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Research Note ETL-RN-73-3

METHODS AND RESULTS OF REMOTE BAROMETRIC ALTIMETRY AND VIEWS ON THE ESTIMATION OF METEOROLOGICAL FIELD VARIABLES

by

Hans Baussus von Luetzow

April 1973

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA

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SUMMARY

This report provides a generalization of classical barometric altimetry for longer distances and explanations for some shortcomings associated with ground temperature and the weather situation. The use of weather forecasts is reviewed and error estimates under consideration of potential Army use are provided. Finally, some general views concerning the estimation of meteorological field variables are presented.

FOREWORD

The basis for this research was available as an interim study in March 1969. The author has made an effort to improve and extend this study because of additional insight into the problem of meteorological field estimation gained during the preparation of his Research Note "The Derivation and Potential of New Filter Equations for Numerical Weather Prediction." Essential agreement exists regarding experimental results by the Research Institute and the author. The author has particularly attempted to provide an analytical as well as multiple regression framework and explanations for certain empirical findings under consideration of meteorological theory.

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METHODS AND RESULTS OF REMOTE BAROMETRIC ALTIMETRY AND VIEWS ON THE ESTIMATION OF METEOROLOGICAL FIELD VARIABLES

1. **Introduction.** Military applications often require a precise height determination for points of interest, although these points lying on the earth's topographic surface may be situated in inaccessible areas where ground pressure, and possible ground temperature, become available only through dropped transmitting devices or by means of some forward observer. For close distances, up to about 100 km, classical methods of barometric altimetry which involve the use of a known reference height at ground level yield generally satisfactory results. However, the ground temperature is not always very representative for the mean temperature of the respective air column, to be considered horizontally uniform, particularly during summer.

This report reviews some of the classical problems involved and provides some explanations for them. Next, the utilization of weather forecasts, primarily numerical ones, is examined from the theoretical and practical standpoints. The time lag between pressure measurements and forecasts becomes rather critical if 12 hours are exceeded. The long range extrapolation method, the main features of which are described, represents a generalization of the classical approach; and it has to be emphasized that the extrapolation takes place on an isobaric surface. It is of interest to note that less information is needed or the results are more precise, respectively, if the difference in height is slight or where the topographic height of the remote station is considerably greater than that of the reference station where the height of the isobaric surface pertaining to the ground pressure of the remote station is known.

Error variances as a function of distance for Washington, D. C., January and July, are listed and some comments are made concerning slight modifications due to several influences.

Emphasis has been placed on providing a suitable and relatively simple extension of classical methods and on demonstrating that remote barometric altimetry for Army purposes is both feasible and generally accurate enough for distances of primary concern.

Finally, the problem of estimation of meteorological field variables is reviewed. As a consequence of this analysis, stationary statistics are limited to moderate anticyclonic, and particularly to moderate cyclonic, weather situations with corresponding large scales. The height estimation accuracy is somewhat impaired under hydrostatic conditions if the hydrodynamic stability; i.e., the excess over the improved critical Richardson number Ri_B (crit), is small. The estimation accuracy is, of course, even more impaired in case of hydrodynamic instability; e.g., during thermo-convective processes.

2. **Classical Short Range Procedure.** Variables and constants to be utilized in the computational procedure are (cf. Fig. 1.)

Z_1^*	reference or base station height
Z_2^*	field station height to be determined
T_{v1}	mean virtual temperature between Z_1^* and Z_2^* of the air column above Z_1^*
p_1^*	barometric (ground) pressure at base station
p_2^*	barometric (ground) pressure at field station
$R = 287\frac{m^2\,sec^{-2}}{degree\ C}$	gas constant for dry air
g	gravity at base station

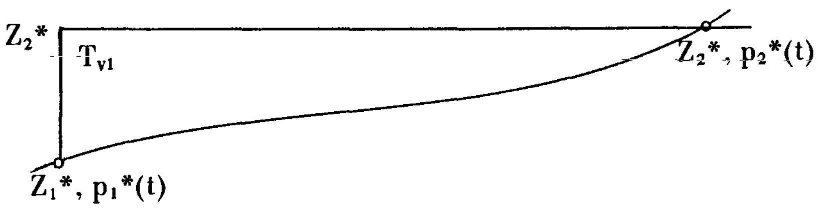

Fig. 1. Short Range Topographic Height Relationship.

As a first approximation, assuming no isobaric tilt and complete temperature correlation between base and field station, we have in view of the hydrostatic equation

$$Z_2^* - Z_1^* = \Delta Z = \frac{RT_{v1}}{g} \ln \frac{p_1^*}{p_2^*} \qquad (1)$$

If a rather up-to-date weather forecast is available, an isobaric correction due to $Z_2\ (p_2^*) \neq Z_1\ (p_2^*)$ can be computed which is simply

$$\delta Z = \frac{\partial Z}{\partial r}\, r \qquad (2)$$

where r denotes the separation between base and field station. Higher derivatives are, of course, possible. According to Bellamy and Lodwice [1] this correction is worthwhile in many cases.

O'Connor [2] concluded from a comparison between actual and barometrically computed height differences involving two Australian stations with an elevation difference of 960 m and separated by 80 km that the substitution of the screen temperature measured close to the ground instead of T_{vl} in (1) leads to a rather systematic bias during the summer months; i.e., to too large height differences on the average. Rather paradoxically, better results were obtained during relatively stronger cyclonic weather conditions.

This is probably due to the fact that the ground screen temperature is less representative for the temperature aloft in the free atmosphere during summer months; i.e., radiative processes appear to have a relatively greater significance during summer.

The above interpretation must be essentially correct since there is a weaker correlation between temperatures aloft (in the free atmosphere) and the temperature on the ground during winter times; i.e., $\frac{\text{cov}[T^*, T(\Delta Z)]}{\sigma_{T^*}\,\sigma_{T}(\Delta Z)}$ for $100 \text{ m} \leq \Delta Z \leq 500 \text{ m}$ is smaller during winter than during summer, or $\frac{\text{var}\,\frac{\partial T}{\partial p}}{\text{var}\,T}$ for an isobaric level close to the ground is greater during winter than during summer. There is also a stronger turbulent diffusion in the vertical during winter months. Winter and summer refer to the northern hemisphere in this regard.

If a representative T_{vl} is taken both during summer and winter, statistical considerations demonstrate clearly that better results can be expected during summer since the variances of height and temperature are considerably smaller during summer than in winter. This is also in agreement with the findings of other authors including Allen [3] and particularly important, if greater distances between two stations are involved. Having clarified this interesting ambiguity, we proceed with an extension of the short range method which is particularly interesting in connection with military applications; e.g., Long Range Position Determining System (LRPDS) and medium to long range Army missile employment. Barometric ground pressure readings are, of course, required for the remote station, either transmitted by dropped devices or by a forward observer. The problem of the determination of a gradient in elevated country as mentioned by O'Connor is, of course, related to this problem.

3. Methods of Long Range Extrapolation or Remote Barometric Altimetry.

a. Use of Numerical Weather Forecasts. If we want to exploit weather forecasts, particularly numerical predictions, we profitably use the height and temperature information on an isobaric surface adjacent to the terrain; i.e., in general low level height and temperature information. The height of a 950-mb surface and an average temperature for the interval $\langle p_2{}^*, 950 \text{ mb}\rangle$ might be utilized, for example. Equation (1) then reads as:

$$Z_2{}^* = Z_2(p) - \frac{R}{g} T_{v2} \, \ell n \frac{p_2{}^*}{p} \tag{3}$$

with $Z_2(p)$ and T_{v2} provided by the weather forecast. The climatological variance of $Z_2{}^*$ follows from (3) after neglecting a small covariance between $Z_2(p)$ and T_{v2} as

$$\text{var } Z_2{}^* = \text{var } Z_2(p) + \left(\frac{R}{g} \, \ell n \frac{p^*}{p}\right)^2 \text{var } T_{v2} \tag{4}$$

This variance is, of course, reduced because of $Z_2(p)$- and T_{v2} - information from the weather forecast. An approximate reduction factor $\omega(t)$ may be taken from Thompson [4].[1]

With the standard deviations of average heights and temperatures listed in Upper-Air Climatology of the United States [5] we arrive, for $\frac{p^*}{p} = 1.05$ and Washington, D. C., at the results shown in Table I for various prediction intervals t:

Table I. Approximate Standard Deviations of Mean Pressure Height (m)

t hours	January	July
2	3.9	2.3
6	7.8	4.6
9	11.7	6.9

It is to be noted that results obtained using weather forecasts are not distance-dependent and would be particularly advantageous with respect to long distances. The quality of the results would, of course, not be uniformly the same because of such factors as density of network. In addition, a large scale weather forecast requires global information to start with. In many military situations, the initial global inputs will not be available, so this method has only limited value.

b. Statistical Extrapolation Methods. The main problem consists of estimating $Z_2(p)$ in eq. (3) from meteorological information available at Station S_1.

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[1] On page 148 $\omega^{1/2}(t)$ is listed for wind.

If $Z_1^* \leq Z_2^*$, it is easily possible to choose an isobaric surface through $Z_1(p)$ in such a way that the difference $Z_2(p) - Z_2^*$ is small. In this case, the error contribution from not knowing T_{v2} is quite small, as can be inferred from eq. (4) (cf. Fig. 2).

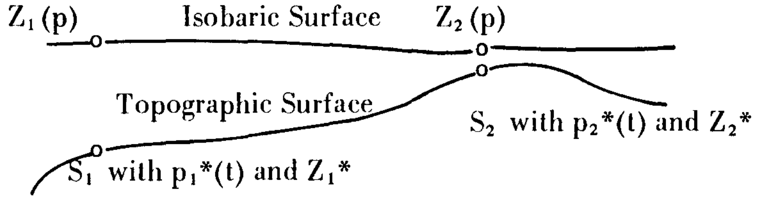

Fig. 2. Height and Pressure on Topographic and Isobaric Surface.

If, however, $Z_2 \leqslant Z_1^*$, it would be necessary to measure temperature T_2^* as well at S_2, i.e., in addition to p_2^*, and/or to extrapolate $T_1(p)$.

A straightforward method would be provided by the simple Taylor expansion

$$Z_2(p) = Z_1(p) + \left(\frac{\partial Z}{\partial X}\right)_{S_1} \Delta X + \left(\frac{\partial Z}{\partial Y}\right)_{S_1} \Delta Y \tag{5}$$

or, in view of $U \approx -\frac{g}{f}\frac{\partial Z}{\partial Y}$ and $V \approx \frac{g}{f}\frac{\partial Z}{\partial X}$ where $f = 2\Omega \sin\varphi$ [2]

$$Z_2(p) = Z_1(p) + \frac{f}{g} V_1 \Delta X - \frac{f}{g} U_1 \Delta Y \tag{6}$$

Although eq. (6) is usable for short distances, statistical methods based on the concept of macro-turbulence are superior. The first work in this connection seems to have been done by Buell [6], and the theoretical structure of applicable regression coefficients has been derived by Baussus von Luetzow [7].

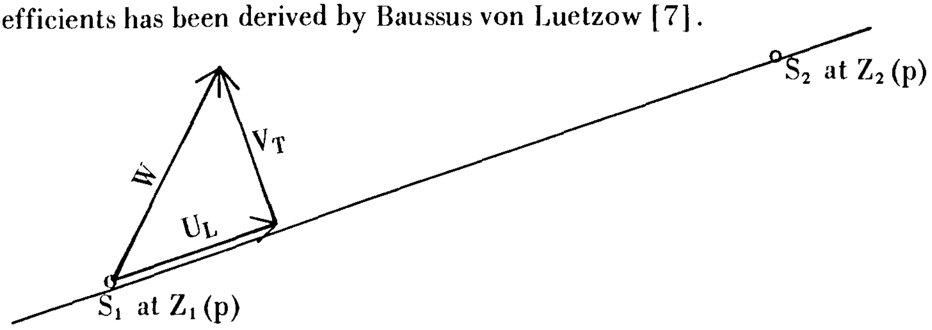

Fig. 3. Decomposition of Horizontal Wind for Distance Correlation.

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[2] f = Coriolis factor

According to Fig. 3, the measured wind W consists of a longitudinal and a transverse component with respect to the straight line going through S_1 and S_2 with heights $Z_1(p)$ and $Z_2(p)$, respectively. With $\overline{S_1 S_2} = r$ a regression equation of the form

$$Z_2 - \overline{Z}_2 = a_1(r)(Z_1 - \overline{Z}_1) + a_2(r)(U_1 - \overline{U}_1) + a_3(r)(V_1 - \overline{V}_1) \tag{7}$$

exists.

In eq. (7) the subscripts L and T have been dropped, and the bars designate climatological means. As to the relationship between $a_1(r)$, $a_2(r)$, $a_3(r)$, reference is made to [6]. It does not present any difficulties to establish optimal regression coefficients as a function of space and climatological season (month).

The reduction of var Z_2 as a function of distance is demonstrated by the lowest curve in the Appendix (Fig. 7 from reference 6). Errors for Washington, D.C. at the 950 mb level are shown in Table II.

Table II. Reduced Standard Deviations of
Mean Pressure Height (m) Through Wind and Height Correlation

r [km]	January	July
100	5	3
200	9	5
300	12	7
400	16	9
500	20	12
600	24	14
700	28	16
800	32	18

Table II lists achievable barometric station height standards deviations $\sigma_{Z_2^*}$ (m) as functions of distance for $Z_2^* > Z_1^*$ and $Z_1^* < Z_2^*$ if p_2^* *and* T_2^* are given (Z_1^* is known). Since eq. (7) is only a linear, though quite effective, model, the actual errors to be expected due to the existence of non-moderate weather situations are supposed to be somewhat higher than those indicated in Table II. Instrumental errors which contribute relatively little for distances exceeding 300 km, have also been neglected. However, an increase in error would also occur in case T_2^* is not given and $\overline{T}_{v2}$ has to be taken instead or T_{v2} has to be determined by two height extrapolations and vertical temperature correlation. The latter error contribution is, of course, also dependent on the ratio p_2^*/p.

In conclusion, it has been ascertained that remote barometric altimetry is feasible, particularly in connection with new meteorological equipment (including computers developed for artillery use) since height errors in the order of 10 m for a range of 200 km and 20 m for a range of 500 km can be considered acceptable.

4. **Some General Views Concerning the Estimation of Meteorological Field Variables.** According to Baussus von Luetzow [8], a "potential vorticity" of the form

$$f + \Delta^2 \Psi_B + f_o \frac{\partial}{\partial p} \left[P(p) \frac{\partial \Psi_B}{\partial p} \right] \tag{8}$$

with f and f_o as a variable and constant Coriolis factor respectively, Ψ_B as the stream function obtained through the classical balance equation, p as pressure and P as a measure of standard static stability would be sufficiently conserved, though only horizontally.

If the subscript B is omitted pertaining to Ψ, the balance equation reads as

$$f\Delta^2 \Psi + 2(\Psi_{xx} \Psi_{yy} - \Psi^2_{xy}) + \Delta \Psi \cdot \Delta f = g\Delta^2 Z \tag{9}$$

where $g = g(Z)$ denotes the vertical gravity acceleration. A simplified ω-equation,[3] involving a static stability $\sigma = \sigma(p)$ and a constant f_0, would be compatible with eqs. (8) and (9). The ellipticity criterion for this ω-equation, which involves terms of the form $\frac{\partial^2 \omega}{\partial X \partial p}$ and $\frac{\partial^2 \omega}{\partial Y \partial p}$, is more stringent than that of the optimal ω-equation derived in reference [8]; i.e., only moderate wind shears can be incorporated in the simple model. This is consistent with eq. (9), which allows only for moderate anticyclonic motion. Consequently, eqs. (8) and (9) are only valid for moderate or large scale cyclones and anticyclones. For this reason, linear statistical forecastings in the form of regression equations and under the assumption that the underlying physical processes are stationary in nature, with a corresponding assumption of stability of statistical parameters, have limitations. Furthermore, with reference to the use of a meteorological variable for statistical forecasting, Ψ-statistics instead of Z-statistics appears to be more profitable.

Stronger cyclonic and anticyclonic activities in the (x,y,p,t)-system can, of course, be described by the primitive equations in conjunction with the

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[3] $\omega = \frac{dp}{dt}$.

isobaric continuity and thermodynamic equation. The underlying process is, however, already a nonstationary one from the statistical standpoint and involves a weaker filtering process with reference to smoothed winds U and V associated with a smooth ω. As to the criterion of hydrodynamic instability involving this filter process and its connection with L. F. Richardson's turbulence criterion, reference is made to Baussus von Luetzow [9]. The incorporation of thermoconvective conditions, whence σ or the effective static stability H_2 is negative, requires even a less stringent filter equation than the hydrostatic one shown in reference [9].

The conclusions of the above analysis are the following. Statistical prediction as well as field estimation, is reasonably stationary and therefore effective under conditions of moderate cyclonic and anticyclonic activity. In the hydrostatic system, both prediction and estimation are more impaired the smaller the positive excess over the improved critical Richardson number Ri_B (crit) according to Baussus von Luetzow [9]. For even smaller scales associated with thermoconvective processes, the extrapolation of Z on an isobaric surface with which remote barometric altimetry is concerned suffers a further degradation of accuracy. The estimation problem of Z on an isobaric surface and of the geoidal height N by means of a homogeneous and isotropic correlation function, the latter well exemplified by Moritz [10], is essentially the same. The assumption of homogeneity and isotropy in meteorological statistics is, of course, only an approximation. As shown by Baussus von Luetzow [7]

$$c(r) = e^{-\left(\frac{\lambda r}{2}\right)^2} \tag{10}$$

is a suitable expression for the pressure height correlation coefficient as a function of the distance r. In eq. (10) it is

$$\lambda = \frac{f}{g} \; \frac{\sqrt{\text{var } U + \text{var } V}}{\sigma_Z} \tag{11}$$

Actually, geostrophic wind variances should be used instead of those determined from direct measurements, but this does not appear to be critical. In addition, monthly or seasonal climatological means, which are generally available, have to be utilized. If, for example, Z_1 at Station P_1 has to be estimated in terms of known Z_2-, Z_3-, and Z_4- values at stations P_2, P_3, and P_4, the reduced variance may be written as

$$\sigma_1^2\,(\text{red}) = \frac{X}{X_{11}}\;\sigma_1^2 \tag{12}$$

with

$$\chi = \begin{vmatrix} 1 & C_{12} & C_{13} & C_{14} \\ C_{12} & 1 & C_{23} & C_{24} \\ C_{13} & C_{23} & 1 & C_{34} \\ C_{14} & C_{24} & C_{34} & 1 \end{vmatrix} \tag{13}$$

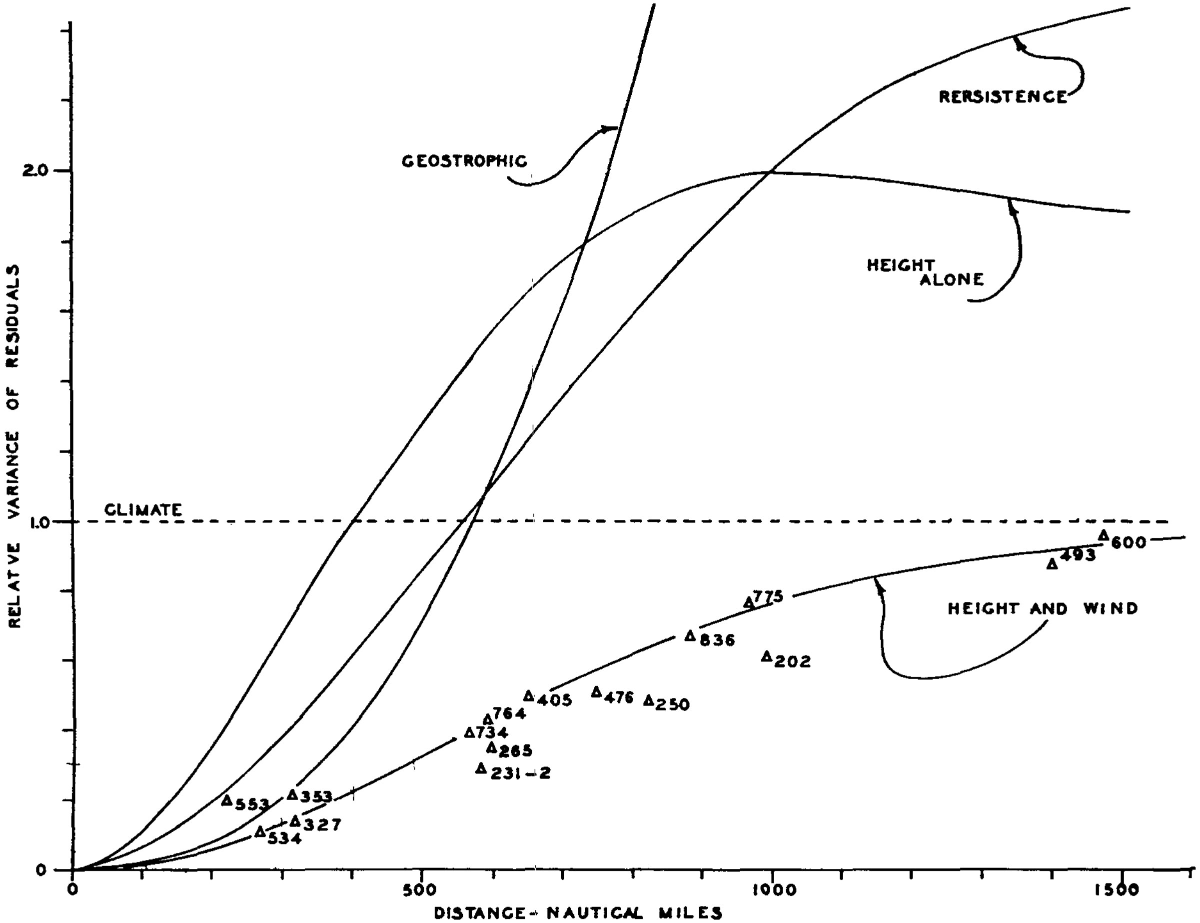
and

$$\chi_{11} = \begin{vmatrix} 1 & C_{23} & C_{24} \\ C_{23} & 1 & C_{34} \\ C_{24} & C_{34} & 1 \end{vmatrix} \tag{14}$$

The availability of two smoothed measured winds, in addition to the pressure height at the same station, is essentially equivalent to the use of three known pressure heights as far as estimation is concerned (cf. p. 5/6). It is necessary to keep in mind that the underlying statistical concept holds well only under moderate weather conditions, as described above. Additional error contributions would have to be included, depending on the degree of stability/instability. These would be of significance during pronounced low pressure situations generally associated with high wind shear.

APPENDIX

From C. E. Buell's "The Correlation Between Wind and Height on an Isobaric Surface" (reference 6). Level: 500 mb, Season: Winter.



RELATIVE RESIDUAL VARIANCE FOR SOME HEIGHT ESTIMATES

Number by data point indicates station paired with 445 to obtain value shown.

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13. ABSTRACT

This report provides a generalization of classical barometric altimetry for longer distances and explanations for some shortcomings associated with ground temperature and the weather situation. The use of weather forecasts is reviewed and error estimates under consideration of potential Army use are provided. Finally, some general views concerning the estimation of meteorological field variables are presented.

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