IN-43-CR
52977
p. 26

JPL PUBLICATION 86-50

Evaluation of Geophysical Parameters Measured by the Nimbus-7 Microwave Radiometer for the TOGA Heat Exchange Project

W. Timothy Liu
Donald R. Mock

(NASA-CR-180151) EVALUATION OF GEOPHYSICAL PARAMETERS MEASURED BY THE NIMBUS-7 MICROWAVE RADIOMETER FOR THE TOGA HEAT EXCHANGE PROJECT (Jet Propulsion Lab.) 26 p CSCL 08E G3/43
N87-17110
Unclas 43689

December 1, 1986

NASA
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL PUBLICATION 86-50

Evaluation of Geophysical Parameters Measured by the Nimbus-7 Microwave Radiometer for the TOGA Heat Exchange Project

W. Timothy Liu
Donald R. Mock

December 1, 1986

NASA
National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ACKNOWLEDGMENTS

We are grateful to Dr. Paul Hwang of the Goddard Space Flight Center for information on the satellite data and to colleague Dr. David Halpern for providing the equatorial mooring data.

ABSTRACT

The data distributed by the National Space Science Data Center on the geophysical parameters of precipitable water, sea surface temperature, and surface-level wind speed, measured by the Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7, are evaluated with *in situ* measurements between January 1980 and October 1983 over the tropical oceans. In tracking annual cycles and the 1982-83 El Niño/Southern Oscillation episode, the radiometer measurements are coherent with sea surface temperatures and surface-level wind speeds measured at equatorial buoys and with precipitable water derived from radiosonde soundings at tropical island stations. However, there are differences between SMMR and *in situ* measurements. Corrections based on radiosonde and ship data were derived, supplementing correction formulae suggested in the data handbook.

This study is the initial evaluation of the data for quantitative description of the 1982-83 El Niño/Southern Oscillation episode. It paves the way for determination of the ocean-atmosphere moisture and latent heat exchanges, a priority of the Tropical Ocean and Global Atmosphere (TOGA) Heat Exchange Program.

CONTENTS

Tables

1. INTRODUCTION

The ocean and the atmosphere exhibit closely coupled variabilities in the tropics. The Tropical Ocean and Global Atmosphere (TOGA) program, organized by the Intergovernmental Oceanographic Commission and the World Meteorological Organization, is a global study of these phenomena. The TOGA Heat Exchange Project (THEP), recently established at the Jet Propulsion Laboratory, is an synergistic attempt to determine monthly mean surface heat flux in the tropical Pacific (Liu and Niiler, 1985) using satellite data. A major component of the ocean-atmosphere heat exchange is the latent heat carried by evaporation. At least three parameters measured by spaceborne sensors are required to determine the latent heat flux (Liu and Niiler, 1984); they are surface-level wind speed (U), sea surface temperature (T), and precipitable water (W). Precipitable water is the total water vapor in an atmospheric column. The Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 measured all three parameters during the 1982-83 El Niño/Southern Oscillation (ENSO) episode which had far reaching economical and ecological consequences (see, e.g., Cane, 1983). The determination of surface latent heat flux during this episode using Nimbus/SMMR data is one of the priorities of THEP.

Measurements of Nimbus/SMMR during the first year after launch were evaluated by Chang et al. (1984) and Gloersen et al. (1984) with optimistic results. During the NASA Sea Surface Temperature Workshops, it was suggested that SMMR calibration does not compensate adequately for changes in the engineering environment (see, e.g., Milman and Wilheit, 1985). This, together with sensor deterioration, may produce systematic errors which are not conducive to the study of short-term climate variability. It is, therefore, important for us to examine the error characteristics of SMMR data before using them in studying the ENSO episode. The ENSO episode, in turn, provides large and clear signals to test the sensor's sensitivity to interannual variation.

In this study, the Nimbus/SMMR geophysical data, archived and distributed by the National Space Science Data Center (NSSDC), are compared with *in situ* measurements at the temporal (monthly) and spatial (2° latitude x 2° longitude) resolution specified by THEP. The surface level mixing-ratio (Q) derived from SMMR W using the relation by Liu (1986) is also evaluated. As discussed in Section 2, different algorithms were used to process SMMR data at different periods. It is also important to remove error due to algorithm changes by comparing the data with *in situ* measurements that have consistent temporal characteristics. Reports from ships of opportunity provide the only *in situ* data set with large coverage and a consistent historical archive. Our present knowledge of large-scale fields of U, T, and Q were derived from these ship data. They are pivotal to our evaluation and form the basis in the determination of correction factors. Ship data are concentrated in the northern part of the tropical ocean and are scarce in equatorial and southern oceans. Ship data are, therefore, complemented by two sets of spot measurements: U and T at equatorial moorings; and W derived from radiosonde reports at island stations.

2. SMMR DATA

SMMR data were arranged according to the "production year" which starts in November and ends in October of the subsequent calendar year. Data from Year 2 to Year 5, covering a period from November 1979 to October 1983, were obtained from

NSSDC in what were indentified as PARM-LO tapes. The contents and processing algorithms for Years 2 and 4 were briefly outlined in the data handbook (NASA, 1985), but no documentation is available for Year 3 or 5. The three parameters U, T and W were extracted with time, earth location, and relevant data flags.

Different algorithms were applied to T in different production years to correct for errors arising from the temporal variation of engineering environment, but the same geophysical algorithm was used to derive U from satellite observations. For Year 2 data only, a table of W correction factors that depend on the month and on direction of the satellite orbit was provided in the handbook to be applied by the user. Different corrections for other years had been incorporated in the data distributed by NSSDC (P. Hwang, personal communication).

The U and T data provided by NSSDC do not include areas within 600 km of land. Daytime measurements of T are also excluded. Additionally, SMMR was turned on only during alternate days. The amount of data available in Year 5 is much less than available for other years, due to reasons yet to be identified.

3. IN-SITU DATA

Surface Marine Data (Tape Deck 1129) archived at the National Climatic Data Center (NCDC) were acquired for 1980-83. Three parameters, U, T, and the dew point temperature (T_d), were extracted after the application of a quality control procedure (see Liu and Niiler, 1985, for details). Comparisons of SMMR and ship data, described hereafter, are based on averages of 2° latitude by 2° longitude monthly bins in which there are more than ten ship reports of all three parameters.

The quality of ship data is unknown. For a quantitative error estimate, coincident 2° latitude by 2° longitude averages of U, T and Q from ship data were compared. For the boreal summer (June, July, and August) and winter (December, January and February) of 1983, all 2° x 2° areas that had more than 20 ship reports in each of the parameters per month were identified. The data in each 2° x 2° areas were then divided randomly into two groups and averaged by month. There were 875 pairs of coincident data during the winter and 1002 pairs during the summer. The standard deviation of the differences of each pair are shown in Table 1; they approximate the noise of ship data at the temporal and spatial scales considered.

As part of the Equatorial Pacific Ocean Climate Studies, moored buoys were deployed on the equator, providing almost continuous measurements of U and T from July 1981 to March 1983 at 95°W, and from August 1980 to April 1983 at 110°W, sampling at every 15 min. This set of data was acquired for evaluation. The average height of the anemometer was 3.8 m and the average depth of T measurements was 1 m (D. Halpern, personal communication).

Monthly mean soundings from radiosonde reports at 37 ocean stations, from 1980 to 1983, were extracted from NCDC Tape Deck 9648. These stations and their locations are listed in Table 2 and shown in Fig. 1. Monthly mean precipitable water was computed by integration using trapezoidal rule after quality selection (see Liu, 1986, for details).

Table 1. Standard deviation of the differences between coincident pairs of 2° latitude by 2° longitude monthly averages of ship measurements

Parameter	Winter	Summer
U (m/s)	1.15	0.88
T (°C)	0.55	0.55
Q (g/kg)	0.49	0.44

Table 2. Locations of radiosonde stations used in the study

Name	Latitude	Longitude	Name	Latitude	Longitude
Pacific Ocean			Atlantic Ocean		
St. Paul	57.2N	170.2W	Lerwick	60.1N	1.2W
Cold Bay	55.2N	162.7W	Stornoway	58.2N	6.3W
Guadalupe	29.2N	118.3W	OWS L	57.0N	20.0W
Midway	28.2N	177.4W	OWS R	47.0N	17.0W
Lihue	22.0N	159.4W	Bermuda	32.4N	64.7W
Wake	19.3N	166.7E	Gr. Cayman	19.3N	81.4W
Johnston	16.7N	169.5W	San Juan	18.4N	66.0W
Guam	13.6N	144.8E	Barbados	13.1N	59.5W
Yap	9.5N	138.1E	Curacao	12.2N	69.0W
Truk	7.5N	151.9E	Trinidad	10.6N	61.4W
Koror	7.3N	134.5E	Ilha Trin.	20.5S	29.3W
Majuro	7.1N	171.4E	Gough	40.4S	9.9W
Ponape	7.0N	158.2E			
Atuona	9.8S	139.0W			
Pago Pago	14.3S	170.7W			
Tahiti	17.6S	149.6W	Indian Ocean		
Nandi	17.8S	177.5E			
Norfolk	29.1S	167.9E	Seychelles	4.7S	55.5E
Lord Huwe	31.5S	159.1E	Cocos	12.1S	55.5E
Campbell	52.6S	169.2E	Nouvelle	37.8S	77.6E
Macquarie	54.5S	159.0E	Marion	46.9S	37.9E

ORIGINAL PAGE IS
OF POOR QUALITY

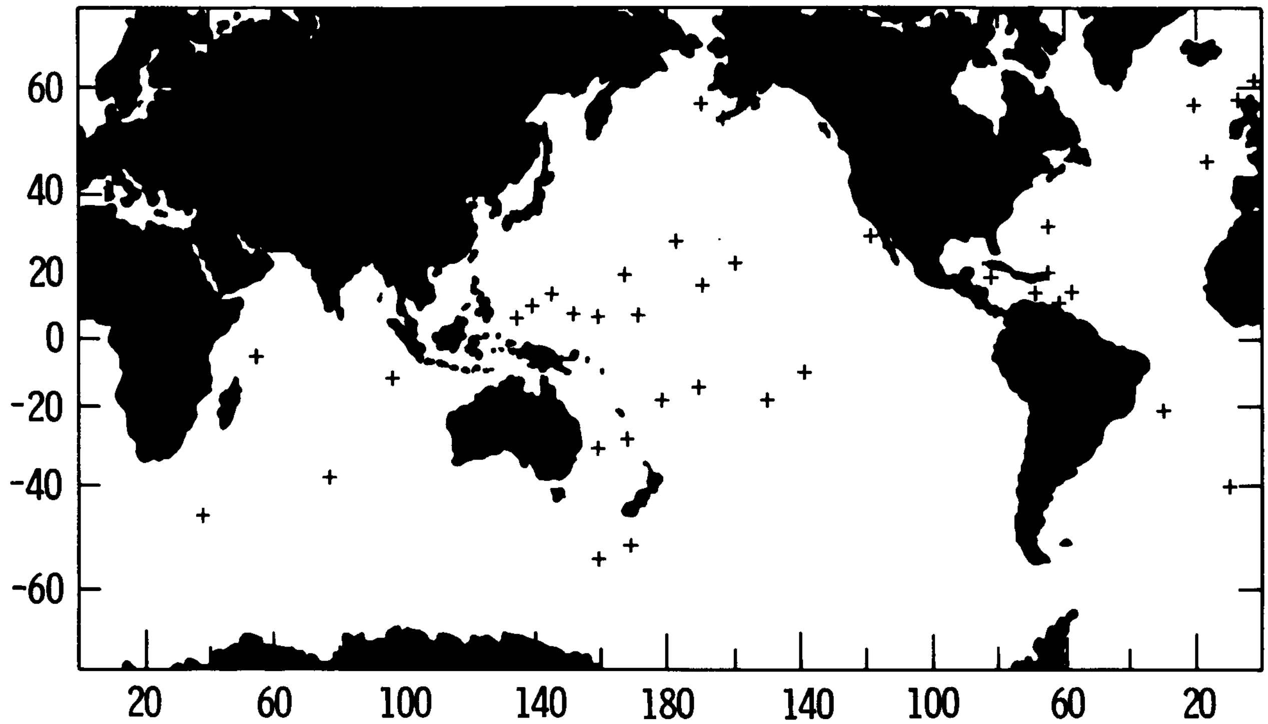

Fig. 1. Location of radiosonde stations used in the study

4. PRECIPITABLE WATER AND SURFACE-LEVEL HUMIDITY

Figure 2 shows the average of precipitable water over global oceans measured by SMMR. The values for 1981 and 1982 are quite constant, there is a large annual cycle in 1980, and the values drop precipitously starting in June 1983. The 1983 drop was probably caused by deterioration of the 21 GHz horizontally polarized channel (P. Hwang, personal communication).

Monthly mean precipitable water from radiosondes (W_r) was compared with the monthly mean from SMMR (W_n) in the 2° latitude by 2° longitude areas in which the radiosonde stations are located. The time series for four Pacific stations (Midway, Majuro, Atuona and Lord Huwe) are shown in Fig. 3 as examples. At Atuona, the data does not start until August 1981. It is shown as an example because its location is important with respect to the ENSO episode. In the Pacific, SMMR underestimates W for all tropical stations; the difference decreases away from the equator until it becomes negligible at midlatitudes. In the high latitude North Pacific (St. Paul and Cold Bay), SMMR overestimates W; but in the high latitude South Pacific (Macquarie and Campbell), SMMR appears to underestimate. In the tropical and midlatitude Atlantic, SMMR behaves as it does in the Pacific; but SMMR agrees closely with radiosonde data at high latitude North Atlantic stations (OWS L, Lerwick and Stornaway). In the tropical Indian Ocean, SMMR underestimates at Cocos but not at Seychelles. SMMR agrees with the radiosondes at midlatitude station Nouvelle, but overestimates at high latitude Marion. Therefore, in the tropics and midlatitudes, there is good agreement on the zonal dependence of SMMR errors in the three oceans. The only exception is at Seychelles but the data at this station may be erroneous. Such zonal dependence is more clearly defined in Years 3 and 4. Since, in general, W decreases away from the equator, the zonal dependence may reflect the lack of sensitivity of the sensor. At high latitudes, the error characteristics are different for the different ocean basins.

Forward stepwise multivariate regressions were used to determine correction formulae, for nine time segments, in the form of:

$$W_r = C_1 W_n + C_2 W_n^2 + C_3|\lambda| + C_4|\lambda|^2 + C_5 \quad (1)$$

where $|\lambda|$ is the absolute value of the latitude in degrees. The value of the coefficients C are listed in Table 3; missing values indicate that they do not pass the 5% significance test. The time segments correspond to one for each SMMR production year except for the last year. Starting in June 1983, each month has its own regression due to the rapid increase in error. There is consistent significant dependence of the error on W_n. The adjusted values (W_{n1}), obtained from (1) in the place of W_r, agree more closely with W_r at all tropical and midlatitude stations except Seychelles. The time series of W_{n1} are included in Fig. 3. Equation (1) does not remove all errors. In a few subtropical stations (e.g., Wake), W_{n1} is consistently lower than W_r during summer months when W peaks. The time series are characterized by predominant seasonal cycles. The 1982-83 ENSO is revealed by both SMMR and radiosonde data as a W deficit east of the dateline at Majuro and a W surplus west of the dateline at Atuona.

Surface-level specific humidity Q_n was derived from W_{n1} using the relation by Liu (1986) and used to compare with the specific humidity Q_s derived from the T_d from ship reports. Figure 4 shows the temporal variation of Q_n and Q_s averaged over all 2° x 2° areas within ± 30° of the equator that have more than 10 ship reports per month. The

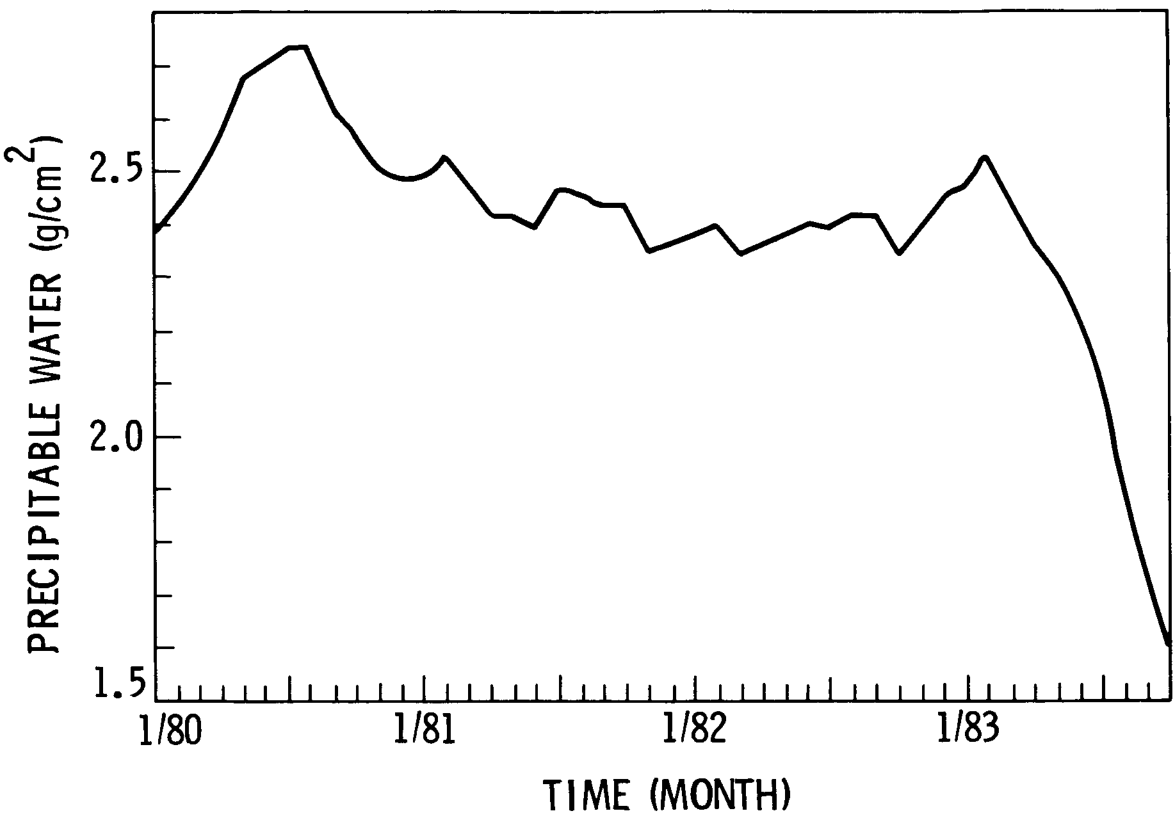

Fig. 2. Temporal variation of precipitable water measured by Nimbus/SMMR over global ocean (average of all binned data)

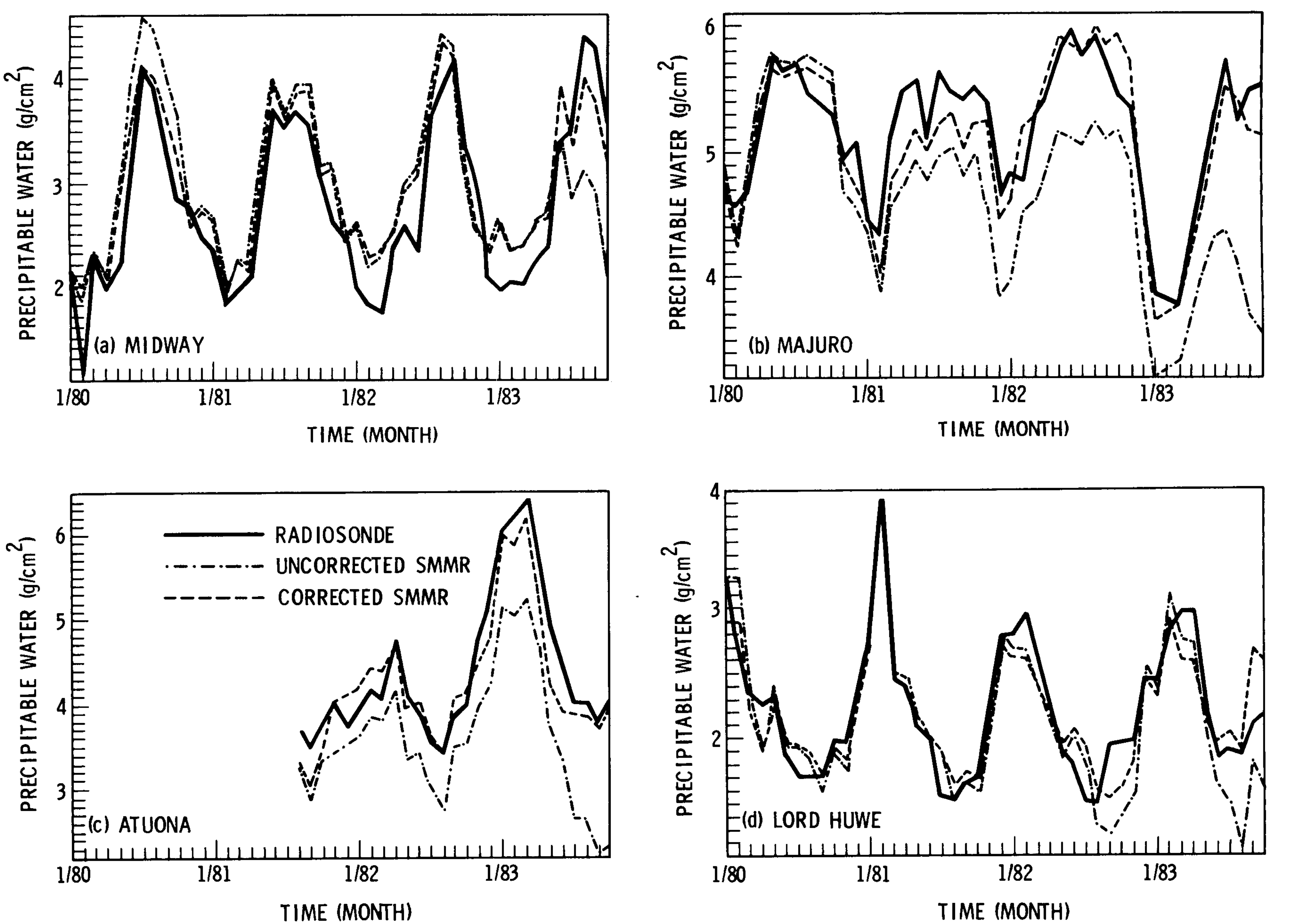

Fig. 3. Comparison of the temporal variation of precipitable water vapor derived from radiosondes, from uncorrected and from corrected SMMR data, at four stations in the Pacific

Table 3. Coefficients of SMMR precipitable water correction equation

Period	C_1	C_2	C_3	C_4	C_5
01/80-10/80	0.426	0.055	-----	-----	1.392
11/80-10/81	0.520	0.071	0.022	-0.001	0.787
11/81-10/82	0.498	0.065	-0.034	-----	1.844
11/82-05/83	-----	0.148	-----	-0.001	2.152
6/83	1.151	-----	-----	-----	0.070
7/83	0.925	-----	-0.036	-----	1.749
8/83	1.041	-----	-----	-----	1.136
9/83	0.964	-----	-0.028	-----	1.788
10/83	0.912	-----	-----	-0.001	1.947

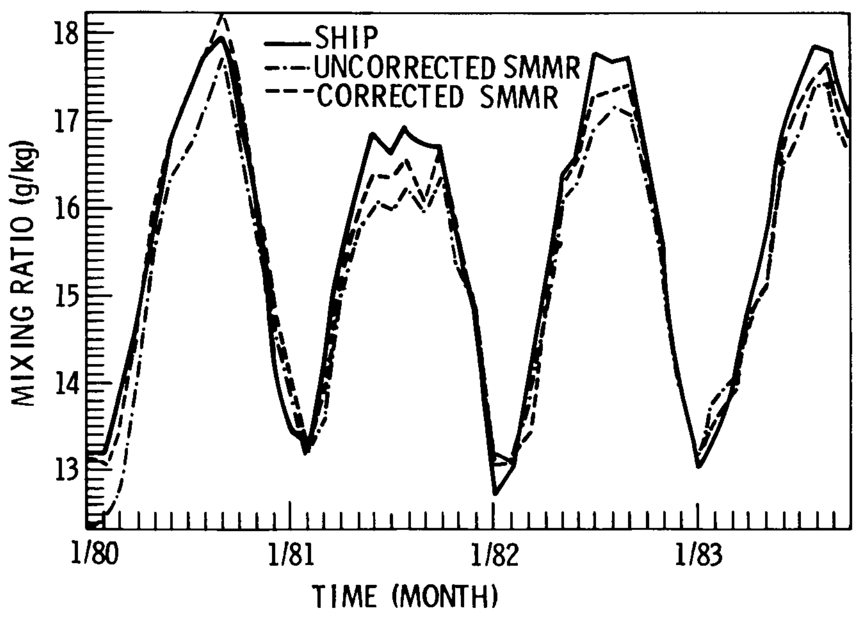

Fig. 4. Comparison of the temporal variation of the mean coincident binned surface-level mixing ratio derived from ship reports, from uncorrected and corrected SMMR data, over the tropical oceans

locations of these areas in January and July 1983 are shown in Fig. 5 as examples. In Fig. 4, Q_n is consistently lower than Q_s during summer and early fall. The reason may be an underestimation of W as discussed. However, inaccuracy of the Q-W relation from Liu (1986) cannot be completely ruled out.

For further adjustment of SMMR data, a forward stepwise multivariate regression in the form of

$$Q_s = C_1 Q_n + C_2 T_n + C_3 \tag{2}$$

was performed on four months (January, April, July, and October) of data for each production year. The coefficients are listed in Table 4. The corrected values (Q_{nc}) obtained in place of Q_s in (2) are also shown in Fig. 4. Figure 6 compares the standard deviation (STD) of Q_n-Q_s and Q_{nc}-Q_s. The correction (2) reduces not only the mean differences, but also reduces the STD by about 2 g/kg. The STD is about twice the values shown in Table 1 which approximates the noise level of ship data. The STD approaches the root-mean-square (RMS) differences as the mean differences become small. From Table 4, it is obvious that the SMMR errors have consistent dependence on T.

5. SEA SURFACE TEMPERATURE

The global mean T from SMMR data is shown in Fig. 7. The 1983 seasonal peak appears to be higher than normal but 1983 is an abnormal year. The temporal variation of binned T_s and T_n averaged over tropical oceans are shown in Fig. 8 similar to Fig. 4. SMMR underestimates ship values in general. Again, four months of coincident data were used to derive a linear regression in the form of

$$T_s = C_1 T_n + C_2 \tag{3}$$

for each production year. The coefficients are listed in Table 5. The corrected values (T_{nc}) obtained from (3) in place of T_s are also shown in Fig. 8. The correction removes most of the mean differences. The standard deviation is about 1.1°C, which is about twice the ship data noise, as shown in Fig. 9.

In Fig. 10, T_n is compared with measurements at equatorial buoys (T_b). Only buoy measurements within the hour of satellite overpass were averaged. Binned averages of T_n at both 1°N and 1°S are shown. At 95°W, the meridional gradient is large, as confirmed by the sea surface temperature fields operationally produced by the Climate Analysis Center (not shown). The temporal variation of T_n follows T_b at 1°S very closely until October 1982, at which time it shifted to follow T_b at 1°N more closely. At 110°W, the meridional gradient is not as large. T_n agrees closely with T_b at 1°S until August 1982. After that, T_n is about 1° lower than T_b. Correction based on ship data, in general, increases T_n by about 0.5°. It is known that ship measurements, taken at boiler intake, are generally higher than buoy measurements (e.g., Tabata, 1978). Again, both SMMR and mooring data show ENSO warming starting in July 1982, superimposed on the regular seasonal cycle.

6. SURFACE-LEVEL WIND SPEED

The temporal variation of the monthly mean U_n over global oceans is shown in Fig. 11. Year 5 data appears to peak higher than that of other years. The temporal variations of the global mean of coincident binned U_s and U_n are shown in Fig. 12. U_n is far

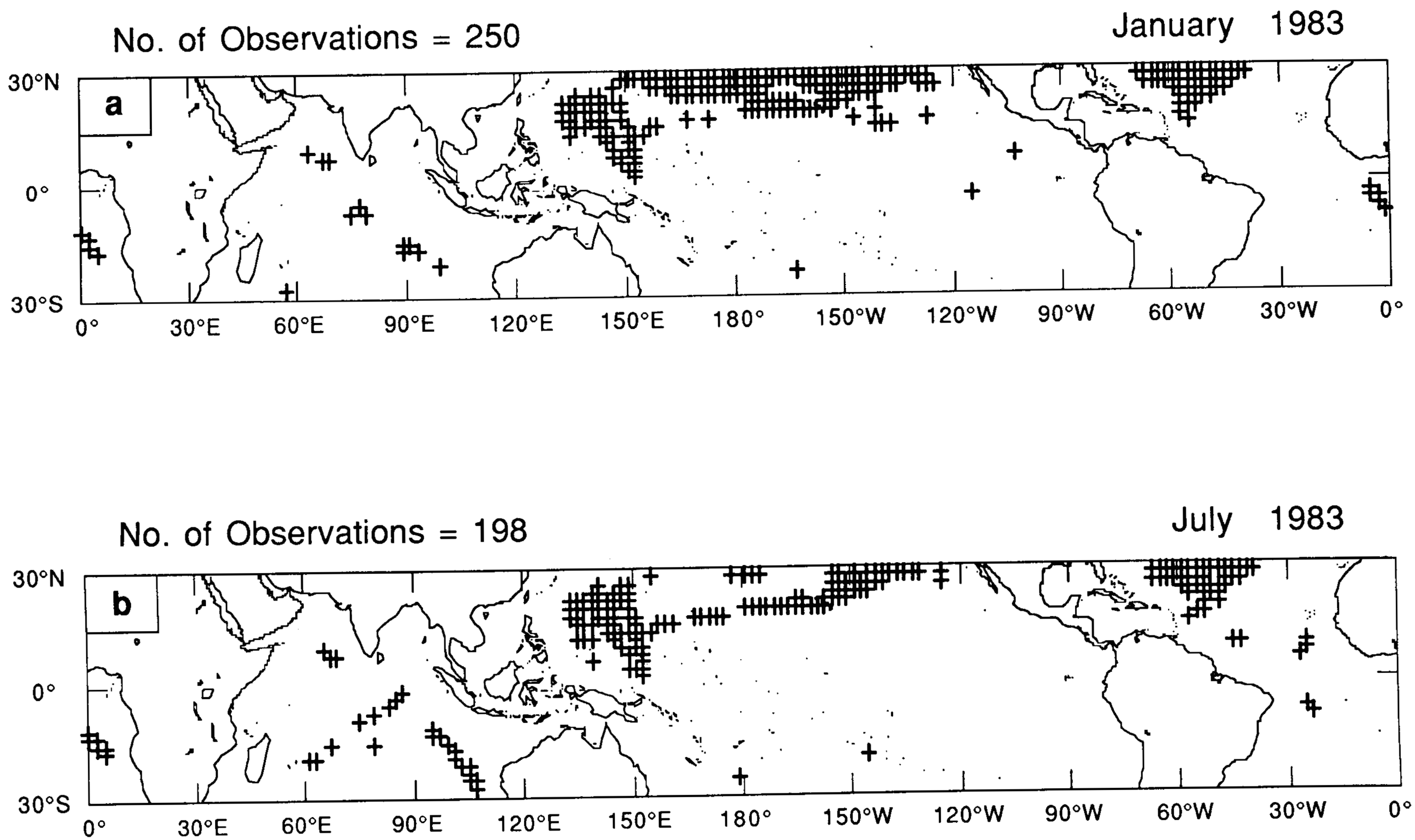

Fig. 5. Locations of 2° x 2° areas at which evaluations, such as that in Fig. 4, were made

Table 4. Coefficients of SMMR surface-level mixing ratio correction equation

Period	C_1	C_2	C_3
Year 2	0.728	0.312	-3.011
Year 3	0.616	0.445	-4.853
Year 4	0.614	0.548	-7.464
Year 5	0.663	0.474	-6.486

Table 5. Coefficients of SMMR sea surface temperature correction equation

Period	C_1	C_2
Year 2	1.000	0.573
Year 3	1.037	-0.339
Year 4	1.000	0.103
Year 5	1.013	0.029

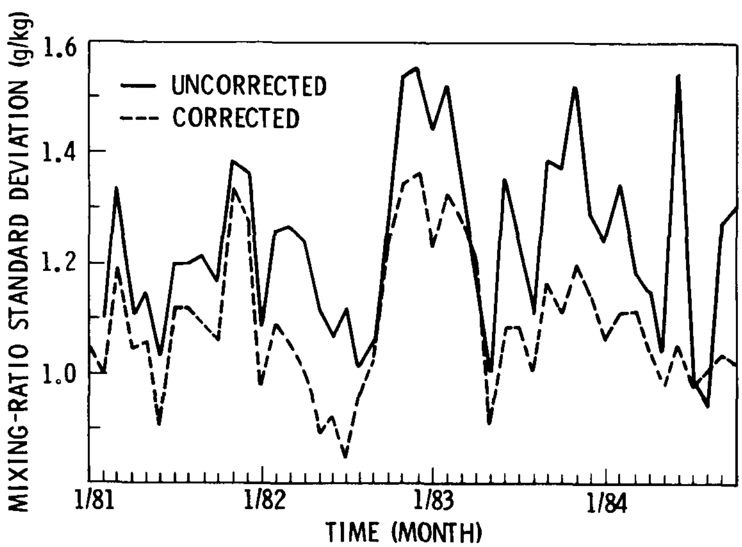

Fig. 6. The temporal variation of the standard deviation of the difference between surface-level mixing ratio derived from uncorrected SMMR data and ship data, as compared with the corrected SMMR data

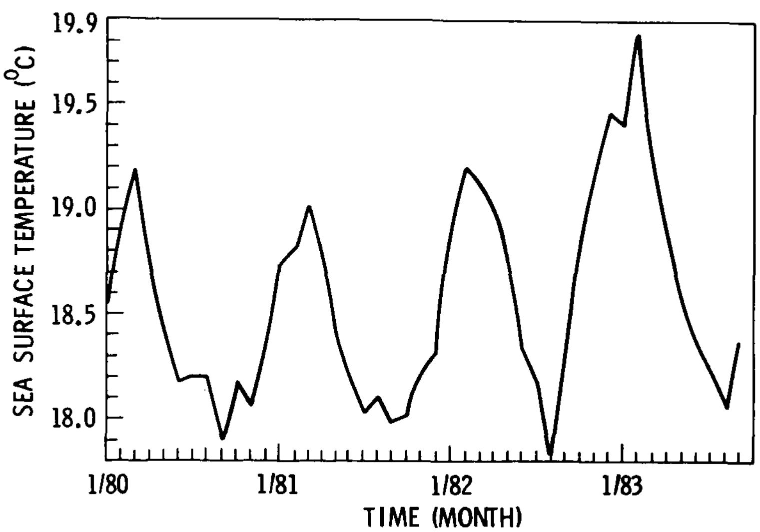

Fig. 7. Same as Fig. 2, except for sea surface temperature

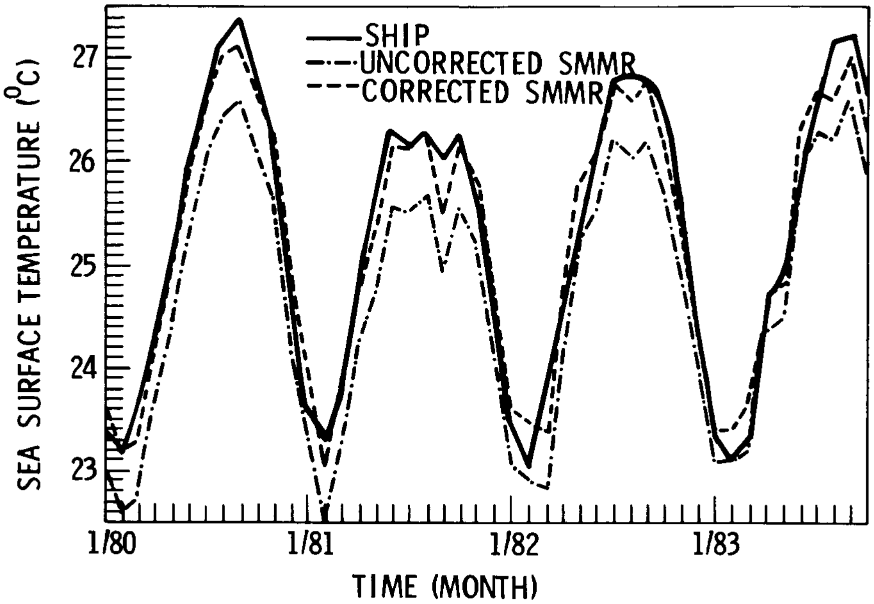

Fig. 8. Same as Fig. 4, except for sea surface temperature

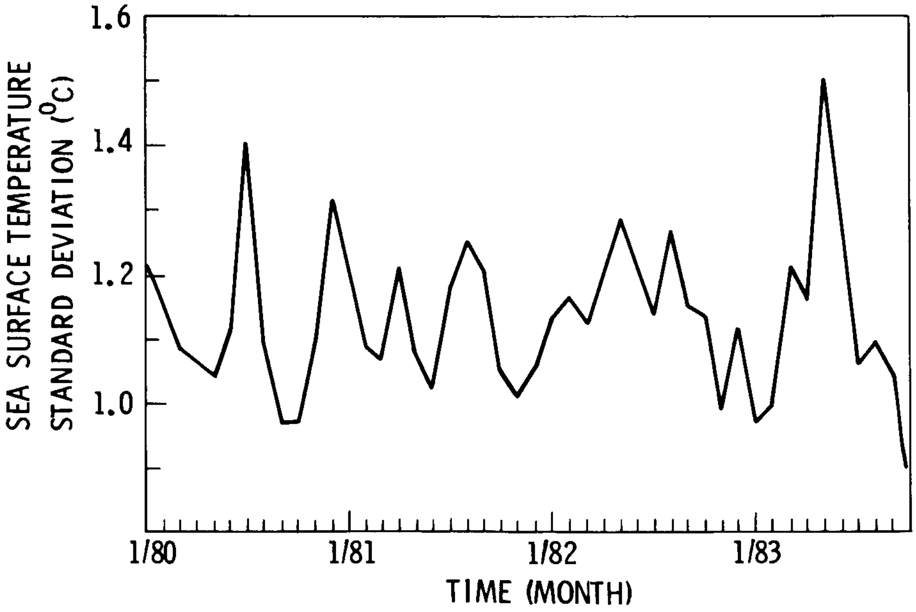

Fig. 9. Temporal variation of the standard deviation of the difference between sea surface temperature derived from SMMR data and ship reports

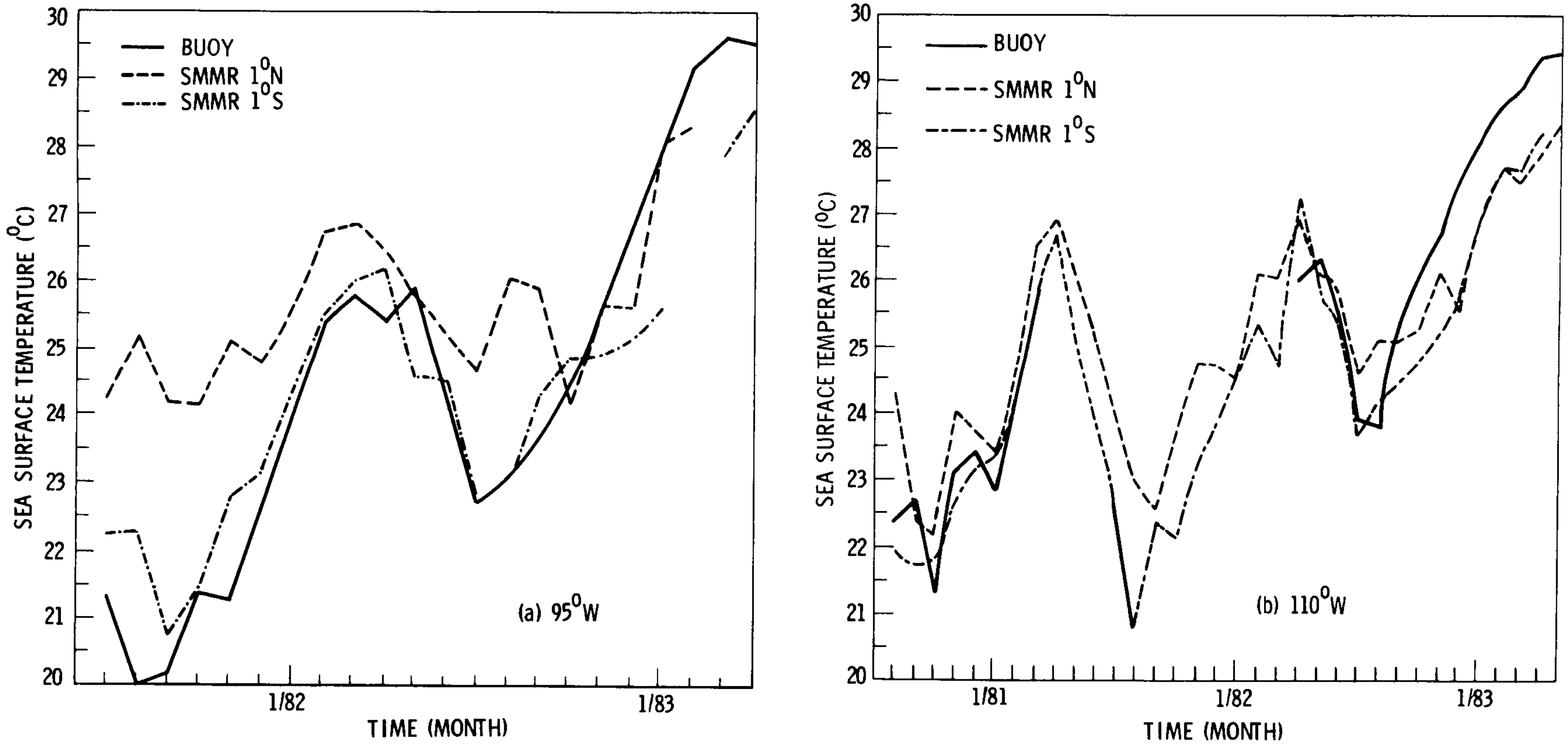

Fig. 10. Comparison of the temporal variation of sea surface temperature derived from binned SMMR data with averaged measurements at two equatorial moored buoys during satellite overpasses

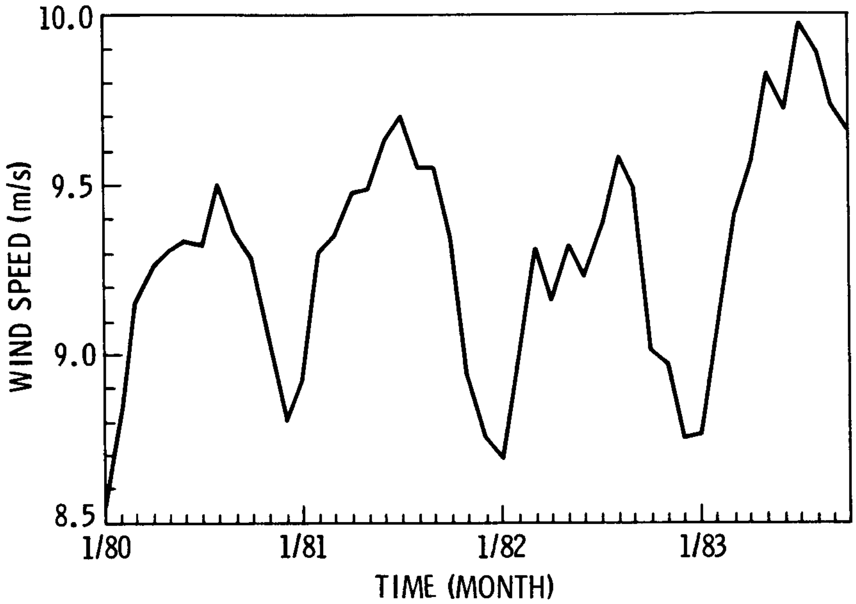

Fig. 11. Same as Fig. 2, except for surface-level wind speed

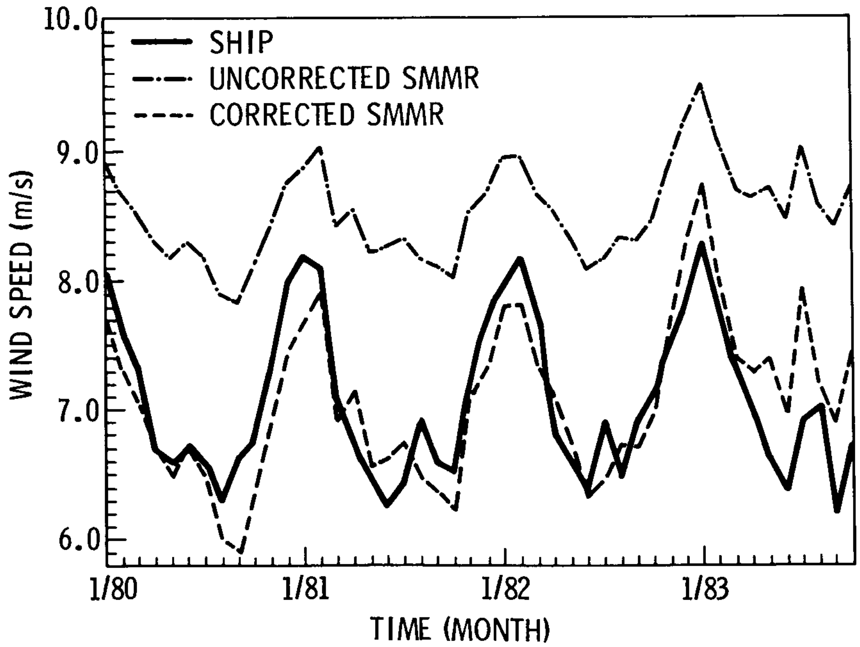

Fig. 12. Same as Fig. 4, except for surface-level wind speed

higher than U_s and has less sensitivity; peak to peak differences are less in U_n than in U_s. The agreement is much improved after application of a correction

$$U_{nc} = 1.71 U_n - 7.5 \quad (4)$$

suggested in the handbook except that U_{nc} is higher than U_s in Year 5. Temporal variation of U_{nc} is also shown in in Fig. 12. Mean differences between U_{nc} and U_s are negligible except for Year 5; their values determined using four months of data per year are shown in Table 6. Application of (4) increases data sensitivity, reduces the bias, but also increases the STD, as shown in Fig. 13. The STD of U_{nc}-U_s is somewhat higher than ship data noise.

In Fig. 14, U_{nc} is compared with buoy wind U_b at two locations. Buoy measurements during the hour of satellite overpass were scaler averaged. U_n is an average of SMMR wind speed within 1° of buoy locations. The time series are coherent, with deviations on the order of 1 m/s. Some of the differences may be due to the velocity gradient in the atmospheric surface layer. SMMR tracks the annual cycles rather well and the ENSO event shows up as an intensification of the annual lows starting in October 1982, particularly at 110°W.

7. DISCUSSION

This study is intended only to provide an evaluation of the products released by NSSDC to general users with regard to applications for the tropical oceans. It has not been an attempt to unravel in detail the sensor problems of Nimbus-7. Comparisons between binned satellite and ship data and comparisons between buoy measurements and coincident satellite measurements during overpasses were performed. For U, the correction suggested by the data source appears to work rather well, except for the last year. Further improvement is difficult because the coincident satellite and *in situ* data are highly concentrated around the mean, such that a linear correction could not be properly determined. Least square regressions, which minimize the variance of the ensembles, would give a small gradient and leave large errors at high and low wind speeds. Such a correction, while reducing the STD, desensitizes the satellite data and introduces large errors in the bias. The errors of Q_n have prominent T-dependence; the removal of such "cross-talk" was attempted. Removal of other types of "cross-talk" was not attempted because the data did not cover a satisfactory range.

The Seasat experience suggests that W is the parameter that spaceborne microwave radiometers can measure best. The algorithm is relatively simple and the accuracy good (cf Alishouse, 1983). In this sense, the Nimbus data, as this study demonstrates, have more problems than expected. The corrections suggested in the handbook and those incorporated in the data are not adequate even for data prior to the sensor change in June 1983. Miscalibration of the 21 GHz horizontal channel is not likely to be the only problem. The W derived by Prabhakara et al. (1985), without using the radiance measured in this channel, also shows temporal and latitudinal dependence, although the error characteristics appear to be different from what we found. The sharp increase in error starting June 1983, not found in Prabhakara et al., is very disturbing and is probably caused by the deterioration of the 21 GHz horizontal channel. The corrections presented here serve only as a temporary measure. A more fundamental correction is being sought by F. Wentz for THEP and also by the Nimbus project for general users.

Table 6. Correction factors for SMMR surface-level wind speed

Period	C
Year 2	0.204
Year 3	0.011
Year 4	0.103
Year 5	-0.600

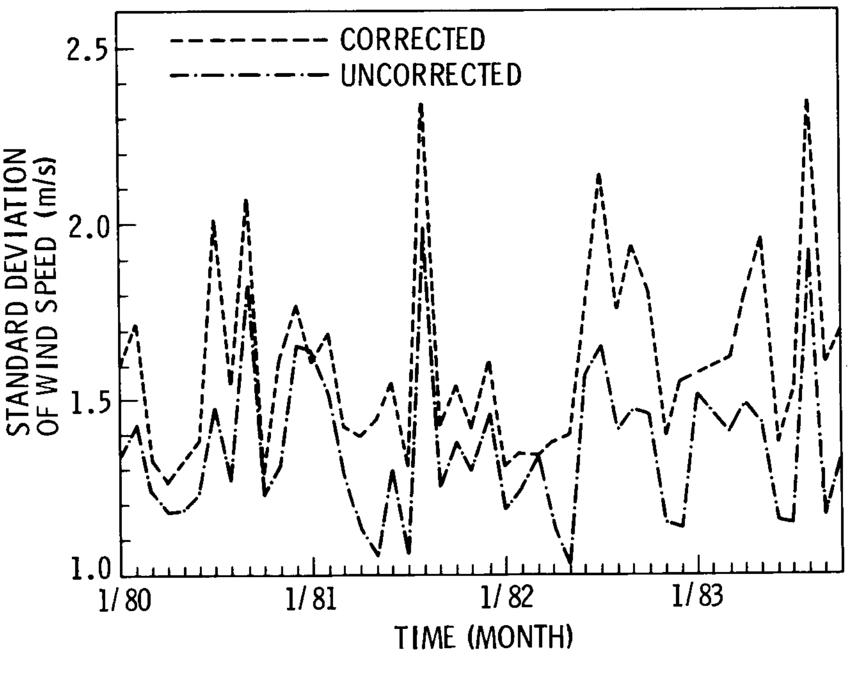

Fig. 13. Same as Fig. 6, except for surface-level wind speed

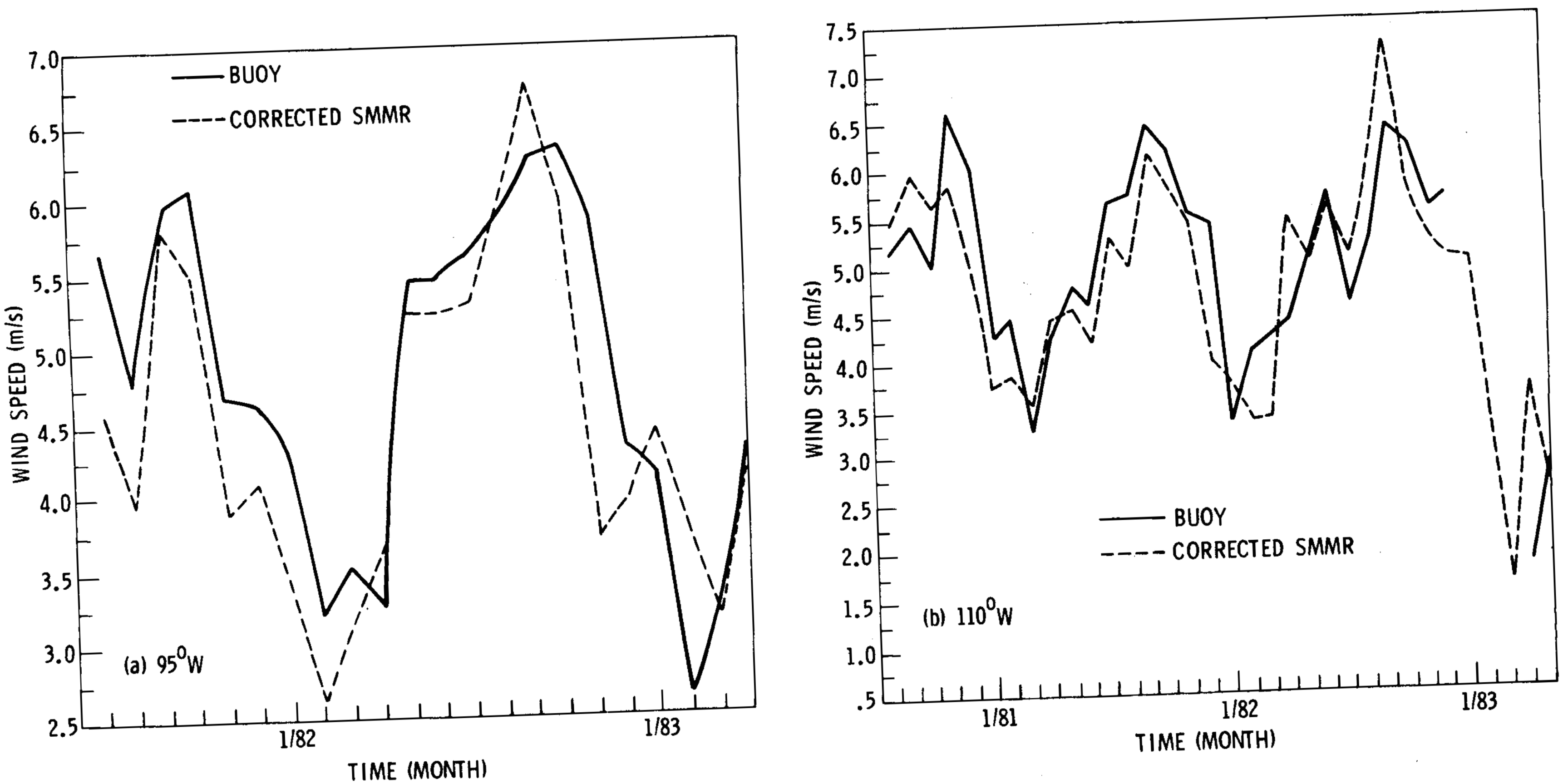

Fig. 14. Comparison of the temporal variation of surface-level wind speed derived from SMMR data with averaged measurements at two equatorial moored buoys during satellite overpasses

One of the inherent difficulties of comparing spatially averaged satellite measurements with spot *in situ* measurements, as frequently discussed, is the spatial variability. Another is due to the vertical gradients in the atmospheric and oceanic surface layer, quantitative descriptions of which were given by Liu et al. (1979) and others. While T_n represents the temperature of the upper few millimeters of the ocean, T_b was measured at 1-m depth, and T_s at depths from 5 to 10 m. Only nighttime SMMR data and buoy data are used in this study and, at nighttime, the gradient is small. U_b in this study was measured at 3.8 m while most ship anemometers are located much higher (20 m). Most ship winds are estimated from observations of the sea states through the Beaufort scale. SMMR observations are closely related to the sea state through surface emissivity but the correction to U_n was derived from comparison with buoy data.

The active participation of scientists studying large-scale ocean-atmosphere interaction and climate variability in the data management of Nimbus/SMMR is important. The algorithm used to exclude data in proximity of land eliminated the opportunity to examine some oceanic and climatic features. As there are different levels of data degradation, the users should be given the choice of using the data. For example, there is no data on T_n and U_n in areas of Micronesia and Polynesia, which are occupied only by scattered atolls, but data from these areas are important to the study of ENSO. In this sense, all data should be included with those of suspicious quality (close to land) flagged. Better documentation and uniform reprocessing of the data would greatly benefit general users. At present, the handbook only gives very brief information on some of the data distributed by NSSDC. Corrections have been applied by NSSDC to some data but not to all data. Making the corrections suggested in the handbook is no easy matter. For example, corrections for water vapor are stratified according to ascending and descending orbits but there is no indicator in the data specifying which measurements belong to ascending or descending orbits.

The Nimbus/SMMR is sensitive to the annual and interannual variations as demonstrated in Fig. 3, 10, and 14. By limiting our evaluation to the tropical oceans, we might have bypassed some more difficult problems. A survey of the global fields of the difference between satellite measurements and ship data in selected months indicated uneven distribution in the high latitude North Pacific and North Atlantic that are not present in tropical oceans. The validity of SMMR measurements in representing large scale mean and anomalous fields in the tropical ocean will be addressed in our next report.

REFERENCES

Alishouse, J.C., 1983: Total precipitable water and rainfall determinations from the SEASAT Scanning Multichannel Microwave Radiometer. *J. Geophy. Res., 88,* 1929-1935.

Cane, M.A., 1983: Oceanographic events during El Niño. *Science, 222,* 1189-1195.

Chang, H.D., P.H. Hwang, T.T. Wilheit, A.T.C. Chang, D.H. Staelin and P.W. Rosenkranz, 1984: Monthly distributions of precipitable water from the Nimbus 7 SMMR data. *J. Geophs. Res., 89,* 5328-5334.

Gloersen, P., D.J. Cavalieri, A.T.C. Chang, T.T. Wilheit, W.J. Campbell, O.M. Johannessen, K.B. Katsaros, K.F. Kunzi, D.B. Ross, D. Staelin, E.P.L. Windsor, F.T. Barath, P. Gudmandsen, E. Langham, and R.O. Ramseier, 1984: A summary of results from the first Nimbus 7 SMMR observations. *J. Geophs. Res., 89,* 5335-5344.

Liu, W.T., 1986: Statistical relation between monthly mean precipitable water and surface-level humidity over global oceans. *Mon. Wea. Rev., 114,* 1591-1602.

Liu, W.T., K.B. Katsaros and J.A. Businger, 1979: Bulk parameterization of air-sea exchanges of energy and water vapor including the molecular constraints at the interface. *J. Atmos. Sci., 36,* 1722-1735.

Liu, W.T. and P.P. Niiler, 1984: Determination of monthly mean humidity in the atmospheric surface layer over oceans from satellite data. *J. Phys. Oceanogr., 14,* 1451-1457.

Liu, W.T. and P.P. Niiler, 1985: *Tropical Ocean and Global Atmosphere (TOGA) Heat Exchange Project - A Summary Report.* JPL Publication 85-49, Jet Propulsion Laboratory, Pasadena, CA.

Milman, A.S. and T.T. Wilheit, 1985: Sea surface temperatures from the scanning multichannel microwave radiometer on Nimbus 7. *J. Geophys. Res., 90,* 11631-11641.

NASA, 1985: *Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) Parm Tape User's Guide.* Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD.

Prabhakara, C., D.A. Short, and B.E. Vollmer, 1985: El Niño and atmospheric water vapor: observations from Nimbus 7 SMMR. *Mon. Wea. Rev., 24,* 1311-1324.

Tabata, S., 1978: Comparison of observations of sea surface temperatures at Ocean Station P and NOAA buoy stations and those made by merchant ships traveling in their vicinities, in the Northeast Pacific. *J. Appl. Meteor., 17,* 374-385.