THE MAGNITUDE AND EFFECT OF ANALYSIS ERRORS OVER THE NORTHEASTERN PACIFIC AS ESTIMATED FROM TRANSOSONDE DATA

J. K. ANGELL

U.S. Weather Bureau, Washington, D.C.[1]

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ABSTRACT

The magnitude of analysis errors over the northeastern Pacific at 300 and 250 mb. is estimated by means of winds and geostrophic winds derived from operational transosonde flights from Japan. The results suggest that the ratio of vector geostrophic wind error and geostrophic wind varies from 0.15 near the west coast of North America to 0.40 in the North-Central Pacific. The influence of these analysis errors upon numerical forecasting, airplane dispatching, and trajectory estimations is indicated. As one of the alternative methods for increasing the number of upper-air observations over the oceans, the present stalemate with regard to the horizontal sounding system is considered, and suggestions made for breaking this stalemate.

1. INTRODUCTION

Knowledge of the magnitude of analysis errors in regions of sparse upper-air data, such as the North Pacific, is desirable in order to estimate the effort and money which should go into increasing the data density. Estimates of such analysis errors have been difficult to obtain because, in general, no independent data have existed with which the conventional analysis could be compared. However, the operational transosonde flights from Japan during 1957–59 provide a means for estimating errors in the conventional analysis over the North Pacific inasmuch as during the first year of operation the transosonde data were hardly ever used as an aid to conventional analysis and during the second year of operation were only intermittently so used. In this paper the error estimates have been limited to the northeastern Pacific because, although conventional upper-air data are sparse in that area, the transosonde positioning accuracy is good, and hence most of the differences between the two sets of data can be reasonably ascribed to errors in the conventional analysis.

The transosonde data were treated by applying a one-two-one smoothing to 2-hourly latitudes and longitudes determined by the Federal Communications Commission (FCC) radio direction finding network, followed by evaluation of the 2-hour-average wind velocity. The geostrophic wind was then estimated from the 4-hour-average acceleration of the transosonde utilizing the equations of motion and neglecting the effects of vertical motion and friction. With this procedure one would anticipate the average error in transosonde-derived wind to be on the order of 5 kt. and the average error in transosonde-derived geostrophic wind to be on the order of 10 kt.

[1] Present assignment, Meteorological Office, Bracknell, Berkshire, England.

2. ANALYSIS ERRORS OVER THE NORTHEASTERN PACIFIC OCEAN

In this section we present individual examples of extreme errors in the 300- and 250-mb. analyses over the northeastern Pacific as well as estimates of the average errors in analysis in that region occasioned by the present-day sparseness of upper-air data.

Figure 1 comprises three diagrams showing (a) the 300-mb. NAWAC analysis over the northeastern Pacific on February 4, 1956, as drawn without knowledge of the transosonde-derived wind (solid wind shaft and letter T designation) at map time, (b) a reanalysis utilizing the transosonde-derived wind and geostrophic wind at map time, and (c) the 300-mb. NAWAC analysis 12 hours later. The dashed wind shaft in figure 1a shows the geostrophic wind scaled from the NAWAC analysis at the point where the transosonde wind existed, but had not been made available to the analyst. The vector difference between the transosonde wind and NAWAC geostrophic wind is about 100 kt. at a point only a few hundred miles off the west coast of the United States. Inasmuch as the transosonde was decelerating quite rapidly at this time (45 kt. in 4 hr.), the comparison between transosonde-derived geostrophic wind and NAWAC geostrophic wind is not this bad. Because of this deceleration, in figure 1b the transosonde wind is shown as directed toward higher contour height, making an angle of 20°–25° with adjacent contours. Figure 1c shows that 12 hours later a trough of considerable amplitude was present along the west coast of the United States. The existence of such a trough might be anticipated on the basis of the reanalysis in figure 1b, but would hardly be anticipated on the basis of the analysis in figure 1a. It is understood that along the Washington and Oregon coasts heavy rains associated

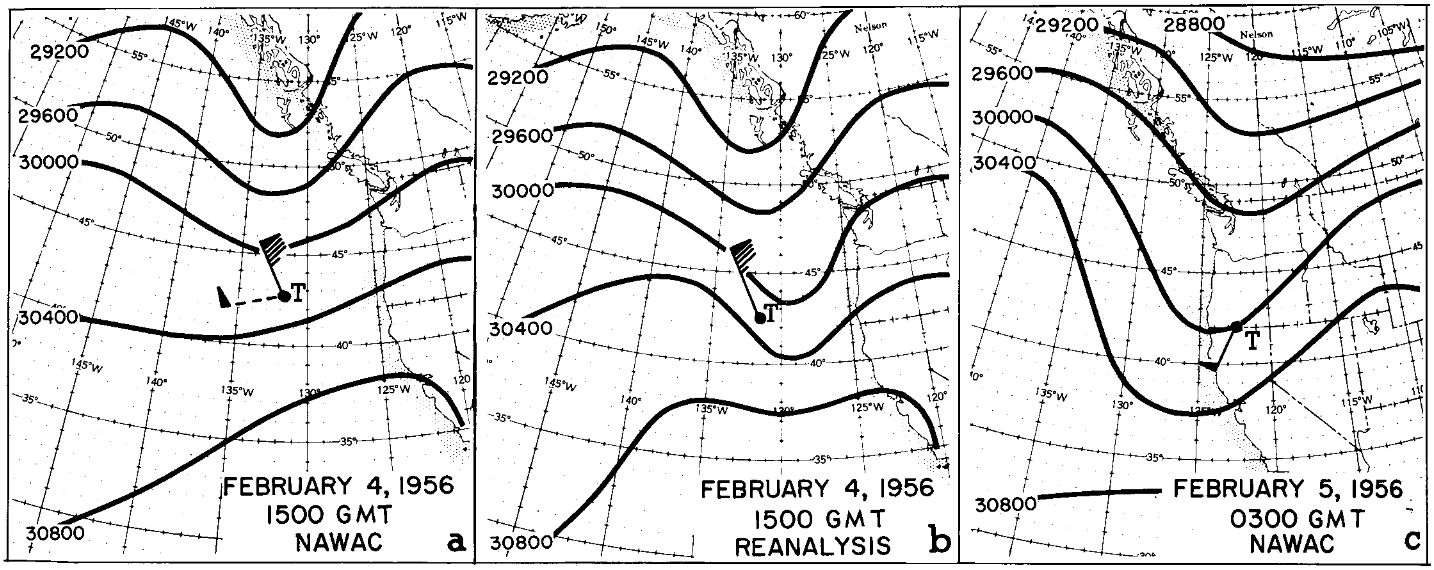

Figure 1.—(a) 300-mb. NAWAC analysis made without knowledge of the wind derived from transosonde flight 27′ (solid wind shaft and letter T designation) at map time; (b) a reanalysis utilizing the transosonde-derived geostrophic wind; and (c) the NAWAC analysis 12 hours later. The dashed wind shaft in (a) shows the geostrophic wind scaled from the NAWAC analysis.

with this trough were poorly forecast owing to the underestimate of the trough amplitude. It might also be mentioned in passing that the trough development may have resulted from horizontal divergence associated with the large ageostrophic flow toward higher contour height illustrated by the transosonde trajectory.

Another extreme case is shown in figure 2. Here the vector difference between transosonde wind and NAWAC geostrophic wind is about 120 kt., but once again the transosonde is decelerating so that the geostrophic comparisons are not this bad. As in figure 1 the analysis in figure 2c does not appear surprising in view of the reanalysis (fig. 2b) for 24 hours earlier with the aid of the transosonde data.

The above examples of analysis error are extreme cases and have been frankly admitted as such. However, it does not take many cases with vector errors of nearly 100 kt. to yield a high average value for the difference between NAWAC geostrophic wind and transosonde-derived geostrophic wind. Figure 3 shows the average

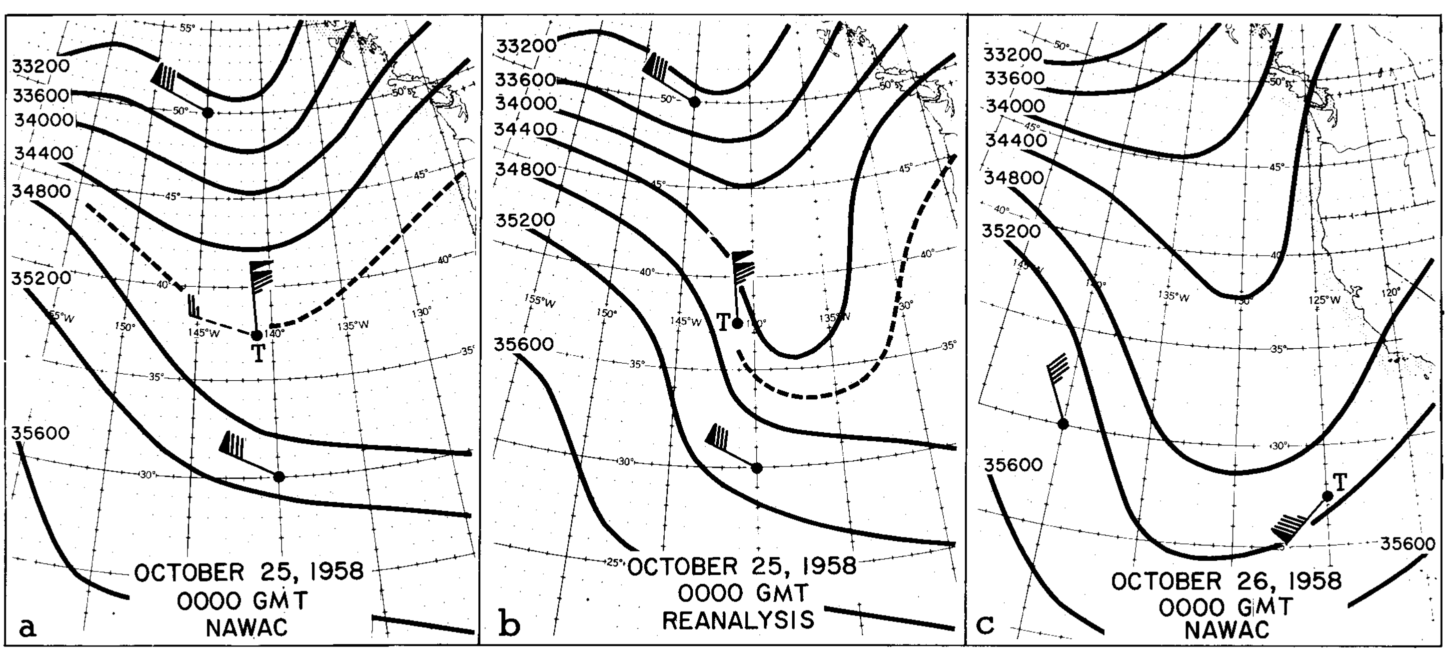

Figure 2.—Wind derived from transosonde flight 155 and maps at 24-hour intervals. Otherwise see legend for figure 1.

magnitude of this vector difference in the northeastern Pacific as derived from all FCC-positioned transosonde flights which traversed this area at 300 and 250 mb. Since it was only legitimate to make the comparisons at synoptic map time, only about 200 geostrophic velocity differences went into figure 3 with the average number of comparisons varying from about three per 5° latitude-longitude area in the belt of maximum flight frequency between 40° and 45° N., to two comparisons per unit area between 50° and 55° N., and one comparison per unit area between 15° and 20° N. The magnitude of the geostrophic velocity difference per 5° latitude-longitude area was twice smoothed in order to provide the regularity of pattern illustrated in figure 3. Bearing in mind the relatively small number of comparisons available, and the smoothing applied, note from figure 3 that the magnitude of the difference between NAWAC geostrophic wind and transosonde-derived geostrophic wind doubles between the west coast of North America and the North-Central Pacific, with the isopleths of the difference approximately paralleling the coast. Presumably this increase in magnitude is due to the increasing sparseness of conventional upper-air data as one progresses westward and southward, although it is surprising that the error does not decrease in the vicinity of the Hawaiian Islands. It is possible, however, that to some extent this increase in magnitude is produced by a decrease in transosonde positioning accuracy as one moves westward, even though the existence of FCC stations in Alaska and Hawaii makes this less likely than if the FCC stations were confined to the contiguous United States.

Inasmuch as the mean 300- and 250-mb. geostrophic wind speed in this area of the northeastern Pacific during the time of these flights was only 80–90 kt., then, assuming an average (and constant) transosonde-derived geostrophic wind error of 10 kt. due to inaccuracy of positioning, the ratio of geostrophic velocity error due to analysis and geostrophic velocity varies from about 0.15 near the west coast of North America to more than 0.40 in the North-Central Pacific. Obviously, unless the transosonde positioning is much worse than believed, an improvement in data coverage at upper levels over the North Pacific appears most desirable.

3. ANALYSIS ERRORS AND NUMERICAL FORECASTING

Numerical forecasts are particularly sensitive to details of the analysis because second or higher order differentiations of the pressure field are frequently required. The effect of data density on numerical forecasts has been considered by many authors. One of the more recent discussions along this line appears in a study issued by the U.S. Weather Bureau [1]. In this study it is shown that the forecast wind error almost doubles in passing from a meteorological network with a density of the Atlantic Weather Ship Network to one having a density

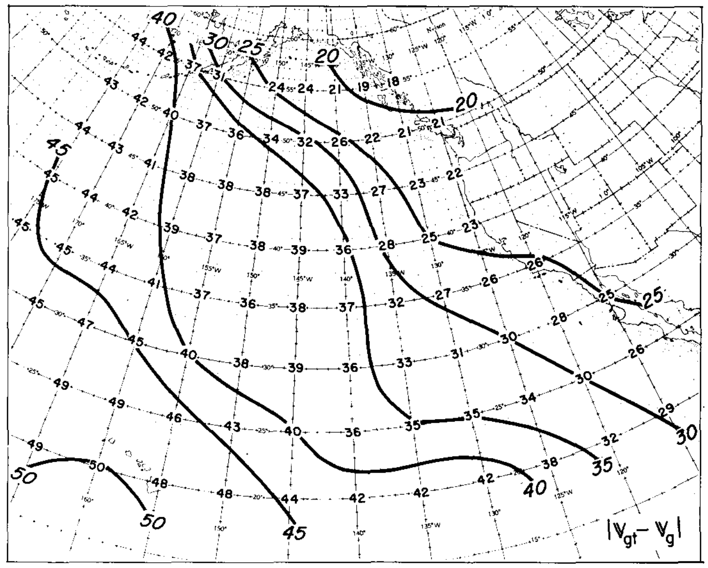

FIGURE 3.—Magnitude of the vector difference (in knots) between transosonde-derived geostrophic wind and NAWAC geostrophic wind at 300 and 250 mb. Data based on FCC-positioned transosonde flights made during the winter of 1956 and during 1957–59.

similar to that found over the North Pacific. The conclusion from this study is that with present numerical forecasting techniques, a reasonable density of upper-air observations is to be found at about the density of the Atlantic Weather Ship Network, namely, one observation every 600–800 n. mi.

No statistics are available on the improvement in numerical forecasting which would have resulted from use of transosonde winds throughout the period of operational flights from Japan during 1957–59. Such statistics would be difficult to obtain because the 500-mb. map is the basic map for barotropic forecast purposes and yet the transosondes were flown at 300 and 250 mb. However, as a suggestion of the improvement in numerical forecasting which would result from an increase in the amount of upper-air data over the North Pacific, figure 4 shows a vorticity analysis over the northeastern Pacific derived from a NAWAC map analyzed without knowledge of the transosonde wind (fig. 4a) and a vorticity analysis derived from a reanalysis utilizing the transosonde-derived geostrophic wind (fig. 4b). With the somewhat unconventional assumption that the vorticity maximum is advected with the speed and direction given by the space-mean contours at the initial point of vorticity maximum [2], figure 4a shows that the vorticity maximum associated with the low center is advected nearly straight eastward to position ①. In figure 4b, however, the strong transosonde-derived north-northwest wind at a more southerly latitude forces a southward extension of the trough and introduces a vorticity maximum near the bottom of the trough partly due to the large cyclonic shear introduced by the reanalysis (difluent trough). The

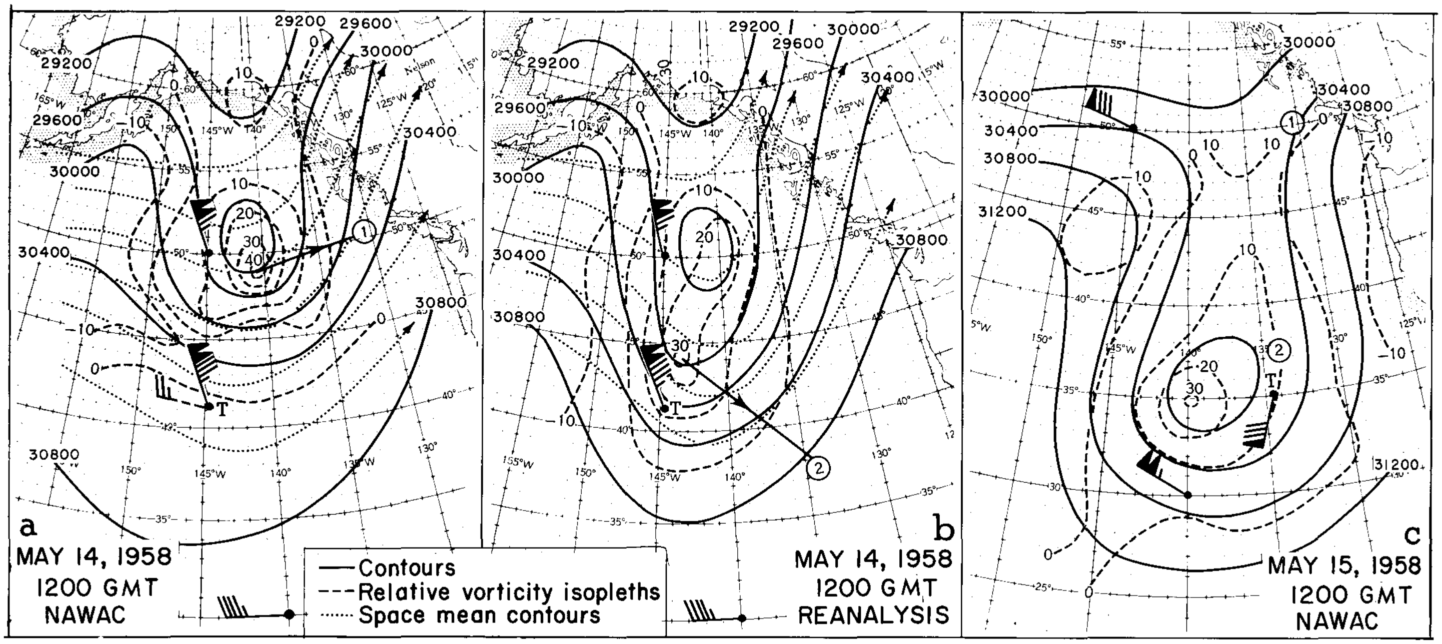

FIGURE 4.—Wind derived from transosonde flight 122 and maps at 24-hour intervals. Otherwise see legend for figure 1, and note the addition of relative vorticity isopleths in arbitrary units (dashed lines) and of space-mean contours (dotted lines). The circled numbers show the points to which the vorticity maxima are advected by the space-mean flow (see text).

space-mean flow is altered sufficiently by the increase in trough amplitude so as to indicate a southeastward advection of this vorticity maximum to position ②. Figure 4c shows the comparison among positions ① and ② and the position of the vorticity maximum 24 hours later as determined from the 300-mb. NAWAC map. Although far from perfect, the vorticity displacement derived from the reanalysis is much superior to the displacement derived from the original analysis. This gives an inkling of the importance for the proper evaluation of vorticity and vorticity advection (and hence the importance for numerical forecasting in general) of additional upper-air data over the North Pacific.

4. ANALYSIS ERRORS AND AIRCRAFT DISPATCHING

Of importance in aircraft dispatching is not the error in contour analysis at a particular point but the error in analysis integrated along the aircraft route. While in the past, forecast errors have been the main source of errors in estimated flight time, as aircraft increase in speed the analysis itself will become of ever increasing importance.

In order to estimate the effects upon aircraft flights of contour analyses based upon sparse upper-air data, the differences between transosonde-derived geostrophic winds and NAWAC geostrophic winds in directions normal and tangential to the mean flow were determined at 12-hour intervals from individual transosonde flights over the northeastern Pacific, and the algebraic difference as a function of travel time was evaluated. In figure 5 the means of these differences as a function of travel distance are expressed as percentages of the difference between transosonde-derived geostrophic wind and NAWAC geostrophic wind at a point. The curve in figure 5 fits both components fairly well and states that over the northeastern Pacific the component analysis error over the distance L is approximately given by the product of the analysis error at a point and e^{-L}, where L is in units of 3,000 n.mi. An exponential form for the curve is not surprising in view of the relatively random nature of analysis errors.

On the basis of figure 5 it would be estimated that, because of the analysis errors resulting from insufficient upper-air data, over the North-Central Pacific a plane

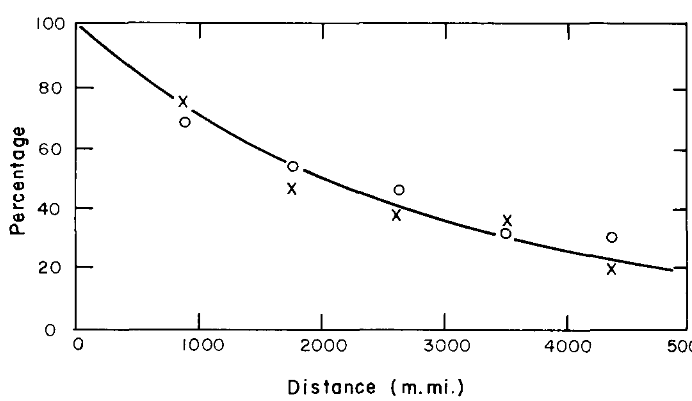

FIGURE 5.—Variation with distance of the average difference between 300- and 250-mb. transosonde-derived geostrophic wind and NAWAC geostrophic wind, expressed as a percentage of the spot difference between these winds. The circles and crosses represent differences tangential and normal to the mean flow, respectively, while the curve gives an analytic approximation to these values.

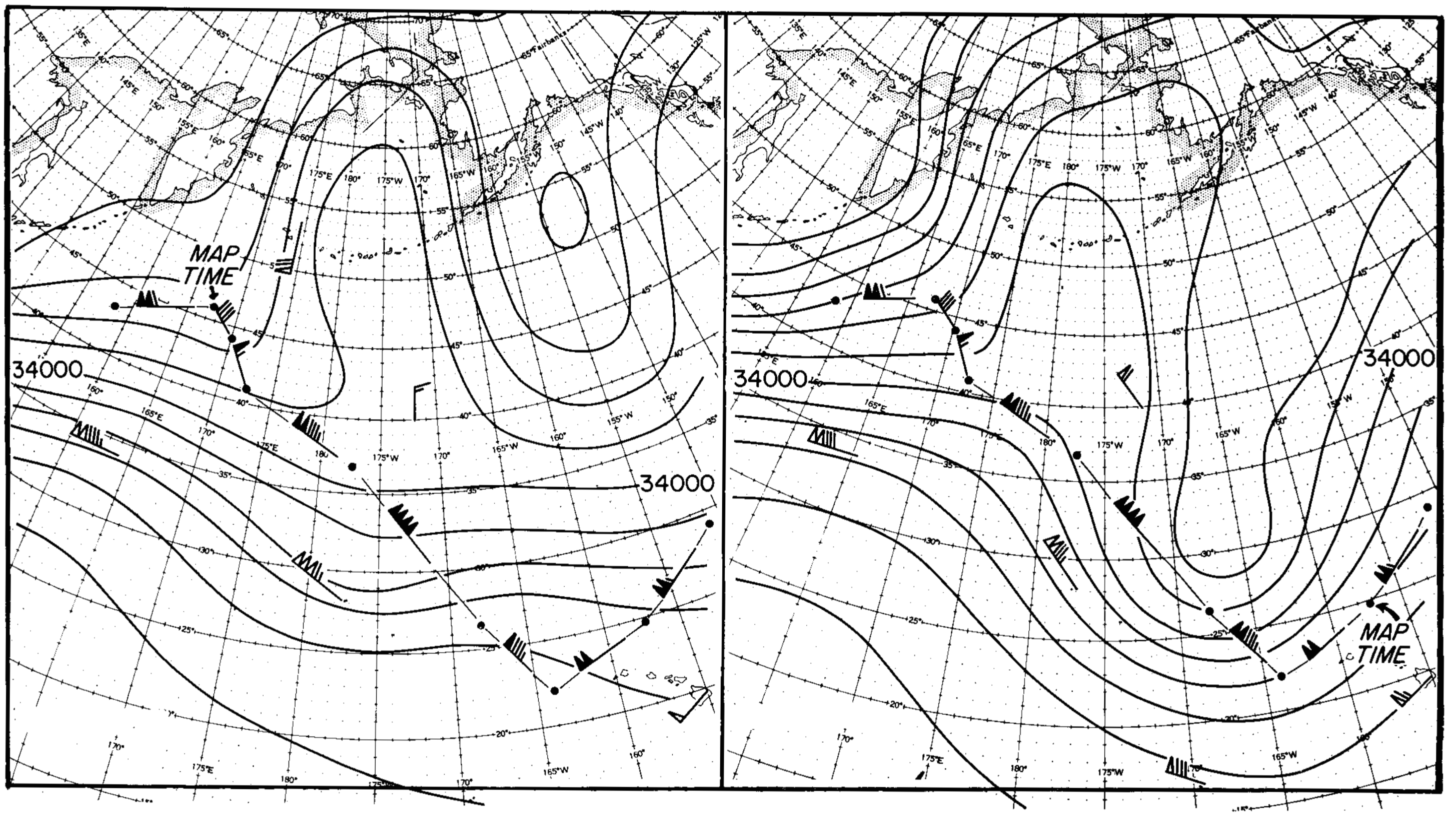

FIGURE 6.—Portion of the 250-mb. trajectory of transosonde flight 202 plotted on NAWAC maps 24 hours apart. Transosonde positions and winds (solid wind barbs) at 4-hr. intervals, contours at 400-ft. intervals.

flying at a speed of 200 kt. over a 1000-n.mi. route would, on the average, mis-estimate its time of arrival by 46 minutes, or 15 percent of the expected flight duration, whereas a plane flying at this same speed over a 3,000-n.mi. route would mis-estimate its time of arrival by 77 minutes or 9 percent of the expected flight duration. On the other hand, for a jet plane flying at 500 kt., on the average the respective mis-estimates would be 7.5 minutes, or 6 percent of the expected flight duration, and 12.2 minutes, or 3.4 percent of the expected flight duration. It would appear from this that the development of jet aircraft has considerably lessened the need for increased upper-air data over the oceans. It must be remembered, however, that owing to their greater rate of fuel consumption the time element is more critical in the case of jets. Thus, although the overall effect is not clearcut, it is likely that even in the case of jet aircraft the obtaining of additional wind data over the ocean would permit the aircraft to depart with greater payload and less fuel reserve, a matter of monetary import.

5. ANALYSIS ERRORS AND TRAJECTORY ESTIMATIONS

The estimation of air trajectories has been an important facet of many meteorological investigations, but with the resumption of nuclear testing this estimation becomes of critical importance in determining the direction of travel of radioactive debris. A perusal of transosonde data shows some large differences between geostrophic trajectories based on the conventional NAWAC analyses and the transosonde trajectories themselves. The discrepancies are largest when a circulation split exists to the east of Japan associated with a blocking situation. For example, figure 6 shows that at map time on January 17, 1959, the transosonde appeared to be firmly embedded in the circulation branch which goes north over the Bering Straits. However, the transosonde decelerated, turned sharply southward, and then almost immediately accelerated as it became embedded in the circulation around the trough to the east of the Central-Pacific ridge. Far from going north over the Bering Straits, the transosonde reached the latitude of Hawaii. In order to explain this trajectory geostrophically, the ridge would have to be transformed into a closed High with an unusually strong pressure gradient. Consequently, it appears likely that in this case a geostrophic flow was partly responsible for the surprising direction of travel of the transosonde balloon. Regardless of which effect predominated, this example points up the trajectory inaccuracies likely to result from the use of contour analyses based on the amount of upper-air data now available over the North Pacific.

Table 1.—*Advantages and disadvantages of alternative methods for obtaining upper-air data in oceanic regions*

Method	Advantages	Disadvantages
Weather ships	1. Tried and true system. 2. Also used for search and rescue, aircraft positioning, etc.	1. Very expensive. 2. Data occasionally lacking in stormy conditions.
Instrumented merchant ships	1. Quite cheap. 2. Conventional data obtained.	1. Suitable rawinsonde equipment not yet available. 2. Gaps in data coverage due to existing ship routes.
Aircraft reconnaissance	1. Data density may be made a function of meteorological activity. 2. Meso-scale type analysis possible as well as direct cloud and turbulence estimates, etc.	1. Quite expensive and some danger to personnel. 2. Non-synoptic observations obtained.
Instrumented commercial aircraft	1. Very cheap. 2. Data obtained at aircraft flight level with no danger to aircraft. 3. Direct cloud and turbulence estimates, etc.	1. Suitable automatic Doppler wind equipment not yet available. 2. Commercial operators may object to weight of equipment. 3. Gaps in data coverage due to existing aircraft routes.
Horizontal sounding system	1. Worldwide capability. 2. Representative winds obtained under all conditions. 3. Ageostrophic flow estimated directly. 4. Vertical velocity estimations from temperature changes. 5. Divergence, vorticity, and deformation obtainable from balloon triads. 6. Direct trajectory estimations.	1. Hazard to aircraft. 2. High cost of suitable positioning system. 3. Problem of overflying foreign nations. 4. Pressure-height data not obtainable. 5. Non-synoptic observations obtained. 6. Data limited to few heights.

6. THE AUGMENTATION OF UPPER-AIR DATA AND THE PRESENT AND FUTURE STATUS OF THE HORIZONTAL SOUNDING SYSTEM

We have shown that the sparsity of upper-air data over the North Pacific results in analysis errors which have a detrimental effect upon numerical forecasting, aircraft dispatching, and trajectory estimations. Presumably, the same deleterious effect is to be noted in other sparse-data regions of the world. Several methods for obtaining meteorological data in such regions exist, each of which has its advantages and disadvantages. A comprehensive examination of these methods has been provided in [1], including an imaginative objective scheme for evaluating the merits of the various methods with particular reference to the North Pacific. Table 1 gives the main advantages and disadvantages of the various methods as seen by the writer. Note that the horizontal sounding system has more advantages and disadvantages, as befits its controversial status. It should be noted also that an instrumented merchant ship program is in existence in the North Pacific and is being expanded. The writer is not in a position to provide a critique of the first four methods or alternatives in table 1. However, perhaps a summary of the present state of development of the horizontal sounding system, and some suggestions for future development, would not be out of place here.

Historically, the U.S. Navy transosonde program is the only example of the large-scale use of a horizontal sounding system for purely meteorological purposes. The 600-pound balloon system used in these operational flights from Japan is no longer satisfactory because of the ever greater heights at which commercial aircraft fly and the potential danger to aircraft of such a heavy balloon system. For several years now a transosonde system has been under development which makes use of a superpressured Mylar balloon to maintain flight along a constant density surface, thus doing away with the heavy ballast system [3]. For this new system the instrumentation is divided between two 6-pound packages, but even this weight is marginal as regards aircraft hazards. The flight duration to be achieved with this system is unknown since the development flights from the east coast of the United States have purposely been terminated west of Europe, but a duration of 1–2 weeks is reasonable. The cost of balloon and attached instruments is about $1,000, but the cost of FCC positioning increases the cost of the system tremendously ($40 per position fix). Thus, at the present time the transosonde system is stalemated owing to (1) the problem of aircraft hazard, (2) the high cost of tracking and positioning, and (3) the inability to fly over foreign nations. Let us consider how these obstacles might be overcome.

The aircraft hazard problem will probably be solved to everyone's satisfaction only by the development of an extremely lightweight system. With recent advances in miniaturization of electronic components an extremely lightweight system appears feasible. Even storage batteries can now be reduced to negligible weight. The ultimate in this concept is the 2-dimensional electronic configuration which is the basis of the GHOST project [4]. The problem of positioning cost could be resolved, in a fashion, by utilizing successive rangings from a satellite or satellites to position the balloon. This method would also provide more accurate fix data than now available and would immediately give a worldwide capability to the system. As discussed by Lally [5], such a satellite-satellite system appears feasible but would require considerable time and development money. Even if planning started now, results from such a system could not be expected before 1966 or 1967. With regard to flying over foreign nations, if these nations remain adamant against such flights, two possibilities are to launch from Japan and terminate the flights west of Europe, or use the capability provided by the satellite and fly the balloon in the Southern Hemisphere. The termination of Japanese flights west of Europe, while increasing the cost of the system per unit of data obtained, would provide the oceanic data so much desired. The usefulness of a Southern Hemisphere horizontal sounding system is now under study.

6. CONCLUSIONS

With the present upper-air data coverage, analysis errors over the North Pacific at 300 and 250 mb. are of significance both on individual days and in the mean. However, the improvement in analysis and forecasting resulting from an increase in data must be balanced against the cost of obtaining the additional data. One of the alternative methods for obtaining additional upper-air data is the horizontal sounding system, highly controversial both because it implies an abrupt break from the conventional vertical-sounding technique and because it represents a large development effort costly in time and money. Inasmuch as a satellite-positioned horizontal sounding system of no hazard to aircraft now appears feasible, the question to be resolved is whether the advantages of such a system outweigh the disadvantages to a degree compatible with the cost and effort necessary to the establishment of such a program.

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