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The Observational Error, Correlation Functions and Structure Functions for Wind Profiling Doppler Radars: Results from the Colorado Network

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ABSTRACT

This paper presents structure and correlation functions both for the vertical and for time for the doppler wind profiler data from four profilers in Colorado for January, 1984. The structure functions are extrapolated to zero separation to get a measure of the observational error. For these two-wind-component radars, the error in each component is found to be $1.49 ms^{-1}$. The structure and correlation functions are modeled with analytic functions, considered to be preliminary.

1. Introduction

This paper describes some characteristics of doppler radar wind profiler data as determined from observations at 4 sites in Colorado during January 1984. Vertical and time correlations and structure functions for the data will be presented. Models for the correlation and structure functions will also be suggested. An extrapolation to zero height separation will be used to estimate the observational error, which include instrumental and non-representativeness error.

Doppler radars measure the radial wind components by measuring the motion of small irregularities in the refractive index. They operate continuously at VHF or UHF frequencies, providing information in the troposphere, lower stratosphere, and even mesosphere for large radars. The four radars which provided the data for this study were deployed in support of the Program for Regional Observing and Forecasting Services (PROFS) in Colorado (Strauch et al, 1984; Shapiro et al,1984). Figure 1 shows the locations of the sites. The Cahone and Lay Creek radars have subsequently been moved to sites in eastern Colorado.

A network of 30 radars is being planned, to be deployed in the midwest, in a NOAA program called the Wind Profiler Demonstration Network. Its purpose is to test the operational requirements, feasibility, and data utilization of wind doppler radars. These radar data should be valuable to the planned Stormscale Operational and Research Meteorology (STORM) project (UCAR, 1983), which will provide research observational data sets and perform experimental forecasts. On the planning horizon is a network of nationwide radars, with a spacing equal to or better

than that of the radiosondes. The operational feasibility of using radar data has been discussed by Larsen (1983) and Balsley and Gage (1982).

As outlined above, this paper will concentrate on statistical measures. The correlation models presented must be considered provisional. The models are useful in future quality control of the data and for optimum interpolation of profiler data when the background used for the analysis is the "normal" value of the winds. The structure function is useful, as already noted, in determining the observational error level of the data. The saturation level of the structure function--the value for large time differences--can be used to determine the variance of the wind for the time period in question.

The errors in doppler radar measurements come from instrumental error, contamination of the signal by electromagnetic "noise", sometime originating from nearby transmissions, and by precipitation, from unrepresentativeness of the sampled volume, and spurious targets. This study enables determination of the sum of instrumental and contamination errors, here called observational error; errors of unrepresentativeness will depend upon the use of the data.

While this study includes data from only half a month, the analysis has been repeated for the Denver profiler (for medium and high modes only, to be explained in the next section) for each month of 1985. All the essential features to be described in this paper hold for those data. However, the data discussed here are more complete and therefore more suitable

for the statistical procedures used in this study.

Some aspects of the profiler performance are affected by the weather, particularly precipitation, but those differences are primarily a quality control problem. This paper concentrates on a statistical measure of the profiler error which is not sensitive to the meteorological regime. The correlation functions derived are not what is required by the optimum interpolation (OI) analysis technique, but they are calculated with OI in mind. Therefore, a stratification has not been made of the data by weather characteristics. Rather, it is appropriate to include a range or conditions. In that sense, a longer period would be preferable for later studies.

2. Wind Profiler Data

The data for this study are for the period 16 January to 30 January 1984 for the following sites: Denver, Fleming, Lay Creek, and Cahone, Colorado. They operate with different resolutions at different heights. The Denver radar uses three resolutions: 0.1 km, 0.29 km, and 0.87 km for the height ranges 0.3-2.5 km, 1.6-8.2 km, and 2.6-13.9 km above ground level, respectively. This radar operates at 915 MHz. The other radars operate at 50 MHz and have two vertical resolutions: 0.29 km and 0.87 km. For Fleming, the height ranges for these resolutions are 1.7-8.4 km and 2.6-17.4 km above ground level. Because of the overlap in the height ranges, there is redundancy of observations at some heights. The time averaging interval for the data is one hour.

A gross error check is necessary to insure that large and easily identifiable errors in the data do not contaminate the

results. The gross error check is performed individually for each of the four radar sites and compares each piece of data with the half-month ensemble within its height interval. One kilometer intervals are used in the vertical, from 1 to 20 km above ground level. Therefore, the ensemble will contain a minimum of 15 (days) times 24 (hours) or 360 pieces of data. Data are rejected if a wind component differs from the mean of all the data for the period of study and height interval by more than $30 ms^{-1}$ or by more than three standard deviations of the sample. The gross check leads to about 600 out of 45,000 observations being rejected.

3. Structure and Correlation Functions

The use of structure and correlation functions in the analysis of meteorological data was introduced by Gandin (1963) in a method which optimally minimizes the interpolation error. These statistics form the basis for comparison of data from different observing instruments. The structure function, which is related to the correlation function, can also be used to obtain a measure of the observational error.

The structure function describes the mean-square of the difference of a pair of observations from the climatological mean at the two points. The structure function is defined as (Gandin, 1963; Morone, 1986)

$$b_f(s_1, s_2) = \frac{1}{n} \sum_{i=1}^{n} [f'_i(s_1) - f'_i(s_2)]^2 \qquad (3.1)$$

where

$$f'(s) = f(s) - \bar{f}(s) \qquad (3.2)$$

and $\bar{f}(s)$ is the climatological mean of observations of a variable f at s: f(s). The variable can be either space or time. The structure function can be related to the variance and covariance of f:

$$b_f(s_1,s_2) = var_f(s_1) + var_f(s_2) - 2\,cov_f(s_1,s_2) \qquad (3.3)$$

where

$$var_f(s) = \frac{1}{n}\sum_{i=1}^{n}[f'_i(s)]^2 \qquad (3.4)$$

and

$$cov_f(s_1,s_2) = \frac{1}{n}\sum_{i=1}^{n} f'(s_1)f'(s_2) \qquad (3.5)$$

The observations may have a mean error and a random error. The mean error may be determined by comparison with an independent instrument of known bias. The random error of observation can be determined by the method which follows.

Let the values be given as a sum of the true value and a deviation, assumed to have a random distribution with zero mean. The author is not aware of direct evidence that profiler winds do or do not in fact have a zero mean.

$$f(s) = f_T(s) + d \qquad (3.6)$$

and thus

$$f'(s) = f'_T(s) + d \qquad (3.7)$$

With this definition, the structure function can be written as

$$b_f(s_1,s_2) = \mathrm{var}_{f_T}(s_1) + \mathrm{var}_{f_T}(s_2) - 2\,\mathrm{cov}_f(s_1,s_2)$$

$$+ \mathrm{var}_d(s_1) + \mathrm{var}_d(s_2) \tag{3.8}$$

The limit for zero separation is

$$\lim_{s_1 \to s_2} b_f(s_1,s_2) = 2\,\mathrm{var}_d(s) \tag{3.9}$$

Therefore, the error variance can easily be determined from the structure function.

This paper considers both the vertical and time structure of the wind profiler data. One usual assumption is that the structure of meteorological data is homogeneous and isotropic. This assumption seems justifiable for time but the correlations to be presented show that the data are not homogeneous or isotropic in the vertical. However, when homogeneity and isotropy can be assumed, then the structure function can be related to the correlation function. Letting

$$\tau = |t_1 - t_2| \tag{3.10}$$

the structure function can be written

$$b_f(\tau) = 2\,\mathrm{var}_{f_T}(0) - 2\,\mathrm{cov}_f(\tau) + 2\,\mathrm{var}_d(0) \tag{3.11}$$

The correlation function in time for f is defined as

$$\mathrm{corr}_{f_T}(\tau) = \frac{\mathrm{cov}_f(\tau)}{\mathrm{var}_{f_T}(0)} \tag{3.12}$$

and the structure function in time can be written as

$$b_f(\tau) = 2\,\mathrm{var}_{f_T}(0)\,[1 - \mathrm{corr}_{f_T}(\tau)] + 2\,\mathrm{var}_d(0) \qquad (3.13)$$

showing the desired relationship.

This paper will show both structure and correlation functions for wind components from the profiler data. Because of the variability in the vertical locations of observations between radar sites, the data have been grouped in 1 km vertical intervals from 1 to 20 km above ground level. Each member in each group is compared with data at heights above (for the same time) for the spatial statistics and compared with data at later hours (for the same height interval) for temporal statistics. The data distribution gives between about 200 and 60,000 comparisons in height for each height group and between 200 and 75,000 comparisons in time for each time group. For both types of comparison, the upper levels have the smallest data samples. The correlations of data with data at a lower height are obtained by the symmetry:

$$\mathrm{corr}_f(z, z-dz) = \mathrm{corr}_f(z-dz, z) \qquad (3.14)$$

where dz is a positive height difference. Time correlations are symmetrical with respect to zero difference.

4. Results

Structure functions and correlations were calculated independently for the east-west and north-south wind components and for the four radar sites for the period of study. The results are similar, so only combined statistics will be shown and discussed. Figure 2 shows the sample correlations at heights above the

ground with respect to height separations. Within a few kilometers of the surface the correlation falls off rapidly with height separation. It also falls off as the sum of height and separation approaches about 14 km or greater above ground level, showing poor correlation across the jet level, and perhaps reflecting more frequent error and a much smaller sample size at higher levels. The anisotropy and nonhomogeneity of the correlation statistics are easily seen from the data. For example, at 3 km height above the ground, the correlation with winds at greater heights is above .50 up to 13 km, or 10 km above the data level. The correlation falls off rapidly with data below, becoming small near the ground, only 3 km below. If we look at 11 km height level, the situation is reversed--the correlation is above .50 for only 4 km above this level, but for over 8 km below this level. Therefore, modeling of the vertical correlation by a method which falls off as the square of the separation, is inappropriate for these data.

The time sample correlation is shown in Figure 3. Values of the correlation decrease rapidly with time, near the surface, and above about 14 km above ground level. At the higher levels, the profiler frequently has poor signal return. For mid-levels, the correlation decreases much more slowly, falling to 0.5 at about 12 hours and to 0.0 by about 30 hours. In all, a good time continuity is shown for the wind field. For wind correlations in time, isotropy is guaranteed since there is no reason to suspect a preferred direction. A measure of the homogeneity can be obtained by splitting the data into subsets, but this has not been done.

Figure 4 shows the wind structure function on height above ground level and height-separation axes, derived from the data. There is a nearly linear increase in value at all heights for small height separations. The structure function is greatest along the two lines z+s = 7 km and z+s = 18 km, where z is the height above ground level and s is the positive separation distance. The largest values are about $350 m^2 s^{-2}$.

Figure 5 shows the time structure function derived from the data. There is a steady increase with time at all heights up to about 15 km. The most rapid increase is near 7 km above station level. For the radar sites in Colorado, this level is near the tropopause. There is also a region of high values above about 16 km which shows no coherent time dependence, due to the erratic signal return above this level. The maximum value at 7 km is about $500 m^2 s^{-2}$, occurring at about 40 hours. The correlation also falls most rapidly at this level, reaching 0.0 at 26 hours. Values extrapolated to zero separation give 1.49 with a standard deviation of $.45 ms^{-1}$ as an average wind component error. The extrapolation is made from data at 1 and 2 hour time separation for the lowest 9 km where the data are most reliable. Strauch, in an ERL NOAA Report (1986) gives an error value of $1.5 ms^{-1}$ for two-beam profilers in good agreement with these results. Better agreement should not be expected since errors of un-representativeness can differ. Other estimates of profiler accuracy appear in Kessler et al (1985), Lawrence et al (1986) and Strauch et al (1986a,b).

5. Correlation Models

At this stage it is felt that it would be most useful to suggest separate models for the height and time correlation variations. It is implicitly assumed that the height and time variations are independent.

A model for the height variation which incorporates a decrease with separation, with approach to the ground, and with approach to 16-18 km is

$$c(s,z) = k_1 \exp(-k_2 s^2)\exp(-k_3 (z+s)^a)(1.-\exp(k_4 z^b))$$

with

$k_1 = .95$ $\quad k_2 = .01$ $\quad k_3 = 6.72\times10^{-14}$

$k_4 = -.693$ $\quad a = 11.2$ $\quad b = 2.0$

k_1 is taken as constant since the height variation for zero separation will be included with the time correlation model. Heights and separations are measured in kilometers. Figure 6 shows the modeled height correlations. It compares reasonably well with the observed correlations below 10 km.

The model for the time correlation uses a familiar exponential decrease with the time separation squared and a function of height. It is

$$c'(t,z) = k_5(z)\exp(-k_6(z)t^2)\exp(-k_3 z^a)$$

with $k_5(z) = \{.72, .74, .81, .99, .97, .95, .95, .96, .97, .98, .95, .88, .81, .65, .6, .5, .35, .15, 0., 0., 0.\}$ and $k_6(z) = \{.13, .08, .03, .008, .008, .008, .008, .007, .005, .004, .004,$

.005, .005, .0, .08, .01, .02, .02, .02, .02, .02, .02} for z at 1 km intervals from 1 to 21 km.

The last factor uses the values of k_3 and a from above; this factor greatly reduces the values above 14 km as observed. The values of k_5 are chosen to make the zero time separation values agree with the observations, while the k_6 values tune the correlations to the observed variations with time at each level. The modeled time correlations are shown in Figure 7. The values suggested for the constants are approximate.

The agreement of the modeled height and time correlations with the observations is qualitatively good, but this does not mean that the same values or forms would be appropriate to other sites, time periods, or other instruments. The upper limit of observation is limited both by the radar--e.g. by its power and frequency--and by the atmospheric properties of the reflecting eddies. Therefore, the approach to zero correlation, which occurs at the upper limit of the instrument sensitivity, would occur at different levels, depending upon the instrumental characteristics. The models presented here represent the data for this study, and perhaps they can find wider application.

6. Discussion

Correlation functions, and the related structure functions, have been used to investigate the structure of winds obtained by wind profiling doppler radars. The structure functions have also

been extrapolated to zero height separation to obtain a measure of the observational error.

The results support the idea that the wind profiler data represent an accurate, coherent data source which should be of important use to operational meteorology. The error level of wind profilers can be compared with the error standard deviations used in the National Meteorological Center global data assimilation system (Dey and Morone, 1985). The radiosonde error standard deviations used vary from 1.8 ms^{-1} at 1000 mb to 5.9 ms^{-1} at jet level. The value that has been obtained in this study for wind profilers is largely independent of height and is about 2.1 ms^{-1} for the vector wind. Not only are the data accurate, but they provide good vertical resolution and excellent temporal resolution. While the temporal correlations show statistically good continuity in time, an examination of plots of the data shows abrupt wind changes with frontal passages. Thus, high temporal resolution is most useful when the weather is significant.

One area for concern is the quality control of the data. Some flaws in the data are obvious. Other, less obvious flaws are harder to determine. Brewster and Schlatter (1986) are working on this problem, which involves both the initial data reduction and the later elimination of suspect reports. The observational error estimate obtained by this work is probably an overestimate since the quality control of the data was not sophisticated enough to remove all suspect data.

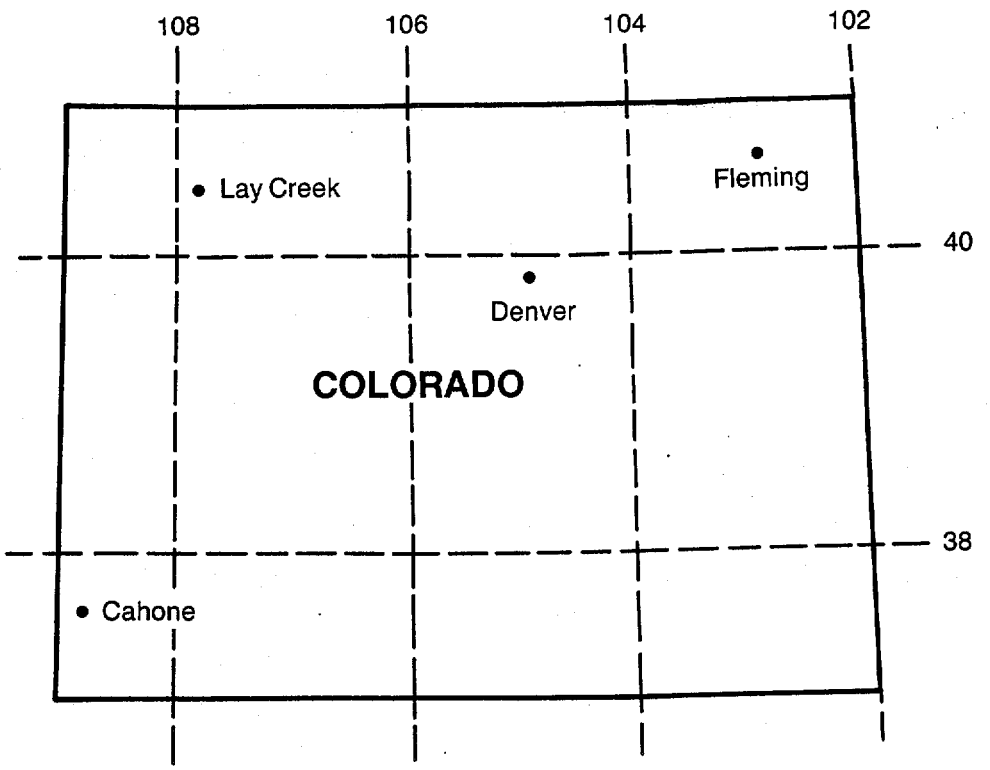

Figure 1. Location of profiler sites.

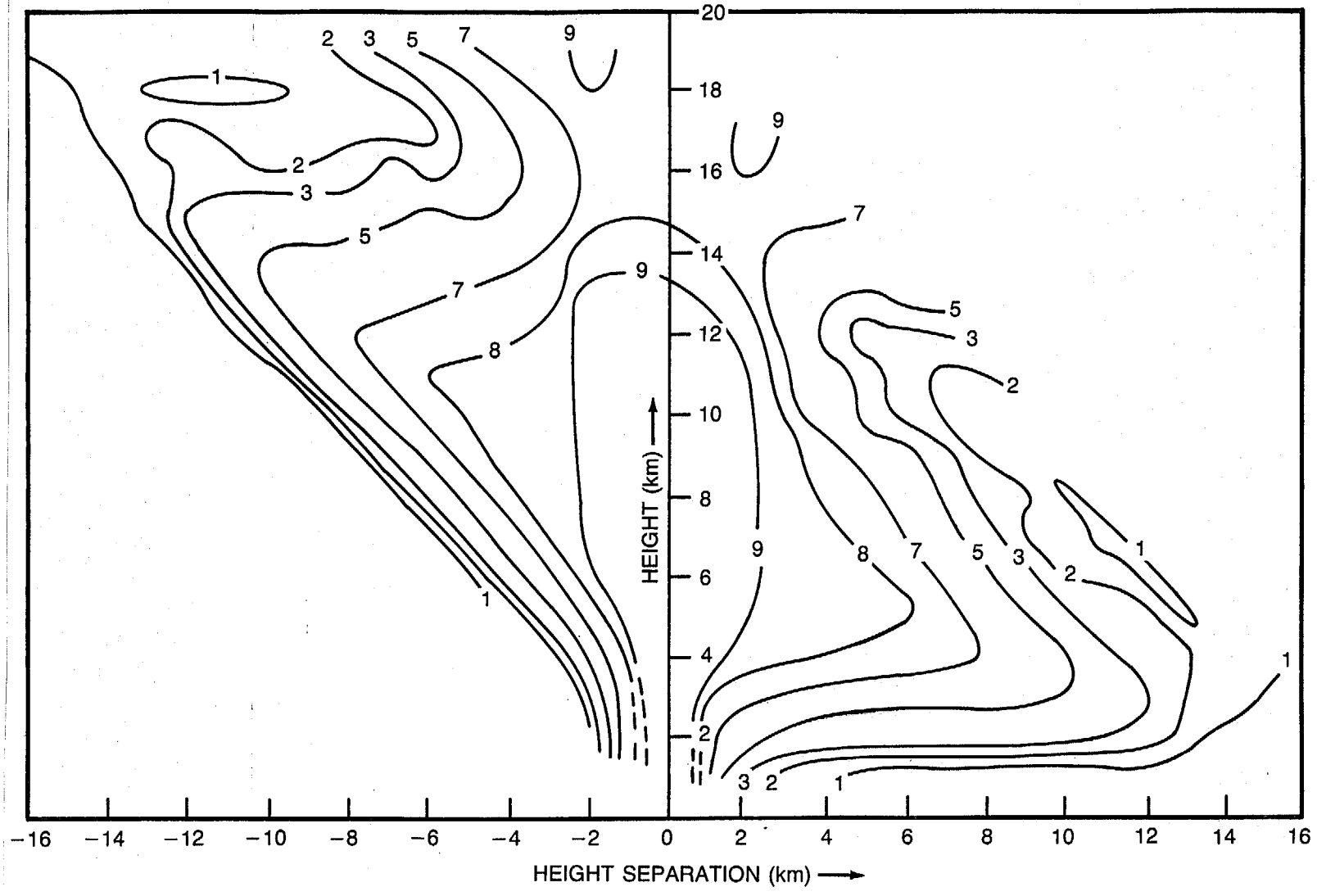

Figure 2. Observed height correlations (in 10th's).

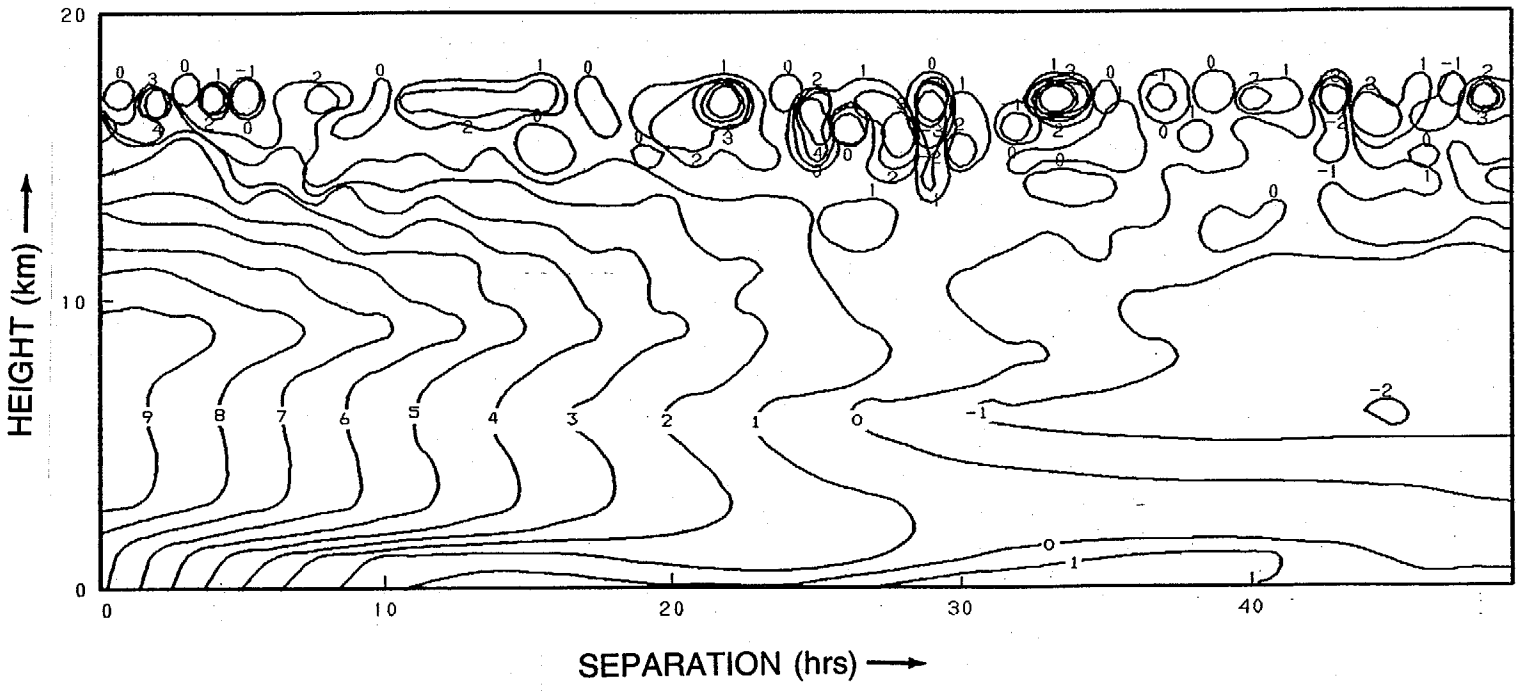

Figure 3. Observed time correlations (in 10th's).

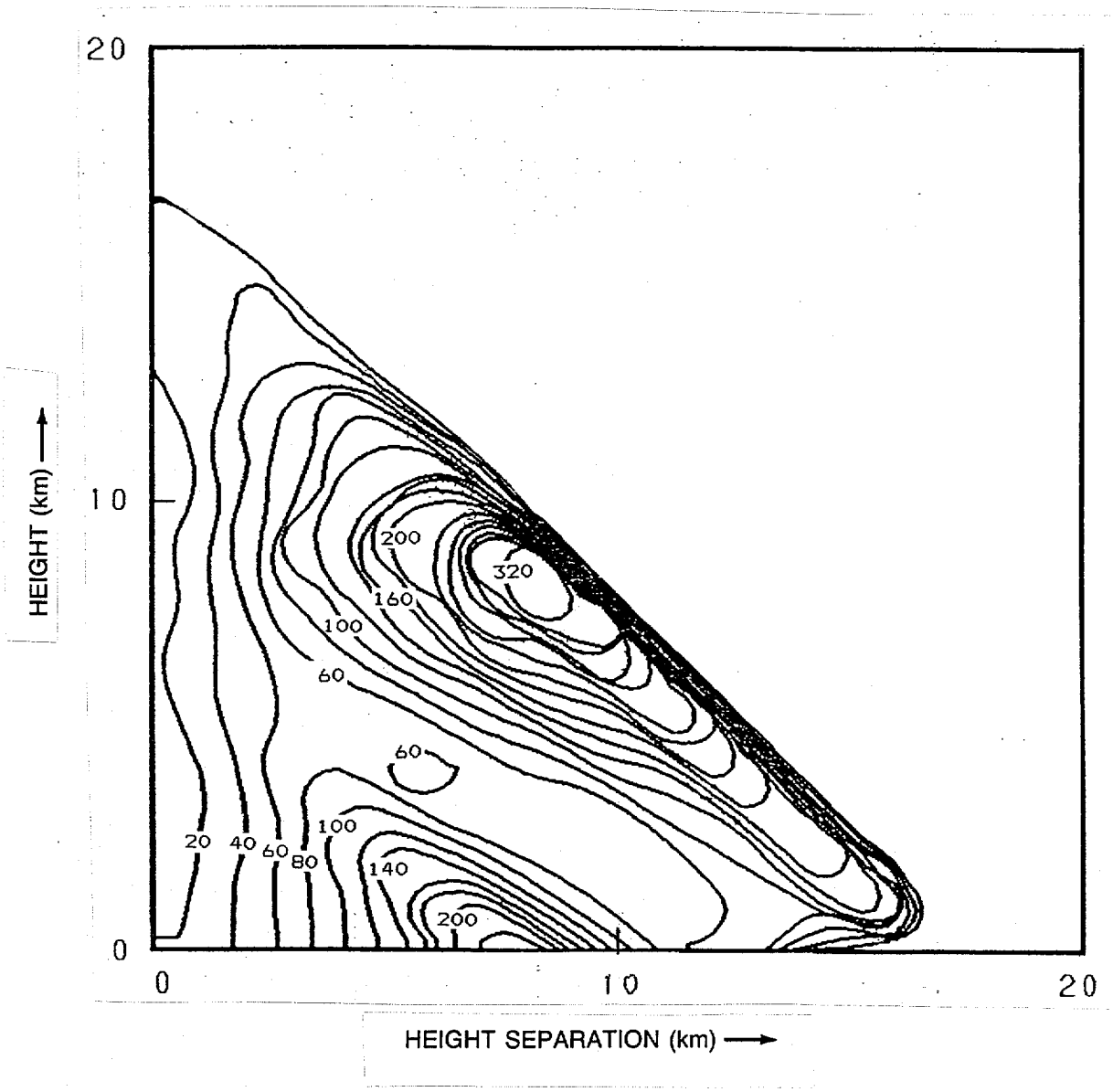

Figure 4. Observed height structure function ($m^2 s^{-2}$).

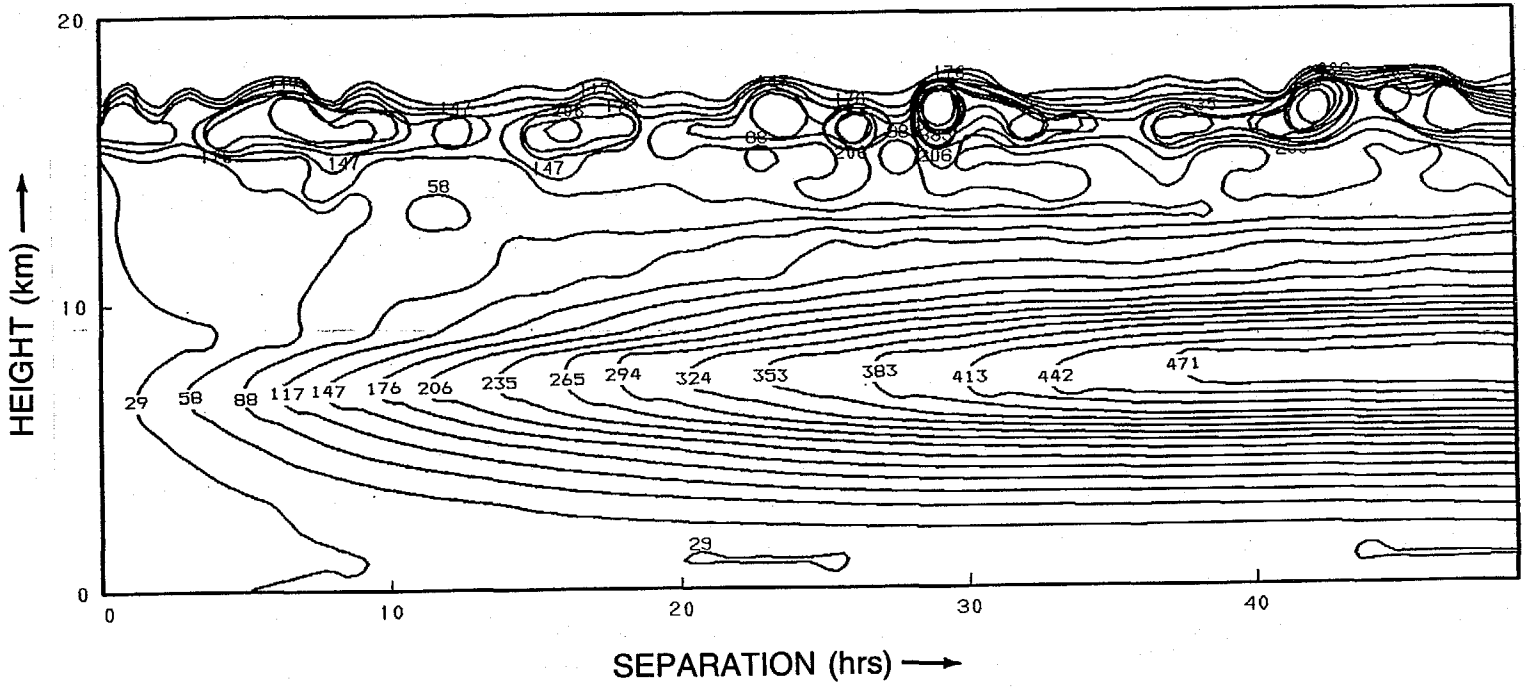

Figure 5. Observed time structure function ($m^2 s^{-2}$).

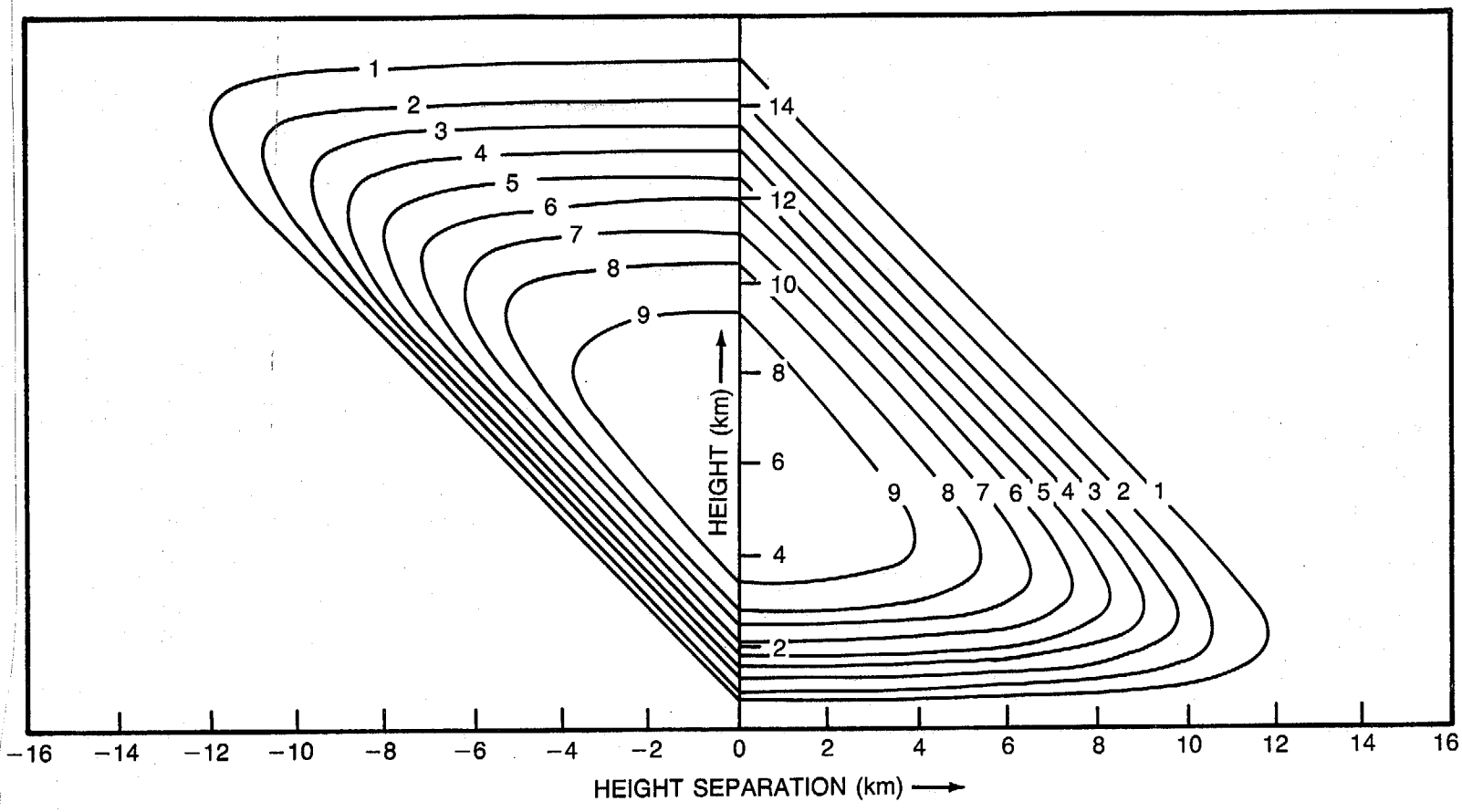

Figure 6. Modeled height correlations (in 10th's).

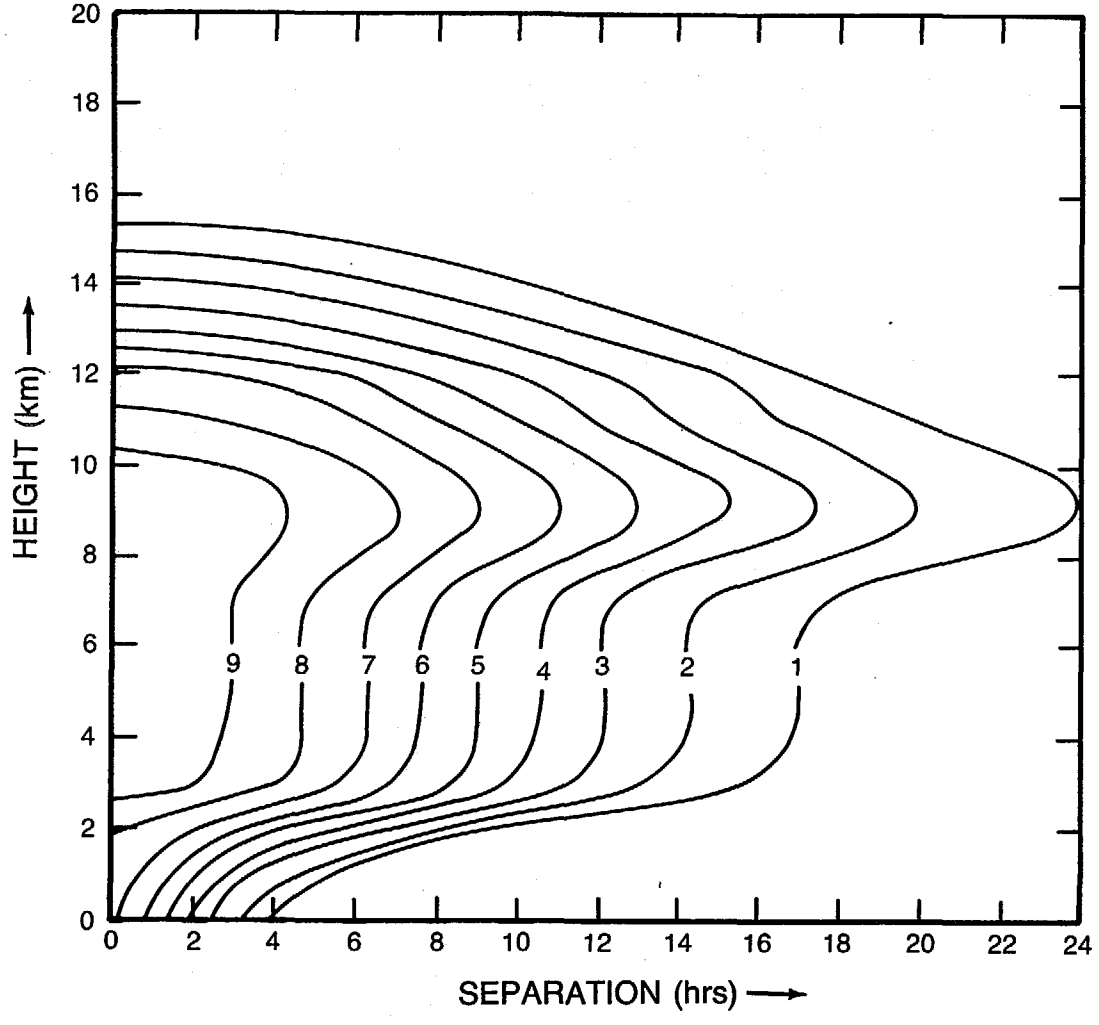

Figure 7. Modeled time correlations (in 10th's).

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