Comparison of Layer Thickness as Observed by Nimbus E Microwave Spectrometer and by Radiosonde

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ABSTRACT

Atmospheric layer thicknesses derived from Nimbus 5 (Nimbus E) Microwave Spectrometer (NEMS) are compared with radiosonde-derived thicknesses for selected short periods, and an average 45 m rms discrepancy is found for the 100–50 kPa layer. The several sources of this discrepancy are quantified in the following ways. Correlation coefficients between pairs of NEMS observations and between pairs of radiosonde observations are each extrapolated to zero separation distance to provide measures of instrument noise; NEMS noise is found to be 16 m rms and radiosonde noise 23 m rms. (This result is substantiated through comparisons of NEMS and radiosonde horizontal layer-mean temperature gradients with independent measures provided by assuming that the smoothed vertical wind profile as measured by rawinsondes is in thermal wind balance.) Correlation coefficient behavior with decreasing separation distance also leads to estimates for those portions of the total discrepancy which are due to different resolution of the sensors (~15 m rms) and real spatial and temporal variation of the atmosphere between observations (~17 m rms). Geometric addition of all contributions yields an estimate (~27 m rms) of NEMS errors (due to basic limitations of a remote sensing system) which vary on longer scales than those previously attributed to noise. Total NEMS error (noise plus more slowly varying error) is then 31 m rms (1.6 K) for the 100–50 kPa layer.

1. Introduction

The Nimbus 5 satellite, launched in December 1972, carries the Nimbus E Microwave Spectrometer (NEMS), described by Staelin *et al.* (1972). Briefly, NEMS consists of five nadir-viewing passive microwave radiometers, three of which sense radiation in a wing of the O_2 absorption complex near 60 GHz (~5 mm) providing information which is used in a statistical inversion scheme to infer a temperature profile in the subsatellite column (Waters *et al.*, 1975). With a half-power beamwidth of 10° and with integration of radiances over 16 s periods, NEMS views a quasi-oval column 200 km wide and 300 km long. Unlike infrared frequencies, the NEMS O_2 channels are virtually unaffected by all but quite dense clouds (Staelin *et al.*, 1975a) and in the present work no corrections for cloud contamination are made.

A realistic assessment of the accuracy of meteorological data obtained from satellite systems is of considerable importance, especially as one contemplates supplementing or replacing the rawinsonde system with this newer one. Several authors have compared temperatures inferred from satellites with nearby radiosonde measurements (e.g., Wark and Hilleary, 1969; Waters *et al.*, 1975). However, these direct satellite-radiosonde comparisons actually yield overestimates of satellite error by not taking radiosonde inaccuracies and other sources of discrepancy into account quantitatively. Comparison with constant pressure analyses (e.g., Johnson and McInturff, 1970; Waters *et al.*, 1975) incorporates several of these discrepancy sources but cannot directly determine the relative accuracies of the satellite and radiosonde systems. Hayden (1971) estimated relative accuracy by finding the discrepancy between a SIRS-A sounding and the average of several nearby radiosondes and comparing it with the discrepancy between one radiosonde and the average of several nearby radiosondes. In the present study the question of accuracy is approached differently: We find discrepancies between NEMS and nearby radiosondes by direct comparison and then apportion this discrepancy between several sources, including errors in NEMS and radiosondes, and differences arising from the different spatial characteristics of the two types of observations, and the real spatial and temporal difference between the observations. In this study, NEMS errors are separated into those which vary on the scale of around 500 km (~1.3 min) or less, which we will call "noise," and those which vary on longer scales.

2. Direct NEMS-radiosonde comparisons

Twice daily global radiosonde data were kindly provided by Dr. John Stackpole of the National

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TABLE 1. Discrepancies between NEMS and radiosonde layer thicknesses (m).[1]

		January			June		
	Layer (kPa)	Mean discrepancy	Standard deviation	Number of cases	Mean discrepancy	Standard deviation	Number of cases
Low-latitude land (equator to 30°)	100–50	68.1	52.7	15	44.0	36.4	9
	50–25	−37.8	49.7	14	−36.0	41.2	10
	25–5	−127.1	158.3	6	−5.4	61.0	3
Low-latitude oceans	100–50	27.8	41.2	17	0.9	19.8	9
	50–25	−55.5	47.1	17	−43.4	30.5	10
	25–5	−73.6	90.4	17	45.2	55.1	6
Mid-latitude land (30° to 55°)	100–50	63.1	43.5	54	3.5	37.4	41
	50–25	47.4	60.8	53	−2.9	46.3	41
	25–5	−172.6	133.2	25	−71.3	142.9	13
Mid-latitude oceans	100–50	27.9	44.9	17	0.9	30.1	16
	50–25	17.2	70.7	17	6.1	59.3	16
	25–5	−95.8	114.7	8	−44.3	84.1	8
High-latitude land (55° to 80°)	100–50	92.2	66.4	75	−7.9	39.4	48
	50–25	35.4	48.2	75	27.4	42.1	45
	25–5	−104.9	127.3	50	−180.5	123.5	15
High-latitude oceans	100–50	59.3	26.6	8	−8.0	19.9	9
	50–25	58.9	28.9	8	−0.7	36.8	9
	25–5	−174.4	45.9	6	−94.9	61.4	3

[1] Mean discrepancies are NEMS minus radiosonde.

Meteorological Center for two periods: 26–31 January 1973 and 18–23 June 1973. Whenever a radiosonde was within 120 km of a NEMS sounding it was considered close enough for comparison provided the time discrepancy did not exceed the following: If the pair was between the equator and 20° latitude, ±5 hours; if between 20° and 30°, ±4 hours; if between 30° and 40°, ±3 hours; and if between 40° and 80°, ±2.5 hours. This variation was based on a desire to obtain a significant number of matches at low latitudes where radiosondes are scarce and is excused by the observation that large-scale weather patterns, on the average, change less rapidly at a station in the tropics than in middle and high latitudes. Applied to the quasi-polar, local-noon-ascending nature of the orbit, these time constraints limit the possible match areas to Africa, Europe, the Atlantic and Pacific Oceans, Alaska, extreme northeastern Asia, extreme northern Canada, Greenland, Australia and Antarctica. Radiosondes selected for comparison were checked for obvious transmission and coding errors, and heights were recomputed hydrostatically.

The availability of only three O_2 channels in NEMS suggests that the maximum number of independent data obtainable is three. Thus, thicknesses for the layers 100–50, 50–25 and 25–5 kPa were computed from the inferred temperature profile and compared with the radiosonde layer thicknesses; mean discrepancies and standard deviations appear in Table 1. The mean discrepancies for the January sample show the NEMS inferences for the two lower layers to be generally 1.5–3 K too warm, while the upper layer is 1.5–3 K too cold. In the June sample, magnitudes of the mean discrepancies are generally smaller and show no systematic pattern. It is reasonable to assume that an improved inversion scheme, using seasonally and geographically dependent regression coefficients, can substantially decrease the mean discrepancies. Therefore, the remainder of this paper will deal with standard deviations, which are considered to be the more important measure of discrepancies. Table 1 gives an indication of regional variation of errors (note that overwater errors are smaller than those overland). But for what follows we combine and average all regions and both periods, yielding standard deviations of 45, 49 and 115 m, corresponding to 2.3, 2.5 and 2.4 K, for the layers 100–50, 50–25 and 25–5 kPa, respectively.

In addition to its own errors, NEMS will disagree with nearby radiosondes due to radiosonde errors and real spatial and temporal variations between the radiosonde track and the subsatellite column. Also, a NEMS sounding represents an integration of radiances over an area $\sim 4 \times 10^4$ km² while a radiosonde measures parameters through one curve in space. These considerations make it very hazardous to draw conclusions about NEMS accuracy from direct comparison with radiosondes without estimates of these sources of disagreement. The next sections describe procedures through which we obtain those estimates.

3. Instrument noise from correlation of thicknesses

a. *NEMS versus NEMS correlations*

NEMS thicknesses were correlated with other NEMS thicknesses which were observed 100, 200, 300, 400 and 500 km downtrack from the first. The January correlations (Fig. 1a) are from pairs of observations taken

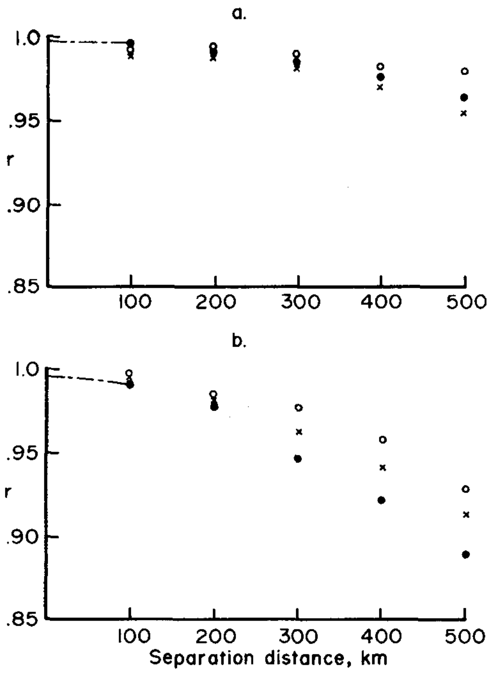

FIG. 1. Correlation coefficient r for NEMS thickness versus NEMS thickness as a function of separation distance between observations: (a) January sample (global), (b) June sample (between 25°N and 60°N). Closed circles pertain to 100–50 kPa thickness, open circles to 50–25 kPa thickness, and crosses to 25–5 kPa thickness. The number of pairs of observations available for each layer at each distance increment is near 300.

from all regions of the globe. Note that the correlation coefficients remain high (>0.95) even at separations up to 500 km. The June thickness correlations (Fig. 1b) decline more rapidly, presumably because of a greater relative influence of smaller scales of temperature variability. Note also that the June pairs were solely from the latitude band 25°N to 60°N.

To gain a measure of noise in the NEMS system, one can extrapolate the correlation coefficients to zero separation distance. An estimate of rms noise is then $[\sigma^2(1-r_0^2)]^{\frac{1}{2}}$, where σ^2 is the variance of the sample and r_0 the (extrapolated) correlation coefficient at zero separation. This technique is part of a statistical objective analysis method proposed by Eddy (1967) and used by Sanders *et al.* (1975) in an operational context. Although correlation coefficients for all three layers are plotted, the (subjective) extrapolation is shown for only the 100–50 kPa layer values as the dash-dot curves in Fig. 1. For January the zero separation intercept occurs at $r\approx 0.997$ which means that $1-(0.997)^2$ or 0.6% of the variance of the data is unexplained by the correlation and can be attributed to noise. For this January period the standard deviation of the NEMS-derived global 100–50 kPa thicknesses is 315 m, so the noise between a NEMS "observation pair" (hypothetically coincident and independent observations) is $[0.006(315)^2]^{\frac{1}{2}}$ or 24 m rms. (Noise values are of course quite sensitive to the extrapolation to zero distance. For example, an intercept of 0.998 yields a noise of 20 m rms and 0.996 yields 28 m rms. The reader should keep this in mind when evaluating subsequent results.) Noise in an observation pair of 24 m rms corresponds to a single observation noise of 17 m rms [i.e., $(17^2+17^2)^{\frac{1}{2}}=24$]. For June the intercept is at $r\approx 0.992$ which leads to a single observation noise of 14 m rms when a sample standard deviation of 160 m is used. (This is a smaller sample standard deviation because the June sample was only from mid-latitude summer regions.) These values average to a single observation noise of ~16 m rms, or ~22 m rms noise between a NEMS observation pair.

b. Radiosonde versus radiosonde correlations

Fig. 2 shows the results of correlations between simultaneous, reported (i.e., not recomputed) thicknesses at nearby pairs of radiosonde stations. Correlation coefficients of pairs separated by 100–150 km are plotted at 125 km, those of pairs separated by 150–200 km are plotted at 175 km, and so forth. The pairs were taken from regions in Europe, the mid-latitude western Pacific and North America during the previously described January and June periods. (The June radiosonde sample has a twist: We accepted only pairs oriented more north-south than east-west. In so doing, we more closely simulated NEMS sampling,

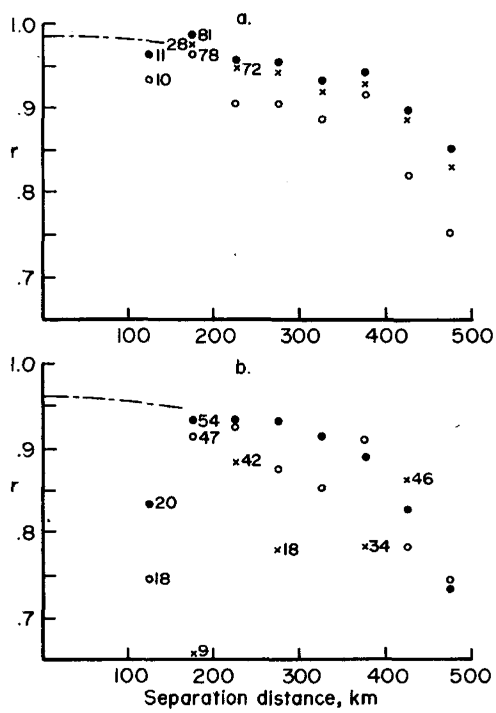

FIG. 2. Correlation coefficient r for radiosonde layer thickness versus radiosonde layer thickness as a function of separation distance between observations: (a) January sample (random orientation of pairs), (b) June sample (primarily north-south orientation of pairs). When number of pairs used is less than 100 the number is shown. Symbols are as in Fig. 1.

which is predominantly north-south in middle latitudes.) Extrapolation to zero separation of the radiosonde 100–50 kPa thickness correlation coefficients yields intercept values near 0.98 for January and 0.96 for June. These correspond to single-observation rms noise levels of 21 m for January ($\sigma=150$ m) and 26 m for June ($\sigma=130$ m), averaging to 23 m rms in a single observation or 32 m rms in an observation pair, significantly larger than NEMS noise. The radiosonde single observation noise is consistent with the ~25 m rms difference between individual radiosondes and good quality objectively analyzed 50 kPa height fields (Gandin and Lugina, 1969).

4. Correlations of horizontal, layer-mean temperature gradients

We also evaluated the relative noise levels of both NEMS and radiosonde systems through comparisons of horizontal, layer-mean temperature gradients with independent measures provided by assuming that the smoothed vertical profile of wind as observed by rawinsondes is in thermal-wind balance. For this comparison, the vertical profile of the wind component perpendicular to a line joining two rawinsonde stations

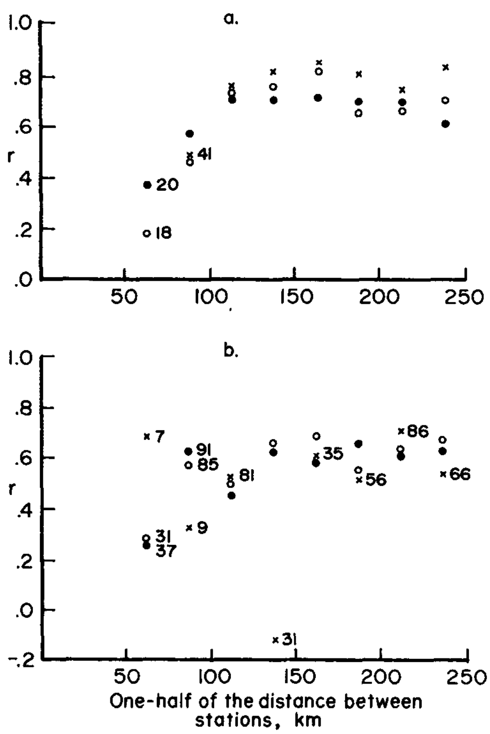

FIG. 3. Correlation coefficients r for radiosonde thickness-determined temperature gradient versus wind-shear-determined temperature gradient. The abscissa is the distance between each rawinsonde station and the midpoint of the line which joins it and its paired station. (a) January sample (random orientation of pairs), (b) June sample (primarily north-south orientation of pairs). When number of pairs used is less than 100, the number is shown. Symbols are as in Fig. 1.

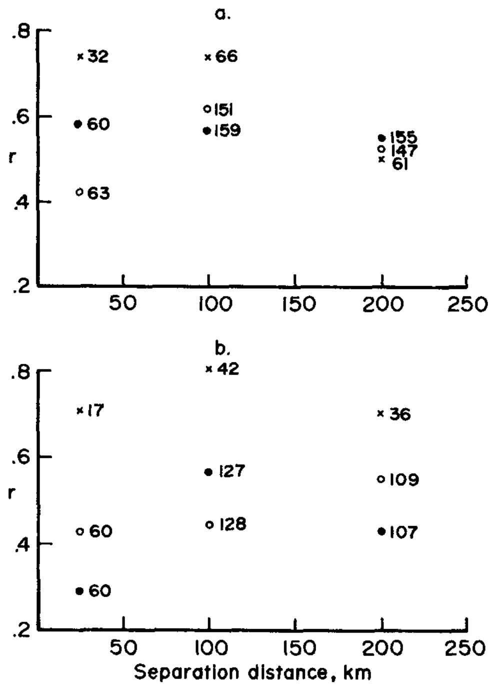

FIG. 4. Correlation coefficients r for NEMS temperature gradient versus wind-shear-determined temperature gradient. The abcissa is the separation distance between rawinsonde and the closest NEMS data. (a) January sample, (b) June sample. The numbers of pairs used are shown. Symbols are as in Fig. 1.

(or to the satellite track) was approximated by a straight line (determined by the method of least squares). The implied temperature gradient, calculated from the thermal wind equation, was compared with thickness-determined temperature gradients from either a close NEMS pass or from the data at the two rawinsonde stations. Correlations between wind-shear-determined horizontal temperature gradient and radiosonde thickness-determined temperature gradient as a function of distance are shown in Fig. 3, wherein distance is half the separation between station pairs because the thickness-determined temperature gradient is assigned to the midpoint between the two stations. As in the thickness correlations, the June experiment sampled pairs whose orientations were more north-south than east-west.

Fig. 4 shows the separation dependence of the correlation coefficient between shear-determined temperature gradient and NEMS temperature gradient. The points plotted at 25 km are correlations between the sets of observations from 0 to 50 km apart, the points at 100 km are for observations between 50 and 150 km apart, and the points at 200 km are for those between 150 and 250 km apart. For the purpose of compatibility with Fig. 3, we used in Fig. 4 a NEMS temperature gradient over a distance comparable to the distance between the satellite track and the rawinsonde station.

Differences between thickness-determined (both NEMS and radiosonde) and shear-determined temperature gradients arise from several sources. However, the present argument relies only upon those errors having effects which depend on separation distance, and these number but two: 1) noise, which acts to decrease correlations with *decreasing* separation, and 2) truncation error (due to real spatial variation of temperature gradient), which acts to decrease correlations with *increasing* separation. Rawinsondes from generally the same geographical regions were used to compare against both radiosonde and NEMS temperature gradients, so the effects of truncation error should be comparable in Figs. 3 and 4. The point we wish to make is that, although lacking sufficient comparisons to permit greater resolution, it appears that the NEMS-rawinsonde (Fig. 4) correlations reach their highest values at shorter separations than the radiosonde-rawinsonde (Fig. 3) correlations. Remembering that the effect of noise is to decrease correlation with decreasing separation, it follows that the maximum correlation at shorter separations in the NEMS-rawinsonde curves means that the noise in the NEMS system is smaller than in the radiosonde systems. Other non-noise errors, whose effects are not separation-dependent in any systematic way, will only act to raise or lower the correlation coefficient curves across the entire range of separations, but cannot alter the position of the maximum along the abscissa. These temperature gradient comparisons, then, qualitatively substantiate the result of the previous section, i.e., that NEMS noise is smaller than radiosonde noise.

5. Other sources of NEMS versus radiosonde discrepancies

So far this paper has presented various comparisons between radiosonde and NEMS systems. Direct matches showed that, in the 100–50 kPa layer, the standard deviation of the NEMS versus radiosonde thickness discrepancy is near 45 m rms, while correlation studies showed that single observation rms noise is 16 m for NEMS and 23 m for radiosondes.

In addition to noise, then, there must be a remaining $(45^2-23^2-16^2)^{\frac{1}{2}}=35$ m rms discrepancy in the direct comparisons. This discrepancy is contributed by a combination of three other factors:

(i) Errors in NEMS which occur on scales of several hundred kilometers or more.
(ii) Real spatial and temporal atmospheric variation between NEMS and radiosonde.
(iii) Effects of the different horizontal resolutions of the instruments.

To estimate factor (iii), the expected error in comparing an area measurement with a "perfect" point measurement at its center, we follow the procedure of Staelin *et al.* (1975b). Normalizing the radiosonde versus radiosonde thickness correlation coefficients (Fig. 2) so that the zero separation extrapolation yields perfect correlations, we then estimate the average correlation coefficient between perfect measurements at a point within a circle of (NEMS) area 4×10^4 km^2 and the circle's center. Again, this is a very sensitive procedure, but we feel that such an average correlation coefficient is near 0.993 for the 100–50 kPa layer in both January and June periods. Applying this result to the previously stated sample standard deviations of 150 and 130 m yields $\sim$15 m rms error due to area versus point observations.

This same procedure may be used to estimate that part of factor (ii) due to real spatial (but not temporal) variation between NEMS and radiosonde. The average separation in the direct matches of NEMS and radiosondes was 60 km, and at this distance the (normalized) correlation coefficient curves of Fig. 2 show a value near 0.995, which leads to 14 m rms discrepancy due to real spatial variability. If we arbitrarily add a 10 m rms discrepancy due to real temporal variability, the total discrepancy due to factor (ii) is $\sim$17 m rms.

Combining these various error estimates we can now estimate the error (i) to be $(35^2-15^2-17^2)^{\frac{1}{2}}\sim27$ m rms. This error, which varies over a longer period than what we have called "noise," is due to basic limitations of this, or any other, remote sensing system. Examples are retrieval errors due to overlapping weighting functions and non-optimum radiosonde sample for regression statistics. Also contributing are variations in surface emissivity, the existence of mountain ranges and areas of dense cloudiness.

Remembering that single observation NEMS noise was 16 m rms, the total error attributable to NEMS is $(16^2+27^2)^{\frac{1}{2}}\sim31$ m or $\sim$1.6 K rms. This agrees with theoretical and other experimental estimates (Waters *et al.*, 1975). We find slightly lower errors, which is consistent with our analysis of layer mean temperatures as opposed to level temperatures.

NEMS total error is larger than radiosonde noise (it is not thought that there is any appreciable additional systematic error in the radiosonde system). Furthermore, the larger part of total NEMS error (i.e., the slowly varying error) would not be appreciably "smoothed out" by objective analysis, since its scale is larger than the scale of typical objective analyses. These results indicate, in agreement with Staelin *et al.* (1975b), that NEMS soundings are not competitive with radiosondes where radiosondes are densely spaced, but are quite valuable over areas where conventional data are sparse or lacking, especially since NEMS soundings are largely unaffected by clouds.

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