COMBINED CAPABILITIES OF DATA FROM ACTIVE AND PASSIVE SATELLITE INSTRUMENTS TO DEFINE ATMOSPHERIC MOTION

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Integrity is the watch word of science. It is important that as we move to the future that we insure the integrity of our work. Too often, a scientist can become so involved in a particular product or area that the product becomes an area unto itself. This can lead to a sense of loyalty to the product, along with a lack of objectivity. This can be dangerous, because once it is perceived by the community at large that a scientist has lost objectivity, then all past work might be brought unrightly into question. Thus, this talk will focus into looking at lessons from the past that can help us not to fall into the trap of introspection without scientific dissection of that process. This talk will cover several areas:

a) Some Lessons from The Past
b) Cloud Location, Type and Movement
c) Cloud Motions and Winds
d) The Atmosphere in Motion
e) Thoughts on Assimilation and NWP

Most of the focus will be on topic (a) - how did we get where we are, and what lessons should we carry forward as we continue to develop our science. The presentation related to this paper can be down-loaded from ftp://orbit35i.nesdis.noaa.gov/pub/ora/purdom/5thWW/[1.]

Perhaps the brightest, most scientifically talented person that I have ever been involved with is Ted Fujita. Ted was one of the original leaders in determining how to best utilize satellite data for a variety of scientific applications. We often think of Ted as a superstar in the area of mesoscale meteorology and tornadoes. That is certainly true, but Ted was also a superstar in the area of satellite meteorology. Why? There were a number of reasons: a) Ted was an expert in atmospheric science; b) Ted's curiosity was boundless; c) Ted was meticulous, you could see that from his early writings in Tellus on mesoscale meteorology - a field which he practically invented; d) Ted's analyses were works of art, but more than that they were precise and always dynamically correct. He knew what he was doing, and with his knowledge of the atmosphere, he knew why? Ted received many awards throughout his career, significant to our science: In 1985 at the 25th anniversary of weather satellites, Ted received a special award for his contributions that led to the success of the U.S. weather satellite program. Ted was cited for 'creative scientific leadership as an enthusiastic pioneer in the use of satellite imagery to analyze and predict mesoscale weather phenomena and to understand severe thunderstorms.'

Ted's pioneering work in the early days of satellite meteorology (for which he was recognized in 1967 with the American Meteorological Society's Clarence Leroy Meisinger Award for pioneering research on mesometeorological analysis and broad contributions to the use of meteorological satellites) made possible much of what we do today. Ted developed the necessary rectification and analysis techniques to make those TIROS satellite photographs useful for estimating the velocity of both low and high level winds. For example, shortly after the launch of TIROS 1, in the study of a 1960 south Pacific tropical storm, Fujita analyzed clouds to provide information about the direction of low level winds and the vertical wind shear between 700 and 200 hPa. He also showed how cloud shadows in these early satellite pictures could be used to quantitatively determine cloud top height (a problem we are still coming to grips with today).

Ted began his career by defining mesoscale meteorology, and under his guidance the Mesometeorology Research Project (MRP) came into being at the University of Chicago. It wasn't long after the launch of TIROS-1 that, recognizing the importance of satellites to meteorology, the MRP changed to SMRP the

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[1] If you want to access the ftp site, please note that you should place the power point presentation and AVI loops into the same folder, then open the power point presentation. That way, the loops will link directly.

Satellite and Mesometeorology Project. The SMRP Research Papers soon became classics in atmospheric research, and are still referred to today.

The Applications Technology Satellite (ATS) era marked the beginning of measurements of cloud motion vectors (cmv's) from space based data. Fujita was there from the beginning, along with Vern Suomi, paving the path for us to follow. Originally, creating cmv's was a manually intensive process. While intensive, such activity had the distinct advantage of engaging the analysts mind into the process. Which cloud, what part of a cloud should be tracked. Which cmv's were representative of the motion of the atmosphere and which were not. Fujita, through his training and research in mesometeorology understood the atmosphere; he knew why the wind was blowing a certain direction and WHY. What he tracked was not a mystery but a revelation for us all. In performing such exquisite scientific work, Fujita lay a challenge for all to follow, as both a scientist and teacher. His QC (Quality Control) indicator was his knowledge and atmospheric dynamics.

An early ATS-1 series of images, from March 6, 1967 were used by Fujita to provide a detailed analysis of cloud motions over the Pacific Ocean area. Using conventional atmospheric analyses, Fujita determined how winds on the synoptic scale should behave, and how the cloud patterns and motions should relate to that. Then, using a series of images over the region, mesoscale cloud tracking was performed. Cloud patterns were selected for computation of cloud velocities, and low, middle, high and unknown initial positions were subjectively assigned. But those subjective assignments were not a mere guesses; they were based on atmospheric physics and understanding. Velocities were computed from cloud displacements between 1223 and 1354 Hawaii Standard Time. Heights were assigned according to cloud movement. From the March 6, 1967 detailed analysis of cloud motions over the Pacific Ocean area, Fujita showed that analysis of ATS cmv's plus conventional data revealed convergence at the 850 hPa level, with large convective clouds forming on the convergence line. This measurement of cloud motions and relating them to dynamic processes in the atmosphere was what was important. This revealing of dynamic processes was utmost in the mind of Fujita and other scientists working in the area of cmv determination in the early days. What, how, why - these were the watch words.

It was recognized early on that humans played an important role in the measurement and determination of cmv's, for the identification of gravity waves, mountain waves, cloud edge erosion and movements that were not direct measurements of the wind. Those phenomena were important, in that they were reflective of various atmospheric processes, but not cmv's in the way we today relate a cmv to a wind

It was recognized early on by Fujita and other pioneers that there was a relationship between image frequency, spatial resolution and the ability to resolve the motion of atmospheric features. For example, early experiments by Shenk and others at NASA, NOAA and in the University community were made to determine life cycles of cumulus over land and water; as well as to study cirrus lifetimes. These aircraft experiments were important components of what evolved into trials of taking images at more frequent that normal intervals (now known as rapid scan) to determine our ability to use cloud motions to determine winds at the mesoscale.

In his cmv research, Fujita showed that it was important to track the appropriate part of a cloud to determine the "wind." For example, Fujita showed that cmv's in various parts of a Florida thunderstorm anvil reveal that the leading edge of a drifting anvil cloud moves faster than the central region of the cloud. Fujita showed, what many of us realized, that the motions of a thunderstorm anvil were not representative of the wind field, but rather were representative of the thunderstorm's divergence at anvil level, plus the wind field into which it evolved. Furthermore, Fujita was the first to make Lear Jet flights (early 1970s) during which thunderstorm overshooting tops were photographed at 30 second intervals to study the dynamics of overshooting tops. In studying those tops, Fujita noted the existence of cirrus in the stratosphere, "jumping cirrus," which streamed downwind from the thunderstorm updraft area (the overshooting top region). In those studies of overshooting tops, many of the things revealed in 30 second and one minute interval GOES visible imagery were recognized. They included strong overshooting with downstream cirrus above the broad anvil top. We now realize that such cirrus often spreads hundreds of miles downwind, and may be related to winds in the stratosphere. Current research of one minute and 30 second interval imagery (super rapid scan) has revealed that clouds all levels are easily followed, and that any number of cmv's might be derived. The question is: "what is the purpose of these winds?" Some of those super mesoscale cmv's are measurements that are representative on the synoptic scale, others are representative of the mesoscale, while some of the measurements reveal the effect of dynamic pressure as winds slow as they approach a mature thunderstorm. When we develop our cmv's today, are we selective and filter out winds that are inappropriate for a given application? In the image, the circle represents a 100 km radius: notice the variability of cirrus motions within that region. Which would you pick, what density, what application?

More than any of us, I believe, Fujita understood the importance of understanding cloud motions from satellites and the importance of their correct utilization in atmospheric science. Fujita was among the first to use stereo from the ground to track clouds and assign their correct heights and motions. We should all understand how important it is to place a cmv at the proper level, especially when wind speeds are strong - recall that while acceleration is directly proportional to horizontal gradients in the mass field, it is proportional to the square of the wind speed (V squared over 2). Thus errors at high wind speeds can be much more damaging for certain applications than similar errors at low wind speeds. But, imagine further the havoc that can result when these winds are placed at the wrong height in a highly energetic region such as the jet stream (a compounding error).

At the second wind workshop in Tokyo, Fujita and I showed results from experiments where ground based stereo cmv's were compared with cmv's derived from GOES data. The GOES cmv's height was determined using cloud shadows, while Fujita tracked the clouds over the same region using his ground based stereo camera system. Fujita stereoscopic whole sky cameras produced many more vectors than were produced with the GOES imagery (as might be expected). Most important, his measurements validated GOES cmv's to be within 1 m/s and 10 deg and 0.5 km. GOES cmv's ranged from 15.7 to 17.1 m/s from 314 to 315 degrees; CO2 slicing and cloud shadows agree on 10.5 km heights for pelican shaped cloud. The winds done for this example were produced in a research environment. Their verification statistics is what we should strive for operationally.

As satellite meteorologists, one of the tenets of which we should be acutely aware is that when we are observing the earth/atmosphere, "each spatial element has a continuous spectrum that may be used to analyze the surface and the atmosphere." In satellite meteorology, we have tended to use "chunks" of the spectrum (channels over selected wavelengths) for our analysis. As we move to the future, this is most definitely the way we DO NOT want to go for a number of applications. After hearing Bill Smith's talk on GIFTS, that seems rather obvious.

NASA has an instrument called AVIRIS, which currently flies on an aircraft. That instrument takes about 240 samples of the spectrum between around 400 and 2400 nanometers (0.4 to 2.4 microns). That very high resolution data may be used to analyze the spectrum in more detail (at each pixel). For example, fire, smoke, land surface and cloud appear very different depending on the wavelength used to observe a scene. While smoke shows up very well at short wavelengths, at long wavelengths we can virtually see right through it! At those longer wavelengths, the heat from the fire can be detected. However, as interesting as the finding and tracking of smoke may be, that is nothing (relatively speaking) when compared to water vapor. If we look at the same scene, using different portions of the AVIRIS spectrum, at 15 minute intervals, we can actually follow plumes of water vapor as they evolve and move. It is this type capability to which we need to evolve!

With our (USA) current GOES we can track motion in five channels. The current GOES is an adaptive observing platform, which allows for different temporal frequencies of observation depending on the feature of meteorological interest. What is interesting with respect to multispectral imaging, is that depending on channel, we can detect cloud phase, temperature, motion, and using stereo or shadows we can assign a fairly precise height. With the infrared channel centered at 6.7 microns, we detect water vapor, but over a fairly deep region in the atmosphere. I believe that great strides forward will be made in the area of motion tracking from satellites when we move out of the channel era and into the era of spectrometers and interferometers.

Tracking of clouds and features in “water vapor” imagery has added a great deal to our knowledge of motions in the broad scale atmosphere. The ability to determine water vapor winds is certainly one of the major accomplishments over the past decade. But while this accomplishment is in its own way monumental, we must not rest on out laurels, but must go back and do as Fujita would have done. We have a motion, it’s now time to take apart its components, give it a good hard scientific look and define where it fits into the big picture. In this area, we need to be careful to work closely with the modeling community to provide the best data possible - while reminding that community of what the measurement they are using represents. I never cease to be amazed when someone makes the observation that while certain types of observations improved an initial analysis, they did not improve, or show a positive impact on the forecast. Think about it.

The ability to provide high density winds, at several levels, remains an important contribution of the satellite community. These winds serve a variety of users. A bench forecaster may use cmv’s and be satisfied to know that the jet stream or low’s position relative to a forecast, and that the winds are strong. However, for a numerical model application that same success might be a disaster if the winds are placed at the incorrect height, or are in a thunderstorm region where they do not represent the atmosphere’s free stream flow. In the former case the cmv can ruin the forecast because it produces unrealistic shears and accelerations into the data field, in the other case the cmv can ruin the forecast because the model lacks the sophistication to use the information. I’m sure one day models will evolve to the level of sophistication needed where they will know convection is present and can use such information as cmv’s in deep convective regions - but they are not there today.

But, in any case, it is important to note that cmv’s play an important role as part of a global observing system where rawinsondes only provide limited global coverage (mostly in the northern hemisphere). It is also important to realize that it is both the mass and the wind fields play an important role in numerical weather prediction. For example, HIRS provides near global coverage every 12 hours. But, those HIRS data are not currently used where there are clouds NOR are the surface sensing channels used over land. I often wonder how much of the lack of impact of satellite sounding (and wind) data in the northern hemisphere is due to its under utilization over land - just look at the percentage of the northern hemisphere, versus the southern, which is covered by land. With microwave data, we can see through most clouds. However, in current NWP that data is under sampled (in some models it’s as poorly as one AMSU sample every 7 AMSU data points), and as with HIRS, AMSU data is not used over land. I personally believe that statements about the “non-impact” or poor or negative impact of satellite data in the northern hemisphere are due to poor models, their inadequate parameterizations and data assimilation systems, and not the quality of satellite observations - but that is another story for another day - or is it? For example we can measure, or infer winds from a variety of satellite based sensors. From QuikSCAT we can measure ocean surface wind speed, representative over 35 to 50 km square areas. ERS-2 provides us with similar capabilities over the ocean. With these systems, aside from the winds themselves, we get accurate locations of low pressure centers, hurricanes, fronts and trough lines. Are these data able to be used effectively in models? In some instances yes. But what happens when the observations stray too far from the model first guess? Most often the observations “loose their influence” due to the lack of match with the model first guess field. Then one might ask, “How can we justify verifying our satellite derived cmv’s against models, especially in data sparse areas?” I believe that is a valid question and concern.

Synthetic Aperture Radar also provides very accurate wind speed information, and on very small scales. Alaska Mariners call them williways - sudden, cold winds that blow from the coast without warning, churning the calmest seas. Using satellite imaging technology designed for other uses, like making topographical maps and gauging the thickness of sea ice, scientists with the National Oceanic and Atmospheric Administration are taking pictures of sea-level winds, including williways. The images they're producing are already making a difference. "The impression we're getting from the mariners out there is a big 'wow' " said Gary Hufford, regional scientist for the National Weather Service in Alaska. "The device that can spot williways is synthetic aperture radar, or SAR. SAR is unique in that it can provide a picture of the winds through narrow mountain passes. Another satellite-mounted tool, a scatterometer, was designed specifically to gather wind information

over wide regions." While a scatterometer cannot spot williways, it does give wind direction which SAR cannot.

Let's focus on a real problem and see some of the things that can be done with satellite observations, aside from the ones that have been discussed thus far. Hurricane Mitch was one of the deadliest hurricanes ever. It was a category five hurricane that stalled and then drifted slowly southward into Central America, producing devastating flooding in Honduras, Nicaragua, and El Salvador. Its motion was continuously monitored (30 minute intervals) using GOES satellite data; yet model predictions for its movement were poor. How could that be? CMV's were derived on a routine basis. Aircraft flights were made into the storm. Its center location was well known. I cannot provide the answer, but believe its solution lies in improving the utilization of satellite data of all types in NWP : 1) full resolution AMSU and HIRS data; 2) full utilization over land; 3) use of precipitation information from satellites; 4) better models and assimilation systems; 5) use of full resolution, satellite derived ocean surface wind data ; 6) use of winds derived from AMSU (to follow); 7) better use of satellite derived sea surface temperature and altimetry; and, 8) other areas which run the gamut from improved satellite measurements to better model physics and improved parameterization schemes. But let's look at a few areas.

With geostationary satellites, observing frequency is important when analyzing a phenomena. A movie loop made from 30 minute interval imagery centered on the eye of Hurricane Mitch provides the illusion of strong anticyclonic rotation about the eye wall. Nothing could be further from the truth. Mitch was an extremely strong storm: what is observed at 30 minute intervals is simply a stroboscope effect. The features being observed made 300 degrees of clockwise rotation between successive images. When viewed at 30 minute intervals, they appear to move 60 degrees counterclockwise! This is consistent with the strong winds with Mitch. Thus, to correctly observe and analyze cloud feature motions in the eye wall in strong storms, an imaging frequency more rapid than 30 minutes is required. How much more frequently? With GOES, images as frequently as once every minute have been made of hurricanes. Those images, when animated (as is the case with hurricane Luis), clearly show strong cyclonic rotation along the eye wall, as well as the development of small vortices along the eye wall. CMV's made from those data have been used to show the deep cyclonic rotation extends to the hurricane's cirrus canopy, with a sharp ridge separating the inner region of cyclonic low from the broader anticyclonic outflow at hurricane canopy level. Does the extent of the cyclonic flow at canopy level relate to storm intensity - it should, and this phenomena deserves further investigation. It can only be observed with "super rapid scan" satellite imagery at resolutions comparable to today's visible image data (1 km).

With current AVHRR imagery we are able to make very nice color images using three channels composites that separate out high clouds from low clouds and ground. No doubt we will learn to improve on that by using multichannel data from MODIS, or MSG, which should also be able to provide further information on cloud particle size and phase. However, as has been demonstrated in this conference, very accurate height assignments can be made using polar orbiting (AVHRR) and geostationary (GOES and METEOSAT) satellite imagery. But what did we learn from that exercise? One point that resurfaced was the importance of the original work of Fujita on rectification, registration and navigation. Others more subtle were the importance of taking into account the curvature of the earth along the cloud trajectory path. There was also the realization that with the computer power available today, that there are opportunities to improve cloud height assignment by using multiple satellite views - beyond that is the exciting opportunity to investigate cloud properties by removing that ambiguity (height) and the applying multispectral analysis!

It is important to realize that the new polar orbiting satellite instrument AMSU (Advanced Microwave Sounding Unit) is providing valuable observations of the atmosphere, especially ia and around hurricanes. When one performs a simple retrieval of temperature (using climatology as a base) and then subtracts out

the mean sounding for the area, you are left with a temperature anomaly field which is solely due to the AMSU temperature observation. Such AMSU derived anomaly fields depict the warm core of hurricanes very well. This is exceptionally important, as will be shown momentarily, because it allows us to develop realistic renderings of a hurricane's wind field from full resolution AMSU data. BUT, realize that these fields were derived using full resolution AMSU data, while models use only a smattering of the available AMSU data. When we realize that we can observe the hurricane's warm core, and that model assimilation system greatly
under sampling AMSU and may not even see the warm region, then go back to the tenant that satellite data is having minimal impact on models is - incredible, simply incredible.

It is instructive to take a look at the information derived from a particular case; hurricane Floyd on September 14, 1999. This was a case where heavy rains and cloud liquid water were located in the northern part of the storm near the eye wall. Because AMSU-A is contaminated at lower levels by heavy rain, when a temperature anomaly is computed, the heavy rain area will show a negative anomaly. When one derives the wind field using rain contaminated anomaly data, the result is an unrealistic anticyclonic circulation away at low levels. Research is underway to best determine how to remove the low level rain contaminated region and replace it with a realistic temperature field. When that is done, the circulation pattern is realistic, although the very strong winds at the eye wall are not reproduced. That is partly because of the footprint size of the AMSU observation. What is very promising, however, is the ability to derive the three dimensional wind field for the hurricane and its environment using AMSU data and a non-linear balance equation. In two dimensional depictions the strong winds around the eye wall are not reproduced, as expected, however, the asymmetric nature of the broad scale flow is captured. For the case of hurricane Floyd, the asymmetric flow compared very favorably with aircraft reconnaissance data. Indeed, while the high wind region around the eye was not well depicted, the outer winds and those of the environment verified very well, as one might expect because of the larger scale coupling between winds and mass field away from the eye region.

AMSU is a global observing tool. It's ability to detect the driving force of the hurricane (warm core), should be expected to, and does, detect baroclinic features at more northern and southern latitudes. Just as the hurricane's warm core can be detected, so can the baroclinic nature of the jet stream. When AMSU is applied in a similar manner as with hurricanes in the westerlies, very good depictions of the flow are yielded. In an experiment underway at CIRA, AMSU derived winds are being compared with winds over Bermuda, where rawinsonde releases roughly coincide with AMSU overpasses. The flow fields that are being derived using AMSU data look very realistic. The accuracy of the AMSU wind derived at the rawinsonde site compares very well with "rawinsonde truth." This brings us to what I believe is an important juncture with our research using satellite data to derive atmospheric winds. We have a variety of tools that can be used for winds: AMSU, radar scatterometry (ERS-2, QuikSCAT), passive microwave (SSM/I), and geostationary satellite cloud tracking and water vapor motion. How can they best be put together? We know that with AMSU there is the opportunity for winds using a nonlinear balance equation, and that some of those winds are in regions where clouds are being tracked at precisely the same time with geostationary satellites, and in such a situation stereo might be able to be employed for determining cloud height. Can these sets of data be combined to develop an improved product? What about in regions of strong dynamics where the AMSU might miss the highest wind speeds, but where the geostationary satellite's cmv's will find them. How does scatterometry fit into this? With that tool we have a good measure of winds at the surface. There's a lot of good research to do, and I believe our end product can be greatly improved by combining these "non-conventional" winds with cmv's from rapid scan imagery. Maybe we can get close to the magic 1 m/sec.

Where do we go from here. We certainly must move forward with a strong research component; a component grounded in science. Let's take a lesson from the giant's who helped give us the opportunity to be involved in the exciting field of satellite meteorology. We owe them scientific integrity, we owe it to ourselves, and we owe it to those who follow in our footsteps. We are not merely generating winds to compare with rawinsondes and improve our verification statistics. Winds that are "errors" for one scale of motion may be important information for another. We must look to the opportunity provided by hyperspectral data which will be available from systems such as GIFTS. GIFTS promises to be a major part of the future for geostationary observing platforms, and ALL countries involved in developing and providing geostationary satellite data must become be involved in GIFTS validation and assessment activities. We must prepare for the veritable onslaught of data that will be available in the future, with higher spatial resolution, more frequent interval sampling, multiple satellites, and interferometry. Satellites have limited life times, we must optimize their utilization both for monetary reasons and for our personal satisfaction as a science community. It is imperative that we work with the NWP community to improve the utilization of satellite data in that important tool. It is unrealistic to think that we will improve forecasting without improvements in NWP and coincident improvements in the assimilation of satellite data and products. Those products include winds, precipitation, cloud type and a variety of other pieces of information. The future is exceptionally challenging, and we must work with our users to insure that future is brought to a clear and exciting reality.