Inferring Spatial Cloud Statistics from Limited Field-of-View, Zenith Observations

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Introduction

Many of the Cloud and Radiation Testbed (CART) measurements produce a time series of zenith observations, but spatial averages are often the desired data product. One possible approach to deriving spatial averages from temporal averages is to invoke Taylor's hypothesis where and when it is valid.

Taylor's hypothesis states that when the turbulence is small compared with the mean flow, the covariance in time is related to the covariance in space by the speed of the mean flow. For cloud fields, Taylor's hypothesis would apply when the "local" turbulence is small compared with advective flow (mean wind).

Thus, if Taylor's hypothesis holds

$$R(dt) = R(dx) \text{ and } dx = U\ dt \qquad (1)$$

along the direction of the mean wind, where R(dt) is covariance in time, R(dx) is covariance in space, and U is the speed of the mean wind. That is, the temporal covariance of the cloud field at a fixed location and the spatial covariance along the direction of the mean wind are the same when Taylor's hypothesis holds.

The objective of this study is to determine under what conditions Taylor's hypothesis holds or does not hold for broken cloud fields. We use one-dimensional and two-dimensional correlations to evaluate the applicability of Taylor's hypothesis. By way of illustration, we use a time series of small field-of-view, zenith measurements of cloud cover to estimate the cloud cover fraction over a 112° view of the sky dome. This is analogous to using a time series of ceilometer measurements indicating cloud/no cloud to determine the cloud cover fraction. We identify the conditions under which the time series can yield reliable estimates of the cloud cover fraction. Whole-sky images (WSIs) provide a useful data set for this evaluation, because the time series cloud cover fraction results can be validated with the 2-D images.

The WSI Data Set

The WSI data set used in this analysis was collected at White Sands, New Mexico, during May 4-5, 1992. Images were acquired using two Scripps, E/O 5 WSIs placed about 5 km apart. This data set was originally used to develop algorithms to determine the cloud base height from paired WSIs (Allmen and Kegelmeyer 1994). The WSI has a fish-eye lens that provides wide field-of-view images (~165 degrees) of the sky dome with an angular resolution of ~1/3 degrees. The images are equal-angle projections with the distance from the zenith in the image being proportional to the zenith angle in the scene. Depending on the cloud height, horizontal cloud distributions from 10 km to 50 km in horizontal extent can be recorded.

A few comments on the character of the WSI images as related to processing the images are appropriate. Because the WSI views clouds from beneath, primarily bottoms of clouds are seen near the center of the WSI image, and progressively more of the sides of the clouds are seen as the view approaches the horizon (i.e., edge of the image). In addition, because of the projection properties of the fish-eye lens, the clouds appear to be more strongly distorted from their apparent shape in the scene, the closer they are to the horizon. Because a common focus is difficult to achieve for a wide field of view, the clouds scenes are slightly blurred at the edge of the image. Also, because of the changing scattering angle, the image is darker away from the sun. These effects will affect the accuracy of the cloud statistical calculation.

Several corrections are done to reduce these effects that would otherwise bias the statistical calculation. First, the dependence of the gray level on the scattering angle is calculated from an overcast stratus cloud image. Based on the relationship of gray level to scattering angle, a range of thresholds is determined to detect and to filter out bright cloud sides from the image. Then the images are normalized to make the gray level more uniform. Finally, the image is "flattened" using a Pseudo-Cartesian coordinate transformation to reduce the projection distortion of the fish-eye lens.

Testing Taylor's Hypothesis

Taylor's hypothesis is often used in field experiments to save the expense and effort of data sampling over a wide area (Powell and Elderkin 1974). Taylor's hypothesis states that if the turbulence is small compared with the mean wind, then the temporal covariance of the cloud field at a fixed location and the spatial covariance along the direction of the mean wind are the same (Taylor 1938). In Atmospheric Radiation Measurement CART sites, many of the measurements are restricted to zenith views of the atmosphere. To see how the fixed point temporal observation can be used to infer the spatial cloud length scale, Taylor's hypothesis is tested for a variety of cases.

First, the horizontal mean wind of the cloud scene is obtained by using cross-correlation techniques (described in the next section). Then the time series of a fixed point in the image in the down-wind direction is extracted from the image. The correlation function of the time series is calculated and compared with the correlation function of the spatial line sampled along the mean wind direction. Figure 1 shows where Taylor's hypothesis holds [i.e., where R(dx) ~R(Udt)]. The images used for this analysis were acquired during a period of one hour in which individual cumulus clouds with a mean cloud base height of about 2.5 km were distributed in a region of about 10 km in the WSI field of view and the mean wind was near constant and about 3.1 m/s (7.5 pixel/min). The results shown in Figure 1 indicate that in about 125 pixels (3.1 km or 17 min), the temporal and spatial correlation functions are similar. Taylor's hypothesis holds during this period of time and over this distance.

Deriving Cloud Cover Fraction from Time Series Measurements

If Taylor's hypothesis holds, spatial averages can be determined from temporal averages. To illustrate this for broken cloud fields, we determine the cloud cover fraction from the

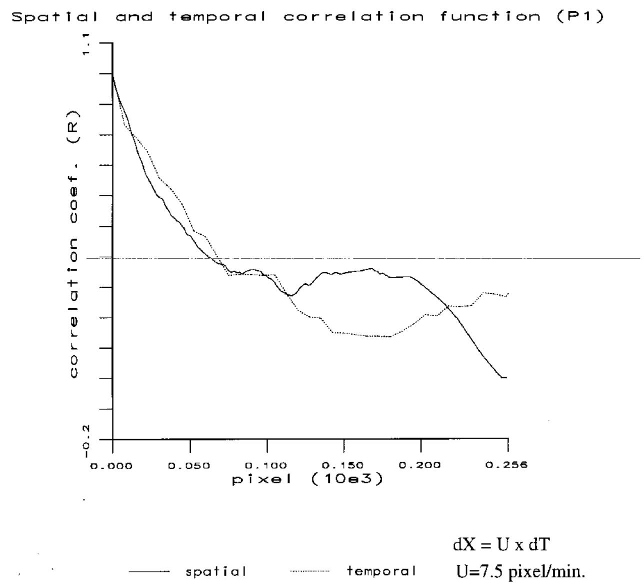

Figure 1. Taylor's hypothesis holds over the range where R(dx)~R(Udt), about 125 pixels. Where Taylor's hypothesis holds, time-series averages can be used to derive spatial averages.

WSI data from a small 15 x 15 pixel (5° x5°) field of view of observation with a moving-window average of 40 minutes. We compare this with the actual cloud cover fraction obtained from wide-field-of-view images (~112 degree). Figure 2 shows the comparison for May 4, 1992. The marks, 1-7, represent different clouds and processes types in the time periods indicated. They are

1. St cloud overcast
2. Broken and decaying St
3. Decaying St and some Cu
4. Individual Cu
5. Clustering and vertically developing Cu
6. 1/2 image clear and horizontal wind shear
7. New, big clustering Cu moving in to view.

When Taylor's hypothesis holds, the time series cloud cover approximation is close to the real situation (i.e., the 1/2-spacial average).

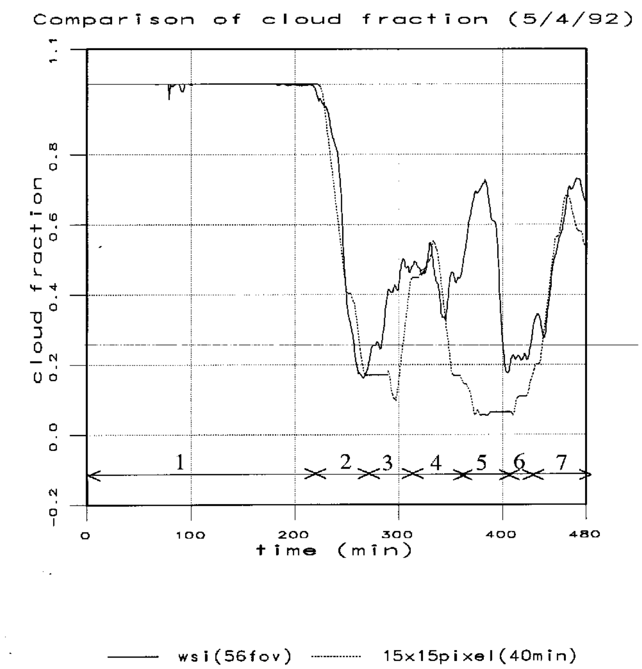

Figure 2. To test Taylor's hypothesis, we use a time-series in the zenith cloudiness to infer the spatial cloudiness (i.e., the cloud cover fraction). Taylor's hypothesis holds where the two curves are nearly equal.

After analyzing different cases for various cloud types and conditions for the May 4-5, 1992, data, we find the following for the applicability of Taylor's hypothesis.

Mean Wind Determination

We calculate the mean wind from the cross-correlation function of two sequential cloud images. First the cloud base height is calculated from pairs of WSI images which are taken from two WSIs separated by 5 km (Allmen and Kegelmeyer 1994). Next, the cloud horizontal displacement can be found from the spatial lag of the maximum of the cross correlation coefficient from the zero lag position. The mean wind is obtained by dividing the displacement by the time lag. Our results show that while the mean wind velocity can be determined in this way, sometimes the calculated wind speed is slower than the real wind. Additional image correction will have to be done to make this approach more reliable. The possible errors come from some stationary but small population noises. These come from either very bright or dark spots in the original images or are introduced when doing the flattening and pixel interpolation following flattening.

2-D Cloud Correlation Function

In this study, 2-D auto- and cross-correlation functions are calculated by first calculating the fast Fourier transform (FFT) of the two images to be correlated (same image for auto correlation; original and time-lagged image for cross correlation), then multiplying the two images together and applying inverse FFT with appropriate normalization to obtain the correlation function.

The 2-D auto-correlation function of the image can be used to show the spatial morphology of the cloud field. By comparing the auto-correlation at various times, the changes in the cloud field can be shown. Figure 3 shows an example of the 2-D auto-correlation function of a cumulus cloud field. The positive contour lines show the coherent structure of the individual cloud and the negative contour lines show the clear sky. The coherent cloud length scale is about 120 pixels (i.e., about 3 km in this case). This is similar to the results shown in Figure 1 for the 1-D correlations.

Combing the correlation function and the mean wind, we can demonstrate when the Taylor's hypothesis holds.

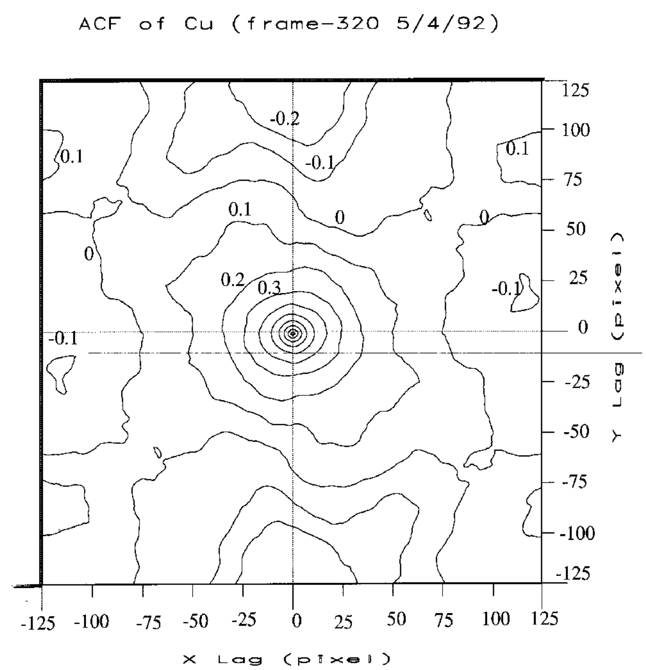

Figure 3. 2-D auto-correlation of a cumulus cloud field. Positive contours indicate the coherent structure of the field. The coherence length is about 120 pixels, consistent with the 1-D correlations shown in Figure 1.

Conclusion

It is often desirable to infer spatial properties of cloud fields from CART zenith, time series observations. This can be done using Taylor's hypothesis when it applies. In this study we have identified some conditions in which Taylor's hypothesis holds and when it does not hold for broken cloud fields. These are summarized in Table 1. In brief we have found that

1. Spatial averages can be inferred from time averages when Taylor's hypothesis holds.

2. Taylor's hypothesis holds for a variety of broken-cloud conditions, generally for cumulus and for mostly overcast stratus.

3. Correlation techniques (giving spatial correlation and mean wind) provide an indication for when Taylor's hypothesis is valid.

4. Correlation techniques can also be used effectively to determine the mean wind speed and direction from WSIs and cloud base height under uniform wind conditions.

Table 1. Conditions and cloud types for which Taylor's hypothesis holds.

Holds for these conditions: • Wind has uniform speed and direction • Statistically homogeneous over horizontal region of greater than 10 km
Generally holds for these clouds: • Stratus (mostly overcast) • Individual Cumulus • Advection of large cumulus
Does not hold for these conditions: • Wind changing in speed and direction • When cloud are developing rapidly • When clouds are dissipating rapidly • When there is horizontal wind shear • When more than one cloud deck exists
Generally does not hold for these clouds: • Cirrus • Clustering cumulus with vertical development • Mostly broken stratus

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