# SATELLITE EVALUATION OF THE IMPACT OF WINDSHEAR AND WATER VAPOR ON CONVECTIVE CLOUDS

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**Introduction**

Convective waves have been engaging the attention of the researchers during the past decade (Beckman, 1986; Purdom, 1990; WMO-OSTIV, 1991; Wan-Shu Wu and Lilly, 1992) consequent on continuous reports of thermal or convective waves among the soaring community. Several researchers have carried out related investigations, for instance, in respect of: wave flow above convection streets (Hamburg, 1972); windshear and thermal waves experienced in Germany (Lindemann, 1972); cloud structure (Levizzani, 1989); the time variation of a mesoscale convective system (MCS) in Spain (Riosalido, 1990); time variation of infrared cloud temperatures outlined by isotherms for a MCS over Texas (Zipser, 1990); the magnitude of solar irradiance reflected from deep cumulus clouds to the ground using observations along the Front Range of Colorado (Segal and Davis, 1992) etc. Muller (1987) has presented results of investigation of cloud streets over northern Germany using inflection point instability theory. Some of the excellent early investigations are due to Malkus (1949,1952,1954), who has carried out limited measurements and also attempted theoretical estimation of the relative speed of cumulus clouds under vertical windshear conditions, taking into account both the entrainment of ambient air into the vertical "jet" of the thermal and the form drag due to its cylindrical shape.

Rovesti (1970) has given a good account of thermal wave ("thermo onda") and has suggested that the thermo onda are produced in three typical situations characterized by:

(a) isolated cumulus clouds which though never merge, tend to align themselves in the downwind zone at a certain distance from each other;

(b) bands of cumulus and stratocumulus clouds forming connected chains of clouds transversely to the wind; and

(c) the bands of cumulus and stratocumulus clouds parrallel to the wind.

Thermal waves as experienced by gliders are gravity waves found in the stable tropospheric layer above a heated planetary layer and are observed to reach down to the boundary layer as well as heights well above the tropopause. Gliders have observed them with and without cumulus convection, though they are easier to detect when clouds are present. The convective waves are found over flat to gentle structured terrain and often far away from mountains. While cumulus and cumulonimbus clouds are of convection type, not all convective clouds are borne by air rising from ground or sea level. This is because occasionally, the temperature lapse conditions conducive to convection are created by airflow patterns well above ground or sea level. "Thermal wave soaring" allows a glider pilot to use wave techniques under specific conditions of thermal convection (Kuettner, 1970). It also suggests the possibility of climbing outside cumulus clouds in clear air to heights exceeding the cloud tops. The cumulus wave forms under conditions of vertical windshear, i.e., an increase of horizontal wind with height. The sailplane begins to climb on the outside of the cumulus cloud in very smooth lift. This appears to hold also for large cumulonimbus. The flight technique resembles slope soaring, the cloud being the mountain slope with the wind blowing against it.

The impacts of windshear and water vapor on convective waves are not clearly understood from the point of view of thermal soaring and there is a need for further investigation. The present study has examined these aspects using Meteosat observations at İnönü, a study area chosen around Eskişehir, in the northwestern Anatolian region of Turkey, shown in Figure 1. The Glider School of Turkish Air League is situated at İnönü.

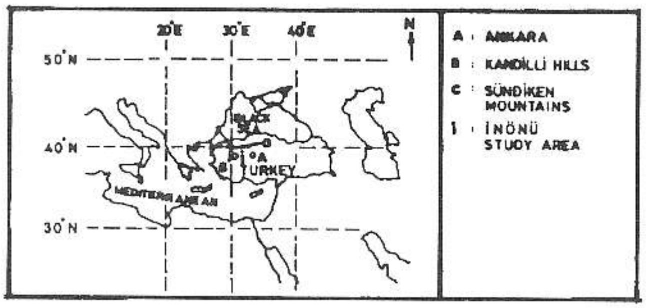

FIGURE 1. The study area.

## Scope of the Work and Methodology

The purpose of this investigation is to:

(a) evaluate the wind speeds and direction at İnönü during the study period using Meteosat cloud motion winds and compare them with the radiosonde winds,

(b) identify the windshear in this strategically important area from the point of view of aviation,

(c) study the impact of water vapor on windshear, and

(d) investigate the convective wave conditions under which thermo onda may be formed in the study area.

The windshear is evaluated through estimation of Meteosat CMWs by means of the Dartcom system. The color images after processing give good indication of the structure and stability of clouds. The CMW approach is well established by now. Indeed, the statistical comparison of the operational CMWs ("SATOB") provides important wind data for numerical weather prediction (NWP) models (Eriksson, 1990) and is suitable for thermal soaring and other aviation applications as well.

İnönü in Eskişehir (latitude: 39°49' N; longitude: 30°31'E; altitude: 844 m), one of the oldest gliding schools of Turkey, presents favorable soaring conditions for pilot training, and constitutes the study area for this investigation. This site is approximately 200 km to the west of Ankara. It may be mentioned that routine radiosonde observations are made twice daily at Ankara. In view of the importance of Inönü for aviation, some investigations have been carried out by various researchers, for instance, by Öney et al. (1987). The relative positions of the nearby Sündiken mountain range and Kandilli Hills in the study area, both of which greatly influence windshear are also shown in Figure 1. Winds which strike a mountain ridge even of moderate height create thermodynamic conditions which characterize situations of thermal wave (Rovesti, 1970). The velocity of the wind increases gradually with the height. The thermal waves are produced due to the downflow from the mountain barriers in conditions of very strong winds at flying altitude. These can be easily identified when the air is sufficiently humid and permits the formation of cumulus or stratocumulus clouds. The bands of thermo onda whether made up of isolated cumulus clouds aligned in the direction of the wind or of true streets of connected cumulus and stratocumulus clouds parallel or transverse to the wind, are produced along a narrow strip affected by more intense phenomena, because they originate in association with the higher mountains more favorably exposed to the wind. These streets of cumulus clouds produced by thermal waves always originate two or three wavelengths from the mountains, in contrast with the cumulus roll clouds which are formed very close to the downwind zone.

When one mountain ridge is downwind from another, as is the case at İnönü, and a wave flow is in resonance with the second obstacle, the conditions of soaring are enhanced by the orographically forced rising of the lower strata of air and the flight becomes extremely easy. These conditions are illustrated in Figure 2 for the İnönü case.

The height assignment for windshear determination

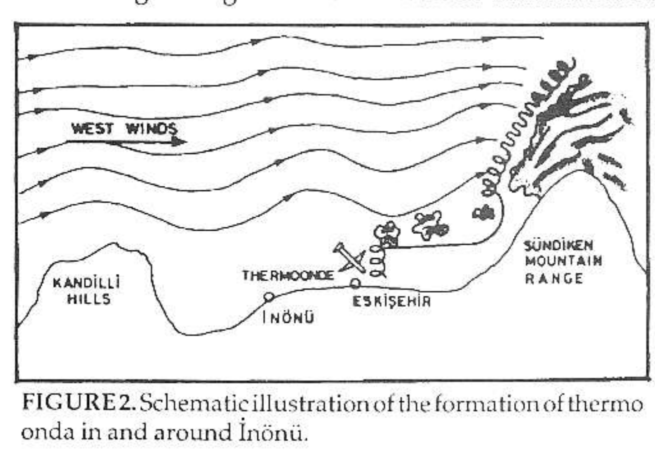

FIGURE 2. Schematic illustration of the formation of thermo onda in and around İnönü.

is based on the IR radiance of the cloud pattern and includes a correction for atmospheric absorption and emission. Hoffman (1988) has divided the CMWs into three levels: high (up to 300 hPa), medium (300-700 hPa), and low (over 700 hPa). For the İnönü windshear experiment, the present investigation has considered three altitude levels defined as very low (around 950 hPa), low (around 850 hPa) and medium (around 700 hPa). The higher altitudes, though desirable have been avoided mainly because of the difficulties in identifying the cloud level based, for instance, on the sea surface temperature.

A sequence of images consisting of 10 x 10 infrared pixels obtained during the autumn, winter and spring of 1992-93 allow for seasonal variations of windshear. The wind vector information can be derived from two or three consequtive satellite imageries in a given time-span, typically one hour (occasionally 30 minutes), based on the false color estimates of position displacement. The images have been subdivided into a number of quadratic segments of 10 x 10 pixels and the displacement of a given segment used to compute wind speed. The CMW vectors are determined from carefully aligned subsequent infrared (10.5-12.5 μm) images using cross-correlation technique over the 10 x 10 IR pixel-segments.

**Limitations Of The Study**

Though the windshear evaluation via Meteosat is fairly reliable for soaring, it has certain limitations. The cloud tracers should faithfully follow the windfield without interaction with the atmospheric dynamics or radiatives, especially in relation to the orographic clouds, warm conveyor belt cirrus etc. (Aslan et al., 1993). The height assignment based on cloud top temperature may produce biased winds, since the radiation from an optically thin cloud may arise from a relatively deep layer (Holmlund and Schmetz, 1990), and the measured displacement is rather a mean value for the corresponding layer than a representative for the cloud top (Raschke, 1988; Quante, 1989). The windshear evaluation occasionally requires tracking of small individual clouds. This is however, very difficult since the resolution of the Meteosat imagery may range from 1-10 km in the visible and infrared bands. Another difficulty in estimating the windshear is that during the Meteosat pass interval of 30 minutes the cumulus clouds and certain types of clouds in the troposphere have limitations of persistence. Such difficulties have been partly overcome in this study by repetitive evaluation of windshear over several meteosat passes using different clouds and positions. It is also not possible to have accurate estimate of water vapor using Meteosat imagery, which provides only a rudimentary understanding on humidity. In such cases, the data needs to be extrapolated with those of the nearest radiosonde observations.

Though the overall impact of the cloud track winds for different applications such as windshear analysis, NWP etc. is beneficial, there is a tendency of high level cloud track winds to underestimate the wind speed especially in jet stream areas (Baede et al., 1985). Past studies by ECMWF, for instance, by Kelly and Pailleux (1989) show that under certain conditions, and over certain regions, CMWs may have a negative impact on NWP. Clearly, for routine evaluation of windshear, adequate quality control is necessary.

**Results And Discussion**

The most important parameter determining the windshear is the wind velocity. Figure 3 shows the Meteosat CMW velocity at Inönü in relation to the radiosonde speed and the best-fit straight line. It is apparent that there is bias at high as well as low speeds. The differential speeds are also due to the fact that the radiosonde facilities are not available at the İnönü study area where the CMW measurements are made. Consequently, the investigation has required extrapolation of the data available from the nearest radiosonde station at Ankara. The CMW direction and the corresponding radiosonde direction are shown in Figure 4. Based on the best-fit curves, the CMW radiosonde models are as follows:

$$y = 0.876931\,x + 1.77966 \text{ (wind speed)} \quad (1)$$

$$y = 0.72353\,x + 41.5528 \text{ (wind direction)} \quad (2)$$

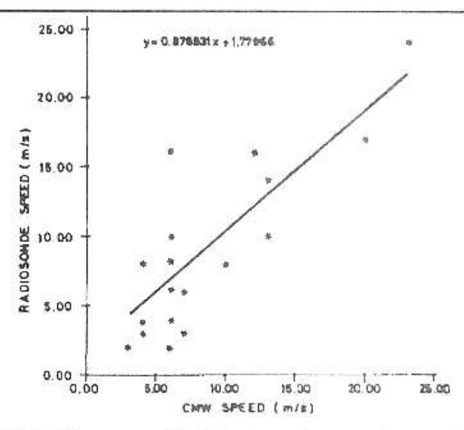


**FIGURE 3.** Meteosat CMW v/s radiosonde speeds at different times during 1992-93.

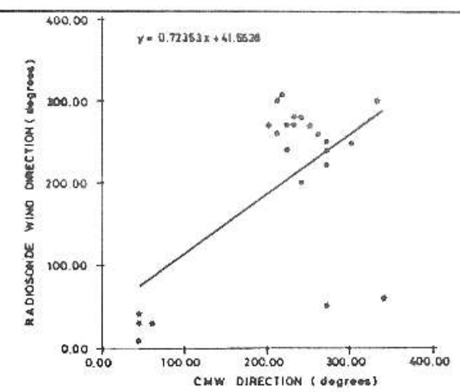


**FIGURE 4.** Meteosat CMW v/s radiosonde directions at different times during 1992-93.

The speed errors are particularly evident at low speeds mainly because of the difficulties in tracking the winds and their calibration. It may be seen from the best fit line that for the CMW speeds of 5 and 20 m/s, the radiosonde speeds are around 6 and 19 m/s respectively suggesting an overall speed error of 5-20% over a range of low and high speeds. For the CMW directions of 100 and 300 degrees, the radiosonde directions are around 110 and 250 degrees respectively, indicating a directional deviation of 10-16% over a range of speeds. These errors are perhaps quite marginal under the limitations of Meteosat winds as well as radiosonde data.

In order to understand the windshear mechanism on a qualitative basis, Meteosat imageries have been acquired on a selected day at various times for different altitudes. Figure 5 shows the time sequence of the Meteosat cloud structures at three different levels, 950 hPa, 850 hPa and 700 hPa on May 5, 1993. The corresponding cloud temperatures are also shown. At higher altitudes, the cloud temperature gets progressively reduced. It is seen that the cloud-shapes are different not only for different times at a given altitude, but also for different altitudes at a given time. The rapid change in the shape of the cloud makes the CMW vector evaluation a difficult exercise, especially for low speeds.

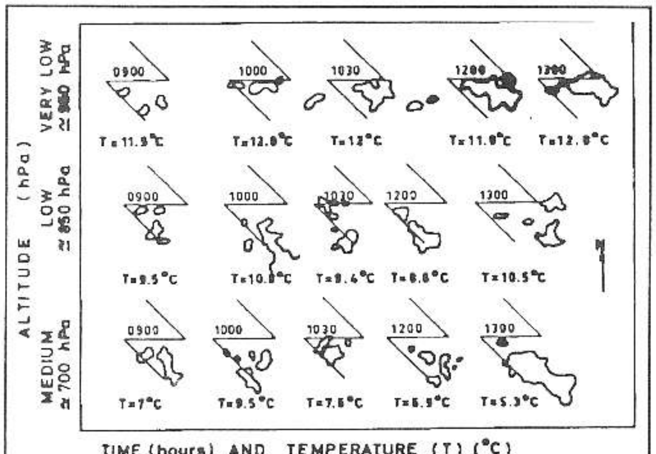


FIGURE 5. Time sequence of Meteosat imagery over Inönü for three different altitudes on May 5, 1993.

The cumulative frequency distribution for the Meteosat and radiosonde wind-speeds is shown in Figure 6, and the corresponding distribution for the wind-directions in Figure 7 for the period September, 1992 to May, 1993. The cumulative frequency shows good agreement between Meteosat and radiosonde in respect of speed as well as direction. It may be noted that speeds in excess of 10 m/s are marked by higher cumulative frequency at Inönü than the relatively lesser speeds for Meteosat as well as radiosonde cases.

In this connection, some explanation is necessary to account for the difference between cloud track and radiosonde winds. A wind measured with a radiosonde

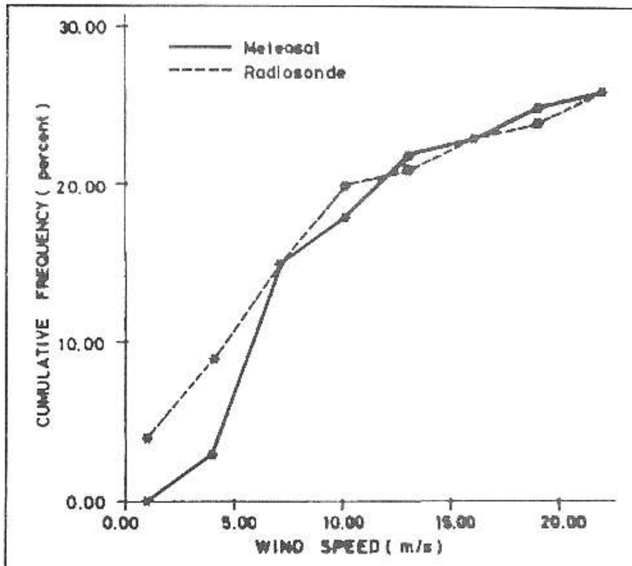


FIGURE 6. Cumulative frequency distribution for Meteosat and radiosonde wind speeds (Sept., 1992 - May, 1993).

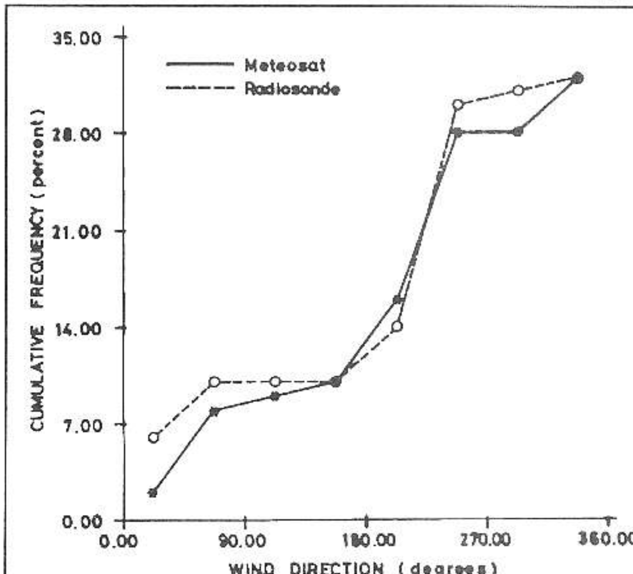


FIGURE 7. Cumulative frequency distribution for Meteosat and radiosonde wind directions (Sept., 1992 - May, 1993).

can be considered as a random sample of the air flow so that a sufficiently large number of measurements represents the true wind. For cloud track winds one can estimate an unbiased wind only if clouds were conservative tracers randomly distributed within and floating with the airflow (Schmetz and Turpeinen, 1986). However, this is not really true. For instance, in jet areas the major part of cloud is found below the level of maximum wind speed and there are seldom any clouds above that level (England and Ulbricht, 1980). The jet core itself is also mostly cloud-free. The vertical and horizontal windshear can be as large as 10 m/s per km and 5 m/s per 100 km, respectively. Thus there is every likelihood to expect from the present cloud track scheme significant difference. Even if there are clouds in the high-speed zone, those are not likely to be useful tracers since they are not long lived enough to be trackable over a period of one hour. This is also a possible explanation for the observation that Meteosat cloud track winds seldom exceed values higher than 60 m/s.

Figure 8 shows the time variation of Meteosat CMW and radiosonde speeds. In all, over 20 sample-observations have been made at different intervals during 1992-93. The time sample number shown in the x-axis simply represents the serial number of observation starting from September, 1992 till May, 1993 and has no other significance. It is seen that while Meteosat underestimates windspeeds in certain instances, there are overestimates in others.

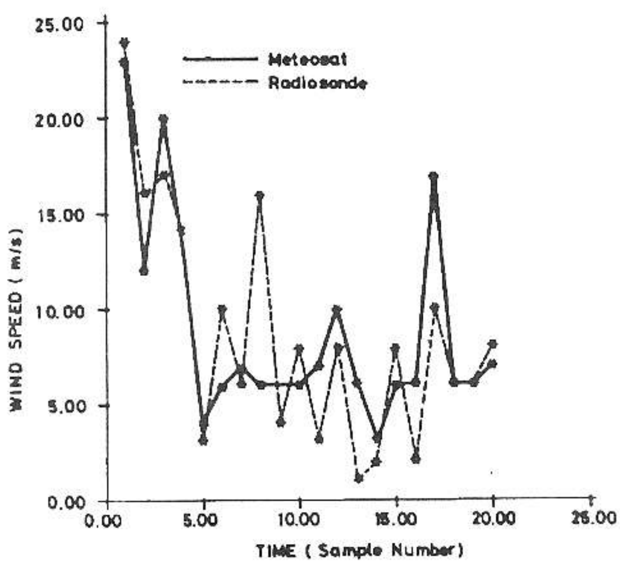


FIGURE 8. Time variation of Meteosat and radiosonde speeds.

The cloud track observations made during 1992-93 at İnönü have enabled the evaluation of the windshear to be made. Figure 9 shows the windshear distribution based on cubic spline curve fitting, for two different (very low and low) altitudes ( around 930-850 hPa and 850-700 hPa) on a specific day in May, 1993 for different times during the day. The maximum windshear per km is 13.5 m/s at 930-850 hPa. The windshear is more for the lower altitude than for the higher. In general, favorable conditions for the development of thermal waves exist when the windshear is over 10 m/s per km.

It may be interesting to examine the maximum possible lift that a glider pilot may obtain as a sequel to the Inönü windshear. It is somewhat difficult to give reliable values of updrafts to be expected in a wavelift outside the cumulus cloud. Based on certain observations and physical considerations, Kuettner (1970) suggests that for a vertical windshear of 5 m/s per km, the rate of climb will be of the order of 1 m/s; weak but consistent. To use this type of lift, the flight technique resembles that of wave soaring in front of a weak wave

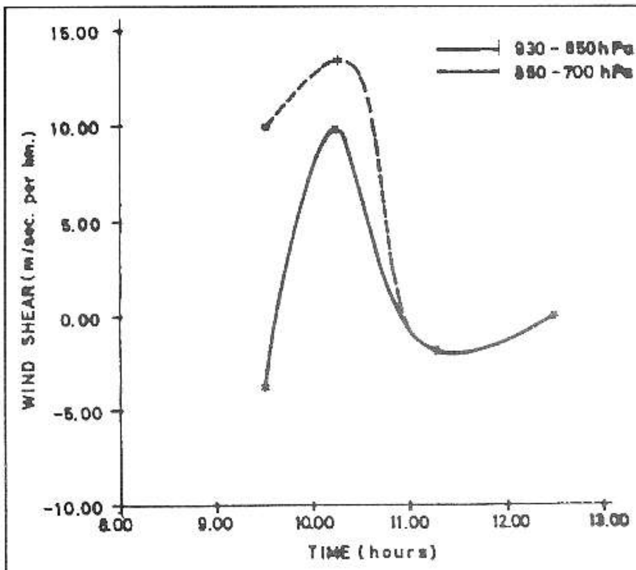


FIGURE 9. Windshear distribution at Inonu for very low and low altitudes.

cloud. The nose of the sailplane is always pointed a little away from the cumulus cloud. This wave lift can often be reached from under the cloud base by penetrating into the wind and the lift may be weak initially. Figure 10 schematically illustrates the thermal wave soaring prospects for a glider pilot based on the maximum windshear observed at İnönü. For the peak windshear of 13.5 m/s per km observed in the İnönü experiment, a glider pilot at an altitude of around 900 hPa may gain over 50 m in 20 seconds and has the opportunity to avoid flight through the cloud on instruments. It may be noted that the windshear through the convective cloud layer causes the cumulus clouds to lean in the downshear direction, though the upshear side of the cumulus tends to be more favorable for lift than the edge of the cloud.

Water vapor influences windshear as the cloud picks up moisture during transit. The convective cloud is influenced by the water vapor of the environment, since in a fairly dry environment, evaporation at the periphery of the cloud will considerably reduce the chances of small individual clouds persisting for longer than about

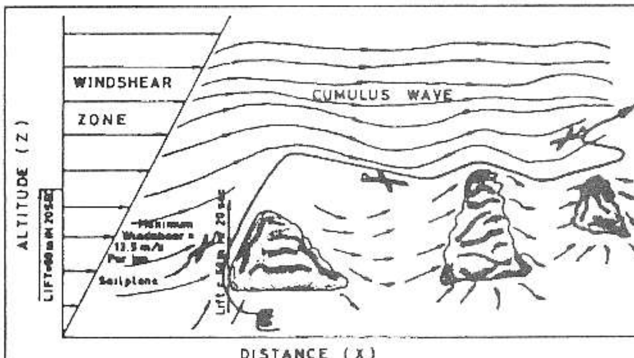


FIGURE 10. Schematic illustration of thermal wave soaring for a sailplane based on the Inönü investigation. (Note the possibilities of sailplane hop from cloud top to cloud top).

15 minutes. However, if the environment is humid, the rate of evaporation tends to get reduced, with the attendant increase in the water vapor content of the immediate environment of the thermal to the saturation value. The cloudiness will spread out from the thermal and the cumulus clouds will degenerate into a large patch of stratocumulus which will literally cast a shadow over thermal soaring prospects for anything between 15 minutes and a few hours. It may be noted that satellite imageries provide relatively poor information in respect of water vapor with the present level of technology.

**Conclusion**

The convective waves have been examined in this paper from the point of view of soaring using Meteosat imagery and collocated radiosonde data for the period September, 1992 to May, 1993 over İnönü at Eskişehir, where major pilot training activities take place. Based on the best-fit curves, an overall error of 5-20% has been observed in respect of wind-speeds and 10-16% in respect of direction, between the cloud track and radiosonde observations over a range of low and high speeds. The cumulative frequency shows very good agreement between Meteosat and radiosonde winds in respect of speed as well as direction. The maximum windshear per kilometer as measured using Meteosat imagery on a representative day in May, 1993 has been 13.5 m/s at 930-850 hPa and it is more for the lower altitude than the higher. Such situations suggest the possibilities of thermo onda in the study area with a probable sailplane lift of over 50 m in 20 seconds at 900 hPa for the peak windshear conditions. While the water vapor does influence the windshear, and hence soaring, satellite imageries are inadequate from the precision standpoint with the current level of technology. Investigation of windshear is of importance from the point of view of cross-country flights resulting from thermic waves as well as aircraft takeoff and landing manoeuvres.

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