1.4 APPLICATIONS AND IMPLICATIONS OF THE NEXT GENERATION METEOROLOGICAL SATELLITE IMAGERS AND SOUNDERS

James F. W. Purdom
Cooperative Institute for Research in the Atmosphere
CIRA/Colorado State University, Ft. Collins, CO

1. INTRODUCTION

The operational meteorological satellite era of today is undergoing a rapid metamorphosis in the strictest sense of the word. Over the next two decades it will undergo a marked alteration in its appearance, character and function. New instruments on research satellites have provided insights into future satellite systems and a variety of environmental applications are growing vigorously. As the remote sensing capabilities of operational and research space agencies evolve, instruments with enhanced capabilities (higher spatial, spectral and temporal resolution) will be demonstrated and their data will be utilized for operational purposes. To take advantage of the future's promise, marked changes will occur in the ways we approach satellite operation, data handling, science, product development, training and utilization. As we look to the next decade: operational polar and low earth orbiting satellites will fly fixed orbits with sensors that operate in routine modes; low earth orbiting commercial and research satellites will operate in much the same manner as the operational polar satellites although some will have more flexibility in where their instruments point along ground track; and, as is the case today, geostationary satellite instruments will operate in adaptive observing modes where scan area and frequency are determined by operational need. The environmental satellite observing system of the future will be exceptionally powerful, how data from the various satellites that make up that system are treated to achieve full utilization is a point that must be addressed. It will require leadership, vision and commitment at a variety of levels: world governments, research and operational satellite operators and space agencies, data users and scientists. This overview addresses the future space based observing system in the context of assuring full utilization by taking full advantage of various satellites systems observing capabilities.

2. A SCIENCE OF CHANGE

From a meager start 40+ years ago, meteorological and oceanographic satellites are now used for a variety of applications that span scales from nowcasting to climate, and include land, ocean, atmosphere and ecological applications. Simultaneously, new instruments on research satellites have provided insights into future satellite systems, such that a variety of environmental applications are growing vigorously. The operational satellite era as we know it today is undergoing a rapid metamorphosis. During the next one to two decades we will have seen, and participated in a marked alteration in its appearance, character and function. During the past decade, data from research satellites have been operationally utilized on a sporadic basis, however, a welcome paradigm shift is underway: during the next decade use of research satellite data for operational purposes will become routine. As the remote sensing capabilities of space agencies evolve, both operational and research, instruments with enhanced capabilities (higher spatial resolution, more frequent observations, and more spectral bands covering more of the spectrum with higher spectral resolution) will be demonstrated and their data will be utilized for operational purposes. A global view embraces the concept of a composite space-based observing system[1] where the distinctions between geostationary, polar and low earth orbiting satellites, research and operational satellites, and various sensors are minimized. As we take advantage of the future's promise, marked changes will occur in

---

[1] This paper focuses on the space-based component of the Global Observing System (GOS). It is well recognized by the author that the earth-based component plays an important role in the composite GOS; however, many advanced space-based observing systems are well defined for the next 15 years, and for that reason this paper is focused into that arena.

the ways we approach data handling, science, product development, training and utilization. To prepare for the daunting task of monitoring and understanding the earth-atmosphere system from these new data, and ensuring their full utilization, we must work together in global science and operational partnerships.

3. EVOLUTION TO TODAY's SYSTEM

Observing the earth and its environment from space has been a science in transition from its very beginning. Indeed, the operational meteorological satellite era of 2004 is undergoing a rapid metamorphosis in the strictest sense of the word. Over the next quarter century it will undergo a marked alteration in its appearance, character and function. It's not new.

By 1948, pioneers in atmospheric science were paving the way for environmental satellite applications with the first serious attempt to analyze the atmosphere from "space" based on cloud characteristics depicted in large area photo-mosaics taken from V2 Rockets (Crowson, 1949). On April 1, 1960, the meteorological satellite era "officially" began with the launch of TIROS 1 (Television and InfraRed Observation Satellite). Since those early days, when satellite images were uncalibrated photographs of clouds and the earth, *growth in remote sensing technology and computer capabilities* have led to the high resolution, multi-spectral digital renderings that satellite data are today. Instrumentation has developed well beyond the era of uncalibrated vidicon camera systems to include passive visible, infrared and microwave imaging systems, passive infrared and microwave atmospheric sounding systems, and active microwave instruments for measuring rainfall, sea level altimetry and sea state. While the type instrumentation mentioned above has become well known to the operational community, specialized instrumentation has also been developed for measuring atmospheric chemistry, ozone, radiation budget, refractive index and lightning. It comes as no surprise, that from that meager start 40+ years ago, meteorological and oceanographic satellites are now used for a variety of applications that span scales from nowcasting to climate, and include land, ocean, atmosphere and ecological applications.[2] Concurrently, utilization has expanded greatly, with meteorological satellites providing essential data for weather forecasting to national weather services across the globe; indeed it would be difficult to find an area of operational meteorology that has not been positively affected by meteorological satellites

The early success of the United States' meteorological space ventures to polar and geostationary orbit led to the development of similar systems by other nations, resulting in today's operational space based Global Observing System (GOS). Polar systems are operated by China, the Russian Federation and the United States. Geostationary systems are operated by: China, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), Japan, the Russian Federation, India, and, the United States. All operational polar and geostationary systems provide multi-channel digital imagery, while the United States' polar system also provides microwave imaging and sounding data and both its polar and geostationary systems provide infrared sounding data. For a more detailed explanation on the evolution of the United States' operational satellite system and products derived from that system see Purdom and Menzel, 1996. Information on operational meteorological satellite systems can be accessed through the WMO Satellite Program's Web Site (http://www.wmo.ch/hinsman/satopstatus.html)

Today's research satellites are designed for lifetimes of five to seven years, and it is not uncommon for them to last longer. Many of the research space agencies are making their data available for operational use, and formal agreements for their participation in the space based component of the Global Observing System (GOS) have been developed through WMO. Research satellite data provide valuable information for earth system science: a variety of environmental applications are growing vigorously (Asrar, 2002; Briggs and Oriol-Pibernat, 2002). Many operational users receive data from research satellites and

---

[2] See the Coordination Group for Meteorological Satellite's (CGMS) Directory of Meteorological Satellite Applications, http://www.wmo.ch/hinsman/index.htm

provide a variety of near real-time products such as rainfall rates, polar water vapor winds, sea surface winds, sea level altimetry, ocean color and surface ice extent and characteristics. Research satellite sensors include multi-channel instruments with high spectral resolution, microwave radars, and hyperspectral imagers and sounders: those instruments continue to help define those for future operational systems. For example, MODIS with high spatial resolution measurements in 36 spectral bands located between 0.4 and 14.5 microns is providing exciting new data for use in ocean, land, and atmospheric science. Among the exciting findings being demonstrated are the ability to determine cloud properties and detect aerosols, to detect hazards such as fires and volcanic ash plumes, to determine ocean properties such as chlorophyll-a and primary productivity, turbidity, and sea surface temperature, and to assess surface features such as snow cover, vegetation health, and surface temperature. The Atmospheric InfraRed Sounder (AIRS) on NASA's Aqua satellite is providing hyperspectral measurements in the infrared portion of the spectrum that are being used with positive impact at Global NWP Centers and in a variety of climate studies.

The move to hyperspectral sensors in the visible and infrared portion of the spectrum for meteorological applications is important for a number of reasons that range from climate (Goody et al, 1998) to real time data analysis – basically, when you "own the spectrum" definition of channels becomes a reality and growth potential is exceptional.[♣] In orbit channel selection is being demonstrated by the European Space Agency (ESA) with ENVISAT's Medium Resolution Imaging Spectrometer (MERIS). MERIS is an imaging spectrometer that measures reflected solar radiation between 390 and 1040 nanometers in 15 spectral bands that are program selectable in both spectral width (1.8 nanometers) and location. Japan's National Space Development Agency (NASDA) and NASA, through their joint Tropical Rainfall Measuring Mission (TRMM) have demonstrated the use of space-based measurements to estimate rainfall rates over the ocean while also providing profiles of precipitation and observations of lightning. Active radar is also used on research satellites to measure ocean surface winds (ESA's ERS and NASA's QuikSCAT) as well as to provide information on sea level topography to study marine geophysics and physical oceanography (Topex/Poseidon and ERS-2).

4. THE COMING GENERATION

Polar: In the polar orbiting satellite arena we will move from today's operational polar system that has four satellites in polar orbit (NOAA-16&17, FY-1C and METEOR 3M-N) to a system with five satellites in polar orbit (NPOESS-AM, NPOESS-PM, Metop, FY-3, and the Meteor 3M series). Each of those satellite series will provide direct readout, and data from a variety of sensors will be stored onboard for later processing and distribution. Coordination between satellite operators is underway within CGMS, with the aid of WMO, to coordinate equator crossing times and direct broadcast characteristics to optimize information that will be available from those systems. In the polar constellation, various satellites will carry high-resolution multispectral imagers, infrared interferometer sounders, advanced microwave imagers and sounders, active microwave imagers, improved ozone monitoring instruments and radio occultation (GPS) sensors. Information on the characteristics of all planned polar satellites can be found through accessing the WMO Satellite Program data base accessible through the WMO homepage: http://www.wmo.ch.

Geostationary: In the geostationary arena, plans are for similar coverage as today with satellites operated by China, India, EUMETSAT the Russian Federation and the United States. Many operators are planning for with satellites with greatly improved spectral and temporal coverage for imaging, and the United States is planning to move to hyperspectral infrared sounding. EUMETSAT has launched the first of its METEOSAT Second Generation (MSG), commissioned as METEOSAT-8. METEOSAT-8's Spinning Enhanced Visible and Infra Red Imager (SEVIRI) represents a major step forward in imaging from geostationary (Schmetz, et al, 2002). The SEVIRI has 12 channels (IR, near

---

[♣] In a satellite scene, each spatial element has **a continuous spectrum** that may be used to analyze the earth and its atmosphere

IR and visible): eleven of those channels are at 3 km resolution, with a broadband visible channel at 1 km resolution. Normal observing frequency for SEVIRI is 15 minutes, but the instrument can operate in a rapid scan mode.

Research satellites: Future research missions will continue to contribute to the space-based component of the GOS while influencing its evolution. Planning is underway for a follow-on mission based on the success of TRMM. That mission, known as the Global Precipitation Mission (GPM), is being led by NASA and NASDA and is engaging both the research and operational communities. Other research missions include investigations of atmospheric chemistry and trace gasses, the earth's gravity field, soil moisture and ocean salinity, atmospheric winds, disaster and environmental monitoring, integrated atmospheric column water vapor, cloud ice content, cloud droplet properties and distribution, aerosols, and polar ice and snow water equivalent. Instrumentation under development to accomplish those measurements include lidar, high resolution and hyperspectral imaging and sounding instrumentation, active and passive microwave sensors, as well as cloud resolving and L-band radars. All of the measurements have potential application, some more obvious than others – for example winds and soil moisture are recognized as important for NWP, while less commonly recognized are the importance of the earth's gravity field and ocean salinity for accurate sea level altimetry measurements which in turn are important for ocean current derivation and seasonal to interannual forecasting. Addressing the full scope of space based research activity related to atmospheric science that is underway within various space agencies (whose countries also provide satellite data for operational meteorological applications) is well beyond the scope of this paper. Those activities tend to focus on areas such as environmental change, climate, aerosols, chemistry, and a variety of earth surface related properties. For detailed information the reader should go to the various web sites of the research space agencies, i.e. NASA (USA), NASDA (Japan), ESA (European Space Agency), ISRO (India); China via http://fas.org/spp/guide/china/earth/ and the Russian Federation using the link (http://sputnik.infospace.ru/).

5. OPPORTUNITY FOR INNOVATION USAGE: POLAR ORBITING SATELLITE FORMATIONS AND CONSTELLATIONS

Today's generation satellite launch vehicles are placing satellites in very precise orbits that have minimal orbital drift. This is important from an operational perspective, leading to extended lifetimes of satellites, and for applications such as climate where orbital drift has made interpretation of data difficult (Christy, et al, 1998). In the research arena, this advanced launch capability has allowed for formation flying, as has been accomplished with Landsat-7, EO-1, SAC-C and Terra. In that formation, the satellites all have the same ground track, but observe the same location of earth at slightly different times (Landsat-7 at t=0, EO-1 at t=1 min., SAC-C at t=13 min., Terra at t=40 min.), with different swath widths and at different spatial and spectral resolutions. In another formation, ERS-2 and Envisat are separated in time by 28 minutes; their common instruments include the Along Track Scanning Radiometer and Synthetic Aperture Radar. While the formations mentioned above were designed for science studies, they provide excellent opportunities for innovative data analysis with value for operational applications such as cloud motion tracking, cloud evolution (particularly over short time frames in Polar Regions), and more opportunities for higher spectral resolution cloud free fields of view of the land and ocean surfaces. While the constellation of geostationary satellites is well recognized, what is less well realized is the opportunity to observe phenomena at high latitudes using the array of polar orbiting satellites. Derivation of cloud motions at high latitudes from sequential polar orbiting satellite imagery is under investigation (Key, et al, 2002). Those high latitude cloud and water vapor motion vectors have shown positive impact in NWP (op cit). Inspection of Figure 1 reveals that there are numerous opportunities for cloud motion tracking (similar to geostationary system capability) using multiple views from polar passes at high latitudes. While those views from different satellites would often be from different viewing perspectives (with the exception of the formations mentioned above) techniques employing asynchronous stereo for cloud tracking can be used to determine both cloud motion and height (Campbell, et al, 1996a,b). Note that Figure 1 shows only 5 satellites – but there are potentially dozens that could fill that figure! Indeed, the capability to observe the earth and its environment from low earth orbiting satellites that are in operation today, and planned for the future, are truly staggering!

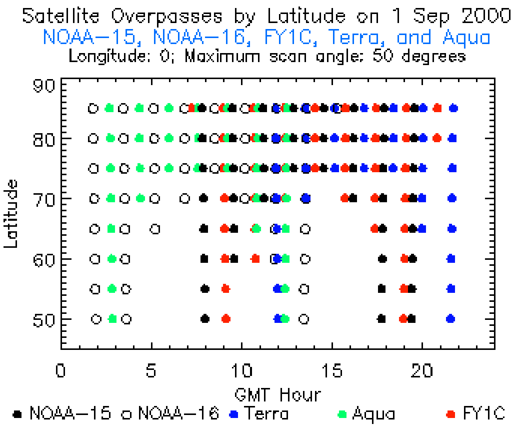

Figure 1. Opportunities for multiple views of same areas as a function of latitude and time. Note the increased polar viewing frequency.

6. BASIC RESOLUTIONS

For the space based remote sensing system of today, and as the space-based remote sensing system of the future develops and evolves, four critical questions must be addressed. They all deal with resolution and by their very nature are focused and driven by a variety of user needs (not necessarily convergent) along with a continuing quest for knowledge and the potential for growth in advanced applications. As mentioned above the four questions all deal with resolution. Those resolutions are: 1) spatial – what picture element size is required to identify the feature of interest, what is its spatial variability, and over what scale must it be observed; 2) spectral - each spatial element has a continuous spectrum that may be used to analyze the earth's surface and atmosphere, what spectral resolution(s) is (are) needed for a particular application; 3) temporal – how often does the feature of interest need to be observed; and, 4) radiometric – signal to noise, or how accurately does an observation need to be. Each of the above resolution questions must be addressed in the context of an evolving space based observing system within which the satellite(s) exists, or will exist. For some applications, optimal resolutions may not be attainable from any one satellite but may be approached using data from a series of satellites. Similar reasoning may be applicable for many of the requirements that satellites are designed to meet – requirements are normally for an observation of a certain phenomena, within resolutions similar to those above (spatial, temporal and acceptable accuracy).

7. FUTURE REALITIES

Requirements: How a requirement is satisfied, or conceptualised, may take on an entirely different meaning if it is addressed from a satellite system concept, rather than a single satellite viewpoint. This approach, using various satellite assets, is currently being done in the rainfall arena where combinations of active microwave (TRMM), passive microwave (TRMM & SSMI) and visible and infrared data from geostationary satellites are being used to derive daily global rainfall. Generally requirements are for a specific satellite's performance with respect to perceived user needs that invariably focus on that specific satellite's data – the validity of that approach is in question, and may well no longer be valid. As we move into the future, user requirements need to be viewed in terms of a system of operational and research satellites in a variety of orbits, and addressed in terms of the four resolutions – spatial, spectral, temporal, and radiometric.

Paradigm shift, the system: The operational satellite system of tomorrow will be comprised of a stable operational component integrated with a dynamic research component. Although research satellites are often one of a kind, their planning timeframe and lifetimes make them very attractive for operational uses. Because there are several years between conception and launch, with proper planning and coordination they can provide data that greatly enhances operational satellite data. In the operational community continuity of services is always an over arching principal that must be kept in focus by data providers. For that reason, as well as economies of scale, operational satellite systems change slowly and often require a decade or more of planning as they transition from one system to another. The operational system of satellites will remain the stable foundation of the space-based GOS, but enhanced by a dynamic research satellite component. Aside from innovative data sets, the R&D satellite data often provide a first glimpse of what future operational data will "look like," and through investigations of those data lead to early and fuller exploitation of a new operational sensor's data.

Data volume: In this decade we will experience a transformation in the space-based GOS that is massive and unparalleled. Research satellite data will become available to the GOS at a time when every operational space system of the past decades is undergoing major upgrades. As pointed earlier, this will offer unprecedented opportunities for the development of variety of sophisticated products and services. However, data volume is about to increase dramatically – about 5 orders of magnitude! Very careful planning will be required to attain maximum utilization from the system of space based observations.

As we prepare for the future, we must think in terms of Satellite Systems and Sensor Synergy. This must be done in the context of a global space based observing system operated in partnership with a variety of earth based remote and in-situ observing systems. However, as mentioned earlier this paper only addresses the space based component.

8. SYNERGY

The spatial and temporal domains of the phenomena being observed drive the satellite systems' spectral needs as a function of space, time, and signal to noise.

One challenge that will be addressed in the future is that of dynamic tasking and adaptive observing. For example, when looking at satellite observing system characteristics, polar orbiting satellites provide global coverage and have fixed ground tracks (well determined orbits) and sensor operational capability (well predictable fixed earth swaths)[3] while geostationary satellite coverage is quasi-hemispheric and its sensors are generally adaptive (point and shoot). As we move to the future, there is a general convergence between geostationary and polar orbiting sensors, i.e. selected visible and infrared sensors will operate over very similar spectral regions. In the geostationary arena, and particularly with the USA's GOES-R system, the spatial, spectral and radiometric resolutions of future sensors will in some cases approach and in other cases surpass those of the polar orbiting satellite systems' sensors. However, it will be many years, if ever, that active sensors move to geostationary orbit, and microwave's domain will likely remain in the realm of low earth orbiting satellites.

Synergy will be addressed here in three aspects: intra-satellite, intra-system and inter-system. Synergy is phenomena or applications driven, and here, for purposes of brevity, the focus will be on the future US GOES-R and NPOESS systems. **Intra-satellite** examples include: a) use of GOES-R and NPOESS high resolution imagery to determine cloud clear fields of view for their respective sounder applications; b) operating the GOES-R Advanced Baseline Imager (ABI) in an adaptive mode (rapid scanning) based on analysis of hyperspectral sounder data from its Hyperspectral Environmental Suite (HES), as in Figures 2a&b, below and on next page (Figures 2a&b are hypothetical based on data taken by GOES-11 on July 24, 2000);

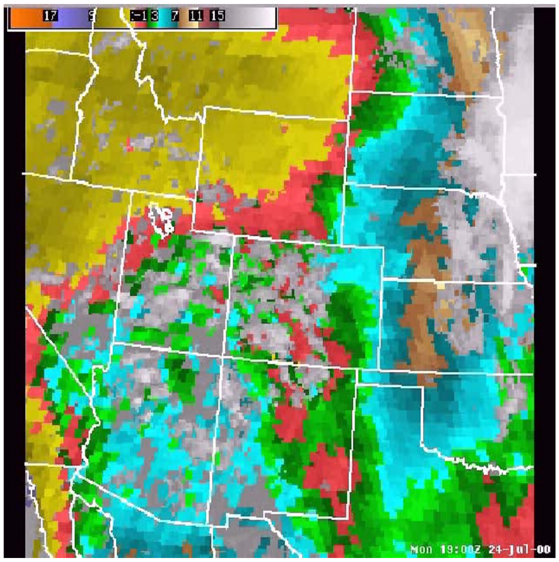

Figure 2. Detection of unstable area over Kansas and Nebraska directs ABI to rapid scan mode over that area.

---

[3] It should be noted that some research polar satellite sensors can be operated in a limited adaptive pointing mode (such as hyperion on EO-1) and that some future research satellites plan on using adaptive pointing.

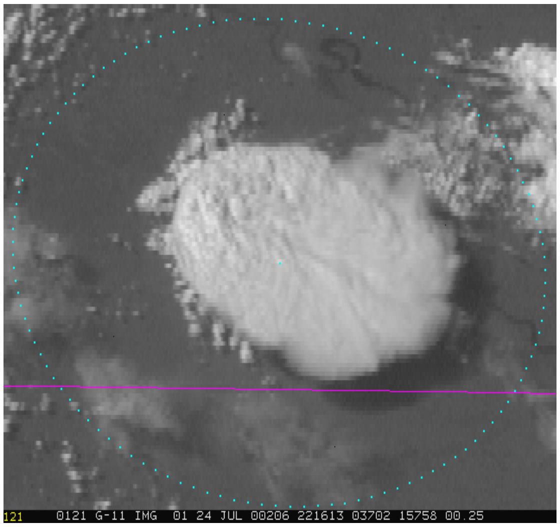

Figure 2b. Severe storm over Kansas being observed at one minute intervals, or more frequently, by GOES-R's ABI.

c) the use of GOES-R ABI imagery to direct the extremely high resolution Visible to Near IR (VNIR) capability of HES to a cloud free coastal region for ocean color measurements, as illustrated using the hypothetical MODIS image in Figure 3 below; and, d) the use of NPOESS VIIRS (multipectral visible and infrared imager), CMIS (microwave imager/sounder) and CrIS (IR sounder) to diagnose hurricane intensity. The most common intra-satellite synergy will likely be from multispectral imagers where products are derived from combinations of different channels: this will be discussed later.

Figure 3. In this hypothetical example, routine 5 minute interval ABI imagery is used to identify a cloud clear region over south Florida which had been cloud covered during the overpass of polar orbiting ocean color satellites. Thus directing the HES VNIR to make its 300 meter resolution measurements.

Intra system could include the use of GOES-East and West ABI imagery for stereographic cloud height determination, and the use of multiple NPOESS passes across the polar region for derivation of cloud and moisture motion vectors. **Inter-system** brings to mind a number of applications and possibilities that span well known applications areas that conveniently scale as a function of time; climate, global NWP, nowcasting, coastal waters, and disasters. It is well known that satellite data has had a major impact in improving the accuracy of global NWP, as illustrated in Figure 4&5. Those data, from both research and operational satellites, include microwave and infrared sounding data, ocean surface winds, precipitation rates, land surface properties and atmospheric motion vectors. The increases in skill reflected in Figure 4 are not solely due to satellite data; they also include better model physics, improved assimilation systems, and some increases in other data sets – however, it must be noted that these improvements occurred during a period of well documented decreases in the global rawinsonde network! Furthermore, Figure 5 clearly shows that removal of satellite observations have the most detrimental impact on forecast accuracy.

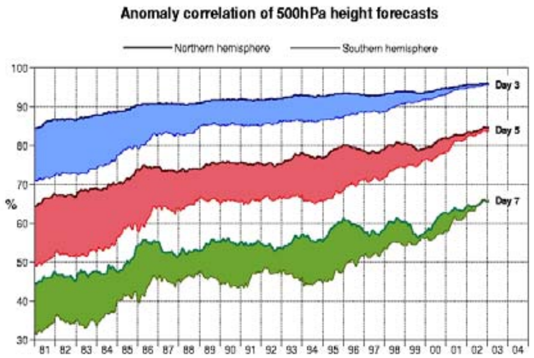

Figure 4. Improvement in NWP skill as revealed anomaly correlation of 500hPa height forecasts for the northern hemisphere (top line of envelope) and southern hemisphere (bottom line of envelope) for days 3 (blue envelope), 5 (red envelope) and 7 (green envelope) from 1981 to 2003.

Other considerations should also be taken into account when interpreting Figures 4&5. Satellite sounding data are not used over land, a science problem; because of volume satellite data are severely thinned before being assimilated into models; and, satellite

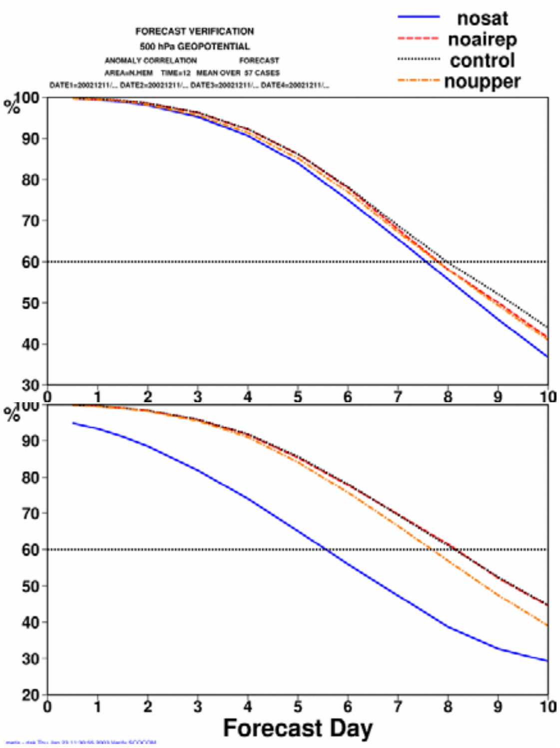

Figure 5. From ECMWF illustrating impact of removal of various observing systems data on forecast verification.

infrared sounder data are not used in cloudy regions, a science problem. Over the next several years there will be a dramatic increase in satellite data accuracy, coverage and volume. For NWP, assimilation systems, models and science will need to advance to take advantage of these new satellite capabilities. An international science program, known as THORPEX, will address many of those problems (selective rather than random thinning of satellite data, use of satellite data over land and in cloudy regions) as well as targeting of observations from many types of observing systems.

Examples of potential of inter-system synergy abound. For example, the intra- and inter-satellite examples presented earlier easily fit into examples where multiple satellite data could be utilized to derive a given product or applied to a given applications area. Indeed, blending of information from various satellites can result in a more accurate measurement than might be derived from either system alone, as has been recently illustrated by Collard and Healy (2003) where GPS and hyperspectral infrared sounding information were combined to produce an exceptionally

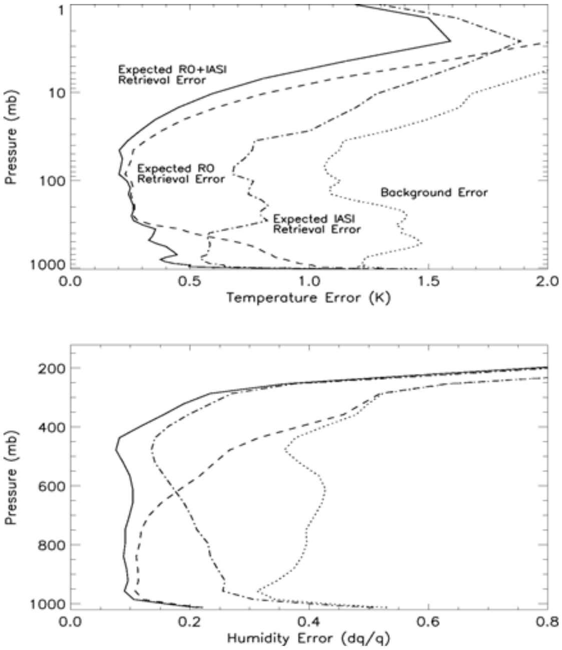

Figure 6. Example of improvement in thermodynamic sounding capability expected when GPS OS information is combined with hyperspectral infrared sounding data.

accurate temperature and moisture profile of the atmosphere, Figure 6. If such a capability can be developed using the high spatial and temporal resolution of GOES-R's HES, then a truly monumental breakthrough in nowcasting for convection and severe weather is at hand. To realize this potential, science needs to address GPS' poorer spatial resolution (200 km in the lowest portion of the troposphere for GPS), but supplemented by multiple views from different azimuths (GPS constellation's observations) across a GOES-HES FOV (around 10 km) during a representative time frame.

Climate monitoring is an area where inter-system synergy must come into play. Climate monitoring requires accurate long term stable and accurate measurements. GOES-R total HES can serve as stable reference basis for other satellites (operational polar and other LEO). Contiguous and high resolution spectral measurements are required for inter-calibration. The nature of HES provides spectral flexibility (adaptability) that allows for spectral matching with other systems' instrumentation. Furthermore, from GOES-R's HES, high spectral resolution radiance measurements for scenes over long time periods by one fixed system at the same viewing angle and from the same altitude will be available, a very important consideration according to Goody, et al (1998). The combination of GOES and other high spectral resolution measurements should allow for the detection and monitoring of long term changes (trends) in water vapor and other gasses. Finally, it cannot go without saying that GPS is a first order measurement that will be very important in climate monitoring, especially above the tropopause.

It was mentioned earlier that the most common intra-satellite synergy will likely be from multispectral imagers where products are derived from combinations of different channels. METEOSAT-8 and EOS MODIS have, and both NPOESS and GOES-R will have over 10 imager channels. From each of those satellites imagers there are over 1000 potential products available from various channel combinations, 2^n – (n+1), or if individual channels are also included, 2^n – 1. Obviously, some channel combinations make no sense so the number may be cut by some factor depending on application. In the next decade the amount of data and potential products will be so tremendous that it becomes unfathomable to imagine that a user would want such a volume of raw data, or products, and expect to make meaningful products or extract information from that data. Consider further the 5 minute global repeat cycle of GOES-R, or GOES-R in rapid scan, it seems obvious that what a user needs is targeted products that are designed for specific applications areas: not nowcasting, but a sub-set of nowcasting applications. For example Figure 7 is a simulated product based on mathematical analysis of MODIS channel data selected to simulate GOES-R ABI data. The product immediately allows the user to detect the dry-line (boundary between dry and unstable air), mid-level moisture, wet ground, unstable air, cirrus clouds (possible jet-streak monitoring) and the severe thunderstorm. Products such as this could be further developed to reflect information on thunderstorm energy potential based on sounding information from HES, GPS OS and polar sounder data (if that observation is taken at the correct time). One can imagine similar products for hurricanes, as visualized in Figure 8, that utilized multi-spectral imagery (cloud phase and winds from rapid scan), microwave image/sounding data (sea surface winds and warm core), altimetry and SST (for storm potential energy source), and sounding suite information as above (for warm core, moisture winds for vertical shear of the environment, and local environment characterization).

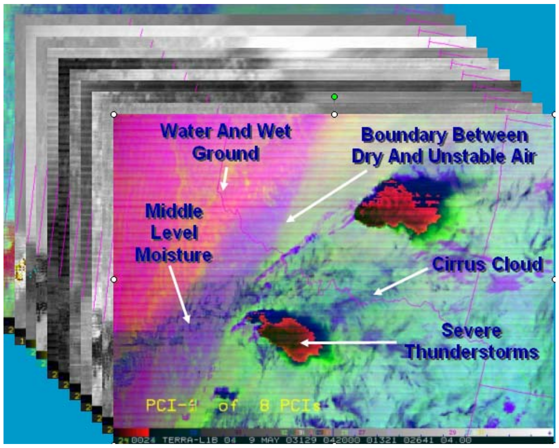

Figure 7. Simulated GOES-R product for severe weather nowcasting based on principal component analysis of it’s infrared channels.

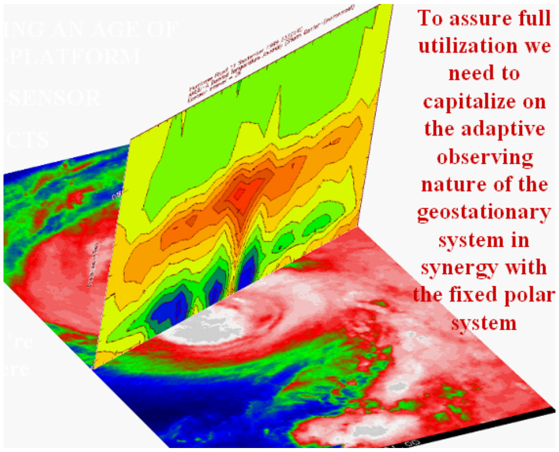

Figure 8. Hypothetical hurricane product revealing storm intensity and other relevant information derived from mutli-satellite data..

9. CONCLUSIONS

We should expect great improvements to the global space based observing system; including very high spatial and spectral sampling from ultraviolet to microwave wavelengths, with both active and passive sensors. In concert with these new capabilities we must prepare for over five orders of magnitude growth in data volume and content which will be available from systems in just the first few decades of this new century. On the horizon lies the promise of hyperspectral observing, first in the lower spatial resolution infrared portion of the spectrum, but eventually across the visible to near infrared to far infrared (at high resolutions). This capability alone will reinvigorate the ongoing revolution in space based remote sensing. Better science will occur by realizing the opportunities afforded by the future through new approaches, international partnerships and science teams. This will all be made possible because of a shrinking distinction between research and operational satellites, with data from polar orbiting and geostationary satellites being treated as a "single system of observations" serving users with information from a rich digital spectral shell that allows data to be captured and focused on a variety of important applications areas. Planning for tomorrow's satellite systems and sensors must take into account all space observing assets, capitalizing on their strengths as part of a composite space based observing system.

In the near future, as a community, we should have access to at least five operational polar orbiting satellites, all carrying sensors with advanced capabilities, and between five and seven operational geostationary satellites with multispectral, high frequency imaging capabilities and some with sounding capability. In the research arena there will be numerous satellites in polar orbit, special satellites orbiting in constellations and formations, perhaps a satellite in geostationary orbit, and all providing advanced data sets for operational utilization. Applications areas are expanding dramatically with an unparalleled opportunity for growth. For almost any given applications area opportunities to exploit multiple data sets from a variety of research and operational satellites, all with different spatial, spectral, temporal, radiometric resolutions will abound. Data volumes will be tremendous in comparison with today's operational systems – at least five orders of magnitude. We strive for full exploitation, but whose responsibility is it to ensure the full system of operational and research satellite data is utilized to maximize benefit in a given applications area: the user, national and international science groups, the operational satellite agency, the research satellite agency, CGMS, WMO? We move forward by building on the successes of today and aggressively planning and developing appropriate mechanisms focused on exploitation as a global community in partnership: the user, national and international science groups, operational satellite agencies, research satellite agencies, CGMS, and WMO. To do this is a challenge, but it is a challenge that must be met.

10. ACKNOWLEDGEMENTS

This work was sponsored by NOAA/NESDIS under NOAA Grant NA17RJ1228.

11. REFERENCES

Asrar, G.R. 2002: Contribution of environmental satellites to WMO Programmes: past and present. *Bull. World Meteor. Org.*, **51**, 120-129.

Briggs and Oriol-Pibernat, 2002: The European Space Agency's contribution to environmental surveylance. *Bull. World Meteor. Org.*, **51**, 130-136.

Campbell, G.G., J.F.W. Purdom and C.E. Vaughn 1996a: Asynchronous stereo height and motion estimation from multiple satellite images. *Proceedings of the International Symposium on Optical Science, Engineering, and Instrumentation.* Denver, CO, 4-9 August, SPIE, 95-110.

Campbell, G.G., J.F.W. Purdom and C.E. Vaughn 1996b: Update on accurate cloud motion and heights using time adjusted stereo. *Proceedings of the 3rd International Winds Workshop*, Monte Verita-Ascona, Switzerland, 10-12 June, EUMETSAT, 241-256.

Christy, J.R., R.W. Spencer, and E. Lobi, 1998: Analysis of the merging procedure for the MSU daily temperature time series, *J. Climate*, **11**, 2016-2041.

Crowson, D.L., 1949: Cloud observations from rockets. *Bull. Amer. Meteor. Soc.*, **30**, 17-22.

Goody, R.M., J. Anderson, and G. North, 1998: Testing climate models: An approach. *Bull. Amer. Meteor. Soc.*, **79**, 2541-2549.

Key, J., D. Santek, C.S. Velden, N. Bormann, J.-N. Thepaut, L.P. Riishojgaard, Y. Zhu, and

W.P. Menzel, 2002, Cloud-drift and Water Vapor Winds in the Polar Regions from MODIS, IEEE Trans. Geosci. Remote Sensing, April 2002.

Purdom, J.F.W. and W.P. Menzel, 1996: Evolution of satellite observations in the United States and their use in meteorology. *Historical Essays on Meteorology 1919-1995, The Diamond Anniversary History Volume of the American Meteorological Society*, J.R. Fleming, Ed., Braun-Brumfield, Inc., pp. 99-155.

Schmidt, J.S., P. Pili, S. Tjemkes, D. Just, J. Kerkmann, S. Rota and A. Ratier, 2002: An introduction to METEOSAT Second Generation (MSG). *Bull. Amer. Meteor. Soc.*, **83**, 977-992.