Determination of Monthly Mean Humidity in the Atmospheric Surface Layer over Oceans from Satellite Data

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ABSTRACT

A simple statistical technique is described to determine monthly mean marine surface-layer humidity, which is essential in the specification of surface latent heat flux, from total water vapor in the atmospheric column measured by space-borne sensors. Good correlation between the two quantities was found in examining the humidity soundings from radiosonde reports of mid-ocean island stations and weather ships. The relation agrees with that obtained from satellite (Seasat) data and ship reports averaged over 2° areas and a 92-day period in the North Atlantic and in the tropical Pacific. The results demonstrate that, by using a local regression in the tropical Pacific, total water vapor can be used to determine monthly mean surface layer humidity to an accuracy of 0.4 g kg^{-1}. With a global regression, determination to an accuracy of 0.8 g kg^{-1} is possible. These accuracies correspond to approximately 10 and 20 W m^{-2} in the determination of latent heat flux with the bulk parameterization method, provided that other required parameters are known.

1. Introduction

The temperature and humidity of the air mass directly above the ocean strongly affect the amount of heat and momentum exchanges between the ocean and the atmosphere. Our knowledge of these properties today mainly comes from meteorological reports of merchant ships and fishing vessels. Along the principal shipping lanes and in coastal fishing grounds, the number of marine reports are adequate to resolve the evolving monthly mean in relation to climatology. But, over vast areas of the equatorial and southern oceans these data are at best able to delineate climatological seasonal means.

Space-borne sensors have the potential of providing repeatable basin-wide to global coverage of these exchanges. The microwave scatterometer can be used to estimate atmosphere–ocean momentum exchange and the basic technique has been established (e.g., Liu and Large, 1981). In vast areas of the tropical oceans, net shortwave radiation and latent heat flux are the principal variable modes of heat exchanges on monthly time scale (Weare *et al.*, 1980). The surface net shortwave radiation can be determined from existing satellite data (e.g., Gautier, 1981). One of the major remaining problems is the global estimation of net moisture flux (or latent heat flux) which affects both temperature and salinity of the upper ocean.

The water vapor flux E can be determined by the bulk parameterization formula:

$$E = \rho C_E U(Q_s - Q), \qquad (1)$$

where ρ is the density of surface air, C_E is the transfer coefficient, Q_s is the saturation humidity at sea surface temperature, U and Q are the wind speed and specific humidity at a reference level in the atmospheric surface layer. The surface layer is the lowest 10–50 m of the atmosphere where the fluxes can be assumed constant. The value of C_E and its variation have been studied by Liu *et al.* (1979) and others. The latent heat flux can be determined by multiplying E by the latent heat of vaporization L. Esbensen and Reynolds (1981) have shown that monthly mean humidity, wind speed and sea surface temperature can be used to compute monthly mean evaporation and latent heat flux by the formula, at least for subtropical midlatitude oceans, and the accuracy can be quite good.

The problem of determination of wind speed and sea surface temperature from space-borne sensors have been discussed in various publications such as SEASAT Special Issue 1 and 2, *Journal of Geophysical Research,* Volumes 87 (C5) and 88 (C3). Validations of these remotely sensed parameters have been mostly spot comparisons with *in situ* measurements. Spatial and temporal averaging should eliminate some of the random error and by establishing some calibration standards in the area and time of interest, the systematic bias can be removed. There is no good direct method of estimating Q from space-borne sensors but it has been demonstrated that the total columnar water vapor (percipitable water) W can be determined very accurately from the Scanning Multichannel Microwave Radiometer (SMMR) on ocean observing

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satellite Seasat (Katsaros *et al.*, 1981; Taylor *et al.*, 1981; Alishouse, 1983).

Reitan (1963), Bolsenga (1965) and Lowry and Glahn (1969) have examined the relation between W and the surface dew point temperature with meteorological reports from selected stations in continental North America. The accuracy of such a relation over oceans is not known. A universal Q–W relation is implied form the existence of a universal vertical profile of humidity. Many investigators have applied standard atmospheric humidity profiles derived from climatological data. For example, Manabe and Wetherald (1967) have derived hemispherical mean profiles of temperature and relative humidity and, based on similar data (London, 1957), Smith (1966) has derived seasonal and latitudinal mean humidity profile. Whether such climatological mean profiles are adequate in describing the evolving monthly mean over a specified region (particularly over oceans) has not been investigated.

In this paper, we will demonstrate a simple statistical technique for obtaining monthly mean Q from satellite observation over oceans. We will obtain correlations, using humidity soundings from midocean small island stations and weather ships. Such relations will be checked against those given by satellite data and ship reports averaged over 2° longitude by 2° latitude areas and a 92-day period in two selected regions. If we take $L = 2.46 \times 10^6$ J kg^{-1}, and in Eq. (1), we assume $\rho = 1.2$ kg m^{-3}, $C_E = 1.2 \times 10^{-3}$, and a typical value of $U = 7$ m s^{-1} in tropical oceans, an error of 0.4 g kg^{-1} in Q is equivalent to an error of 10 W m^{-2} in latent heat flux or 4×10^{-6} kg m^{-2} s^{-1} in evaporation rate.

TABLE 1. The scatter above the linear regression of Q versus W for one year of radiosonde soundings at 11 stations.

Station	Lat (deg)	Lon† (deg)	Year	N	Scatter (g kg^{-1}) All data	Scatter (g kg^{-1}) Monthly mean
			Atlantic Stations			
OWS B	56N	309	1972	561	0.84	0.26
OWS C	52N	325	1972	552	1.14	0.44
OWS D	44N	319	1972	599	1.95	0.48
Bermuda	32N	296	1978	672	2.52	0.48
Puerto Rico	18N	284	1978	712	1.79	0.63
Barbados	12N	301	1978	642	1.05	0.38
			Pacific Stations			
OWS P	50N	215	1978	651	0.93	0.29
Johnston	16N	191	1978	721	1.13	0.40
Koro	7N	134	1978	346	0.97	0.27
Majuro	7N	171	1977	363	0.94	0.18
			1978	363	1.01	0.40
			1979	486	1.08	0.40
			1980	369	0.96	0.17
Pago Pago	14S	190	1978	728	1.30	0.45

† Longitude degrees east of Greenwich meridian

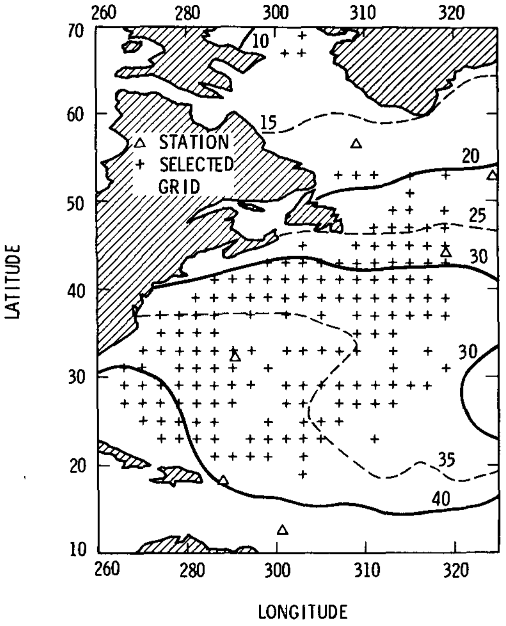

FIG. 1. Distribution of 92-day 2° average of column water vapor (kg m^{-2}) from Seasat-SMMR with positions of the selected grids and radiosonde stations in North Atlantic.

2. Radiosonde reports

Table 1 shows the latitude (Lat) and longitude (Lon) coordinates of the 11 stations whose humidity soundings were used to examine the relation between Q and W. All stations except one are located in the two regions shown in Figs. 1 and 2. The soundings are radiosonde reports archived as Tape Deck 5681 in the National Climatic Center. Reports for the year of Seasat, 1978, were first selected, but Ocean Weather Station (OWS) B, C, and D were not operative in 1978 and soundings form 1972, the last year of full operation, were used instead. For Majuro, three additional years of soundings were used to examine interannual variation. soundings are generally available twice daily except for Majuro and Koro which report only once a day. Quite a number of reports from OWSs B, C, and D are missing. The specific humidity at the lowest sounding level (surface) was used to represent Q. To obtain W the soundings were integrated by trapezoidal rule up to the highest reported level below 200 mb. Reports from higher levels were found to be generally unreliable and there is only negligible amount of water vapor above 200 mb. Those soundings with less than 3 levels and those with the highest reported level below 500 mb were discarded. Table 1 also shows the number (N) of soundings used.

Individual humidity soundings show correlation between W and Q with considerable scatter. The correlation of monthly averages, however, are much better. The last two columns of Table 1 are the

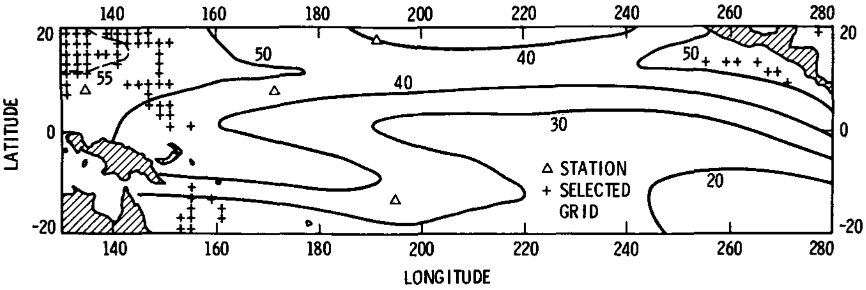

FIG. 2. As in Fig. 1 except in the tropical Pacific.

scatter (rms deviation from the predicted values) above the Q–W linear regression for all individual soundings and for the 12 monthly means for each year. The scatter for the monthly mean is generally about ⅓ of that for individual data. The data for some stations, such as Bermuda, show much larger reduction in the scatter.

Figures 3–6 are Q versus W plots. Each point is a monthly mean and there should be a point for each calendar month for each station. The curve in each figure is the polynominal regression determined by minimizing the mean-square difference between the data and those from the regression. The figures have different scales but the bars in all the figures represent 0.4 g kg $^{-1}$ in Q which is equivalent to 10 W m^{-2} in latent heat flux. Figure 3 shows the latitudinal variation (from 12 to 56°N) of the monthly means for six stations in the North Atlantic in addition to the annual variation at each station. The 1972 data appear to merge well with those of 1978. The annual variation at Bermuda is large, equivalent to a large part of the latitudinal variation shown in the figure. The scatter above the regression is 0.77 g kg^{-1}, equivalent to less than 20 W m^{-2} in latent heat flux. Considering the range of humidity involved, this is a good accuracy.

Figure 4 shows data derived from 1978 soundings of four tropical Pacific stations within +20° of the equator. Two of them, Majuro and Koror, lie within the migration of the Intertropical Convergence Zone (ITCZ) with the former in the Mid-Pacific and the later far to the west in the Monsoon area. Data from all four stations follow the same relation. The scatter above the regression is 0.42 g kg^{-1}. Figure 5 shows 4 years of data at Majuro from 1977 to 1980 with a scatters of 0.28 above the regression, smaller than the 0.4 g kg^{-1} represented by the bar. The 4 years of data follow the same relation indicating that W is sensitive to the interannual variation of Q. In Fig. 6 the monthly means from the six Atlantic stations are plotted together with those form the four stations in tropical Pacific. The data from OWS P are added to compare with Atlantic stations at high latitude. The figure demonstrates that there is no practical difference between the relation in the two oceans. The existence of a global relation is evident. The scatter above data regression in Fig. 6 is 0.83 g kg^{-1}, equivalent to slightly higher than 20 W m^{-2} in latent heat flux.

There have been suggestions that the relative humidity over oceans is approximately constant and,

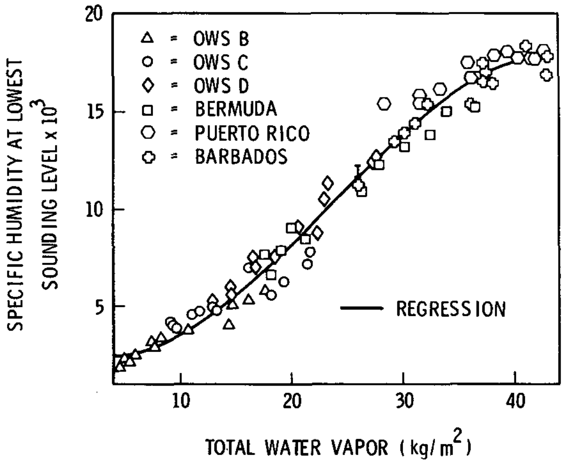

FIG. 3. Specific humidity at the lowest sounding level versus total water vapor from radiosonde reports at six stations in North Atlantic. Each point is a monthly average.

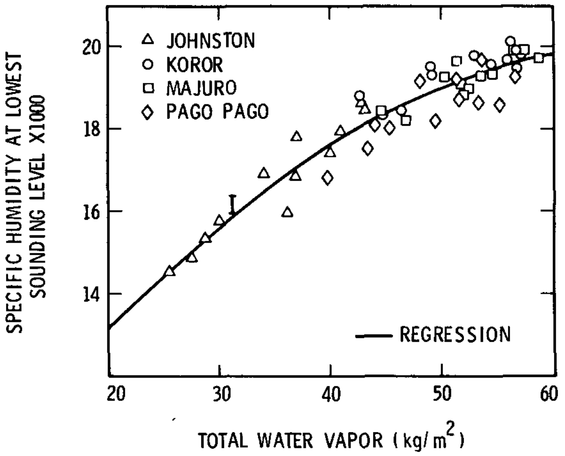

FIG. 4. As in Fig. 3 except for four stations in tropical Pacific.

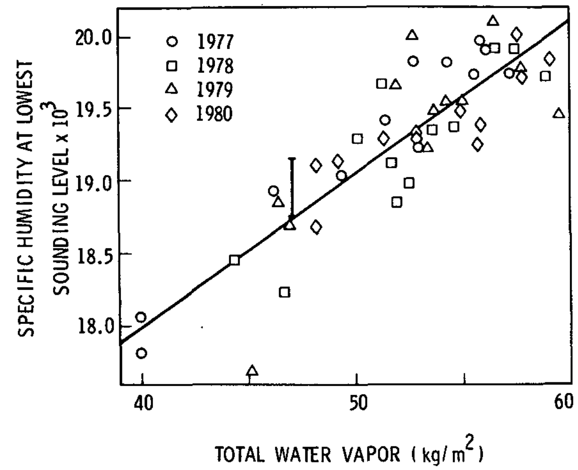

FIG. 5. As in Fig. 3 except for four years of data at Majuro.

therefore, Q can be specified from temperature alone. Our data indicate that the variation in Q is not entirely due to variation in temperature. The monthly mean relative humidity generally varies by 10–20%: for example, those for OWS B changes from 71–90%; for Bermuda, from 57–77% and for Majuro, from 71 to 83%.

3. Ship reports and satellite observations

It would be rewarding if the Q–W relation developed from radiosonde soundings could be applied to determine Q from satellite observations averaged over some desired spatial and temporal scales. Observations from Seasat, which was operative for three months in 1978, were used to test this relation. There are no *in situ* measurements available for verification over extended areas except for ship reports. Away from coastal regions, where land contamination affects SMMR observations, all the ship reports in a 2° area during a 92-day (11 July to 10 October 1978) period have to be used to get satisfactory averages. Due to the poor quality and distribution of ship reports, they are used not as a standard to establish the Q–W relation but as a check to the relations determined from radiosondes. The two regions of study are in the eastern North Atlantic (10–70°N, 280°E–320°E) and in tropical Pacific (20°S–10°N, 130°E–280°E).

The ship data used were ship radio reports of dew point temperature collected by the Fleet Numerical Oceanographic Central during the Seasat period. A quality selection procedure was applied. The first step was an attempt to remove reports with position and time errors. Data with positions on land were first discarded. The displacement and time elapsed between consecutive reports by the same ship were used to evaluate mean ship speed. When the speed exceeded 35 knots, the second report was discarded. The second step removed those data with dew point temperature below −10°C and above 40°C. In the last step, the mean and standard deviation for each 2° area and the 92-day period were calculated. Dew point temperature outside ±2 standard deviations from the mean were discarded.

The satellite observations were the total water vapor in the atmospheric column as measured by Seasat-SMMR from the streamlined geophysical data archived by the Pilot Ocean Data System at the Jet Propulsion Laboratory. It has been known that sun-

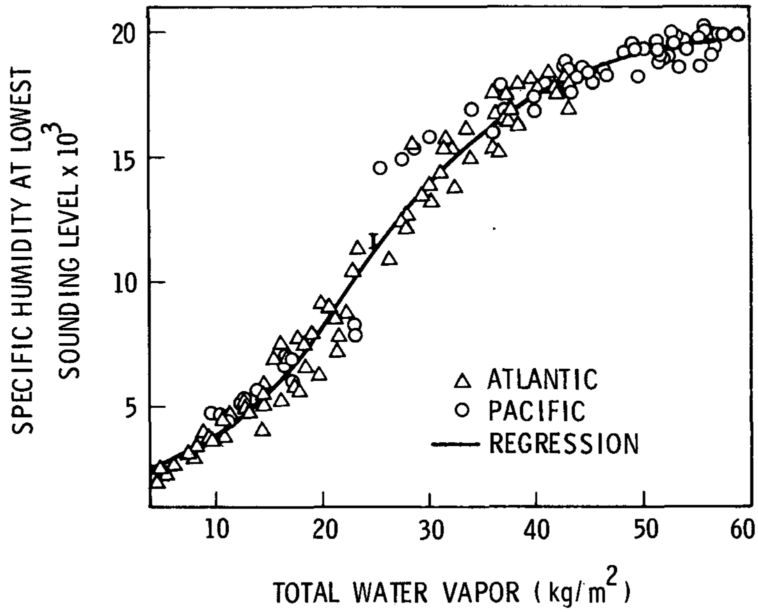

FIG. 6. As in Fig. 3 except for five additional stations in Pacific.

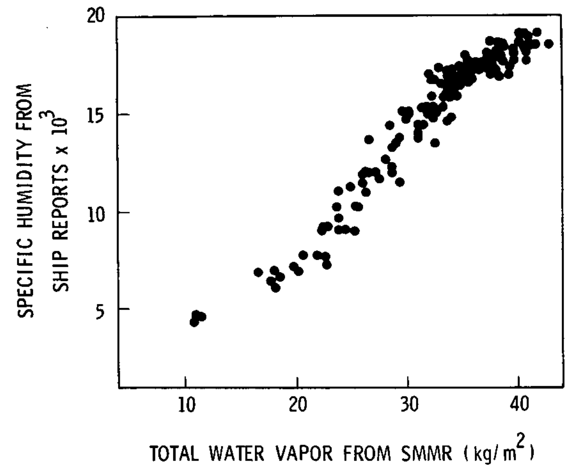

FIG. 7. The specific humidity determined from dew point temperature of ship reports versus the water vapor in the atmospheric column measured by the Seasat-SMMR. Each point is an average over 2° area and a 92-day period in the North Atlantic.

glint, rain and proximity to land degrade SMMR observations. Therefore, data for which rain was indicated (the rain rate is another parameter measured by SMMR) and for which the angle between the antenna boresight direction and the line to the reflected sun was less than 10° were discarded before the 2° and 92-day averages were formed. The isopleths of these averages are shown in Figs. 1 and 2.

Figures 7 and 8 are *Q–W* plots on the same scales as Figs. 3 and 4, except that *Q* is determined from ship reports and *W* from Seasat-SMMR. In the Atlantic region only those 2° areas with more than 20 ship reports, after quality selection, were used. In the Pacific region there are far too few areas with more than 20 reports and, therefore, the requirement was relaxed; those areas with more than 10 reports were used. Areas within 300 km from land were not used to avoid contamination of satellite data. The positions of those 2° areas for which data were used in Figs. 7 and 8 are shown in Fig. 1 and 2. The *Q–W* relation demonstrated in Figs. 7 and 8 agree very well with those shown in Fig. 4 and 5 although data from the two sets of figures were measured by different methods and averaged over different spatial and time scales. The agreement demonstrates that *Q* can be derived from satellite observation and that satellite sensors are sensitive to the temporal and spatial variation in *Q*.

To facilitate comparison of satellite observations with climatological distribution which is more readily available in form *Q* than *W*, mean *Q* were determined from mean SMMR *W* with the *Q–W* relations given by the regression in Figs. 3 and 4. The distributions are shown in Figs. 9 and 10 and they are consistent with climatology with high ridges extending northeast from the Caribbean and along the ITCZ in the Pacific. The mean of 161 values (2° means) of ship-*Q* in Fig. 7 is 15.10 ± 3.65 g kg^{-1} and the mean of 68 values of ship-*Q* in Fig. 8 is 19.24 ± 1.95 g kg^{-1}. The standard deviations 3.65 and 1.95 approximate the natural variations in the two regions. The mean differences between SMMR-*Q* and ship-*Q* are −0.49 ± 0.90 g kg^{-1} in the North Atlantic and −0.52 ± 0.67 g kg^{-1} for one tropical Pacific. The means of the difference (bias) are small, only about 3% of the mean *Q* in both regions. Their negative values imply that the *Q–W* relations determined from radiosondes underestimate ship-*Q*. This may be partly due to systematic difference between the heights of the lowest radiosonde sounding level and that of ship measurements. A closer examination, however, reveals that underestimation occurs only in areas of high humidity. One probable explanation is that SMMR-*W* is biased low at the high end. The standard deviations of the differences are comparatively high; about 25 and 34% of the natural variations in the two regions. Noisy ship data are perhaps the reason.

With a minimum of only 10 reports averaged in each *Q*, the mean *Q* from ship used in Fig. 8 are noisy. The mean of the standard deviation for the data in each grid is 1.41 g kg^{-1} or 72% of natural variation. Even with the relaxed requirement, the large area in the central tropical Pacific does not have enough ship reports to qualify. If we further relax the requirement to 5 reports per 2° area, we would include some areas in the central tropical Pacific, but the data would be so noisy that a *Q–W* relation cannot be clearly defined.

4. Discussion

Liu (1984) shows that a large portion of the water vapor is concentrated in the atmospheric boundary layer. The vertical distribution of water vapor varies

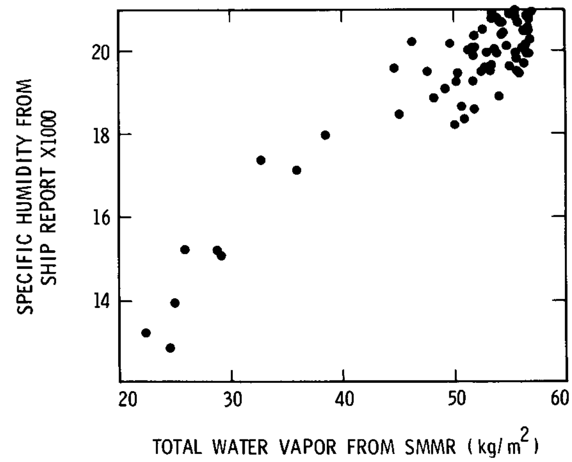

FIG. 8. As in Fig. 7 except for tropical Pacific.

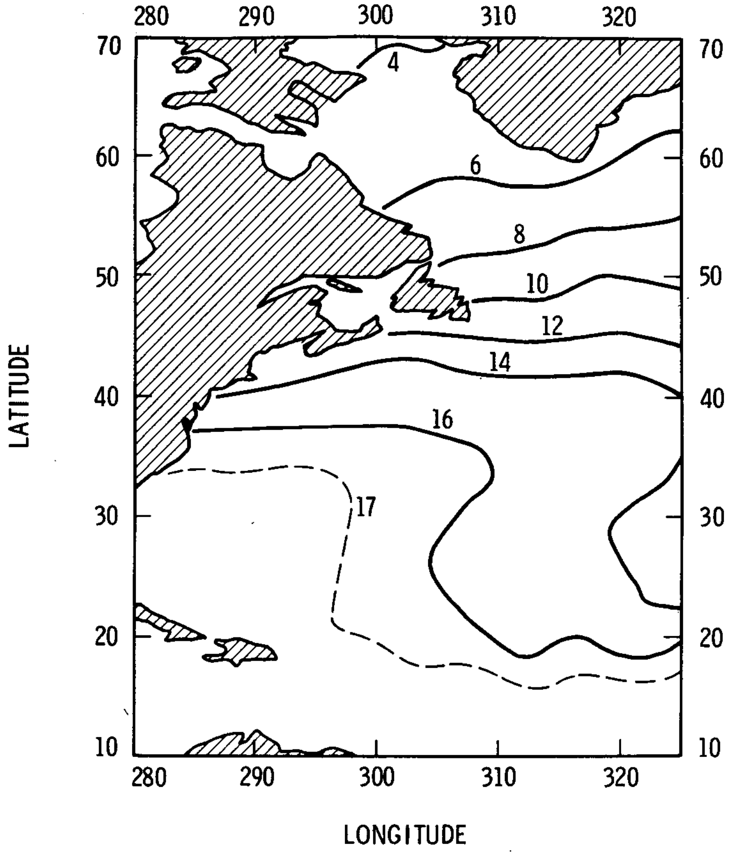

FIG. 9. Distribution of near surface specific humidity in g kg^{-1} as derived from columnal water vapor measured by Seasat-SMMR in the North Atlantic.

with diurnal and synoptic fluctuations of the boundary layer at time scales shorter than a month. The variance profiles have peaks at the top of the boundary layer, and this variance could be sharply reduced by averaging the soundings ovér a month. For monthly-mean humidity profiles, over 90% of the variance can be described by a single empirical orthogonal function which is simple in form. The results shown in Table 1 are consistent with these findings.

Both radisonde and satellite data show that the water content of the atmosphere generally, decreases from the ITCZ towards the poles. As revealed by the radiosonde reports (Figs. 3 and 4), the ratio of Q to W is largest at the position of the subtropical high pressure systems where atmospheric subsidence dominates, and decreases towards the equator and the poles. London (1957) noticed the persistence of extremely dry air in the subtropical middle and upper troposphere and this may be the cause of the large humidity gradient in the lower atmosphere and the large Q to W ratio. The empirical regressions of our radiosonde data appear to be adequate in accounting for such variations. Data with more extensive spatial and temporal coverage are being examined to assure

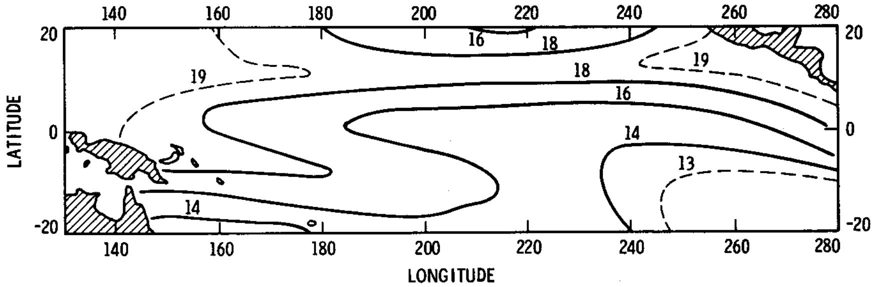

FIG. 10. As in Fig. 9 except for the tropical Pacific.

universality. Further studies are required to establish a theoretical explanation or physical models of a global Q–W relationship.

This study underscores the deficiency, particularly in distribution, of ship reports. In the two regions of study, however, they do verify the relation we determined from radiosonde data. The variation of Q with height in the atmospheric surface layer is likely to contribute to data noise. The random component of the variation of height, whether it is the lowest sounding level or the level of ship observation, should have been reduced by averaging. The variation is more important in areas with low wind speed and high evaporation. Under typical tropical conditions, Q would vary by 0.4 g kg^{-1} only for a height difference greater than 20 m.

The radiosonde soundings show that, by using a local regression, Q can be estimated from satellite observation to an accuracy corresponding to about 10 W m^{-2} in latent heat flux. By using global regression, a corresponding accuracy of 20 W m^{-2} in latent heat flux is possible. Deriving Q from air temperature by assuming constant relative humidity would lead to larger error. The accuracy of latent heat flux depends also on the accuracy of C_E, and U and Q_s as demonstrated by Liu (1984). The spatial and temporal variations of latent heat flux in the tropical Pacific, however, often exceeds 100 W m^{-2} (see Weare *et al.,* 1980) and the accuracy in Q provided by satellite observation is adequate to detect such signal. The ability of one sensor—SMMR to provide all the parameters Q, Q_s and U in (1) raises the possibility of relating latent heat flux directly to more basic instrumental observations, such as the brightness temperatures; the feasibility and merit of such approach requires further study.

There are atmospheric sounders on NOAA operational satellites but the capability of these instruments in measuring humidity profiles, which can be related to Q, has not been adequately examined. A microwave radiometer similar to that on Seasat has been operative on Nimbus-7 since 1979 and the DMSP spacecraft scheduled to be launched in 1986 would carry the Special Sensor Microwave/Imager that also measures W. With careful calibration and validation, these instruments should provide long term monitoring of Q over global oceans. The potential of monitoring the largest time variable components of surface heat flux (carried by insolation and evaporation) over global low latitude oceans from space-borne sensors is good. Together with surface stress, they provide the data base for accurate modeling of the evolution of sea surface temperature anomalies in tropical oceans. Satellite sensors can play a major role in the studies related to the interannual variability of the tropical oceans and the global atmosphere (JSC Study Group, 1983).

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