A refined statistics of cloud band orientation versus the wind vector

by J. H. Reuss

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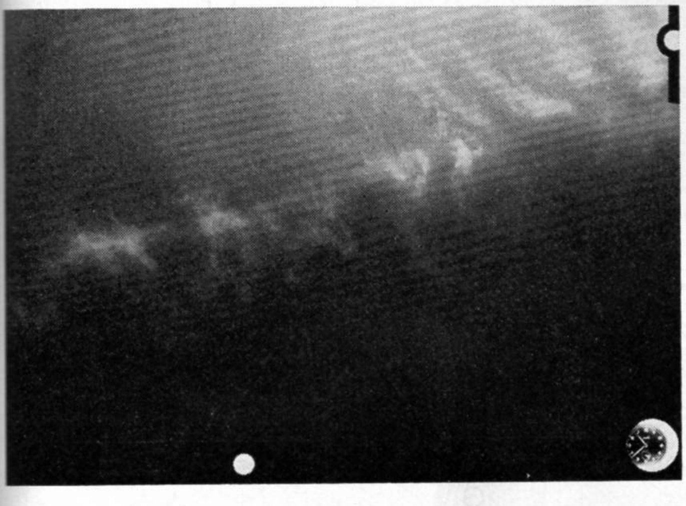

Introduction

For soaring, the knowledge of the horizontal wind vector **u** is important for an estimate both of the backing or contrary wind and the existence, position and force of hill updraught or downdraught. Due to this significance, **u** is in general of greater interest than large scale lift or subsidence since these are known to be of the order of magnitude of only 0.01–0.1 m sec^{-1}. On the other hand, the conditions of small scale updraught over local «hotspots»[1], in thunderstorm clouds and below the axes of street cumulus [3] are well known and hardly need further discussion.

Therefore this study, based upon stereo-photogrammetry [5] and RADAR observations, is devoted mainly to these questions: Which—with respect to (the orientation of) large scale cirrus bands—are the properties of (1) the wind vector **u** at band level, the coinciding wind vector $\mathbf{u}_{800mb}$ at 800 mb, and (2b) the components v of (1) and (2a) normal with respect to the cirrus band orientation and hence approximately normal to high and lower level fronts? Finally, the question will be discussed: Which is, in general, the wind vector and the orientation of temperature discontinuities at both cumulus streets and banded precipitation RADAR echoes.

The wind vector at cirrus bands

One of the major features the free atmosphere holds for the recognition of many of its respective properties are pronounced, large scale bands of cirrus and cumulus. Let us first and in full investigate the motion of the former.

Earlier research has proven that their orientation parallels a vector **s** of rather strong vertical wind shear which often would attain its maximum amount only a few hundred meters below the convective base of the cirrus. (in addition, they also parallel the isopleths of a number of parameters which have in common that they are invariant to the Galilei transformation [6]). It therefore suggests itself to define an earth-fixed coordinate system the positive s-axis of which points into the direction of vertical wind shear and hence parallels the bands. By introducing the shear direction as the positive axis, this coordinate system eliminates the ambiguity of the mere band orientation by the angle of 180° and thus permits establishment of a statistics which includes the full angle ψ_{ci} between **s** and the wind vector (fig. 1).

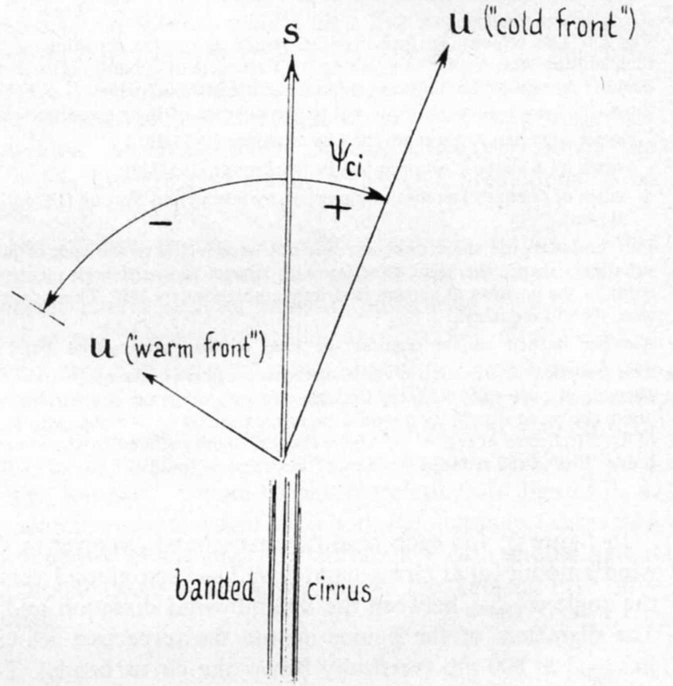

Fig. 1 – Semi-schematic representation of ci bands and the vertical shear vector **s** to which they are linked. ψ_{ci} denotes the angle from **s** to the wind direction (= band motion) at band level

Figure 2 describes a total of 37 cases of the occurrence of cirrus bands analyzed as to their motion vector. (for the extensive technical description and the sources from which the basic data were obtained, see the text to fig. 2). Two aspects of this distribution can be recognized at once: When cirrus bands move at great speed, ψ_{ci} is in by far most of the cases positive, i. e. their motion has a component to the right of s. Also, ψ_{ci} and its statistical spread keep within small amounts. Towards slower velocities, the spread of ψ_{ci} is strongly increased and reaches far into negative values. (If reduced to acute angles, ψ_{ci} obeys relation [1] described in [6] and other reports [4, 7]). Before discussing further the meaning of this result let us first investigate the wind at lower levels when cirrus bands occur.

The wind at 800 mb as related to **s** *and* **u**

For the glider pilot the wind in the lower troposphere will most often be of greater interest than that at cirrus level. Let us therefore investigate whether, and if so how, the wind at

[1] Acc. to a denotation by F. H. Ludlam.

800 mb is related to the orientation and motion of cirrus bands overhead. (The level of 800 mb has been chosen as it will in general lie just above the surface friction layer and hardly be subjected to local and thermal disturbances).

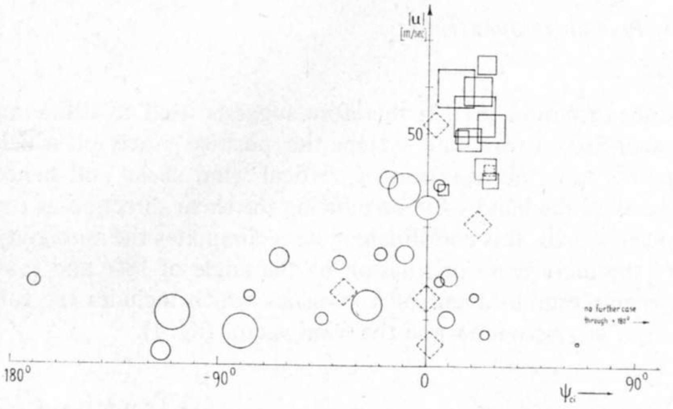

Fig. 2 – The velocity |**u**| [m/sec] of ci bands versus the direction ψ_{ci} of their motion with respect to **s** (see fig. 1). Each case of ci band occurrence is denoted by one of the following figures, the diameters of which—except for the dashed ones—are proportional to the amount of their respective shear

□ cases of ci bands photographed by Conover (1956/59)

○ cases of ci stereo-photographed in Darmstadt (1954/65)

◇ cases of ci bands stereo-photographed by Süring and Sprung (1896/97 in Berlin).

For the latter, the shear direction was not known due to the lack of pibal soundings; hence the wind direction with respect to **s**, although most probably in the position as shown, is strictly ambiguous by 180°. These squares were therefore dashed.

Another dashed square denotes the case of less pronounced banding. This statistical distribution is valid for the troposphere of the northern hemisphere, and over solid surface. For the atmosphere in the southern hemisphere the point distribution would be approximated by the reflected image of fig. 2 (reflected at $\psi_{ci} = 0$). Above the sea, slightly altered conditions may prevail due to the reduced surface friction there of low level winds.

In figure 3, for each case of cirrus band occurrence the wind amount [**u**] at cirrus band level has been plotted versus the angle ψ_{800mb} between the 800 mb wind direction and **s**. The diameters of the figures denote the respective velocity [$\mathbf{u}_{800mb}$] at 800 mb (vertically below the cirrus bands). The diagonal lines indicate whether the migration of the cirrus band itself has a component to the left side (line from lower left to upper right) or to the right side (lower right to upper left) of **s**. These diagonal lines were chosen also to symbolize vertical cross sections of warm and cold fronts. Thereby this graph demonstrates that fast moving cirrus bands not only migrate towards the right side of **s** but also are most likely to be

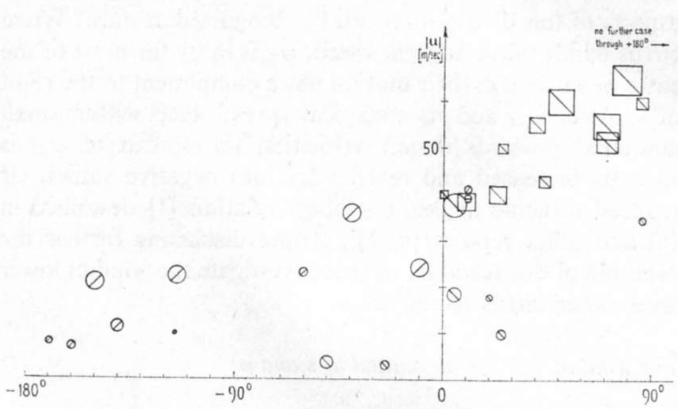

Fig. 3 – The velocity |**u**| [m/sec] of ci bands versus the direction ψ_{800mb} the wind at 800 mb—vertically below ci bands—has with respect to **s** (=ci band orientation).
Diameter $\triangleq$ speed |$\mathbf{u}_{800mb}$|, four fold of the |**u**|-scale

linked to a considerable 800 mb wind component as well directed towards the right side of **s**. Likewise, cirrus bands which move slowly and at greater angle—or nearly cross—with respect to their orientation, are likely to be linked with

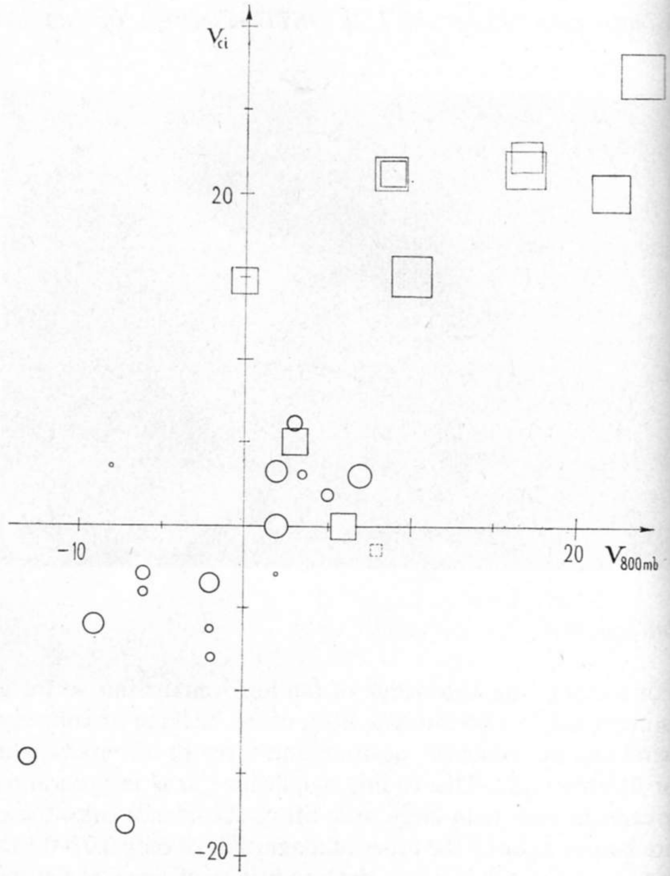

Fig. 4 – The wind components: $v = |\mathbf{u}| \sin \psi_{ci}$ versus the wind components; $v_{800mb} = |\mathbf{u}_{800mb}| \sin \psi_{800mb}$.
Both components are hence normal with respect to **s** (see also fig. 5).

an 800 mb wind which also has a component towards the same direction of sidewise migration. For the average behaviour of the motion vectors at cirrus level and at 800 mb when migrating to the left ("warm front") or to the right of **s** ("cold front") see figure 5 on the next page.

The migration of high and low level front

At this stage, the migration of fronts or boundaries of air masses normal to their orientation has to be considered. In doing so, we retain the "classical" definition according to which the main criterion of a cold/warm front—irrespective of the level at which it is encountered—is whether the cold air progresses/retreats with respect to an earth-fixed coordinate system.

Since pronounced, large scale cirrus bands are known to parallel high level isotherms (on a surface p = const.) where the horizontal temperature gradient is of rather great amount [2, 6, 7] it is evident that their position and orientation is closely related to high level fronts. We therefore make the supposition that the sidewise migration of cirrus bands, i. e. their motion component normal to **s**, well approximates the advance of the high level front in its respective direction. It should be noted in this connection, however, that in the lower troposphere, at least for cumulus streets this relation does not hold since there the vertical shear vector results from the superimposition of the thermal wind with the effect of surface friction known to cause the Ekman spiral. Due to this effect, cumulus streets in general will not parallel low level fronts but rather tend to cross them (for details see next chapter). Since fronts close to the surface are known to migrate at 80–90% of the geostrophic wind component normal to the front's orientation, and because of the experience that low level fronts orient towards the right of **s** at cold fronts and to the left of **s** at warm fronts, we may conclude that cold fronts advance at roughly the same velocity at low as at high levels; while at warm fronts the tendency seems to prevail that at high levels the front advances faster than at low levels.

The properties of vertical shear and wind at cumulus streets

A total of 14 cases of synoptic scale cumulus streets and banded RADAR echoes seems to indicate these average conditions: The vertical shear vector to which they orient parallel deviates towards the right of the thermal wind by roughly 30° due to the effect of surface and turbulence friction mentioned above. The wind direction at these cases showed a preference for the shear direction at considerable wind velocities but was almost evenly distributed to both sides of the shear vector at slow wind amounts.

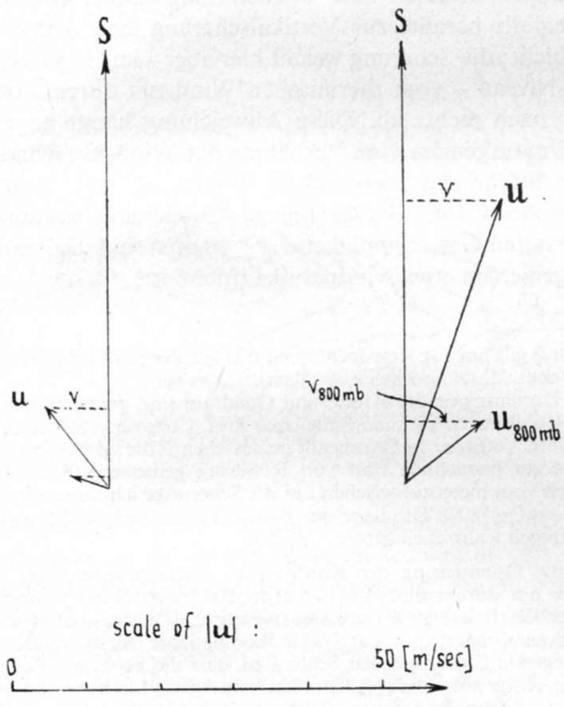

Fig. 5 – The mean directions and amounts of **u** and $\mathbf{u}_{800mb}$ with respect to **s**. For both the cirrus band level and the 800 mb level the arrows towards the right side denote the "cold front" situation, while the arrows towards the left side denote the "warm front" case.
For a better understandig of fig. 4, the v-components are shown as dashed lines

Conclusions

The results here presented (see fig. 5) reveal a few rules as well as the limits of their validity. The most reliable rule appears to be that cirrus bands which move fast and possess a component v towards the right of **s** (i. e. their orientation) are accompanied by a component v_{800mb} of the 800 mb wind of nearly the same amount. The probability of this coincidence apparently exceeds 0.9.

A less reliable coincidence is that bands moving slowly and at great angle with respect to their orientation are accompanied by an 800 mb wind which has a component $v_{800mb} \approx v/2$ also into the direction of the migration v of the cirrus bands. It can be expected that rather pronounced bands comply better to these rules than do bands of less pronounced character. At cirrus bands moving extremely slowly the spread is too great to enable reasonable predictions to be made.

The present studies are almost entirely empirical; this implies that cirrus band cases were not distinguished by synoptic citeria such as areas of positive or negative acceleration and the corresponding ageostrophic effects—these hardly reflect in the phenomenology of these clouds and can therefore not be recognized reliably by an observer. It should also be noted that inaccuracies of measurement, especially of the vertical shear but also of v, superimpose, and hence add to the statistical spread of the correlations in figures 3, 4. Measurements intensified as to both the number of cases and the accuracy of the basic meteorological data should reveal additional detail and knowledge on the subject here presented.

Literature:

[1] *Conover, J. H. (1959):* Harv. Univ., Fin. Rep. Contr. AF 19 (604)–1589; Boston, June 1959.

[2] *Endlich, R. and G. McLean (1957):* J. AMS *14*, 6, 543–552.

[3] *Kuettner, J. P. (1959):* Tellus *11*, 267–294.

[4] *Reuss, J. (1963):* Beitr. Phys. Atmosph. *36*, 173–188.

[5] *(1965):* Bildmessung und Luftbildwesen *33*, 43–51.

[6] *(1966):* Aero Revue *41*, 558–560.

[7] *(1967):* Beitr. Phys. Atmosph. *40*, 7–15.

Zusammenfassung der in vorliegendem Bericht beschriebenen Ergebnisse:

Die ungefähre Kenntnis von Windrichtung und -stärke ermöglicht dem Segelflieger, Rücken- oder Gegenwind sowie Lage und Stärke von Auf- oder Abwinden an Berghängen abzuschätzen. Ein Hinweis auf den Windvektor auch in der unteren Troposphäre (800 mb) lässt sich aus Auftreten und Verhalten grossräumiger Cirrus-Bänder ablesen.

An Hand von Messergebnissen der Stereo-Photogrammetrie [5] an Wolkenbändern sowie von Radar-Aufnahmen bandförmiger Echos werden folgende Fragen beantwortet:

1. Inwieweit hängt die Orientierungsrichtung grossräumiger Cirrus-Bänder zusammen mit den Windvektoren

1.1. **u** im Cirrus-Niveau, und mit

1.2. $\mathbf{u}_{800\text{mb}}$ im Niveau 800 mb senkrecht unterhalb der Ci-Bänder;

2. Wie korrelieren die Komponenten der Seitwärtswanderung (d. h. quer zur Orientierungsrichtung) von Ci-Bändern mit jenen des Windes in 800 mb, und

3. Inwieweit weicht infolge der Bodenreibungsschicht das Verhalten von Cumulus-Strassen von jenem der Ci-Bänder ab?

Frühere Untersuchungen haben erwiesen, dass Ci-Bänder knapp oberhalb einer Schicht starker vertikaler Scherung **s** entstehen und zu letztgenannter parallel liegen. Es empfiehlt sich deshalb, ein Koordinatensystem einzuführen, das erdfest ist und dessen positive s-Achse in Scherungsrichtung zeigt und damit zur Orientierung der Bänder parallel liegt (Fig. 1). Diese Festlegung beseitigt die ansonsten bestehende Zweideutigkeit ($\pm$ 180°) der Bänderorientierung.

Die Abweichung der Windrichtung von **s** nach rechts wird durch positive Winkel $0 < \psi < 180°$ bezeichnet (Fig. 1); wandern hingegen die Bänder nach links, so wird ψ negativ.

Aus der statistischen Verteilung ψ (**u**) von 37 gemessenen Fällen von Ci-Bändern (Fig. 2)[1] ist folgendes abzulesen: Cirrus-Bänder, die mit $|\mathbf{u}| \gtrsim 40$ m/s ziehen, haben fast stets eine Komponente nach rechts («Höhen-Kaltfront»); bei geringerer Zuggeschwindigkeit hingegen streuen die Winkel statistisch sehr stark und reichen weit in das Gebiet negativer ψ; bei sehr geringer Zuggeschwindigkeit überwiegen demnach die Fälle der (oft okkludierten) «Höhen-Warmfront».

Figur 3 stellt die Geschwindigkeit der Ci-Bänder der Richtung des (senkrecht unterhalb vorherrschenden) 800-mb-Windes in Bezug auf **s** gegenüber (vgl. auch Fig. 5). Die Durchmesser der Kreise und Quadrate sind hier proportional zur Geschwindigkeit des 800-mb-Windes gewählt (1 m/s der **u**-Skala $\triangleq$ 4 m/s in 800 mb). Diagonale von rechts unten nach links oben – sie sollen die Kaltfront symbolisieren – bedeuten, dass die «zugehörigen» Ci-Bänder nach rechts wandern. Liegen Figuren mit dieser Diagonale im Bereich positiver $\psi_{800\text{mb}}$, so liegt in 800 mb – gegenüber den Ci entsprechend seitlich verschoben – wie auch im Cirrus-Niveau eine (meist zusammenhängende) Kaltfront vor. Bei den anderen Diagonalen, soweit sie links von $\psi_{800\text{mb}} = 0$ liegen, handelt es sich um Höhenwarmfronten, die aber nicht notwendig einer Bodenwarmfront zugehören.

Noch deutlicher wird dieser Zusammenhang, wenn man die Komponenten der seitlichen Wanderung der Cirren, $v = |\mathbf{u}| \sin \psi$, mit denen des Windes in 800 mb, $v_{800\text{mb}} = |\mathbf{u}_{800\text{mb}}| \cdot \sin \psi_{800\text{mb}}$ korreliert[2] (Fig. 4). Die Durchmesser der Quadrate und Kreise sind proportional zu $|\mathbf{u}_{800\text{mb}}|$ gewählt; 1 m/s der v-Skala $\triangleq$ 4 m/s in 800 mb.

Zur Beurteilung der Zusammenhänge nach Figur 3 und 4 sei daran erinnert, dass der meteorologisch bedingten Streuung sich Messfehler (in **u**, ψ und v) überlagern, welche allgemein die resultierende Streuung vergrössern und den Korrelationskoeffizienten verringern.

Schlussfolgerungen:

1. Bei sehr grosser Geschwindigkeit der Cirrus-Bänder beträgt die Wahrscheinlichkeit, dass ihre Zugrichtung nach rechts von **s** abweicht und der 800-mb-Wind ebenfalls eine Komponente nach rechts aufweist, mindestens 0,9 (vgl. auch Fig. 5, die das mittlere Verhalten beschreibt).
2. Bei mittleren und geringen Zuggeschwindigkeiten der Ci-Bänder streut ψ stark; die Richtung von **s** ist in diesen Fällen für den Betrachter ohnehin um 180° zweideutig. Die Komponente des 800-mb-Windes quer zur Ci-Band-Orientierung hat aber auch hier mit grosser Wahrscheinlichkeit das gleiche Vorzeichen wie die Komponente um Ci-Niveau (Fig. 4, 5).
3. Cumulus-Strassen und -Niederschlagsbänder liegen zwar ebenfalls parallel zur Vertikalscherung ihrer konvektiven Schicht; die Scherung weicht hier aber – im Gegensatz zum Ci-Niveau – vom thermischen Wind um durchschnittlich 30° nach rechts ab. Diese Abweichung hängt im Einzelfall naturgemäss vom Verhältnis der Windgeschwindigkeit zur Stärke des thermischen Windes ab und streut entsprechend (um die genannte Abweichung herum). Bei grösseren Geschwindigkeiten ($\gtrsim$ 10 m/s) sind die Bänder im allgemeinen etwa windparallel orientiert.

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[1] Figur 2 gilt nur für Kontinente und nur auf der nördlichen Halbkugel (auf südl. Halbkugel spiegelbildlich).
Die Durchmesser der Kreise und Quadrate sind proportional zu $|\mathbf{s}|$. Die Quadrate bezeichnen Fälle nach J. H. Conover (1); Kreise geben die vom Verfasser in Darmstadt gemessenen Fälle wieder; strichlierte Quadrate bezeichnen fünf von R. Süring gemessene Fälle, für die jedoch vom meteorologischen her die Scherungsrichtung nicht angebbar war ($\pm$180°). Die Lage der Punkte ist die nach vorliegenden Erfahrungen wahrscheinlichste.

[2] Da die Orientierung der Kaltfront in Bodennähe von der in der Höhe um durchschnittlich nur etwa 20° (nach links) abweicht, da ferner die Front in Bodennähe mit etwa 80% der quer zur Front gerichteten geostrophischen Windkomponente fortschreitet, lassen vorliegende Ergebnisse den Schluss zu, dass die Front am Boden und in der Höhe mit etwa gleicher Geschwindigkeit fortschreitet.