The Relation Between Cloud Pattern Motion and Wind Shear

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ABSTRACT

Cloud motions in the immediate vicinity of a tropical disturbance, measured with geosynchronous satellite data, were compared with independent aircraft wind observations by Smith and Hasler (1976). These data have been further analyzed here to determine whether a component of cloud pattern motion might be associated with vertical shear.

An association was detected between vertical shear and cloud pattern motion only in the region of enhanced convection east of the disturbance center. The shear-related effect is to produce a motion component (probably cloud generation) that can add to or subtract from the speed and direction of the cloud patterns as they are advected by winds in the cloud layer.

1. Introduction

Wind estimates based on satellite-tracked clouds have become an important source of meteorological information. The National Environmental Satellite Service routinely provides this type of data over a large latitudinal zone from 20°W to 170°E longitude and other nations plan to operate their own systems to complete the girdling of the globe. It is therefore important that we understand the mechanisms that may cause differences between satellite wind estimates and other wind observations.

Convective clouds over oceans provide most of the low-tropospheric wind tracers because they are abundant and well-suited to tracking by various methods. But convective clouds are not inert bodies. While the air parcels are carried along by the wind, individual clouds appear and disappear—some with a lifetime no longer than 30 min. Most cloud displacements are measured from images which are taken at half-hour intervals. It is clear that imagery with 7 km resolution, taken at half-hour intervals, cannot depict the motion of these individual cumuli. What, then, are the targets which are tracked?

Animated sequences taken at different time intervals reveal that mesoscale patterns of trade cumuli and cumulus congestus have lifetimes of the order of hours. Vertical motions organized into mesoscale patterns produce clouds in their upward moving branches and suppress clouds in their descending branches. Sometimes these patterns are comprised of polygonal cells (Hubert, 1966), but in other conditions only irregular groups of cumuli are observed to retain their size, shape and spacing for many hours. These are the mesoscale patterns which are tracked as they are carried along with the wind. Fortunately, many studies have shown that the motion of these patterns is not very different from the air motion—hence the value of these measurements as a source of wind observations.

Little is known about convective dynamics on this scale. It appears that heat exchange may be proceeding at two dominant scales, that of the individual cumulus cell and that of the slower but more massive mesoscale overturning. Where this complex circulation is embedded in a vertical sheared layer, some interaction might be expected between vertical shear and the motion of these mesoscale patterns. This communication examines the data and analyses published by Smith and Hasler (1976) for evidence of such interaction.

Earlier studies have shown that the motion of low cloud patterns correspond closely to the wind near cloud base. Hasler et al. (1976) conducted a multi-aircraft experiment to measure simultaneously cloud motions and winds at various levels. The report of a similar experiment presently being prepared by Hasler (private communication) further documents this tendency. Hubert and Timchalk (1972) analyzed satellite winds in connection with BOMEX ship data and also showed that patterns tended to move with cloud base winds. The agreement was much poorer than that obtained by Hasler et al. (1976), probably the consequence of less accurate data and space and time variations which did not enter into the aircraft experiments. The Hubert-Timchalk data were examined for the influence of vertical shear with no definitive results (again perhaps due to error and to the time and spatial variation). Shear effects could not be studied with the aircraft measurements presented by Hasler et al. (1976) because vertical shear was very small.
These studies suggest that shear-produced motion of mesoscale patterns (if it exists at all) may be small relative to the wind velocity that is associated with a sheared cloud layer. Nevertheless, such a motion component, even no larger than a few meters per second, could be important. If, for instance, a change of vertical shear from one local region to another could change the cloud vectors by that amount, derived patterns of divergence and vorticity might be seriously distorted.

Smith and Hasler (1976) compared the motion of satellite-tracked low clouds with wind fields observed from aircraft during the BOMEX project. They found marked variations of these deviations in various parts of a tropical disturbance and speculated that it might be related to differences in the dynamics of cloud motions in different circulation regimes. Those data afford another opportunity to search for shear effects. Their analysis of aircraft-measured winds provides more accurate wind field analyses than was previously available. While the small number of cloud vectors and the inherent random error preclude results that are statistically significant, a tendency can be detected in the convective region behind the tropical disturbance for a shear-related component of cloud (pattern) motion. No such effects could be discerned north of and ahead of the disturbance.

2. Data and analysis

Fig. 1 is a reproduction of Smith and Hasler’s Fig. 3, showing the aircraft data for the 850 mb level and its analysis together with the cloud vectors. The aircraft observations were 1 min averages but the analysis smooths the small (space and time) scales. Hence the analyzed flow and the cloud vectors (derived from about 3 h trajectories) represent about the same scale
of motion. In order to correct for local wind changes caused by motion of the tropical disturbance, Smith and Hasler repositioned the cloud vectors relative to the moving system. They divided the tropical disturbance into three regions:

Region 1. The convectively active region behind (east of) the trough.
Region 2. The convectively inactive region ahead of (west of) the trough.
Region 3. The relatively undisturbed region north of the disturbance center with typical trade wind convection.

Two vectors (numbers 3 and 4 in Region 1) were grossly unrepresentative and therefore excluded from their analysis. The method and rationale for these analysis procedures is described in their paper, together with an outline of the technique used to derive low cloud vectors.

For the purpose of the present study, I have taken the wind velocities from their published 1000 and 850 mb analyses at the locations of the cloud vectors shown on Fig. 1, deleted vectors number 3 and 4, and analyzed the data separately for Regions 1–3. Two vector differences were calculated: 1000 mb wind minus 850 mb wind (V_{1000} − V_{850}) and cloud vector minus 850 mb wind (V_{cloud} − V_{850}).

The natural coordinate system used to define the sign convention is shown in Fig. 2a, while Figs. 2b and 2c are examples of these vector differences and the signs of their components. This sign convention was adopted for the convenience of the following comparisons, but it should be noted that it is opposite to the conventional sign for vertical shear.

Table 1 summarizes, by regions, deviations of the cloud vectors from the 850 mb wind and the vertical shear between the 850 and 1000 mb winds. These differences are also compared graphically on a polar diagram (Fig. 3) which will be described later.

<table>
<thead>
<tr>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta u )</td>
<td>-5.1</td>
<td>-0.02</td>
</tr>
<tr>
<td>( \Delta u )</td>
<td>5.1</td>
<td>1.1</td>
</tr>
<tr>
<td>( \Delta s )</td>
<td>0.06</td>
<td>1.8</td>
</tr>
<tr>
<td>( \Delta s )</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>( \Delta V )</td>
<td>5.5</td>
<td>2.9</td>
</tr>
<tr>
<td>( \Delta V )</td>
<td>1.9</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 1. Deviations of cloud patterns from 850 mb wind and vertical wind shear 1000 to 850 mb for 26 July 1969 (after Smith-Hasler analysis of BOMEX data).

* See text for definition of Regions.
** See Fig. 2 for definition of components.

\( \Delta u \) Algebraic mean of cross-wind component
\( |\Delta u| \) Mean without regard to sign
\( \Delta s \) Algebraic mean of along-wind component
\( |\Delta s| \) Mean without regard to sign
\( |\Delta V| \) Mean of magnitude of vector deviation or shear
\( |\Delta V|_{rms} \) Root mean square of vector magnitude deviation or shear

In Region 1 the \( \Delta u \) components of both shear and deviation were all of the same sign, while the \( \Delta s \) components were smaller and of mixed sign. The similarity or difference of signs is shown by comparing means computed with regard to sign (\( \Delta u \) and \( \Delta s \)) with component means computed without regard to sign (\( |\Delta u| \) and \( |\Delta s| \)). Thus Region 1 is characterized by direction deviation of cloud motion to the left of the 850 mb wind (\( \Delta u < 0 \)). The wind at 1000 mb also lies to left of the 850 mb wind. Deviations and shear were smaller and mixed in Regions 2 and 3.

3. Relation between shear and cloud motions deviations

Fig. 3 illustrates two aspects of cloud motions. First it reveals which cloud motions were different from the 1000 mb wind, or from the 850 mb wind, or from any weighted average of those winds. Second, a clustering of points indicates that a non-advective component of cloud motion has a fixed relationship to vertical shear. Scattering of the points might be due to the absence of any shear-related motion or to random error. These interpretations come about as follows.

The inset of Fig. 3 illustrates the manner in which the polar diagram has been constructed. The direction
Fig. 3. Relation between vertical shear and cloud vector deviation from 850 mb wind. Angle is difference in directions of those vectors while radial distance is normalized magnitude of deviation vector (see text). Inset: an example of the method of constructing this polar diagram.

of the vertical shear vector is held fixed (directed toward 0°) and assigned a normalized value of unity. Plotted points are the heads of vectors representing normalized deviations of the cloud motions from the 850 mb wind. Angles on the polar diagram represent the differences between direction of cloud vector deviation from direction of the shear vector. Radial distance \( R \) is expressed in terms of the shear magnitude, i.e., \( R = \text{(magnitude of deviation vector)} \div \text{(magnitude of shear vector)} \).

Consider two cloud vectors, the first exactly equal to the 850 mb wind and the second exactly equal to the 1000 mb wind at their respective locations. The former would produce a point at the center of the polar diagram, while the latter would be plotted at the coordinate \( \theta = 0^\circ, R = 1.0 \). Cloud motions corresponding to any weighted mean of the winds at those levels would be plotted on the line segment between those two points. Points displaced from that line segment represent cloud motions that cannot be accounted for by mixing momentum of those two levels and suggests some dynamical component. Grouping of points would indicate the dynamical component bore a fixed relationship to vertical shear.

The inset to Fig. 3 illustrates such a non-adveitive component. The point plotted at \( \theta = -30^\circ, R = 2.0 \) is the result of a cloud motion 30° to the left of the shear vector direction (as defined here) moving with a speed that differs from the 850 mb wind by an increment twice that of the shear magnitude.

Fig. 3 shows a tendency for the data from Regions 1 and 3 to lie in the quadrant from 0° to -90°, but the radial dispersion is large. Random error is no doubt a significant factor in the scatter. Smith and Hasler estimated an rms error of 2.3 m s⁻¹ for differences between winds and cloud motions. Table 1 shows such errors to be about the same as the vector means (\( \text{rms} \)) of both shear and cloud deviations in Regions 2 and 3. For that reason, little can be inferred about shear-related effects in those regions. Both shear and cloud deviations are larger than this random error in Region 1, however. Therefore, despite sizeable random errors, a tendency appears for cloud motions in Region 1 to lie to the left of the shear vector. Since the scatter of radial distance is large, no reliable estimate can be made of the magnitude of this shear-related effect, but the mean radial distance may be somewhat greater than unity. Considering that the mean shear is 4 m s⁻¹, a significant dynamic component is suggested.

In addition to random error, non-representative shear may have contaminated the data in Region 2. Subsi-
Table 2. Hypothetical examples of mesoscale pattern motions resulting from a shear-produced dynamic component: $\theta = -50^\circ$, $R = 1.0$.

<table>
<thead>
<tr>
<th>Wind at 850 mb (deg/m s$^{-1}$)</th>
<th>Wind at 1000 mb (deg/m s$^{-1}$)</th>
<th>Dynamic component (deg/m s$^{-1}$)</th>
<th>Total velocity of mesoscale pattern* (deg/m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>090/07.5</td>
<td>090/10</td>
<td>040/02.5</td>
<td>078/09</td>
</tr>
<tr>
<td>090/07.5</td>
<td>090/05</td>
<td>220/02.5</td>
<td>108/06</td>
</tr>
<tr>
<td>090/07.5</td>
<td>120/10</td>
<td>116/05</td>
<td>101/12.5</td>
</tr>
<tr>
<td>090/07.5</td>
<td>120/05</td>
<td>185/04</td>
<td>119/08.5</td>
</tr>
<tr>
<td>090/07.5</td>
<td>060/10</td>
<td>322/05</td>
<td>045/06</td>
</tr>
<tr>
<td>090/07.5</td>
<td>060/05</td>
<td>260/04</td>
<td>101/03.5</td>
</tr>
</tbody>
</table>

* Equal to 850 mb wind plus dynamic component.

dence ahead of the disturbance may have created conditions of stability and shear quite different from the other two regions. Smith and Hasler presented two hodographs for Region 2. Two vertical soundings were made by aircraft which showed wind maxima between 1000 and 850 mb. Were these profiles typical for all vector locations in Region 2, greater speeds near cloud bases could have accounted for departures of cloud motions from both the 1000 and 850 mb winds. It is plausible that shear was more nearly linear between 1000 and 850 mb in regions of active convection (Region 1), while subsiding areas (Region 2) may be characterized by profiles illustrated by the Smith-Hasler hodographs. Thus the 1000–850 mb difference may yield good estimates of shear in Region 1, but badly distorted estimates in Region 2. To test for the effect of such speculated shear, data points were recomputed for Region 2 after “adjusting” the low-level wind. The Smith-Hasler hodographs showed the wind maximum to average 22° clockwise from the 1000 mb wind and 5 kt faster. These differences were added to the 1000 mb winds in Region 2 and the shear then recomputed between the “adjusted” winds and the 850 mb wind. This is a crude simulation of a more representative value of shear within the layer of convection. These “adjusted” points for Fig. 3 (not shown) exhibited a reduced radial dispersion but about the same angular scatter.

In summary, vertical shear and deviations of cloud vectors from the 850 mb winds in Regions 2 and 3 are no larger than the estimated random error. Moreover, shear computed from 1000 to 850 mb may not be representative of the cloud layer shear in Region 2. For these reasons, no conclusions can be made concerning shear-produced motions in Regions 2 and 3. Region 1, by contrast, is characterized by larger vertical shear and larger deviations between cloud motion and the 850 mb wind. While no statistical significance can be claimed for this small sample, Fig. 3 reveals a marked tendency for the points in Region 1 to lie in a single quadrant at radial distances greater than $R = 1.0$. That is, the data from Region 1 suggest that in addition to displacement by the 850 mb winds, cloud patterns tended to be deflected to the left of the vertical shear vector (as defined here). The deflection speed appears to be at least as large as the speed difference between the 850 mb wind and the 1000 mb wind. The following hypothetical cases illustrate this effect.

For the purpose of constructing illustrative examples, let us assume there is a dynamic component whose direction lies near the median direction of Region 1 points, viz., $\theta = -50^\circ$, and assume the magnitude is $R = 1.0$. Adding this shear-related dynamic component to the 850 mb wind produces motions listed in the last column of Table 2.

4. Conclusions

This analysis of the Smith-Hasler data reemphasizes their conclusion that cloud motions near tropical disturbances do not represent wind at any one level.

In the region of enhanced convection immediately east of a tropical disturbance, deviations of the cloud patterns from the 850 mb wind appeared to be associated with the vertical shear from that level to the 1000 mb level. Because the convective cloud layer is not limited to that stratum, the data available for this study may not have been suitable to reveal the true nature of the influence of shear on pattern motion. Further study of this subject is needed. The results reported here indicate that the active parts of tropical disturbances would provide the most fruitful data.

Failure to discern any shear effect in other portions of the disturbance may have been the consequence of error and shear being about the same magnitude, as mentioned earlier. On the other hand, the possibility exists that shear effects in undisturbed regions are so small that they can be treated as random noise.

Acknowledgment. I am indebted to Mr. Clark L. Smith for providing me with a pre-publication copy of their paper and the discussions we have had concerning the problem of interpreting these satellite data. Mr. Clark generously provided a print of their Fig. 3 which is reproduced here.

REFERENCES


