by roughly the distances typical of satellites and radiosondes.

The radiation effect of radiosondes is the source of several errors. The basic problem is the well-known fact that at low pressures, the effects of solar and earth radiation in the determination of the sensor temperature increase relative to the effect of the air itself. However, for use in evaluating satellite soundings, the lack of a uniform policy for applying corrections is a significant additional source of error. As a result of this lack of a consistent policy, some are corrected by the country of origin and some are not. Those that are corrected are corrected with different procedures.

The subject of radiation corrections is covered by McInturff *et al.* (1979). They compared three subsequent radiosondes (12 hours apart) to estimate errors caused by solar radiation. The resulting estimates are listed by pressure and by solar elevation for each instrument type. There is a large variation from instrument to instrument. However, the problem is clearly not restricted to the upper atmosphere. At 700 mb, a relatively high pressure, they reported a correction of 0.8 K for the French Mesural instrument. The correction is also surprisingly large at 10 mb where they report a correction of 11.4 K for the same instrument. This instrument had the largest correction and is not typical, but corrections of 2.0 to 3.0 K at 10 mb are.

The NMC applies temperature corrections to some instruments, but does so only for pressures that are no higher than 100 mb. In addition, these corrections were applied to the radiosondes used to generate retrieval coefficients, but until 18 November 1981 a coding problem resulted in their not being applied to the comparisons used in this study. It should also be noted that NMC does not have corrections, and thus does not apply them, to all radiosonde types. The net result is a mixture of radiosondes corrected by the country of origin with radiosondes corrected by NMC with radiosondes that are uncorrected.

As mentioned earlier, some radiosondes have significant radiation corrections at pressures greater than 100 mb. The NMC correction programs provide corrections only for pressures of 100 mb or lower, even though they provide a height correction at 100 mb which implies radiation corrections for higher pressures. The application of a significant correction at 100 mb with no correction at higher pressures caused a discontinuity in the structure of TOVS retrievals at 100 mb. To solve the problem, the National Environmental Satellite Service (NESS) used the height and temperature corrections provided at 100 mb to infer temperature corrections at lower levels. An additional constraint was required so a form for the correction as a function of pressure was assumed. Two functions were considered. In the first, the correction was assumed to be a linear function of the pressure. In the second, it was assumed to be a linear function of the logarithm of pressure. To select the form, temperature and height corrections at 70 mb were used to infer the temperature correction at 100 mb. At 100 mb, the inferred value was compared to the value given. Even though the first form seems to fit physical intuition, the second form provided the best agreement and was selected. If the temperature correction at 100 mb is denoted ΔT, the height correction by ΔZ, and the pressure at which the correction becomes zero by p_0, then p_0 is given by

$$p_0 = 100 \exp(0.5 gR\Delta Z\Delta T),$$

where g is the acceleration of gravity and R the gas constant for dry air. For some instruments p_0 turns out to be greater than 1000 mb. For these instruments p_0 is set to 1000 mb and the temperature correction ΔT at 1000 mb is adjusted to match the value of ΔZ at 100 mb.

It should be emphasized that the radiation correction for pressures greater than 100 mb is applied to the TOVS retrievals through the retrieval coefficients. Outside of TOVS, radiosondes are not corrected for radiation effects at these pressures and its inclusion in TOVS retrievals is not well known. As a result, the difference caused by the use of the correction in the derivation of TOVS soundings, but not in radiosondes used to evaluate the soundings, is mistakenly attributed to an additional error in the TOVS retrievals rather than to a correction that the retrievals have made to compensate for a radiosonde error.

4. Retrieval accuracies

Figures 2–7 show the mean squared differences from radiosondes as a function of time for eight atmospheric layers. The contiguous layers are separated by the nine pressure levels of 1000, 850, 700, 500, 400, 300, 200, 100 and 70 mb. Yearly values for the period 1 November–31 October have been calculated for the three years of complete data and are shown in Table 1.

The figures are separated by the three retrieval types of clear, partly cloudy, and cloudy. These retrievals are explained more fully in Smith *et al.* (1979) and McMillin and Dean (1982). Briefly, clear retrievals are produced in areas where tests for cloudiness fail to detect any clouds. These retrievals can be in error if a small amount of cloud is present, but it is not detected by the tests. Partly cloudy retrievals are produced by adjusting measured radiances for cloud effects. An error is produced in the adjustment when clouds differ in height. Various tests have been designed to identify these cases, but some cases are not detected. As a result, partly cloudy retrievals are slightly less accurate than clear retrievals. Cloudy retrievals are produced when attempts to produce clear or partly cloudy retrievals fail. Although the areas frequently are mostly cloud covered, an area with less cover but with many cloud levels can also fail the other attempts. Cloudy retrievals are produced with only microwave measurements of the lower atmosphere. Because this particular microwave instrument was designed to supplement the infrared rather than do a complete sounding, the infor-

TABLE 1. Squared differences between satellite retrievals and radiosondes.

Layer (mb)	Squared difference from radiosonde (K^2)								
	Clear			Partly cloudy			Cloudy		
	79–80	80–81	81–82	79–80	80–81	81–82	79–80	80–81	81–82
100–70	4.65	4.16	4.06	4.66	4.22	4.31	5.04	5.26	4.58
200–100	4.27	3.59	3.88	4.80	3.87	3.97	5.42	4.87	4.93
300–200	5.23	4.54	4.57	6.11	5.36	4.62	8.01	5.98	6.06
400–300	5.18	4.97	4.68	5.62	5.83	5.32	8.80	8.49	7.01
500–400	5.35	4.95	4.88	5.80	5.81	5.39	8.77	8.84	7.72
700–500	4.09	3.90	3.80	4.59	4.50	4.13	7.50	7.30	6.47
850–700	5.53	5.35	5.39	7.45	7.77	6.94	11.30	9.81	10.26
1000–850	7.90	7.59	8.27	9.59	10.50	9.17	14.33	13.50	13.13

mation is limited and the cloudy retrievals are the least accurate of the three types. In areas of heavy rainfall, even the microwave measurements are affected and no retrievals are produced when these areas are identified.

Perhaps the most obvious feature on the graphs is the annual variation in accuracy. As mentioned earlier, the statistics are biased toward the Northern Hemisphere because about 85% of the matches with radiosondes are north of the equator. In the Northern Hemisphere summer, the temperature variability and the temperature gradients are both smaller than in winter. The smaller temperature variability tends to make retrievals more accurate. However, the smaller gradients tend to reduce the errors due to location and time differences between the satellite and the radiosonde. It would be wrong to attribute the seasonal change in accuracy to either of these effects alone.

There is also a tendency for the curves to be smoother in 1982 than in 1979 and 1980 when the system had just become operational and many changes were being made. This tendency is particularly evident in the middle layers for the clear and partly cloudy cases. Many of the jumps in accuracy are the result of changing a system that uses regression based on past data. When the system has a problem that produces an error that is either a bias or is correlated with one of the predictors, the regression will, to some extent, remove the error. When the problem is corrected, coefficients should be generated from data processed after the change has been made. However, computer resources are not always available to process data twice for the month it takes to accumulate a data set in some latitude zones. After the problem is corrected and the error is removed, the coefficients attempt to remove the error until the time that the data set used to generate coefficients contains enough data processed after the change. Since coefficients are updated once per week using data that is evenly distributed over two to four weeks depending on the number of radiosondes available in a particular latitude zone, the error caused by the coefficients is slightly improved after the first update. This update occurs from several days to one week after the change, and the error persists to some extent for a period of two to five weeks depending on the day of the change and the particular latitude zone. Early in the development of the processing system, there was a series of changes and recoveries and the system seldom stabilized from the effect of a given change before another one was made.

Because of the pronounced seasonal change and the fact that an improvement may produce a temporary increase in error followed by a decrease to a stable level about a month later, it is difficult to associate changes with particular events. In addition, effects of major changes to the system are obscured by effects of minor adjustments that are made, frequently because a major change failed to handle an infrequent event that did not occur in the testing done before the change was made, but was discovered once the change began to process thousands of soundings per day. When these factors are considered, along with the fact that the changes in error are partly masked by the radiosonde error that is part of the radiosonde-to-satellite difference, it is not surprising that individual events are difficult to identify.

Several major changes have been made to the processing system. A new procedure for producing partly cloudy radiances (McMillin and Dean, 1982) was introduced in the last half of June 1980. Evaluation of the effect of this change is hampered by two other events. Recall that the last point in June and the first point in July 1980 are the most accurate points for many levels for the clear and partly cloudy retrievals because they were limited to radiosondes within ±1 degree rather than ±3 degrees of the retrieval location. In addition, on 10 September 1980 a correction for an instrumental scan bias for the microwave instrument was introduced. It was inadvertently removed at some unknown time and re-introduced on 26 March 1981. It is suspected that the increase in error observed in the fall of 1980 was due to these factors in addition to the normal seasonal increase. From the winter of 1980–81 to the present, errors seem to be lower and less erratic than during the earlier period. However, the improvement in accuracy is best determined by comparing data from similar seasons over several years.

In August 1980 a change suggested by N. Phillips was introduced into the microwave retrievals. This change used the sea surface temperature to supplement the meager information about the lower atmosphere given by the microwave retrievals. However, the change in its initial form was applied only to a limited latitude region and even when it was expanded to all latitude regions, it was applied only over oceans. Thus the change is not present in a large portion of the radiosondes shown in these statistics, since most radiosondes are over land. In another modification, procedures were developed to detect areas of heavy rainfall where the cloudy retrievals are subject to errors due to the effects of rain on the microwave measurements. These soundings are rejected.

Few changes have been made to the procedure used in clear areas and little change in accuracy is observed. Figs. 2 and 3 which show the squared difference from radiosondes as a function of time, show little change except near the tropopause (particularly 300–200 and 200–100 mb). The yearly averages shown in Table 1 show a decrease the second year and little change the third year. However, the surface layer of 1000–850 mb shows an increase the third year. The reason is not known.

Most of the changes have involved the methods used for partly cloudy retrievals (Figs. 4 and 5). These retrievals tend to be more important for forecasts than clear retrievals because clear retrievals frequently clus-

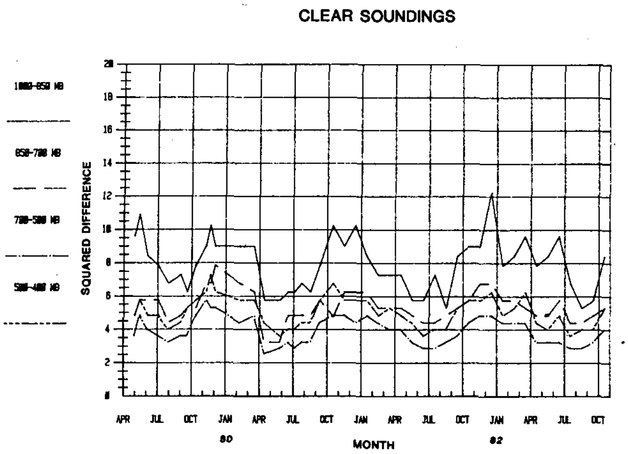

FIG. 2. Squared rms differences (K^2) between clear satellite retrievals and radiosondes for the period March 1979 through October 1982 for four lower atmospheric layers.

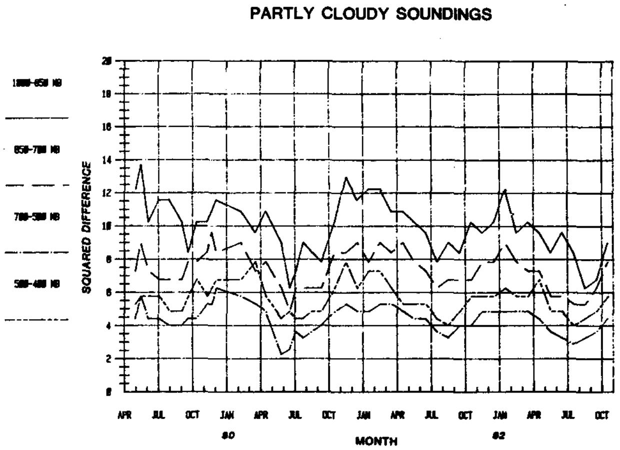

FIG. 4. As in Fig. 2 but between partly cloudy satellite retrievals and radiosondes for four lower atmospheric layers.

ter in areas of uniform temperature where dense measurements are not required. Partly cloudy retrievals are also subject to an error caused by the fact that the procedure used to produce clear radiances from partly cloudy observations assumes a uniform cloud height in the two adjacent scan spots used. Frequently, two adjacent scan spots differ in average cloud height as well as cloud amount. The resulting errors are difficult to detect, but various tests have been developed (see McMillin and Dean, 1982). The major changes were made in June 1980, and as mentioned earlier, it is suspected that the scan bias increased the error level temporarily that fall. With this exception, values after the change are generally lower. This is also shown by yearly averages in Table 1. Values for most layers show significant decreases between the second and third years. For the 300–200 mb layer, the squared difference changes from 6.11 the first year to 4.62 the third year. In the lower atmosphere where clouds are expected to have the largest effects, substantial improvements occurred between the second and third years. Between the first and second years, values became worse for the bottom two layers. Most of the difference in the 1000–850 mb layer is due to the high levels in January and February. The cause is not known. However, a comparison of the first and third years shows substantial improvement for all layers.

Values for the cloudy soundings are shown in Figs. 6 and 7. Differences from radiosondes are larger than for the other retrieval types. Fluctuations are also large, particularly for the layers near the surface. Table 1 shows changes that are not immediately obvious from the figures. The second year shows increases in accuracy over the first year at most levels and the third year is better at all levels. Apparently changes to correct scan bias in the microwave instrument and use of the ocean surface temperature to improve the retrievals at the lower levels and to detect areas of heavy rainfall have made significant changes in accuracy.

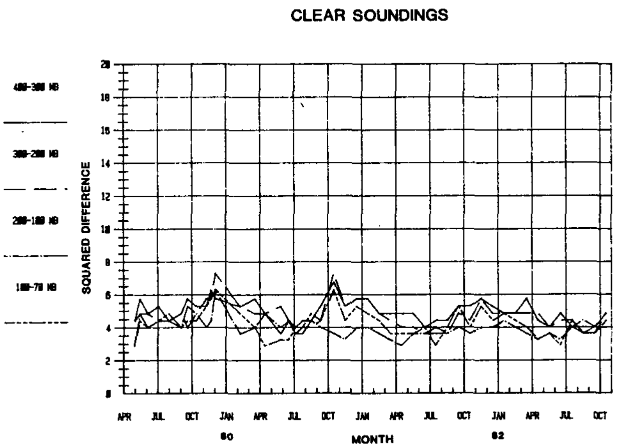

FIG. 3. As in Fig. 2 but for four upper atmospheric layers.

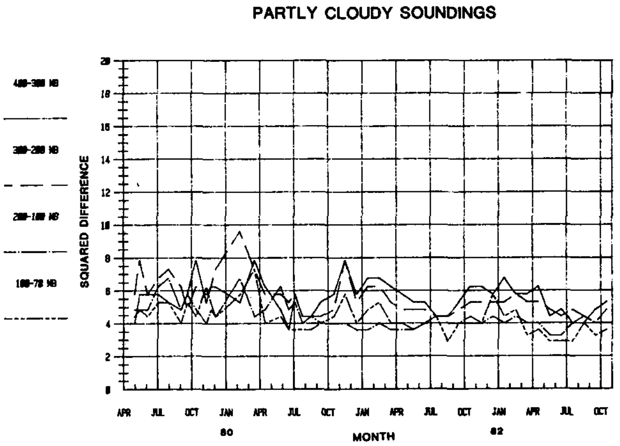

FIG. 5. As in Fig. 4 but for four upper atmospheric layers.

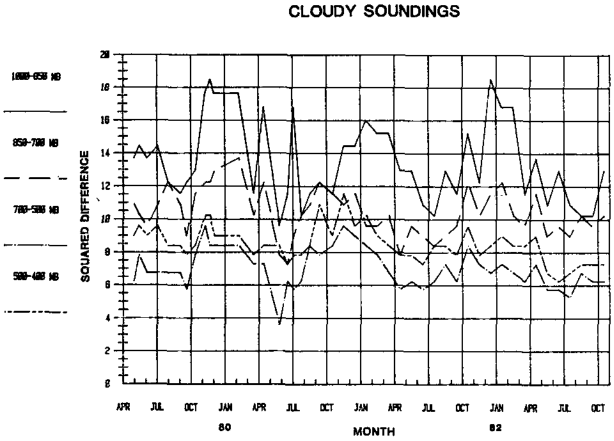

FIG. 6. As in Fig. 2 but between cloudy satellite retrievals and radiosondes for four lower atmospheric layers.

When all retrieval types are compared over the three year period, only one layer shows a decrease in accuracy. One implication of this result is that case studies of satellite retrievals at a particular time result in conclusions that may not be valid for extended periods. Care should be taken if these conclusions are extrapolated beyond the time the data was produced. One example is the data taken during the First GARP Global Experiment (FGGE) that was processed early in the first year of satellite processing. Conclusions about the nature of satellite data processed at that time are valid for that data, but may not be valid for data that are processed now. It is also obvious that care should be used when results from one season or latitude are extrapolated to another. There is a strong seasonal dependence.

For all retrieval types, the retrievals at the surface have larger errors than retrievals at other levels. This is partly due to the difficulty sounding techniques have in retrieving sharp temperature discontinuities such as occur at the surface. However, many radiosondes are located over land where there is a large diurnal change in temperature. For a given difference in time, the large diurnal temperature change causes a large difference between the satellite and radiosonde temperatures. Thus only a portion of the increase in difference at this level is due to the accuracy of the satellite retrievals.

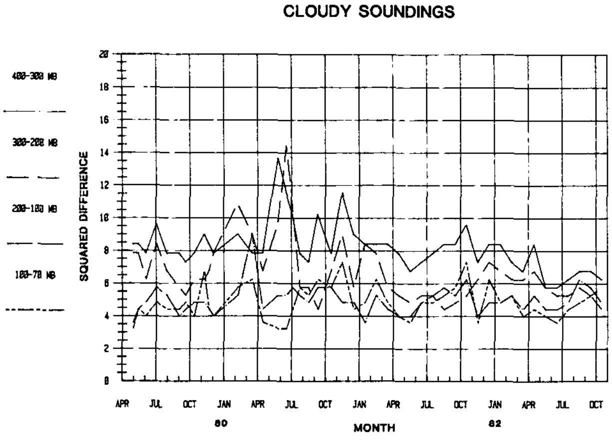

FIG. 7. As in Fig. 6 but for four upper atmospheric layers.

5. Summary and conclusions

An accuracy level of 1 K has been generally accepted as a goal for atmospheric soundings. This study showed squared differences from radiosondes are in the range of 4 to 5 K^2 for many layers. When other factors, such as radiosonde errors and differences in time and location are considered, the combined effect of these factors is 3–4 K^2. Thus true errors in satellite retrievals are between 1 and 1.5 K over the atmospheric layers where satellites do well. It is also clear that the continuing efforts to improve the system have resulted in more accurate retrievals. The largest increases are observed in the cloudy retrievals, followed by the partly cloudy and clear retrievals. Two year improvements as high as 1.4 K are observed in the cloudy retrievals.

It is also obvious that accuracies at many levels are approaching or even exceeding the accuracies of the estimates of truth when the combined effects of radiosonde errors and differences in time and location are considered. It is essential that these components of the radiosonde to satellite temperature difference be considered when satellite soundings are evaluated. Some of these other factors could be eliminated in comparisons, but are included in this paper because the comparison is consistent over a long time period. In spite of the other factors that contribute to the difference, the comparisons provide a useful evaluation of sounding accuracy as long as the other factors affecting the difference are considered.

Clear and partly cloudy soundings are approaching the accuracies expected from studies using simulated data (see Fleming and Smith, 1971). Major increases in accuracy for representative samples should not be expected with current instruments. However, there are still subsets of soundings which are too few in number to affect gross statistics, but may still impact certain meteorological conditions. An example is the bias due to radiosonde types. Presently this bias appears as one component of the noise present in data used to generate regression coefficients and it increases the noise. The increased error tends to produce coefficients which respond to extreme temperatures less effectively than coefficients generated from data with the bias due to radiosonde type removed. Removing this effect may produce significant improvements in a few retrievals, but the effect on the rms of a large sample is expected to be small.

Cloudy retrievals near the surface show the greatest departure from clear values, and thus have the most potential for improvement. They are also the ones for which noise levels are likely to be a serious problem in their use and thus where improvement is needed. Unfortunately, the major factor limiting the accuracy of these soundings is the lack of information in this region of the atmosphere when clouds are present. This lack, in turn, is due to the limited sounding capability of the present microwave instrument which has only four channels. It is unlikely that any future modifications to the processing system can compensate for the limited information available from the present instrument.

The main point of this discussion of radiosondes is that the satellite – radiosonde difference contains factors other than the satellite retrieval error. If these differences are to be used to evaluate satellite results, then these other error factors must be considered. It is important to note that the value of 1 K, that is sometimes regarded as a goal for satellite soundings, exceeds the combined effects of errors due to radiosondes, time differences, and location differences. Thus this goal will never be achieved as long as other errors which affect satellite–radiosonde differences are ignored. As an example, consider a satellite versus radiosonde difference of 2.0 K which is typical of many clear and partly cloudy retrievals above the surface layer. Also consider a combined error in radiosondes of 1.5 K due to radiosonde limitations as well as location and time differences, a typical value. The estimated error in satellite retrievals, assuming the errors are independent, is the square root of $(2.0^2 - 1.5^2)$ or 1.3 K. Thus in the upper part of the atmosphere above 700 mb, where satellite retrieval errors are small and radiosonde errors increase (Bruce *et al.,* 1977), the error can be expected to increase even more in satellite comparisons because of the larger variation of radiation effects; satellite errors are comparable in size to the other factors contributing to the satellite-to-radiosonde difference. Above 100 mb, it is likely that the errors in satellite retrievals are smaller than the other effects if the combined radiosonde–location error of 1.7 K, which has been reported for that region, is used.

Preliminary results from some other studies designed to estimate the magnitude of some of the errors help illustrate some of the problems. Fig. 8 compares errors for the space and time differences allowed in this study with errors for a sample in which radiosondes 12 hours apart are interpolated to the time of the satellite observation, and satellite retrievals for an area are interpolated to the radiosonde location. This procedure is designed to eliminate differences in space and time. A second difference in the curves is that one is for levels and one is for layers. Averaging over layers tends to reduce the error in satellite retrievals. However, in spite of the fact that the values including the location and time errors are averaged, they are still significantly larger except at the tropopause where averaging has a large influence. Retrievals shown are for the same time of year so it is clear that differences in time and location have a significant effect on the retrievals.

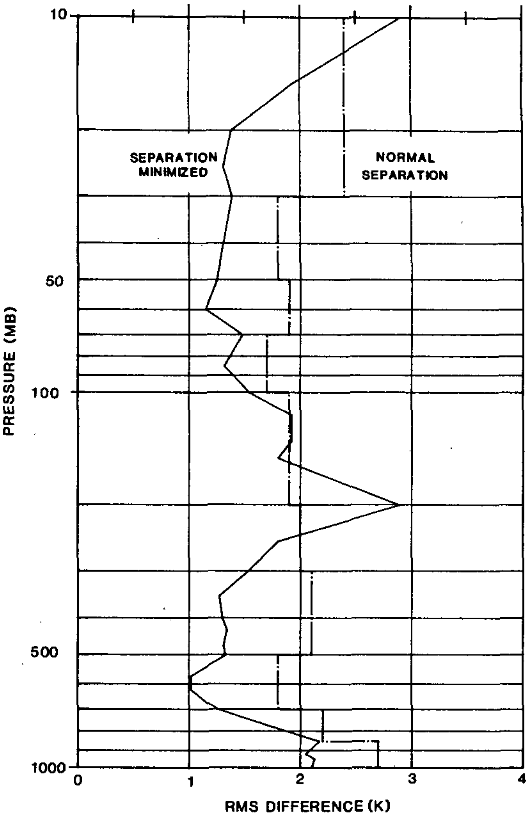

FIG. 8. Root-mean-square differences between satellite retrievals and radiosondes as a function of pressure. Values for the solid curve are for satellite retrievals interpolated to the radiosonde time and location. Larger values shown by the dashed curve are for differences of up to three hours and three degrees of latitude.

Another preliminary study compared averages of satellite to radiosonde differences as a function of radiosonde type. When average differences for the two most numerous radiosondes (U.S. and U.S.S.R.) were compared, it was found that the bias of the two instruments differed by 2.0 K in the upper atmosphere. In the future, biases will be calculated for radiosonde locations in an attempt to remove this source of error from radiosondes used to generate retrieval coefficients. A difference of 2.0 K between the two most numerous radiosondes is a substantial component when compared to the total satellite to radiosonde difference.

To summarize, it is clear that differences between satellite retrievals and radiosondes must be properly interpreted if they are to be used as a measure of satellite retrieval accuracy. The differences are a mixture of errors from various sources, only one of which is the satellite error. In addition, the difference is subject to a rather pronounced seasonal variation. Only a portion of this annual variation is due to changes in the satellite retrieval accuracy. Part of the variation is due to seasonal changes in meteorological gradients which determine the temperature error that results from space and time differences. Finally, there has been an increase in retrieval accuracy with time. Because of these changes in accuracy, characteristics of satellite soundings determined at a particular time should be extrapolated to other seasons or to other years with great caution. The potential for invalid extrapolations is greatest for special data collection periods where the satellite data are processed shortly after the measurement is obtained, but used in studies for many years.

Acknowledgment. We thank Dr. N. Phillips for the helpful comments on this manuscript.

REFERENCES

Bengtsson, L., and P. Morel, 1974: The performance of space observing systems for the First GARP Global Experiment. GARP Working Group on Numerical Experimentation, Rep. No. 6, 31 pp.

Bruce, R. E., L. D. Duncan and J. H. Pierluissi, 1977: Experimental study of the relationship between radiosonde temperatures and satellite-derived temperatures. *Mon. Wea. Rev.,* **105,** 493–496.

Fleming, H. E., and W. L. Smith, 1972: Inversion techniques for remote sensing of atmospheric temperature profiles. *Temperature: Its Measurement and Control in Science and Industry,* H. H. Plumb, Ed., Vol. 4, Part 3, ISA, 2239–2250.

Hohne, W. E., 1980: Precision of National Weather Service upper air measurements. NOAA Tech. Memo. NWS T and ED-16. Environmental Science Information Center (D822) EDIS.

McInturff, R. M., F. G. Finger, K. W. Johnson and J. D. Laver, 1979: Day–night differences in radiosonde observations of the stratosphere and troposphere. NOAA Tech. Memo. NWS NMC 63.

McMillin, L. M., and C. Dean, 1982: Evaluation of a new operational technique for producing clear radiances. *J. Appl. Meteor.,* **21,** 1005–1014.

Smith, W. L., H. N. Woolf, C. M. Hayden, D. Q. Wark and L. M. McMillin, 1979: The TIROS-N Operational Vertical Sounder. *Bull. Amer. Meteor. Soc.,* **60,** 1177–1187.