ASYNCHRONOUS STEREO HEIGHT AND MOTION ANALYSIS: APPLICATIONS

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ABSTRACT

The technique of asynchronous stereo height and motion analysis is discussed for complex cases with various clouds types and instrument combinations. It uses several observations in time and from more than one view point to derive both height and motion of clouds. The use of 1 km resolution geosynchronous satellite data provides better than 200 m height accuracy. Further applications of the method to more difficult situations are presented. Different combinations of satellites and different resolutions show useful results. Cases for AVHRR plus GOES, GOES IR and Water Vapor and Meteosat visible data are discussed.

Introduction

As represented by these workshops, there has been a long history of tracking clouds to estimate wind. Separately there have been efforts to measure cloud heights from simultaneous stereo analysis. Here we discuss the merger of those techniques into a combined analysis to measure geometric height and cloud motion. The analysis technique has been described in Campbell et al 1996 and Campbell and Purdom 1999. There are a variety of combinations of satellites which can be used to make these measurement. This paper discusses mixtures of GOES, Meteosat and AVHRR data including Visible, IR and water vapor channels. Images from this paper can be viewed at www.cira.colostate.edu/geosci/windZ/windZ.htm.

The basic idea is to first track clouds in a sequence of images from one satellite view point by maximizing the correlation between patches of pixels. Then using a remapped image from another view point, the cloud is located by the same correlation method. If there are more than one image from the second view point, the object is tracked in that sequence. The precise time of the measurement of each object (scan line time) and their apparent locations provide the input to the analysis.

Consider an object viewed at different times, t, and from different view points, $\mathbf{R}s$. The navigation code will return apparent locations, $\mathbf{P}(t)$. The true cloud location, $\mathbf{R}(t)$, is located on the line of sight between the satellite and the apparent location, equation 1.

1. $\mathbf{R}(t) - \mathbf{R}s = f\,(\mathbf{P}(t) - \mathbf{R}s)$

Let us assume that the cloud moves at constant height and constant speed. This is presented by equation 2. the cloud position with a starting point **R**(0), a velocity **V**(0) and a acceleration, **S**:

2. $$\mathbf{R(t) = R(0) + V(0)\ t + 1/2\ S\ t2}$$

The acceleration term was added to tip the wind into approximately horizontal motion. S is approximated by centripetal acceleration (V^2/Rearth) pointing toward the center of the earth. Combining these two and recognizing that no measurement is perfect, eq 3 represents the error between the assumed motion and the observations.

3. $$\mathbf{E}(t) = \mathbf{R}(t) – \mathbf{R}s – f\ (\mathbf{P}(t) – \mathbf{R}s_i)$$

By summing over many observations, a minimum of the Σ ($\mathbf{E}(t) \bullet \mathbf{E}(t)$) provides an estimate of the initial position and initial velocity by solving for the unknown factors f and the initial location and the initial velocity. The cloud height is then calculated by subtracting the local earth radius from the initial location vector.

Applications: GOES East plus GOES West Visible 1 km data.

Using the finest space resolution will produce the most accurate results. Figure 1 shows the analysis of a cloud in Arkansas, U.S.A. The upper number in the pair next to the vector is the wind speed in m/sec and the lower number is the height in hectometers. A measure of the accuracy of the method is show by the consistency of high and motion of the two clouds at 8.8 km.

The reservoirs to the south east show consistent heights at -1.8 and -2.0 km. These are not 200 meters (the geographic height) because there is an inconsistency in the navigation from GOES 8 and GOES 10. This error does not affect typical cloud track wind analysis because time sequences of GOES data are usually offset from correct navigation by a constant amount. We treat these ground point heights as systematic errors which can be added to the cloud heights to give accurate results. For this case, 2.1 km should be added to all the heights to get correct results. The clouds to the north of the image have a variety of heights.

There is a NOAA wind profiler located at DeQueen, Arkansas (DQU) between the two 8.8 km clouds (the location of DQU is shown by the "+" symbol in Figs. 1 and 2). At the corrected height of 10.9 km, the profiler observed a westerly wind (269°) at 15.0 m/sec (these values are for the 10445 to 11444 m gate). The asynchronous stereo result of 15.6 m/sec at 267° compares well with the wind profiler observations. Also plots of the NESDIS automatic winds in this show results similar to these analyses.

IR 11 um 4 km resolution results.

Visually one can see shifts between IR 4km imagery due to the parallax from different geosynchronous view points. Figure 2 shows the analysis of IR data matching the case discussed around figure 1. The river valley provides a land mark and the zero point for this analysis is plus 4.8 km. Correcting the heights, there is a reasonable match between the visible and IR results.

Figure 1: GOES West 1 km visible data from day 273 in 1998. Data used in the analysis included the 16:45, 17:15 and 17:45 GOES 10 and 17:15 GOES 8 images.

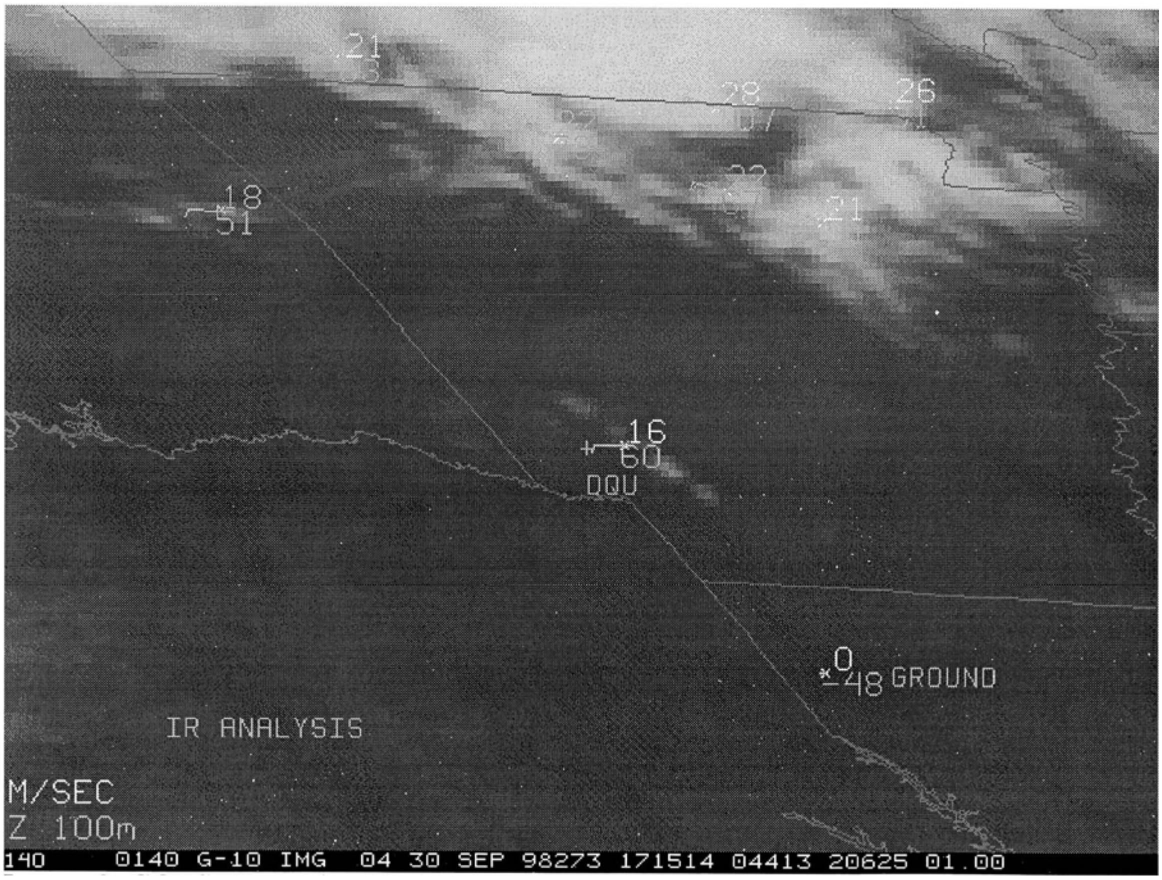
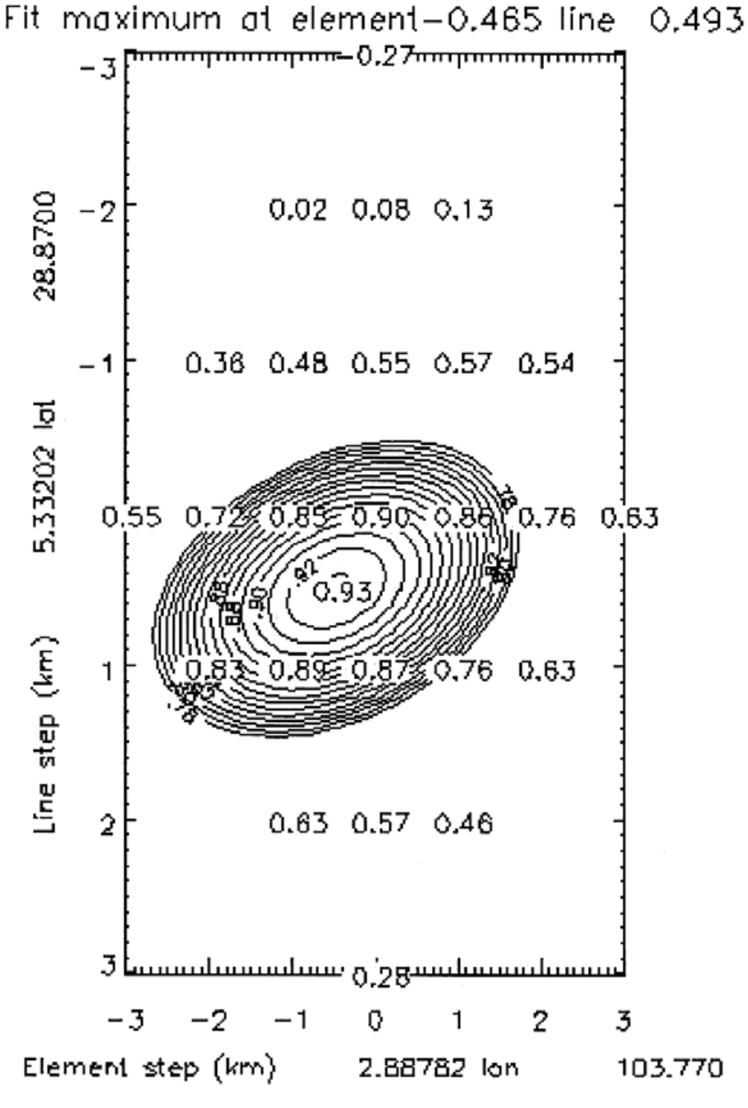


Figure 2. GOES West 4 km IR data from day 273 in 1998. Data used in the analysis included the 16:45, 17:15 and 17:45 GOES 10 and 17:15 GOES 8 images.

In order to consider the analysis of larger pixels than the 1 km GOES visible data, locations to better than ± 1 pixel are required. We have introduced a general procedure applicable to all cloud alignment problems. Figure 3 shows a plot of the correlations calculated at many different pixel offsets. Looking at the numbers, one sees that this is a smooth convex shape. The peak of the function provides a better estimate of the cloud alignment that the pixel offset with the largest correlation coefficient. Representing the pixel offset as a real number rather than an integer allows useful results with large pixels. This is all possible because the alignments is not being done with a single pixel, but with an extended object 20 to 40 km is diameter.

Figure 3. Correlation function of a sample cloud matching. Superimposed is a fitted quadratic surface whose maxima occurs at +.046 elements (east-west) and +.493 lines (north south



Water vapor 8 km resolution result

The case from figure 1 and 2 was repeated with GOES 6.7 mm data. Figure 4 shows the heights and motions. There is no ground reference point available in this channel, but comparisons are possible to the cloud heights from the other channels. Remarkably it is also possible to estimate the stereo heights for water vapor contours which are not clouds. The exact meaning of this is still under study because the weighting function of this channel is at least 50 mb (~1km) thick. Comparisons were made to NESDIS water vapor winds at the results match for the motions.

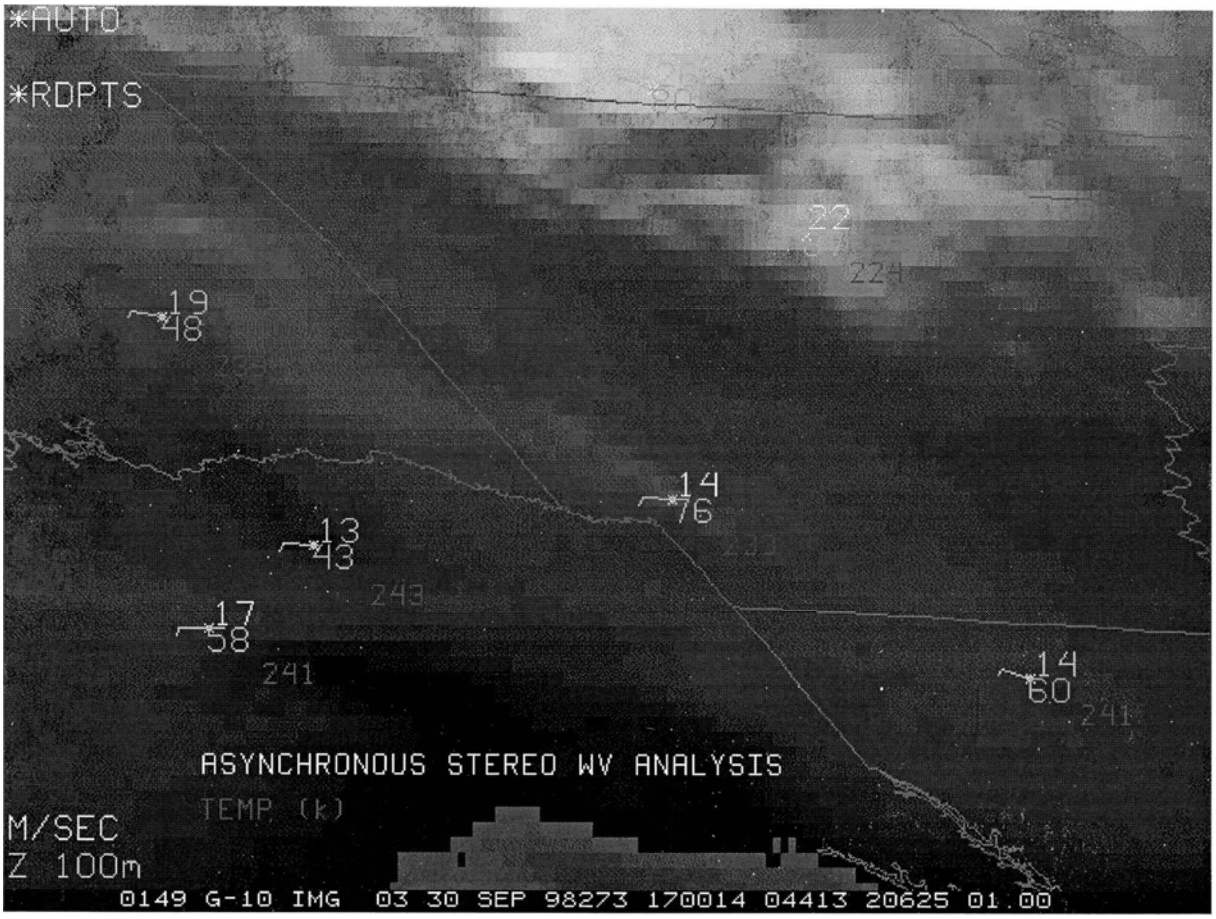


Figure 4, Asynchronous stereo and motion analysis of GOES Water vapor imagery. This matches the data in figures 1 and 2. The objects to the left in the image are water vapor contours, not clouds. The temperatures are shown to the lower right of each object and warmer water vapor temperatures generally indicate lower heights.

GOES East/ GOES West plus AVHRR

Figure 5 shows the results of a mixture of GOES 8 and AVHRR. Matching analyses were performed for GOES 9 + A VHRR, GOES 8 IR + AVHRR and GOES 8 and GOES 10. (These are available at the WWW site). A height comparison can be made using the shadow edge for the cirrus blow off from the storm. Table 1 shows the heights for some clouds with different analysis methods. Different ground reference corrections are required for these combinations because of inconsistencies in the navigation. After correction, the cirrus cloud heights are similar. A separate geometric height can be estimated from the shadow position is some agreement with the multiple satellite result.

Table 2 Matching clouds for 98 273 GOES + AVHRR (km) adjusted for ground reference (Cr).

G8 + AVHRR	12.0	12.3	2.7	2.2		Cr: 0.
G8 + AV IR	11.0	11.0	2.6	0.8		Cr. 1.7
G8 + GI0	12.5	13.3	2.7	2.3		Cr. -1.1
G10 + AVHRR	12.9	14.5	3.2	3.2		Cr. .4
Shadow height	13.2	11.5	3.4			

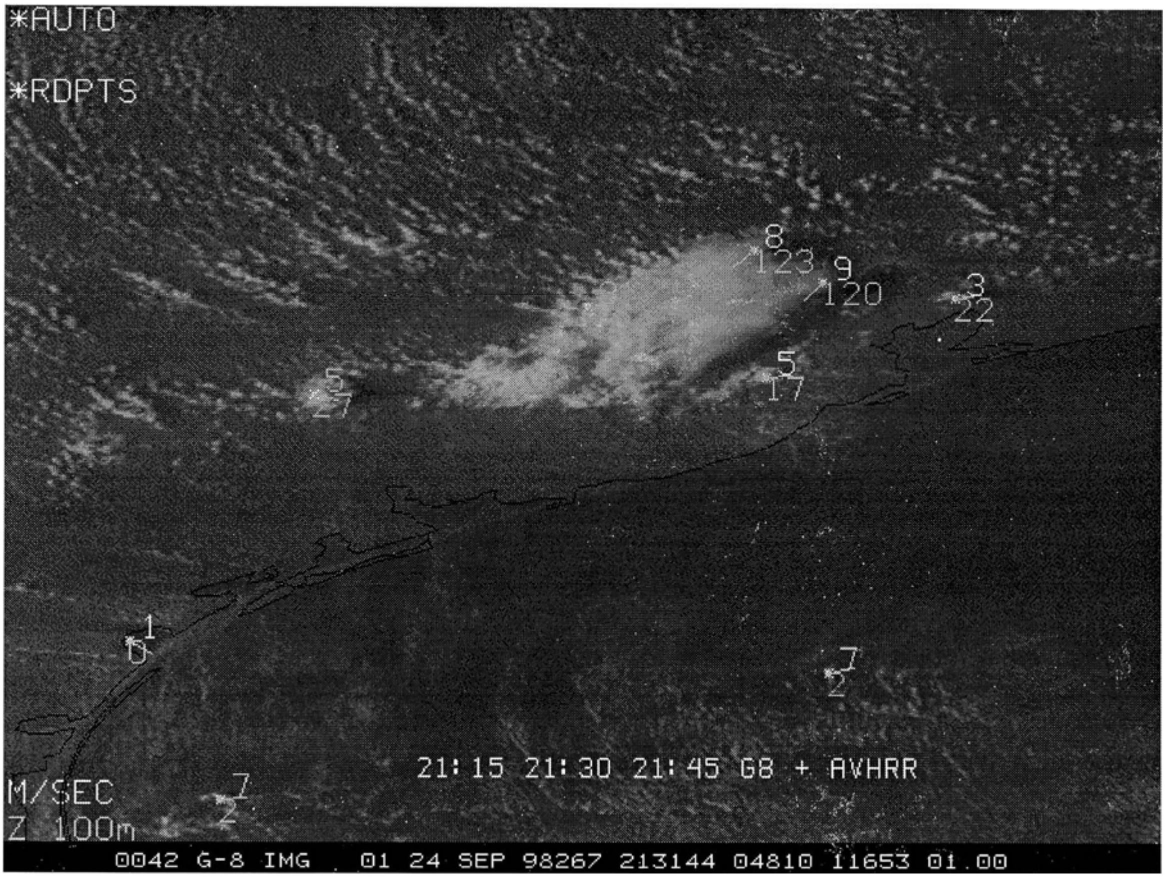


Figure 5 GOES 8 plus AVHRR LAC (1km) analysis for 1998/267 21:30 Z.

Meteosat 7 plus Meteosat 5

Since there are now two Meteosat satellite operating over Africa, it is possible to apply this analysis to that data as well as GOES. This is particularly interesting case because the two Meteosat imagers are close together in time (< 10 sec difference) so a pure stereo result is possible. Table 2 shows corresponding height estimates. The cloud location matching was done with the same software as the asynchronous analysis. For perfect asynchronous results, the clouds need to remain unchanged in time for the analysis period, in this case 1 hour. The simultaneous analysis is dealing with the same object from two viewpoints and would generally be more accurate.

Table 2 Comparison of asynchronous stereo extending over 1 hour and simultaneous stereo from Meteosat 5 and 7 to match figure 6.

Asynchronous	2.9	7.1	10.1	9.6	10.4	9:00+9:30 M7 10:00 M5
Simultaneous	2.8	7.9	8.9	8.0	7.7	10:00 M7 + 10:00 M5

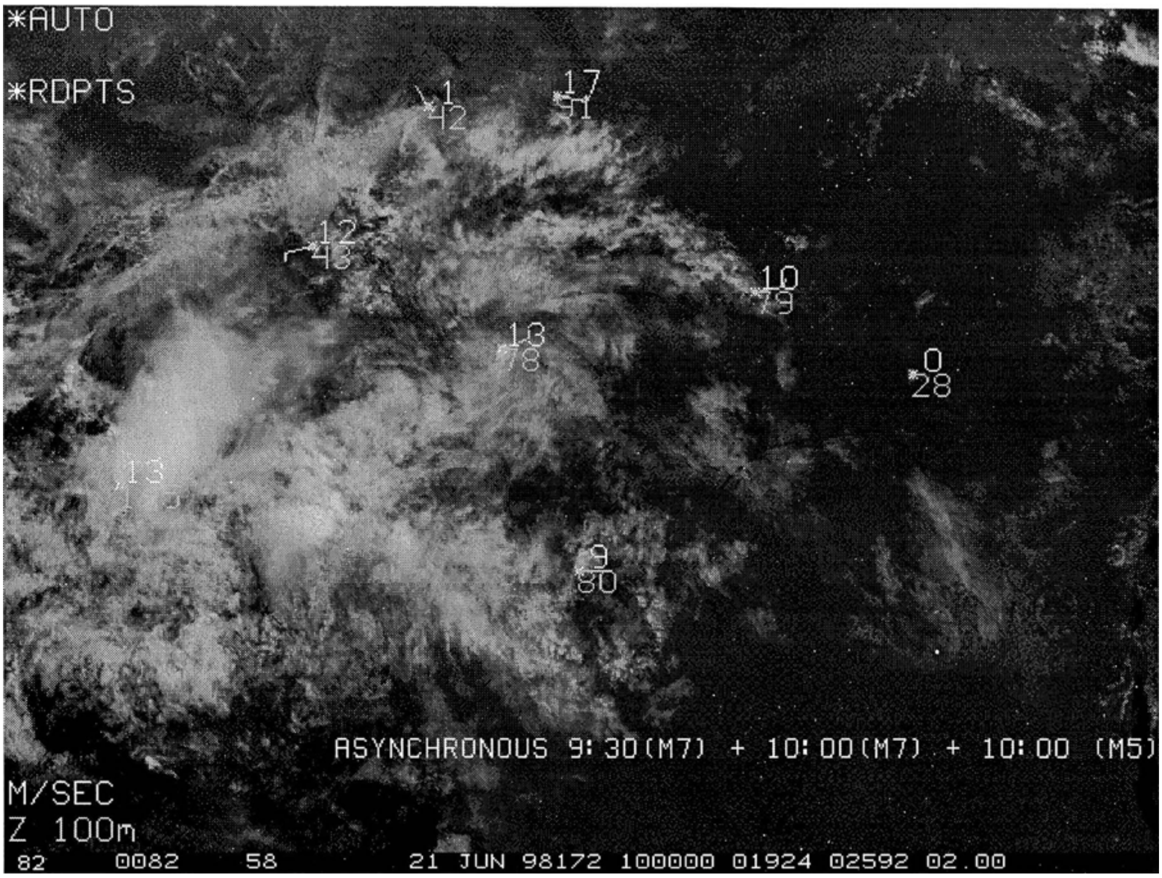


Figure 6 Meteosat 7 + Meteosat 5 1998 / 172/ 10Z using 5 and 2.5 km data.

We would like to acknowledge the help of Victor Manual da Silva of EUMETSAT who supplied a stereo pair of Meteosat 7 and Meteosat 5 data from a special experiment. These were combined with some data collected at CIRA via the NOAA DOMSAT retransmission of Meteosat data.

Automation

An attempt has been made to write computer code to automatically pick out features and then track them with out selecting objects by hand. This produces some good and some bad results like the standard wind analysis techniques. For operational use, NESDIS and other centers filter the resulting wind vectors for consistency and reasonableness. Duplicating those schemes would be a large effort

Plotting the automatic IR NESDIS results on top of the satellite images and comparing to the selected clouds gives a clue for automating the method. We are in the process of modifying the analysis software to read the NESDIS results. Then the objects selected in the automatic analysis can be tracked. The NESDIS results act as a pre-selection of recognizable features already filtered for reasonable motion. The asynchronous stereo analysis would then primarily act to calculate geometric heights for the objects.

Accuracy

The accuracy of these results is dependent upon the pixel size of the measurement and the precision of the navigation constants and software. As we saw above there is a miss alignment between the IR and visible data in GOES. A careful look at the data also shows that different

GOES scan modes produce artifacts in the navigation. NESDIS in their automatic IR Wind analysis adjusts the navigation by searching for land marks. For our demonstration purposes we have relied upon hand picked land marks to provide a zero point for the analysis. As we combine the automatic winds with the stereo heights, we will be able to evaluate whether stereo from IR or Water vapor channels is better than the conventional IR temperature height method.

A good remap program is important to the procedure. We have been using code written in McIdas which is 20 years old and there are artifacts in that software which results from approximations used to speed up the process. This is being rewritten with fewer simplifications to provide a more accurate results. This paper does not use that new software, but it will improve the results for some IR data sets.

Our bottom line estimate of the accuracy is measured by reproducibility. The visible motion and heights at two ends of a cloud are consistent to ± 1 m/sec and 200 meters. Testing thousands of clouds will be needed to arrive at a better estimate of this and we plan to do that once a more automatic scheme can be implemented.

Conclusions

These results show that it is possible to derive geometric heights from a variety of satellite combinations. Many clouds change in one hour, so 3 images in 30 minutes provide better (more reproducible) results. Surprisingly it is possible to obtain some geometric height information even with 8 km resolution water vapor imagery.

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