NOTICE

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RELATION BETWEEN WEST COASTAL RAINFALL AND NIMBUS-6 SCAMS LIQUID WATER DATA OVER THE NORTHEASTERN PACIFIC OCEAN

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16. Abstract

We describe a research study in which we explored the application to rainfall prediction of cloud liquid water data obtained from the SCAMS experiment of Nimbus-6. The study area is the Pacific Northwest coast of the United States, where rainfall is produced by extratropical storms that approach from across the Pacific Ocean.

SCAMS data related to cloud liquid water over the ocean, and coastal rainfall data, are analyzed for 20 different storm systems in the northeastern Pacific Ocean; these produced significant rainfall from Washington to central California during the period October 1975 through March 1976. Results show that the distribution of storm-cloud water analyzed from the SCAMS data over the ocean foreshadows the distribution of coastal rainfall accumulated from the storm at a later time.

We conclude that passive microwave sensor measurements of cloud water over the ocean, when used in conjunction with numerical and other objective guidance, can be used to enhance the accuracy of predictions of coastal rainfall distribution.

Limitations in the SCAMS measurements and in the data analysis and interpretation are noted.

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PREFACE

Under Contract NAS5-24450, SRI International performed a study entitled "Application of Nimbus-6 Microwave Data to Problems in Precipitation Prediction for the Pacific Coast." Emphasis was on the analysis and interpretation of data related to total precipitable water and non-precipitating cloud liquid water obtained from the Scanning Microwave Spectrometer (SCAMS) of Nimbus-6. The objective was to see if satellite microwave data related to storm-cloud water over the northeastern Pacific Ocean can enhance precipitation prediction for the Pacific West Coast.

SCAMS data over the ocean, and coastal rainfall data, are analyzed for 20 different storm systems in the northeastern Pacific Ocean; these produced significant rainfall from Washington to central California during the period October 1975 through March 1976. Results show that the distribution of storm-cloud water analyzed from the SCAMS data over the ocean foreshadows the distribution of coastal rainfall accumulated from the storm at a later time. The distributions of SCAMS cloud liquid water show a more obvious relation than do the distributions of SCAMS total vapor, to observed rainfall.

We conclude that passive microwave sensor measurements of cloud water over the ocean, when used in conjunction with numerical and other objective guidance, can be used to enhance the accuracy of predictions of coastal rainfall distribution. Limitations in the SCAMS measurements and in the data analyses and interpretation are noted.

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I INTRODUCTION

In the Pacific Northwest west of the Cascades, rapid increase in mountain snowpack or in runoff can be predicted reliably only if precursor meteorological conditions can be diagnosed over the northeastern Pacific Ocean, where little or no conventional weather data exist.

At present, the regional Limited-Area Fine-Mesh Model (LFM) of the National Meteorological Center (NMC) predicts precipitation for the West Coast. However, as pointed out by Fawcett (1977), the model is less accurate for the western United States than for other geographic areas, due to the absence of observations over the eastern Pacific and the failure to correctly model atmospheric convection and effects of complicated terrain on the atmosphere. The output of the numerical prediction models is currently complemented by objective precipitation forecasts from the Model Output Statistics (MOS) technique and the map-type Probabilities of Precipitation (PoPs) method (Klein and Glahn, 1974; Rasch and MacDonald, 1975); also, cloud-image data from satellites are increasingly used in forecast preparation. It remains difficult, however, to identify those storm systems over the ocean that produce surges of heavy precipitation over land, especially between October and April, which is the time of greatest rainfall.

Passive microwave sensors carried on research satellites provide measurements inside extensive storm-cloud systems that the visible and infrared radiometers cannot obtain. For example, the Electrically Scanning Microwave Radiometer (ESMR) and Scanning Microwave Spectrometer (SCAMS) instruments on the Nimbus-5 and -6 satellites have provided data directly related to precipitable water, cloud liquid water, and rainfall over the ocean (Staelin et al., 1975; Wilheit et al., 1977; Chang and Wilheit, 1978). This information should be exploited in research related to the precipitation and the hydrology of the Pacific West Coast states, since conditions prior to significant precipitation, and those with which numerical prediction models must be initialized, develop over the ocean.

This final report describes the principal results of a research study carried out under Contract NAS5-24450. The study emphasizes the analysis and interpretation of data related to total nonprecipitating cloud liquid water obtained from the Nimbus-6 SCAMS. The objective is to see if satellite microwave data related to storm-cloud water over the northeastern Pacific Ocean can enhance precipitation prediction for the Pacific West Coast.

II METHOD OF DATA ANALYSIS

We have analyzed SCAMS data to obtain the distribution and amounts of liquid water* in 20 cyclonic storm situations; these occurred in the northeastern Pacific Ocean and resulted in rainfall along the west coast of the United States during the winter season October 1975 through March 1976.

Table 1 lists the 20 three-day periods for which storm cases were selected. In each case, the storm system moved eastward toward the West Coast.

Nimbus-6 SCAMS digital data tapes were used in the analyses. Two time periods at intervals of 10 to 13 hours (ascending and descending node) were available for each storm day.

Table 1

STORM CASES IN NORTHEASTERN PACIFIC OCEAN SELECTED FOR ANALYSIS

Case No.	Dates	Case No.	Dates
1	7-9 October 1975	11	23-25 December 1975
2	15-17 October 1975	12	6-8 January 1976
3	24-26 October 1975	13	12-14 January 1976
4	27-29 October 1975	14	25-27 January 1976
5	3-5 November 1975	15	11-13 February 1976
6	12-14 November 1975	16	19-21 February 1976
7	17-19 November 1975	17	23-25 February 1976
8	3-5 December 1975	18	26-28 February 1976
9	10-12 December 1975	19	17-19 March 1976
10	19-21 December 1975	20	20-22 March 1976

*Similar analyses were made using SCAMS data related to total precipitable water; results, however, were not as significant and are not included in the final report.

Daily precipitation records were examined in conjunction with sequences of SMS-2 cloud images to determine the time period during which each selected storm system affected rainfall along the West Coast. For this time period (usually three successive days), rainfall observations at 27 coastal stations extending from Quillayute, Washington (47.95°N) to Santa Maria, California (34.90°N) were analyzed in terms of variation in latitude or distribution of coastal precipitation.

The computer program used in analyzing the Nimbus-6 SCAMS digital data and the coastal rainfall data has three major subroutines. One subroutine prints the satellite scan spot values for a given time period on a Mercator map extending from 30°N to 54°N latitude and 120°W to 168°W longitude. The second subroutine averages these data on a 1°-mesh, grid-point array (25 rows, 27 columns). For each time period, the third subroutine characterizes the storm (on the basis of the SCAMS data) in terms of the distribution of liquid water as a function of latitude from north to south across the storm area, and computes the degree of linear correlation between the observed distribution of coastal precipitation and the antecedent conditions of the storm's liquid water distribution over the ocean.

To illustrate the above method of analysis, Figure 1 shows the conditions of SCAMS-derived cloud water associated with a major storm system over the ocean identified by SMS-2 data at 0230 PST 7 October 1975, and about 24 hours later, at 0100 PST 8 October 1975. These conditions preceded the coastal rainfall shown in Figure 2, which shows the observed distribution of 24-hour coastal rainfall for 8 to 10 October and the 72-hour cumulative total for the three days. In Figure 1, the SCAMS liquid water contents derived from SCAMS data (middle frames) are analyzed on the 1°-mesh, grid-point array. Each printed number represents the vertically integrated (columnar) liquid water, averaged over the grid square, expressed in units of 10^{-2} mm (mg/cm^2). Maximum values range from 100 to 138 mg/cm^2 in the northern part of the cloud system on 7 October, and from 100 to 129 mg/cm^2 in the southern part on 8 October. The characteristic distributions of total liquid water (1° latitude strips across the grid-point area), expressed in units of 10^8 tons, are shown on the right side. The data of Figures 1 and 2 show that the distribution of cloud water analyzed from SCAMS has a maximum ($>0.9 \times 10^8$ tons) at about 0100 PST 8 October between latitude 45°N and 37°N; coastal rainfall has a maximum on 9 October and also in the three-day cumulative total, between these same latitudes. Thus, the distribution of the cloud-water content obtained from the Nimbus-6 SCAMS over the ocean is positively correlated with the distribution of coastal rainfall observed at a later time. Analyses such as illustrated in Figures 1 and 2 were made for all 20 storm cases.

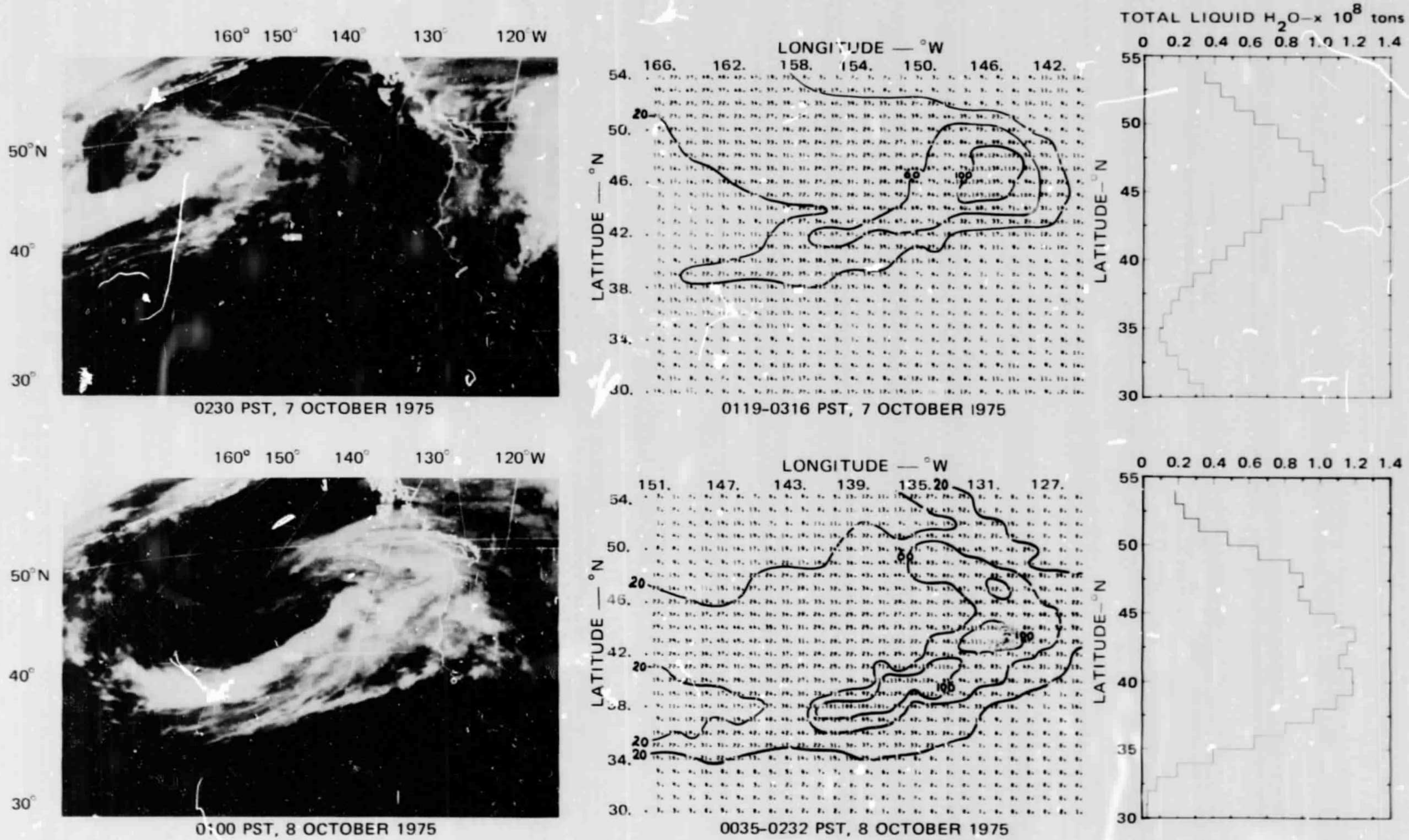

FIGURE 1 SMS-2 INFRARED CLOUD IMAGE (LEFT FRAME) AND ANALYSIS OF NIMBUS-6 SCAMS CLOUD LIQUID WATER CONTENT (MIDDLE FRAME, UNITS OF mg/cm^2) FOR STORM SYSTEM AT 0230 PST, 7 OCTOBER 1975, AND APPROXIMATELY 24 HOURS LATER AT 0100 PST, 8 OCTOBER. Distributions of cloud liquid water across the storm area (right frames) are used to obtain information on coastal rainfall distribution

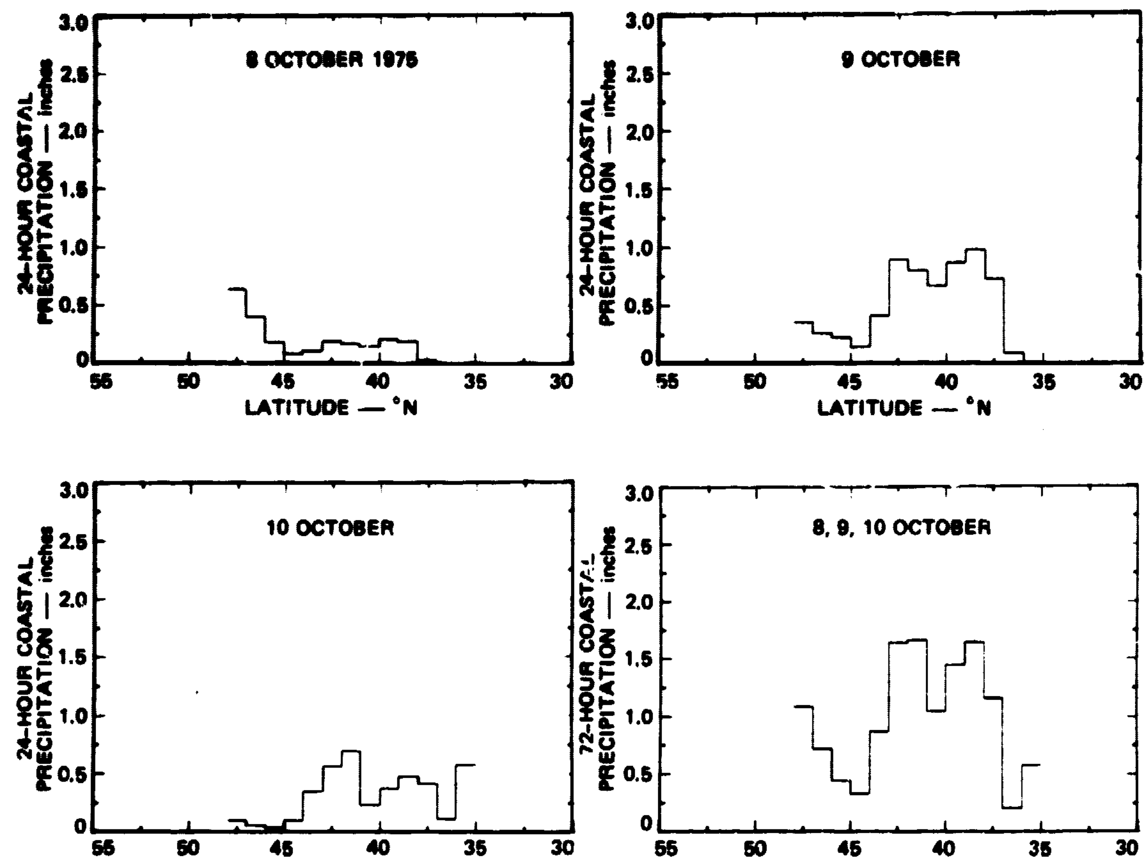

FIGURE 2 OBSERVED COASTAL RAINFALL DISTRIBUTION FROM WASHINGTON (48°N) TO CENTRAL CALIFORNIA (34°N) DURING THREE-DAY PERIOD IN WHICH STORM SYSTEM OF FIGURE 1 AFFECTED WEATHER CONDITIONS

III RESULTS

For each of the 20 cases analyzed, the distribution of 72-hour cumulative rainfall along the West Coast from Astoria, Oregon to Santa Maria, California (46°N to 34°N) was correlated with the distribution of storm-cloud water over the ocean analyzed from the SCAMS data at times ranging from 36 hours to 96 hours earlier. The particular antecedent time at which the positive correlation was maximum was identified for each case. Table 2 shows how these maximum correlations are distributed with respect to the corresponding antecedent time period for all 20 cases analyzed, and, in parentheses, for those 14 cases that had maximum correlation coefficients $\geq$ +0.70. In the primary (20-case) data sample, the lowest and highest correlations were, respectively +0.39 (Case 4) and +0.99 (Case 1?). It is seen that the 72-hour coastal rainfall distribution is most frequently correlated with the storm-cloud liquid water distribution over the ocean analyzed from SCAMS data that are available 60 to 72 hours earlier. The 72-hour cumulative rainfall was correlated with the antecedent cloud-water distributions, because it represents the total precipitation from the storm system. Also, high positive correlations occurred most frequently when the two stations in the state of Washington (Quillayute and Hoquiam), where rainfall is significantly affected by orography, were eliminated from the data samples.

Table 2 shows that for the storm cases examined in October, November, January, and March, the distribution of the 72-hour cumulative coastal rainfall is highly correlated with the distribution of storm liquid-water content over the ocean at a time period 60 to 72 hours earlier, exclusively. The December and February cases include results with variable antecedent time periods. Storm development and movement were not accounted for in our analyses but must be considered when interpreting the correlation coefficients. For example, Figure 3 presents the individual data sets and linear correlations (r) of the three-day cumulative coastal rainfall distribution observed at t_0 (lower frames) and the antecedent distribution of SCAMS liquid water over the ocean at t_0 − 72 hours (upper frames) for Cases 1 through 4 (October 1975). For Cases 2 and 3, the storm's direction of movement was eastward and, consequently, the correlation coefficients are relatively high. For Cases 1 and 4, however, storm movement was southward and northward, respectively. Translation of the antecedent water distributions to account for storm movement during the next 72 hours would have increased the coefficients to +0.80 or larger.

For the 14 storm cases associated with correlation coefficients $\geq$ +0.70, Figure 4 shows the relationship, expressed by linear regression, between total storm water (W) over the ocean and total 72-hour rainfall (P) subsequently recorded along the coast from 46°N to 34°N. The standard deviation of P (±14.67 cm) about the linear fit is too large to give

Table 2

FREQUENCY (NUMBER OF CASES) OF MAXIMUM POSITIVE CORRELATION BETWEEN 72-HOUR RAINFALL ALONG THE WEST COAST (46°N-34°N) AND ANTECEDENT SCAMS CLOUD-LIQUID WATER OVER THE EASTERN PACIFIC OCEAN

Antecedent Time of Maximum Correlation (hours)	Frequency of Maximum Positive Correlation						
	October 1975	November 1975	December 1975	January 1976	February 1976	March 1976	$\sum$
96							
84			1(1)		1(1)		2(2)
72	4(2)*		1(1)	1(1)		2(2)	8(6)
60		3(3)	1	2(1)	1(1)		7(5)
48			1(1)				1(1)
36					2		2
Totals	4(2)	3(3)	4(3)	3(2)	4(2)	2(2)	20(14)

*Numbers in parentheses refer to cases with maximum correlations $\geq +0.70$.

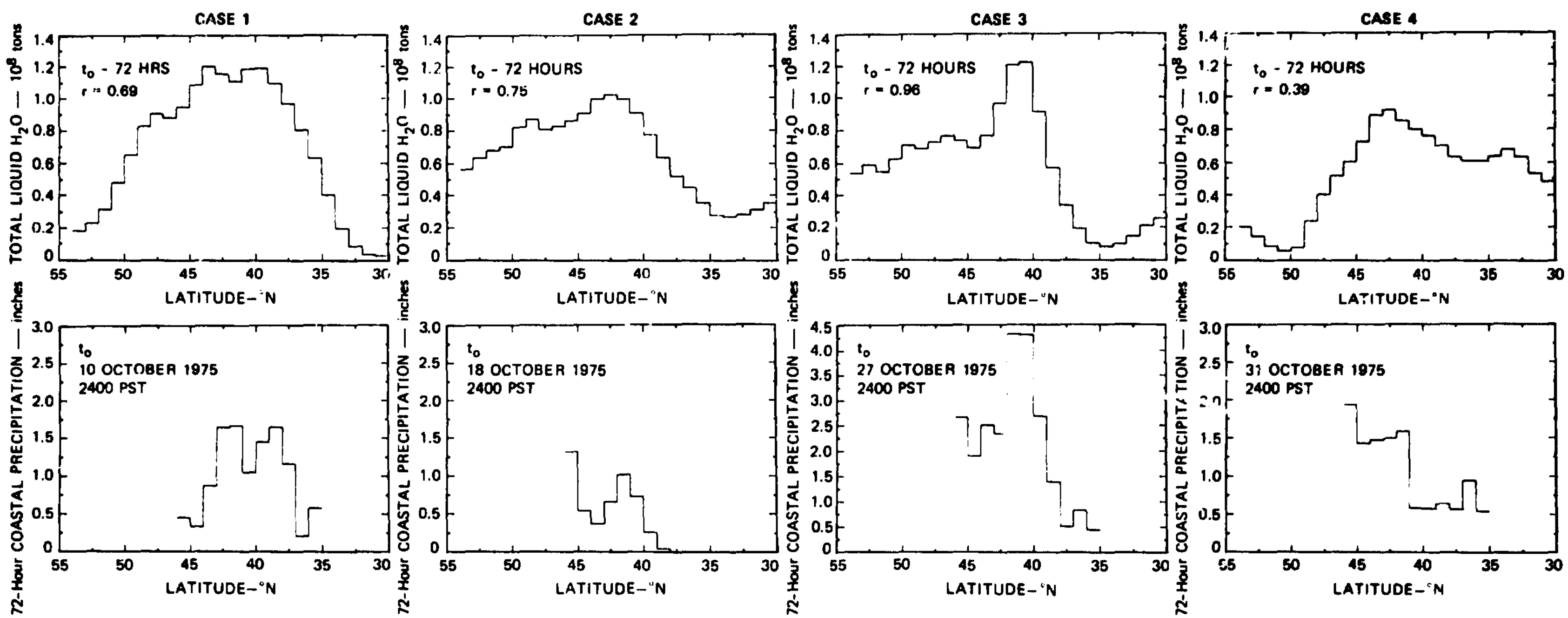

FIGURE 3 DATA SETS AND LINEAR CORRELATIONS (r) FOR THE THREE-DAY CUMULATIVE COASTAL RAINFALL DISTRIBUTION OBSERVED AT t_0 (LOWER FRAME) AND THE ANTECEDENT DISTRIBUTION OF SCAMS LIQUID WATER OVER THE OCEAN AT t_0 – 72 HOURS (UPPER FRAME) FOR CASES 1 THROUGH 4 (OCTOBER 1975)

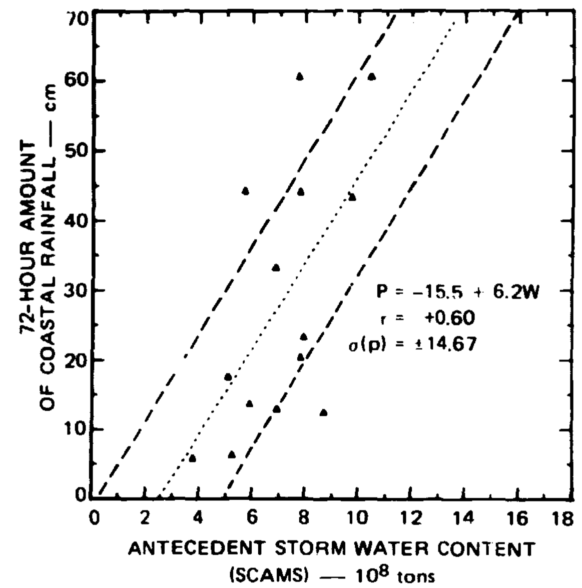

FIGURE 4 TOTAL 72 HOUR COASTAL RAINFALL (P) FROM 46°N TO 34°N VERSUS ANTECEDENT SCAMS-DERIVED TOTAL STORM-WATER CONTENT (W) OVER THE NORTHEASTERN PACIFIC OCEAN

much practical significance to the regression equation. This indicates that the point measurements of liquid water obtained from SCAMS do not represent the rainfall for the entire storm. It is encouraging, however, that in spite of the large field of view of SCAMS (100 to 200 km) ard the simple algorithm used to derive liquid water from SCAMS measurements, a positive correlation between remotely sensed total storm water over the ocean and recorded total rainfall along the coast is evident. Such a quantitative relationship would be very useful in operational weather prediction and hydrology and should be further explored with cloud-water data such as those available from the Scanning Multichannel Microwave Radiometer (SMMR) of Nimbus-7.

IV DISCUSSION

In interpreting the study results, we must remember that cloud water in the form of ice crystals does not interact significantly with microwave radiation and is not accounted for in the SCAMS data. Furthermore, the algorithm by which SCAMS radiance data are converted to liquid water is based on the assumption that the transmittance of water clouds is proportional to the total (integrated) liquid-water mass regardless of distribution of drop size. This Rayleigh approximation applies to clouds with water-droplet radii smaller than about 50 μm. Thus, the SCAMS liquid-water values are derived by neglecting scattering and increased absorption due to precipitation. Grody (1976) has pointed out that the SCAMS algorithm used to derive liquid water results in an overestimate for cases where precipitation is present. Since precipitation was always present in the storm-cloud systems examined, our study emphasizes (and its results reflect) the application of relative variations (distributions) in storm-water content rather than of absolute values.

As noted, storm development and movement were not accounted for in our analyses but must be considered when interpreting the correlation coefficients. The analyses are straightforward when storm systems move from west to east, and our grid area (25° latitude × 26° longitude) encloses only one system at a time, as was the case in October, November, January, and March. For December and February, however, two frontal-wave systems moving from southwest to northeast were frequently present within the area of analysis. In such cases, the computer program should be expanded to enable the separation of liquid-water distributions of the two storms and to account for direction of movement.

V CONCLUSIONS

Our study indicates that passive microwave sensor measurements of storm-cloud water over the ocean, when used in conjunction with numerical and other objective guidance, can enhance the accuracy of predictions of coastal rainfall distribution. This application is further examined by comparing our data with LFM forecasts of the amount of coastal precipitation, at times corresponding to those of some of our case studies. LFM forecast periods of up to 36 hours are available. Forecasts for longer time periods would have been preferable for comparison with the results of our case studies, which showed high positive correlation between 72-hour coastal rainfall distributions and the 60- to 72-hour antecedent SCAMS liquid water distributions over the ocean. From the available data, the LFM 24-hour precipitation predictions were selected for further analysis in the following manner:

- The case studies for which LFM data are available were reexamined for high positive correlation between the distributions of observed 24-hour coastal rainfall and of SCAMS data over the ocean at antecedent time periods less than those considered previously.
- For these "short-term" periods, our computer program analyzed and compared the corresponding data sets of observed rainfall over land and antecedent total liquid water abundance over the ocean in a fashion similar to that shown in Figure 3. However, the coastal distributions of LMF-predicted 24-hour precipitation closest in validation time to the time of observed precipitation (2400 PST) were included.

Two examples are illustrated in Figure 5. Figure 5(a) shows the 24-hour LFM prediction of 24-hour cumulative coastal rainfall distribution for 0345 PST, 26 October 1975 (lower frame), the rainfall distribution observed 3.5 hours earlier at 2400 PST, 25 October (middle frame), and the storm-water distribution analyzed from SCAMS over the ocean approximately 24 hours earlier at 0047-0243 PST, 25 October (top frame). The LFM-predicted rainfall distribution shows general agreement with the observed distribution and with the SCAMS data analysis. In this particular case, if SCAMS data had been available, their analysis would have reinforced the accuracy of the LFM prediction. On the other hand, Figure 5(b) shows a case for which the LFM prediction could have been amended on the basis of the SCAMS data analysis, since the latter is in better agreement with the observed rainfall distribution than is the LFM prediction.

Application of satellite remote measurements of cloud liquid water to rainfall prediction, as discussed above, requires the availability of near-real-time satellite data. It remains to be determined whether the

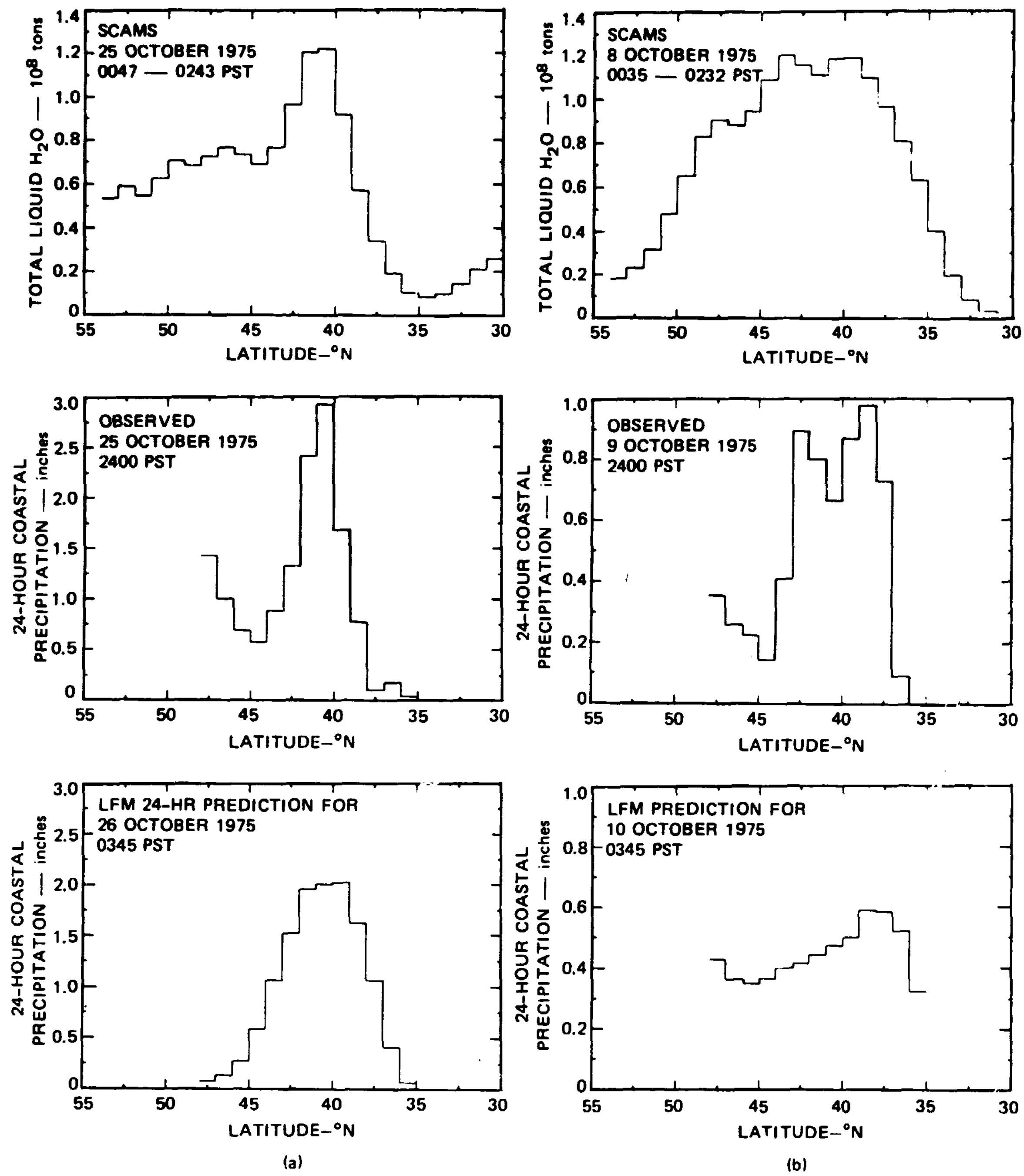

FIGURE 5 COMPARISON BETWEEN LFM PREDICTION OF COASTAL RAINFALL DISTRIBUTION (LOWER FRAMES), OBSERVED RAINFALL DISTRIBUTION (MIDDLE FRAMES), AND ANTECEDENT SCAMS LIQUID WATER DISTRIBUTION OVER THE OCEAN (UPPER FRAMES) FOR TWO DIFFERENT CASES. Data comparisons show how cloud liquid water data from passive microwave sensors over the ocean can be used to reinforce (a), and amend (b) numerical predictions of coastal rainfall distribution.

potential for enhanced accuracy in predicting coastal rainfall distribution justifies the cost of making such data available.

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