An Experiment in the Use of Satellite Data in a Numerical Cloud Prediction Program

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ABSTRACT

Cloud data derived from TIROS VII photographs over the North Pacific area were used to supplement synoptic surface cloud data in an automated layered-nephanalysis program. During the test period, cloud data from nine TIROS VII orbits were used in the automated layered nephanalyses. These nephanalyses provided additional moisture data input over sparse-data areas to the Air Weather Service Numerical Cloud Prediction program.

The total-cloud cover forecasts were improved for 12-, 24- and 36-hr periods. Improvement in the layered-cloud forecasts also was found in the case of moisture decreases at the 700- and 400-mb levels. Other layered-cloud modifications were inconclusive.

The importance of establishing a reliable initial moisture field over low-density areas for input to the cloud forecast program was confirmed. Although further refinements must be made in the designation of cloud layers and the merging of satellite cloud data with primary cloud observations, the study showed that satellite cloud data can be effectively processed as input to automated nephanalyses and cloud forecast programs.

1. Introduction

The automated Air Weather Service Numerical Cloud Prediction Model presently used at the Air Force Global Weather Central (AFGWC), Offutt AFB, Nebr., produces hemispheric moisture and temperature forecasts at four levels of the atmosphere. These are converted to layered-cloud and icing forecasts as well as total-cloud forecasts. The program employs appropriate layered nephanalyses to modify the initial moisture field at each of the four forecast levels, 850, 700, 500 and 400 mb. These fields are advected with three-dimensional trajectories on the basis of 2-hr forecasts of horizontal and vertical winds obtained from the AFGWC six-level baroclinic model. The forecast moisture fields are then converted to cloud amount by use of an empirically developed technique. The model has been described in detail by Edson *et al.* (1966). The moisture parameter employed in the model is condensation pressure spread (CPS) which is defined as the difference between the pressure of an air parcel and the pressure at which condensation will take place if the parcel is lifted dry adiabatically. In this paper, the model will henceforth be referred to as the CPS-Trajectory Forecasting Technique.

Prior to the use of surface synoptic data as input to the layered nephanalysis, the cloud forecasting program relied on approximately 400 radiosonde reports to establish the initial moisture fields. Although the present technique utilizes up to 4500 cloud reports to augment the initial moisture information, there remain large gaps in data coverage. This is particularly true over oceanic and sparsely populated areas. If one considers that insufficient data in these areas can adversely affect cloud forecasts well over 1000 mi away in 36 hr, the importance of complete and reliable nephanalyses is readily apparent.

A partial solution to this problem is the use of satellite (TIROS) data in the layered nephanalyses. The satellite information must be of sufficient horizontal and vertical resolution, however, to provide a three-dimensional moisture pattern which can be effectively employed in the CPS-Trajectory Forecasting Technique. For example, low-level clouds under a strong subsidence inversion may move in a circulation completely different from that which exists 10,000–15,000 ft above. Introduction of moisture information at the wrong level could yield erroneous forecasts. The effects of variable flow paths produced by the trajectory technique at different levels will be illustrated later in the study.

To determine the feasibility of supplementing the automated layered nephanalysis with synoptic satellite cloud data for further application to the cloud prediction program, a test employing three days' data was conducted in the spring of 1964. Cloud data from TIROS VII photographs at, or close to, 0000 GMT over 18–20 January 1964 were collected and interpreted by the Air Force Liaison Office of the National Weather Satellite Center. The test period was chosen during a time when TIROS VII was over the eastern North

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Pacific between the Hawaiian Islands and the west coast of the United States. We may note that this was a period when the orbital nodal precession allowed the satellite to view the sun-illuminated eastern North Pacific (Widger and Wood, 1961). The intention was to increase initial data coverage over the normally low-density areas and to provide trajectories of moisture which could be verified over the North American continent, or close to it, where a reasonably high density of data exists.

2. Processing data

An essential ingredient in the initial processing of TIROS data was the categorization of low, middle and high clouds. This was done through visual interpretation of the TIROS VII photographs and associated synoptic weather charts. Cloud amounts were indicated in eighths of low, middle and high clouds for data from nine TIROS VII orbits used in the study.

The interpreted TIROS cloud charts were turned over to the 3d Weather Wing Aerospace Sciences Division, Development Branch, where the layered-cloud data were extracted and merged with the complete Northern Hemisphere layered-cloud machine nephanalyses. These nephanalyses yield total-, low-, middle- and high-cloud charts and are produced four times daily (0000, 0600, 1200 and 1800 GMT) from all available surface synoptic data. The grid used for the nephanalyses is approximately 16 times as dense as the normal AFGWC grid. At 35N, there are approximately 60 mi between fine grid points. If no reports are available for a desired fine-grid point, the surrounding grid points are systematically searched and the cloud reports in each search are averaged. The search radius is expanded by one grid point until at least one report is found or until the search has expanded to three points in each direction. If there is still no observation, a "99" is encoded, indicating that there are insufficient data to complete the nephanalysis for that grid point. In the TIROS analyses, the lower-cloud amounts were interpreted as unknown whenever a higher ceiling prevented observation of the lower clouds. Similarly, in the determination of cloud amounts from conventional surface synoptic observations, higher-cloud amounts are listed as unknown whenever a lower ceiling prevents a reasonable interpretation of higher-cloud conditions. In the present study, the TIROS VII information was given precedence over synoptic surface data whenever an overlap of information existed. That is, in the analysis, whenever TIROS and surface synoptic data both existed for the grid point, the cloud value indicated by the TIROS observation was used. This was done to test the effectiveness of pure satellite information on the forecast cloud product. In future operational applications, it is anticipated that surface synoptic data will be merged systematically with satellite data to produce the most complete and effective nephanalysis.

Fig. 1 shows the low-cloud nephanalysis valid for 0000 GMT 19 January 1964, prior to the incorporation

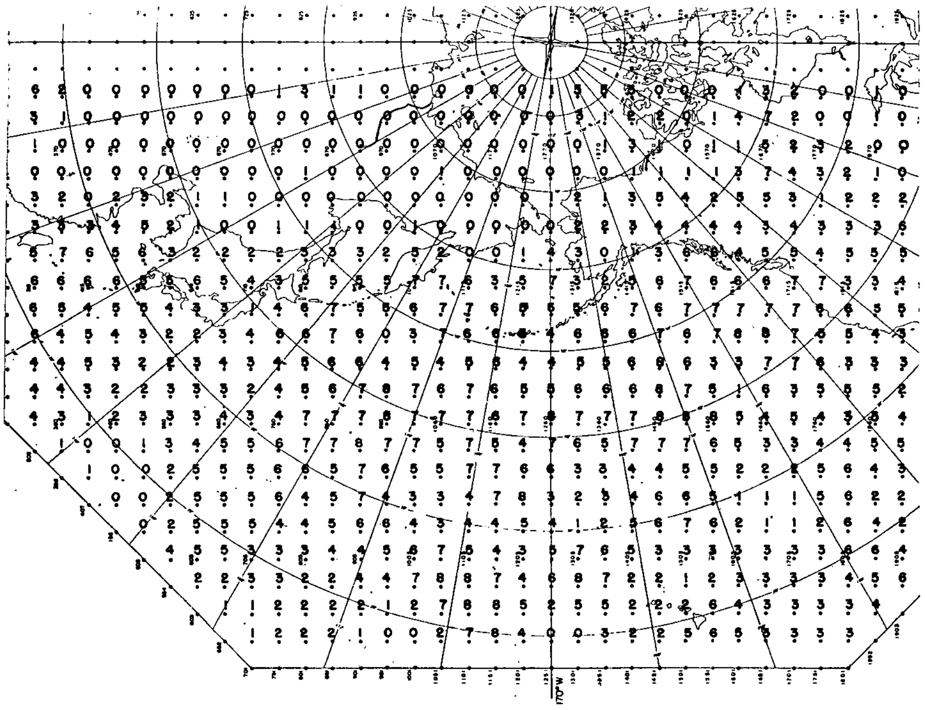

FIG. 1. AF Global Weather Central automated low-cloud nephanalysis for 0000 GMT 19 January 1964. Cloud amounts are in eighths.

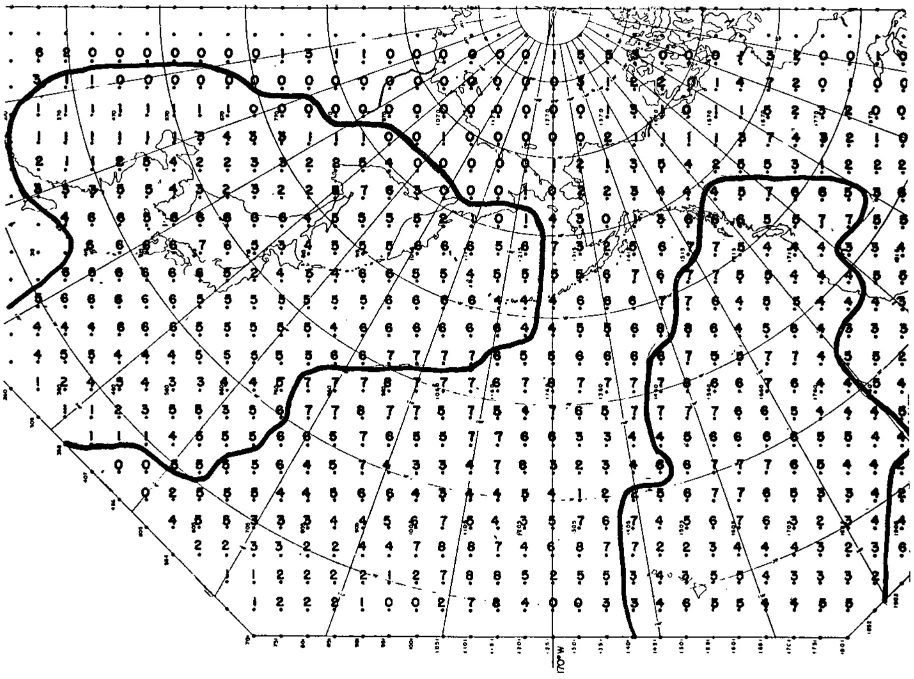

FIG. 2. AF Global Weather Central automated low-cloud nephanalysis modified with TIROS data for 0000 GMT 19 January 1964. Cloud amounts are in eighths.

of TIROS data, while Fig. 2 shows the same nephanalysis with TIROS data included. The TIROS data in this case were valid for 1956 and 2313 GMT 18 January 1964. The modified areas are circled by a solid black line. Figs. 3–6 show the differences between the modified and the unmodified cloud analyses for total, low, middle and high clouds, respectively. The TIROS-modified nephanalyses include cloud data over areas where, for the most part, data are normally sparse. As such, they must be assumed to be the more accurate of the two

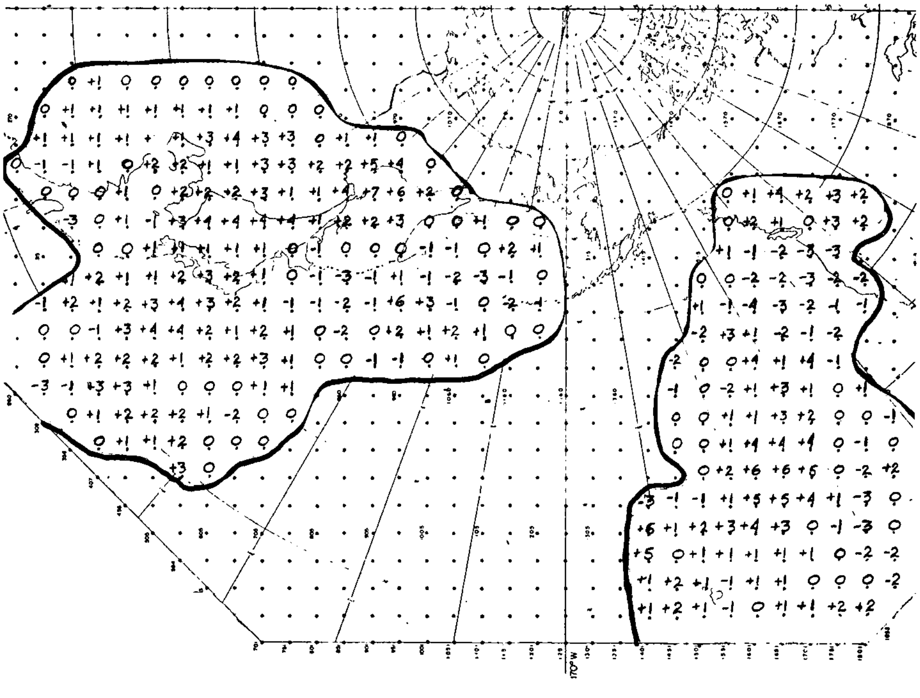

FIG. 3. Differences occurring at 0000 GMT 19 January 1964 between the regular AF Global Weather Central automated total-cloud nephanalysis and the automated total-cloud nephanalysis including TIROS' cloud data. Cloud amounts are in eighths.

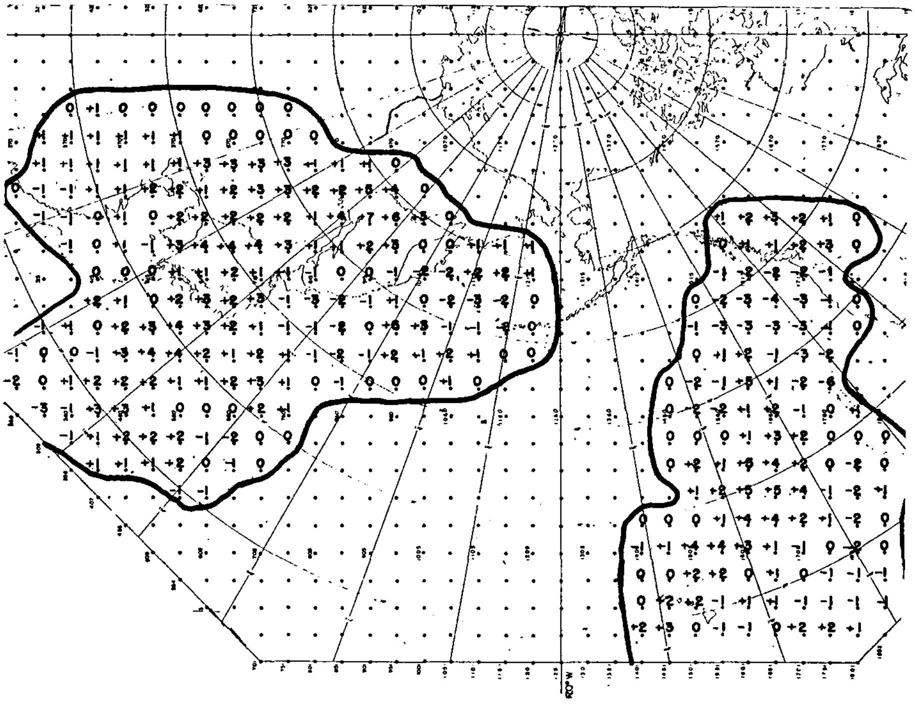

FIG. 4. Same as Fig. 3 except for low-cloud nephanalyses.

series, particularly in the case of the total-cloud chart. The same assumption can be made for the layered-cloud chart provided the categorization of low, middle and high clouds was accomplished with reasonable accuracy.

Before the nephanalyses are incorporated into the CPS-Trajectory Forecast Program, the fine grid is reconverted to the normal AFGWC grid. The low-cloud nephanalysis is used for modifying the AFGWC-analyzed 850-mb moisture field; the middle-cloud nephanalysis for the 700- and 500-mb moisture fields; and the

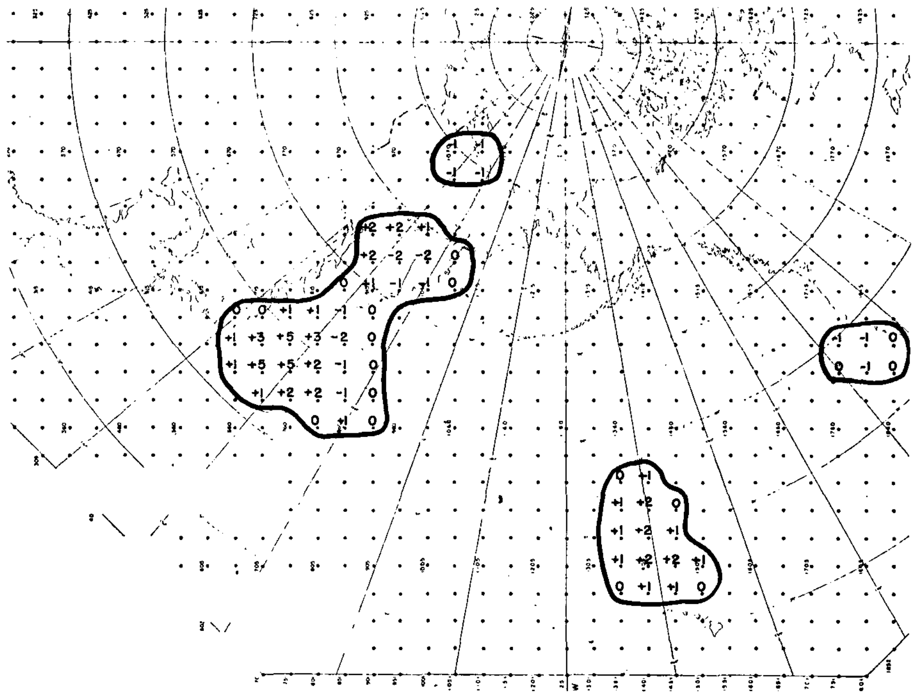

FIG. 5. Same as Fig. 3 except for middle-cloud nephanalyses.

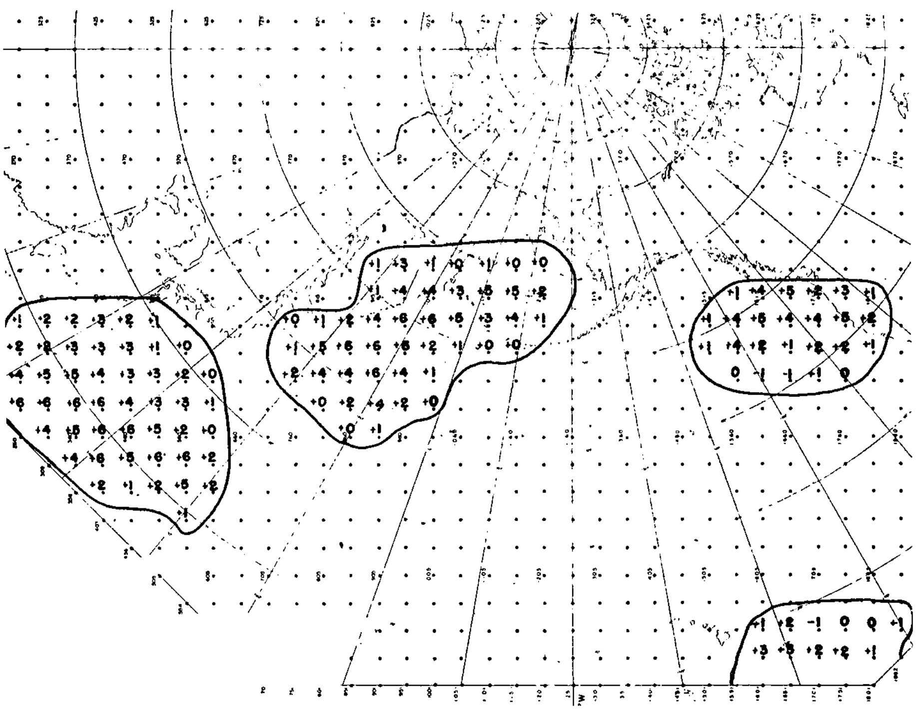

Fig. 6. Same as Fig. 3 except for high-cloud nephanalyses.

high-cloud nephanalysis for the 500- and 400-mb moisture fields. The procedure for making these modifications is as follows: CPS values are converted to cloud amounts using the condensation pressure spread to cloud amount conversion curves shown in Fig. 7. These curves are modifications of those originally derived by Essenwanger and Haggard (1961). The converted cloud amounts are then compared with the nephanalysis, and discriminant adjustments are made to the CPS value for each AFGWC grid point at each level where a significant difference, approximately two-eighths cloud amount, is observed. If the observed cloud amount is greater than two-eighths of the computed cloud amount, moisture is added to the initial CPS

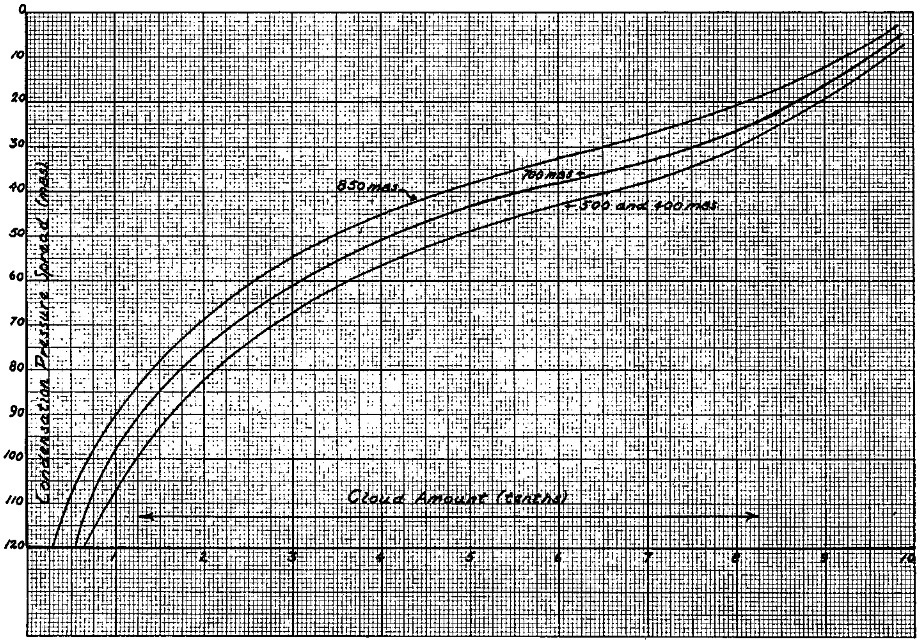

Fig. 7. Condensation pressure spread vs cloud amount at various pressure levels.

TABLE 1. Influence of TIROS-modified nephanalyses on condensation pressure spread (CPS).*

	Forecast period		
	12 hr	24 hr	36 hr
850-mb trajectories			
Total grid points affected	225	248	267
Grid points with moisture increases	130	159	179
Average spread decrease for above grid points (mb)	10.4	7.5	6.3
Grid points with moisture decreases	95	89	88
Average spread increase for above grid points (mb)	5.2	2.9	3.9
700-mb trajectories			
Total grid points affected	157	196	242
Grid points with moisture increases	109	146	189
Average spread decrease for above grid points (mb)	8.3	4.5	3.2
Grid points with moisture decreases	48	50	53
Average spread increase for above grid points (mb)	4.1	3.6	2.6
500-mb trajectories			
Total grid points affected	164	220	262
Grid points with moisture increases	128	177	216
Average spread decrease for above grid points (mb)	8.7	6.7	4.6
Grid points with moisture decreases	36	43	46
Average spread increase for above grid points (mb)	2.8	1.9	1.4
400-mb trajectories			
Total grid points affected	165	240	267
Grid points with moisture increases	129	173	200
Average spread decrease for above grid points (mb)	20.3	13.8	9.5
Grid points with moisture decreases	36	67	67
Average spread increase for above grid points (mb)	2.9	2.5	2.3

* Figures are averaged for the three-day period; total number of grid points in the forecast field is 1457.

field; if the observed cloud amount is less than two-eighths of the computed cloud amount, moisture is removed from the initial field. The quantitative value of the adjustment has been derived to produce optimum forecast results and differs for each level. On a typical forecast run approximately 30–40% of the initial CPS grid values are modified.

The final modified CPS fields are employed in the adiabatic trajectory scheme to produce forecast CPS fields at the four levels for 12, 24, 36 and 48 hr. These moisture fields are reconverted to cloud amounts from which layered- and total-cloud forecasts are produced.

TABLE 2. Radius of influence of TIROS data for 0000 GMT 19 January 1964 on condensation pressure spread (CPS) trajectory forecasts.

Pressure level (mb)	Radius (mi) of influence from initial modification		
	12 hr	24 hr	36 hr
850	600	1170	1600
400	1400	2800	4000

Cloud forecasts with TIROS-modified initial data were made at four levels for 12, 24 and 36 hr for each day's data. These were compared with non-TIROS cloud forecasts for the same period.

3. Summary of data

Table 1 is a summary of the number of forecast AFGWC grid points that were in some way influenced by the TIROS VII modification.

Several conclusions may be drawn from this summary:

a. Moisture increases exceeded moisture decreases at all levels.

b. Forecast moisture increases at the highest level (400 mb) were considerably larger in amount than in the three lower layers. This can be explained to some extent by the fact that non-satellite high-cloud nephanalysis is the weakest of the three analyzed cloud layers, as it contains the least amount of useable data. Consequently, satellite data should have its greatest influence here. The satellite view of cloud cover is directly opposite to that of the ground observer. While the ground observer can always determine the lowest clouds but cannot see clouds above the overcast, a satellite photograph shows the highest clouds but cannot show cloud cover below an undercast.

c. It is clearly evident at all levels that the number of grid points affected increases with time, while the amount of moisture change at a specific grid point decreases. This suggests that the CPS-Trajectory Technique to some extent identifies large-scale diffusion of moisture, a characteristic of the atmosphere, from an initial source. We may note that the fact that the effects of the initial cloud or moisture conditions decrease with time has been reported by Nagel *et al.* (1966), in an independent study of basically the same forecasting problem.

Table 2 shows the influence of the initial moisture fields on the CPS-Trajectory forecasts. Figs. 8 and 9 illustrate the areas at 850 mb and 400 mb, respectively, where 12-, 24- and 36-hr forecasts were changed after nephanalyses were modified with TIROS data. One may note that there are several distinct modified areas at 850 mb. As can be seen from both the table and figures, the 400-mb radius of influence was more than twice that of the 850-mb area. The 400-mb forecast changes were confined to the prevailing westerly flow at high levels. The 850-mb moisture differences were more distributive, moving in part in an eastward and southeastward direction and in part in a northward direction around the backside of a low-level anticyclonic circulation over the eastern North Pacific. These results strongly confirm the importance of careful vertical definition of the satellite cloud data into layers for use in the nephanalysis and cloud forecast programs. Incorrect determination

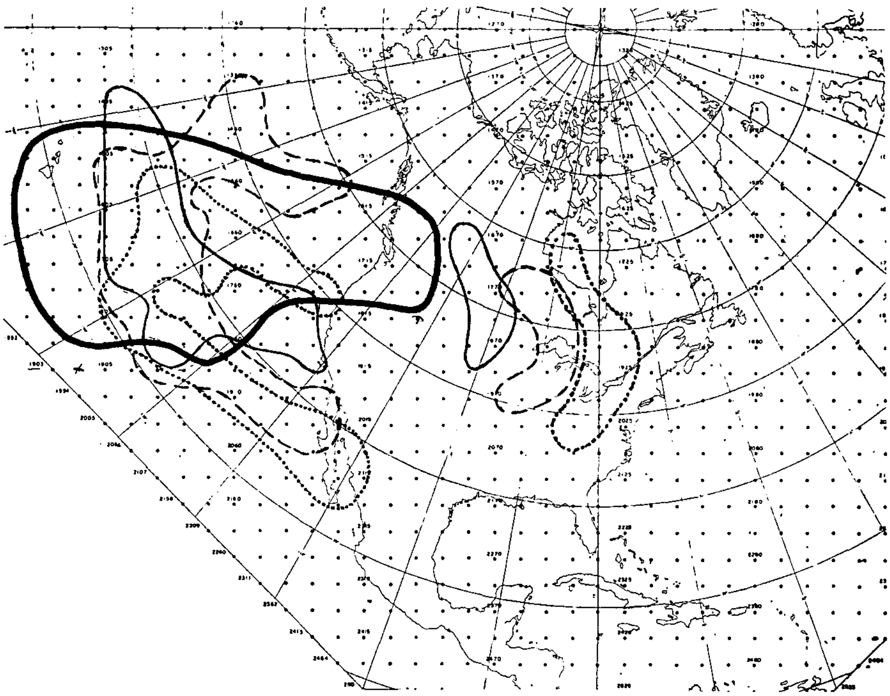

Fig. 8. Areas affected by changed 850-mb condensation pressure spread resulting from TIROS-modified nephanalysis at 0000 GMT 19 January 1964: heavy solid line, TIROS-modified initial data area; light solid line, area of 12-hr CPS forecasts changed by TIROS input; dashed lines, area of 24-hr CPS forecasts changed by TIROS input; dotted lines, area of 36-hr CPS forecasts changed by TIROS input.

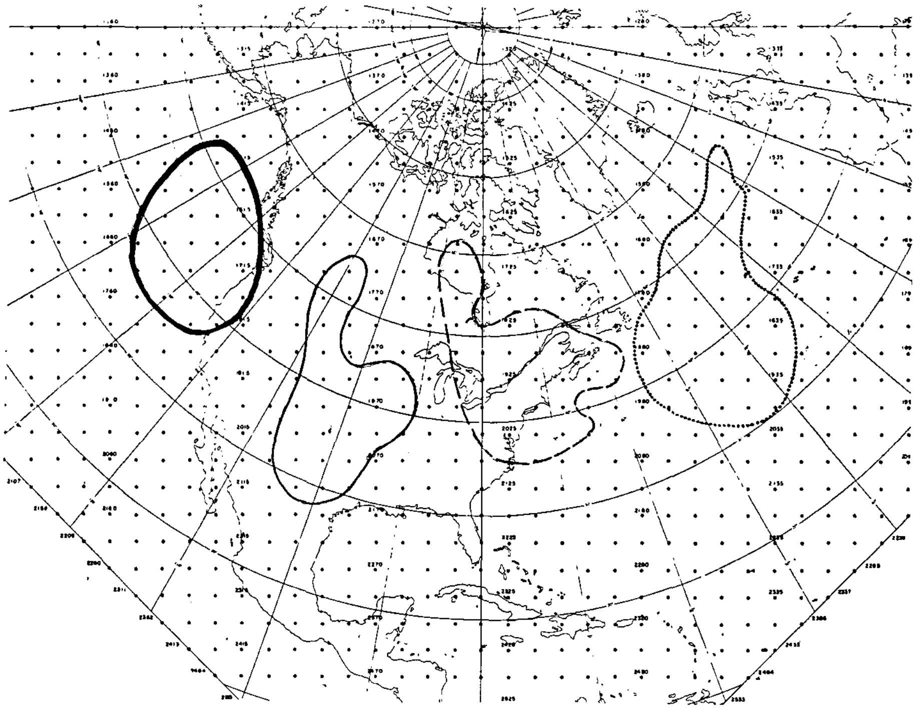

Fig. 9. Same as Fig. 8 except for 400 mb.

TABLE 3. Cases where modified total-cloud forecast indicated broken-to-overcast and unmodified forecast indicated clear-to-scattered.

	12 hr	24 hr	36 hr
Total number of forecasts changed to broken-to-overcast	156	144	96
Observed broken-to-overcast	114	108	69
Observed clear-to-scattered	42	36	27

of cloud heights over the eastern North Pacific in the example shown could have resulted in erroneous 24-hr 850-mb CPS forecasts over Lower California (Fig. 8) and erroneous 400-mb CPS forecasts over the northeastern portion of the United States (Fig. 9). As a point of clarification, it should be noted that the final CPS forecasts are further modified by the vertical displacements derived from the six-level model winds (Edson, 1965). Consequently, a parcel which is lifted 10 mb during the course of its trajectory will have its forecast CPS reduced 10 mb while a parcel which sinks 50 mb will have its forecast CPS increased 50 mb. Although these dynamic adjustments become increasingly important with time, experiments by Derrickson (1967) have shown that for the first 24 hr, the initial moisture condition predominantly determines the forecast.

The number of grid points influenced by TIROS-modified data (Table 1), and the location and magnitude of the changes produced in turn by the adjusted moisture fields would be more meaningful if one could state precisely the extent to which CPS and cloud forecasts were improved. Unfortunately, sufficient upper air observations were not available, particularly over sparse-data areas, to provide statistical data of significance for direct verification of CPS values. However, useful inferences can be drawn from the available surface cloud observations which were received at approximately a 10 to 1 ratio over radiosonde reports. Forecast modified CPS fields for 12, 24 and 36 hr were converted to cloud amounts using Fig. 7 and were verified against the observed total and layered cloud nephanalyses. While this also included some sparse-data areas, the overall results appear conclusive (Tables 3 and 4).

Satellite-induced moisture increases and decreases produced changes in both the layered- and total-cloud forecasts. Many of these changes were quite small, particularly along the fringes of the modified areas. In order to establish criteria for evaluating the operational significance of the modifications, emphasis was placed on isolating those forecasts which resulted in changing the forecast category from clear-to-scattered to broken-to-overcast and, vice versa, ceiling to no ceiling. The greatest success was achieved in the cases of TIROS-induced moisture increases which resulted in broken-to-overcast total-cloud forecasts. Moisture decreases resulting in scattered layered-cloud forecasts, with the exception of the 850-mb level, also showed improvements. The effect of moisture decreases on total cloudiness could not be evaluated. Finally, layered-moisture increases showed poor improvement when compared with the unmodified layered-cloud forecasts. These results are outlined below:

a. In the AWS Numerical Cloud Prediction Program, the total-cloud amount is determined empirically by adding to the largest of the four forecast cloud amounts the increments from the other three levels. Thus, a broken-to-overcast forecast at any one level is sufficient to account for a broken-to-overcast total-cloud forecast. The effect of moisture increases is summarized for the three-day period in Table 3, which shows those cases where TIROS-modified increases would have been sufficient to change the cloud forecast category from clear-to-scattered to broken-to-overcast. We note that TIROS changes improve the forecasts at an approximate 3 to 1 ratio for all time periods. For example, of the 156 12-hr forecasts changed from clear-to-scattered to broken-to-overcast as a result of TIROS modifications, 114 forecasts were improved while 42 were not improved.

b. It is difficult to verify TIROS moisture decreases at a specific level against total cloudiness since sufficient moisture at another level may still result in broken-to-overcast sky conditions. Nevertheless, it was possible to evaluate TIROS moisture decreases at each level against the observed layered cloud.

Table 4 shows an excellent correlation at the 700- and 400-mb levels between TIROS-deduced moisture decreases and the existence of clear-to-scattered sky conditions for middle and high clouds. There is poor correlation between TIROS-deduced moisture decreases at 850-mb and the existence of low cloudiness. To some extent this may be accounted for by the fact that

TABLE 4. Condensation pressure spread moisture decreases in cases where TIROS-modified layered-cloud forecast indicated clear-to-scattered.

	Forecast clear-to-scattered (total cases)		
	12 hr	24 hr	36 hr
850 mb			
Total forecast clear-to-scattered	38	46	48
Observed low cloud, broken-to-overcast	23	25	27
Observed low cloud, clear-to-scattered	15	21	21
700 mb			
Total forecast clear-to-scattered	25	18	16
Observed middle cloud, broken-to-overcast	3	2	3
Observed middle cloud, clear-to-scattered	22	16	13
400 mb			
Total forecast clear-to-scattered	14	18	13
Observed high cloud, broken-to-overcast	0	2	0
Observed high cloud, clear-to-scattered	14	16	13

the 850-mb condensation pressure spread is not indicative of the existence of all low clouds. Low-level stratus and other low clouds may exist below this level and never be reflected in the 850-mb moisture. Physical processes below 850 mb are not simulated in the cloud prediction model (Edson, 1965; Edson *et al.* 1966).

c. In additional tests, CPS-TIROS-modified moisture increases at 850, 700 and 400 mb were compared with observed low-, middle- and high-cloud amounts, respectively. Surprisingly, increases in moisture at the various levels did not show the same corresponding verification improvement in layered clouds as one might anticipate from the total-cloud results. Out of 132 forecasts in which the forecast category was changed from clear-to-scattered to broken-to-overcast only 69 cases, or 53%, showed an improvement. A possible explanation for this result concerns a general weakness in the layered-cloud nephanalyses which are, for the most part, dependent upon conventional data and often fail to specify clouds above an overcast. (Inferences must be made from surrounding observations.)

Failure to achieve a significant improvement in layered-cloud forecasts associated with TIROS-modified moisture increases may also be related to the initial subjective determination of moisture from the satellite data. One must assume in this case that there was a residual effect on the total-cloud forecasts but the detail and accuracy was insufficient to improve the layered-cloud forecasts. Neither of these premises is conclusive. Still another source of error may be that satellite-observed cloud cover differs from surface-observed cloud cover. Satellite-observed cloud cover averages some 14% less than ground-observed cloud cover (Barnes, 1966). This would suggest that a revision in Fig. 7 may be in order when it is used with satellite observations. Further investigation is required both in the detailed specification of cloud data using satellite information and in effective utilization of this data in the cloud forecast model.

4. Conclusions

The following conclusions can be drawn from the study using three days of TIROS VII cloud data to modify condensation pressure spread trajectory cloud forecasts.

a. The TIROS-modified layered-cloud nephanalyses effectively improved total-cloud forecasts for 12, 24 and 36 hr.

b. The TIROS-modified layered-cloud nephanalyses effectively improved layered-cloud forecasts in the case of moisture decreases at the 700- and 400-mb levels. Other layered-cloud modifications were inconclusive.

c. The importance of establishing a reliable initial moisture field over low-density-data areas for input to the CPS-Trajectory Forecast Program was confirmed as significant. Forecast moisture changes occurred as far as 4000 mi from the initial input area over a 36-hr period.

d. Although further refinements must be made in the designation of cloud layers and in the merging of satellite data with primary cloud observations, satellite data can be effectively processed as input to an automated cloud forecasting technique. It is obvious, however, that if this is to be done on a real-time, operational basis, the data must be processed by objective automated methods. The 1966 report of Bristor *et al.* is an example of automated processing already being used at least experimentally. It also appears evident that present and future physical-numerical experiments in the use and interpretation of infrared measurements will provide the ability to distinguish cloud heights and amounts to a high degree of accuracy. The processing and analysis of this derived data will undoubtedly provide the basis for more advanced forecasting techniques.

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