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AN EVALUATION OF VAS SATELLITE MOISTURE RETRIEVALS AND MOISTURE BOGUS DATA IN THE GULF OF MEXICO

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Cooperative Institute for Meteorological Satellite Studies

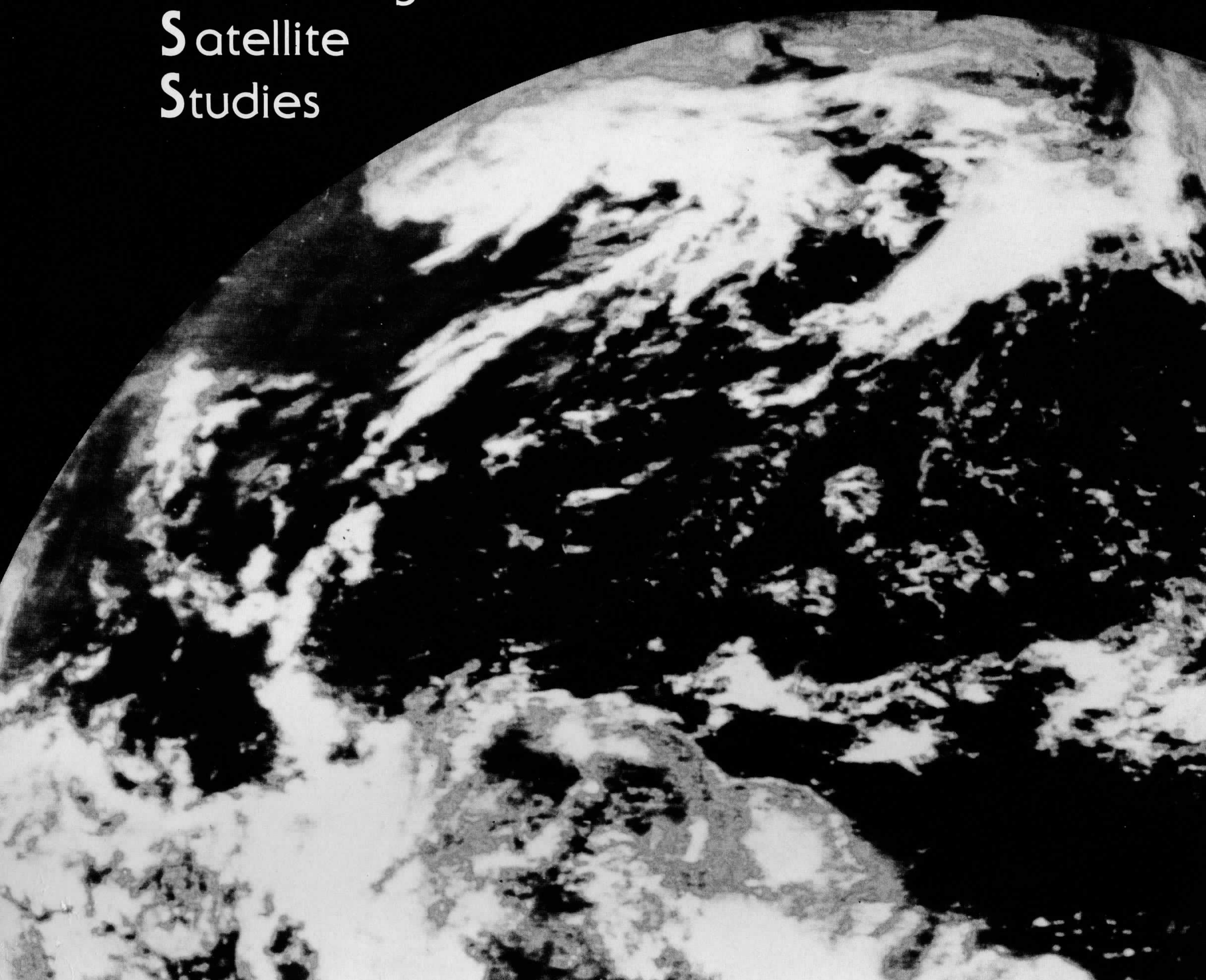

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TABLE OF CONTENTS

I. INTRODUCTION

With the ongoing improvement in numerical weather prediction models, initialization of the moisture distribution is becoming increasingly important. An area of particular concern is the Gulf of Mexico and the neighboring western Atlantic which serve as a moisture source for most of the central and eastern U.S. Apart from a few island stations, this ocean area is very sparse in upper air measurements, and satellite data are expected to provide primary information. The method used operationally to date (since the early 1970's) is the moisture bogus technique (Chu, 1977). In this technique, GOES cloud images are used to discriminate from a set of 13 pre-defined relative humidity profiles according to the analyst's interpretation of the synoptic situation shown by the GOES Infrared (IR) and visible (if available) imagery. For each profile, relative humidity is defined for six mandatory pressure levels from 1000hPA to 300hPA or three layers defined in sigma coordinates, depending on whether it is to be used in the global or regional models, respectively.

Moisture data are also available from the retrievals obtained with the TIROS Operational Vertical Sounder (TOVS) and the VISSR Atmospheric Sounder (VAS). Timchalk (1986) made a comparison between the moisture bogus technique (MBT) and moisture retrievals derived from the TOVS. In this study he found the TOVS moisture soundings to be of higher quality than the MBT, but, they are not always available at synoptic times over a large area.

In cooperation with the National Meteorological Center (NMC) the University of Wisconsin CIMSS/NESDIS group has been investigating the moisture retrievals of the VAS over the Gulf of Mexico and the neighboring West Atlantic as part of the VAS Model Impact Study (VMIS) (Siebers et al., 1986). A prime objective of the VMIS is to evaluate the impact of the VAS data on model precipitation generated by the Regional Analysis and Forecast System (RAFS) which provides the short-term operational numerical forecasts of the National Weather Service (NWS). Preliminary to the model impact studies, we have conducted a data evaluation, comparing the VAS moisture retrievals to the available radiosondes, and comparing their accuracy to that offered by the MBT and the RAFS 12-hour forecast. The period of this study covers three weeks from 2 May 1988 to 20 May 1988, when moisture retrievals were generated near 1200UTC (from the 1248/1318UTC VAS dwell sounds).

II. TECHNIQUES

As mentioned above, the MBT is comprised of 13 categories or profiles. Each one of these categories represents a synoptic, three-dimensional moisture distribution, which is chosen based on GOES visible and IR data. The categories range from an area of vertically solid cloudiness with moderate to heavy precipitation (Cat.1) to perfectly clear skies (Cat.10). Categories 11 through 13 are slightly modified versions of earlier categories. At the National Environmental Satellite, Data, and Information Service (NESDIS), a synoptician with the aid of GOES imagery and surface data determines the best fitting relative humidity profile for the data sparse ocean regions surrounding the United States. For a more detailed description of the moisture bogus categories and the procedure used to enter this information into the NWP models see Smigielski et al. (1982).

The VAS retrieval algorithm used is the "simultaneous" method (Hayden, 1988 and Smith et al., 1984). It employs an atmospheric first guess and a surface analysis made up of a 1000hPa height in meters, surface temperature analysis in degrees Kelvin, and a surface dew point depression (K). The atmospheric first guess for this experiment was comprised of the 12-hour forecast of 0000UTC Regional Area Forecast System (RAFS) model run, which verifies at 1200UTC. The surface analyses were derived by blending the first guess with surface reports in the data sparse regions of the Gulf of Mexico and the western Atlantic.

Some minor modifications to the retrieval algorithm have been made since the "simultaneous" method was first introduced. The original "simultaneous" method uses three VAS bands in the form of weighting functions to provide basis functions for the moisture. Those bands were the "dirty window" channel (band 7, 12.66 micrometers) and the two water vapor bands (band 9, 7.26 micrometers and band 10, 6.73 micrometers). The current operational version has increased the number of moisture basis functions from three to four and uses Gaussian shaped curves instead of actual weighting functions. The peak sensing levels are at 350hPA, 500hPA, 700hPA, and 900hPA. The half-width of the curves decrease for the lower two basis functions relative to the 350hPA and 500hPA curves. The main impetus for changing from three to four basis functions and using Gaussian curves rather than the weighting functions was to stabilize the moisture retrieval as well as to add more information at the lower levels of the atmosphere, decreasing dependence on the first guess. An example of the old moisture weighting functions (bands 7, 9, and 10) and of the new Gaussian curves is shown in Figs. 1A and 1B, respectively.

Since the VAS does not directly measure level information, we have opted to verify the retrieved moisture quantities in the form of layered precipitable water (LPW). This maximizes the utilization of the horizontal advantages of the satellite information and minimizes the poor vertical resolution of the remotely sensed data. To eliminate the effects of terrain, satellite-derived LPW is derived in sigma coordinates (pressure divided by surface pressure). The LPW is available in 15 layers from 0.98 sigma to 0.10 sigma. This study concentrated on the surface to 0.70 sigma layer and the surface to 0.30 sigma layer to study the impact of the VAS derived data for low level and total precipitable water, respectively.

III. DATA COLLECTION

VAS radiance data were collected and processed for two (three, including the one week spin-up) weeks over southeastern United States and the adjoining Gulf of Mexico. A brief summation of what data was produced is shown in Table 1. As can be seen, no VAS data were collected or processed on weekends otherwise, with the exception of two days, satellite moisture information was continuously generated. The only day in which VAS

TABLE 1

DATE	DWELL SOUNDS		MOISTURE PRODUCTS	
	1248Z	1318Z	RETS	L.P.W.
02May	yes	no	1/2	no
03May	yes	yes	yes	yes
04May	yes	yes	yes	yes
05May	yes	yes	yes	yes
06May	yes	yes	yes	yes
09May	yes	yes	yes	yes
10May	no	no	no	no
11May	yes	no	1/2	yes
12May	yes	yes	yes	yes
13May	yes	yes	yes	yes
16May	yes	no	1/2	yes
17May	yes	yes	yes	yes
18May	yes	yes	yes	yes
19May	yes	yes	yes	yes
20May	yes	yes	yes	yes

radiance data was not received was 10 May. The reason for failure on this day is the result of a power outage at UW.

Unfortunately, the success rate for receiving the Moisture Bogus Product was not nearly as high. This was a new venture for us, and because the VDUC does not archive this product only four of the possible ten (fifteen, if the "spin up" week is included) days were collected. Of those four days, three occurred during the last week of experiment. This is barely a representative sample from which to make comparisons, and the study is ongoing.

All radiosonde observations for the period 1-20 May were collected and modified into LPW format as were the satellite moisture retrievals and the limited sample of moisture bogus soundings. For this study only, raobs within the Gulf of Mexico region were included in the statistics generated in section IV.

TABLE 2
LAYERED PRECIPITABLE WATER
(Surface to 0.70 Sigma)

DATE	SAT VS RAOB			1ST GSS VS RAOB			BOGUS VS RAOB		
	BIAS	RMSE	CC	BIAS	RMSE	CC	BIAS	RMSE	CC
02May									
03May	-1.98	4.61	0.95	3.48	7.05	0.90			
04May	2.33	4.13	0.91	6.74	7.55	0.96			
05May	0.71	3.72	0.94	4.37	6.92	0.90			
06May	-1.11	3.76	0.93	2.77	5.97	0.85			
09May	-0.98	4.09	0.75	2.32	3.71	0.89			
10May									
11May									
12May	2.77	6.69	0.75	6.74	7.86	0.93	1.69	6.27	0.71
13May	2.95	5.84	0.81	7.97	10.16	0.76			
16May									
17May	3.80	6.69	0.92	5.97	8.30	0.84			
18May	-2.24	5.28	0.72	3.72	6.04	0.76	-0.93	5.62	0.59
19May	0.51	5.34	0.85	6.36	7.87	0.93	-0.22	4.85	0.91
20May	-0.49	6.87	0.46	4.10	6.56	0.74	0.72	6.04	0.61

All statistics were derived in the following manner:

*Using the three-dimensional recursive filter analysis system developed by Hayden and Purser (1988), three analyses of layered precipitable water in sigma layers were derived: an analysis of the first guess only; an analysis of the VAS-derived moisture retrievals; an analysis of the moisture bogus data. The latter two analyses used the first guess as background field.

*Statistical comparisons of radiosonde observations vs. values interpolated in the analyses were collected over an area in the Gulf of Mexico from 17N to 30N and 70W to 98W, concentrating on the surface to 0.70 Sigma level and surface to 0.30 Sigma level, which is found in Table 3.

IV. RESULTS

A. Statistical Results

Table 2 and 3 compare the VAS moisture retrievals, the moisture bogus soundings, and the first guess to radiosonde observations. Tables 2 and 3 describe the bias, root mean square error (rmse), and the correlation coefficient (cc), respectively. All data sets verify at or near 1200UTC.

TABLE 3

LAYERED PRECIPITABLE WATER
(Surface to 0.30 Sigma)

DATE	SAT VS RAOB			1ST GSS VS RAOB			BOGUS VS RAOB		
	BIAS	RMSE	CC	BIAS	RMSE	CC	BIAS	RMSE	CC
02May									
03May	-2.73	5.50	0.94	2.23	7.40	0.89			
04May	2.34	3.77	0.95	5.54	6.51	0.95			
05May	0.22	4.02	0.96	3.75	7.05	0.93			
06May	-2.31	4.42	0.94	1.86	6.17	0.86			
09May	-3.19	5.96	0.65	0.48	3.97	0.78			
10May									
11May									
12May	0.04	6.34	0.73	4.82	6.01	0.93	-0.02	6.44	0.72
13May	1.12	6.65	0.79	6.51	10.53	0.72			
16May									
17May	3.24	6.72	0.94	4.56	7.90	0.86			
18May	-2.89	6.14	0.72	2.15	5.71	0.74	-2.03	7.02	0.53
19May	-0.10	6.51	0.84	4.93	7.51	0.92	-1.22	5.45	0.93
20May	-1.89	8.64	0.58	1.45	6.46	0.77	-0.37	6.87	0.72

When comparing the statistical results for the three data sets, with the exception of the systematic differences in the bias, it becomes apparent no one group consistently outperforms the other two. The statistics indicate that each day is independent of the previous or following day. We are not convinced the systematic difference in the bias shows superiority of the satellite data (the differences are very consistent, between 3.0 and 5.0 millimeters of water and seemingly independent of height, found in both Table 2 and 3). The apparent superiority may be an artifact of the verification method. Further investigations in this phenomena are being carried out. Very similar results found in Table 2 are also described in Table 3. No systematic improvement or degradation are observed when comparing statistics at the lower layer versus those same statistics for the larger layer (surface to 0.30 sigma).

Composite statistics for the entire three week period were also derived and are shown in Fig. 2. The layered precipitable water from the surface to 0.70 sigma derived from VAS radiances (A), the RAFS 12-hour forecast valid at 1200 UTC (B), and the moisture bogus soundings (C) are compared to the 1200UTC radiosonde observations. Unfortunately, there are only four days worth of data available utilizing moisture bogus information, therefore the moisture bogus statistics are not the same representative sample. These statistics again display the systematic difference in the bias between the VAS and moisture bogus versus the First Guess. The variance for all three data sets is very close. The correlation coefficient for the moisture bogus is noticeably lower than the others, but this may be a result of unequal sample sizes. The major difference between the Figs. 2a and 2b is the increased distribution of the loci of points at the moist end of the curve for the VAS-derived moisture versus the RAFS forecast. The cause for this "fanning" may be a result of the relative dry satellite soundings versus moist radiosonde observations in the Gulf for the 20 May case study day, which will be discussed in detail in the Analyses section.

TABLE 4
LAYERED PRECIPITABLE WATER
(Surface to 0.70 Sigma)

DATE	SAT VS FIRST GSS			BOGUS VS FIRST GSS		
	BIAS	RMSE	CC	BIAS	RMSE	CC
02May						
03May	-4.51	5.19	0.93			
04May	-4.31	5.17	0.93			
05May	-3.16	4.19	0.92			
06May	-4.52	5.36	0.92			
09May	-3.42	4.21	0.86			
10May						
11May						
12May	-3.68	4.57	0.75	-4.52	5.52	0.66
13May	-6.08	6.99	0.74			
16May						
17May	-3.55	4.61	0.77			
18May	-4.94	5.78	0.82	-4.95	5.92	0.81
19May	-5.43	6.03	0.84	-6.72	7.05	0.90
20May	-4.66	5.77	0.76	-3.67	4.50	0.85

Table 4 is included to demonstrate the relative independence of the satellite-derived LPW and the modified moisture bogus from the RAFS 12-hour forecast. Here again, as in Tables 2 and 3 the results can at best be described as mixed. Using values of correlation coefficient for each of the days, on some days considerable independence is observed (e.g., 12, 13, 17, and 20 May), yet on other days strong dependence is seen (e.g., 3, 4, 5, and 6 May). Is this a result of tenacious guess-dependence of the retrieval algorithm; or due to a "good" atmospheric guess only slightly improved by the VAS data; or a coincidental result of the statistics? This question can only be answered by looking at the analyses themselves.

B. Analyses

Figures 3 through 13 show (A) the LPW analyses based on the VAS-derived radiances, (B) the RAFS 12-hour forecast valid at 1200UTC, and, (C) (when available) the moisture bogus soundings. All analyses are for the surface to 0.70 sigma layer. The isolines are in units of millimeters of water vapor. Data locations for the VAS-derived moisture retrievals are plotted over the VAS analysis (A); the radiosonde values for 1200UTC are plotted on the first guess analysis (B); and the calculated values of LPW for the moisture bogus are plotted in C. The box delineated in A of all the figures defines the area of statistical verification. LPW from the surface to 0.30 sigma is not included in this set of figures, since the major features defined in the lower layer are for the most part repeated in the total layer.

When comparing the first guess used in generating the VAS-derived moisture retrievals to the satellite soundings, one notices initially the minimal amount of influence the soundings had over the conventionally data rich region of the United States. This indicates that the RAFS 12-hour forecast for these case study days is a good initial product in continental regions. The area of greatest modification by the satellite-derived moisture analyses (STAN) and, by default, the moisture bogus analyses (MBAN) is in the Gulf of Mexico and its littoral. This is the region which we will primarily concentrate on for the remainder of the comparisons.

Figures 3-6 depict the LPW for the 0.70 sigma layer during the first week of the data test. In Fig. 3 (3 May, 1988), the STAN correctly increases the LPW through 0.70 sigma over the Greater Antilles (Cuba and Santo Domingo) relative to the first guess moisture analyses (FRAN). The STAN also pushes more moisture into eastern Texas, which is verified by the radiosonde observations in the region. In Fig. 4, again over eastern Texas the STAN increases the overall LPW compared to the FRAN, and as in the 3 May case this is confirmed by the conventional radiosondes. Although the STAN (Fig. 4a) increases the moisture slightly over the Gulf Coast relative to the FRAN, it is still not as moist as the raob data indicates over that region. Both Figs. 5a and 6a correctly show an increase of layered moisture over the Greater Antilles, which is not shown in the RAFS 12-hour forecast analysis of precipitable water (Figs. 5b and 6b). The radiosonde value of 33 millimeter for the 0.70 sigma layer located at Vera cruz, Mexico in Fig. 5b is substantially higher than the FRAN, but more in line, although not perfectly with the STAN (Fig. 5a). This same situation is observed on the 6 May case study day (Fig. 6). On this particular day, the satellite derived analysis increases the moisture along the Gulf Coast, but is higher than described by the radiosonde observations.

The second week (Figs. 7-9) of the experiment, 9-13 May, only includes three case study days (Table 1), and the first opportunity to compare the results obtained using the moisture bogus soundings. Throughout the week clouds extended over the Gulf of Mexico, especially the western region. Consequently, satellite sounding coverage was less than desired, and resulted in only slight modifications to the first guess. On 9 May (Fig. 7) the VAS-derived analysis (a) increases the LPW over the Florida peninsula relative to the FRAN (b) in agreement with the observed radiosondes. In contrast the STAN defines a local maximum over the Yucatan peninsula, which differs with the Merida sounding. Examining these retrievals more closely showed them to be considerably more moist than the observed radiosonde. These specific retrievals were apparently incorrectly defined as clear-column temperature/moisture profiles; when, in fact, the radiances were cloud contaminated. Figure 8 is the first case study day including the moisture bogus data (MBAN). The resulting surface to 0.70 sigma layer analysis resembles the FRAN, but there are areas which are quite noisy, for example the region over Cuba. (In general, it is frequently difficult to analyze the derived moisture bogus soundings since the categories can impose sharp transitions.) Overall, for this particular day there is no clear cut winner, especially when the region from Grand Cayman, Jamaica, and Guantanamo Bay, Cuba is examined. In this region the STAN, FRAN, and MBAN all substantially under-estimate the observed low level moisture. On 13 May (Fig. 9), the RAFS 12-hour forecast very poorly defines the LPW over the Florida peninsula as well as over Jamaica and eastern Cuba. The satellite derived analysis (Fig. 9a) improves considerably in these regions, but still is not as moist as the observed radiosonde data.

Figures 10-13 (17-20 May) portray the analyses for the third week of the VAS moisture test. During that week, the STAN shows a dry wedge moving from the western Gulf of Mexico on 17 May (Fig. 10a), weakening slightly on 18 and 19 May, then strengthening again on 20 May (Fig. 13a) off the west coast of Florida and extending south, just east of the Yucatan peninsula. This pattern is weakly reflected in the FRAN (Figs. 10b-13b), and poorly defined in the MBAN (Figs. 11c-13c). The radiosonde observations reflect the eastward progression of this dry pocket. By observing three stations; Victoria, Boothville, and Key West, (which are underlined) the dry pocket can be traced. Both the STAN (A) and the MBAN (C) define a relative maximum over the Greater Antilles which is more moist and better collated with conventional radiosondes than the RAFS 12-hour forecast. The moisture bogus analysis tends to extend this relative maximum northeast into the Atlantic, which is a data void region for the satellite-derived analyses.

As mentioned previously, the STAN shows an area of relative drying just west of Florida and north of Cuba extending down from the eastern half of the United States for the 20 May case study day (Fig. 13a). This feature is not supported by the radiosondes along the west coast of Florida and Grand Cayman (Fig. 13b), but both band 10 and 9 VAS imagery confirm a dry intrusion. Admittedly though, their peak sensing levels are higher in the atmosphere than the layer being observed. To get better insight in this case, calculated brightness temperatures were generated for the radiosonde at Grand Cayman and compared to the observed brightness temperatures from VAS for bands 7 and 8, the "dirty window" and longwave window channels, respectively. The results are shown in Table 5.

TABLE 5
BRIGHTNESS TEMPERATURES

	Calculated		Observed
Station#	78384	Grand Cayman	
Band 7	286.91K		292.16K
Band 8	293.02K		296.37K
Station#	72232	Boothville	
Band 7	287.88K		288.33K
Band 8	293.44K		293.29K

The difference between bands 7 and 8 (split window) as a rough estimate of low level or surface moisture (Chesters et al., 1983). The larger the difference between the two bands the more moisture present. The difference for the calculated is slightly over 6K, while for the observed, it is around 4K. Thus, the observed brightness temperatures imply less low level moisture than the calculated brightness temperature values, which is what the VAS analysis shows compared to this radiosonde. For comparison a similar calculation was made for a location (72232) where the STAN and the conventional radiosonde concur. In this case, Boothville demonstrated excellent correlation between observed and calculated brightness values.

V. SUMMARY

For a three week period during the beginning of May 1988, a test was run to compare the results using moisture retrievals derived from VAS radiances, the first guess (12-hour RAFS forecast) used to generate those moisture retrievals, and the moisture bogus data to each other as well as the radiosonde observations in the Gulf of Mexico and its littoral. All data was defined in terms of layered precipitable water in a sigma coordinate system. Based on the results of these comparisons, a number of conclusions can be made.

The 12-hour RAFS forecast valid at 12UTC is a good first guess of the moisture. Consistently, throughout the VMIS experiment period, the first guess exhibited a high correlation, and small values of variance with only one or two days being the exception. Over the United States the FRAN, in areas rich in traditional observations, is able to consistently define the major (synoptic) dry and moist regions. Over the Gulf of Mexico, the FRAN is not as consistently good. This is shown for several days, especially along the Greater Antilles, which includes observations at Grand Cayman, Jamaica, Cuba, and the Dominican Republic.

The satellite derived analyses show no tendency to degenerate the first guess (12-hour RAFS forecast) for case study days during these three weeks, even over the data rich areas where the FRAN is highly accurate. This is not obvious in the statistical tables, but is consistently seen in the analyses. Larger changes are seen over the data sparse areas from which we infer that the VAS data are adding information. In addition to enhancing the analyses in regions over the Gulf, the remotely-sensed moisture retrievals improved the STAN relative to the FRAN with respect to the conventional radiosonde data over the United States (for example, see Fig. 8).

Throughout this entire study, the VAS-derived moisture soundings are presented in terms of "layered product". The reason for this has been intentional. Previous investigations using VAS data as "level product" have at best been inconsistent (O'Lenic, 1986; Mostek and Olsen, 1986), although these studies only dealt with geopotential heights. We feel by exploiting the horizontal advantage of the remotely sensed data and integrating over layers to compensate for the poor vertical resolution is another reason for the positive impact demonstrated in the Gulf of Mexico and its littoral.

Finally, this study has concentrated on the advantages of using VAS derived moisture retrievals in lieu of the moisture bogus in the Gulf of Mexico. Previous studies have shown the advantages of using TOVS derived moisture products over the moisture bogus (e.g., Timchalk, 1986). In no way is this study attempting to supplant those efforts, but instead the two sounding systems complement each other. The two satellite platforms perform on different scales: TOVS offers global coverage while the VAS is capable of functioning on a regional scale. Therefore, the two-satellite system will produce moisture information on a global/synoptic scale (TOVS) as well high frequency time and spatial resolution data (VAS) for use in weather analysis and numerical weather prediction models.

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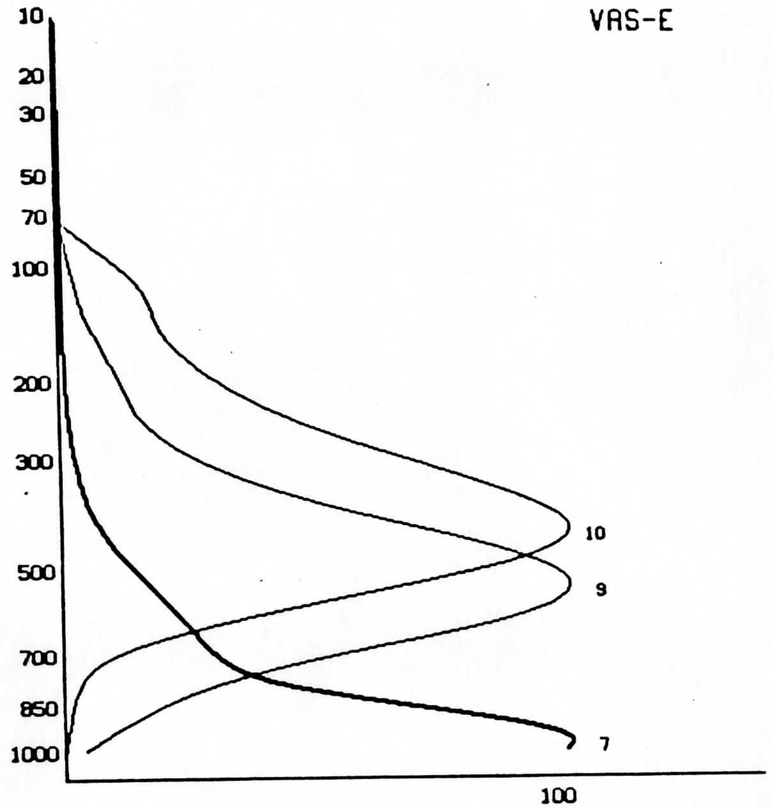
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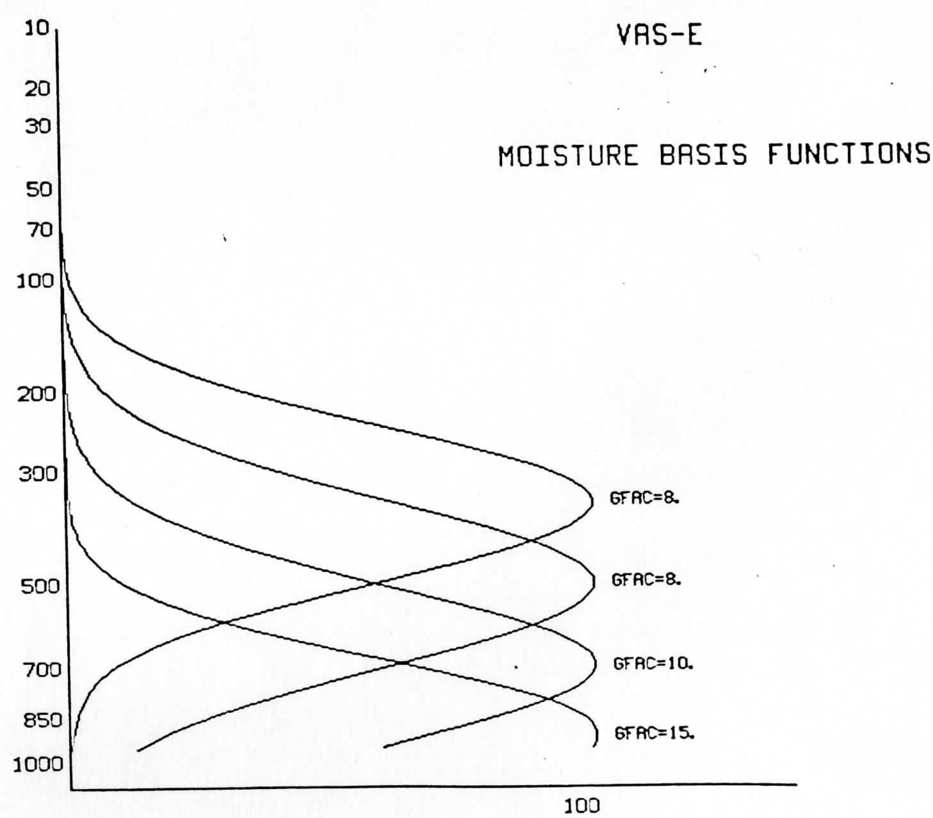
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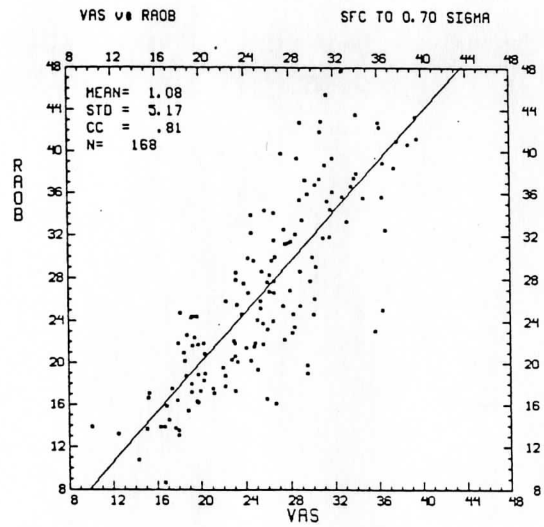
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RAOB
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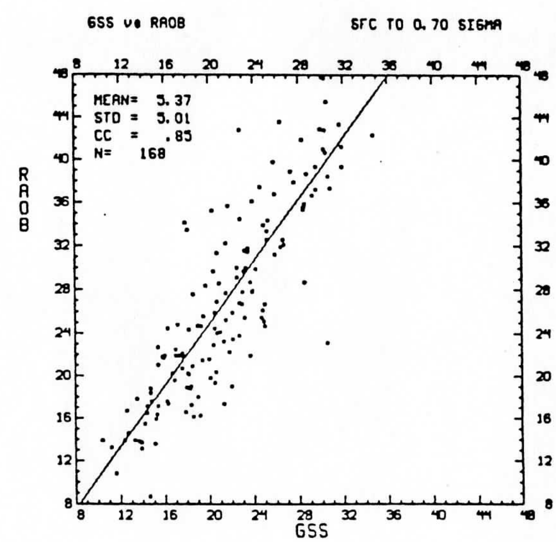
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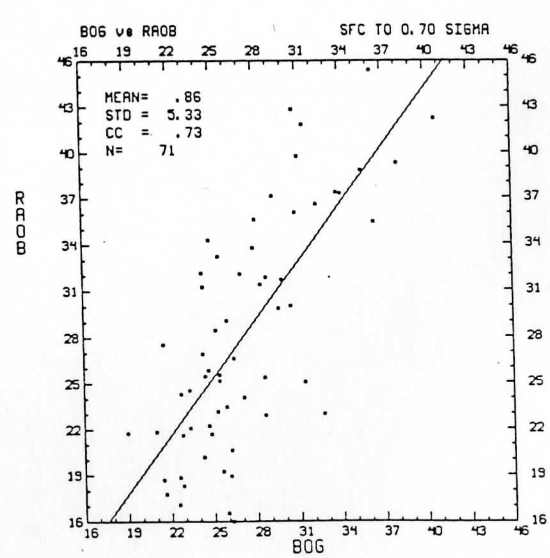
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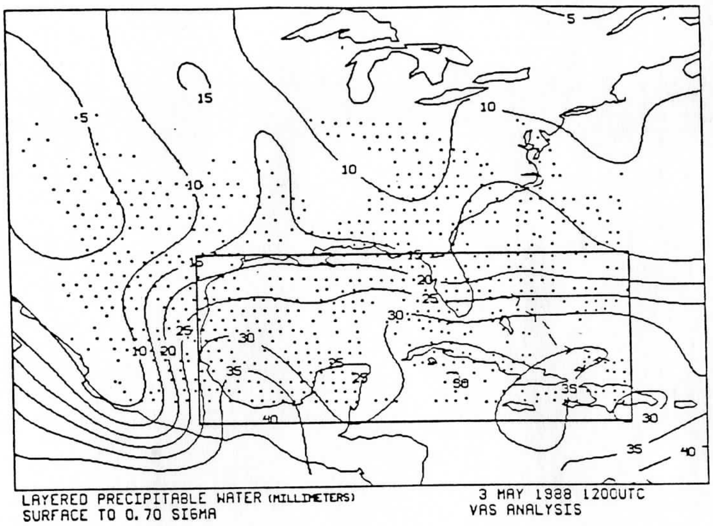
RAOB
BOG

(C)

Figure 2



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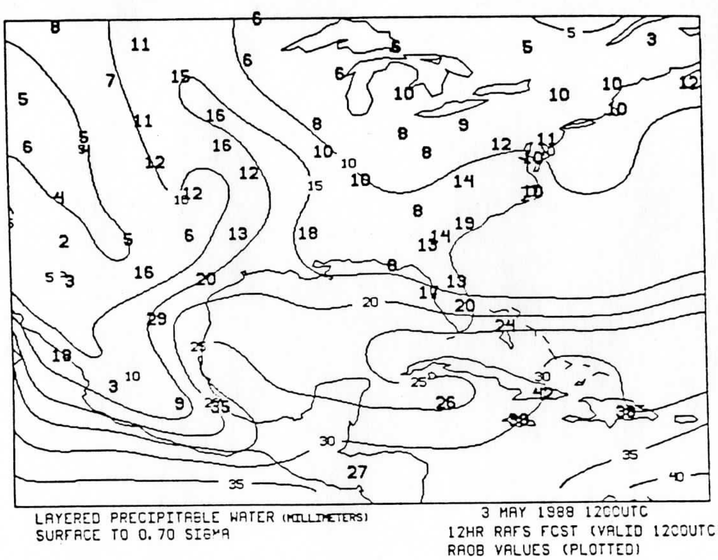

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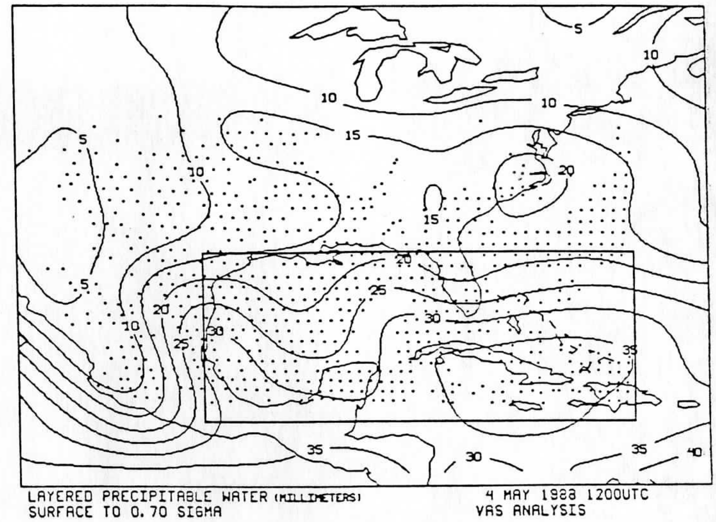
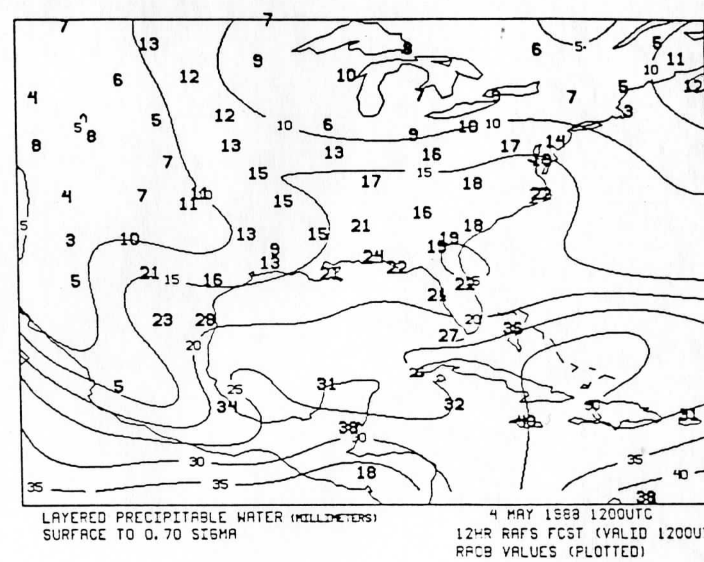
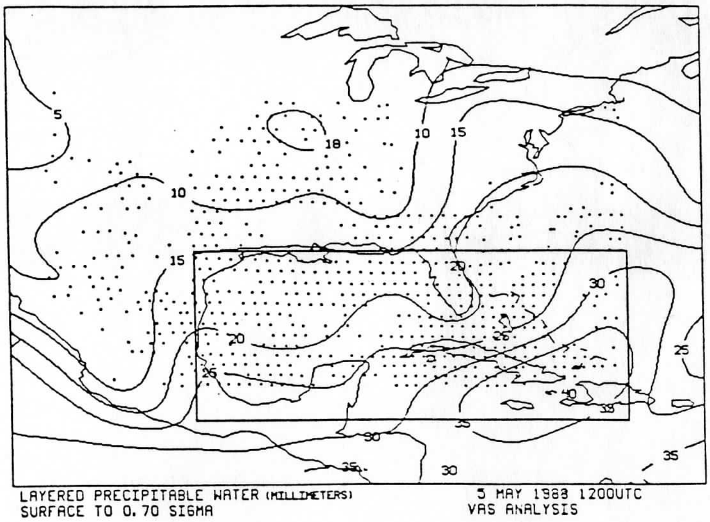


(A)

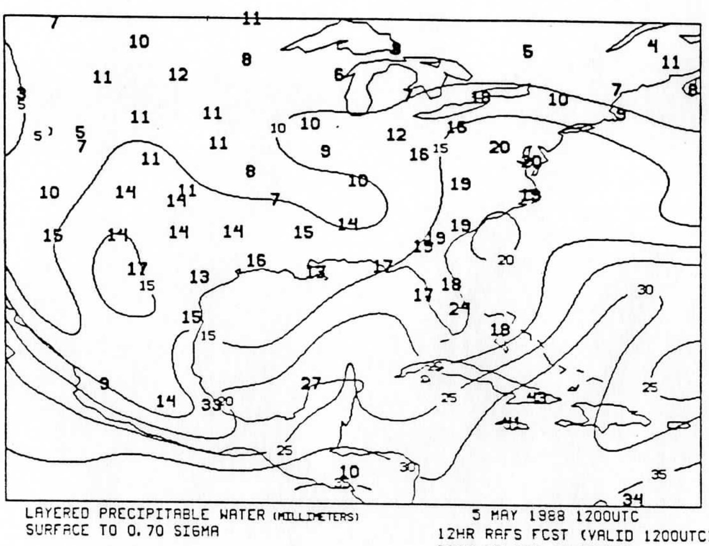


(B)

Figure 4

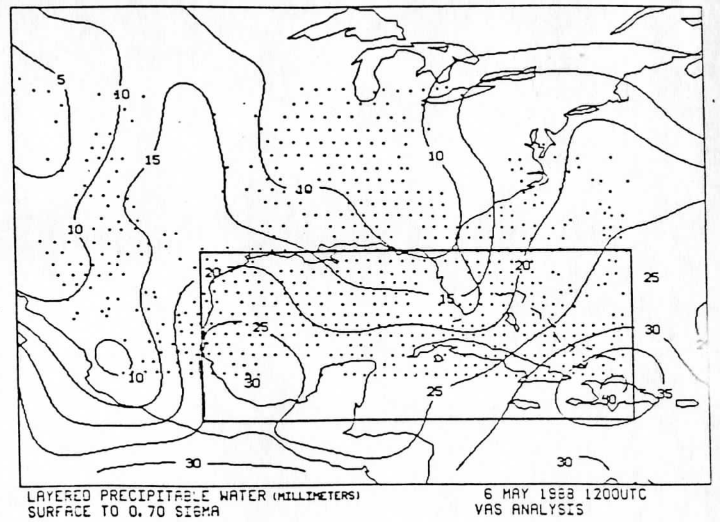


(A)

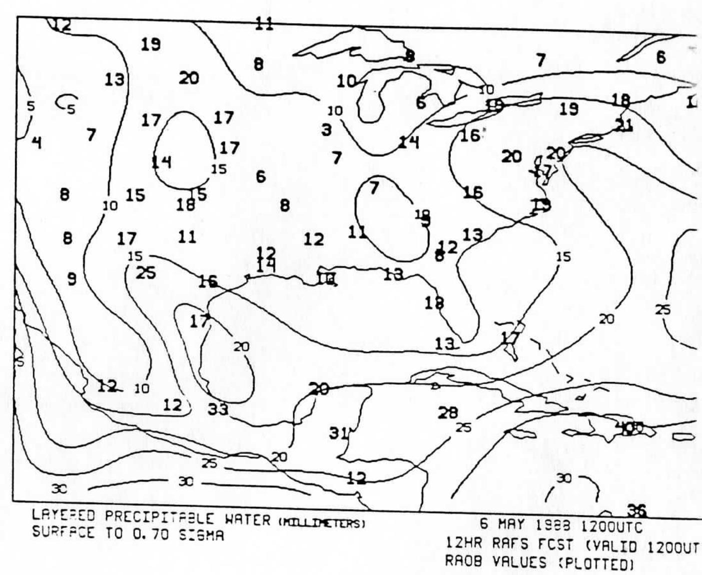


(B)

Figure 5

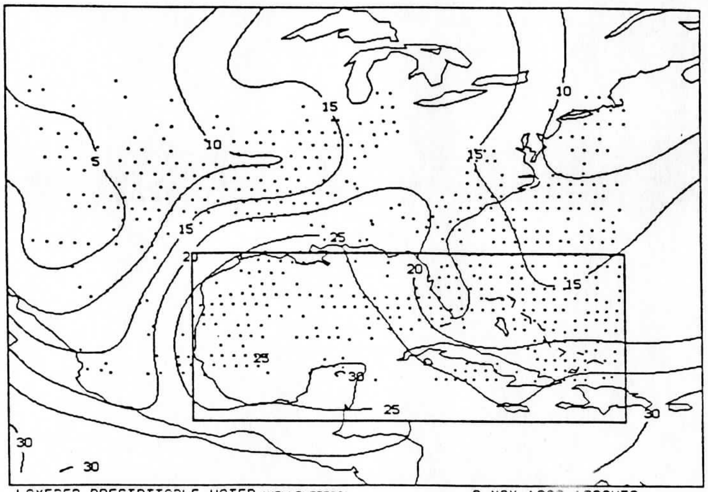


(A)



(B)

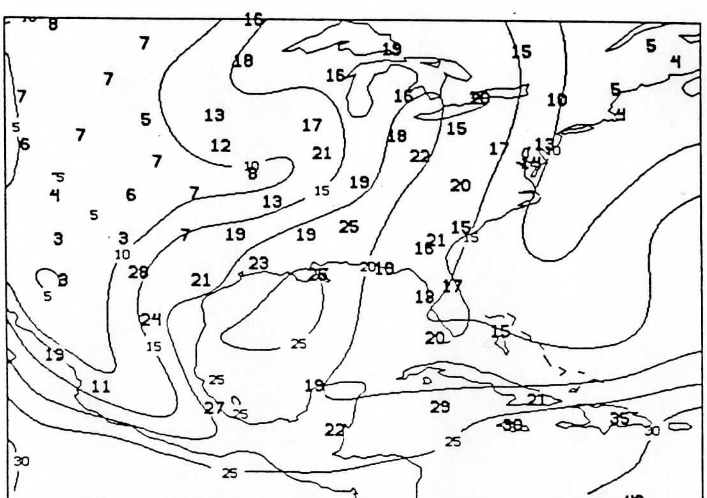
Figure 6



LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

9 MAY 1988 1200UTC
VAS ANALYSIS

(A)

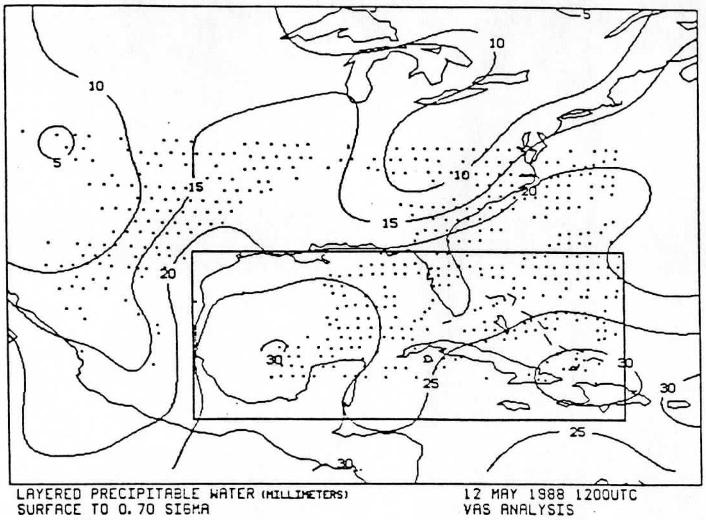


LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

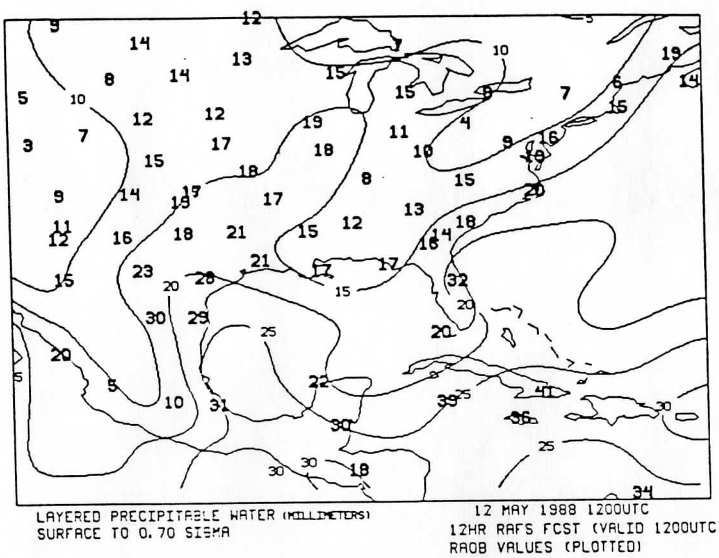
9 MAY 1988 1200UTC
12HR RAFS FCST (VALID 1200UTC)
RAOB VALUES (PLOTTED)

(B)

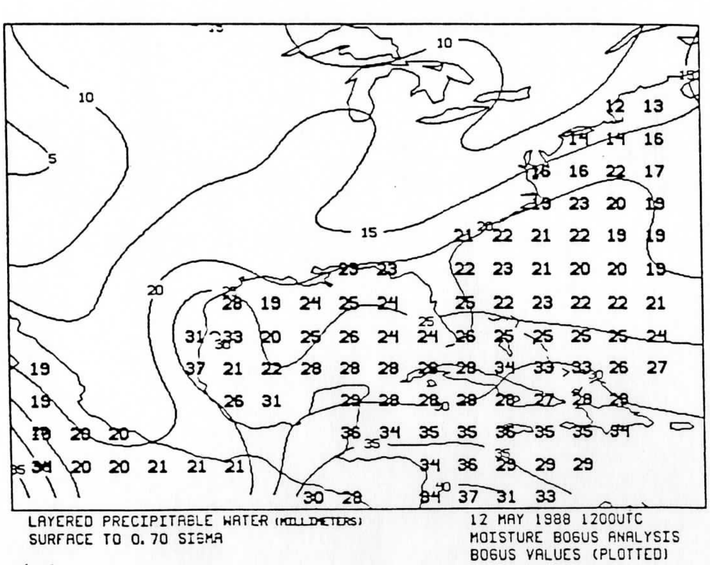
Figure 7



(A)

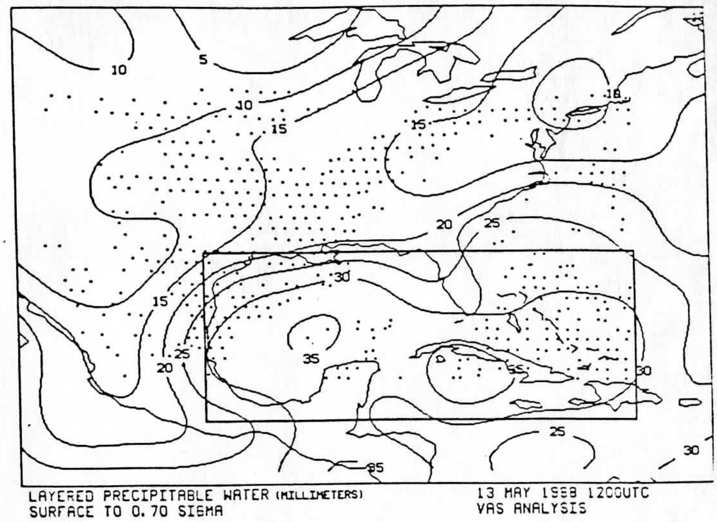


(B)

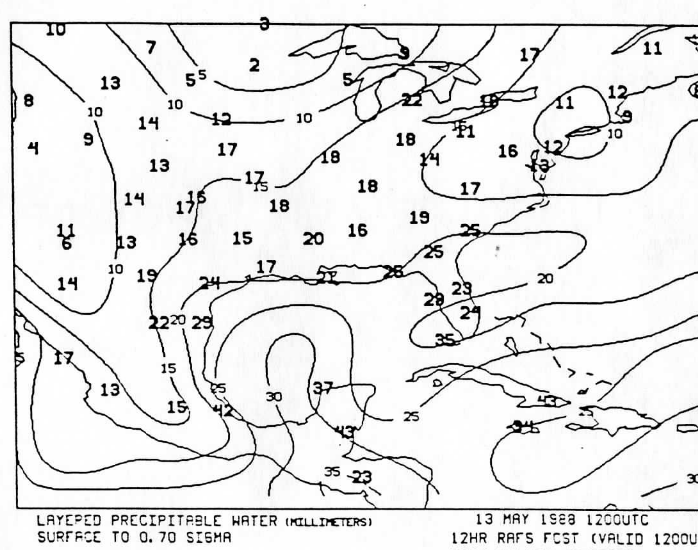


(C)

Figure 8

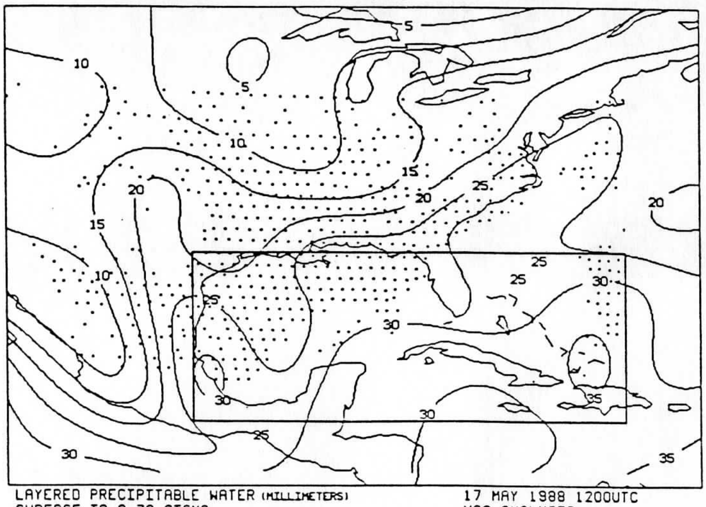


(A)



(B)

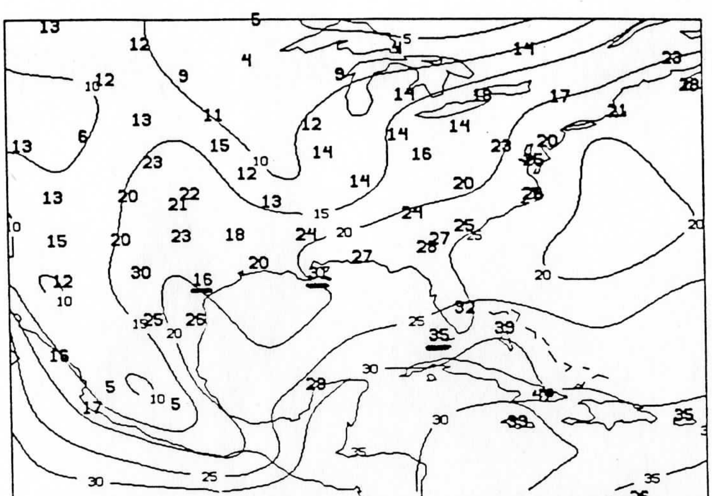
Figure 9



LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

17 MAY 1988 1200UTC
VAS ANALYSIS

(A)

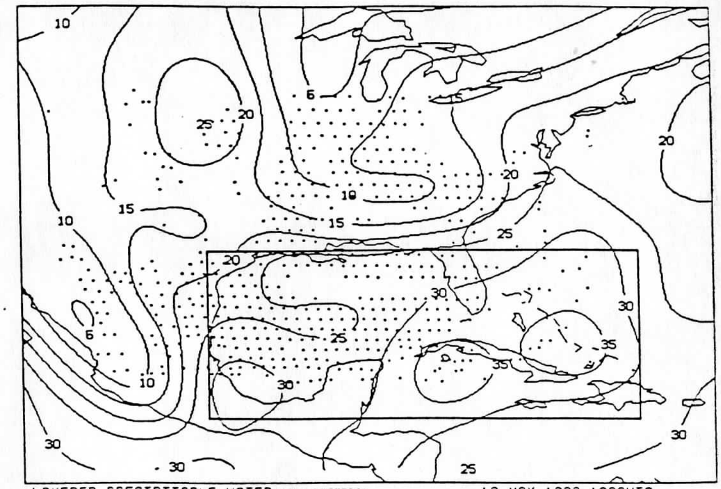


LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

17 MAY 1988 1200UTC
12HR RAFS FCST (VALID 1200UTC)
RAOB VALUES (PLOTTED)

(B)

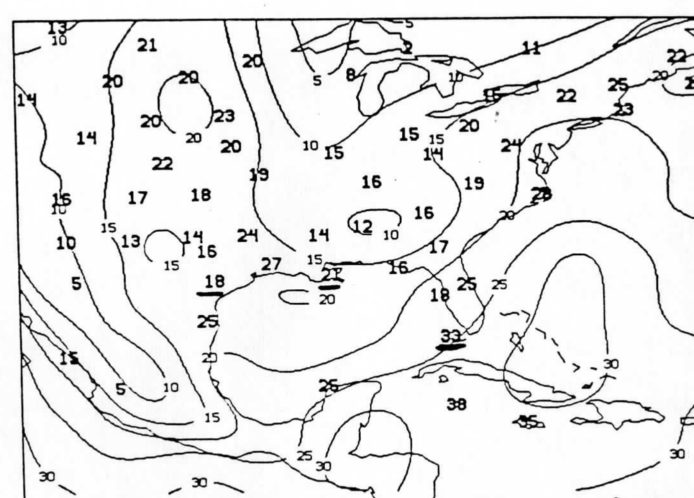
Figure 10



LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

18 MAY 1988 1200UTC
VAS ANALYSIS

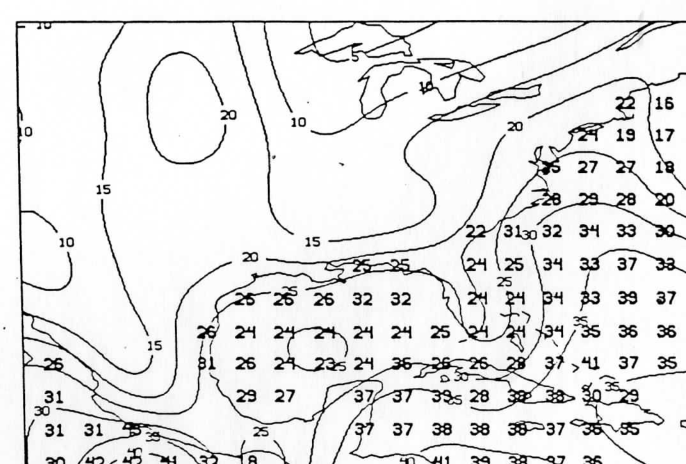
(A)



LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

18 MAY 1988 1200UTC
12HR RAFS FCST (VALID 1200UTC)
RAOB VALUES (PLOTTED)

(B)



LAYERED PRECIPITABLE WATER (MILLIMETERS)
SURFACE TO 0.70 SIGMA

18 MAY 1988 1200UTC
MOISTURE BOGUS ANALYSIS
BOGUS VALUES (PLOTTED)

(C)

Figure 11

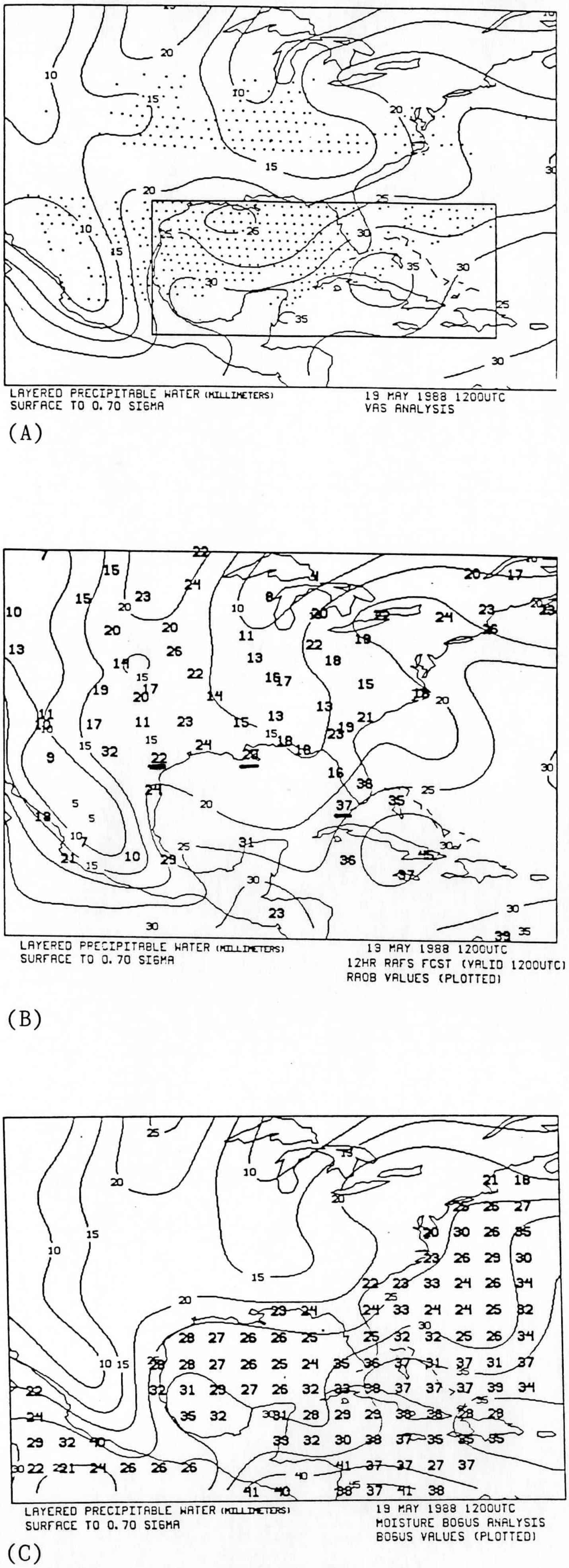


Figure 12

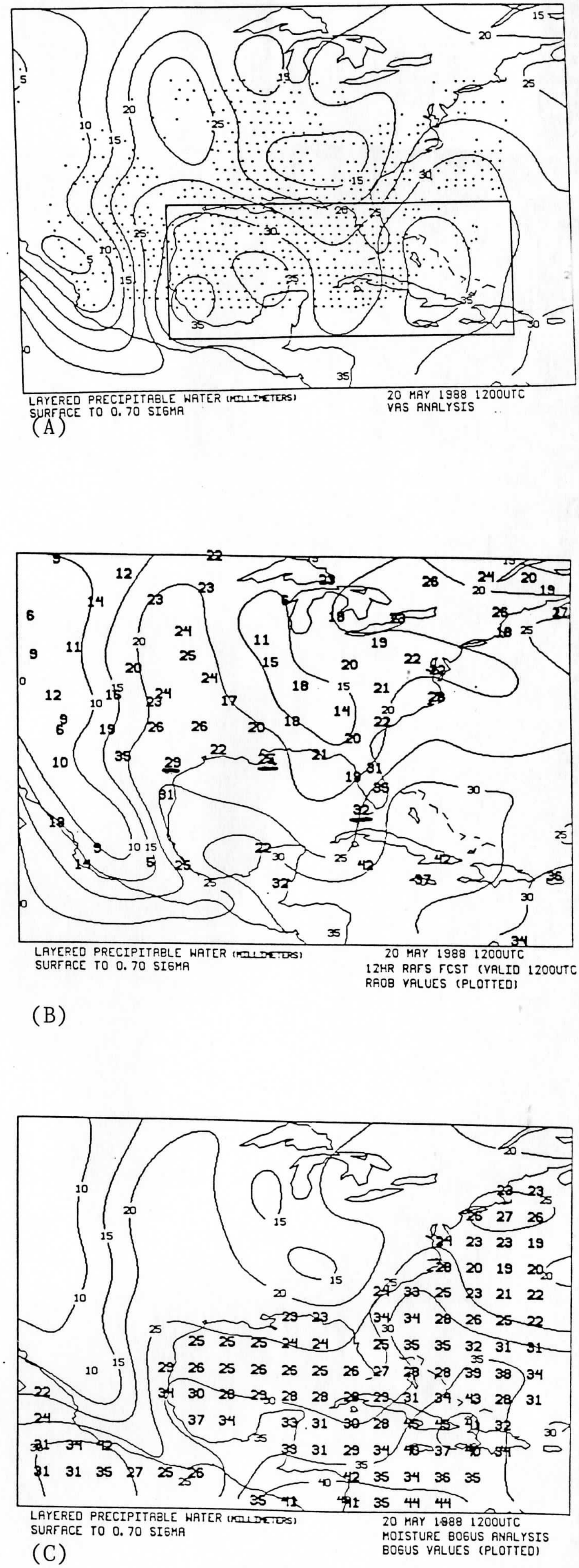


Figure 13