The Northern Hemisphere Sea-Level Pressure Data Set: Trends, Errors and Discontinuities

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ABSTRACT

A detailed examination of the Northern Hemisphere monthly mean sea-level grid-point pressures shows a disappointingly large number of problems. The data set extends from 1899–1977 but has originated from eight different sources and discontinuities have been identified with every change in source. We have documented corrections for many of these and have also catalogued 3263 serious errors. These have been corrected or set to missing. Most of the errors are over Asia and are predominant before 1922 or during World War II.

Analyses of several different aspects of the data that reveal both the problems and real changes in the atmospheric circulation are presented, along with a comparison of the monthly mean operational U.S. Navy versus U.S. National Meteorological Center analyses. A plea is made for a greater effort in archiving quality controlled climatological data.

1. Introduction

One of the few sets of instrumental data covering a substantial portion of the globe for a long period is the series of Northern Hemisphere daily sea-level pressure grids beginning in 1899. This series has been summarized into monthly means and is potentially useful for investigations into changes in the atmospheric circulation. As made available through NCAR, it consists of grid-point values at every 5° of latitude and longitude from 20°N to the pole, although several values are missing prior to 1946, most notably at high latitudes (see Table 1).

The grid-point data originate from several sources, as shown in Table 1. Unfortunately, these changes in source and the corresponding analysis techniques used have introduced several spurious inhomogeneities into the data set which limit its usefulness. There are also quite a large number of points in error. It is the purpose of this paper to outline the procedures we have used 1) to check for and eliminate errors, 2) to document and remove some discontinuities in the data, and 3) to consider the reality, or otherwise, of long-term trends. We also report on a comparison between the Navy and NMC monthly mean analyses.

Our original version of the data set contained Navy analyses through November 1975 and NMC analyses for December 1975–February 1977, but recently we obtained an update of Navy analyses through 1977. Our original error analysis found many inexplicable errors in the 1970's, and a comparison of the NMC-Navy analyses for the overlap period showed poor agreement. Subsequently, it was realized that the Navy analyses were offset by one grid square of the original Navy polar stereographic grid (~340 km) due to an error in the NCAR computer program that translates from the Navy grid to a latitude-longitude grid. Cross-checks revealed the error was present in all Navy analyses January 1973–November 1975 and accounted for all of the previously unexplained errors found in this period. With the corrected Navy analyses, further comparisons with the NMC analyses were carried out and the entire discontinuity analysis reported here was redone.

van Loon and Williams (1976a,b) used this data set to outline certain changes in the circulation that have taken place this century, and they discovered several flaws in the data. These were further documented by Madden (1976) and Williams and van Loon (1976) but the latter used only seasonal averages in their analysis and warn that their listing of flaws is far from complete. They note that use of seasonal means can mask errors in individual months, and an example can be found in Table 1 and Fig. 4 of Williams and van Loon which indicates that an error occurred in winter of 1906 at and

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1 NCAR is the National Center for Atmospheric Research and is sponsored by the National Science Foundation.

2 NMC (the U.S. National Meteorological Center) operational analyses have undergone many procedural changes and the Navy analyses have been preferred for this data set (Jenne, personal communication). See Fig. 10 for an example of this.
Table 1. Sources of sea-level pressure data grids. All are based on daily analyses except as noted. Continual updates of this series are made from time to time.

<table>
<thead>
<tr>
<th>Dates Year (month)</th>
<th>Source</th>
<th>Comment</th>
<th>Time (GMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 1899(1)–1939(6)</td>
<td>NCC*</td>
<td>Historical map series</td>
<td>(1300)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>75, 85, 90°N missing</td>
<td></td>
</tr>
<tr>
<td>2. 1939(7)–1944(11)</td>
<td>MIT**</td>
<td>85°N missing</td>
<td>(1200)</td>
</tr>
<tr>
<td>3. 1944(12)</td>
<td></td>
<td>All missing</td>
<td>(1200)</td>
</tr>
<tr>
<td>4. 1945(1)–1945(12)</td>
<td>Scripps Institute of Oceanography</td>
<td>Monthly means only</td>
<td>(1200)</td>
</tr>
<tr>
<td>5. 1946(1)–1955(3)</td>
<td>NCC*</td>
<td>Digitized with curve follower and</td>
<td>(1200)</td>
</tr>
<tr>
<td>6. 1960(4)–1962(6)</td>
<td>(Navy contracts)</td>
<td>objectively analyzed by Navy</td>
<td>(1200)</td>
</tr>
<tr>
<td>7. 1955(4)–1960(3)</td>
<td>NMC</td>
<td>433L-ESSPO Project</td>
<td>(0000, 1200)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(hand-drawn analyses)</td>
<td></td>
</tr>
<tr>
<td>8. 1962(7)–1977(12)</td>
<td>Navy</td>
<td>Operational objective analyses</td>
<td>(0000, 1200)</td>
</tr>
</tbody>
</table>

* NCC: National Climatic Center (Asheville, NC).
** MIT: Massachusetts Institute of Technology.

around 65°N, 140°W, whereas in fact the error was not in the grid-point data but rather in the station data they were using for comparison. On close examination, it seems that the pressure at Dawson in December 1906 was coded as 28.06" but should have been 29.06". This brings winter 1906 into line with the other years from 1902–09, but it is nevertheless also clear (as shown by Fig. 4 of Williams and van Loon) that there is a spurious jump in the grid-point values for 1902–09 in this region (see Section 3b1).

The use of the data set by van Loon and Williams was well within the limitations imposed by the problems but it is currently unsuitable for many purposes. All authors mentioned above were content to merely document the problem areas, and subsequently exclude them from the analyses. For many purposes this is not appropriate since it can destroy continuity, and it also throws away data which may have some value. We have therefore attempted to go two stages further 1) by using monthly data and 2) by correcting for the errors where possible. Undoubtedly, for some purposes, these corrections are sufficiently radical as to be unacceptable but they nevertheless more clearly indicate the problems with such a data set and alert the analyst to other possibly spurious signals in the data.

In an analysis of variance, it is often desirable to apply various pre-whitening and filtering techniques, and any inhomogeneities, large errors (wild points) and systematic errors can destroy the usefulness of results unless care is taken to minimize their effects. This has been the approach adopted here. Therefore we have undertaken the task of compiling a preliminary documentation of points which are either in error or suspicious as well as determining corrections where possible. This includes detailing the corrections for the discontinuities that occurred between 1) June and July 1939, 2) December 1945 and January 1946, and 3) during 1956. In some areas it proved to be an impossible task to correct the values and the only alternative seems to be to exclude those areas or the periods in question from subsequent analysis.

2. Method

a. Error analysis

A complete documentation of errors and problem areas would involve a reanalysis of the maps using all available data, and this was a task far beyond our means or desires. Instead, the approach adopted was to document those errors which could prove problematical in a statistical analysis (i.e., those points which contribute a large amount of variance). Where convenient, a comparison was made between grid-point sequences and monthly mean station data from nearby points. In some areas, such a comparison revealed very little agreement and we had little basis for knowing which might be closer to the truth; therefore, if the time series was well-behaved (i.e., no points greater than 3 standard deviations from the long-term mean, no discontinuities or long-term trends) then it was not altered. In such a case the values may well still be nonsense, but at least they are reasonable nonsense.

For the most part, the analysis consisted of a detailed examination of the time series at each grid point. Roland Madden kindly provided us with a copy of his plots of normalized time series at every second grid point for January, April, July and October. In these, the normalization was performed using the standard deviation estimated to be associated with the natural variability [e.g., see Fig. 5 of
Madden, (1976)]. However, we also found it useful to produce plots for each grid point with the 12-monthly time series aligned side by side. Frequently, this was very helpful in revealing systematic problems that were not obvious for an individual month. Time series of annual mean pressures were also useful in this respect. All these plots were normalized using the standard deviation as calculated from the time series, and this was often spuriously large owing to the errors, discontinuities and trends in the data.

We generated time series plots on the line printer for all grid points from 20°–70°N (792 points) for each month (9504 time series) as well as the annual mean time series for all grid points (1009 time series). The examination of these for errors was a tedious task and a certain element of subjectivity was present but we attempted to be conservative by assuming the grid value was acceptable if doubt existed. A separate printout was made of all points more than 3 standard deviations away from the long-term mean (1899–1977) and these were all carefully scrutinized.

There were 79 years (948 months) of data on the 72 x 14 + 1 = 1009 point grid. Of these, aside from the points where no analysis existed (see Table 1), there were 10 154 (out of a possible 879 509) values missing (1.2%). Most of these were over Siberia from 1916 to late 1921, in May 1922, and from May 1938 to June 1939.

In order to allow sensitivity analyses to the different assumptions about errors, three classes of error were defined. These were assigned a status of 0 for a confirmed error, 1 for a probable error and 2 for a suspicious point.

Confirmed errors are those where contrary evidence exists from another source (World Weather Records or the NCAR data bank). If a station was very close to the grid point, it was often possible to estimate a rough correction. However, many points were ranked as confirmed errors because they were associated with a point where such a comparison could be made but were not sufficiently close to estimate a correction with confidence. Also, at many locations it was possible to confirm an error but, without redoing the analysis, a correction was not possible because of uncertainties in the sea level pressure values, particularly in areas of significant orography. In every case where a correction was estimated, the correction was based on the relative values in adjacent years. The revised series were later checked for discontinuities and, in many cases, a second correction applied.

Probable errors (status 1) are those which could not be confirmed but whose values were sufficiently extreme to indicate that a problem existed with reasonable confidence. Most of these were adjacent to a confirmed error but sufficiently remote not to warrant the rank confirmed. Others were in areas of known data problems (e.g., missing data) and were in excess of 3 standard deviations away from the long-term mean.

The errors of status 2 include all points greater than 3 standard deviations away from the long-term mean but which could not be checked and any other points about which we were suspicious. Generally, we regard these points as probably correct.

As a check on our analysis, maps were plotted showing 1) the distribution and status of all errors and 2) the corrections, in order to check for spatial consistency. In further analysis of the data all errors of status 0 or 1 were either corrected or set to missing before we analyzed the discontinuities.

b. Discontinuity analysis

After correcting for the errors adjustments were determined for discontinuities between 1) June and July 1939, 2) December 1945 and January 1946, and 3) during 1956. The first and last were recognized by van Loon and Williams (1976a,b), Williams and van Loon (1976) and Madden (1976) [henceforth vLWa, vLWb, WvL, vM] but we have also found it desirable to separate out the World War II years.

Several methods were tried in order to isolate the discontinuities in the time series. This involved two parts: 1) locating grid points where discontinuities were present; and 2) locating the discontinuities themselves. As outlined below, some objective techniques were tried but with little success, particularly in marginal areas, and ultimately the only satisfactory solution was a comparison of the grid-point values with observations. However, although this frequently enabled us to define the discontinuity it did not permit corrections to be made owing to the complications of the high orography usually present.

We began by computing the first four moments of the time series for each month at each grid point in the expectation that these would help define the area of discontinuity. The variance (second moment) was certainly enhanced in the region of the discontinuities but the border of this region was poorly defined. The skewness proved to be small over most of the grid and the few significantly skewed areas were randomly distributed from month to month. Unfortunately, the kurtosis also proved to be of little value. There were roughly 30% more points than expected for a normal distribution where the kurtosis was outside the ±5% significance levels. Many of these exhibited no set pattern, although all months in the Indian plateau region showed significantly low kurtosis values (i.e., a flat-topped distribution) as might be expected in an area where

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3 A normal distribution has a kurtosis of 3.0 and the ±5% significance levels are 2.31 and 3.84 for 78 observations (Croxton et al., 1967).
discontinuities were present, but nearby over the Himalayan region significantly high values of kurtosis (i.e., a highly peaked distribution) occurred, also as a consequence of a discontinuity. In retrospect, this is not surprising since the kurtosis will depend on the size of the discontinuity relative to the standard deviation⁴ (see also Fig. 4).

In the analysis of the annual time series it was apparent that the variance associated with the spurious discontinuity frequently overwhelmed the signal in the time series. For instance, at 20°N, 80°E the standard deviation of the annual series was 2.23 mb compared to ~0.6 mb expected (or as found at 20°N, 40°E); so that 92.8% of the variance was associated with the error. At 30°N, 80°E about 69% of the annual variance was associated with errors. Since such large amounts of variance were apparently involved with the discontinuities we attempted an empirical orthogonal function (EOF) analysis of the main suspect region defined by M and vLWa. However, it was necessary to carry out such an analysis using monthly data in order to define corrections for each month and since, as we shall see later, there is also a seasonal component to the discontinuity pattern. The EOF analysis is capable of isolating spatial patterns in the data which explain most of the variance (e.g., Kutzbach, 1970; Trenberth, 1975). Some results of this analysis for January and July are presented later. However, it was not successful in isolating the discontinuities since 1) the variance explained by the discontinuities amounted to just over 20% in both January and July for the entire region 20°–50°N, 10°–120°E, and 2) there were different patterns associated with each of the three main discontinuities.

The actual method used to remove the discontinuities was based on a point-by-point examination and, when possible, comparison with station data. At 20°N, 80°E, where orography is not a complicating factor, a discontinuity in 1956 was nevertheless present although there was no perceptible trend in the data of a nearby station (Nagpur, Akola). Although vLWa shows a small trend to be present in station level pressures over Asia for 1950–64 (see their Fig. 12), the trend appears to be negligible for longer intervals. We cannot establish that this is the case everywhere and for all the subperiods we have considered, but the assumption that there is no trend in the pressures between subperiods provides a practical method for eliminating the discontinuities.

The method used to remove discontinuities was 1) to define the date of the discontinuity; 2) obtain the means and standard deviations for each subperiod between these dates; 3) apply a Student t test on the differences between the means, and use the results to define the grid points affected; and 4) obtain the corrections for the grid points in question.

The definition of the discontinuity was not an easy task, and discontinuities were found in every case of a change in source given in Table 1. These are discussed in detail in section 3b.

c. Final checking

At this stage we had 1) determined the corrections for points in error or set them to missing, and 2) made adjustments for the discontinuities. It was then necessary to check that the corrections had had the desired effect. This was done by again determining the standard deviations at each grid point and rechecking all points greater than 3 standard deviations away from the revised long-term mean.

3. Results

a. Errors

It is not feasible to list here all the errors we have documented, but various statistics are given below

<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1092</td>
<td>510</td>
<td>269</td>
<td>418</td>
<td>724</td>
<td>206</td>
<td>26</td>
<td>18</td>
</tr>
</tbody>
</table>

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⁴ For a series divided in half, with each half normally distributed and the same standard deviation, it can be shown that the kurtosis will be greater than 3 if the discontinuity in mean is less than 3 standard deviations, and less than 3.0 if the discontinuity is more than 3 standard deviations.

Table 2. Distribution of errors of status 0 and 1 for bands 5–120°E (Asia), 125°E–120°W (Pacific), 120°W–0° (N. America-Atlantic) and 10° latitude bands.

<table>
<thead>
<tr>
<th>Latitude (°N)</th>
<th>20–25</th>
<th>30–35</th>
<th>40–45</th>
<th>50–55</th>
<th>60–65</th>
<th>70–75</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>920</td>
<td>427</td>
<td>348</td>
<td>58</td>
<td>62</td>
<td>7</td>
<td>1882</td>
</tr>
<tr>
<td>Pacific</td>
<td>500</td>
<td>32</td>
<td>59</td>
<td>7</td>
<td>223</td>
<td>136</td>
<td>957</td>
</tr>
<tr>
<td>N. America-Atlantic</td>
<td>323</td>
<td>19</td>
<td>8</td>
<td>0</td>
<td>87</td>
<td>47</td>
<td>484</td>
</tr>
<tr>
<td></td>
<td>1743</td>
<td>478</td>
<td>415</td>
<td>65</td>
<td>372</td>
<td>190</td>
<td>3263</td>
</tr>
</tbody>
</table>
and many have been listed by WvL. A copy of the errors, the corrections to discontinuities, and the revised sea level pressure fields can be supplied to those interested on request to the Data Support Section of NCAR.

Of the 948 months, 448 contained errors of type 0 or 1, 338 contained errors of type 2, and 391 months were free from errors. The total number of errors of type 0 or 1 was 3263 and a further 912 points were coded as type 2, giving a total of 0.47% of the points as errors. There were 2310 points initially which were greater than 3 standard deviations from the long-term mean, but this number is very conservative owing to the inflated standard deviations due to errors and discontinuities. Of these, 1104 (48%) were among those finally coded up as errors and the others were considered to be acceptable by comparison with station values.

Table 2 shows a breakdown of the distribution of errors of status 0 and 1 for the 120° longitudinal bands 5–120°E (over Asia including the area of main discontinuity), 125°E–120°W (Pacific) and 120°W–0° (North America and Atlantic). The majority of the errors are over Asia and are mainly associated with the complicated orography and the discontinuities present (see later) or the regions of Siberia where data were very sparse from 1916 to 1922. Most of the errors are also concentrated in low latitudes.

Table 3 shows the number of errors present in each decade. Most of the problems occurred before about 1922 or during World War II. By far the worst year was 1945 with 378 errors, followed by 1900 (198) and 1909 (171). All of the errors in the 1970’s are in the vicinity of the Himalayas.

Corrections were estimated for 840 of the points in error and the others were set to missing. This left 12,634 points missing, aside from the areas where no analysis was present. These are allocated as shown in Table 4, with previous values given for reference.

With the discontinuities and errors eliminated, the field of standard deviations (SD) for each month appeared reasonable, without the previously inflated values. Table 5 shows a breakdown of the number of points outside certain limits compared with that expected for a normal distribution with the same number of points (75, 85 and 90°N were excluded). As we shall see later, there are still small spurious and real trends present in the data set and this contributes to high kurtosis values producing a more peaked distribution than the normal, as revealed in Table 5. Note that most of the points greater than 4 standard deviations from the long-term mean (1899–1977) occurred after 1939. This occurs because a spurious discontinuity in 1945 (see Fig. 8) results in the mean being closer to the 1899–1945 mean and the more recent period then appears to have more extremes.

### b. Discontinuities

Discontinuities were found in every case of change in source. The following is a summary of the main results (D refers to discontinuity):

(i) Several areas exhibited problems prior to World War I but the discontinuities were either diffuse and could not be well defined or the date of D appeared to vary regionally. These have not been corrected for in any way. The main problems are as follows.

(a) 20–35°N, 90–120°E: very high pre-1915; possible D ~ 1915;
(b) 55–80°N, 180–100°W: very high 1902–1909;

M comments briefly on some aspects of (a) and (c) (see his Fig. 4), and WvL make note of problem (b)

<table>
<thead>
<tr>
<th>Table 4. Numbers of missing data in the corrected and original data set. The month is given in parentheses.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original</strong></td>
</tr>
<tr>
<td><strong>Corrected</strong></td>
</tr>
<tr>
<td><strong>11 747</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5. Number of points departing from the long-term mean by 3.0, 3.2, 3.5 and 4.0 standard deviations compared to a normal distribution (ND).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N</strong></td>
</tr>
<tr>
<td>1899(1)–1939(6)</td>
</tr>
<tr>
<td>1102</td>
</tr>
<tr>
<td>1899(1)–1977(12)</td>
</tr>
<tr>
<td>2175</td>
</tr>
</tbody>
</table>
Fig. 1. Differences in analyzed sea level pressure (mb) between March 1902–July 1909 and August 1909–August 1916 for three sets of months (a) March, April and May; (b) June, July, August, September and October; and (c) November, December, January and February. The plus sign indicates the location of Dawson. Negative contours are dashed.

(see their Fig. 4 and the comments in our Section 1). Further documentation of this is given later.

(ii) A major discontinuity occurred over Asia between June and July 1939. It corresponds to a change in source for the analyses and many examples have been shown by vLWa (Fig. 3), WvL (Fig. 3) and M (Fig. 5).

(iii) M notes the extra problems during World War II and this whole period is somewhat suspect (see Fig. 10 of vLWb and Fig. 2 of WvL). 1945 was generally at odds with all other years (e.g., Fig. 8 of WvL) and comes from a different source. We have grouped it with the other World War II years, but many points were individually coded up as errors. A discontinuity occurred in 1945 over the Mexican highlands (see Fig. 8 of this paper).

(iv) The discontinuity in 1956 over Asia was also clearly recognized by M and WvL and it appears to be associated with the introduction of the International Barometric Conversion in 1956\(^6\) (vLWa) but it is complicated by a second discontinuity in the

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\(^6\) The discontinuity is also manifest in station sea level pressures over India but it occurs at the end of 1960. As noted in World Weather Records 1951–60, a correction was apparently applied to maintain homogeneity of those records for the decade.

Fig. 2. The empirical orthogonal functions which explain most of the variance for (a) January and (b) July. The patterns are normalized so that the sum of the squares of the grid point values is unity. If the product is taken with the standard deviation (not given) it represents a departure pattern, in millibars, corresponding to 1 unit in the time series of Fig. 3.
same region between March and April 1955 which corresponds to a change in source (see Table 1). The former discontinuity is more widespread but mainly present in the winter half-year (e.g., vLWa, Fig. 2). On the other hand the latter discontinuity is more marked in summer and seems to be confined to 25–30°N, 50–65°E (e.g., vvL, Fig. 3). We have chosen to place the discontinuity between May and June 1956, but where it was clearly in 1955 the individual points have been adjusted to be compatible with this assumption. The 1955 discontinuity is also present over the Mexican highlands (see Fig. 8).

The 1960–62 period, which again comes from a separate source (see Table 1), also exhibits peculiarities, generally in the same region which exhibited the discontinuity in 1955, but also extending...
further east. This problem is also evident in Fig. 3 of WvL and, since it was for such a short period, it was corrected for individually.

In two other areas only the period 1956–59 was relatively high and individual corrections were also coded for this. The areas affected are 20–25°N, 15–40°E and 40°N, 90–105°E. An example of the latter is given in Fig. 9 of WvL (see also Figs. 2b and 3b of this paper).

1) High latitudes

The first problem area where discontinuities have been documented is 55–80°N, 180–100°W. We compared grid-point values at 65°N, 140°W for all months with observations at Dawson (64°N, 139°W). This showed the grid-point values to be at a higher level in all months for March 1902–July 1909. Detailed agreement between the time series was not
good but the discrepancy in each month, calculated by comparing this subperiod with other values from 1902–15, was fairly consistent. In several months the discrepancy was sufficiently similar for these to be grouped together in order to increase the statistical significance of the results. The discrepancy was 7.6 mb (March, April, May), 5.4 mb (June, July, August, September, October), and 11.6 mb (November, December, January, February).

In order to determine the extent of this problem we evaluated the means at all grid points for each month for March 1902–July 1909 and compared them with means for August 1909–August 1916. The difference between these values is shown in Fig. 1 for the region where it was clearly significant. Dawson is located near the center of the anomaly pattern and the values agree with the discrepancies noted above. This shows that the mean was nearly stationary for this period and allows us to assume that the values given in Fig. 1 are appropriate correction patterns for this region. However, we have not applied these corrections to our data set owing to the dubious quality of the analyses at high latitudes in early years. Rodewald (1950) and M present
2) **Empirical Orthogonal Function Analysis**

In an attempt to objectively determine the discontinuity patterns and their associated patterns an empirical orthogonal function analysis was made of the main suspect region (20–50°N, 10–120°E) for January and July. In order to place equal weight on all of the grid points, the data were first normalized using the long-term standard deviation. The eigenvectors and eigenvalues of the covariance matrix of the departures from the long-term mean were then computed. The prior normalization makes this step equivalent to using the correlation matrix. The eigenvalues represent the variance explained by each of the eigenvectors and the latter determine the spatial patterns of the field. The coefficient matrix, which determines the temporal variations of each eigenvector, was then computed.

The three eigenvectors which explain most of the variance are shown in Fig. 2a (January) and Fig. 2b (July). Fig. 3 shows the corresponding time series.
where heavy arrows have been used to denote the discontinuities and the percentage variance explained by each eigenvector is given.

In January, discontinuities are present between 1939–40 and 1956–57. The first eigenvector, which explains 30.5% of the variance, has the same sign over the entire grid and therefore confirms that a large drop in analyzed pressures extended throughout this region from 1940–56. Note also that the mean before 1940 differs slightly from the mean after 1956. The second and third eigenvectors, which explain 17.3 and 12.5% of the variance, respectively, act to refine the pattern associated with each discontinuity.

In July, the first three eigenvectors (JUL1, JUL2, JUL3) explained 28.6, 15.8 and 10.4% of the variance and all exhibited discontinuities between 1938 and 1939 (consistent with the discontinuity being between June and July of 1939). There is also evidence for the change in level in 1917, or thereabouts, in JUL3. The latter further shows the problems with the World War II years. The JUL1 time series also shows discontinuities between 1955–56, 1959–60 and 1961–62, and thereby illustrates some of the conclusions given earlier.

All of the time series presented in Fig. 3 exhibit natural variability from year to year which evidently occurs with spatial patterns similar to those associated with the discontinuities. If the discontinuities are removed from Fig. 3, by assuming the mean for each subperiod is constant, the variance explained by the discontinuities sums to 23.2% of the total in January and 20.3% in July. This still leaves each of the first three patterns explaining more of the variance than the fourth eigenvector; consequently, it is not possible to associate any of the eigenvectors solely with the discontinuities and limits the usefulness of this approach.

3) Asian discontinuity

Fig. 4 shows some of the results of the discontinuity analysis with the data set divided into the subperiods 1) 1899(1)–1939(6); 2) 1939(7)–1945(12); 3) 1946(1)–1956(5); and 4) 1956(6)–1977(12). The Student’s $t$ values of the differences between the means of the first three subperiods with period 4 are presented for January, April, July and October. The null hypothesis used was that there were no differences between the means. Although this hypothesis does not allow for any real trends that might be present, it is justified by the comparison with station data (see Section 2b). The number of degrees of freedom in each varies somewhat from grid point to grid point (because of missing values) but averages about 59 for 1 versus 4, 25 for 2 versus 4 and 29 for 3 versus 4. The Student’s $t$ values of 2 (~95% significance), 4 (~99.99% significance) and 10 have
Fig. 7. Correction patterns for subperiods 1, 2 and 3 compared to subperiod 4. Values are in millibars and the contour interval is 1 mb. Highs and lows are given in tenths of a millabar. The domain contoured extends from 15–60°N, 15–150°E with latitude and longitude lines every 15°.
been contoured. Further charts were prepared for all months and a systematic pattern was clear although there was a marked seasonal variation present. Similar maps were prepared for subperiods 1 versus 2 and 2 versus 3. We also performed a test using groups of three (assumed independent) monthly values since this effectively eliminates non-systematic effects and greatly enhances the significance. Student's $t$ values in excess of 10 were abundant on all of the 12 three-month charts except one.

Each discontinuity was considered separately and the area influenced was determined. However, the differences in the areas affected by each discontinuity were so similar that it was possible to adopt the same area for all, shown in Fig. 5. A core area, assumed to be totally affected by the discontinuity, and a merge area were defined. At the outer points of the merge area it was assumed that half the discrepancy between subperiods was caused by the spurious discontinuity. However, owing to the peculiarities of some of the patterns, an extended merge area was defined from $45-55^\circ$N, $75-120^\circ$E (see Fig. 5) where the interior points were assigned weights between 0.5 and 1.0.

Ideally, it is desirable that the correction patterns to be applied should tend to zero at the edge and, using the above merge pattern, this was achieved for all months except month 12, subperiod 2, where corrections at the edge were as large as 2.7 mb. All subperiods were corrected to the means of subperiod 4 and many of the resulting correction patterns bear a remarkable resemblance to the smoothed orography for the same region shown in Fig. 6 [adapted from Berkofsky and Bertoni (1955)]. The correction patterns themselves are shown in Fig. 7 (for contouring purposes, a correction has also been assigned at $15^\circ$N, equal to one-half the correction at $20^\circ$N).

In winter, the correction patterns show the strongest resemblance to the orography and are fairly similar except for differences in amplitude and a large negative region for subperiod 1 over India. The corrections exceed 10 mb in several cases. Possibly the resemblance with the orographic pattern would be greater were it not for the very large number of points in this region already adjusted for errors.

In summer the patterns become rather different but clearly exhibit continuity from one month to the next within each subperiod. Largest corrections in summer, of over 7 mb, occur in subperiod 2 and are concentrated over the western part of Asia.

Highly significant Student's $t$ values are also found in areas outside of Asia (Fig. 4) especially in low latitudes. These trends also appear to be mostly spurious, as shown in Fig. 8. Here annual mean time series are presented since a similar pattern occurred in all months. Fig. 8a shows a comparison between pressures at Hawaii ($21.3^\circ$N, $157.9^\circ$W) with grid-point values interpolated to $20^\circ$N, $157.9^\circ$W, and the mean difference between them; (b) grid-point values at $20^\circ$N, $100^\circ$W (Mexican highlands) with two discontinuities indicated by heavy arrows; (c) grid-point values at $25^\circ$N, $80^\circ$W versus Key West ($24.6^\circ$N, $81.8^\circ$W).

[Fig. 8. Time series of annual mean pressures: (a) grid point values interpolated to $20^\circ$N, $157.9^\circ$W versus Hawaii ($21.3^\circ$N, $157.9^\circ$W), and the mean difference between them; (b) grid-point values at $20^\circ$N, $100^\circ$W (Mexican highlands) with two discontinuities indicated by heavy arrows; (c) grid-point values at $25^\circ$N, $80^\circ$W versus Key West ($24.6^\circ$N, $81.8^\circ$W).]
only four grid points and it was clearly inappropriate to extend our correction method to this region, so that the spurious trend in low latitudes is included in our revised data set.

Note that there is almost no trend present at Key West and only a slight downward trend at Hawaii owing to very low pressures in the 1960's. Some doubt is therefore cast on the conclusions by M concerning the signal-to-noise ratio associated with linear trends in low latitudes since these were based on the grid-point data.

4) ZONALLY AVERAGED PRESSURES

An analysis has also been made of the zonally averaged and hemispherically averaged sea level pressures for each of the subperiods, before and after the discontinuity corrections were applied. Fig. 9a shows the annual mean profile for each subperiod after the errors were corrected but before the discontinuity analysis. The hemispheric mean is given in the insert, and is defined as the average from 17.5°N to 87.5°N by assuming each latitude is representative of a 5° band except 80°N is assumed representative of 72.5°–87.5°N. Fig. 9b shows the revised profiles after the corrections for the discontinuities have been applied. Values are unchanged north of 50°N.

The largest changes of 0.6 mb at 35°N for the annual mean occurred in subperiods 2 and 3, but corrections as large as 1.2 mb occurred in winter for subperiod 2 at 40°N. The high pressures at low latitudes in Figs. 4 and 8 for subperiod 1 are again in evidence. At 80°N the spuriously high pressures for subperiod 1 can also be seen. If we had applied the correction pattern shown in Fig. 1, the largest change would be at 65°N where zonal mean pressures for subperiod 1 would be reduced by 0.2 mb.

The hemispheric mean pressures indicate subperiod 1 to be high, and we have shown that this is spurious. In contrast, pressures in subperiod 2 are low, with differences between subperiod 2 and 4 of 0.6 mb at 45°N. Most of this arises from the very low values analyzed in the Aleutian low in December, January, February and April of subperiod 2 (see Fig. 4). At 50°N, 170°W the mean January pressure for subperiod 2 was 991 mb compared to 1002 mb for subperiod 4. We cannot say whether this is real or whether it arises from the data difficulties associated with World War II.

5) COMPARISON OF NAVY AND NMC MONTHLY MEAN ANALYSES

For December 1975–February 1977 it was possible to compare the monthly mean sea level pressure analyses produced by the U.S. Navy and NMC. Fig. 10 shows the NMC-Navy differences for January 1976 and 1977, and July 1976. The January patterns are typical of other winter month differences and July was fairly typical of the summer differences. We have confirmed that the large differences over the Himalayas are caused by errors in the NMC analyses. In early 1976 NMC was having problems in some areas of high orography but apparently gradually modified their procedure during the first six months. The excessively high pressures over the Himalayas (1052 mb) and Greenland (1019 mb) in January 1976 were reversed a year later and became excessively low. In most months there was also a tendency for NMC values to be lower over the Arctic, and over the Rocky mountains of North America values were low in summer and high in winter. Systematic differences were also present over Africa (see Fig. 10).

4. Conclusions

A detailed examination of the Northern Hemisphere monthly mean sea level pressure grid-point
analyses has shown a disappointingly large number of problems. In this paper the approach has been to attempt to eliminate the extreme errors and we have presented correction patterns that may be applied to the Asian highlands in order to remove the main discontinuities present there. There remain several problem areas in which the only solution seems to be to omit the periods or areas in question from subsequent analysis. This applies to the following regions.

1) High latitudes. This problem apparently arises from the sparse data in this region, and is illustrated by Figs. 1, 4 and 9. Pressures appear to be unreliable, and generally high, up to about the end of 1923. Although the effects are greatest at 80°N, they are also present at 70°N, and further south in the Siberian sector.

2) Low latitudes. These problems are discussed more fully in Section 3b and are partly illustrated in Figs. 4 and 8. They partly arise from the low signal-to-noise ratio in this region since the natural variability is often smaller than the observational errors. In the Asian region, this gave rise to Student's t values in excess of 10 when the means for
two subperiods were compared. This undermines our confidence in the analyzed pressures at 20 and 25°N, but the main period affected is limited to before about 1918.

The procedure used to eliminate the discontinuities has also removed any real trends between the four subperiods in the Asian region. Nevertheless, the revised data set should now prove useful for investigating such things as interannual variability.

Some of the results presented include real changes in the atmospheric circulation (Figs. 4 and 9) but they mainly illustrate the problems with this data set. Sea-level pressure, in contrast to precipitation or temperature, is a fairly robust atmospheric parameter in the sense that it is not sensitive to changes in station site. Nor should it be very sensitive to changes in station elevation. However, a majority of the problems are associated with the complex orography, especially in the vicinity of the Himalayas, and the number of errors found was disconcertingly large. We also suspect that there are other errors present, not detected by our analysis. In order for definitive studies of climate to be possible, it is clearly desirable that a greater effort be made in archiving quality controlled climatological data with accompanying documentation as complete as possible.

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