Atmospheric Motions Derived From Space Based Measurements: A Look To The Near Future

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1. Introduction

This short note addresses opportunities to better define the atmosphere's wind field using data from both polar orbiting and geostationary satellites. This opportunity exists because of recent advances in the ability to observe the atmosphere from space: its thermodynamic structure in both cloudy and clear regions using NOAA-15 data ; sea surface winds using data from ERS-2 and SSM/I; and, rapid scan imaging over targeted areas with GOES. Among the ideas that will be addressed in this note are: the use of geostationary satellites as adaptive observation platforms; the importance of field experiments to advancing the utilization of satellite data for the determination of Atmospheric Motion Vectors (AMVs); optimum observing frequency from GOES for the derivation of AMVs; and, the use of Advanced Microwave Sounding Unit (AMSU) data to define the atmosphere's mass field. Suggestions of how to merge AMSU mass information and satellite derived AMVs to define a consistent dynamic state of the atmosphere will be discussed. To illustrate the potential of the proposed method, AMSU data taken over hurricane Bonnie during this past August are presented. Issues for future work include testing this idea to see if a spatially coherent wind field can be developed from the proposed method (as well as limits to the utility of the method based on latitude); how to best take advantage of adaptive observing and image frequency; the use of super rapid scan imagery for nowcasting various phenomena, especially severe and tornadic storms; and determination of AMVs using non-conventional tracers. The imagery and animations which are referred to in this paper are the same as those which were presented at the Workshop; the Workshop presentation (in Power Point) with loops is available through the WMO satellite home page (hereafter referred to as WMOSatHP). It is not copyrighted; copy and use it as you please - I only ask that credit be given to NOAA/NESDIS when using that material.

2. Adaptive Observations

One of the attributes of NOAA's new generation of Geostationary Operational Environmental Satellites (GOES) is that their imaging and sounding systems can be operated in adaptive observational modes. This allows for more frequent observations over regions with interesting weather phenomena, but at the expense of larger area coverage. To try and optimize the use of GOES, NESDIS supports field experiments whose results can be used, among other things, to determine optimal observing scenarios for GOES. In addition, to provide research data sets for the study of atmospheric phenomena such as hurricanes and severe storms, NESDIS occasionally operates the GOES imager in special super rapid scan operation (SRSO) modes where imagery has been taken as frequently as once every 30 seconds over limited areas, although most SRSO imagery is at one minute intervals.

SRSO data sets serve as valuable resources in helping define future satellite requirements.

2.1 *Special Field Experiments*

It is well known that one of the strongest El Nino's on record occurred during 1997/1998. Intense winter storms moved into the West Coast of the United States causing heavy rains over portions of California. An example of one such storm system is shown using imagery from the 6.7 micron (water vapor) channel, Figure 1. The movie sequence from that figure shows an intense storm system as it moves into the west coast, along with a strong jetstream to its south. During the winter of 1997, NOAA undertook the lead in an ambitious field experiment known as NORPEX (Northern Pacific Experiment). During NORPEX, research aircraft flights released numerous dropsondes, while special high density wind sets were derived from GOES-9. The positive impact of GOES high density winds have been reported on throughout this workshop and will not be repeated here. However, it is in part because of such experiments and the positive results high density winds have had on numerical weather prediction models that NESDIS is moving forward with an operational high density winds product; an example is shown in Figure 2.

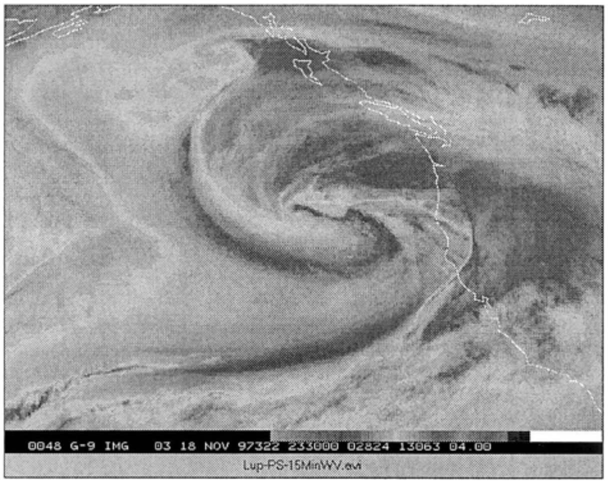

Figure 1. GOES 6.7 um image (loop available through (WMOSatHP) of a West Coast Storm, September 18 & 19, 1997.

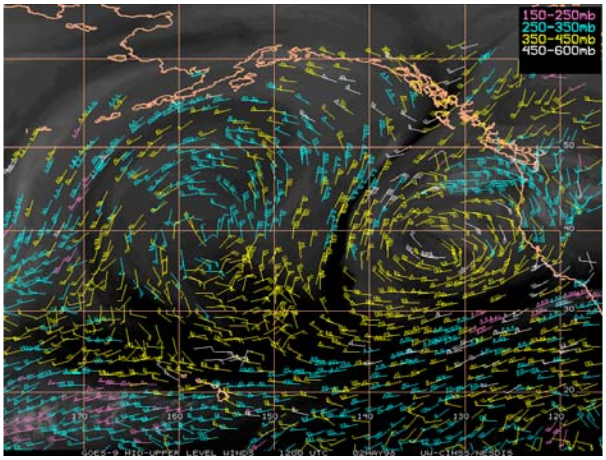

Figure 2. Coverage provided by GOES mid and upper level high density winds from May 2, 1998 (close-up views on WMOSatHP).

2.2 *Image Frequency*

The importance of image frequency in target selection for tracking is well recognized. Indeed, examples that compared 30, 15, 5 and 1 minute interval imaging over thunderstorms and hurricanes were shown by this author at the Third International Winds Workshop. During the spring of 1998 NOAA's GOES-10 satellite was undergoing post-launch testing prior to its being placed in a standby mode. As a part of that testing, the satellite's imager was placed in a near continuous 5 minute interval imaging mode for one month. Imagery taken during that special test provided routine coverage of the entire continental United States and its coastal waters. Those data were used to study a variety of meteorological phenomena, such as tornadic storm outbreaks, as in Figure 3. While such studies are important, equally important are studies that have used that data to focus on the question of optimum imaging frequency for deriving Atmospheric Motion Vectors (AMVs) using the various GOES imager channels.

Initial results from analyses undertaken at NOAA's Cooperative Institute for Meteorological Satellite Studies (CIMSS) showed **(for an imager with GOES-10 characteristics)** that for 10.7 micron channel infrared imagery the optimum observing frequency for determination of AMVs was 10 minutes, and that for visible tracers over land (mainly cumulus) that the optimum sampling frequency was 5 minutes; the number and quality of clear air water vapor winds did not improve for imaging frequencies faster than 30 minutes. Examples, courtesy of Chris Velden of CIMSS, are available through WMOSatHP, with AMVs for the 6.7 micron channel and visible channel shown in Figures 4a and 4b. In Figure 4a, notice how well the 6.7 micron channel AMVs taken at 30 minute intervals reveal the upper low over Kansas and jetstream extending from Texas into the southeast United Stated. Low level flow into the squall line area is best depicted by visible AMVs at 5 minute intervals. Concerning the visible winds, it should be realized that there was no imagery at intervals shorter than five minutes during this test period. However, the reader is invited to view loops of the area shown in Figure 5 to judge for themselves what can be seen in imagery taken at intervals as frequently as once every 30 seconds. That special imagery was taken on May 31, 1996, a day with tornadic storms over eastern Colorado, Nebraska and Oklahoma. In the one minute

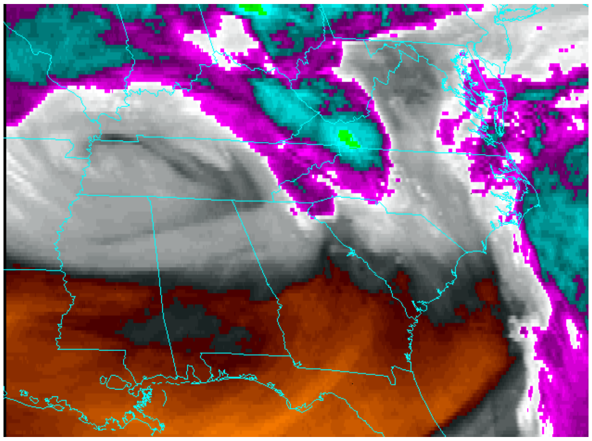

Figure 3. 6.7 micron channel image from GOES-10 special test period taken on March 20, 1997, a morning with intense tornadoes in north Georgia. (A 5 minute interval loop is available through WMOSatHP).

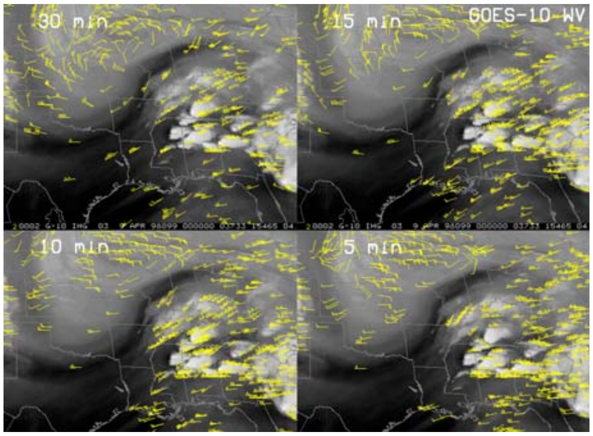

Figure 4a. Example of 6.7 micron channel AMVs from GOES-10 special test period (April 9, 1998). From upper left to lower right the panels show winds computed from imagery at 30, 15, 10 and 5 minute intervals.

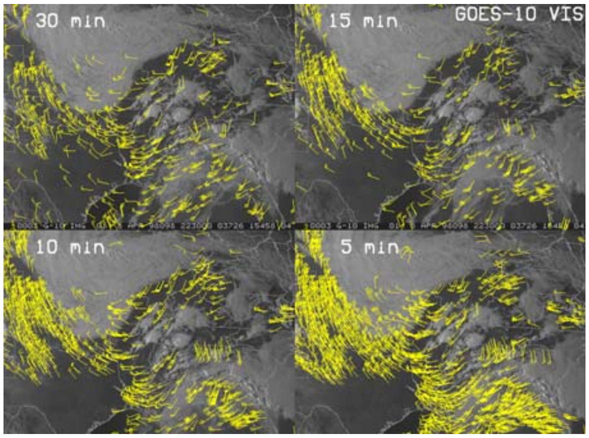

Figure 4b. Example of visible channel cloud drift winds from GOES-10 special test period (April 9, 1998). From upper left to lower right the panels show winds computed from imagery at 30, 15, 10 and 5 minute intervals.

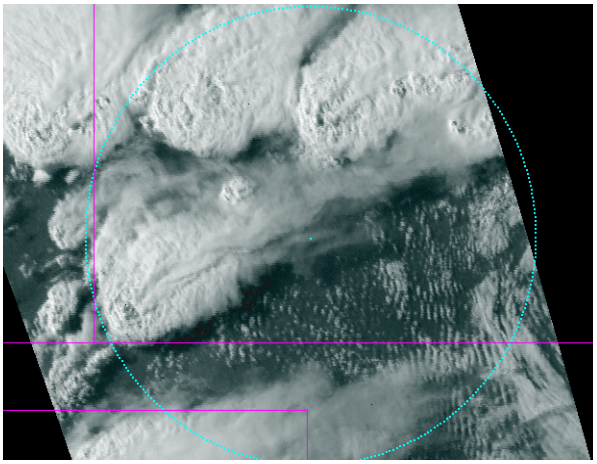

Figure 5. Visible channel GOES-8 imagery mapped to radar projection centered on Dodge City, Kansas, with range circle at 100 n.mi. SRSO loop available through WMOSatHP, with close-ups views of the Ness City, Nebraska, and the eastern Colorado tornadic storms.

and 30 second interval imagery the overshooting top of a tornadic storm near Ness City, Nebraska is seen to rotate cyclonically during the latter portion of the animation; while with the tornadic storm in eastern Colorado, merger of a low level outflow boundary from a storm immediately to its northeast occurs during the time of tornado development. Hurricanes have routinely been studied using SRSO imagery. Analysis of those data are showing that anvil features and eye wall circulations that are difficult (perhaps impossible) to track at 15 minute intervals are easily followed with one minute interval imagery. Figures 6a and 6b were taken by GOES-9 while that satellite was undergoing science checkout prior to its becoming operational. Loops of those figures reveal the difference in observing a hurricane using fifteen and one minute interval imagery. In the fifteen minute loop, hurricane motion is easily followed, as are cirrus clouds away from the central dense overcast (CDO) region but nothing can be followed within the eye wall. By contrast, in the one minute interval loop, features are easily followed at the top of the CDO. The change at CDO level from cyclonic near storm center to anticyclonic further out is apparent, and small scale features can be followed as they race around the eye wall.

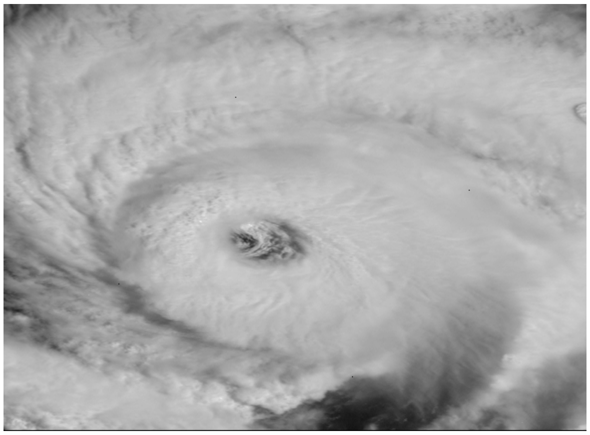

Figure 6a. Image of hurricane Luis taken Sept. 6, 1995; a 6 image animation, from 15 minute interval imagery, is available from WMOSatHP.

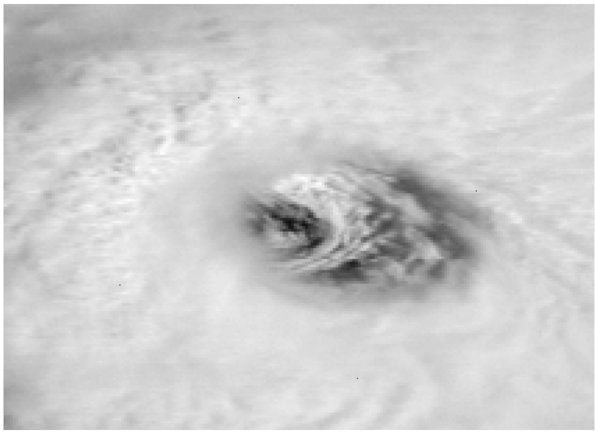

Figure 6b. Close-up view of hurricane Luis taken September 6, 1995; animation of 1 ½ hours of 1 minute imagery is available on WMOSatHP.

All color figures are available on the WMO Web Page http://www.wmo.ch/index.html.

3. Using The Mass Field

Meteorologists have long recognized the relationship between atmospheric mass and motion fields. The thermal wind equations for simplest situation, using normal meteorological notation, are

$$\delta v/\delta z = 1/fT\,(g\,[\delta T/\delta x] + fu_g/T[\delta T/\delta z])$$

$$\delta u/\delta z = -1/fT\,(g\,[\delta T/\delta y] + fv_g/T[\delta T/\delta z]).$$

These simple equations show that for geostrophic flow the change in wind with height is a function of horizontal temperature gradient ($\delta T/\delta x$, $\delta T/\delta y$), plus the slope of isobaric surfaces (u_g, v_g) and vertical temperature gradients ($\delta T/\delta z$). These simple thermal wind equations for geostrophic flow can be generalized to gradient flow (BAMS, 26, 1945, 371-5). Why is this of particular importance in the context of this conference? With the launch of NOAA-K early this year, the possibility exists to define the mass field at high spatial resolution (even in the presence of clouds) using information from the portion of that satellite's Advanced Microwave Sounding Unit that is designed for atmospheric temperature measurements (AMSU-A). For example, Figure 7 is an AVHRR image of hurricane Bonnie while Figure 8 (for the same time) is a vertical temperature anomaly produced from AMSU-A derived retrievals (revealing $\delta T/\delta x$, $\delta T/\delta z$). Adequate cloud cover exists over Bonnie for the derivation of AMVs from GOES (especially with SRSO). Combining highly accurate wind fields from a geostationary satellite with coincident AMSU-A retrievals should allow for the development of a dynamically consistent three dimensional wind field (exceptions are deep tropical areas where the mass and wind field are not balanced, and far northern latitudes where geostationary observations are unsuitable for AMV derivation.

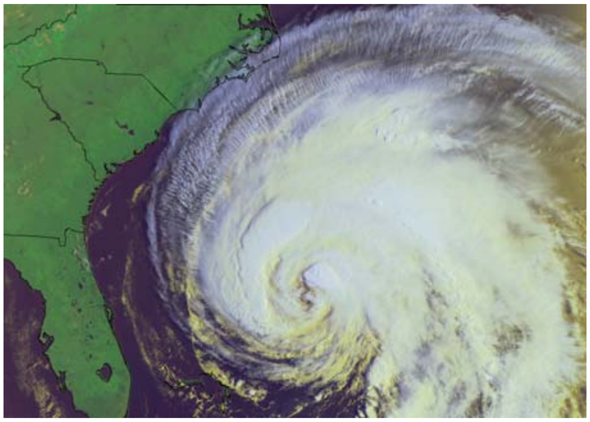

Figure 7. AVHRR 3 channel composite view of Hurricane Bonnie the morning of August 25 (taken from the CIMSS web page).

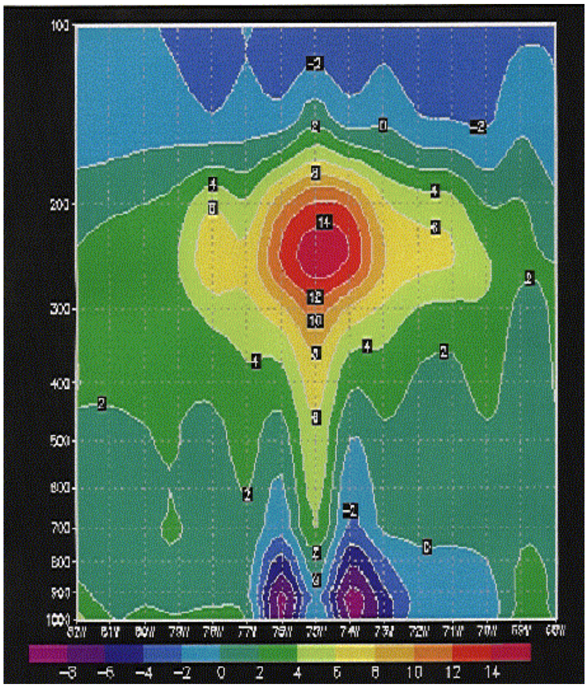

Figure 8. AMSU Temperature Retrieval Anomaly Cross Section at 29 latitude, August 25, 1998. This cross section should be compared with data from research aircraft fights through hurricane Hilda (see WMOSatHP).

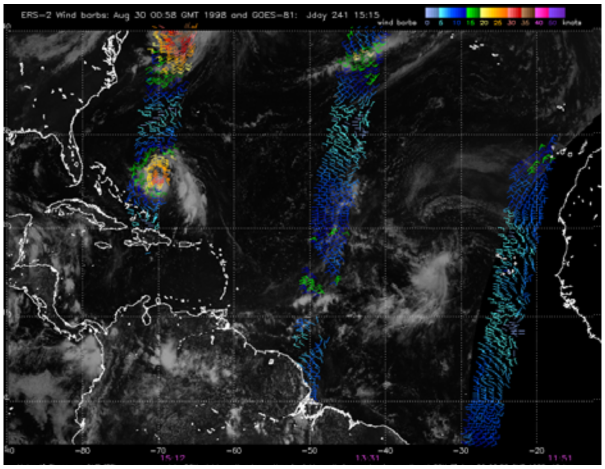

Figure 9. ERS-2 wind barbs over GOES-8 infrared image near 01 GMT on August 30, 1998.

Furthermore, even though not usually available at the same time as NOAA polar orbiting data, over oceans surface winds from scatterometers (Figure 9) might be applicable for the same type application, although there are assumptions that would be required in the boundary layer. A look at another paper presented at this workshop, by Campbell on stereo heights, points to the potential of assigning very accurate cloud heights using stereo techniques with GOES and AVHRR imagery: this is important to the concept presented above. Finally, it should be pointed out in this sub-section that the concept presented here needs to be developed, however, it is not limited to hurricanes but should be applicable to a variety of situations where clouds are present. There will no doubt be limitations where the flow is highly ageostrophic.

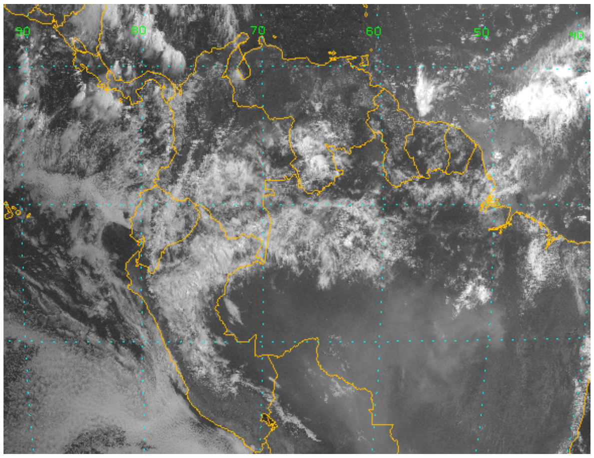

Figure 10a. GOES-8 visible channel image showing sun glint off the coast of South America at 1315 GMT on August 28, 1998.

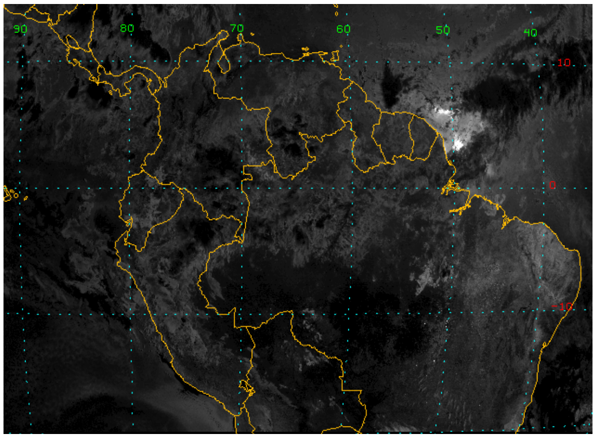

Figure 10b. GOES-8 3.9 micron channel image showing sun glint off the coast of South America at 1315 GMT on August 28, 1998.

4. Non-conventional Tracers

There are features that appear in satellite imagery, not normally used to derive AMVs, that have potential for that application. Although sun glint has been used for years to describe areas with low surface winds over water, those earlier studies were limited to visible satellite imagery. With the new generation of GOES, imagery from the channel at 3.9 microns is also affected by sun glint; indeed, this affect is more pronounced than in visible channel imagery. This is because of differences in the index of refraction of water at the two above mentioned wavelengths. This difference in glint intensity has not been studied to see if distributions of low velocity winds over the sea surface can be determined. This is very important over water where scatterometry works well at higher wind speeds, but has problems where surface winds

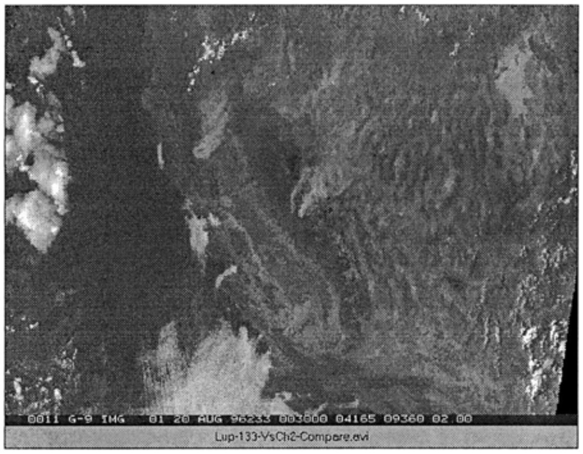

Figure 11. Image of smoke plumes from fires over California, from GOES-9 on August 20, 1996 (animation available from WMOSatHP).

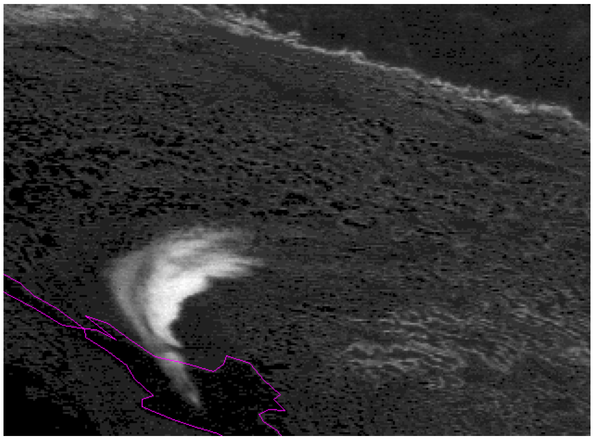

Figure 12. Derived product image of volcanic ash plumes over New Zealand, as detected by GOES-9 on June 16, 1996 (animation available from WMOSatHP).

are low. Differences in sun glint can be seen by examining the visible and 3.9 micron channel movie loops of Figures 10a and 10b, which may be accessed through the WMOSatHP. There are a number of other potential tracers that can be used for determination of AMVs if their heights can be properly assigned. They are smoke plumes from fires, Figure 11, and volcanic ash plumes, Figure 12. If very high spectral resolution imagery becomes available in the future, one day it might be possible to determine AMVs very accurately by tracking different atmospheric constituents.

5. Conclusions

This note has dealt with near opportunities for using satellite data to improve AMVs using data from both polar orbiting and geostationary satellites. It has not looked into the next twenty years when active systems, such as space based lidars, may become a major contributor to this venture. This near term opportunity exists because of recent advances in polar orbiting and geostationary satellites observing capabilities. The note was meant to raise challenges in some important areas. Perhaps the foremost practical challenge is determining how to best use geostationary satellites as adaptive observation platforms, with imagery taken at frequencies appropriate to the scale of the system being investigated, while meeting the demands of operational numerical weather prediction systems and other users that require routine coverage. Suggestions of how to merge AMSU mass information and satellite derived AMVs to define a consistent dynamic state of the atmosphere was discussed; and although there are obvious pitfalls in this area, it should be investigated in its own right for the purpose of determining just how well AMVs can be determined from space based observations alone. The importance of field experiments to advancing the utilization of satellite data for the determination of Atmospheric Motion Vectors (AMVs), as well as other science, was addressed - it is gratifying to see that geostationary satellite operators across the globe are actively involved in the support of field experiments. It is also exciting to realize that every geostationary satellite operator at this workshop has planned improvements underway for their geostationary satellite's meteorological imaging capability.