AU/ACSC/Wacker/AY09

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

THE NEED FOR A CONTINUOUSLY UPDATED DEPARTMENT OF DEFENSE ENVIRONMENTAL SATELLITE REQUIREMENTS DOCUMENT

by

Robert S. Wacker, Major, USAF

A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

Advisor: Col Zoe M. Hale

Maxwell Air Force Base, Alabama

April 2009

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
APR 2009	**N/A**	**-**

4. TITLE AND SUBTITLE	
The Need For A Continuously Updated Department Of Defense Environmental Satellite Requirements Document	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Command And Staff College Air University Maxwell Air Force Base, Alabama**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

The original document contains color images.

14. ABSTRACT

Air Force Weather (AFW), and its Navy equivalent, the Commander Naval Meteorology and Oceanography Command (CNMOC), are tasked with characterizing the current and future state of the environment in all warfighting domains. In order to do this, they employ a wide range of in situ and remotely-sensed observations of the atmosphere, space environment, and land and ocean surfaces. Weather satellites of several types operated by the Departments of Defense (DoD) and Commerce (DOC), the National Aeronautics and Space Administration (NASA), and several foreign governments are a key platform for collection of remotely-sensed environmental data. AFW and CNMOC consume a wide range of observational data types from this extensive array of weather satellites. Several factors occurring now and in the near future will change the manner in which the DoD meteorology and oceanography (METOC) community consumes environmental satellite data, though. These factors should prompt DoD to update its environmental satellite data requirements. Joint Chiefs of Staff Memorandum 154-86 from 1986 and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Operational Requirements Document (IORD) II from 2001 are the current benchmark satellite requirements documents and both offer several instructive lessons upon which to build. This paper examines the need for, and proposes some key considerations of, creating an updated statement of the DoD METOC community’s environmental satellite requirements.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**34**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Disclaimer

Contents

Illustrations

Abstract

Air Force Weather (AFW), and its Navy equivalent, the Commander Naval Meteorology and Oceanography Command (CNMOC), are tasked with characterizing the current and future state of the environment in all warfighting domains. In order to do this, they employ a wide range of *in situ* and remotely-sensed observations of the atmosphere, space environment, and land and ocean surfaces. Weather satellites of several types operated by the Departments of Defense (DoD) and Commerce (DOC), the National Aeronautics and Space Administration (NASA), and several foreign governments are a key platform for collection of remotely-sensed environmental data. AFW and CNMOC consume a wide range of observational data types from this extensive array of weather satellites. Several factors occurring now and in the near future will change the manner in which the DoD meteorology and oceanography (METOC) community consumes environmental satellite data, though. These factors should prompt DoD to update its environmental satellite data requirements. Joint Chiefs of Staff Memorandum 154-86 from 1986 and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Operational Requirements Document (IORD) II from 2001 are the current benchmark satellite requirements documents and both offer several instructive lessons upon which to build. This paper examines the need for, and proposes some key considerations of, creating an updated statement of the DoD METOC community's environmental satellite requirements.

1. Introduction

Weather observing has been a part of US military operations for nearly 200 years. The history of organized weather support to the US military began in 1814, when the Army Surgeon General directed that weather observations be taken and recorded at all Army posts.[1] The Army's weather support function underwent a number of organizational changes, falling at times under the US Weather Bureau and the Army Signal Corps before finding a home in the Army Air Corps in the years prior to World War II.[2] Like the Air Force itself, the Air Corps Weather Service, later renamed Air Weather Service (AWS), underwent rapid expansions in both World War II and the Korean War, only to contract equally quickly in the wake of both conflicts. After remaining relatively static in both organization and size during the bulk of the Cold War, AWS underwent dramatic reorganization and downsizing during the 1990s, again mirroring changes in the larger Air Force.

The common mission of AFW and CNMOC is to characterize the current and future state of the environment in all warfighting domains--air, sea, land, space, and even cyberspace (if one considers that conditions in the near-Earth space environment affect communications links of networked systems). The goal of the DoD METOC community is encapsulated in AFW's motto: *Coelum ad Proelium Elige* (Choose the Weather for Battle). Certainly US forces should never be surprised by adverse environmental conditions. But more than that, they should be able to exploit their superior knowledge of the current and future state of the environment in all domains as an asymmetric advantage over any adversary.

Accurate observations in sufficient quantity are the key to correctly characterizing and forecasting the state of the environment, whatever the domain. Unfortunately, direct *in situ* measurements of atmosphere, oceanic, land, and space parameters are extremely limited.

Globally, there are only a few thousand surface weather observing sites, a few thousand aircraft, ships, and ocean buoys with observing capability, a few hundred weather balloon sites, and a few tens of upper atmospheric and ionospheric sounding sites. The bulk of observational data in all environmental domains, then, is remotely sensed.[3] A number of terrestrial observation systems collect remotely-sensed data: weather radar, Doppler wind profilers, laser cloud ceilometers, and ionospheric sounding systems. The vast majority of the remotely-sensed observations used today, though, are collected by satellite-based instruments. Since the launch of the first weather satellite in 1960--followed closely by the launch of the first *military* weather satellite in 1963--the DoD meteorology and oceanography (METOC) community has come to rely greatly on a diverse constellation of weather satellite types.[4]

By the 1980s, numerical weather prediction (NWP) computer models depended on satellite-derived temperature and moisture profiles for proper initialization and forecasters themselves depended on still and animated cloud imagery as an integral forecasting tool.[5] The DoD METOC community had arguably reached the point where it could not accomplish its mission of characterizing and forecasting environmental conditions without weather satellites. Unfortunately, DoD's weather satellite reliance extended far beyond its own DMSP constellation, spreading to civil, foreign, and research and development (R&D) satellites as well. Clearly, reliance upon satellites outside DoD's direct control brings with it the vulnerability of losing critical satellite data sources at any time. While constrained resources probably made such a situation inevitable, a share of the blame rests with the METOC community itself because it has failed to consistently, clearly, and correctly identify its environmental satellite requirements. Past efforts have been made to do so, notably 1986's Joint Chiefs of Staff Memorandum 154-86 and 2001's National Polar-orbiting Operational Satellite System (NPOESS) Integrated

Operational Requirements Document (IORD) II. Both fall significantly short of expressing the METOC community's complete environmental satellite data needs today and in the future. To ensure its ability to successfully support its operational users, AFWA and CNMOC should begin producing a regularly-updated comprehensive environmental satellite data requirements document. This paper makes recommendations on the contents of such a document.

2. Environmental Satellite Data Use by the DoD METOC Community

a. Weather Satellite Instruments and the Electromagnetic Spectrum

With a few exceptions, satellite-based environmental remote sensing instruments make passive use of the electromagnetic spectrum. That is, they sense from space the visible, infrared (IR), or microwave energy radiated or reflected by the Earth's atmosphere or surface. Figure 1 includes example images from the spectral regions described below.

The visible band, which resides at wavelengths between .4 and .7 µm (microns or 10^{-6} m), is the easiest region of the spectrum to grasp because our own eyes operate in this band. Max Planck discovered the function that tells us how an object's temperature governs both the intensity of the electromagnetic energy emitted by the object and the region of the spectrum where it emits most of that energy.[6] By virtue of its nearly 6000°C surface temperature, the sun emits most of its energy in the visible portion of the spectrum. In this band, the fraction of incident radiation reflected by terrestrial objects varies considerably. Clouds reflect strongly, land surfaces moderately, and water surfaces poorly. Visible satellite imagery is most useful for observing the amount and type of cloud cover, particularly when images of the same geographic area are displayed in an animated sequence. Cloud identification can be performed, either qualitatively by a human forecaster, or quantitatively by automated algorithms. The

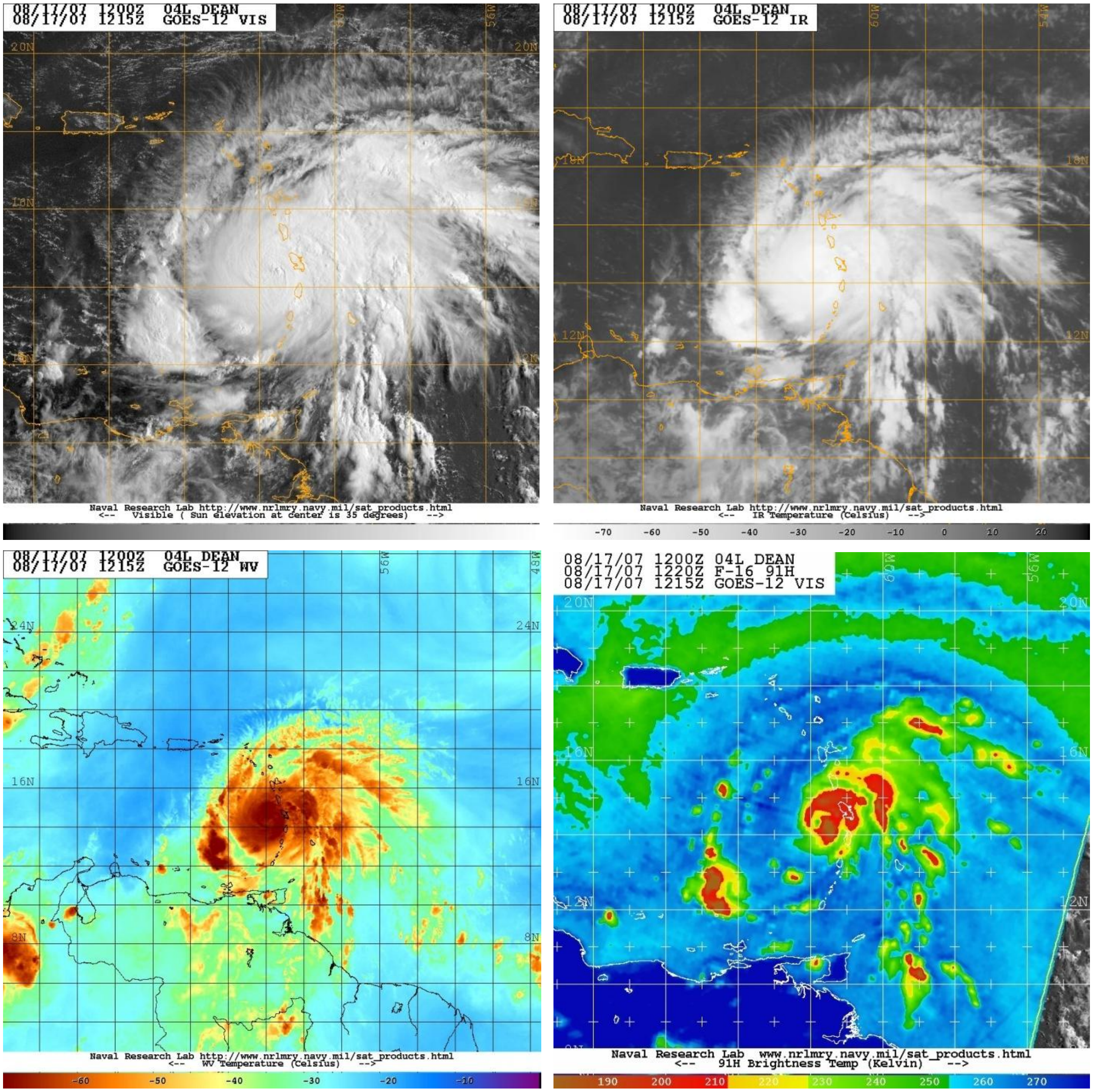

Figure 1: Environmental Satellite Spectral Regions. Visible (upper-left), thermal IR (upper-right), and water vapor (lower-left) imagery from the GOES-12 geostationary weather satellite, and 91 GHz microwave imagery from the DMSP F-16 satellite, of Hurricane Dean (04L) all from approximately 1200 Universal Coordinated Time on 17 Aug 07.

disadvantage of visible imagery, though, is that it requires a sunlit scene and thus is only usable during daylight hours.

The IR band resides wavelengths longer than the visible band. The Earth's surface and clouds are nearly blackbodies--perfect absorbers and emitters--in the far IR region of the spectrum, between wavelengths of 4 and 50 μm. This means that the energy observed by a radiometer looking at the Earth in the far IR band is not reflected solar radiation, but rather energy emitted directly by the surface, clouds, and the atmosphere. The temperature of the emitting object, via the Planck function, determines the intensity of the IR radiation it emits. While the poorer spatial resolution of far IR imagery makes it less useful than visible imagery for distinguishing fine details of cloud structure, the temperature information it contains allows us to determine cloud height. Furthermore, IR imagery is always available, regardless of solar illumination. As with visible imagery, IR imagery is most useful to human forecasters when animated. Automated cloud analysis algorithms combine IR imagery with visible imagery to determine both cloud coverage and cloud layer heights.

The gases that compose the atmosphere combine to create a complex spectrum of absorption bands in the far IR band. This makes far IR radiation less straightforward to use for remote sensing, but also allows several other uses in addition to cloud imagery. At wavelengths approaching these absorption bands, the atmosphere becomes progressively more opaque, and the energy observed from space originates from progressively higher in the atmosphere. This allows construction of vertical temperature profiles, similar to those obtained from weather balloons, by combining the energy observed in a number of closely-spaced channels on the fringe of an absorption band.[7]

While it is a subset of the far IR band, meteorologists treat the region near 7μm wavelength as a unique band unto itself. Atmospheric water vapor (WV) absorbs strongly in this band, so in regions of dry air, the atmosphere becomes nearly transparent, allowing a space borne instrument to see, in some cases, all the way to the surface. In regions with a deep layer of high humidity, the atmosphere becomes opaque. The contrasting brightness temperatures observed from space enable visualization of the wind flow in the middle and upper regions of the troposphere, the lowest 10 km or so of the atmosphere, by effectively using water vapor in the atmosphere as a tracer. Forecasters use animated WV imagery to identify jet streams and other large-scale atmospheric flow features. Automated algorithms use sequences of water vapor imagery to infer mid- and upper-level wind fields through water vapor feature tracking.

The next spectral region of interest beyond the far IR band is the microwave portion of the electromagnetic spectrum, with wavelengths ranging from 1 mm to 10 cm. As with the far IR, the energy observed when looking downward from space is entirely terrestrial, rather than solar, in origin. However, in the microwave band, cloud, ocean, and land surface emissivities vary strongly with frequency. Additionally, since the shorter microwave wavelengths are comparable in size to raindrops, snowflakes, and hailstones, liquid and frozen precipitation in the atmosphere strongly scatter radiation at these wavelengths. Cloud droplets, typically two to three orders of magnitude smaller than precipitation drops, have little to no effect on most microwave wavelengths. This makes microwaves effectively able to penetrate clouds, enabling vertical temperature profiles similar to those possible in the far IR band, but in cloudy in addition to only clear conditions. Microwave imagery is particularly useful for peering through dense high-level cirrus cloud cover and identifying, for example, the spiral bands of precipitation indicating the center of a tropical cyclone.

The microwave spectrum also yields vertical humidity profiles by exploiting water vapor absorption. Since ocean surface emissivity varies with the roughness of the sea, microwave techniques can be used to infer ocean surface wind speeds. Land surface emissivity varies with soil moisture content, vegetation, and snow cover, enabling use of the microwave band to infer land surface properties as well.

While most satellite-based instruments are passive, there are some active remote sensing instruments that make use of the microwave spectrum. Scatterometers compare the returned energy from transmitted beams at different scan angles to infer not only the roughness of the ocean surface, but the orientation of the waves, enabling both ocean surface wind speed and direction to be determined. Sensitive radar altimeters are also employed to measure minute variations in ocean surface height, yielding surface topography and allowing ocean currents to be determined.

While the visible, far IR, WV, and microwave bands account for the majority of satellite-based remote observations of the atmospheric, land, and ocean domains, most space environment parameters are observed differently. Imagery of the sun in the x-ray band indicates the presence of sunspots, prominences on the solar surface, and solar flares. Sensitive magnetometers aligned along orthogonal axes precisely measure the strength and three-dimensional orientation of the Earth's geomagnetic field. And particle counters measure the number density of energetic particles emitted during solar flares. All three types of data enable forecasters to analyze, and increasingly, numerical models to forecast, conditions in the near-Earth space environment.

b. Weather Satellite Orbit Types

Nearly all environmental satellites inhabit either sun-synchronous polar orbit or geostationary orbit. The Defense Meteorological Satellite Program (DMSP) program satellites have always been polar-orbiting satellites. They orbit approximately 850 km above the Earth's surface in a plane rotated about 98° degrees from the equatorial plane. This yields a ground track oriented roughly north and south from pole to pole, but slightly retrograde, against the direction of Earth's rotation. At this altitude, one orbit takes approximately 101 minutes. The orbital planes of satellites remain nearly fixed in space, while the Earth rotates beneath them. The relatively low altitude of polar orbits means a satellite can only sample a swath of roughly 1000 km to either side of its ground track. As the Earth rotates beneath the satellite's orbital plane, this 2000 km-wide swath covers most of the planet's surface every 12 hours.

The combination of the Earth's slightly oblate shape and the inclination and altitude of polar orbits causes the orbital plane to precess--change its orientation--at roughly the same rate that the Earth revolves around the sun, so that the angle between the sun and the orbital plane remains nearly constant. Thus, the orbit is sun-synchronous, and the satellite passes over a given point on the Earth's surface at nearly the same local time each orbit. Ground control stations for polar satellites are generally concentrated in high-latitude regions, which are visible by the satellite on nearly every orbit as the ground tracks converge toward the poles. These satellites store the data they observe onboard and transmit it back to Earth every orbit, or every few orbits, when passing over a ground station.

Satellites in geostationary orbit, by contrast, fly approximately 36,000 km above the Earth's surface in an orbital plane that coincides with the equatorial plane. At this altitude, one orbit takes almost exactly one sidereal day--the same amount of time it takes the Earth to complete its rotation--so the satellite remains permanently fixed above the same longitude along the Earth's equator. From this vantage point, it can see an area spanning roughly 60° east and west of its longitude along the equator, and from 60° North latitude to 60° South longitude.

Geostationary satellites, then, are used for applications requiring frequent coverage of the same limited local region of the Earth's surface, while polar satellites are used for applications requiring periodic global coverage, and/or coverage of polar regions. By virtue of their lower altitude, polar satellites are capable of higher resolution imagery, but limited to the narrow 2000 km swath and with poor timeliness due to the limited contact with ground stations.

Geostationary satellites sacrifice resolution and global coverage for rapid refresh rate and greater timeliness.

A few environmental satellites make use of other orbit types. NASA's Tropical Rainfall Measuring Mission (TRMM), for example, is in a low-Earth orbit similar to polar satellites, but only inclined about 25° from the equator, confining its ground track to the tropics. Satellites which need to combine frequent refresh rates and high latitude coverage often use highly-elliptical orbits (HEO). These orbits combine a roughly 60° inclination from the equator with very high eccentricity, a very elongated shape, causing them to rapidly skim the surface at the low end of their orbit, and then hang for a prolonged period near the high end. Finally, some space-environment satellites are lofted to a Lagrange point between the sun and the Earth, where the net gravitational force of the sun and Earth on the satellite causes it to remain at a nearly fixed point relative to the two bodies. This enables the satellite to provide some warning of high-energy particle streams headed for the Earth's geomagnetic field from solar flares.

c. Past, Current, and Future Environmental Satellites

The Department of Commerce's (DOC) National Oceanographic and Atmospheric Administration (NOAA) operates the government's fleet of polar and geostationary environmental satellites, used primarily by the National Weather Service (NWS). This Polar-orbiting Operational Environmental Satellite (POES) constellation traces its lineage back to the first weather satellite, the Television Infrared Observational Satellite, launched in 1960.[8] DoD's weather satellite history extends nearly as far back; the first ancestor of today's DMSP constellation was launched in 1963 to provide global cloud-cover imagery in support of Corona, the nation's nascent satellite reconnaissance program.

Due to its low altitude, polar orbit is by far the easiest of the two orbit types to access. For this reason, a geostationary weather satellite didn't exist until 1966.[9] However, by the mid 1970s, the US had its Geostationary Operational Environmental Satellite (GOES) program in place. Today, the two primary GOES satellites, at 75° and 120° West longitude, provide continuous coverage of the continental US, Hawaii, Central America, a large portion of North and South America, the Atlantic, and the Pacific. NOAA and NASA are currently developing the next generation in the GOES series, GOES-R, slated for first launch in 2015.[10]

Foreign governments began to enter the environmental satellite arena in the 1980s, when the European Meteorological Satellite (EUMETSAT) organization and the Japan Meteorological Agency (JMA) first placed geostationary satellites into operation. Both organizations recently began operations of a second generation of geostationary satellite, on a par with the US' GOES constellation. Russia, India, and China have also operated geostationary satellites at times since the 1980s.[11] China has flown POES-like polar-orbiting environmental satellites since the mid-1990s, and EUMETSAT recently began operations of its MetOp polar-orbiting constellation, designed to work in concert with POES and NPOESS.

The 1990s witnessed a dramatic increase in the number of one-of-a-kind R&D missions carrying environmental remote sensing instruments. NASA's Earth Observing System (EOS) is responsible for most of these missions. Four EOS missions, all launched in the late 1990s and still operating today, have become widely used by the DoD METOC community: QuikScat provides scatterometer measurements of ocean surface wind vectors; TRMM, which provides valuable imagery and precipitation products from its microwave instruments; and Terra and Aqua, which both carry the Moderate-Resolution Imaging Spectroradiometer (MODIS), by far the most capable visible and IR imaging instrument ever used for environmental applications.

d. Current DoD METOC Use of Environmental Satellite Data

Joint METOC doctrine and Air Force-unique weather doctrine both outline similar five-step continuous processes for producing accurate, timely, and relevant environmental support for operational users.[12] Step 1, collection, is the continuous process of gathering *in situ* and remotely-sensed environmental data from each of the warfighting domains. Step 2, analysis, is the process of combining the collected observations into a depiction of the current state of the environment at regular intervals. Step 3, prediction, employs both NWP models and human forecasters to project the future state of the environment. Step 4, product tailoring, combines analyses and forecasts with detailed knowledge of the environmental sensitivities of the supported operational mission to produce accurate and relevant products easily consumed by operational users. Finally, step 5, dissemination, is ensuring that tailored environmental products are always in the hands of operational users in time to be incorporated properly into their cycle of planning, executing, and assessing.

According to recent doctrine, the collection, analysis, and prediction steps are best centralized.[13] Both AFW and CNMOC are organized in a strategic-operational-tactical hierarchy. The strategic centers--the Air Force Weather Agency (AFWA) at Offutt AFB, Nebraska, the Naval Oceanographic Office (NAVOCEANO), at Stennis Space Center, Mississippi, and the Fleet Numerical Meteorology and Oceanography Center (FNMOC), at Monterey, California--are tasked with worldwide environmental data collection, atmospheric, oceanic, and space environment analysis, and global, fine-scale, and specialized numerical weather prediction. All three strategic centers have extensive infrastructure to receive environmental satellite data via communications relay from US and foreign geostationary, civil and DoD polar-orbiting, and NASA R&D satellites in near real-time.

The strategic centers produce analyses and forecasts for each domain on a global scale. In parallel with the NWS' National Centers for Environmental Prediction, FNMOC produces a global NWP model each 12 hours. Both FNMOC and AFWA produce regional fine-scale NWP models at 6-hourly intervals. NAVOCEANO produces global models of wave heights and ocean currents regularly as well. Satellite data is integral to NWP model forecasts. IR and microwave temperature and humidity profiles, feature-tracked winds, and land and ocean surface temperatures are all assimilated to produce the analyses from which the forecasts are initialized.

The strategic centers tailor and disseminate global-scale products for strategic-level users. The first of these is AFWA's hourly global cloud analysis and forecast product. Automated algorithms analyze cloud cover, type, and layer heights using visible and IR data from both geostationary and polar satellites as it is received at AFWA. Each hour, all the analyses produced are merged into a single worldwide cloud analysis. An NWP model then forecasts the evolution of that cloud field in time.

AFWA is also responsible for producing analyses and forecasts of the state of the geomagnetic field and the near-Earth space environment. The forecasts are used to: 1) protect space assets from damage following solar flares; 2) predict and mitigate terrestrial high-frequency and satellite-based ultra high frequency communications, radar tracking, and global positioning system (GPS) accuracy degradation due to ionospheric disturbances; and 3) minimize physiological hazards to astronauts and high-altitude flight crews from energetic particle emissions following solar flares. Space environmental data from both geostationary and polar satellites, primarily GOES, POES, and DMSP, constitutes the vast majority of the observational data driving these analyses and forecasts.

Finally, NAVOCEANO produces worldwide analyses and forecasts of ocean surface and undersea conditions using satellite-based IR and microwave ocean surface temperature observations, microwave ocean surface wind speeds, scatterometer ocean surface wind vectors, and radar altimeter ocean surface height observations.

The remaining steps of the METOC product generation cycle--product tailoring and dissemination--are best decentralized at the operational and tactical levels.[14] Both CNMOC and AFW maintain regional METOC forecasting facilities to produce theater-level operational products. The Air Force operates four continental US and two overseas operational weather squadrons (OWS), while the Navy operates Naval Meteorology and Oceanography Centers (NMOC) for both the Pacific and Atlantic. These regional forecasting hubs are tasked with providing environmental support to theater-level commands and are consumers of both the raw environmental data collected by the strategic centers and the analyses and forecasts they produce. Satellite data use at the regional hubs centers on qualitative use of animated geostationary visible, IR, and WV imagery by forecasters to identify and track synoptic (continent-sized) and mesoscale (storm-sized) weather features and provide METOC briefings to their operational users. A few regional centers possess the capability to receive satellite data directly from geostationary and polar environmental satellites, but most rely on communications links back to the strategic centers to receive the satellite imagery they consume along with other observations, analyses, and forecasts.

The Navy and Air Force together operate the Joint Typhoon Warning Center (JTWC) at Pearl Harbor, Hawaii, to provide tropical cyclone (TC) warnings for DoD assets in and around the Pacific and Indian Oceans. JTWC is unique among the regional centers in its added dependence on microwave imagery. Prior to 1986, JTWC relied heavily on aircraft reconnaissance to pinpoint TC locations and directly measure their peak wind speeds. In 1986, though, the Air Force discontinued aircraft reconnaissance in the Pacific, choosing to rely almost entirely on satellites. Because of its ability to penetrate the dense cirrus cloud cover that is ubiquitous to TCs, microwave imagery from DMSP, POES, and TRMM polar satellites is crucial to JTWC's ability to observe TC locations and intensities. Additionally, JTWC has come to rely heavily on QuikScat ocean surface wind vectors.

Navy METOC detachments ashore and embarked on surface vessels, and Air Force weather flights (WF) within Operations Support Squadrons and attached to Army division-level headquarters provide environmental support at the tactical level. Here, product tailoring--where detailed knowledge of METOC and space environment impacts on customers' operations--is paramount. As with the operational level, animated geostationary visible, IR, and WV imagery are the primary tools tactical-level forecasters use for their own environmental situational awareness and as a briefing aid for their customers. Tactical-level METOC teams primarily rely on communications reach-back to the strategic- and operational-level centers to obtain their satellite imagery.

e. Factors Changing How DoD Will Use Environmental Satellite Data

Six significant operational changes have affected, or will soon affect, the extent and manner of DoD's environmental satellite data use. The first of these was AFW's inauguration of the Cloud Depiction and Forecast System II (CDFS II) in 2002. Prior to that time, AFWA's cloud analysis and forecast products were produced in a time-critical, event-driven cycle triggered by the receipt of DMSP visible and IR imagery. CDFS II incorporates most other geostationary and polar-orbiting sources of visible and IR imagery and replaces the event-driven analysis with a regular hourly worldwide analysis and forecast of cloud cover, type, and layer heights. CDFS II has arguably increased the utility and accuracy of AFWA's cloud-free line of sight (CFLOS) products for a variety of users. One of the many changes it brings, though, is a greatly diminished role for DMSP in the very application for which it was originally conceived. Except in polar regions, geostationary imagery--which offers much higher refresh rates, more spectral content, and quicker data transmission--will almost always be chosen by the CDFS II analysis.

The second factor changing DoD satellite data use is the emergence of AFW's machine-to-machine (M2M) weather support paradigm. As intelligence, surveillance, and reconnaissance (ISR) capabilities increase and air operations centers (AOCs) mature they continue to refine and, most importantly, *accelerate* the find-fix-track-target-engage-assess cycle. Increasingly, operational decisions are being made within the air tasking order (ATO) cycle more quickly than a human forecaster can be incorporated into the process. AFW envisions a future where its role is primarily one of continuously updating a central repository of current and future environmental data.[15] This net-centric database will be accessed by operational users' situational awareness and planning systems and environmental data will be incorporated with intelligence and other planning factors into the users' decision-making process.[16] This will have the effect of diminishing the importance of today's paradigm of animated geostationary imagery aiding a human forecaster and emphasizing the quality of the global and fine-scale NWP forecasts that populate--without human intervention--the central data cube. As a result, IR and microwave temperature and moisture profiles, land and ocean surface parameters, and space environmental parameters, rather than visible and IR imagery, may soon become the most critical environmental satellite data.

The third change is the increasing reliance of deployed METOC units on satellite communications. As recently as five years ago, reachback capability was much less robust and tactical METOC teams deployed with bulky terminals dedicated to receiving direct-readout data from DoD and civil weather satellites. While some direct receiving equipment remains with tactical-level teams, it is no longer their primary means of obtaining satellite imagery. As a result, direct readout capability to tactical terminals, once one of DoD's most critical requirements for DMSP, is becoming much less critical.

Fourth, the changing nature of both global and fine-scale NWP models is changing the way DoD uses weather satellite data. This change was triggered by the introduction of direct radiance assimilation during the 1990s.[17] Prior to this time, atmospheric temperature and moisture profiles were generated from IR and microwave satellite data alone and incorporated into an analysis along with profiles from weather balloons and other sources. The NWP forecast model was then run with the analysis as its initial condition. Direct radiance assimilation skips the intervening steps of generating the satellite-based profile and merging them into an analysis with other data sources. Instead, direct radiance assimilation uses a previous NWP forecast to predict what the IR and microwave energy emitted by the atmosphere should be observed from space. Then it compares the predicted radiances to the IR and microwave radiances observed by satellite and iteratively adjusts the forecast until the difference between predicted and observed radiances is minimized. This adjusted forecast then becomes the current analysis and the cycle is repeated. The result is that DoD's IR and microwave satellite data consumption has shifted away from stand-alone satellite-derived temperature and moisture profiles and now emphasizes the raw radiance data instead.

The fifth major change in DoD satellite data consumption is the growing maturity of space environment forecast models. The relatively small community of space environment researchers likens our current capabilities in this domain to our weather forecasting abilities 50 years ago--able to observe and forecast based on empirical rules and lacking useful numerical forecasting capability, but on the verge of developing it.[18] Soon, forecast models will be able to predict future conditions of the geomagnetic field and ionosphere with measurable skill. This will significantly increase the demand for quality space environment observations optimized for assimilation into space environment forecast models, in much the same way that the maturation of atmospheric and surface data assimilation changed the types of satellite data consumed in NWP model production.

The final factor affecting DoD satellite data use is the changing nature of weather reconnaissance by aircraft. As previously discussed, aircraft weather reconnaissance is nearly non-existent in the Pacific and Indian Oceans. It persists, but in a limited fashion, in the Atlantic basin. This has shifted the burden for TC reconnaissance squarely to satellites over the past two decades. However, the emergence of long-range uninhabited aerial vehicles (UAVs) for environmental monitoring may reverse this trend and once again make aircraft reconnaissance of TCs and other weather phenomena, particularly over data-sparse regions like the Pacific Ocean, commonplace.[19] If that becomes the case, then environmental satellite data requirements may have to adjust to exploit the possibility of combined aircraft-satellite observational techniques.

f. DoD's Environmental Satellite Problem

The environmental data requirements of AFW's and CNMOC's operational users drive the types and dissemination methods of the products they are provided. These products in turn dictate the METOC analyses and forecasts that must be produced. The analysis and forecast requirements, finally, determine environmental data collection requirements. The discussion in the previous section should make clear the extent to which METOC data collection relies on environmental satellites.

The collection of weather satellites and associated ground infrastructure used today by the DoD METOC community has evolved piecemeal over the 45 years since the first military weather satellite. Part of this evolution is AFW's and CNMOC's growing dependence upon civil, foreign, and R&D satellites for a large fraction of their critical environmental satellite data needs.[20] Each of these non-DoD controlled satellite types has significant drawbacks. Civil satellites, like NOAA's POES constellation, are plentiful and very robust, but are optimized for missions other than those critical to DoD--IR temperature sounding, for example, instead of the high-resolution imagery necessary for cloud analyses. Foreign geostationary satellites, particularly Europe's MSG and Japan's MTSAT, are robust, and by virtue of World Meteorological Organization membership, at least some of their data must always be made freely available. But they are ultimately outside the US' direct operational influence. Finally, dependence upon R&D missions--QuikScat, TRMM, and Terra/Aqua in particular--is dangerous for DoD, because by nature, this type of satellite is one-of-a-kind, with no plans for sustainment or replacement.

Despite its critical dependence upon environmental satellite data, the DoD has no single, comprehensive, current statement of its environmental satellite data requirements. Without such a statement, neither the severity of the loss of one or multiple sources of environmental satellite data, nor the urgency of its replacement, can be clearly articulated by the Pentagon acquisition community. As a result, the DoD METOC community continuously lives at risk of losing a key data source, and in turn, failing to meet its obligations to the operational users it supports.

3. Evaluating Past Satellite Requirements Documents

The landscape is not devoid of past satellite requirements documents. The two most noteworthy are a 1986 memo, MJCS 154-86, from the Joint Staff to the Undersecretary of Defense for Research and Engineering and the 2001 Integrated Operational Requirements Document II for NPOESS.

a. MJCS 154-86

MJCS 154-86 was the last in a string of semi-regularly updated joint statements of weather satellite data requirements beginning in 1976.[21] Despite its age, MJCS 154-86 is still frequently cited today. The memo contains two sections. The first is a very comprehensive description of the missions supported by environmental satellite data and the characteristics of the satellite data required for operational support in the air, land, sea, and space domains. This document was, in fact, the first to address all four domains simultaneously and refer to *environmental* rather than *meteorological* satellites. The second section of MJCS 154-86 is a detailed list of specific data requirements for the Air Force's proposed DMSP Block 5D-2 and the Navy's proposed Naval Remote Ocean Sensing System (N-ROSS) acquisition programs.

MJCS 154-86 has two main strengths. The first is its careful analysis and detailed justification of the requirements it contains. By first discussing the missions supported by environmental satellite data, then the specific data types required for each type of support, it establishes strong traceability of satellite requirements to operational users' requirements. MJCS 154-86's second strength is the extremely detailed description of the requirements themselves. Horizontal and vertical resolution, measurement precision and accuracy, and data refresh rates and timeliness are all carefully specified, and meticulously justified.

MJCS 154-86's first weakness is that it is focused primarily on polar satellites. At the time of its writing, geostationary satellites were in use but their relatively poor horizontal resolution and their lack (at the time) of IR temperature profiling capability made them useful only for the animated imagery used qualitatively by forecasters. Polar satellites were seen as primary due to their high-resolution cloud imagery, temperature and moisture profiling capability, and tactical direct-readout capability for deployed users.

Its second weakness is simply that it is far out of date. The requirements it so carefully analyzes fail to contemplate patterns of satellite data usage that have become the norm over the past 15 years: direct assimilation of IR and microwave sounding data by NWP models; automated global cloud analyses using visible and IR imagery; the introduction of space environmental forecast models; and imagery transmission robust broadband communications between strategic centers and deployed tactical METOC teams.

b. NPOESS IORD II

The NPOESS program was created by Presidential directive in 1994 intended to cut government waste by combining its two polar-orbiting weather satellite programs--POES and DMSP. Since the 1980s, both satellites have shared a common spacecraft bus and very similar data storage and downlink architectures. The resulting program is a tri-agency effort among DOC, DoD, and NASA, led by an integrated program office (IPO) in Silver Spring, Maryland. The DoD is the lead agency for NPOESS procurement. This is significant, because it requires NPOESS to conform to DoD's rigorous requirements definition process.[22] Each of the three participating agencies is represented at each of the three tiers of the NPOESS requirements approval hierarchy. The Joint Agency Requirements Group (JARG) consists of the working-level members who drafted both the initial IORD and its final version, IORD II. The Senior

Users Advisory Group (SUAG) is comprised of the AFW and CNMOC directors and their NOAA and NASA equivalents; it provided agency-level approval of the IORD. Finally, the ultimate approval authority for IORD II rested with the Joint Requirements Oversight Council (JROC), the Joint Staff's body for adjudicating and approving all DoD acquisitions. The Deputy Joint Chief of Staff's (Gen Peter Pace at the time) signature, as the JROC Chair, is on IORD II.

Coordination on the successive drafts of the NPOESS IORD and IORD II occurred during the late 1990s and early 2000s, and at times became quite contentious. What was not foreseen at NPOESS' conception was the degree to which DOC's and DoD's requirements would conflict, despite their use of very similar polar environmental satellites. For example, DOC's climate-monitoring responsibilities require visible and IR imagery of very high spectral resolution and radiometric accuracy. This conflicted with DoD's requirement for low instrument data rates to facilitate direct downlink to tactical users at relatively low data rates. DOC's NWP models primarily assimilate IR radiances, while DoD's primarily rely on microwave radiances, necessitating the inclusion of both a highly capable IR sounding instrument and a highly capable microwave imaging and sounding instrument. The result is a document that was intended to be a merged consensus of DOC, DoD, and NASA polar-orbiting satellite requirements, but became a summation of all three agencies' individual requirements. Unfortunately, the DoD METOC community failed to recognize that many of the requirements it fought to retain in the NPOESS IORD II were becoming obsolete, even as they were fighting for them. The need for high resolution imagery for cloud analyses and extremely timely data availability were largely negated by CDFS II. Similarly, the diminished need for direct tactical readout of satellite data makes the requirement for a deployable NPOESS ground processing segment largely moot.

The IORD II also follows the recent acquisition trend of requiring an end-to-end product. IORD II requires not just raw data from the satellites' sensors, but all of the meteorological, oceanographic, land-surface, and space environmental products derived from that data. This makes all the ground processing that is performed by the individual strategic centers today to be incorporated into the NPOESS Integrated Data Processing Segment (IDPS). Early on in sensor and algorithm development, a complex network of interdependencies among NPOESS' various sensors developed, and with those interdependencies came a sub-layer of additional derived requirements the instruments had to meet.

The NPOESS program has been plagued by problems almost since the total system performance responsibility was awarded in 2004.[23] Both the System Program Director and the contractor's program manager have been replaced. NPOESS has suffered two Nunn-McCurdy budget breaches (a greater-than 25% cost overrun), necessitating delays in launch of the first NPOESS satellite from 2010 to beyond 2015, and a painful de-scoping of the program. NPOESS has now lost its primary microwave imaging and sounding instrument, to be replaced with one roughly equivalent to the instrument flown by DMSP today. Perhaps more significant is the near total elimination of NPOESS' space environment instrument suite. Finally, the constellation has been pared from three polar orbital planes to only two, diminishing the data refresh rate and overall amount of data available.

While the exact causes of NPOESS programmatic difficulties are arguable, technical difficulties with two of its primary instruments, the Visual and Infrared Imaging Radiometer Suite (VIIRS) and Conical Scanning Microwave Imager/Sounder (CMIS), share much of the blame. In both cases, the technical difficulties associated with the unprecedented combination of high spatial, high spectral resolution, and high radiometric accuracy requirements derived from the users' requirements in IORD II have proven very problematic.[24]

NPOESS' future remains highly uncertain, as another Nunn-McCurdy breach may prove fatal to the whole program. If it survives, the de-scoped two-satellite NPOESS constellation will fail to deliver all that was originally envisioned. Had its original requirements been more disciplined, VIIRS and CMIS arguably would have had a better chance of meeting those requirements, and the program as a whole would have had a higher likelihood of success.

4. Toward an Updated DoD Environmental Satellite Requirements Document

With its careful tracing of weather support requirements back to environmental satellite data requirements, MJCS 154-86 Part I exemplifies how a DoD environmental satellite requirements document should look, while NPOESS IORD II illustrates the perils of saddling one satellite system with unrealistically stringent requirements. Both are instructive studies for the authors of an updated DoD environmental satellite requirements document. While MJCS 154-86 offers a good starting point, the change factors discussed in Section 2 present a number of other considerations for an updated requirements statement.

First, the document should be independent of any individual satellite program. NPOESS IORD II failed to adjudicate the competing requirements of the three participating agencies. Instead, it attempted to satisfy them all within the limited means of a single polar-orbiting satellite program. Neither DOC nor NASA possesses an institutional culture of rigorously determining requirements before acquiring systems. DoD, for its part, had failed to update its own requirements for over a decade when it embarked on NPOESS. Environmental satellite data requirements should be determined first, then acquisition programs formulated, to satisfy some or all of those requirements as priorities and resources allow. When the reverse is allowed to occur, the result is a significant risk of failure to satisfy any requirements, as typified by NPOESS.

Second, the updated environmental satellite data requirements document should be unique to DoD. Another lesson from NPOESS is that the environmental data requirements of DOC and NASA are diverging from those of DoD. DOC and NASA are increasingly focusing on long-term climate monitoring, requiring careful, time-consuming processing under no stringent timeliness criteria. DoD's requirements trend is in the opposite direction. The speed with which raw satellite data must be turned into environmental analyses and forecasts, and then incorporated into the operators' decision-making cycles is increasing. While the goal of merging two seemingly similar government satellite programs was admirable, its execution has proven nearly untenable.

Third, given the rapidity with which operational concepts change, and with which DoD's METOC support functions change in response, any environmental data requirements document must be refreshed often. While nothing is on the horizon akin to the change wrought by the introduction of environmental satellites themselves, there is continuous progress in the fields of data assimilation and space environment forecasting that necessitate continuous, sometimes subtle, adjustments to these processes' data requirements. Changes to the threat environment will affect satellite data requirements as well. While DoD's recent trend has been away from direct tactical downlink of satellite data, threat of future cyber attacks may necessitate retention, or even re-emphasis, of such a capability. DoD's satellite requirements document should thus keep pace with changes to the operational concept, scientific techniques, and threats.

Fourth, at least some of the updated requirements should be framed in a manner that permits their accomplishment by platforms other than dedicated environmental satellites. During the late 1990s, the Space-Based Infrared System (SBIRS) attempted to incorporate a package of "battlespace characterization" capabilities in its requirements. SBIRS is intended to replace the Defense Support Program constellation in its missile launch detection role by using a mixed constellation of geostationary and HEO satellites with high resolution imagery capability across the IR spectrum. While it could have proven useful to the METOC community, the battlespace characterization initiative never gained traction, partly because there was no extant METOC requirement it could satisfy. Similar future opportunities provided by commercial satellites or other DoD programs may prove successful if backed by a current, carefully-analyzed requirement.

Fifth, the document should prioritize the requirements in a manner that clearly highlights the severity of the failure to meet any individual or set of requirements. DoD's resources are always constrained, and the coming decade promises to exacerbate that problem with a stagnant national economy and the necessity to recapitalize forces worn thin from the Long War. Clearly, not all--maybe not even very many--of the requirements specified in the updated document will be satisfied. Prioritizing among the stated requirements is thus critical.

5. Recommendation

Today the DoD METOC community is lucky to have access to ample environmental satellite data. The DMSP constellation continues its reliable service after 4 1/2 decades. NOAA's GOES and POES programs are both extremely healthy. Europe and Japan enjoy service from a new generation of geostationary satellite. NASA's remarkable suite of EOS missions continues to soldier on a decade after their launch. This fortunate circumstance is not likely to persist, though. Unforeseen spacecraft hardware failures are inevitable. QuikScat, TRMM, Terra, and Aqua will soon be gone. The last of the POES spacecraft, NOAA-N', was launched as this was being written.[25] NPOESS' future is anything but clear.

The METOC community needs an authoritative source document to use to quantify the shortfall in its capability to support its operational users that would result from the loss of one or more of the environmental satellite systems it uses today. Furthermore, the same source document must exist as the foundational need statement for future DoD environmental satellite and ground processing systems. In order to be a credible and authoritative source, AFW and CNMOC need to devote the resources and talent to continuously re-assessing the requirements it contains, and updating it regularly to accommodate changing operational concepts, scientific progress, and evolving threats. An update to MJCS 154-86 should serve as the starting point for such an updated requirements document and the NPOESS IORD II should serve as a cautionary example of the consequences of not carefully constraining the stated requirements.

Air Force Weather and the Naval Meteorology and Oceanography Command should make the creation and sustenance of an updated DoD environmental satellite requirements document a priority. The continued high standard of operational support they provide their operational users depends on it.

---

[1] Nolan and Murphy, *Air Force Weather: A Brief History*, 1
[2] Ibid, 2
[3] Kalnay, *Atmospheric Modeling, Data Assimilation, and Predictability*, 14
[4] Strom and Iwanaga, "Overview and History of the Defense Meteorological Satellite Program"
[5] Kidder and Vonder Haar, *Satellite Meteorology: An Introduction*, 208-209
[6] Ibid, 53
[7] Ibid, 184-188
[8] Hall, "A History of the Military Polar Orbiting Meteorological Satellite Program," 1
[9] Kidder and Vonder Haar, *Satellite Meteorology: An Introduction*, 7
[10] GOES-R Program Office Website
[11] Kidder and Vonder Haar, *Satellite Meteorology: An Introduction*, 423-437

---

[12] AFDD 2-9.1, 8, and JP 3-59, IV-12
[13] AFDD 2-9.1, 14
[14] Ibid
[15] *AFW Transformation*, 19, and *AFWA TN-005/001*, 2
[16] *Air Force Weather Operations Functional Concept*, 3, and *Managing Net-Centric Environmental Data and Services*, 1
[17] Kalnay, *Atmospheric Modeling, Data Assimilation, and Predictability*, 19
[18] American Meteorological Society, *Space Weather Policy Statement*, 17
[19] NASA Release 09-008
[20] Bjorkman, *Should Non Department of Defense Meteorological Satellites be Used...?*, 14-20
[21] Burpee, *MJCS 154-86*, cover letter
[22] NPOESS JARG, *IORD II*, cover letter
[23] General Accounting Office, *Information on Program Cost and Schedule Changes*, 10-18
[24] Government Accountability Office, *Cost Increases Trigger Review*, 11 and 15
[25] NASA Goddard Spaceflight Center, *NOAA-N Prime Environmental Satellite Successfully Launched*

Bibliography

AFW Transformation: Air Force Weather Strategic Plan and Vision FY2008-2032. August 2004.

Air Force Doctrine Document (AFDD) 2-9.1. *Weather Operations*. 3 May 2006.

Air Force Weather Operations Functional Concept. Version 1.5. Washington, DC: Director of Weather, Deputy Chief of Staff for Air and Space Operations, Headquarters United States Air Force, November 2005.

American Meteorological Society. "Space Weather: A Policy Statement of the American Meteorological Society." *Bulletin of the American Meteorological Society*, June 2008, 16-18.

Bjorkman, Christopher S. *Should Non Department of Defense Meteorological Satellites be used to Meet Department of Defense Environmental Requirements?* Master's Thesis. Ft. Leavenworth, KS: United States Army Command and General Staff College, 2003.

Burpee, Lt Gen Richard A., Director for Operations, Joint Chiefs of Staff. To Undersecretary of Defense (Research and Engineering). Joint Chiefs of Staff Memorandum MJCS 154-86, 1 August 1986.

Geostationary Operational Environmental Satellite R-Series Program Office, "Welcome to the GOES-R Program Office Website," http://goes-r.gov/.

Hall, R. Cargill. *A History of the Military Polar Orbiting Meteorological Satellite Program*. Office of the Historian, National Reconnaissance Office, 2001.

Joint Publication (JP) 3-59. *Joint Doctrine, Tactics, Techniques, and Procedures for Meteorological and Oceanographic Operations.* 23 March 1999.

Kalnay, Eugenia. *Atmospheric Modeling, Data Assimilation and Predictability*. Cambridge, UK: Cambridge University Press, 2003.

Kidder, Stanley Q. and Thomas W. Vonder Haar. *Satellite Meteorology: An Introduction*. San Diego, CA: Academic Press, 1995.

Managing Net-Centric Environmental Data and Services. Version 1.0. Washington, DC: Director of Weather, Deputy Chief of Staff for Air and Space Operations, Headquarters United States Air Force, May 2006.

National Aeronautics and Space Administration. *NASA Debuts Global Hawk Autonomous Aircraft for Earth Science*. Release 09-008, 15 Jan 2009. http://www.nasa.gov/home/hqnews/2009/jan/HQ_09-008_Global_Hawk.html.

National Aeronautics and Space Administration Goddard Spaceflight Center. *NOAA-N Prime Environmental Satellite Successfully Launched*. 06 Feb 2009. http://www.nasa.gov/centers/goddard/news/noaan_launch.html.

National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Joint Agency Requirements Group (JARG). *Integrated Operational Requirements Document (IORD) II*. 10 Dec 2001.

Nolan, Lilian E. and John M. Murphy. *Air Weather Service - A Brief History: 1937-2000.* Offutt AFB, NE: History Office, Air Force Weather Agency, 2001.

Powner, David A., Director, Information Technology Management Issues, United States Government Accountability Office. *Polar-Orbiting Environmental Satellites: Information on Program Cost and Schedule Changes*. Report to the Subcommittee on Environment, Technology, and Standards, Committee on Science, United States House of Representatives, September 2004.

Powner, David A., Director, Information Technology Management Issues, United States Government Accountability Office. *Polar-Orbiting Operational Environmental Satellites: Cost Increases Trigger Review and Place Program's Direction on Hold*. Testimony Before the Subcommittee on Disaster Prevention and Prediction, Committee on Commerce, Science, and Transportation, United States Senate. 30 March 2006.

Strom, Steven R. and George Iwanaga. "Overview and History of the Defense Meteorological Satellite Program." *Crosslink - The Aerospace Corporation Magazine of Advances in Aerospace Technology*, Winter 2005. http://www.aero.org/publications/crosslink/winter2005/02.html.

Value of Weather Services to the Combatant Commands. AFWA/TN-05/001. Offutt AFB, NE: Air Force Weather Agency, 30 June 2005.