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# On the Impact of Radiometric Sounding Data Upon Operational Numerical Weather Prediction at NMC

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## I. Introduction

Atmospheric temperature soundings derived from the radiance measurements obtained by satellite first entered the operational data base at the National Meteorological Center (NMC) in 1972. Despite high expectations of both data producers and users, however, the promise of global, reasonably high quality data leading to increased accuracy of forecasts has not yet been realized. To date, there simply has been no convincing demonstration that satellite soundings produce a significant, beneficial effect upon operational numerical weather prediction in the Northern Hemisphere. The purpose of this paper is to review and explore reasons for NMC's disappointing experience with radiance derived sounding data. The next section summarizes results of the principal tests conducted at NMC to assess the impact of satellite soundings, while the third section offers a set of five possible explanations for those results. Finally, the main conclusions are summarized in section four.

## II. A Review of NMC Impact Tests

Thus far, there have been two major experiments explicitly designed to assess the impact of radiometric sounding data upon NMC's analysis and forecast system: i) the VTPR test conducted in 1973, and ii) the recently completed experiments conducted in conjunction with the NASA Data Systems Test (DST-5).

### VTPR Test (Bonner, et al, 1976)

In this test, two sets of numerical analyses were produced for a 30 day period in March and April 1973. The operational, or A-mode, analyses incorporated radiosonde observations, aircraft and ship reports, cloud-tracked winds, VTPR temperature retrievals and "bogus" reports. The parallel set of analyses, or B-mode, included the same data base, except VTPR soundings were omitted and a different set of bogus was utilized. The B-mode bogus differed from that produced operationally for A-mode in that it was generated without benefit of VTPR observations.

A- and B-mode analyses were produced utilizing the same procedures and codes, the method of analysis based upon the successive correction technique (Cressman, 1959) with the first guess provided by the Shuman and Hovermale (1968) 6-layer primitive equation model. The update interval was 12 hours. For 9 days when relatively large differences appeared between A- and B-mode analyses, 6-layer forecasts from 0000 GMT were made to 48 hours. Comparison of the differences between analyses and between the forecasts generated therefrom constitute the impact test. Note that inclusion of separate bogus data in A- and B-modes makes it difficult to assess the direct impact of VTPR data. However, since B-mode bogus was produced without knowledge of the satellite soundings, the experiment as designed does answer the fundamental question of what has been gained operationally through use of the VTPR data. That is, the B-mode simulates the system as it would have existed if there were no VTPR reports.

Despite the presence of an average of about 100 VTPR reports over the Northern Hemisphere (e.g., see Fig. 1) in each operational analysis, results indicate that differences between A-mode and B-mode 500 mb height analyses averaged only about 15 m in the Atlantic and 25 m in the Pacific. These differences are less than errors in a typical 12 hour forecast and probably not much larger than differences one would expect from bogusing alone. Large differences were observed only in one instance, and in that case the differences were largely due to A-mode bogus reports.

Overall, the sample of 9 forecast days shows a slight improvement in forecast skill in 36- and 48-hour forecasts of heights, winds, and height gradients over North America from use of VTPR data. Differences, though, are in the order of only a few meters in root-mean-square height error, a few tenths of meters per second in 300 mb wind error and about 1 percent in S1 score. Such differences are neither meteorologically or statistically significant. Forecast verifications over Europe, the eastern Atlantic, and eastern Pacific show a similar lack of impact from use of VTPR data.

DST-5

The most recent impact test conducted at NMC has been in conjunction with the NASA GARP Data Systems Test (DST-5). For the period 18 August - 4 September 1975, parallel sets of analyses were generated with and without the soundings obtained from the operational VTPR instrument aboard NOAA-4 and the experimental infrared (HIRS) and microwave (SCAMS) instruments aboard Nimbus-6. Data available to both satellite and no-satellite modes consisted of the conventional observations available routinely at NMC, plus data obtained especially for the DST, including cloud-tracked winds derived at the University of Wisconsin and TWERLE constant level balloon data. No bogus was utilized in either mode. Figure 2 typifies the data coverage during DST-5.

It should be noted that the Nimbus-6 sounding system is considered the most sophisticated orbited to date and, indeed, is the prototype of TIROS-N operational system programmed for 1978 and beyond. Of particular import is that, unlike VTPR, the microwave sounder of Nimbus-6 gives the capability to "see" through clouds, and, therefore, the Nimbus-6 system provides soundings in the most meteorological active regions of the globe.

Analyses for the DST-5 impact test were produced by the Flattery (1970) global spectral analysis scheme with the first guess provided by the NMC 9-layer global forecast model (Stackpole, et al, 1974). Hemispheric forecasts were generated with the NMC 6-layer PE model to 84 hours from the 0000 GMT analyses for 10 days of the DST-5 period. Differences between analyses and the overall gain or loss in forecast skill which result from the satellite data, as with the VTPR test, were assessed both objectively and subjectively.

Results, as exemplified by the plots of System 1 (satellite) versus System 2 (no-satellite) S1 scores shown in Figs. 3 and 4, indicate that the satellite soundings had little, if any, positive or negative impact upon forecasts over the Northern Hemisphere. There were, however, systematic differences between analyses produced with and without satellite data: weather systems, as defined by the height and/or thermal field, were generally weaker, i.e., had less amplitude, in the analyses which incorporated satellite soundings.* This fact is best illustrated by the time traces of eddy available potential energy (AE), a measure of the temperature variance about latitude circles, shown in Fig. 5. As discussed further in Section III, the relative smoothness of features in the satellite mode analyses reflects the inherent tendency of the satellite soundings to underestimate the true variance in the thermal structure of the atmosphere.

## III. Discussion of the Impact Tests

Each of the impact tests discussed above indicate that satellite soundings, contrary to widespread expectations, have no significant impact upon forecasts. The reasons for this must be addressed.

First, we must note that the tests discussed in the previous section were conducted by NMC scientists using NMC analysis and prediction models. The question then arises as to whether the NMC experience is unique, or in agreement with that of other investigations. There is very little to be found in the formal literature on this question. The British conducted an impact test of the VTPR data (Atkins and Jones, 1975) in connection with the withdrawal of U.S. support for the ocean ship stations in the North Atlantic. Their assessment was that "in general the inclusion of satellite data in the objective analyses produced small beneficial effects on the forecasts ..." and that "the operational use of SIRS** data would on the

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* The question of systematic differences of this sort between satellite and no-satellite mode analyses was not explored in the VTPR test.

** Here, SIRS (Satellite Infrared Spectrometer) is equivalent terminology for VTPR (Vertical Temperature Profile Radiometer) whole be beneficial and would not produce any worsening of the forecasts." To the authors' knowledge, this is the only formally published article on the subject of the impact of remote sounding data. There are other, less formal, articles in the form of technical memoranda, progress reports, etc. Halem's group at the Goddard Institute for Space Studies (GISS) has been particularly active in impact testing, but provides mostly informal documentation. Without getting into the details of the GISS tests, our interpretation of their results is that they have generally found the impact to be positive, but very small. Hayden (1976) has also performed some limited types of impact tests, although he used the NMC analysis/forecast system. He has found small, but beneficial, impact of the sounding data.

Thus, there is some disagreement as to whether the sounding data are helpful; but all investigators agree that their impact is quite small. We conclude, therefore, that the NMC experience is not unique.

Ignoring for the moment whether the small impact is beneficial or detrimental, let us focus on the question of why it is small in the first place. The following five reasons may be considered as possibilities:

1. Remote sounding data are of inferior quality
2. Remote sounding data are superfluous
3. Analysis systems are inadequate
4. Forecast models are insensitive
5. Impact tests run on the wrong cases.

This list is probably not exhaustive.

Data Quality

A debate over the quality of the remote sounding data has continued for years. The central difficulty is the lack of "ground truth." In most examinations of remote sounding data quality, retrievals have been paired with nearby radiosonde reports, a sample of such pairs collected, and root-mean-square differences at standard levels are calculated. The result is usually referred to as the "error" of the remote sounding data. Developers and advocates of the remote sounding data rightly complain of unfairness here, since it is well known that not only do the radiosonde reports contain errors, but the natural variance across the colocation "window" in space and time is contained in the "error" attributed to the remote sounding data. Furthermore, it is argued that a sounding retrieval represents an integrated estimate of temperature over some volume in space, whereas the radiosonde is much closer to a point measurement and therefore contains small-scale variability. Since this small-scale variability cannot be adequately represented in current analysis and forecast models, the argument goes, it should be removed before comparing with the remote soundings.

This argument may be examined by reference to Table 1. In it are displayed root-mean-square differences between approximately colocated remote-sounding (VTPR) and radiosonde temperatures. Both radiosonde and VTPR profiles in each colocated pair were fit by least squares to the same number of empirical orthogonal functions beginning with two functions and increasing to twelve. Of the total difference (averaged over 12 standard pressure levels) of 2.91 degrees, only 25% is accounted for by small-scale variability, represented by modes 5 through 12. These calculations were done for a February 1975 sample of 117 colocated radiosondes and VTPR soundings; they have not been repeated for the Nimbus soundings, which presumably have greater vertical resolution.

Most of the RMS difference between remote soundings and nearby radiosondes is therefore attributable to a mixture of errors in measurement of the large-scale variability of the atmosphere by both satellite and radiosonde, and natural variability across the colocation window. It is exceedingly difficult, if not impossible, to separate the contributions from these sources. Further pursuit along these lines is not profitable.

It is somewhat more instructive to examine some other characteristics of the remote sounding data. In particular, evidence is accumulating which suggests that the remote sounding system is a "conservative" observing system: that is, it consistently underestimates the amplitudes of weather systems.

Recall from discussion of the DST-5 impact test that weather systems systematically have less amplitude in the analyses which incorporate satellite soundings than in those from which the satellite data is excluded. A key question is whether these systematic differences truly reflect an underestimate by the satellite data of the actual variance in the thermal structure of the atmosphere. A priori, an alternative hypothesis is that the greater amplitude (or AE) in the analyses excluding satellite soundings is artificially introduced over data spase regions through the forecast providing the first guess. Inclusion of satellite information, it might then be argued, reduces the AE to values more closely approximating the true state of the atmosphere.

Results of an experiment which addresses the above question appear on Fig. 5. The point labeled "NO SAT/FG" is the AE of the first guess valid 0000 GMT 23 August generated by the 9-layer forecast model from the previous no-satellite mode analysis. As exemplified here, there is characteristically a significant loss of AE in proceeding from analysis to the subsequent first guess.* Clearly, the greater AE in the analyses produced without satellite data is not introduced by the first guess.

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* Most of the loss is likely a consequence of sigma to p interpolations, rather than from the forecast model per se.

In order to ascertain the inherent information content of the satellite soundings, an analysis which utilized satellite soundings but excluded RAOB information was produced for 0000 GMT 23 August from the "NO SAT" first guess. The AE of the resulting analysis is labeled "SYS3" on Fig. 5. One can see that, whereas the analysis produced from conventional data alone ("NO SAT") raises the level of AE from that of the first guess, the analysis generated with satellite soundings (NO RAOB) results in a noticeable loss of AE. In fact, the "SYS3" AE lies at a level comparable to the relatively low value of AE contained in the first guess of the satellite mode analysis (SAT/FG). That is, the information content of the satellite data in terms of AE is approximately that contained in the first guess of the satellite mode analysis, which in turn is considerably less than the satellite mode analysis itself and the first guess of the analysis which excludes satellite data.

Note that the above specifically relates to the information content of the satellite data within the context of the NMC analysis scheme. Hayden* (NESS) has shown, however, that the relative lack of variance exhibited by the satellite data is not model dependent, for a direct comparison between the variance contained in radiosonde versus satellite soundings yields a similar result.

Finally, one can reasonably conclude that the lesser amplitude of systems in the satellite mode analyses represents a systematic degradation in the quality of analyses by the satellite data.

Superfluity of the Remote Sounding Data

It has been fashionable for decades to point to the world's oceans as data-void regions responsible in large measure for the errors in numerical weather prediction. In fact, our experience indicates that the operational data base for the Northern Hemisphere oceans is quite substantial without considering remote sounding data. The combination of surface reports from ships and islands, aircraft reports, cloud-tracked winds, a few radiosonde reports, and subjective "bogus" reports based on cloud imagery permit the large-scale features of the flow to be defined rather well. Moreover, when analysis mistakes are made, a recovery is usually delayed only until the next major observation time, or about 12 hours. The environment into which the remote soundings are introduced is therefore one in which there is much less room for improvement than is generally realized.

To illustrate this, Fig. 2 shows the locations of conventional and satellite observations for 0000 GMT 23 August 1975 (DST-5). Figure 6a and 6b show the 500 mb analyses produced for that time after five days of

* Personal communication

cycling with and without the satellite soundings, while Fig. 6c displays the difference field, SAT-NO SAT. It is clear from Fig. 6c that the difference is not large and, in fact, no differences larger in magnitude occur at any time during the DST-5 period.

Inadequacy of the Analysis Model

The possibility has been raised that the remote sounding data may be badly treated by an analysis system geared to an upper air observing network composed largely of radiosondes reporting each 12 hours. In the experiments discussed in previous sections, three different analysis models were used. For the NMC VTPR impact test of 1973, the then-operational Cressman (1959) model was used. The DST-5 NMC experiments involved a global spectral objective analysis model (Flattery, 1970). The British experiment with VTPR (Atkins and Jones, 1975) used a polynomial-fitting technique developed by Dixon, et al (1972). Significant differences exist between the three systems...the Cressman scheme is a local, successive approximations method, the British method uses local least-squares fitting to polynomial basis functions, and the spectral technique uses series expansion in terms of quasi-orthogonal eigenfunctions...yet tests with all three produced essentially the same null impact of satellite soundings upon forecasts.

Nevertheless, in the spectral objective analysis model now operational at NMC there are deficiencies which could adversely affect the remote sounding data. Most obvious is the 12-hour update interval, which was designed primarily for twice-daily radiosonde observations. Such a long interval is clearly inappropriate for sounding data from polar-orbiting satellites, which are distributed in time as well as in space. Indeed, with a 6-hour "window," and the orbital characteristics of present sounding satellites, it is possible for the objective analysis system to consider swaths of retrieved data nearly adjacent in space but 11-12 hours different in time. During the past year, a 6-hour update interval has been introduced into experimental systems, and will become operational by early 1977. Recently, however, a limited rerun of the DST-5 impact test was performed using the 6-hour update. The results indicate the impact of satellite soundings, or lack thereof, is essentially unchanged from the basic 12-hour update experiment.

Another deficiency of the analysis method is that the data are not systematically given relative weights according to the accuracy of the data. There is a provision currently in the analysis system which gives preference to radiosonde observations over nearby remote soundings. This is a relative weighting system, albeit an indirect one. Recognition of this deficiency in part stimulated the development of a new analysis system based on optimum interpolation. This system offers a more intelligent method of blending data from different sources, and hopefully will result in a more reasonable treatment of the remote sounding data. However, an assumption implicit in the system is that the errors of observations are uncorrelated with the true state of the atmosphere. If, in fact, the remote sounding data consistently underestimate the true variance of meteorological fields, then this assumption is not valid.

Finally, Hayden (1976) has argued that the mass-motion law inherent in the present operational analysis is such that adjustments to the mass field from remote sounding data do not produce commensurate adjustments in the motion field. Data assimilation experiments in recent years have clearly shown that without such adjustments to the motion field, the prediction model will quickly "forget" the adjustment to the mass field. Thus, the impact of the remote sounding data is lost after only a few time steps. This is an area of active interest, and experiments are planned to investigate the problem. It should be noted, however, that if the remote sounding data are consistently deficient in representing amplitudes of weather systems, it is not clear that adjusting the winds to such a mass field is a prudent idea.

In summary, then, the suggestions that the remote sounding data have no impact because of shortcomings of the analysis system have been, or are presently being investigated. The corrections of the deficiencies that have so far been accomplished have failed to change the lack of impact by remote sounding data.

### Forecast Model Insensitivity

Simulation studies (e.g., Williamson, 1973) indicate that the error growth rate in primitive equation models is large. Thus, predictions made from basically the same initial state, but slightly perturbed, deviate from one another with time during the integration. The higher the resolution the more rapid the deviation. Thus Williamson's investigation indicates that higher resolution models are more sensitive to small differences in the initial conditions than are lower resolution models.

The results of impact tests indicate that current prediction models are relatively insensitive to differences in the initial state which characteristically occur through inclusion of remote sounding data. Further, our experience is that a prediction will deviate much more rapidly from the real atmosphere than from a parallel forecast made from a slightly different initial condition. Williamson's work suggests that this is due to inadequate resolution of the prediction model. Operational experience at NMC with higher resolution models tends to support the view that such models are indeed more responsive to differences in initial conditions.

We believe, then, that the insensitivity of the prediction models that have been used in NMC impact tests has been a large factor in the lact of impact of remote sounding data. Clearly, experiments with higher-resolution models are desirable. In the immediate future, limited impact tests will be conducted with the NMC LFM, a limited-area high-resoultion version of the hemispheric six-layer model. Simultaneously, a concerted effort is being made to develop a "frontier" model: i.e., an experimental model of such resolution as to run at the very limit of present computational capability. Impact tests will then be conducted with confidence that the model would be more responsive to changes in the initial state.

### Improper Selection of Cases for Impact Testing

We have suggested in the preceding paragraphs that in the Northern Hemisphere, the combination of conventional data base and insensitive forecast model is sufficient, most of the time, to suppress any impact of the remote sounding data. On occasion, however, lack of conventional data must contribute critically to subsequent failure of the model to predict some significant weather event. It is on these occasions when remote sounding data could be expected to have a greatest impact. In reviewing the impact tests conducted at NMC, we are unable to find a single such case. We believe this difficulty arises merely because such cases are relatively rare, in the Northern Hemisphere. Nevertheless, an effort should be made to isolate and retain such cases for impact testing. Efforts should also be directed toward the impact of the remote sounding data in the Southern Hemisphere, where the paucity of conventional data surely contributes much more significantly to forecast errors.

## IV. Conclusions

The impact of remote sounding data on operational numerical weather analysis and prediction has been minimal to date. This conclusion has been reached by all groups that have reported on the question. Our examination of the impact tests that have been conducted in recent years leads us to conclusions which may be stated as follows:

- The remote sounding data are generally of reasonable quality, but are not as good as conventional data. In particular, the remote sounding data exhibit systematic errors with respect to the amplitudes of meteorological systems;

- Contrary to a widespread impression, the remote sounding data do not fill a data void over the Northern Hemisphere oceans, but compete with a rather extensive conventional data base which is usually sufficient to define the larger features of the mass and motion fields;

- The analysis method presently operational at NMC possesses certain features which do not recognize unique characteristics of the remote sounding data, such as their asynopticity and incompleteness, and is therefore unable to use the data in a completely proper way;

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- The prediction models used in impact testing have invariably been of far too coarse resolution and, thus, insensitive to small nuances of the initial state;

- Most of the time in the Northern Hemisphere it appears that forecast skill scores averaged over a period of time are model-limited rather than data-limited. Occasionally, it undoubtedly happens that initial state errors lead to forecast failures, but such cases are evidently quite rare; and none have been found during the periods of impact testing conducted at NMC;

- The single most important step that could be taken to demonstrate impact of the remote sounding data would be to conduct the impact tests with a very high resolution prediction model, for neither improved data nor analysis models will matter if the prediction model is insensitive to small differences in the initial state;

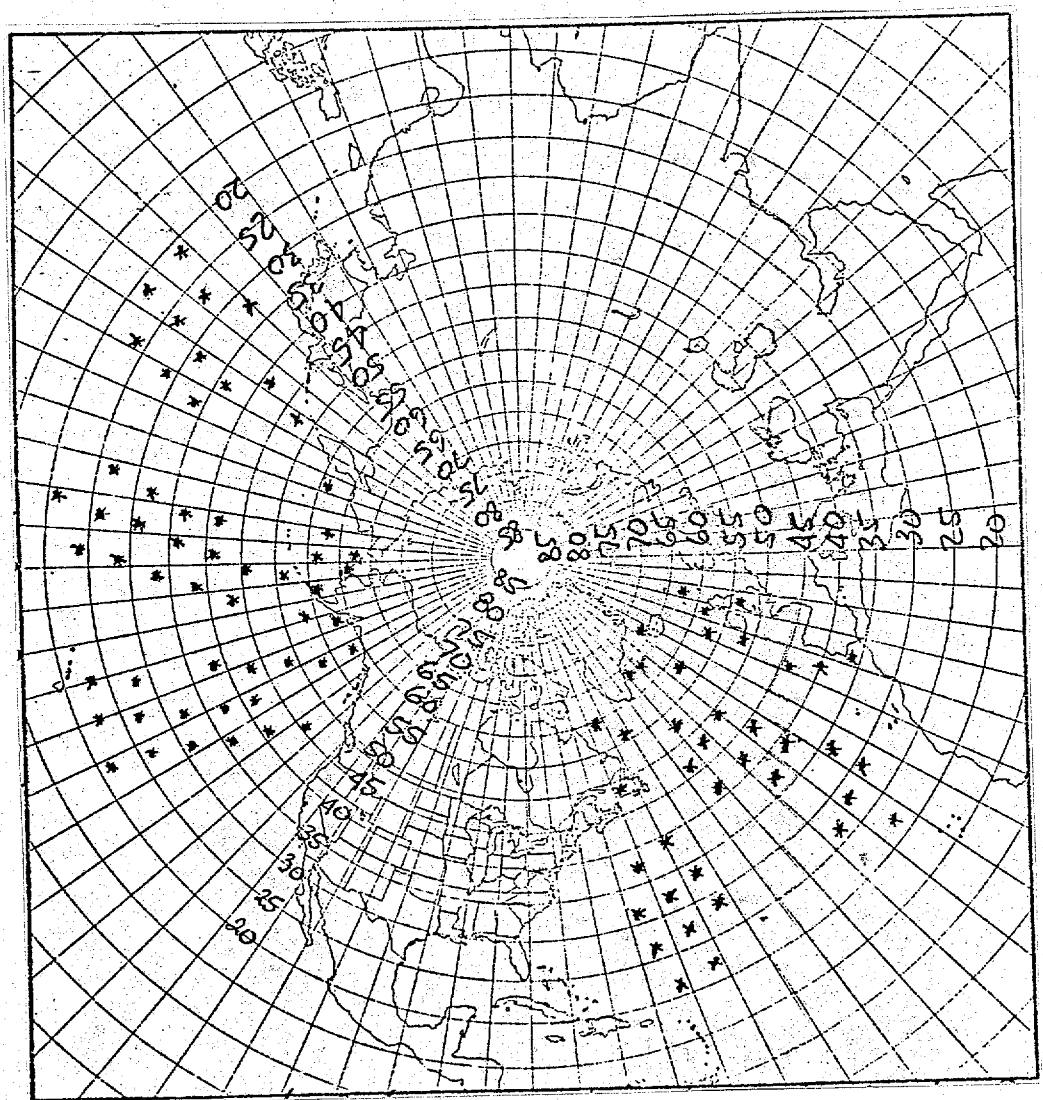
- If the above step were taken today, the likely result would be an impact of the remote sounding data, but a negative one, because of the quality of the data. As the resolution of the prediction model increases, so do the requirements for the accuracy of the data, and the quality of the analysis system.

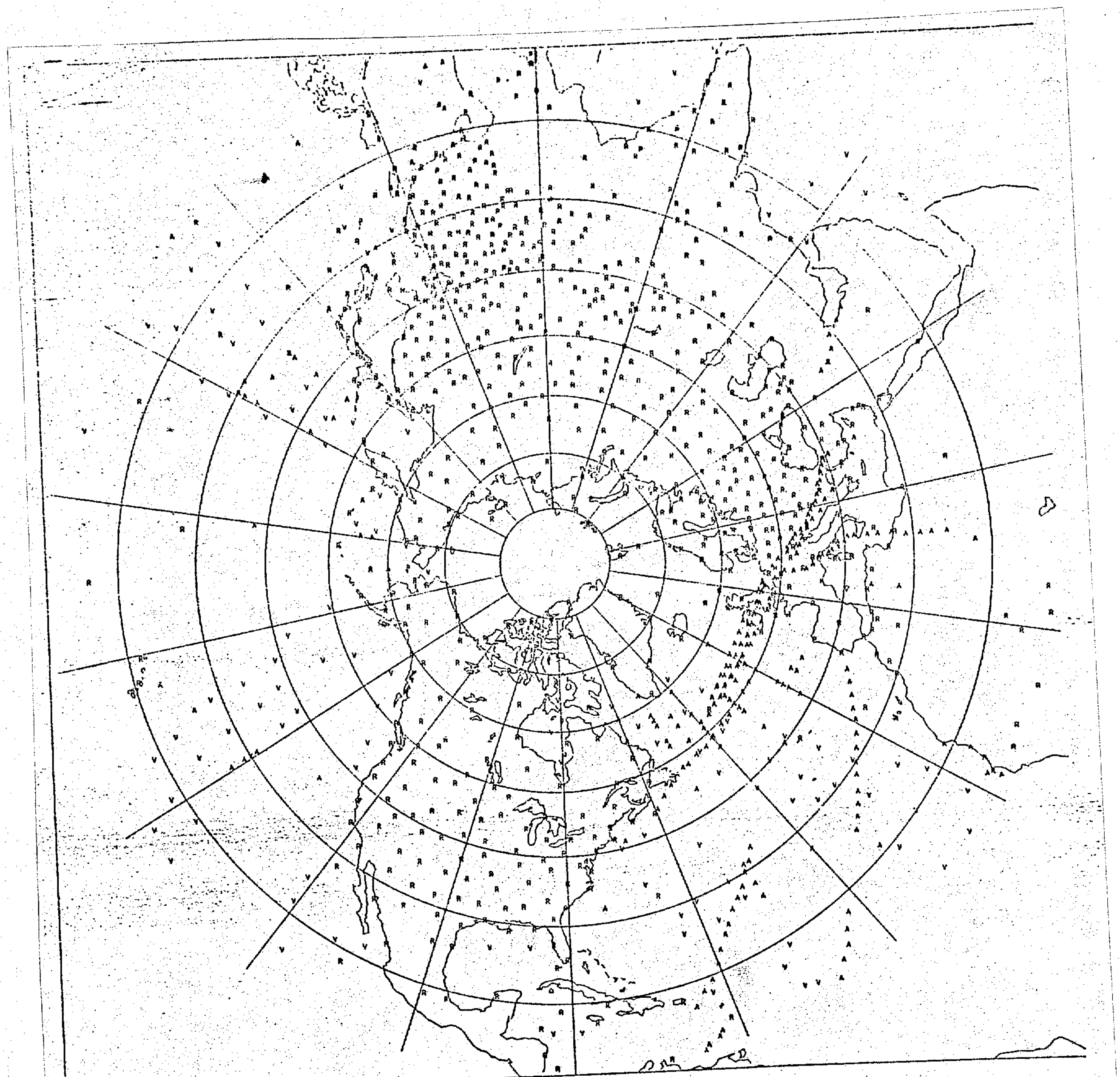
Most of the conclusions expressed here rest upon a foundation of fragmentary evidence; there is no firm, unassailable proof to be found. But the foundation is braced by the fact that the accumulated weight of evidence consistently points in the same direction:

> There will be no impact of remote sounding data in the Northern Hemisphere until the resolution of the prediction model is greatly increased; and in that event the impact will be negative unless the quality of the data is improved.

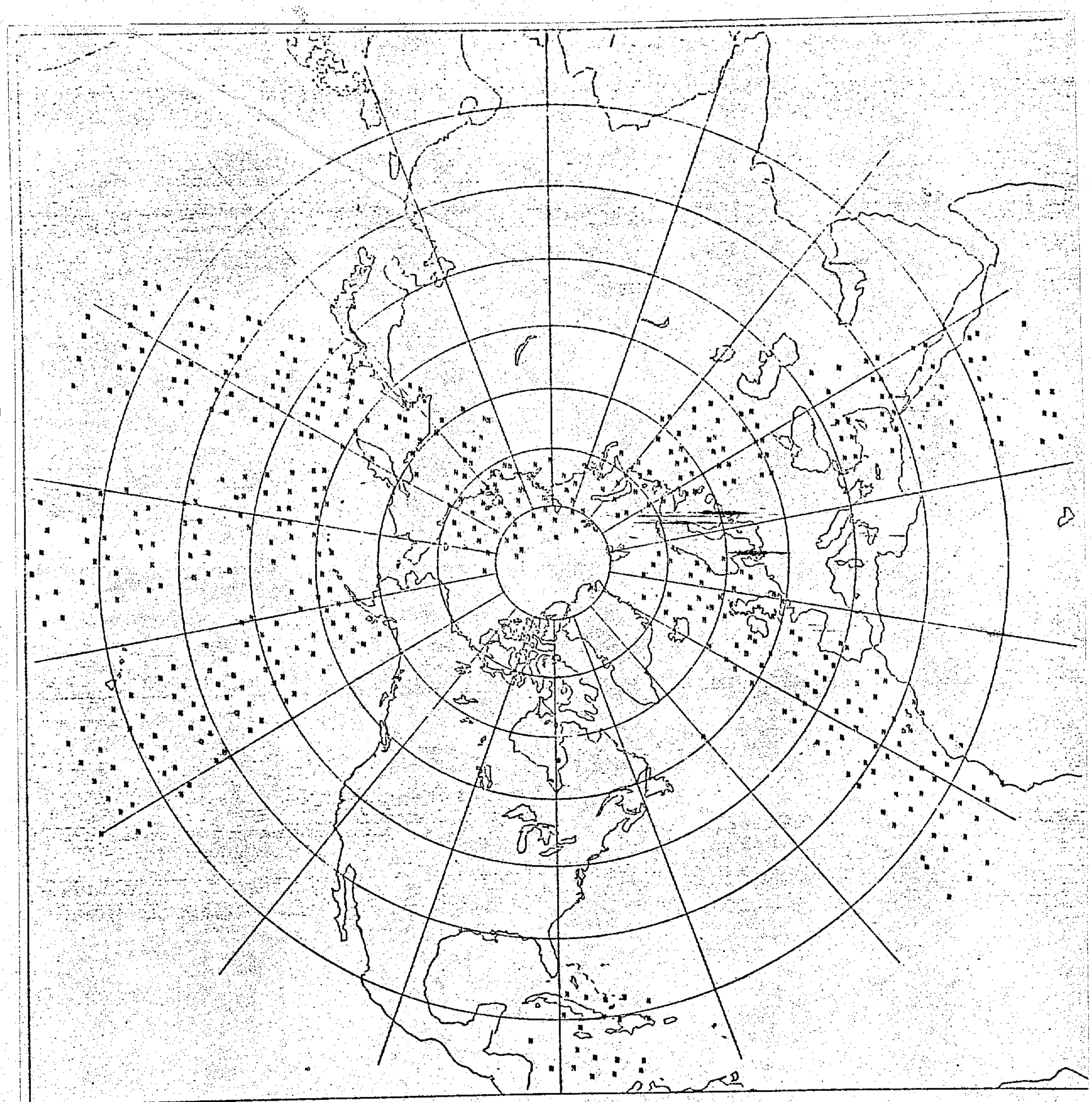
Table 1. RMS differences between VTPR (regression) and radiosonde temperatures as a function of the number of emperical orthogonal functions used to represent the profiles. February 1975 data set.

| | FUNCTION | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LEVEL | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 1000 | 1.79 | 2.99 | 3.06 | 3.10 | 3.15 | 3.14 | 3.18 | 3.19 | 3.26 | 3.25 | 3.26 |
| 850 | 1.48 | 2.31 | 2.41 | 2.44 | 2.76 | 2.72 | 2.77 | 2.76 | 2.97 | 3.03 | 3.04 |
| 700 | 1.48 | 1.64 | 1.84 | 1.89 | 2.42 | 2.37 | 2.36 | 2.66 | 2.62 | 2.79 | 2.81 |
| 500 | 1.74 | 1.73 | 1.98 | 1.99 | 1.99 | 2.15 | 2.20 | 2.52 | 2.53 | 2.24 | 2.81 |
| 400 | 1.84 | 1.89 | 1.95 | 1.93 | 1.96 | 1.93 | 1.93 | 1.99 | 1.95 | 1.93 | 2.01 |
| 300 | 1.83 | 2.01 | 2.02 | 2.02 | 2.04 | 2.27 | 2.34 | 2.56 | 2.61 | 2.66 | 2.66 |
| 250 | 1.58 | 1.78 | 2.29 | 2.32 | 2.33 | 2.94 | 3.03 | 3.02 | 3.02 | 3.05 | 3.14 |
| 200 | 1.43 | 1.53 | 2.24 | 2.24 | 2.51 | 2.48 | 2.56 | 2.80 | 3.27 | 3.31 | 3.34 |
| 150 | 1.61 | 1.65 | 1.64 | 1.73 | 2.24 | 2.63 | 2.59 | 2.44 | 2.42 | 2.45 | 2.44 |
| 100 | 1.95 | 2.27 | 2.62 | 2.75 | 2.97 | 3.14 | 3.12 | 3.22 | 3.22 | 3.21 | 3.21 |
| 70 | 1.74 | 1.89 | 2.07 | 2.64 | 2.72 | 2.79 | 3.07 | 3.13 | 3.13 | 3.14 | 3.15 |
| 50 | 1.56 | 1.62 | 1.62 | 2.03 | 2.21 | 2.21 | 2.73 | 2.70 | 2.75 | 2.75 | 2.76 |
| Overall | 1.68 | 1.98 | 2.18 | 2.29 | 2.47 | 2.59 | 2.69 | 2.77 | 2.84 | 2.89 | 2.91 |





DS<sup></sup>T COVERAGE R=RAOB A=ARCFT S=NESS WND W=WIS WIND V=VTPR N=NIMBUS T=TWERLE
AUGUST 23, 1975 00 Z RAOB, AIRCRAFT, AND VTPR



D: COVERAGE R=RAOB A=ARCFT S=NESS WND W=WIS WIND V=VTPR N=NIMBUS T=TWERLE
AUGUST 23, 1975 00 Z NIMBUS ONLY

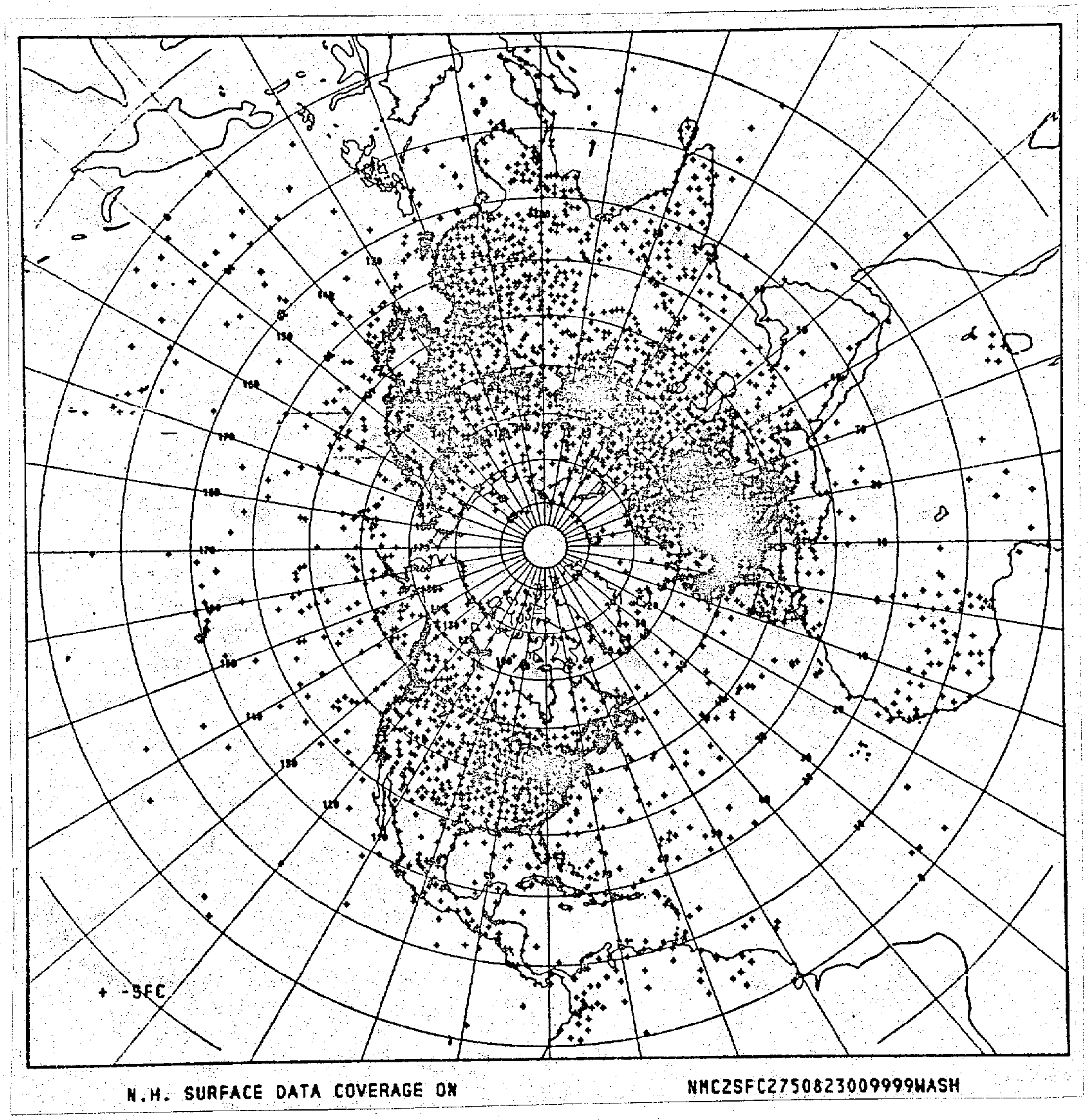

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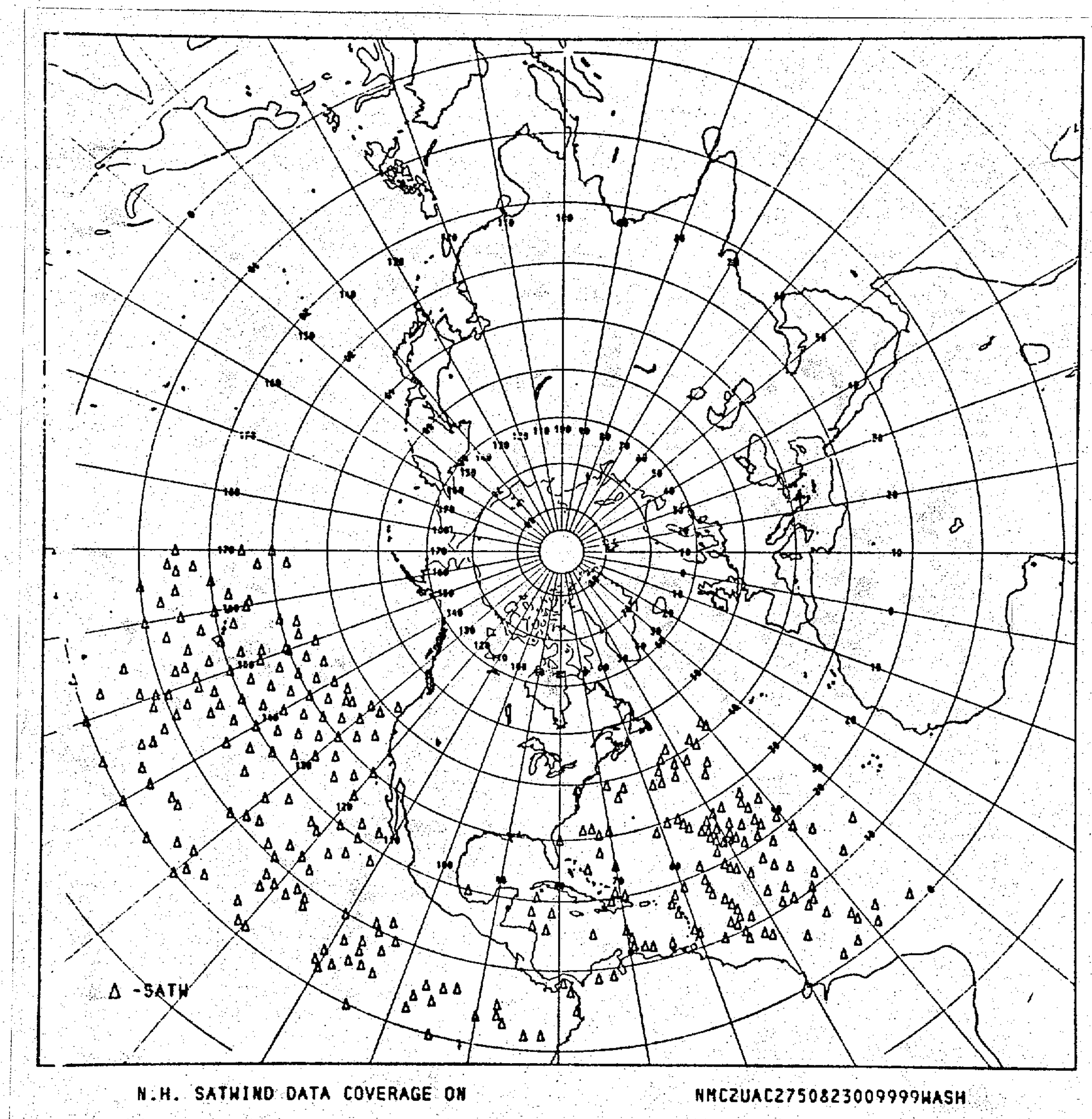
Figure 2c



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N.H. SATWIND DATA COVERAGE ON
NMCZUAC2750823009999WASH


Figure 2d

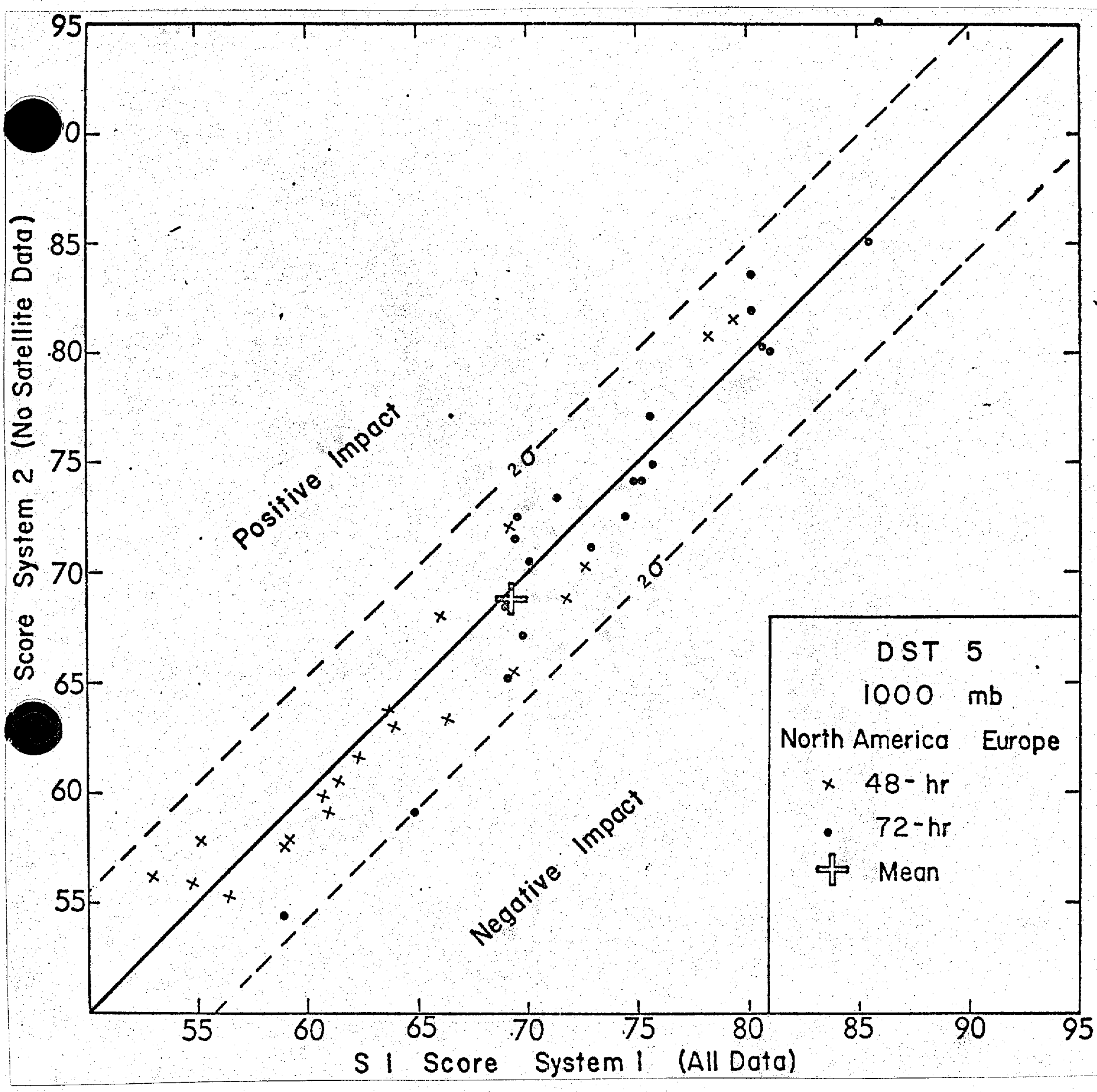


Figure 3. Collective results of 48- and 72-hour forecasts over North America and Europe at the 1000 mb level in terms of plots of the System 1 (satellite) and System 2 (no-satellite) S1 scores. The sigma (σ) of the 2σ lines is the standard deviation of the set of differences between System 1 and System 2 scores.

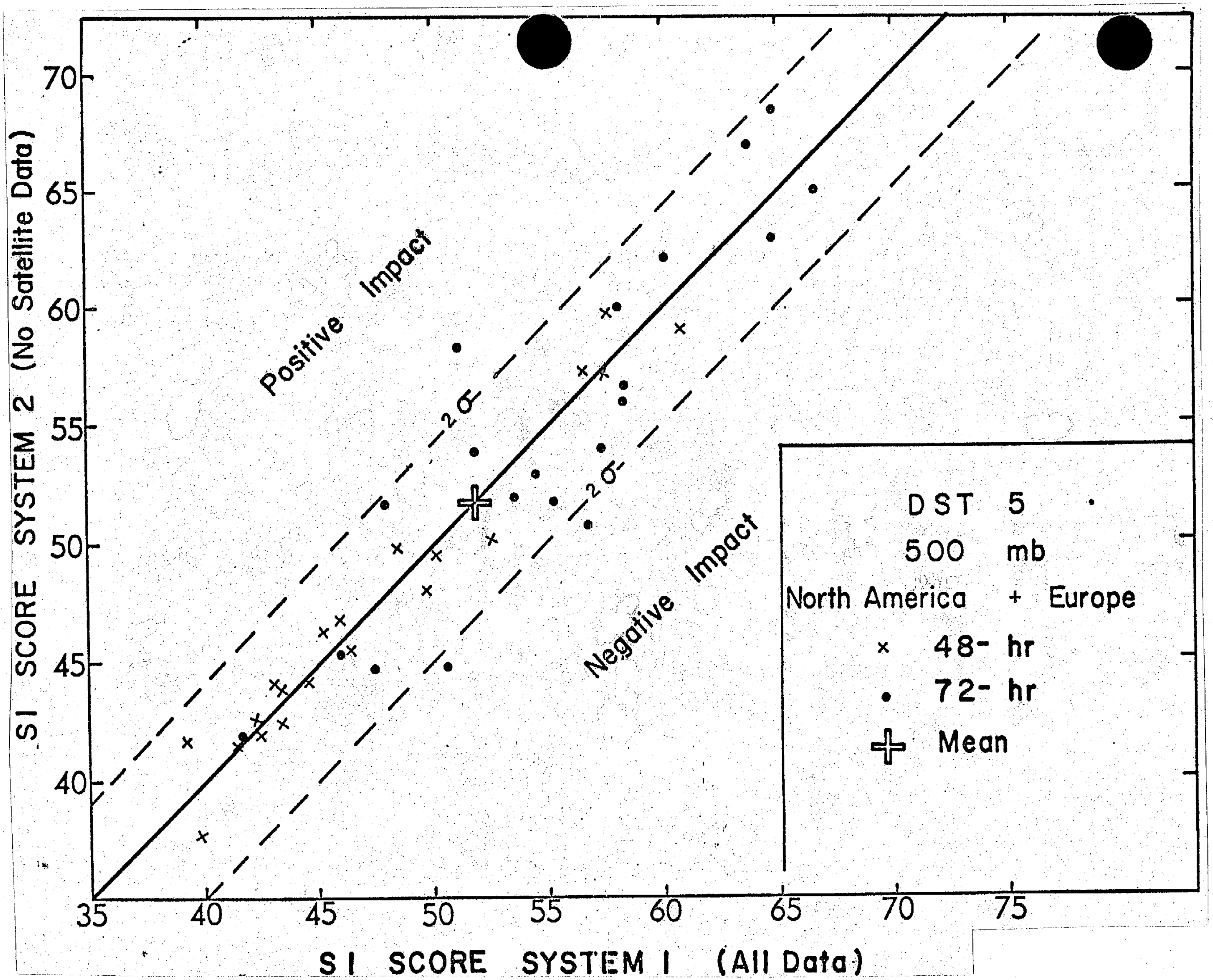


Figure 4. Same as Fig. 3, except for 500 mb.

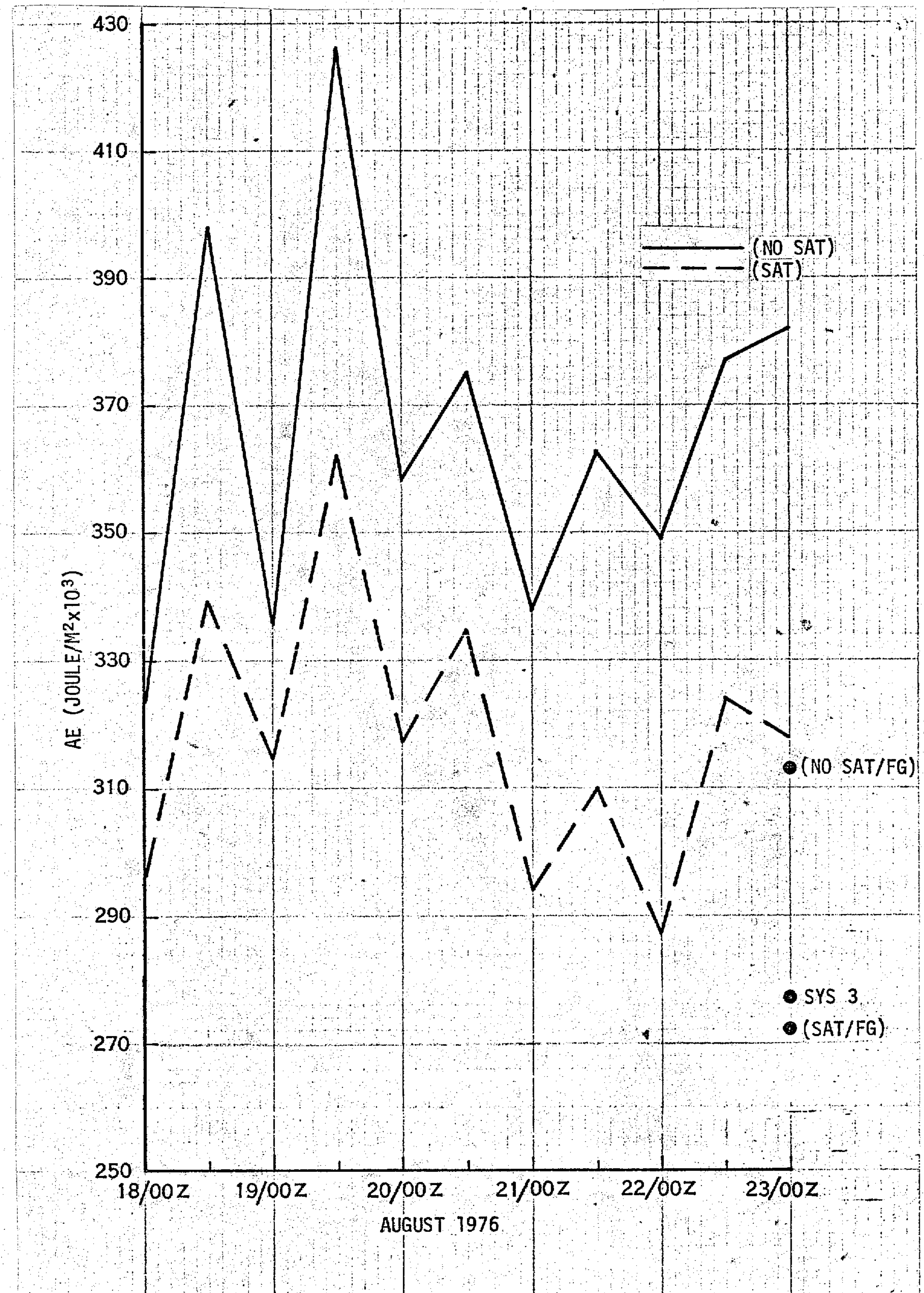


Figure 5. Time trace of eddy available potential energy (AE) for satellite (— — —) and no-satellite (———) mode analyses. AE here is an integrated sum from 20°N - 90°N and from 850 mb - 200 mb. See text for meaning of points plotted for 0000 GMT 23 August.

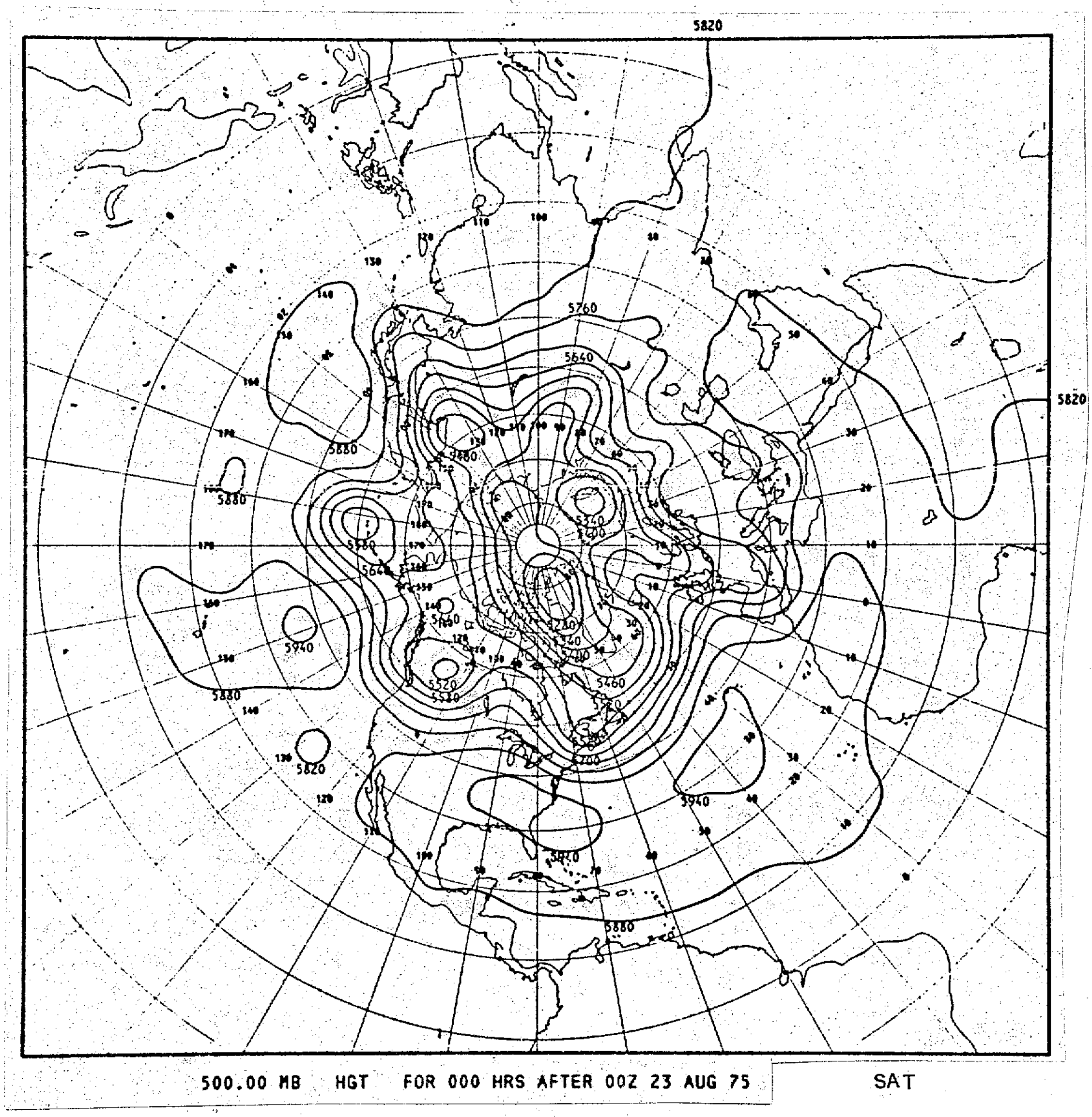


Figure 6a

Figure 6. Satellite (a) and no-satellite (b) mode 500 mb height analyses, and difference field, SAT-NOSAT (c) for 0000 GMT 23 August.

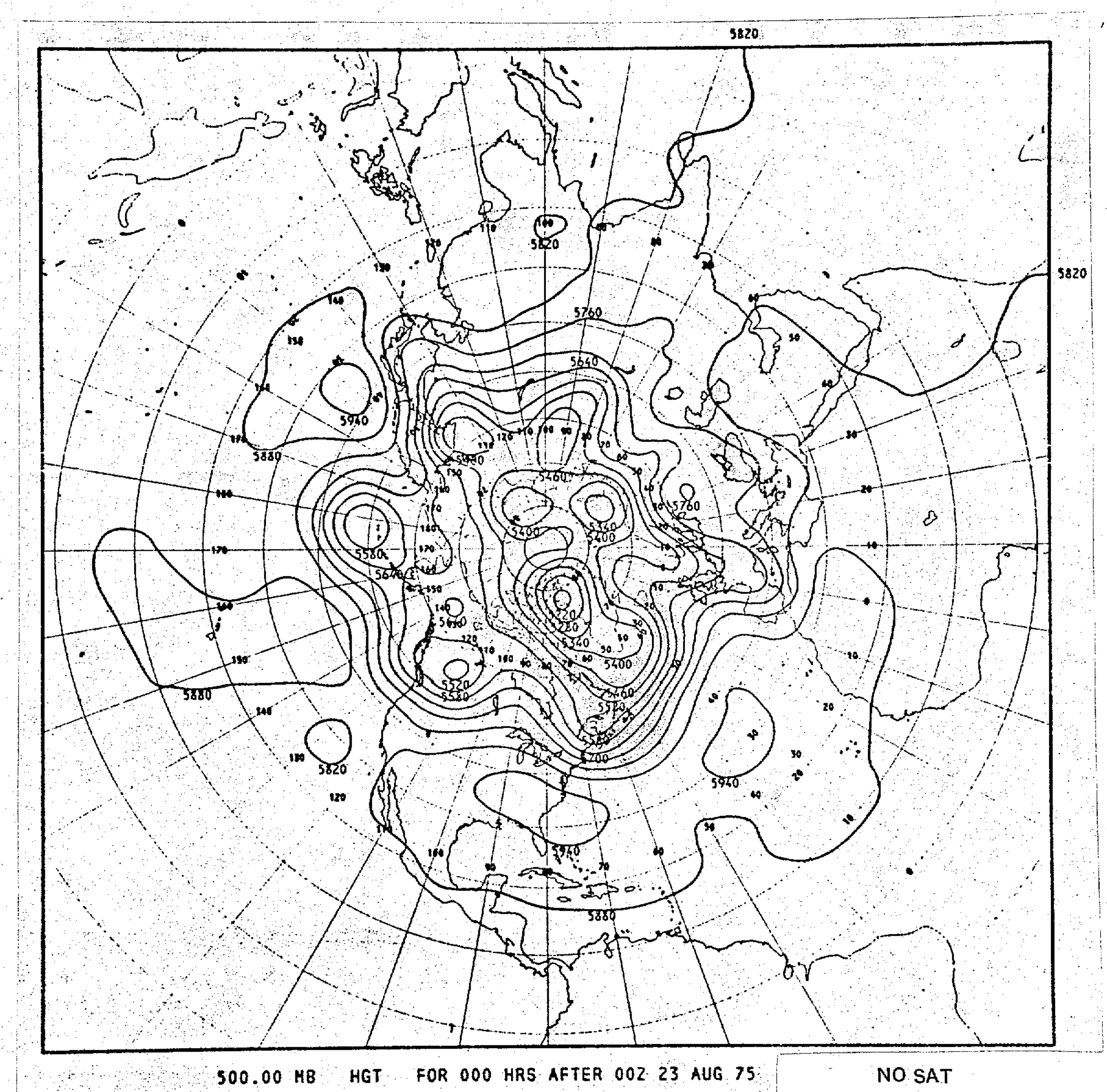
500.00 MB HGT FOR 000 HRS AFTER 00Z 23 AUG 75
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Figure 6b

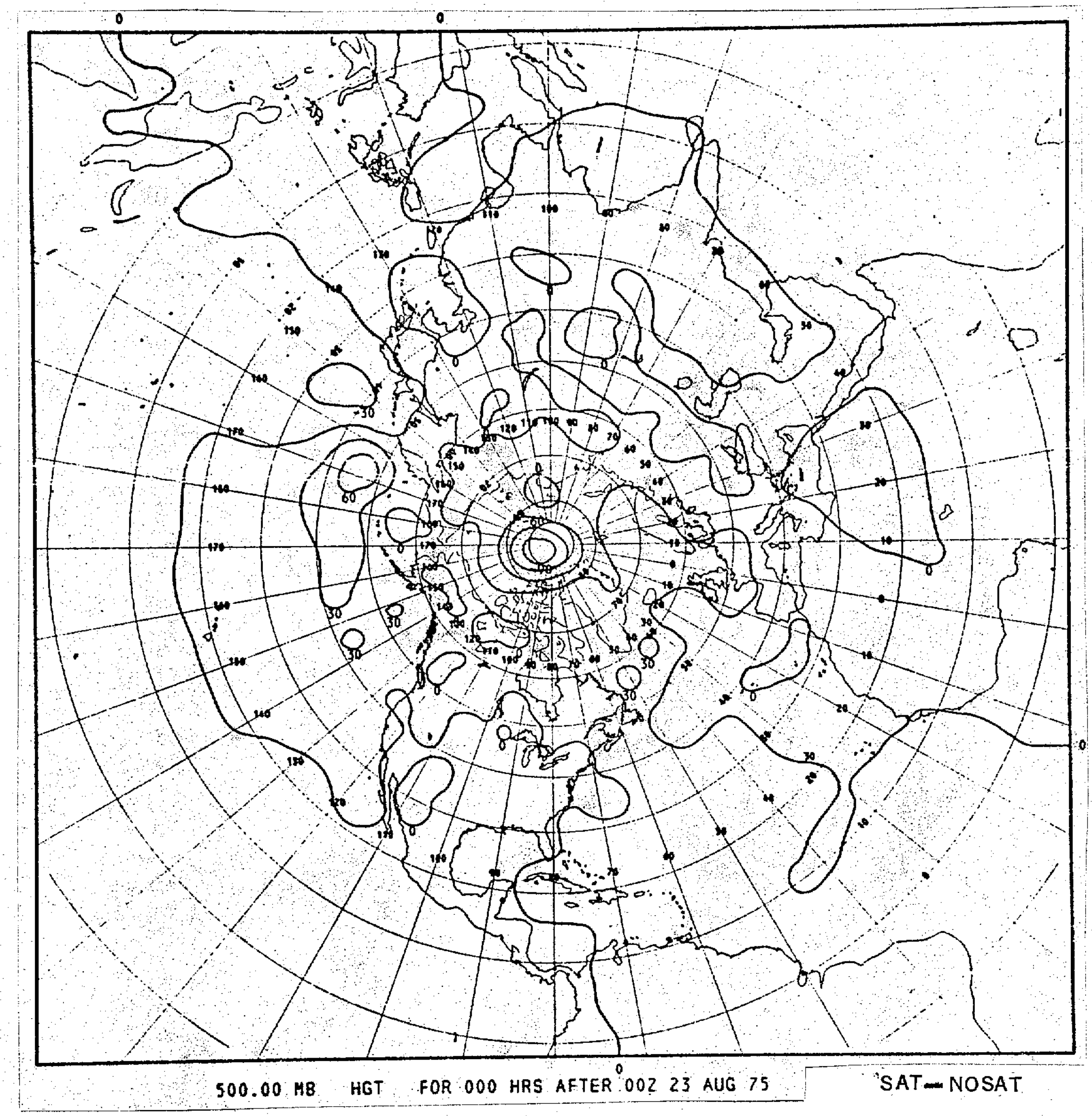


Figure 6c