Suggestions for improving the derivation of winds from geosynchronous satellites

William E. Shenk

NASA / Goddard Space Flight center, Severe Storms Branch, Code 912, Greenbelt, MD 20771, USA

ABSTRACT

For more than the past two decades and for the foreseeable future measurements from geosynchronous satellites will be a major contributor to the determination of winds, especially over oceanic areas. The winds can be determined from features (e.g. clouds) that closely follow the air motion, and from the thermal wind relationship poleward of the tropics. Major improvements in accuracy and coverage should be possible during the coming decades through the combination of better sensors and their operation and the increased use of interactive systems. These data could contribute significantly to a long-term wind data base associated with global change studies.

Introduction

In an earlier paper, Shenk (1985) presented a summary of the basic characteristics and uses of winds derived from cloud motions along with some suggestions on the future satellite requirements that could improve their accuracy and coverage. This paper will update that document and will also discuss methods for deriving winds from other tracer motions, and from the thermal wind relationship. In the future these data could be combined with the planned Doppler lidar derived winds from low earth orbit for high quality global wind data sets.

Winds derived from tracer motions

Around the globe, there are several groups that derive winds from cloud motion using the image series from geosynchronous satellites. Most of the motions are derived over water with 30 min interval data using automated cloud tracking procedures followed by manual postediting to remove questionable vectors. While these procedures have produced worthwhile results, as evidenced by their use in global numerical models, there remains a substantial difference between the accuracies, spatial resolutions and coverage achieved versus what is possible considering the accuracy limits of cloud motion-wind relationships and the resolution and coverage that are determined by cloud availability. If we can approach these limits, then not only will the value of the product be greater for present applications, but the potential is substantial for a wider range of uses, especially for global change, storm, and mesoscale applications.

Some basic elements and philosophies that should be considered in designing future winds from cloud motion systems are: (1) they should allow the accuracy to approach the limits of cloud

TABLE 1

Suggested future wind derivation system components

Scene characteristics	Satellite system parameters (GOES I-M)	Satellite system operation (GOES I-M)	Cloud height calculation	Cloud tracking procedure
Single layer of clouds	—Imager Chs. • Visible • IR (4, 6.7, & 11 μm) —Sounder Chs. for altitude meas. • Several in 13–14 μm • Temperature profiles	—Full disk—Imager only —Mesoscale–Regional "Simultaneous" imaging-sounding —Imager Temporal Resolution • Middle and high clouds—15 min • Low clouds over water—71/2–15 min • Low clouds over land- $\leq$ 3 min	—Cloud top heights • Stereo when and where possible (test IR stereo with GOES I-M) • 6.7 and 11 μm Ch. combination for cirrus with imager • Temperature profiles from sounder or model output • Use CO_2 tech. with sounder —Cloud motion winds derived from tropical cumulus over oceans placed at cloud base (near 950 mb) —Estimates of cloud bases (low clouds) • Climatology–tropics and most oceans • Stereo • Surface reports	—Time lapse imagery —Use full length of time lapse sequence for vector calculations • Water—45–60 min • Land • Low clouds 15–20 min • Higher clouds 45–60 min —Use visible ch. wherever possible —Manual selection of areas for automated tracking from time lapse sequences —Manual tracking when in doubt
Multiple cloud layers	Same as single cloud layer	Same as single cloud layer except for better temporal resolution • Middle and high clouds 7 1/2–15 min • Low clouds over water $\leq$ 7 1/2 min • Low clouds over land $\leq$ 2 min	Same as single cloud layer—low cloud layers identified either by cloud type ID algorithm, cloud top heights, or time lapse sequences	Same as single cloud layer except manual cloud tracking should be used

motion–wind relationships; (2) automated cloud tracking techniques should be used only in areas where relatively straightforward cloud situations (e.g. single layer of clouds) exist, and require that areas tracked to determine each vector be as small as possible to increase the chance for homogeneous cloud conditions within each area; (3) the GOES I-M series and other future geosynchronous satellites are expected to have improved performance characteristics (e.g. higher spatial resolution, increased visible channel sampling frequency) that should benefit cloud motion wind determination; (4) these data can be combined with wind measurements from other sources (e.g. the new profiler network); and (5) the basic properties of viewing from geosynchronous satellites as described by Shenk et al. (1987) can be employed (e.g. the consistency of the measurements from one image series to the next).

Tables 1 and 2 provide more detail on the suggestions, which are subdivided into scene characteristics categories that include cloud conditions, moisture areas, and thermal wind relationship derived winds. The suggestions are mostly aimed at the GOES I-M satellite series although many of them apply to geosynchronous satellites in general. Each table considers which satellite system parameters will be needed (e.g. GOES I-M spectral channels), how the satellite could be operated, the suggested methods of cloud height determination, and the recommended procedure for tracking the tracer, or in the case of the derived winds from the thermal wind relationship, checking the consistency of the results.

For a single layer of clouds (upper portion of Table 1) four of the five GOES I-M imager channels could be used. From the GOES I-M sounder, when it can scan the same area as the imager with reasonably close time proximity, several of the 13–14 μm channels can be employed for cloud height determination (Menzel et al., 1983) and the temperature profiles can help to estimate infrared derived cloud altitudes. The key item in the satellite operations column is the critical temporal resolution of the images. Previous studies (e.g. Rodgers et al., 1979) have shown the value of high temporal resolution for correctly identifying the cloud elements being followed during an entire image series, which improves accuracy, derived wind resolution, and coverage. The highest temporal resolution is for low clouds, with low clouds over land requiring the highest image frequency since they change more rapidly than similar clouds over water. Cumulus clouds require the highest frequency, especially in storm situations, where 1–2 min intervals are required.

Figure 1 is an attempt to generalize the effects of temporal resolution on an important component of cloud tracking results. The abscissa is a logarithmic scale of image interval and the ordinate

TABLE 2

More suggested future wind derivation system components

Scene characteristics	Satellite system parameters (GOES I-M)	Satellite system operation (GOES I-M)	Scene characteristic identification and altitude assignment	Tracking procedure
Discrete moisture areas	—Imager—6.7 μm Channel —Sounder— •6.7, 7.3, & 11 μm Channels • Temperature profiles	—Full disk—imager only —Mesoscale/regional-imager and/or sounder —Temporal resolution 15–30 min	—Test for moisture areas with comb. of moisture and 11 μm channels —Altitude based on moisture channel rad. and temperature profile	—Time lapse sequences —Basically manual tracking following target selection —with more experience perhaps automation of carefully selected areas
Fields of temperature profiles—winds derived from thermal wind relationship	Sounder—temperature profiles	—Mesoscale/regional sounder coverage —Temporal resolution—$\leq$ 60 min	—Good cloud testing essential —Altitude based on temperature profile	—Results should be consistent with time-use time lapse to check results

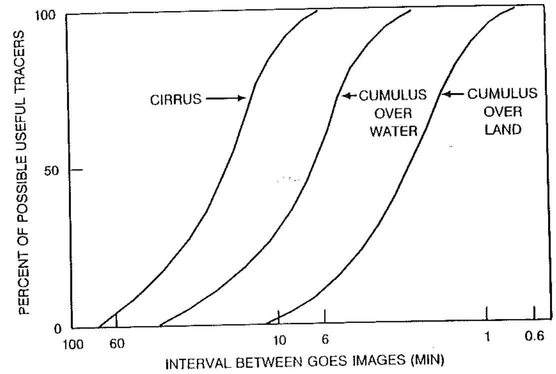

Fig. 1. Optimum GOES image interval for computing winds from cloud motions.

is an estimate of the percentage of trackable clouds that can be followed with a given image temporal resolution. Three curves for three different types of clouds were drawn from the combination of published results and years of cloud tracking experience. Figure 1 shows the benefits of high temporal resolution for being able to follow the tracers, and the suggestions in Table 1 are based on these curves. Figure 1 indicates that, with a 30-min interval, we are not close to the full potential of geosynchronous measurements for high clouds (and probably middle clouds) and are vastly underutilizing the potential for low clouds over water. Low clouds over land are virtually impossible to track using 30-min interval imagery.

There are three cloud top height measurement techniques that represent worthwhile advances over the simple assignment of cloud top altitude to the 11 μm temperature fit to a temperature profile. These techniques are the combination of the 11 μm and 6.7 μm channels for high clouds (Szejwach, 1982), the combination of 11 μm and one or more channels in the 13–14 μm region for clouds at all altitudes (Menzel et al., 1983) and stereographically determined heights using the common region simultaneously seen by two satellites (Hasler, 1981). Since they are based on longwave infrared channels, the first two methods can be used all the time, as long as the viewing angles are not too large (typically local zenith angle of ≤ 65°). The use of stereo is restricted to a simultaneously viewed common area within a local zenith angle limit of 75°, and the highest accuracy is achieved during the daytime using the visible channel. Despite its current coverage limitations, stereo should be used whenever possible since:

(1) It is the most accurate method (500 m single pixel visible channel accuracy with current GOES data). The accuracy from GOES I-M should be closer to 300 m due to the increased visible channel sampling frequency. Multiple samples on a given cloud at the same altitude improve the accuracy by approximately $\sqrt{n}$ where n is the number of pixels.

(2) Different cloud layers can be easily separated, especially with stereo imagery seen in time lapse form. Infrared sensing integrates the results of different layers.

(3) The visible channels provide the highest resolution, so small clouds can be effectively followed and their heights accurately determined since the pixel is usually completely filled (which is often another problem in the infrared).

(4) Since stereo is a geometric measurement, temperature ambiguities near the tropopause are avoided, which is a major infrared limitation. This is especially important for cirrus near the tropopause.

The most representative wind level for convective low clouds in the tropics over water has been determined to be at the cloud base which Hasler et al. (1979) found to be mostly at 950 mb. Cloud base estimates can be made from surface reports, climatology and/or stereo. In the sample measured by Hasler et al. (1979), placing the wind vectors at higher levels (e.g. mid cloud or cloud top) resulted in errors of 2–8 m/s depending on the amount of shear in the cloud layer.

The final column on cloud tracking procedure in Table 1 concentrates on three major suggestions:

(1) The total tracking time for the clouds should be long enough to reduce errors caused by incorrect location of the vectors at the beginning and end of the image sequence, yet within the lifetime of the cloud elements.

(2) The use of the highest resolution visible channel data will allow the selection of small tracers and reduce the location errors.

(3) Manual selection of areas where automated procedures should be used. The automated proce-

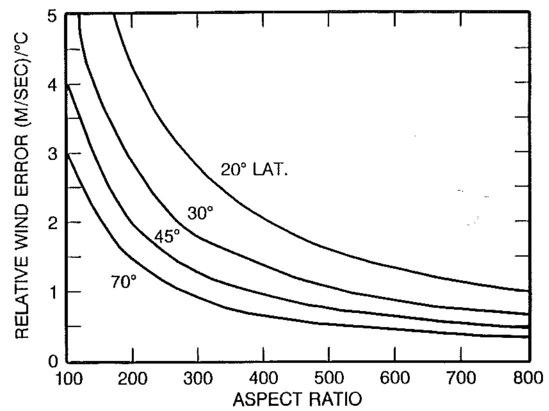

Fig. 2. Satellite temperature sounding vertical resolution and accuracy requirements for determining winds from the thermal wind equation. Aspect ratio is defined as the ratio of the horizontal spacing of the wind data to the vertical resolution of the temperature sounding retrieval (taken from Smith, 1990).

dures will have the greatest success in areas where the cloud field has a simple repeatable structure with time.

The suggestions in the lower portion of Table 1 are recommended when multiple cloud layers exist. The principle differences with the upper portion of Table 1 are:

(1) Higher frequency imagery to successfully follow the cloud elements.

(2) Identification of the different cloud layers with cloud type identification techniques (e.g. Desbois et al., 1982; Shenk et al., 1976).

(3) Use of manual cloud tracking techniques.

Table 2 contains suggestions for moisture tracking and fields of winds derived from the thermal wind relationship. For moisture tracking the GOES I-M satellite system parameters include the 6.7 μm channel from the imager and the 6.7 μm and 7.3 μm channels from the sounder. The temporal resolution can be more relaxed than for clouds for both moisture tracking and for the winds derived from the thermal wind relationship. A combination of a moisture channel and the 11 μm channel each seen in time lapse mode should be useful for determining that it is truly a moisture feature that is being tracked and not a cloud. For moisture tracking manual tracking procedures should be used until we feel more comfortable using automated methods.

Winds derived from the thermal wind relationship

In the middle and high latitudes, winds can be derived from the thermal wind relationship. Smith (1991) has prepared a nomogram (Fig. 2) which shows wind error relative to temperature retrieval error as a function of horizontal to vertical resolution aspect ratio for selected latitudes. The ratio is the ratio of the horizontal spacing of the wind data to the vertical resolution of the temperature profiles. Thus, the resultant wind error for a given horizontal spacing and latitude is sensitive to the

TABLE 3

Expected results from tracer motions

	Goes I-M	Later geosynchronous satellites
Vector accuracy (m/s)		
—Low clouds		
• Water	2 – 3 (2– 4)	1 –2 (1.5–3)
• Land	2.5– 4 (3– 5)	1.5–3 (2 –4)
—Middle clouds	2 – 4 (3– 6)	1 –2 (2.5–5)
—High clouds	3 – 7 (5–10)	2 –4 (4 –8)
—Moisture motion	5 –10	3 –8
( ): Outside of stereo areas		
Increased coverage and density (all future satellites)		
—Both land and ocean		
—More middle clouds (particularly in stereo areas)		
—More cloud motion derived vectors/unit area and time		
• Consistent with global model development		
• Storm/mesoscale analyses		

accuracy and vertical resolution of the temperature profiles. Thus, at 45° latitude, a wind measurement every 400 km derived from a temperature accuracy of 1 K where the vertical profile resolution was 2 km (aspect ratio of 200) would have relative wind error of 2 m/s. Improving the vertical resolution of the profile to 1 km would reduce the relative wind error to 1 m/s.

Estimate of the expected wind accuracies resulting from the suggested improvements

Table 3 provides an estimate of the expected accuracies of tracer motions from GOES I-M and from more advanced later geosynchronous satellites provided that the suggested improvements were implemented. For clouds, the estimates are subdivided into regions where stereo is used and outside of the stereo regions. Stereo should have an increasing effect with altitude, with high cloud results being the most affected since altitude determination with infrared methods is the most difficult in this region due to cloud properties (e.g. emissivity) and since the wind shear is usually the greatest in the upper troposphere. Stereo should also be beneficial in detecting trackable middle level clouds, which often are located in regions with multiple cloud layers. The results for low clouds over water should approach the empirical limits determined by Hasler et al. (1979) for the satellites beyond GOES I-M. Moisture motions are likely to have relatively larger errors at any given level in the atmosphere because the channels that are used respond to moisture throughout relatively deep layers.

Other considerations

Table 4 presents a list of other topics for consideration and additional research that would be beneficial. While comparisons can be made between cloud motions and winds from a variety of sources, the aircraft method is believed to be the best since near perfect time and space matching of wind and cloud motion is achievable using the same platform (i.e. the aircraft) for both measurements. Cirrus clouds are the targets which should receive the most attention since the low bias problem has been noted for these clouds in jet stream situations.

The next to last suggestion at the bottom of Table 4 is an extension of some early work by Shenk and Kreins (1970) in which successful infrared tracking was done at high latitudes using consecutive Nimbus orbits. The imagery from two or more satellites should improve significantly on their results since the clouds would be viewed more frequently. The final suggestion will depend on microwave sensing from geosynchronous orbit and is based on early experience with millimeter

TABLE 4

Other considerations

—Major effort to understand cloud motion and moisture motion-wind relationship. Most comparisons with:
- Aircraft winds
- Profilers
- Doppler radar
- Rawinsondes

—Comparisons mostly needed for:
- Cirrus
- Low clouds over land
- Middle level clouds
- All moisture motions

—Comparison of automated and manually derived winds—gradually increase the complexity of cloud fields

—Comparison of water vapor and cloud motion winds in areas where reasonable space and time proximity exist

—High latitude cloud motions—overlap between polar orbiting satellite orbits—especially effective with ≥ 2 satellites

—Microwave sensors in geosynchronous orbit for cloud tracking underneath cirrus frequency data from aircraft showing that small precipitating cells (~ 5–10 km diameter) can be seen below a dense cirrus overcast.

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