An Intercomparison of Temperature and Moisture Fields Derived from TIROS Operational Vertical Sounder Data by Different Retrieval Techniques. Part I: Basic Statistics

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ABSTRACT

Fields of temperature, thickness and precipitable water, derived from common sets of Tiros Operational Vertical Sounder (TOVS) radiance data have been intercompared. These fields were produced by a variety of institutions using different retrieval techniques. The fields have been derived over three regions; the Alpine Experiment (ALPEX) in 1982, the Tasman Sea, and the United States. Basic statistics have been produced by comparing these derived fields to analyses produced by the European Centre for Medium Range Weather Forecasts (ECMWF), and with collocated radiosonde (RAOB) data.

In most cases it appeared, for both physical and statistical retrieval techniques, that in the midtroposphere (700 to 400 mb) the satellite temperature soundings exhibited rms temperature differences of near 2 K when compared to ECMWF analysis or collocated radiosonde data. These figures include significant contributions due to radiosonde error, collocation differences, analysis error and other factors. Different vertical resolutions among the compared fields contributed to the larger differences which were evident near the tropopause and the surface. Near the surface the differences appeared to be more a function of the use of ancillary data or constraints, rather than the retrieval scheme. Basic statistics for thickness and moisture fields have also been presented in this study.

1. Introduction

The First International TIROS Operational Vertical Sounder (TOVS) Study Conference (ITSC-1) was held in Igls, Austria from 29 August to 2 September 1983. It was attended by scientists from 14 different countries.

Most of these countries were already producing soundings with high horizontal resolution from the direct readout of TOVS data for research and operational applications. This widespread use of TOVS data in forecasting and research at all scales has led to a common goal among satellite sounding producers, namely to optimize and, where appropriate, standardize, TOVS processing procedures so that accurate and uniformly consistent satellite temperature and moisture soundings can be made available to the international meteorological community. In order to achieve this goal, one of the key activities of this conference was an evaluation of TOVS processing techniques and data analysis. The ITSC-1 conference made initial qualitative assessments on retrievals from the ALPEX and Tasman Sea regions (Menzel and Lynch 1983). It was concluded, however, that a quantitative comparison of temperature and moisture soundings derived by the participants was a vital part of the intercomparison which remained to be addressed. In this study, basic statistics have been derived for temperatures, layer mean temperatures, geopotential thickness and precipitable water observations derived from satellite radiances. The statistics have been derived by comparing these fields with the corresponding ECMWF analyzed fields (which over land have not used the NESDIS operational soundings) and to collocated radiosonde data. A representative subset of this intercomparison data, which includes fields nominated for intercomparison at ITSC-1, is presented here. A comparison of these results with those of other similar studies which essentially concentrated on NESDIS produced regression retrievals (Schlatter 1981; McMillin et al. 1983) is contained in section 5.

A description of the synoptic situations associated with the cases studied here is found in Menzel and Lynch (1983).

2. The contributions to the intercomparison study

Eighteen sets of atmospheric soundings derived from common sets of radiance data were provided by the 11 institutions involved in the intercomparison study. The sounding sets were generally a mix of clear and cloudy cases. The participants, and a summary of the datasets they have provided, are given in Table 1. The entries in Table 1 are grouped according to the cases studied, i.e., the ALPEX, Tasman Sea or United States

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TABLE 1. Summary of contributions to the intercomparison study. Note that T represents temperature data, Z represents thickness data, and P represents moisture data. The ITPP1, ITPP2 and ITPP3 represent the International TOVS Processing Package, 1), 2) and 3) respectively; RFG represents regression first guess field; CFG represents climatology first guess field; MFG represents first guess fields derived from a forecast model; SD indicates use of surface data in the retrieval scheme; AVHRR represents the use of AVHRR in the data processing algorithms; LRC represents the use of locally generated regression coefficients; NRC indicates the use of NESDIS regression coefficients.

Data origin	Case	Abbreviation	Content	Nobs	Retrieval scheme
ALPEX					
British Meteor. Office	1) ALPEX	ALUK	T, Z, P	~695	Statistical (modified ITPP1) (NRC)
CIMSS/NOAA-NESDIS, Wisconsin	2) ALPEX	ALWI1	T, Z, P	~1717	Physical (ITPP2, RFG, SD)
	3) ALPEX	ALWI2	T, Z, P	~1818	Physical (one step) (ITPP3, CFG, SD)
	4) ALPEX	ALWI3	T, Z, P	~1828	Physical (one step) (ITPP3, RFG, SD)
DFVLR, West Germany	5) ALPEX	ALDF	T, Z, P	~1376	Physical (iterative) (modified ITPP2, RFG, SD)
Laboratoire de Meteorologie Dynamique, France	6) ALPEX	ALFR	T, Z, P	~4080	Physical/statistical
NASA/GLAS, United States	7) ALPEX	ALNA	T, Z, P	~903	Physical (relaxation) (MFG)
NOAA-NESDIS, Washington	8) ALPEX	ALNE	T, Z	~213	Statistical (operational algorithm)
University of Bologna, Italy	9) ALPEX	ALIT1	T, Z, P	~1514	Physical (iterative) (modified ITPP2)
	10) ALPEX	ALIT2	T, Z, P	~1757	Physical (iterative) (modified ITPP2, SD)
Western Australian Institute of Technology	11) ALPEX	ALWA	T, Z, P	~2807	Statistical (modified ITPP1) (NRC)
TASMAN					
Bureau of Meterology, Australia	12) TASMAN	TAAU	T, Z, P	~2755	Statistical (modified ITPP1) (discriminant anal., LRC, operational algorithm with SD)
CIMSS/NOAA NESDIS, Wisconsin	13) TASMAN	TAWI	T, Z, P	~1625	Statistical (ITPP2, RFG, SD)
New Zealand, Meteorological Service	14) TASMAN	TANZ	T, Z, P	~2009	Statistical (modified ITPP1) (NRC)
NOAA-NESDIS, Washington	15) TASMAN	TANE	T, Z	~217	Statistical (operational algorithm)
UNITED STATES CASE					
Atmospheric Environment Service (AES), Canada	16) US	USCA	T, P	~254	Statistical (modified ITPP1) (NRC)
British Meteor. Office	17) US	USUK	T, Z, P	~163	Statistical (modified ITPP1) (NRC)
CIMSS/NOAA-NESDIS	18) US	USWI	T, Z, P	~132	Physical (iterative, AVHRR)

case. A description of, or reference to, the retrieval techniques used in the production of the soundings provided for this study can be found in the technical proceedings from the ITSC-1 and ITSC-2 (Menzel 1983, 1985). A summary of the salient features of the retrieval schemes is presented in the table along with the approximate number of soundings received for intercomparison.

3. The intercomparison

Fields nominated for intercomparison at the ITSC-1 included: temperatures at the fifteen standard levels; geopotential thickness of the layers 1000 to 700 mb, 700 to 500 mb, 500 to 300 mb, 300 to 100 mb and 1000 to 500 mb; and the precipitable water in the layers 1000 to 400 mb, 850 to 400 mb, 700 to 400 mb and 500 to 400 mb. These have been compared to their respective ECMWF analysis fields and interpolated to the sounding position in time and space. These satellite data have also been compared to collocated (within 150 km) RAOB data. In the ALPEX and United States cases, the RAOB data used was subjected to a gross error checking procedure using the ECMWF analyses. The operational validation procedure at the Australian Bureau of Meteorology was used to check the RAOBs in the Tasman Sea case.

Biases, rms differences and the standard deviation of the difference (standard difference), between the satellite observations and the related ECMWF and RAOB data have been computed. The standard deviation of standard level temperatures both from satellite measurements and from ECMWF analyses or RAOB measurements about their respective means has been calculated at the satellite sounding points. Several of these standard deviations along with corresponding ECMWF or RAOB data have also been displayed. The basic statistics are seen in Figs. 1 through 4.

4. The basic statistics

a. ALPEX case

Comparison of the satellite soundings for the ALPEX case with ECMWF data (Figs. 1a through 2f) indicated that both the physical and statistical retrieval schemes generally have standard differences just below 2 K between 850 and 400 mb, while a comparison with RAOB data indicates standard differences close to 2 K. Comparison of this radiosonde dataset with ECMWF data has indicated a standard difference near 1.5 K between 850 and 300 mb (Fig. 5), reflecting both the lack of small horizontal scale detail in the ECMWF archived analyses, which have a grid resolution near 200 km, and also the errors and systematic differences among the radiosondes themselves. The standard differences above 850 mb generally appeared larger in comparison to RAOB data as a result of the inherent smoothing in the TOVS and ECMWF profiles relative to the radiosonde profiles. This was quite noticeable near the tropopause where the larger standard differences compared to RAOB data were around 4 K, while compared to ECMWF data they were closer to 3 K.

Near 850 mb and below, the standard difference for both physical and statistical schemes was generally significantly larger than in the 850 to 300 mb layer and was strongly influenced by the use of ancillary data or other constraints. This can be seen by examining the basic statistics for the ALIT1 and ALIT2 cases, which differ in that the ALIT2 case used surface data as a constraint when solving for the temperature and moisture profiles. It can also be seen in the statistics shown in Smith et al. (1983), relating to a similar change in constraints and in the ALFR case, which used ECMWF forecast data as part of an ancillary dataset.

An examination of the biases for these ALPEX soundings indicated that most soundings have been too cold relative to radiosondes near the surface. They also had smaller biases in the midtroposphere and then often exhibited a negative bias (too cold near 300 mb), positive bias (too warm near 200 mb), then negative bias (too cold near 100 mb) with increasing altitude near the tropopause. The inherent vertical smoothing of the TOVS profile in this region of sharp vertical temperature gradient contributed to this variation in bias near the tropopause. A similar variation in bias was seen when comparing the ALPEX radiosonde data with ECMWF data around the tropopause region (see Fig. 5). Again near 850 mb and below, the biases showed the strong influence of ancillary data or other constraints on the soundings. The basic statistics for the ALIT1 and ALIT2 cases (Smith et al. 1983) and the ALFR case again illustrated this point.

Root-mean-square difference statistics reflected the net effect of bias and standard difference. As a result, they were generally larger near the tropopause and near and below 850 mb where they were strongly influenced by ancillary data or other constraints. Near the tropopause, rms differences compared to ECMWF data were generally a little larger than 3 K, while compared to RAOB data they were generally just over 4 K. (Again it is useful to note that rms differences for RAOB temperatures compared to ECMWF data near the tropopause are near 2.2 K.) Comparison of the sounding data with ECMWF data also indicates rms deviations in the 850 to 400 mb layer to be just below 2 K, while comparison with RAOB data indicates rms differences close to 2.2 K.

The thickness data from the intercomparisons with RAOBs are illustrated in Figs. 4a through 4c. Statistics for TOVS thicknesses compared to ECMWF data were similar and have not been displayed. The statistics generally showed a cold bias in the lowest level, 1000 to 700 mb. The rms differences for the 700 to 500 mb

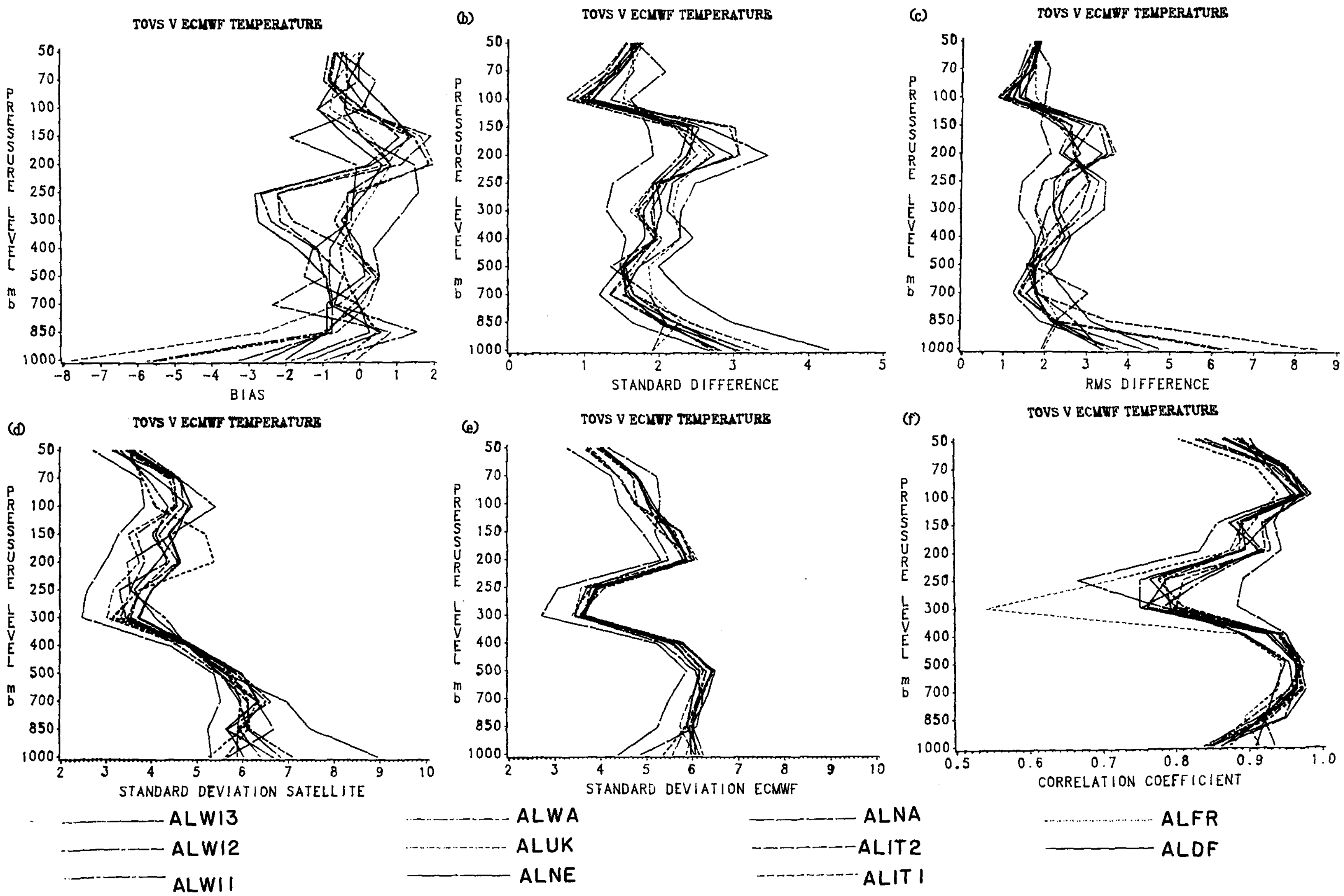

FIG. 1. Basic statistics for the TOVS retrievals compared with ECMWF data, for the ALPEX Case. Temperature units are degrees Kelvin and the legend uses Table 1 acronyms.

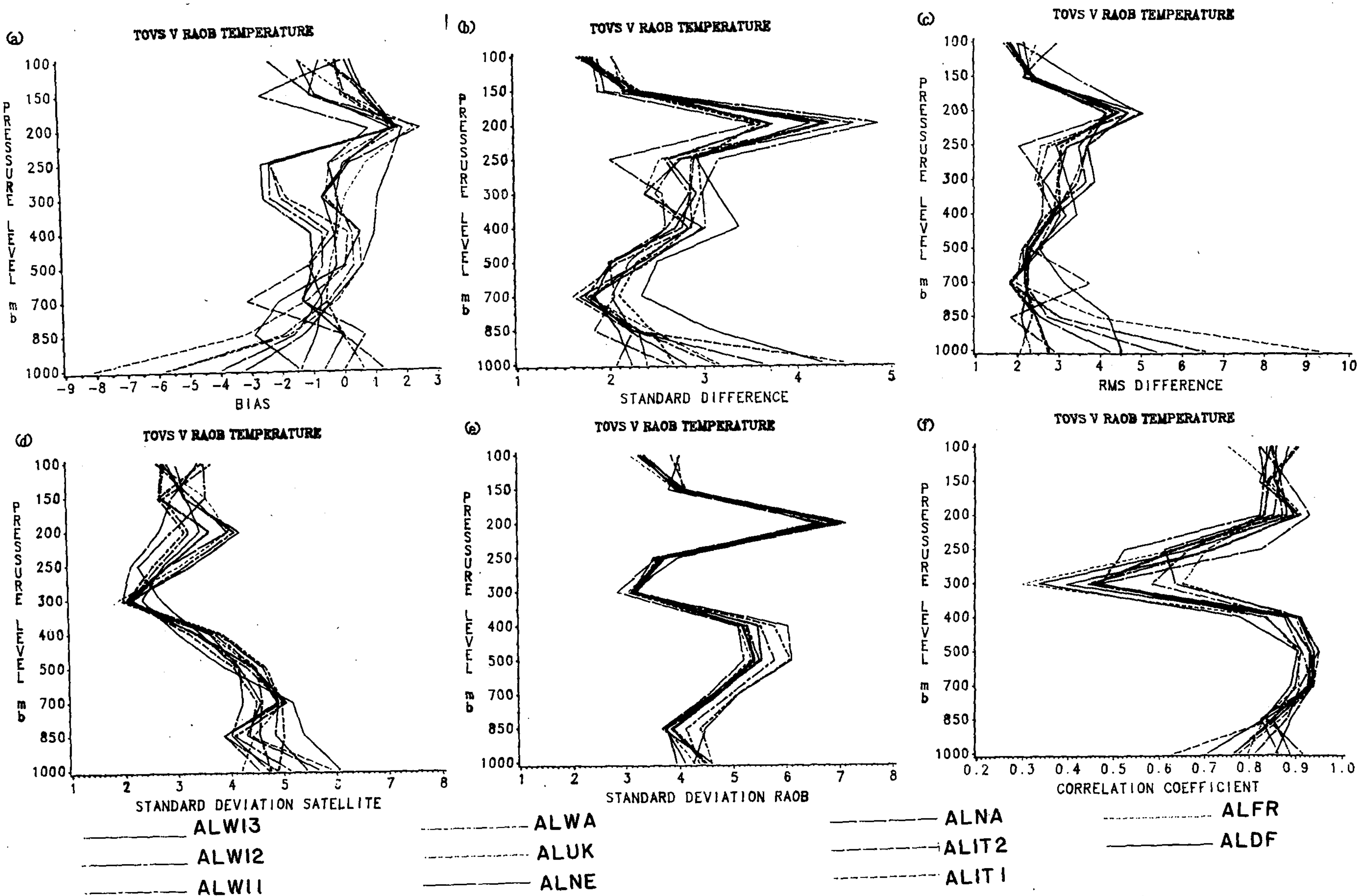

FIG. 2. As in Fig. 1 but in this case the basic statistics are derived by comparison with radiosonde observations (RAOB) for the ALPEX Case.

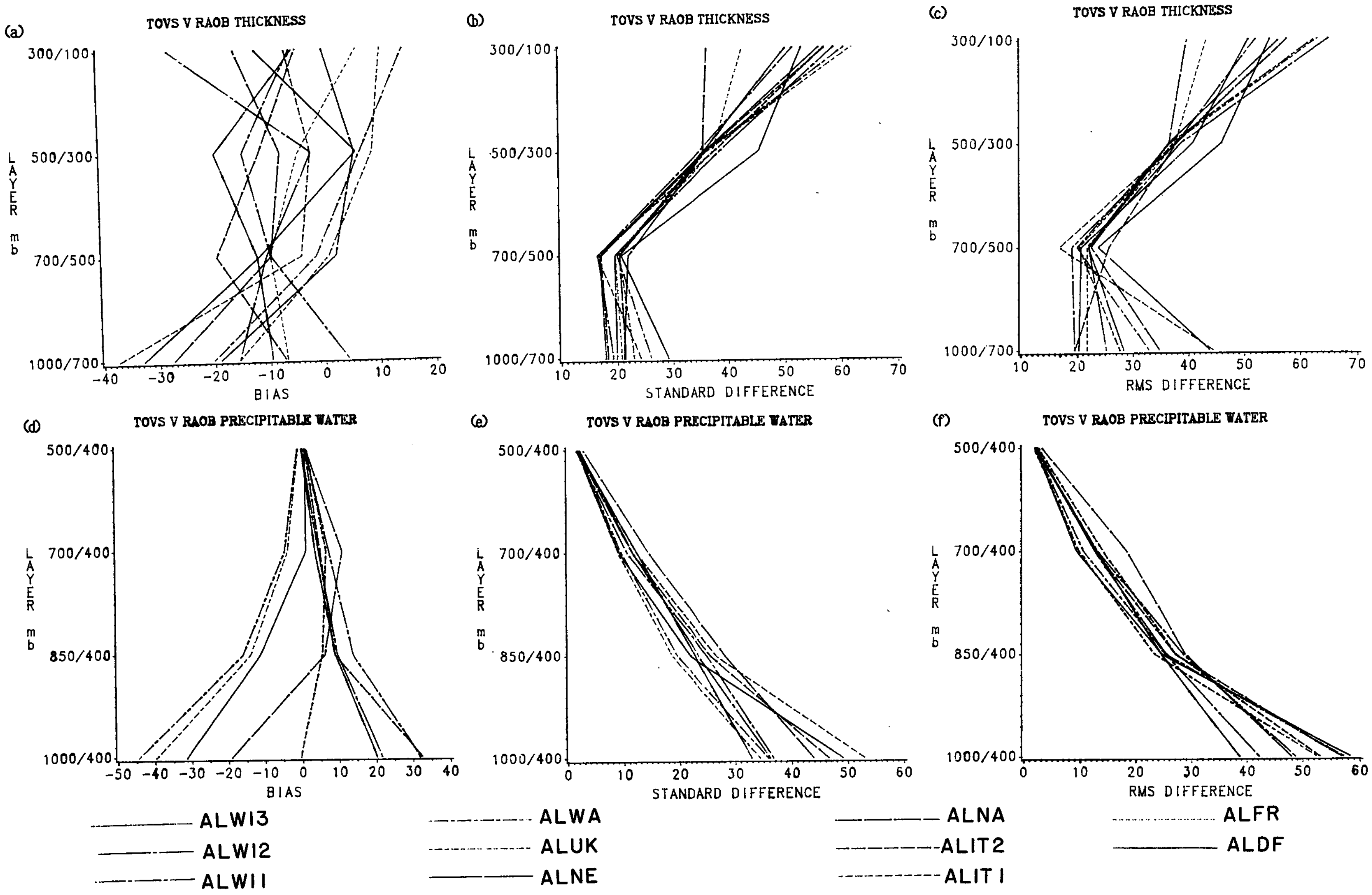

FIG. 3. Basic statistics for the TOVS retrievals compared with radiosonde observations (RAOB) of TOVS based thickness and precipitable water observations for the ALPEX Case. Units are geopotential meters and cm × 100, respectively.

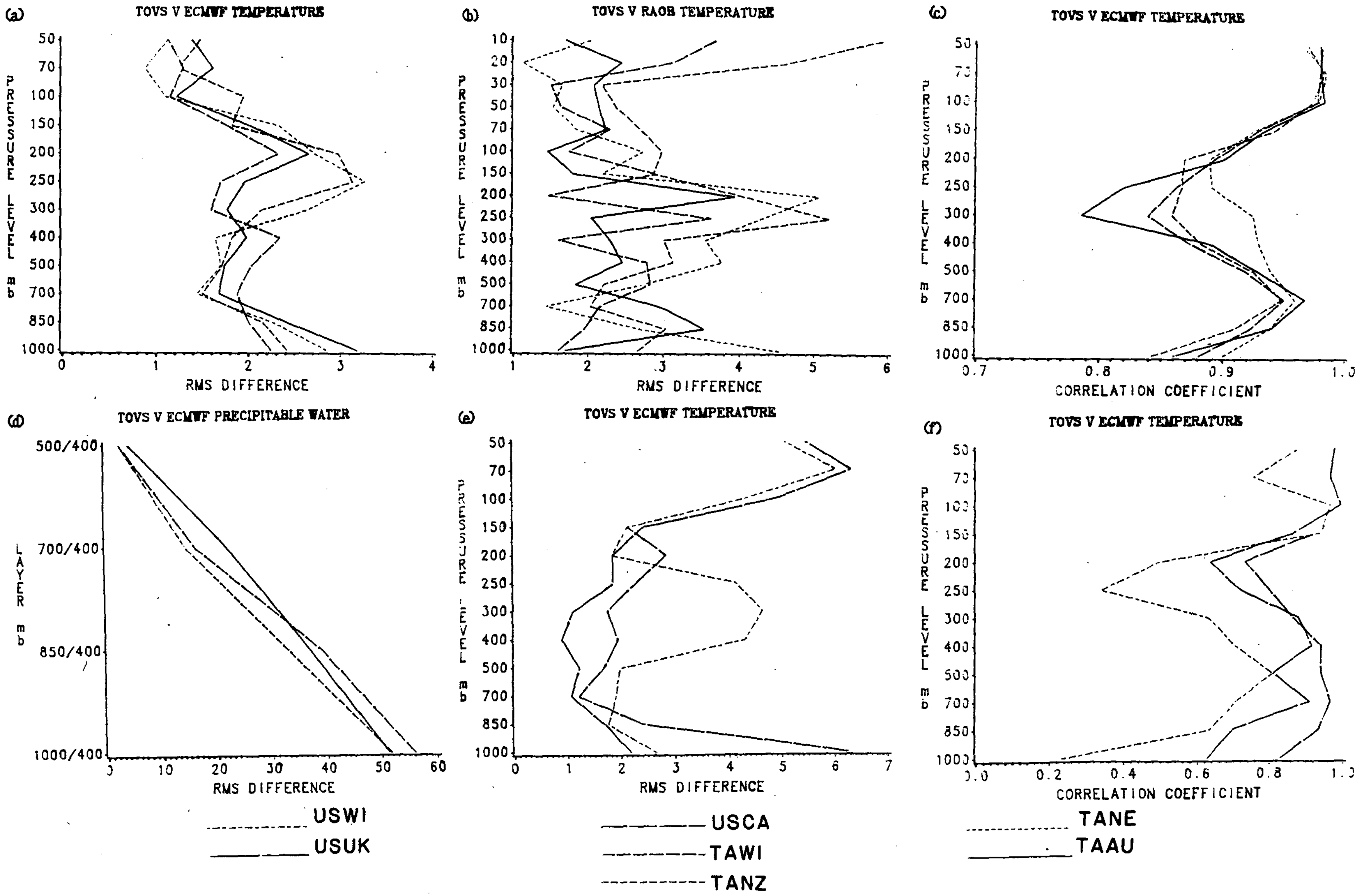

FIG. 4. Basic statistics for the TOVS retrievals compared with ECMWF data and radiosonde observations (RAOB) for the Tasman Case [panels (a–d)], and the United States case [panels (e, f)]. Temperature units are in degrees Kelvin.

layer were near 20 m, and for the 500 to 300 mb layer mostly between 30 and 40 m. The mean 1000 to 500 mb thickness rms difference, compared to the ECMWF analyses, was only 32 m.

The correlation coefficients relating coincident satellite and ECMWF standard level temperatures have also been illustrated, in Fig. 1f. Generally, the coefficients exceeded 0.9, except near the surface and tropopause and above 100 mb. The impact of surface constraints can be seen by examining the data for ALIT1 and ALIT2. The correlation coefficients relating collocated satellite and RAOB temperatures (Fig. 2f) showed a similar variation with height. They were reduced in magnitude compared to the satellite/ECMWF comparison data, particularly near the tropopause, where the difference in resolution of the two data forms is expected to have an influence.

The standard deviation (SD) of both the satellite standard level temperature and the related collocated RAOB or coincident ECMWF temperatures is illustrated in Figs. 1d, 2d, 1e and 2e. Although the vertical variation of satellite and related comparison fields with height were similar, some differences were seen, particularly in relation to the TOVS/RAOB comparison. In comparison to radiosondes, the TOVS data almost always appeared to have a similar SD near 700 mb, a larger SD below about 700 mb and a lesser SD above about 700 mb. A significant reduction in SD for the satellite data compared to the RAOB data was seen near the tropopause as expected, while the effect of surface constraints could also be seen in the SDs (see e.g. ALIT1 and ALIT2. Explanation of the relative size of the SDs near the surface depends on, among other things, the completion of an examination of the horizontal distribution and correlation of differences at those levels. In comparison to ECMWF analyses, the TOVS data, in the majority of cases, showed a larger standard deviation near the surface and usually had a smaller SD in the mid- and upper troposphere. A significant reduction in SD was again evident near the tropopause (around 200 mb).

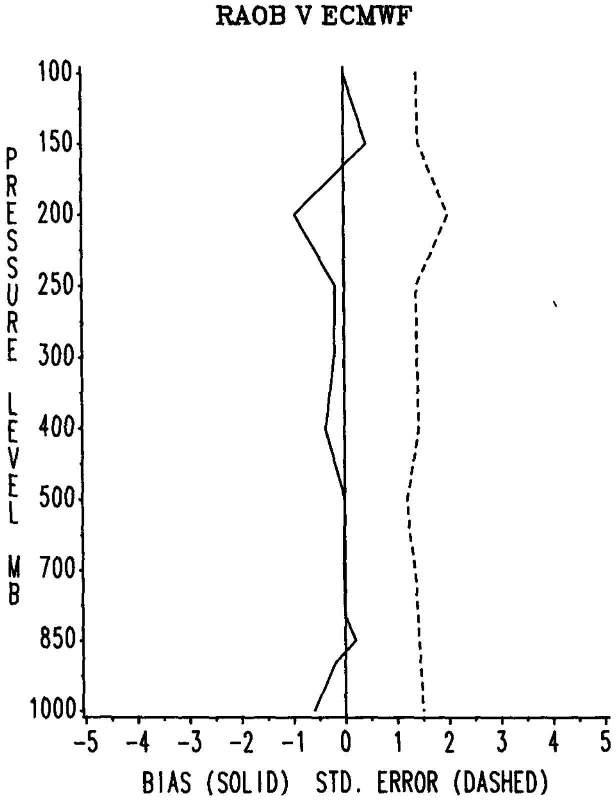

FIG. 5. Bias and standard difference between radiosonde data and the ECMWF analyses for the ALPEX case.

The basic statistics for the retrieved precipitable water are illustrated in Figs. 3d, 3e and 3f. They show only small differences between the regression and statistical schemes in an rms sense; the regression schemes appeared to have slightly larger biases and smaller standard differences. The simultaneous solution scheme, however, appeared quite skillful in estimating the moisture in the lowest levels, a result consistent with previous simulation studies (Smith and Woolf 1984). In the ALPEX case, rms differences for precipitable water often represented just over 40% of the moisture in the 1000 to 400 mb and 850 to 400 mb column. It should be noted, however, that moisture varies rapidly in time and space. This, combined with the errors associated with the measurement of moisture by radiosonde (Nash et al. 1985), and the resolution of the ECMWF analyses and the collocation criteria employed, may result in the basic statistics not truly reflecting the skill of the various schemes in depicting the mesoscale structure of these moisture fields. As a result, further detailed intercomparisons of these moisture fields are presently underway.

b. *Tasman Sea case*

The four datasets examined for the Tasman Sea case exhibited basic statistics that were similar, in many ways, to those seen in the ALPEX study. The problem with the Tasman Sea study, however, was that there was a lack of nonsatellite data for the intercomparison. As a result, the comparisons with RAOB data often represent only 10 to 20 collocations. In the study, the ECMWF analyses (which are predominantly over the sea) have been influenced by NESDIS sounding data. Interpretation of the intercomparison is further complicated by the use of NESDIS retrieval coefficients in the New Zealand retrieval scheme. Nevertheless, some of the basic statistics have been presented in Figs. 4a and 4b, chiefly because they provide some broadening of the intercomparison study.

The comparison of the satellite measured standard level temperatures with ECMWF analyses again showed rms differences near 2 K in between 850 and 300 mb, while comparison with the very limited number of radiosondes resulted in a wider scatter of results. The characteristics of the standard differences and rms differences near the surface and tropopause appeared similar to those for the ALPEX case. An examination of the biases for these Tasman Sea soundings indicated that they appear a little cold relative to the ECMWF analyses and RAOBs between 800 and 400 mb, and too warm near 200 mb. The variation in bias near the tropopause again reflected the inherent vertical smoothing of the TOVS data in that region.

The basic statistics for the thickness data were also calculated. Generally, the rms differences compared to either ECMWF or RAOB data for the 1000 to 700 mb layer were around 20 m; for the 700 to 500 mb layer, 20 m; and for the 500 to 300 mb layer near 25 m. The mean rms difference for the 1000 to 500 mb layer compared to ECMWF analyses was 29 m.

The correlation coefficients related to coincident satellite and ECMWF or RAOB standard level temperatures were calculated and are illustrated for the ECMWF comparisons (Fig. 4c). They had a similar variation with height to the ALPEX case. The standard deviations of the standard level temperatures were also calculated. Although the sample in the RAOB comparison is very small (and possibly not representative), it appears that the standard deviation of the satellite standard level temperatures below 100 mb is generally smaller than those of the RAOBs or the ECMWF analyses.

The standard difference of the precipitable water fields generated by different retrieval techniques were very similar to each other when compared to the ECMWF data, while in comparison to the very small radiosonde sample there was a wider scatter of results. Variations in rms differences when compared to ECMWF data (Fig. 4d) reflected a divergence in bias among the sets of sounding data. The rms differences compared to the ECMWF moisture data represent over 30% of the moisture for the 1000 to 400 mb column and well over 40% of the moisture in the 850 to 400 mb column.

c. United States case

Three datasets have been examined for the United States case and some of the basic statistics are seen in Figs. 4e and 4f. For the standard level temperatures, the standard difference and rms difference distributions derived by comparison with ECMWF or RAOB data are of the same general shape as those for the ALPEX study. The standard differences and rms differences were mostly near or below 2 K between 850 and 300 mb and are larger near the surface and tropopause. The small gradients in the temperature fields probably contributed to the general reduction in the magnitude of these differences compared to those of the ALPEX study, as they mitigated differences caused by the collocation criteria, interpolation and the different resolution of the data being compared.

Basic statistics for thickness were calculated for the USCA, USUK and USWI datasets. The rms differences compared to ECMWF fields or RAOB data for the 1000 to 700 mb and 700 to 500 mb layers were generally near or less than 20 m. The mean rms difference for the 1000 to 500 mb thickness compared to ECMWF was 28 m.

The correlation coefficients relating coincident satellite and ECMWF or RAOB standard level temperatures were computed and are illustrated for the ECMWF case. They had a similar variation with height to the ALPEX data, but had a reduced magnitude. This was caused, in part, by the lack of variation in the temperature field. This lack of variance in the temperature field was reflected in the reduced values of standard deviations which were apparent at most levels.

The precipitable water intercomparison showed that the rms difference compared to the ECMWF analyses represented over 30% of the moisture in the 1000 to 400 mb column and just over 40% of the water in the 850 to 400 mb column. The differences compared to RAOB data represented over 30% of the moisture in both the 1000 to 400 mb and in the 850 to 400 mb column.

5. Summary and conclusions

Eighteen sets of soundings from internationally distributed institutions, which were derived using a variety of statistical and physical retrieval techniques, have been intercompared. No attempt has been made, nor is there any intention, to rank the retrieval schemes relative to one another. The statistics presented here are not simply a function of the basic retrieval method but are related, in a complex way, to:

(i) The number of retrievals, i.e.; they are very susceptible to change as a result of editing procedures and, as a result, to which particular radiances are processed (see Table 1).

(ii) The characteristics of the first guess fields (see for example, Smith et al. 1983, and Susskind et al. 1985).

(iii) The use of ancillary data, i.e.; the use of surface observations, AVHRR data, etc. (compare for example ALIT1 and ALIT2).

(iv) The scheme used to remove the effect of clouds from the observed radiances (compare for example, Hayden et al. 1985; Susskind et al. 1985).

(v) The resolution of the retrieval scheme, i.e.; the number of radiance observations used to generate each retrieval and, in some cases, whether the same radiances have been used in the generation of different soundings (compare for example, Chedin and Scott 1983; McMillin 1983).

(vi) The relative contributions of clear, cloudy and overcast soundings, and a variety of other influences.

With these considerations in mind, however, valuable general comments about the salient features of the various retrieval schemes can be made:

1) Notwithstanding the recognized advantages of the physical retrieval schemes (Menzel and Lynch 1983; Smith et al. 1983), the general accuracy and consistency of the retrieved soundings at the scale examined were, to a significant degree, independent of the retrieval scheme used. This was illustrated by comparison of satellite significant level temperature, thickness, and precipitable water values to both ECMWF and RAOB data. This is no indication that the advantages of physical schemes compared to some common statistical methods are insignificant in areas such as limb correction (Le Marshall and Schreiner 1985) and, for example, in the explicit accounting for emissivity, elevation and skin temperature in the profile solutions. It also does not indicate the possible advantages of using a model first guess as part of a physical retrieval scheme. In that case, perturbation of the profile in such a way as to be consistent with the observed radiance field, while at the same time maintaining, where possible, its fine structure and baroclinic characteristics, should improve the retrieval fields in a way significant to numerical weather prediction. These results do indicate, however, that the use of statistical regression techniques which are simpler, faster and require smaller computing resources still deserve attention because of their clear utility to a large number of user groups. Improvements in these schemes in areas such as limb correction (noted in Le Marshall and Schreiner 1985), in cloud clearing, in the use of surface elevation and other parameters in the profile solution would benefit these schemes considerably.

2) Both operational and research processing of TOVS radiances data has indicated that the TOVS instrument is capable of providing soundings with rms differences near 2 K compared to ECMWF analyses and RAOB data from 850 mb to the tropopause region. The size of these differences points to the utility of the data, especially when one considers the differences in scale associated with the RAOB and ECMWF data; differences generated as a result of the collocation criteria and the errors in the RAOB and the ECMWF temperature values themselves. The TOVS versus RAOB statistics can be further analyzed using the figures provided by Bruce et al. (1977) to estimate radiosonde errors and to estimate the temperature variability over small horizontal distances. A typical calculation for the midtroposphere shows that the contribution resulting from comparison of an area averaged temperature and a point temperature is near 1 K for typical separation distances in this study. At 700 mb for example, removal of these effects reduces a typical rms difference of 2.1 K to 1.8 K. This figure (1.8 K), however, still contains differences due to the systematic errors arising from the use of different radiosonde types and correction procedures for radiation effects (see, e.g., McMillin et al. 1983). These factors were not included in the Bruce et al. 1977 study. The figure also contains differences due to the time differences between the compared soundings, the effects of RAOB translation during flight, and other factors.

3) There was an increase in the magnitude of the differences near the tropopause and surface. The inherent vertical smoothing of the TOVS profile in these regions of sharp vertical temperature gradient contributed to this increase. These differences were changed considerably by the ancillary data (e.g. surface data) or constraints.

4) The magnitude of geopotential thickness differences displayed in this study attests to the utility of the data, particularly those thicknesses over significant layers where a cancellation of biases tends to occur. The 1000 to 500 mb thickness, for example, shows rms differences of only three to four dm. In the Southern Hemisphere the alternative to using these data over most of the hemisphere is cloud picture interpretation (Guymer 1978), where the resulting rms errors are considerably higher.

5) The basic statistics associated with the retrieval of moisture show a useful degree of skill, particularly when one considers the effects of comparing a field of such high spatial and temporal variability with ECMWF fields and RAOB data and when the errors associated with the measurement of moisture by radiosonde are taken into account (Nash et al. 1985). The degree of skill shown suggests a utility for both NWP and nowcasting applications, where a detailed horizontal distribution as well as the vertical distribution of moisture is required for forecasting purposes. The utility of the sounding data for nowcasting applications has already been demonstrated by Keller and Smith (1983) in a study of severe weather occurrence over the United States.

Comparisons of the differences in this study with those in previous studies of both Nimbus 6 and TIROS-N statistical retrievals (Schlatter and Branstrator 1979; Schlatter 1981; Gruber and Watkins 1982; McMillin et al. 1983) show roughly similar magnitude differences for both experimental and operational retrievals of temperature in the midtroposphere for the periods studied. The figures in these studies, however, were derived for layer mean temperatures, which makes direct comparison of difference data difficult because of the reduction in larger differences when layer averages are compared to level data. In particular, differences near the tropopause are not only dependent on the sample studied but are particularly dependent on the precise temperature fields compared. The comparison of satellite derived mean layer temperatures, using layers typically as deep as 100 mb to 200 mb (with layer mean thickness from analyses in some of these studies) has led to statistics showing smaller differences near the tropopause. This reduction of large (level temperature) differences near the tropopause by comparing layer mean temperatures is illustrated, for example, in Fig. 8 of McMillin et al. (1983).

In summary, 18 sets of sounding data derived using different retrieval techniques have been examined. The basic statistics for the derived temperature, geopotential thickness and moisture have been calculated, illustrated and summarized. Two major problems still hinder further refinement of the intercomparison study. One is use of radiosondes which, as yet, have not been reliably intercalibrated. Although this task is being addressed by recent WMO intercomparison studies (Kitchen et al. 1985; Schmidlin and Finger 1985; etc.) and several data analysis centers, there is still no way of removing systematic differences reliably from data derived from different radiosondes. The establishment of a baseline upper-air network may be a significant step in solving this problem. The second problem concerns the estimation and removal of differences generated by comparing quantities observed at different resolutions. This problem, and particularly how it relates to the moisture field, is presently being examined. A study of the effects of measurement scale on the intercomparison, additional statistics and further contrasting of the differences between the physical and statistical techniques is currently underway.

Overall, however, the differences illustrated in this study indicate that an almost uniformly high standard of retrieval skill has been established on an international level. Differences between retrieval level temperatures and ECMWF analyses or RAOB data were seen to be near 2 K through much of the troposphere and differences were seen to be near 3 K or 4 K around the tropopause. These figures suggest that the goal of satellite sounding producers to optimize and, where appropriate, standardize, TOVS processing procedures so as to provide accurate and uniformly consistent soundings to the meteorological community is rapidly being achieved.

With regard to retrieval techniques themselves, three directions of development appear warranted.

The skill shown by the statistical techniques suggests that their further development is important to provide fast, efficient and accurate retrievals requiring limited computing resources. There are several areas in which the retrieval process would clearly benefit from such development. These include limb correction which, for instance, may be done in the future after cloud clearing, or avoided by using regressions associated with a particular angle. The use of ancillary data such as surface data and surface elevation would also benefit many schemes. The statistical schemes are comparatively simple and efficient and require limited computing resources. This makes them particularly suitable for use by groups establishing direct readout stations. At the same time, the demonstrated quality of their statistical retrievals make them useful for both nowcasting and NWP applications.

The clear advantages of the physical retrieval schemes in several areas have been recorded previously (Smith et al. 1983). These include explicit treatment of skin temperature, emissivity, elevation and the proper treatment of limb effects in obtaining a temperature profile. These advantages, combined with those of using the characteristics (such as baroclinicity or the detailed structure) of a numerically predicted first guess field and the ease of the use of the ancillary data, suggest that appropriately developed versions of these schemes are a favored option for future operational use. In particular, the early indications of skill in the simultaneous schemes in the area of moisture retrievals make their development an important priority, given the importance of moisture distribution in both nowcasting and numerical weather prediction. It should also be noted that the requirement for coincident RAOB/satellite data is substantially lessened, in comparison to the usual statistical schemes, for the operational running of these schemes.

The remaining direction for development is in the area of the direct use of radiances in numerical analysis schemes themselves (see e.g. Durand and Juvanon du Vachat 1983). These schemes have the advantage of using both the first guess fields, ancillary data and radiances in a statistically optimal way. They also facilitate horizontal consistency in the resultant temperature and moisture fields. The widespread use of these schemes relies, however, on several factors. These especially include the generation of a suitable statistical dataset for use in these analysis schemes and, in some cases, the production of high quality limb corrected radiances.

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