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Department of
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VERTICAL MOTION CALCULATIONS AND SATELLITE CLOUD OBSERVATIONS OVER THE WESTERN AND CENTRAL UNITED STATES

SCIENTIFIC REPORT NO. 2

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John Hansen, Capt., USAF, and Aylmer H. Thompson

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Geophysics Research Directorate
Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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a	mean radius of the earth
t	time
T	absolute temperature
u, v, w	wind component in the x, y, and z directions, respectively
$\hat{V}$	wind vector
$\hat{V}_g$	geostrophic wind vector
$\hat{V}_H$	horizontal wind vector
x, y	Cartesian coordinates; also coordinates to the east and north, respectively
z	height above sea level
γ	atmospheric lapse rate
γ_a	adiabatic lapse rate
ϕ	latitude
ρ	atmospheric density
$\nabla(\quad)$	differential operator
$\nabla_H(\quad)$	horizontal differential operator

ABSTRACT

Vertical motions over the western and central United States during a three day period in August, 1961, were computed by several methods. The resulting analyses, applicable at 700 mb or 10,000 ft (600 mb for the JNWP vertical motion fields) were compared both subjectively and objectively to each other and to approximately synoptic TIROS nephanalyses. The results of the comparisons showed only moderate agreement among the various methods and between the vertical motion analyses and the TIROS information. The kinematic method, based on observed winds, appeared to give the best agreement with the satellite picture indications of vertical motion, though it seemed little better than some of the other methods. The use of satellite data shows definite promise as a means of evaluating computed vertical motion fields and should eventually contribute to the improvement of the procedures used to compute vertical motions.

A lag, or "trailing effect," was noted in the relation between the vertical motion patterns and the cloud distribution. The regions of cloudiness often were displaced from the centers of upward motion. This effect seemed particularly evident for rapidly moving vertical motion patterns. The cloud activity was most frequently displaced in the direction from which the vertical motion patterns were moving.

1. Introduction

Though vertical motion is one of the most important quantities to be considered in atmospheric studies, meteorologists have been plagued for some time with the problem of properly determining such motions, since direct measurements usually are not feasible and indirect methods must be employed. Techniques for computing this velocity component have been available for over 50 years (V. Bjerknes, 1911; Fleagle, 1947), but the determination on a regular basis of values of vertical motion associated with the large-scale cyclones and anticyclones was impractical until the present radiosonde (now rawinsonde) station networks were placed into operation, thus providing the reliable, closely-spaced information required for evaluation of the vertical motion equations. However, it was still impractical to compute vertical motions on a regular, synoptic scale. The techniques of computation were time-consuming and found little use, except as tools for atmospheric research. Only within the last few years, through use of high-speed electronic computers, has knowledge of large-scale vertical motions been available on a regular basis. The Joint Numerical Weather Prediction (JNWP) Unit at Suitland, Maryland, prepares vertical-motion computations on a synoptic scale, and supplies the information to the weather forecaster in the field in time for prognostic use.

The magnitudes of vertical motions and related divergence are relatively small and accurate determination of their values is difficult. This difficulty arises from the fact that these quantities are not, under normal circumstances, physically measurable on a meteorologically significant scale, and it has been necessary to estimate their values by indirect means and approximations, using quantities which are measurable. The results are only estimates, the relative validity of which is difficult to determine. Vertical motion and divergence distributions, as determined by the various methods, show considerable variation in procedure of application and in results (Miller and Panofsky, 1958). Vertical motion calculation techniques provide results which are averages either in space or in time or both. The nature of meteorological data is such that there is a preference for averages over large areas, covering about 50,000 to 250,000 km^2 (House, 1958; Miller and Panofsky, 1958; Panofsky, 1946; Panofsky, 1951), or a 12-hr time average. This tends to smooth out most of the small-scale synoptic features.

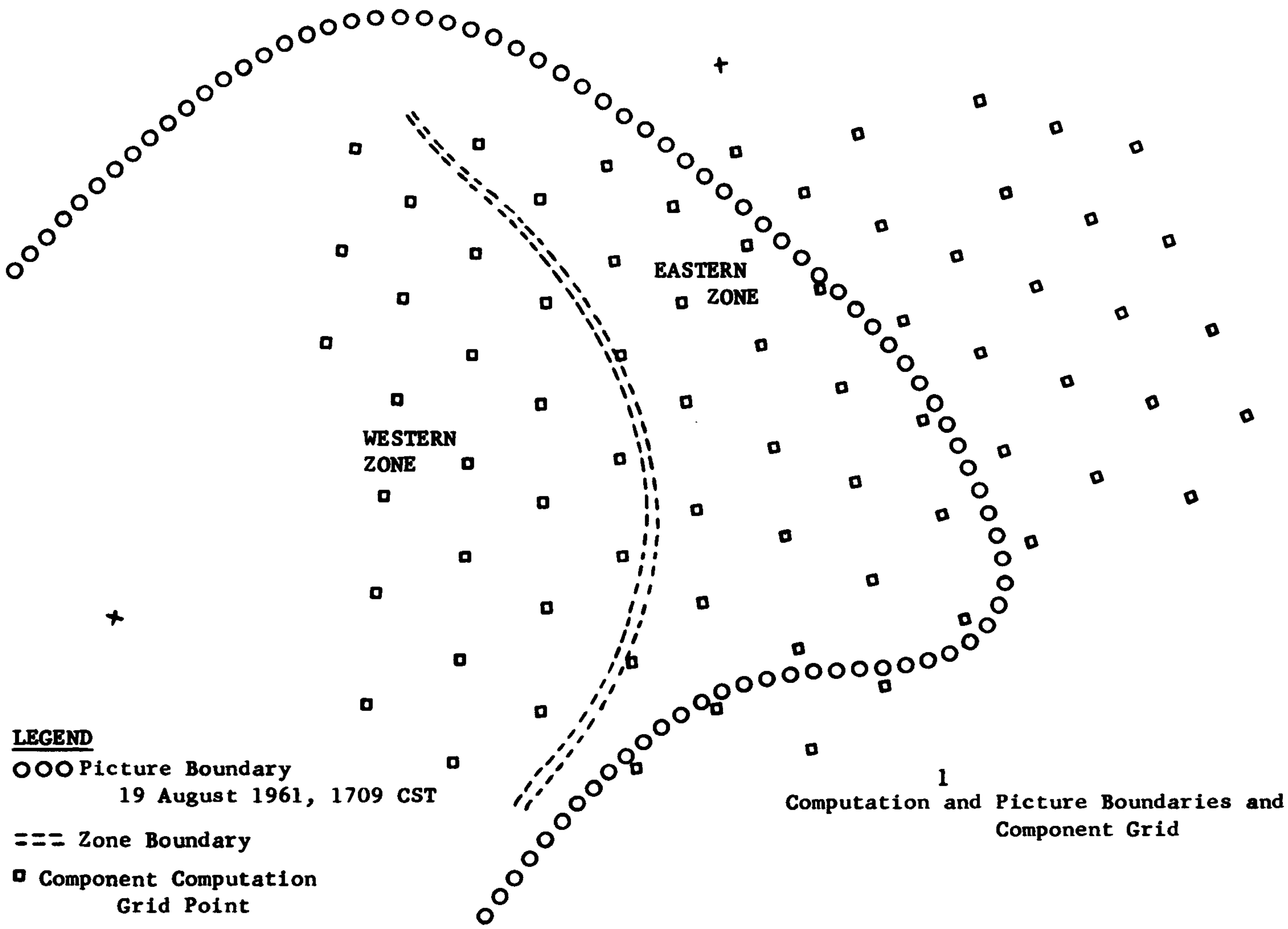
The sign, but not more than a very rough value of the magnitude, of vertical motions in the atmosphere can also be estimated by an analysis of precipitation patterns or of cloud distributions. The precipitation patterns would give estimates of the general nature of the vertical motion field during a previous time interval while the nephanalysis would suggest the pattern of vertical motion occurring at some specific time. These two analysis procedures also suffer limitations due to station density and the accuracy of the subjective evaluation, encoding, and analysis of the actual precipitation and cloud observations.

Since 1 April 1960 the TIROS (Television Infra-Red Observation Satellite) weather satellites have provided a new method for estimating the sign of atmospheric vertical motions. Like the precipitation and nephanalysis techniques, TIROS cloud photographs can only indicate regions where upward vertical motions sufficient to result in cloudiness are present and do not give the magnitude of these motions. Also, extensive cloud areas can form due to processes other than vertical motion. However, despite their limitations (Erickson and Hubert, 1961) the TIROS photographs provide relatively continuous coverage for large surface areas, whereas other similar verification procedures rely on precipitation or cloud observations made at widely separated points.

The purposes of this paper are to present several estimates of large-scale atmospheric motions as determined by different calculation procedures, and to compare the resulting vertical motion distributions with each other and with the patterns of vertical motion as indicated by the actual cloud and weather distributions, particularly the TIROS cloud observations. The investigation considers vertical motions over the western and central United States for the period 19-21 August 1961. During this particular period, the TIROS cloud observations over the western and central states were taken about one to two hours before the 1800 CST upper-air synoptic observation times, or mid-afternoon local time. Detailed discussion of the results for the 19th is followed by a brief discussion of the remaining days studied. The area studied was divided into two zones for discussion and verification purposes (Fig. 1). The western zone is predominantly a mountainous region while the eastern zone is relatively flat.

2. Analysis and evaluation procedure

The procedures for computation of vertical motion used in this study were selected as among the most frequently utilized techniques and because they were easily adaptable to electronic computer processing. Detailed derivations of the several procedures are available elsewhere. It is sufficient here merely to note the final result and to discuss the information from which the calculations were made. The computer programs utilized in this study, with the exception of the JNWP program, were prepared by one of the writers.



1

Computation and Picture Boundaries and Component Grid

It is important to remember that a great deal of subjective judgement enters into all phases of the problem of computing vertical motions. The extraction of the data, the technique of computation, the interpretation of results, and the verification of results are all affected to some extent by the individuals concerned. These same factors are pertinent to the study reported here.

Kinematic method. This method of determining vertical velocities was first presented over 50 years ago (V. Bjerknes, 1911); it is still one of the more frequently used methods. This method has several advantages since no stringent physical assumptions are required, and it yields instantaneous vertical motions. One serious disadvantage is that accurate and closely spaced wind observations are highly desirable. Nevertheless, applications of this method, utilizing observed winds, by Landers (1955), House (1958), Curtis and Panofsky (1958), and Vaisanen (1961) all yielded results which appear to be in good agreement with the observed weather. From the work of Landers and of House, it appears that the upper-air observations normally available in the United States are generally adequate for the use of this method. Both writers stress the need for a very careful analysis of the observed data so that the analyzed wind field is representative of the actual wind field. Curtis and Panofsky considered a summer situation.

There are many different techniques for computing vertical motions by the kinematic method. The differences between them generally lie in the procedure used to determine horizontal divergence. The basic relationship, derived from the continuity equation (Landers, 1955), is

$$w_2 = \frac{\rho_1}{\rho_2} w_1 - \frac{1}{2}\left(\frac{\rho_1}{\rho_2} \nabla_H \cdot \hat{V}_1 + \nabla_H \cdot \hat{V}_2\right)\left(Z_2 - Z_1\right). \tag{1}$$

The symbolism in Eq (1) is explained in the List of Symbols. The subscripts 1 and 2 refer to the bottom and top, respectively, of a given atmospheric layer. Evaluation of Eq (1) is carried out step-wise for a succession of layers, assuming that w is zero at the ground. In a curvilinear coordinate system, the horizontal divergence becomes,

$$\nabla_H \cdot \hat{V} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} - \frac{v}{a} \tan \phi. \tag{2}$$

In order to evaluate Eq (1), Eq (2) was determined from analyzed wind component charts constructed using semi-mesoscale analyses of surface and upper air charts which retained all the minor details of isobars or contours and isotherms. Standard finite difference techniques (Petterssen, 1956) were employed in evaluation of the differential expressions encountered in this and where appropriate in other techniques. Evaluation was for every 2000 ft at each of the points shown in Fig. 1. Values for three different grid sizes were averaged for the final kinematic vertical motion map.

The horizontal divergence may also be determined using the Bellamy method (Bellamy, 1949) which utilizes actual wind observations directly. This technique was adapted to machine methods and used in a second evaluation of Eq (1) for 2000-ft layers. The location of the centroids of the various triangles used in the Bellamy technique are shown in Fig. 2.

Henceforth, the two methods of evaluating Eq (1) will be referred to as the component technique and the Bellamy technique.

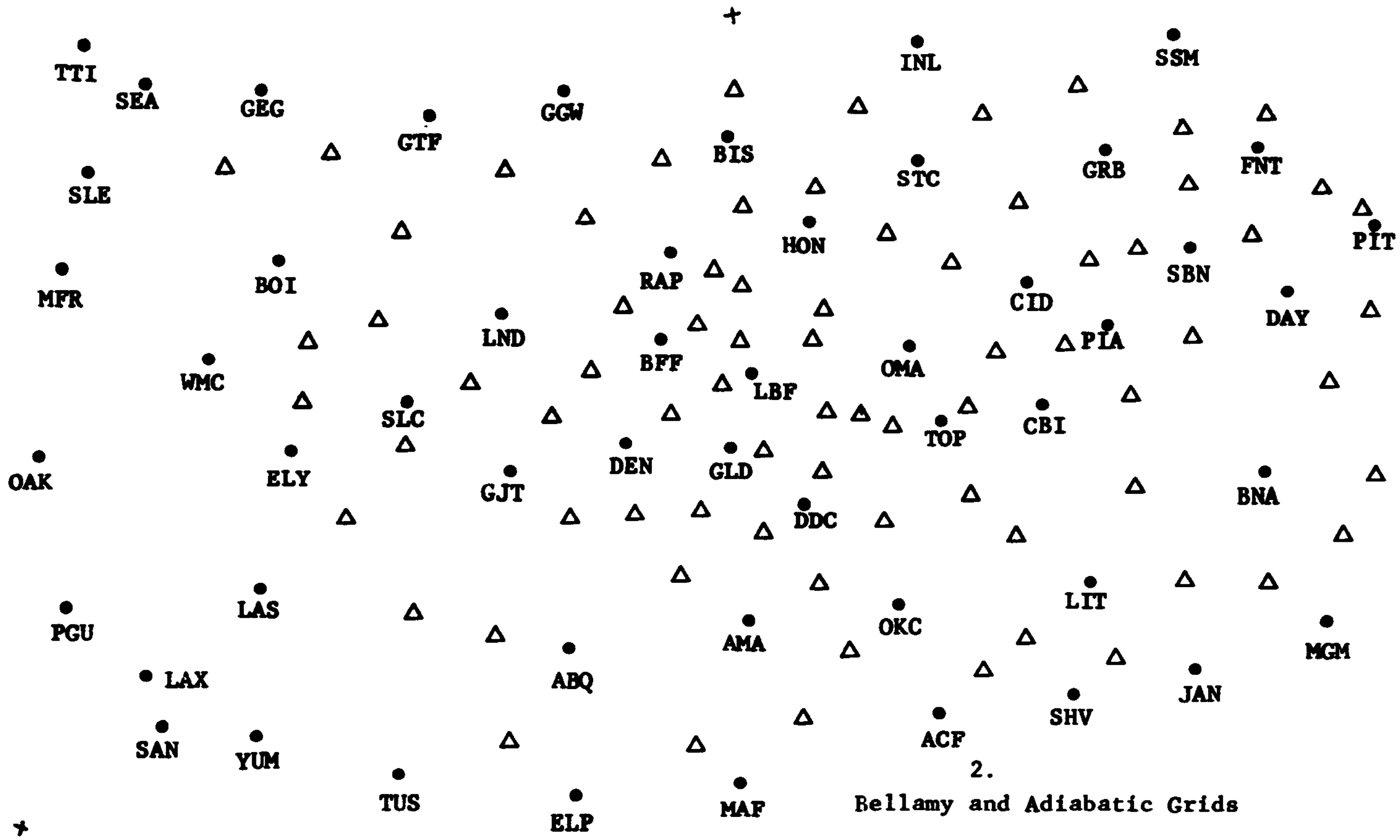
The reliability of calculations made using either of these two methods depends primarily upon the reliability of the divergence calculations. This in turn depends on the reliability with which the wind can be determined.

Adiabatic method. The derivation of this technique is based on the assumption that atmospheric vertical motions are adiabatic, both dry and moist adiabatic motion being considered, and that the individual parcels undergo no other thermodynamic process. The major advantage of this method over the kinematic method is that it is not overly sensitive to wind errors, so that geostrophic winds can be used. However, this method has a serious disadvantage. The vertical motions computed by this method are usually 12-hr averages, which means that the values are six hours old even before the data necessary for their determination is observed. Vertical motions determined by the adiabatic method have little operational use in prognosis since at best the values are about nine hours old before they are available for general use. This method can be of value in certain types of research. Inaccurate results are obtained when this method is applied to non-adiabatic motion, and when the atmospheric lapse rate is approximately adiabatic (moist or dry as appropriate).

Vertical motions determined by this method generally are obtained by evaluation of the expression

$$w = \frac{-\left[\frac{\partial T}{\partial t} + \hat{V}_H \cdot \nabla T\right]}{\gamma_a - \gamma}, \qquad (3)$$

or some equivalent form (Panofsky, 1951; Petterssen, 1956). For large-scale flow patterns in middle latitudes, the real horizontal wind can be approximated by the geostrophic wind $\hat{V}_g$. The appropriate adiabatic lapse rate must be



2. Bellamy and Adiabatic Grids

● Location of Rawinsonde Stations (adiabatic grid).

Δ Location of Bellamy Triangle Centroids.

inserted, depending on whether the air is unsaturated (dry) or saturated (moist). All other values can be determined from a set of standard meteorological charts and atmospheric soundings by using finite difference techniques.

The adiabatic technique was used to prepare two different types of vertical motion analyses. Vertical motion analyses were prepared with velocities determined from the evaluation of Eq (3) first when γ_a was assumed always to be equal to the dry adiabatic lapse rate, and secondly, when γ_a was assumed to be equal to the moist adiabatic lapse rate if saturated conditions occurred. Vertical motions based on the adiabatic techniques were computed at each rawinsonde station in or near the study area (Fig. 2).

The JNWP method. The JNWP method makes use of both the adiabatic law and the vorticity equation. It is then possible to remove time derivatives; thus, the most serious objection against the use of the adiabatic method of computing vertical motion is eliminated. Vertical motions determined by the JNWP method are instantaneous values of vertical motion with respect to the 600 mb level. For this study, the maps of vertical motion prepared for facsimile transmission were used. The only modification made was to relabel the lines in terms of units comparable to those obtained by the other computation procedures. The procedures used to prepare the JNWP vertical motion analyses are described elsewhere (Ellsaesser, 1960; Petterssen, 1956).

Evaluation of the vertical motion analyses. The 700 mb (or 10,000 ft) vertical motion analyses (except for the JNWP analyses) were selected for evaluation and verification purposes. On comparing the major features of the 700 mb vertical motion analyses and the vertical motion analyses at higher levels, a general similarity in vertical motion patterns was noted, though magnitudes were generally higher at higher elevations. Middle level clouds, usually associated with large-scale vertical motion fields, are generally found near the 700 mb level. The motions which create these middle level clouds should be apparent on the 700 mb vertical motion analyses. Cumulus cloud activity, where the clouds have such dimensions that they are detectable by TIROS, generally penetrate the 700 mb level. However, under certain conditions TIROS may detect low level cumulus cloud activity which exists entirely below 700 mb. This particular situation can generally be detected from surface cloud observations or rawinsonde data.

It is recognized that extensive layers of clouds can form without rising motions; for example, advection fog and stratus, and cirrus. However, except for some cirrus areas which were excluded from consideration, such layers generally were not present over the study area during the period investigated.

When atmospheric vertical motions are approximately zero, most of the equations used for computing vertical motions are quite sensitive to small errors in the quantities used to evaluate them (Landers, 1955). For this reason, computed vertical motions with small magnitudes may have an error in sign. For comparison and verification purposes, the tables presented throughout the remainder of this study generally include, for values between ± 1.5 cm/sec, the following vertical motion classes: $-1.5 \leq w < -0.5$, $-0.5 \leq w \leq 0.5$, $0.5 < w \leq 1.5$, $-1.5 \leq w < 0.0$, and $0.0 \leq w \leq 1.5$ cm/sec. The velocities in the class $-0.5 \leq w \leq 0.5$ cm/sec (near zero) are subjectively considered as being either positive or negative for verification purposes.

TIROS cloud data in various forms were utilized in evaluating the derived fields of vertical motion. The objective vertical motion verification procedure was based on rectified representations of TIROS data as prepared for U. S. Weather Bureau facsimile weather network distribution. The appropriate unmodified TIROS nephanalysis is overprinted on each of the maps of the following section. The necessary operational limitations in the accuracy of this unmodified analysis were recognized. Nonetheless, it was felt desirable to use the unchanged map for verification. TIROS photographs as well as TIROS facsimile nephanalyses were used in preparing subjective evaluations of the various vertical motion analyses. Fig. 3 is the legend to be used for interpreting the TIROS nephanalysis (facsimile) charts reproduced on later figures.

The objective evaluation technique employed in verifying the vertical motion analyses was as follows:

1. Broken and overcast cloud areas depicted by the TIROS facsimile representations were drawn onto the various vertical motion charts. No adjustment of the vertical motion fields or cloud area locations was made on the basis of the time difference between the two types of data.

2. With a planimeter, the broken and overcast cloud areas within each vertical motion class were measured.

3. Cloud areas measured in Step 2 were compared with the area of the vertical motion class.

Boundaries of Cloud Systems
- Major
- Minor ———

Vortex

Cloud Cover

Clear	C	Heavy	+
Scattered	S	Thin	-
Broken	B [Crosshatched]		
Overcast	⊕ [Shaded, Stippled]		

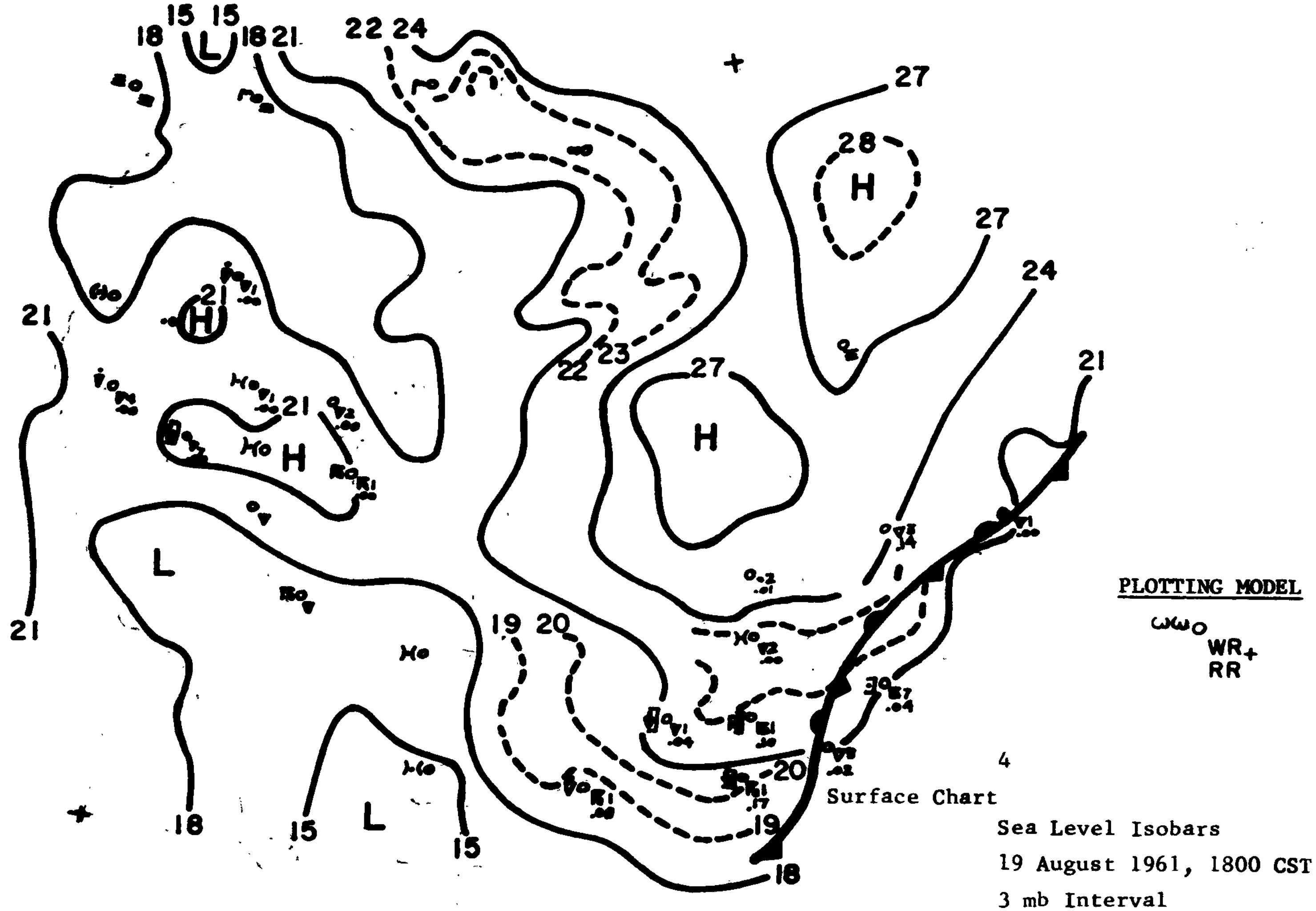
Clouds
- Stratiform
- Cumuliform
- Cirriform
- Cumulonimbus
- Bands ←→

Figure 3. Legend used on nephanalysis (facsimile) charts prepared by the United States Weather Bureau from TIROS III pictures.

The results are presented and discussed below.

3. Presentation and interpretation of results

Evaluation of the 19 August 1961 1800 CST vertical motion analyses. On most of this day the surface synoptic pressure pattern was dominated by two major systems. A pressure ridge extended from southwestern Colorado northeastward across the Great Lakes, with high centers in northeastern Colorado and central Minnesota at 1800 CST. The Pacific coast states and the western half of the mountain states were dominated by a quite irregular trough. Lowest pressures of this trough were in northwestern Mexico and southwestern British Columbia. Small high and low centers dominated the rest of this area. High pressure dominated the eastern Pacific Ocean. A dissipating frontal system was located over northern Texas and Oklahoma. These features are illustrated in Fig. 4. This figure also contains a highly abbreviated station model plot, including only the present and past weather and precipitation data. Note in particular the agreement between the reported precipitation and the cloud masses as indicated by the TIROS nephanalysis overprinted in Fig. 4. See also Fig. 7, a composite reproduction of the actual TIROS photographs. The TIROS satellite did not photograph most of Texas so that no comparison of satellite photographs and the precipitation occurring there can be made.



4

Surface Chart

Sea Level Isobars

19 August 1961, 1800 CST

3 mb Interval

PLOTTING MODEL

C_H
C_M N
O
C_L N_h
h

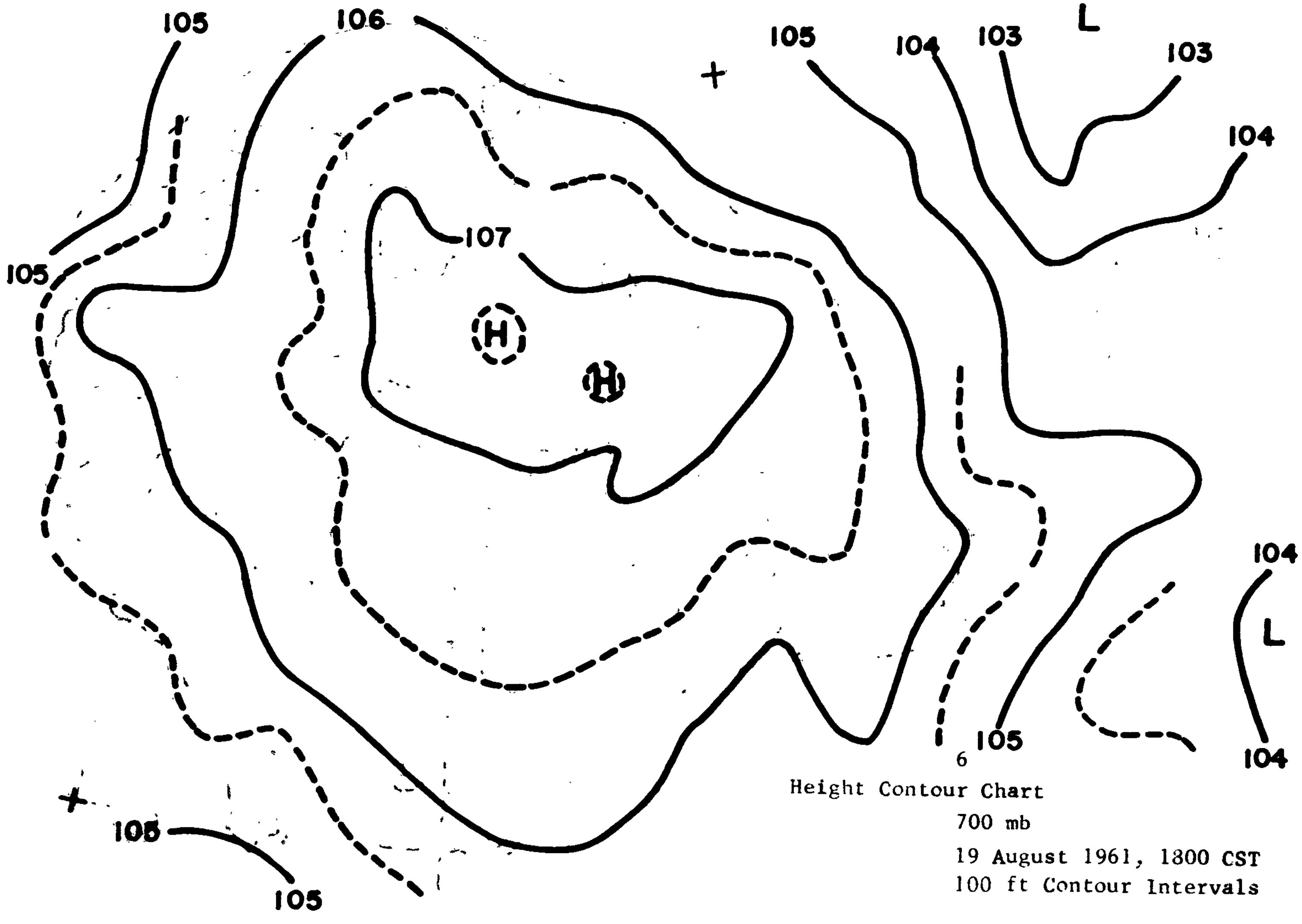
5

Cloud Data

Composite

19 August 1961, 1800 CST

Cloud Symbols



Height Contour Chart

700 mb

19 August 1961, 1800 CST

100 ft Contour Intervals

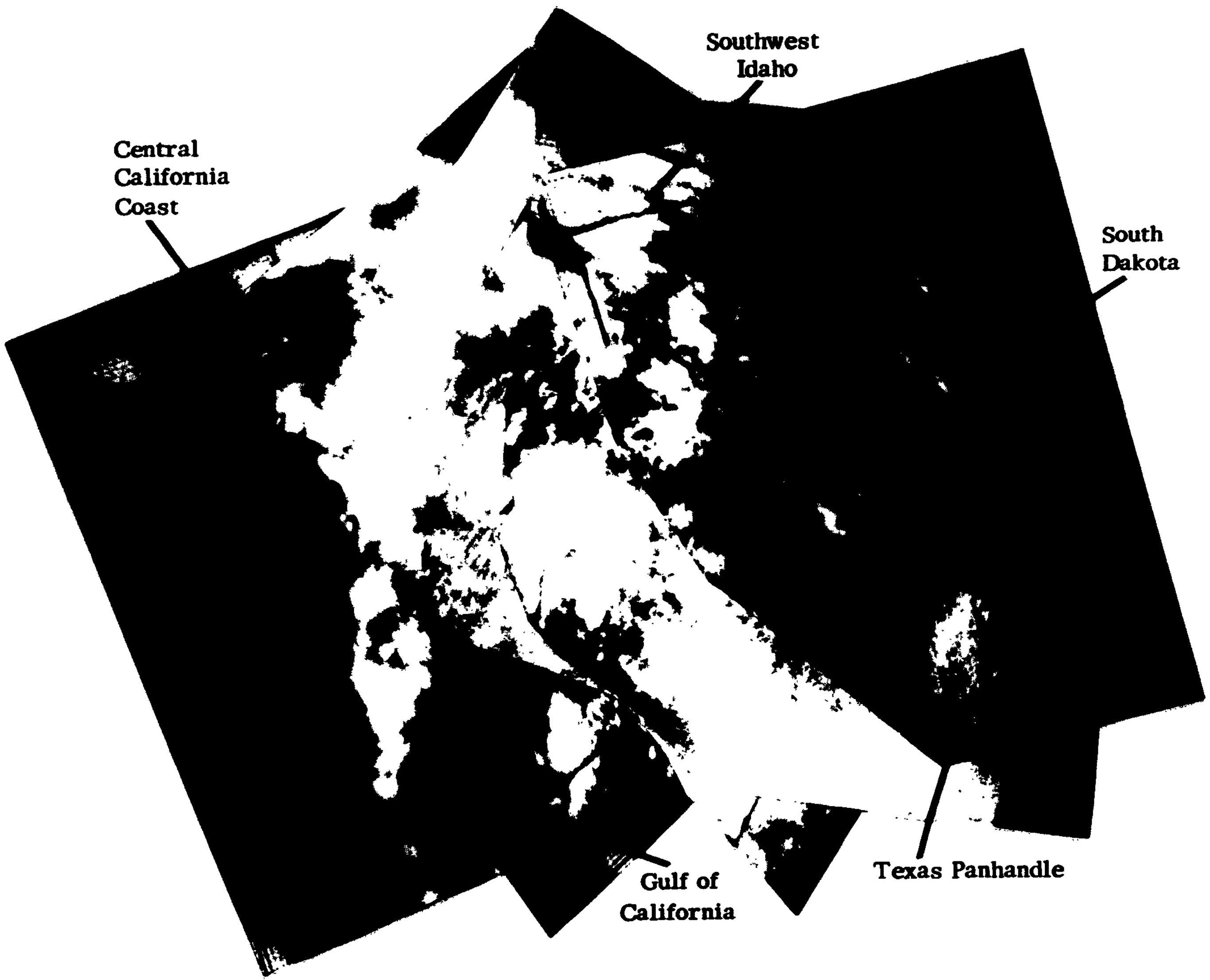


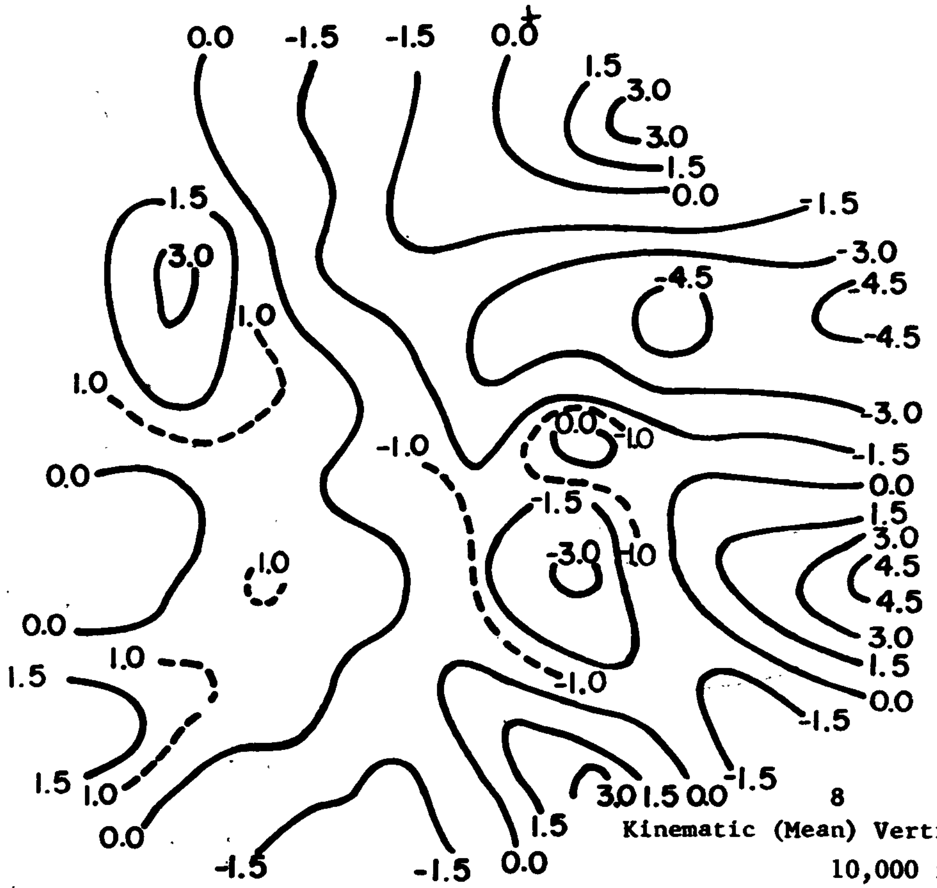
Fig. 7.-- Composite of frames 1 to 5 inclusive of Orbit 553 R/O 552, photographed from TIROS III on 19 August 1961 at 1709 CST.

Fig. 5 contains, in addition to the superimposed nephanalysis, a plotting of the cloud groups for many of the stations in the central and western United States. Good agreement between the nephanalysis and the reported cloud groups is apparent. The principal disagreement is in areas of scattered clouds and/or cirrus clouds. Of course, as mentioned earlier, the operational limitations in preparing the facsimile nephanalyses did not allow the indication of details in the regions of scattered clouds and of high clouds.

The 700 mb chart is considered fairly representative of mid-tropospheric conditions. At 1800 CST on the 19th (Fig. 6), a high pressure area centered over Wyoming dominated the mid-tropospheric pattern of the western half of the United States. Several minor troughs and ridges occurred around the periphery of this high pressure area. Some of these minor perturbations appeared to be closely associated with the smaller cloud systems indicated by the nephanalysis. The moisture pattern, not indicated on the charts presented here, suggested an extensive area of considerable depth where the moisture content was relatively high. This moist area began in an area south-southeast of the 700 mb high center and extended clockwise around to the region west-northwest of the center.

The results obtained from the use of the objective vertical motion verification procedure at 1800 CST are summarized in Table 1. The cirrus clouds which were over central Idaho and southwestern Montana were not included in the cloud area tabulations. With the exception of the Bellamy technique, all the techniques evaluated by the objective verification procedure appeared to be quite satisfactory in the western zone on this particular day, especially when values greater than or equal to -0.5 cm/sec were considered (Table 1). Although the results in this zone were generally quite good, inspection of the various vertical motion analyses, Figs. 8, 9, 10, 11 and 12, reveals a considerable variation in the velocity magnitudes and in the detail of the vertical motion fields. These variations will be described in more detail in the individual evaluations which follow. In the eastern zone, agreement was poor.

A mapping of the component technique vertical motions computed for the 10,000 ft level is presented in Fig. 8. The gross picture suggests a line of zero vertical motion running approximately north-south through the center of the 700 mb high. To the west of this line there was generally ascending motion while to the east there was generally descending motion. This is in accord with the classical picture of ascent to the west of the upper high and descending motion to the east of the high. Looking at the details of the vertical motion pattern in the western zone, it is apparent that the overall



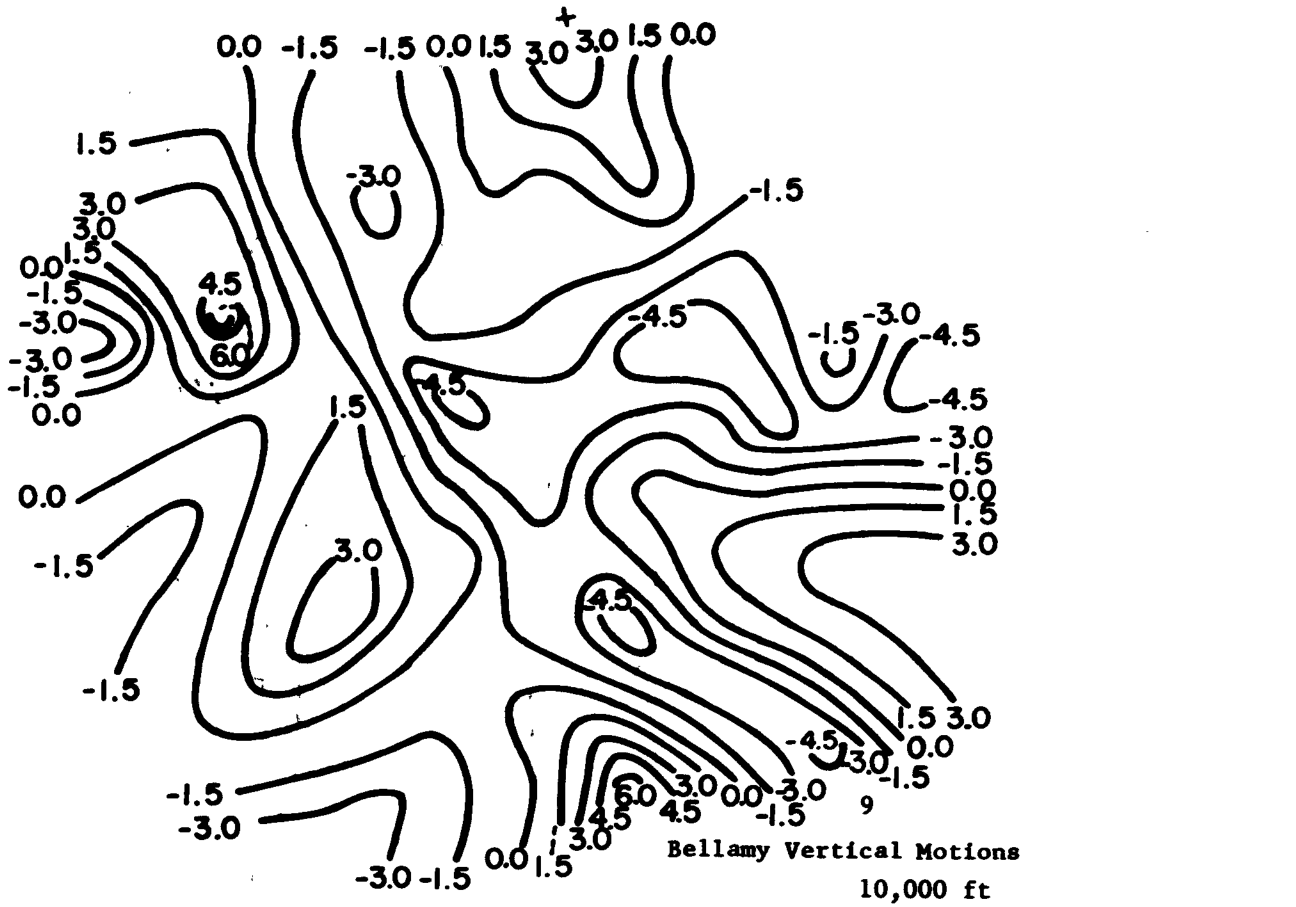
8

Kinematic (Mean) Vertical Motion

10,000 ft

19 August 1961, 1800 CST

cm/sec

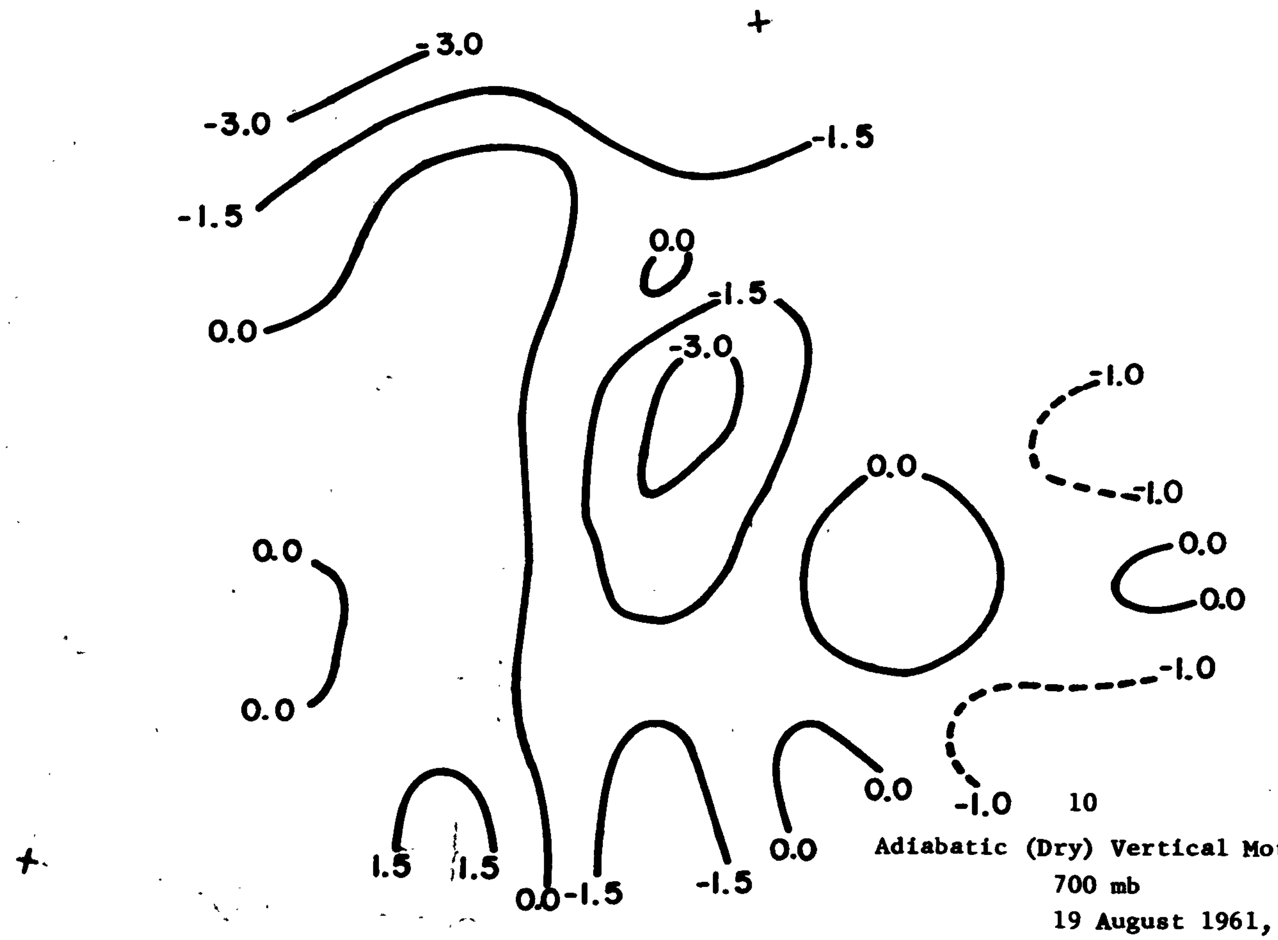


Bellamy Vertical Motions

10,000 ft

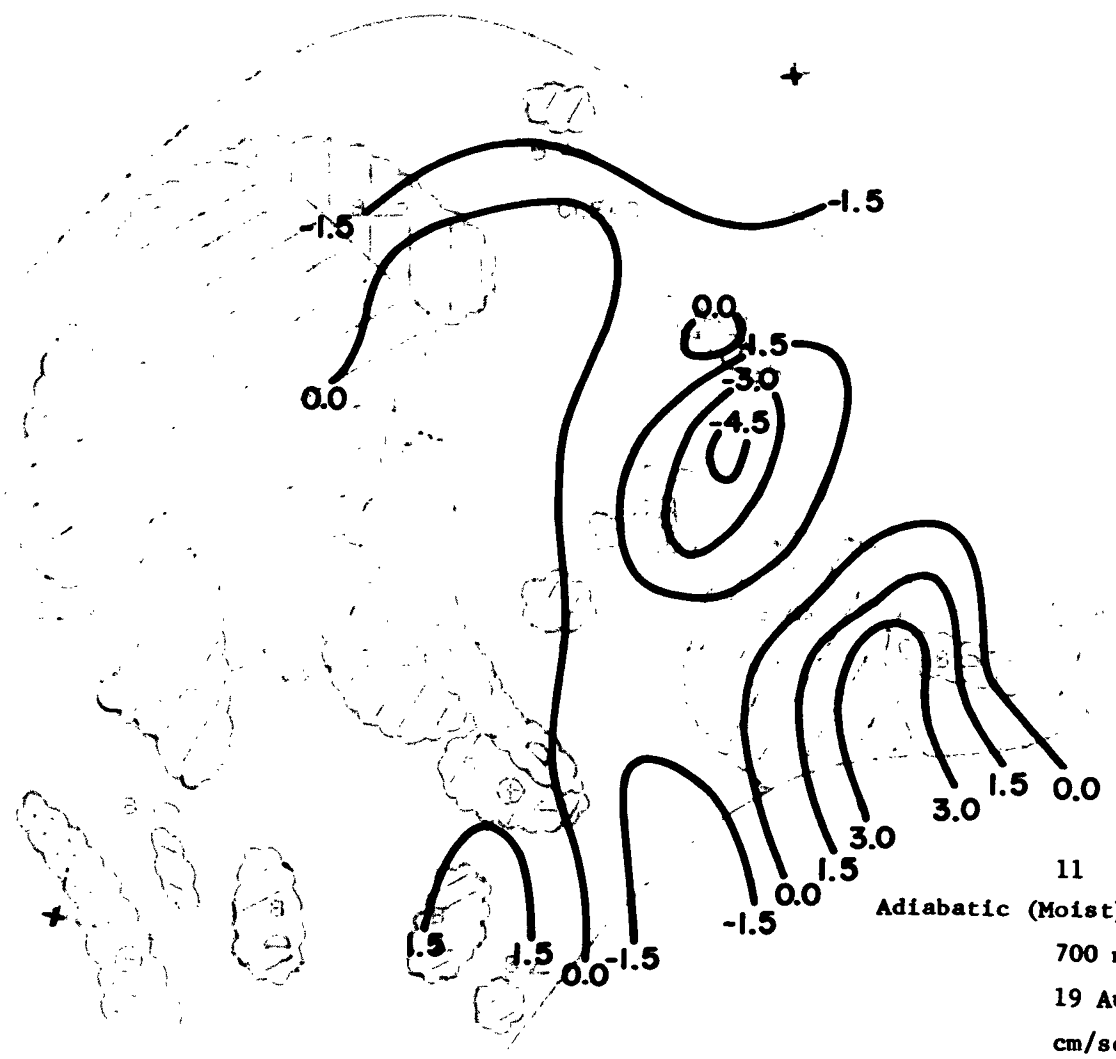
19 August 1961, 1800 CST

cm/sec



10

Adiabatic (Dry) Vertical Motions
700 mb
19 August 1961, 1800 CST
cm/sec



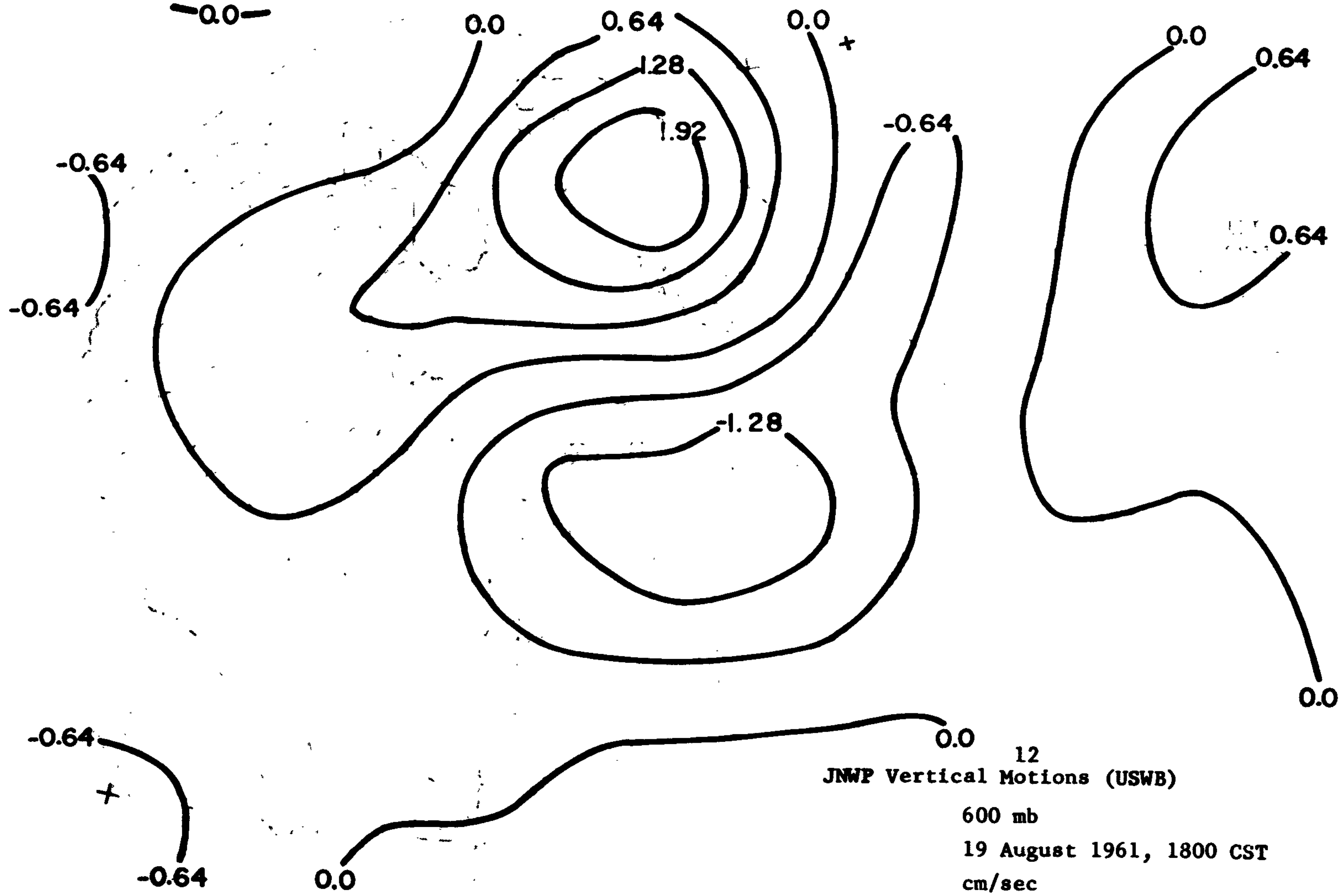
11

Adiabatic (Moist) Vertical Motions

700 mb

19 August 1961, 1800 CST

cm/sec



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JNWP Vertical Motions (USWB)

600 mb

19 August 1961, 1800 CST

cm/sec

Table 1. Percent of area of broken or overcast cloud for which rising or slight negative vertical motion was calculated. 19 August 1961 1800 CST. Adiabatic technique results are for a 12-hr period ending at 1800 CST.

Technique	Western Zone		Eastern Zone		Combined Zones	
	$w \geq -0.5$	$w \geq 0.0$	$w \geq -0.5$	$w \geq 0.0$	$w \geq -0.5$	$w \geq 0.0$
Component	91	67	34	28	64	49
Bellamy	55	45	30	28	44	37
Adiabatic (Dry)	81	74	41	20	62	49
Adiabatic (Moist)	89	82	72	52	81	68
JNWP	84	27	26	14	57	21

configuration of the cloud patterns was similar to the component vertical motion fields but the cloud patterns frequently appeared to trail the vertical motion fields (Fig. 8). In particular, the centers of rising motion seemed to be over clear or scattered areas. This apparent "trailing" by the cloud patterns seemed to occur in some cases when the vertical motions were associated with small scale moving upper air troughs or ridges (Fig. 6) and suggests changing or moving vertical motion fields. The time difference between the TIROS observation and the valid time of the vertical motion computation would account for some but by no means all of this displacement. Also, broken or overcast clouds do not form immediately after the beginning of positive vertical motion in an area, even if moisture is available for cloud formation. Note for example the areas of positive vertical motion in southeastern Idaho and in southwestern Arizona. Prior to 1800 CST the clouds in these two regions consisted generally of scattered cumulus clouds or high clouds, as indicated by surface reports as well as the TIROS pictures. By 1800 CST there was some increase in the low and middle level cloudiness (Fig. 5). By 2100 CST (not illustrated) the areas were covered with broken or overcast low and middle level clouds.

The descending motion in the vicinity of southwestern Utah appears to be the indicator of the decrease in the amount of clouds from central Utah and northwest Arizona westward. Such negative motion cannot, here or elsewhere in such regions, be a true indicator of the microscale or the mesoscale vertical motion patterns. The cloud and weather patterns (Figs. 4 and 5) suggest that there are scattered small regions of fairly pronounced rising vertical motions. In this particular case these may be overbalanced by a general tendency for sinking motion and dissipation of the overall cloud mass. This latter type of motion is all that is shown by the techniques used for this study. Both the objective and subjective verification results for the western zone appear to be quite good. It appears that there would probably be some improvement in the result if the TIROS data had been valid at 1800 CST or some short time later.

The values of Table 1 suggest that in the eastern zone the component vertical motion calculations are not particularly satisfactory. However, this is evidently a case where TIROS data may provide misleading information as to the location of a positive vertical motion area. Over 65% of the cloud in the eastern zone was concentrated in one cloud area, located in the vicinity of the Oklahoma and Texas Panhandles. The size and location of this area appeared to be relatively constant during the several hours preceding 1800 CST (Fig. 5). The precipitation in this region ended one to two hours prior to 1800 CST. Evidently, much of this region started to change from positive to negative vertical motions sometime between 1600 and 1800 CST. Additional evidence of this change was found on the 2100 CST surface analysis (not presented) which showed considerable clearing in the area; cloud areas changed from broken or overcast to clear or scattered. This appeared to be associated with the dissipation of the surface front over the Texas region and the dissipation of a small trough which had been present over the Texas Panhandle. This trough, while not present on the 1800 CST surface map (Fig. 4), had been present on earlier maps and was still present at 700 mb (Fig. 6). South of this area of descending motion and dissipating clouds was an area of rising motion (Fig. 8). This area coincided well with the precipitation and cloudiness observed over west-central Texas. This provides another example of the "trailing" feature, discussed in connection with the clouds of the western zone. The two cloud bands over Oklahoma coincided well with the rising motion calculated for that area. The size of the rising motion area would suggest that the cloud mass should be larger, or the rising motion area should be smaller.

The cloud area in Wyoming and South Dakota, occurring in a region of calculated negative velocities, was evidently caused by a combination of events. There probably was some orographic lifting of the air over the Black Hills. Further, Fig. 6 shows that there was a small trough in the upper air pattern moving into this area from the northwest. During the several hours preceding 1800 CST, scattered cumulus buildups and showers were associated with the movement of this upper-air trough and with the surface trough. Thus, although the component technique suggests a general negative vertical motion in this region, there was some indication that there may have been some small areas of positive vertical motion. The technique determines the average vertical motions for areas which evidently are larger than the actual positive motion areas of this region. Also, the actual surface vertical motion was evidently a factor which should have been considered.

The assumption of zero vertical motion at the surface when evaluating the component technique usually seemed to have little effect on the results obtained with the objective verification technique, especially when all values greater than -0.5 cm/sec were considered as being positive for verification purposes. This was probably due to the fact that most of the surface winds were light. There were, however, several cloud areas in central Colorado, as well as the one mentioned in the preceding paragraph, which were located in regions where the calculated vertical motions were negative, about 0.0 to -1.0 cm/sec. These clouds might have been located in an area of positive vertical motion if a positive surface vertical motion had been used, since the clouds evidently were orographically induced. Throughout this study, the orographically induced clouds generally were found in regions where the calculated vertical motion was small and often negative.

Vertical motion fields as determined by the Bellamy technique are shown in Fig. 9. A comparison with the vertical motions as calculated using the component technique (Fig. 8) revealed a great deal of similarity in the overall patterns. Most of the discussion relating the component vertical motion field to the observed weather and cloud pattern is applicable also to the comparison of the Bellamy vertical motion field.

The only place of major disagreement occurred over southwestern Idaho. This negative area is the principal reason for the low objective verification of the Bellamy technique, as displayed in Table 1. Such a downward motion is not apparent in the TIROS facsimile charts (Fig. 9) or in the surface cloud observations (Fig. 5). However, the TIROS photograph (Fig. 7) does show what appears to be a large break in the cloud deck in about this region at 1709 CST and on all the upper level charts through 400 mb there was an upper air ridge in this approximate area at 1800 CST. Although examination did not reveal any error in the computations themselves, it is quite possible that in this particular area, where the computation triangles for a Bellamy technique are fairly large, and where in this case the winds are light and variable, a combination of errors in the actual observation could have summed up to give unusually high negative motion such as suggested in Fig. 9.

Both the component and the Bellamy techniques indicated general negative vertical motions in the regions of the two small cloud areas in Montana and South Dakota. Both techniques determine the average vertical motions for areas which evidently were larger than the actual positive motion areas of these regions. Also, the actual surface vertical motion may well have been a factor which should have been considered in order that vertical motions of the proper sign be determined.

The vertical motion fields determined by the two adiabatic techniques are shown in Figs. 10 and 11. These velocities are normally considered to be 12-hr averages and are commonly considered to be applicable midway in the 12-hr period (1200 CST for this study). The TIROS data used for all days in this study were observed after 1600 CST, but the cloud masses were generally fairly persistent and not rapidly moving, so comparison does not seem to be improper.

The gross patterns are in agreement with those of Fig. 8. The dry and the moist adiabatic techniques yielded essentially the same vertical motion patterns because saturation generally occurred about 700 mb. The only region of notable difference in the patterns of Figs. 10 and 11 is in the vicinity of the cloud mass located near the Texas Panhandle. In this area the moist adiabatic technique suggested rising motion over the cloud mass. Recalling the discussion of Fig. 8, which suggested that the vertical motions over the Panhandle regions had changed from rising motion during the middle of the day to descending motions by the time of Fig. 8 we see rather close agreement with this conclusion. The rising motion of Fig. 11, valid at 1200 CST, compares rather well in this sense with the sinking motion of Fig. 8, valid at 1800 CST.

Two minor points remain to be discussed. The area of northwestern Arizona indicated as having descending motion in Figs. 8, 9, and 10 is an area of rising motion in Fig. 11. Fig. 11 is probably a little more representative of the cloud pattern. Also, the slight descending motion of western Idaho as indicated by the two adiabatic techniques is more in agreement with the Bellamy technique than with the component technique. For other areas and features the discussion of Fig. 8 is appropriate for the purposes of this paper.

The final vertical motion technique considered is that prepared by the JNWP unit. The map is presented as Fig. 12. The patterns are much smoother and the magnitudes of the maximum vertical motions are much less than displayed by the other techniques (note that the interval between the lines is less than half that of Fig. 8 through 11). The objective verification rating (Table 1) of the

JNWP method for this day was overall the lowest of all the methods for positive velocities only, but quite high when small negative motions are included. The cloud mass over the northwestern United States was associated with a region of calculated ascending motions, but the region of maximum ascent in eastern Montana was a region of generally clear conditions except for some high clouds. The surface observations (Fig. 5) indicated a slight increase in amount and intensity of the cumulus activity in this region between 1200 and 1800 CST. The regions of descending motion in the south central United States and near the west coast match well with the observed dissipation of the general cloud masses over those areas. As indicated by data for the 20th, the cloud mass in the northwestern United States spread eastward toward the region of indicated maximum rising motion. The lag is extreme, however. At the same time, the clouds in the vicinity of the JNWP descending motion continued to dissipate. Thus, it seems that the JNWP vertical motion calculation was an indicator of the large-scale motion and development patterns rather than the smaller scale details shown by some of the other vertical motion calculation patterns. The JNWP technique appears to be ineffective when the vertical motions are orographically produced or associated with small upper-air troughs. Evidently, the grid system utilized is of such a size that it smoothed the small troughs and the JNWP orographic corrections were evidently not applicable to small-scale terrain features.

The vertical motion analyses of 20 and 21 August 1961. Detailed presentation of results for the other two days for which vertical motions were calculated is not made in this paper. The results and discussions were generally of the same nature as those of the 19th, and it is not felt necessary to discuss the individual analyses in this paper.

Objective comparison of results for all days. The discussion of the results for the 19th included a table in which was indicated the percent of areas of broken and overcast clouds having positive or near positive vertical motions according to each of the calculation techniques. The corresponding information summed for all three days studied is presented in Table 2.

The various techniques appeared almost equally effective in the combined verification zones when velocities greater than or equal to 0.0 cm/sec were used as the basis for comparison. Using velocities greater than or equal to -0.5 cm/sec and considering the two zones separately resulted in quite different apparent effectiveness of the various techniques. The component technique was apparently most effective for the western zone, while the JNWP technique appeared most effective in the eastern and combined zones. It must be remembered, however, that the JNWP technique gives magnitudes somewhat less than half that of the other techniques. This would make the JNWP technique show up favorably for this

Table 2. Percent of area of broken or overcast cloud for which rising or slight negative vertical motion was calculated, 19-21 August 1961. Times are 1800 CST, except adiabatic techniques are for a 12-hr period ending at 1800 CST. Satellite picture times are one to two hours earlier.

Technique	Western Zone		Eastern Zone		Combined Zones	
	$w \geq -0.5$	$w \geq 0.0$	$w \geq -0.5$	$w \geq 0.0$	$w \geq -0.5$	$w \geq 0.0$
Component	94	77	57	45	74	59
Bellamy	75	63	52	46	61	54
Adiabatic (Dry)	39	35	52	40	46	38
Adiabatic (Moist)	50	45	66	58	59	52
JNWP	85	48	87	59	86	54

particular verification procedure. Although the component and Bellamy techniques frequently were rated less effective than the JNWP technique, inspection of the individual vertical motion analyses revealed that the component and Bellamy procedures provided more detail and a better relationship between positive vertical motion fields and cloud area. Leaving out the JNWP technique, the component technique gave the most satisfactory results in the combined zone and the moist adiabatic technique was most effective in the eastern zone. As a whole, however, the adiabatic techniques were least satisfactory. Other comparisons are left to the reader.

Of interest also is the distribution of vertical motions in the areas of clear and scattered cloudiness. Table 3 presents a summary of this information for the entire 3-day period studied. The adiabatic methods both suggest that more than 75 percent of the areas of clear sky or scattered cloudiness were areas of descending motion. The other three methods gave descending motion in such areas only slightly over half the time. Certainly some ascending motion would be expected in such areas for several reasons. If the air were very dry and if upward vertical motion had been going on for only a short period of time cloudiness certainly would not be expected. Also, areas of scattered clouds can certainly

Table 3. Sign of the vertical motion in the areas of clear sky or scattered clouds. Values are percent of clear and scattered areas, 19-21 August 1961. Map times are 1800 CST, except adiabatic techniques are for a 12-hr period ending at 1800 CST.

Technique	Positive Vertical Motion	Negative Vertical Motion
Component	44	56
Bellamy	41	59
Adiabatic (Dry)	15	85
Adiabatic (Moist)	24	76
JNWP	45	55

exist in regions where the overall motion is sinking while air associated with the individual cloud masses would be rising. Further information concerning the relation between the vertical motion patterns and the areas of clear sky or scattered clouds can be gleaned from the individual maps presented earlier. For the purposes of this paper it was not felt necessary to discuss these motions in detail.

A comparison of the several techniques with each other was also carried out. This comparison was not restricted to values obtained in broken and overcast cloud area alone. Rather, vertical motion values obtained by each of the methods at the various grid points of Fig. 1 were used. The computed vertical motions were divided into 5 classes (units in centimeters per second): $w \leq -1.8$, $-1.7 \leq w \leq -0.6$, $-0.5 \leq w \leq 0.5$, $0.6 \leq w \leq 1.7$, and $w \geq 1.8$. The results of the comparison are presented in Table 4. This comparison does not establish the validity of the results obtained by any of the various techniques, but does add quantitative weight to the qualitative discussion of agreement (or lack thereof) of the vertical motion analyses of Fig. 8 through Fig. 12.

Table 4. Comparison of 700 mb vertical motions computed by the different techniques. Symbols used in table: A is the percent agreement in sign and near zero class, B is the percent agreement in class, and C is the percent agreement in ± 1 class. See text for determination of the classes.

Techniques	Western Zone			Eastern Zone			Combined Zones		
	A	B	C	A	B	C	A	B	C
Component: Bellamy	91	34	82	83	52	86	86	45	84
Component: Adiabatic (Dry)	47	13	51	66	19	63	59	17	58
Component: Adiabatic (Moist)	48	18	84	63	20	62	53	19	71
Component: JNWP	76	48	88	55	19	55	68	31	68
Bellamy: Adiabatic (Dry)	43	19	39	69	25	67	66	23	56
Bellamy: Adiabatic (Moist)	39	22	46	60	25	57	52	24	53
Bellamy: JNWP	61	25	64	60	14	56	61	18	59
Adiabatic: Adiabatic (Dry) (Moist)	93	67	87	88	62	92	90	64	90
Adiabatic: JNWP (Dry)	70	19	45	59	32	78	70	27	66
Adiabatic: JNWP (Moist)	67	22	61	66	37	72	67	31	68
Average	64	29	66	68	31	69	67	30	67

4. Summary and conclusions

The Bellamy and the component techniques provided vertical motion patterns which were very similar. The Bellamy technique was the simplest procedure to use, but the component technique yielded results which were somewhat more consistent and realistic. From the results of this work it appears that some form of the kinematic method would be suitable for detailed analysis almost approaching that of meso-scale atmospheric vertical motions, but accurate and complete wind data are necessary when using a kinematic method for such motions (Miller and Panofsky, 1958). When information on systems approaching a meso-scale phenomenon in size is desired, great care must be taken in constructing accurate upper-air charts containing fine detail, including the location of minor troughs and ridges. A comparison of the TIROS cloud data and the standard level upper-air charts indicate that many of the small troughs and ridges which are smoothed out of conventionally drawn upper-air charts are associated with cloud areas and are apparently a primary cause of these clouds. Even with carefully drawn analyses, the necessity for using finite difference techniques will introduce considerable smoothing into the final vertical motion patterns. The component technique itself is objective except for the initial analysis of the wind field and the final analysis of the resultant vertical motions at the various grid points. The Bellamy technique can be completely objective, except for final analysis of the vertical motion field, but the scale of phenomenon which can be examined depends entirely on the density of the observing network.

The two adiabatic vertical motion techniques did not produce as satisfactory results. Further, considerable subjective judgement was required in the preparation of these analyses. From the results of this research, it appeared that the use of these techniques for atmospheric research should generally be limited to very large scale atmospheric motions when 12-hr average vertical motion values are satisfactory. This technique does not seem suitable for detailed study of smaller scale atmospheric motions.

The JNWP method provided vertical motion patterns which seemed to be fair representations of the larger cloud masses. However, for the period studied, clouds associated with small troughs or orographically created clouds were frequently not in agreement with the JNWP vertical motion field. This technique seemed to determine vertical motion values which were much smaller in magnitude than those determined by the other techniques. The patterns seemed to be quite smooth compared to the other results. The results should apparently be applied only to the very large-scale vertical motions in the atmosphere.

For extensive cloud masses there was good agreement between the cloud observations as indicated by the TIROS satellite pictures and the various vertical motion analyses. In the case of the smaller cloud masses the agreement was moderate, except for the JNWP and the adiabatic techniques. The TIROS data are not yet completely suitable for verification purposes due to incomplete coverage, lack of agreement of time between the satellite observations and the standard observation time, and the slowness of rectifying and accurately interpreting the satellite data. With the advent of the more sophisticated meteorological satellite systems some of these difficulties should be eliminated.

TIROS data might prove to be of more immediate value as a subjective aid in more accurate analysis procedures leading to vertical motion calculations and distribution rather than as an objective verification procedure. It should be possible to improve the technique for estimating atmospheric vertical motions through comparison and subjective evaluation of the vertical motion analyses, the standard meteorological analyses, and the TIROS data. These data should be used in conjunction with surface weather observations and carefully analyzed upper-air charts. Studies of this nature may help to develop procedures for eliminating the smoothing techniques now frequently employed in preparing weather charts, as well as eliminating the use of certain assumptions. The satellite data must either include, or be supplemented by, studies of short period changes in the cloud mass structure, amount and location. There also must be an investigation of the cloudiness associated with small troughs and ridges.

There yet remains the question of whether the three-day sample is of adequate length. In the writers' opinion, further studies would result in similar conclusions. A good test might be the study of a case from another summer and from a winter. The best results probably would be obtained by waiting until the next generation of meteorological satellites (NIMBUS) is operating, but valuable results could be obtained using the TIROS IV, V and VI observations.

REFERENCES

Bellamy, J. C., 1949: Objective calculations of divergence, vertical velocity and vorticity. Bull. Amer. Meteor. Soc., 30, 45-49.

Bjerknes, V., et.al., 1911: Dynamic Meteorology and Hydrography, Part II. -- Kinematics. Carnegie Instn. Wash. Publ., 88, part II, 175 pp.

Curtis, R. C., and Panofsky, H. A., 1958: The relation between large-scale vertical motion and weather in summer. Bull. Amer. Meteor. Soc., 39, 521-531.

Ellsaesser, H. W., 1960: JNWP office note no. 15 (revised)., Rev. 1 Oct. 1960., U. S. Dept. of Commerce-Weather Bureau. Washington 25, D. C., 36 pp.

Erickson, C. O., and L. F. Hubert, 1961: MSL Report No. 7, identification of cloudforms from TIROS I pictures. Manuscript of the Meteorological Satellite Laboratory, United States Weather Bureau, Washington, D. C., 68 pp.

Fleagle, R. G., 1947: The fields of temperature, pressure, and three-dimensional motion in selected weather situations. J. Meteor., 4, 165-185.

House, D. C., 1958: Air mass modification and upper-level divergence. Bull. Amer. Meteor. Soc., 39, 137-143.

Landers, H., 1955: A three-dimensional study of the horizontal velocity divergence. J. Meteor., 12, 415-427.

Miller, A., and Panofsky, H. A., 1958: Large-scale vertical motion and weather in January, 1953. Bull. Amer. Meteor. Soc., 39, 8-13.

Panofsky, H. A., 1946: Methods of computing vertical motion in the atmosphere. J. Meteor., 3, 45-49.

__________, 1951: Large-scale vertical velocity and divergence. Compendium of Meteorology., American Meteorological Association, 639-646.

Petterssen, S., 1956: Weather analysis and forecasting, 2nd Ed., Vol. 1, McGraw-Hill, New York, 428 pp.

Vaisanen, A., 1961: Investigation of the vertical air movement and related phenomena in selected synoptic situations., Societas Scientiarum Fennica Commentatienes Physica-Mathematicae, XXVI 7, Centraltryckeriet, Helsingfors.