

# Environmental Changes and National Security Space Programs

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*Abstract*—Concerns regarding the strategic impacts of environmental change will soon begin to affect space system requirements and budget priorities. Various climate impacts are projected globally in this century. The predicted impacts of these global changes are already becoming hard to ignore, and the U.S. Department of Defense, the U.S. Census Bureau, and the Intergovernmental Panel on Climate Change, as well as numerous other organizations have identified specific regions and phenomena of significant concern. The focus of this research project is to better understand the impacts of changing climate scenarios on national security issues and requirements, and to explore new mission needs that are arising as a result of changing military priorities, missions, and technologies. Our approach is to cross-reference climate change threats with vulnerable geographic regions, then match existing space-based assets with potentially useful capabilities in suitable orbits (e.g., polar, low-inclination, or geosynchronous) to each regional threat pairing. Several examples of vulnerable regions and threats are: melting ice/opening seas in the Arctic; sea level rise near worldwide coastal military bases and launch facilities; severe storms and flooding in the Gulf Coast and Mississippi River Valley regions. This task will help us determine where there are gaps in capabilities, leading to recommendations for future missions.

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## 1. INTRODUCTION

Climate change appears to be trending in the wrong direction to be dismissed simply as a natural variation in earth’s weather patterns. Historical evidence shows that Earth has enjoyed a relatively stable, temperate climate for the last twelve thousand years or so. Trends observed in ice-core samples and geological evidence, as well as in Milankovitch cycles (which consider variations in Earth’s

**Table 1. Summary of Recent Evidence of Global Climate Change [1].**

<p>Evidence of Global Climate Change:</p> <ul style="list-style-type: none"> <li>• increasing average global air and ocean temperatures</li> <li>• widespread melting of snow and ice</li> <li>• decreasing average annual Arctic sea ice extent over the last 30 years by:             <ul style="list-style-type: none"> <li>○ 2.7% per decade in winter</li> <li>○ 7.4% per decade in summer</li> </ul> </li> <li>• decreasing mountain glaciers and snow cover in both hemispheres</li> <li>• rising average global sea levels             <ul style="list-style-type: none"> <li>○ at an average rate of 1.8 mm/year since 1961</li> </ul> </li> <li>• widespread increasing temperatures             <ul style="list-style-type: none"> <li>○ greatest at higher northern latitudes</li> <li>○ warming of land regions faster than oceans</li> </ul> </li> <li>• increasing intense tropical cyclone activity in the North Atlantic since 1970</li> </ul>
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orbit, axial tilt, & wobble), show that Earth should be close to the brink of another ice age. Yet during the twentieth century alone, the increase in average global temperatures was about 0.6 degree Celsius, or 1 full degree Fahrenheit. The rate and duration of warming of the twentieth century has been much greater than in any of the previous nine centuries, and the current rate of warming is unprecedented in at least 20,000 years. Volcanoes, solar activity, greenhouse gas levels (e.g., water vapor, carbon dioxide, methane, etc.), and the Milankovitch cycles are generally agreed upon as historically responsible factors for variations in the earth's climate. Today, human activity (cars, coal, forest burning, industry, etc.) plays a significant role. Ice core sample data indicate that the concentration of carbon dioxide in Earth's atmosphere (currently at about 395 ppm) is higher now than at any time over at least the past 650,000 years [1][2][3][4].

Escalating concerns regarding the strategic impacts of environmental change will soon begin to affect space system requirements and budget priorities. Recent Presidential and Congressional directives require that potential climate change impacts be considered in future Department of Defense (DoD) and Intelligence planning activities [5]. Examples of such impacts include Arctic melting, sea level rise, flooding, ocean changes, glacial

melting, water redistribution, weather-related disasters, disease migration, heat waves, altered precipitation patterns, drought, fish and crop losses, and many others. Our research focus is on understanding how these evolving environmental threats could affect current National Security Space (NSS) mission requirements, as well as on exploring new NSS mission needs as a result of changing U.S. military priorities, missions, and technologies. The purpose of this paper is to explore the capabilities of existing and planned national security and civilian space programs to support future military activities arising due to various impacts of global climate changes, as well as to identify potential new NSS missions that will be needed to support these activities.

## 2. OVERVIEW

The worldwide effects of climate change identified in Table 1 (above), together with other localized effects are likely to pose strategic challenges to the United States in coming decades, including the prospect of military intervention. Climate-induced crises might bring down governments, empower terrorist movements and destabilize entire regions. Recent war games and intelligence studies suggest that sub-Saharan Africa, the Middle East and South and Southeast Asia in particular are facing prospects of food shortages, water crises and catastrophic flooding.

**Table 2a. Overview Page from Climate/Weather Space-Based Instruments Database.**

<b>Climate Category</b>	<b>Climate Observable</b>	<b># Instruments Used</b>	<b>DoD Instruments</b>
Greenhouse gases:	Carbon Dioxide (CO2)	5	
	Methane (CH4)	7	
	Ozone (O3 -- total, profile)	28	
Cryosphere	Sea Ice area, extent, thickness	4	1
	Land Ice extent, thickness	1	
Hydrosphere	Sea, lake & river water Level		
	Water Vapor	2	2
	Rainfall	3	1
	Cloud coverage, type, T	2	
	Extreme Weather		
	Flooding/storm surge	1	
Air Quality	Soil moisture		
	Aerosols	6	
Biosphere, Carbon budget	Pollutants	1	
	Ocean acidification, Productivity (color)	3	
	Vegetation, Deforestation	2	
Energy Balance/flux	Solar flux	3	
	Albedo (cloud, ground/ice)	1	
	Land/Sea/Air Temperature	3	1
	Winds	2	
	Pressure		

**Table 2b. Examples of Instruments & Spacecraft (from Climate/Weather Space-Based Instruments Database) Capable of Sensing Observables Related to Climate Threats.**

Climate Threat:	Examples of Sensors:	Examples of S/C:	Orbits & Swaths:	Revisit Time vs. Latitude
Sea Level Rise	Poseidon-2,3; RA, RA-2	Jason-1,2 (Poseidon), ERS-2 & Envisat (RA)	Jason: 1336 km alt, 66 deg; ERS-2/Envisat: 785-800km, 98.5 deg, nadir only -- 2-10km nadir resolution	Jason: 10 days; ERS-2/Envisat: 35 days
Cryosphere Melt	SSMIS, AMSR-E, ASTER	<b>DMSP-18 (SSMIS);</b> Aqua/EOS PM-1 (AMSR-E); Terra (EOS AM-1, ASTER);	<b>DMSP-18 833 km SSO;</b> Aqua/EOS PM-1 & Terra 705 km SSO, 98.5 deg; Swaths: SSMIS & AMSR-E 1445km, ASTER 60 km	ASTER 16 days repeat
Storms/Increased Regional Precipitation	OLS, VIIRS, GOES Imager	<b>DMSP-18, NPP, DWSS, GOES</b>	<b>DMSP-18 &amp; NPP &amp; DWSS 833 km SSO, 3000km swath;</b> GOES GEO (near-hemispheric coverage)	GOES 15-30 minute
Flooding		DMC, TRMM, Landsat		
Reduced Regional Precipitation	TMI (TRMM), AMSR-E, SSMIS,	TRMM; Aqua/EOS PM-1 (AMSR-E); <b>DMSP-18 (SSMIS);</b>	TRMM 350 km 35deg, TMI 760km swath; Aqua/EOS PM-1 705 km SSO, 98.5 deg; DMSP-18 833 km SSO; Swaths: AMSR-E & SSMIS 1445km;	DMSP & Aqua 1.7 hrs at poles to 3 days at equator, TRMM no revisit above 40 deg lat
Heat Waves	SSMIS, AMSU(-A)	<b>DMSP-18 (SSMIS);</b> POES & Aqua & MetOp-1 (AMSU),	<b>DMSP-18 833 km SSO;</b> Aqua/EOS PM-1 705 km SSO, 98.5 deg; Swaths: SSMIS 1445km,	
Winds	SeaWinds	QuikSCAT	803 km, 98.6°, 1800 km swath	
Wildfires	ASTER, ALI, GOES Imager	Terra (EOS AM-1, ASTER); EO-1 (ALI); GOES (Imager)	Terra 705 km SSO, 98.5 deg, 60 km swath; GOES GEO (near-hemispheric coverage)	ASTER 16 days repeat; GOES 15-30 minute
Drought	ATSR; AMSR-E; C-band SAR/ASAR;	ERS; Aqua, SMOS, HYDROS; ERS-1/2, ENVISAT, RADARSAT-1/2		
Degraded Air Quality	AIRS, SCIAMACHY	Aqua (AIRS); Envisat	Aqua 680 km, 98.2 deg, AIRS 1700 km swath; Envisat 800 km SSO, SCIAMACHY 1000 km swath	Aqua AIRS <1 day above 45 deg lat ; Envisat 35 day repeat, 1-3 day revisit (1.7 hrs at poles to 3 days at equator)
Disease Spread	ETM+, HRVIR	Landsat-7 (ETM+); SPOT-4 (HRVIR)	Landsat-7 705km SSO; SPOT-4 832 km SSO, HRVIR 2200km swath	1.7 hrs at poles to 3 days at equator
Ecosystem Impacts	ETM+, HRVIR	Landsat-7 (ETM+); SPOT-4 (HRVIR)	Landsat-7 705km SSO; SPOT-4 832 km SSO, HRVIR 2200km swath	1.7 hrs at poles to 3 days at equator
Crop/Farm/Fish Failures	ETM+, HRVIR	Landsat-7 (ETM+); SPOT-4 (HRVIR)	Landsat-7 705km SSO; SPOT-4 832 km SSO, HRVIR 2200km swath	1.7 hrs at poles to 3 days at equator
Climate Intervention	AIRS, OMI, TOMS, GOME, SCIAMACHY, MODIS	Aqua, Terra		

A recent National Intelligence Council assessment warns that storms, droughts and food shortages resulting from a warming planet will create numerous relief emergencies [6]: “The demands of these potential humanitarian responses may significantly tax U.S. military transportation and support force structures, resulting in a strained readiness posture and decreased strategic depth for combat operations.” Nancy Colleton, president of the Institute for Global Environmental Strategies (IGES), cites ...“the need to better measure and monitor the planet to more effectively manage it has never been greater, and this is especially true for our military. Climate change is the ultimate moving target and is defining a whole new battle space [7].” All of these increasing demands come at a time of shrinking budgets. Preparedness and the ability to respond will require justification for advance military resource reallocation. This will necessitate clarity and foresight of the evolving climate situation, which in turn depends on the global and persistent view of satellites.

The initial phase of this study involved surveying the threats and impacts of potential climate change scenarios on national security mission requirements and operations. We then created a database indexing the capabilities of existing and planned national security and civilian space programs that could be useful in supporting future military activities arising due to various impacts of global climate changes (sample pages from this database are shown in Tables 2a and 2b above). Some of these existing space assets might be used to monitor climate trends leading up to drought or flooding, which in turn may lead to significant natural disasters, mass migrations, and/or border/territorial conflicts. Maintaining an awareness of the status of developing climate threat scenarios could be important enough (for preparation purposes) to re-focus existing space assets. When disaster strikes, the ability to provide space-based communications, navigation, and tracking of traffic, assets, or other targets becomes vitally important. The threat/impacts survey together with the climate instruments database enabled us to identify potential new NSS missions that will be needed to support these future military activities.

In order to prepare for global changes, we have identified geographically vulnerable areas of interest. Our research project includes a survey of major (in terms of financial and human life/injury costs) climate and weather related disasters over the past 50 years within the U.S., which indicates repetitive occurrences of:

- 1) flooding and ice storms/blizzards in the Northeast;
- 2) tornadoes in the South and Central U.S.;
- 3) severe storms and flooding, alternating with heatwaves and drought in the Southeast;
- 4) tornadoes and thunderstorms in the Midwest;
- 5) drought and wildfires, as well as freezing and flooding in the West and Southwest.

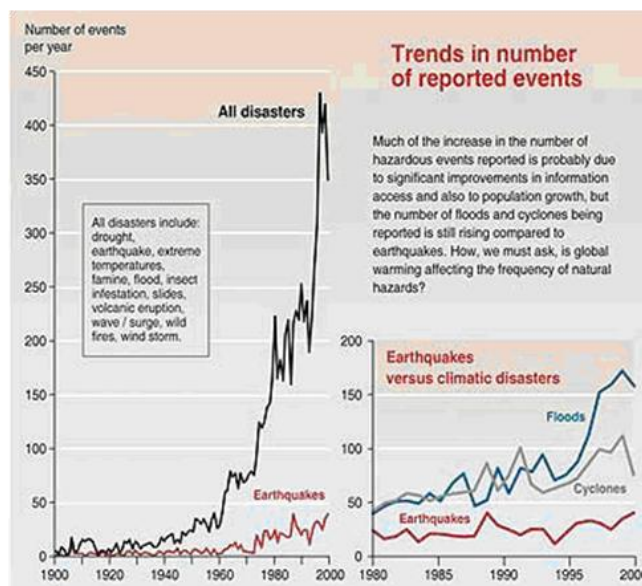
A recent National Climatic Data Center study reports 108

separate billion-dollar magnitude disasters in the US since 1980, with 9 occurring in 2011 just through August, tying the 2008 record. Texas alone has had 16 such events since 1980, resulting in increased insurance premiums [8].

Examples of climate threats emerging in vulnerable regions of the U.S. and installations abroad are: melting ice/opening seas in the Arctic; sea level rise near worldwide coastal military bases and launch facilities; severe storms and flooding in the Gulf Coast and Mississippi River Valley regions; drought and wildfires in the Southwest threatening military installations and weapons labs.

Around the globe, there have been repetitive instances of flooding and famine in Southeast Asia, drought and famine in Africa, and various worldwide disease epidemics that have claimed hundreds of thousands of lives. Conflicts over water rights in Africa, the Middle East, Central Asia, and South America are being exacerbated by climate changes. Climate change induced drought, famine, and flooding exacerbate existing border tensions and territorial issues. The U.S. military is increasingly called upon for disaster response/relief operations around the globe, and increasingly severe weather brought about by climate change will only intensify that growing responsibility.

Figure 1 (below) shows the increasing trend of reported weather-related natural disasters as compared to the relatively level trend of earthquakes, indicating a likely connection to global warming. Concurrently, associated costs of extreme weather events have risen dramatically over the past 25 years or so [8].



(c) United Nations Environment Programme/GRID-Arendal

**Figure 1 – Trends in Reported Natural Disasters [9].**



### 3. KEY FINDINGS

Through our research we have identified and cross-referenced potential impacts of climate change within three terrestrial latitude bands (tropical, mid-latitude, and polar) in order to assess satellite coverage of vulnerable geographic regions. We then categorized the geographic regions within these latitude bands with regard to each selected climate change impact. Within each latitude band we assessed the capabilities of existing space-based assets that could provide useful coverage in the event of climate related threats or emergencies. Table 3 (below) is our assessment of where additional satellite coverage or enhanced satellite/technology capabilities will be needed to better monitor potential threats and support potential U.S. military involvement arising from climate changes.

The tropics and polar regions are likely to experience the most dramatic changes due to global warming. Less stable developing countries tend to be located in the tropical latitude band. Greater poleward heat transport will likely also result in more extreme weather in mid-latitudes due to increased baroclinic and cyclonic activity, causing higher winds, precipitation and storms, which can lead to flooding and launch facility impacts.

The text within color-coded cells in Table 3 highlights potential climate-related near and longer term shortfalls in satellite and technology capabilities and coverage in each latitude band. Attributes of satellite coverage differ for the three latitude bands. For example, low inclination and equatorial geosynchronous orbits do not cover the poles. Conversely, high inclination and polar orbits revisit specific equatorial regions less frequently. Table 3 summarizes the “gaps” where additional or enhanced satellite/technology capabilities (or different orbits) may be needed to better monitor potential threats and support potential U.S. military involvement. Frequently recurring themes across various latitude bands include enhanced weather prediction technologies, as well as disaster relief support. These and other potential new NSS missions are outlined below.

#### *Improved Disaster Relief Coverage of Tropical Latitudes*

Climate models predict that the tropical regions will experience earlier and more severe effects of climate change. As mentioned above, military planners worry that climate crises may depose governments and fuel terrorist movements in the global south, regions vulnerable to looming prospects of food shortages, water crises and catastrophic flooding.

A recent National Intelligence Council assessment warns that... “[t]he demands of these potential humanitarian responses may significantly tax U.S. military transportation and support force structures, resulting in a strained readiness posture and decreased strategic depth for combat operations [8].” Perhaps most troubling are threats to food production, which must rise to meet a 70 percent increase in the demand by 2050 [10]. Weather-related disasters due to climate

change (such as severe storms, flooding, drought, wildfires and famine) are likely to place increased demands on already-cash-strapped humanitarian programs. To quote Dr. E.D. McGrady, CNA Research Analyst, we can expect “more disasters, greater economic stress and increased migration, which can exacerbate instability, particularly in already fragile states [11].” The 2010 Quadrennial Defense Review cites the need for increasing military capabilities to rapidly respond to natural disasters to avoid destabilization and conflict in volatile regions of the world [12].

The Navy, Air Force, and Army have begun incorporating the demands of future foreign disaster relief operations into their force planning activities, especially for logistics and communications. Disaster relief operations in some developing countries could also require supporting counterinsurgency operations to stabilize the situation and protect relief workers and supplies. With disaster relief becoming a core military mission, national security space planners must begin exploring how future space systems can enhance disaster relief capabilities. Military forces in the region will require satellite communications support that is interoperable with international military and civilian relief organizations. Continuity of communications during transit from military bases in CONUS to the deployed areas is also an important requirement.

The recent Haitian disaster-response mission experience was the largest in modern U.S. military history, suggesting that proactive planning and innovative thinking (especially with regard to interfacing with NGOs, local authorities, and the internet) can have a big payoff. According to Paul Stockton, assistant secretary of defense for homeland defense and Americas' security affairs: “Civilians will always be in charge of disaster response. Defense will only be in support of those civilian leaders. But in a catastrophe, let's face it, sometimes defense establishments are where the capability is. We need to be able to harness those defense capabilities to serve the requirements established by civilian authorities in the country that's been struck by the disaster in a way that's much more effective than we had in Haiti [13].”

U.S. military support of disaster relief operations in the vulnerable tropical region will also require improved satellite surveillance, communications, and asset tracking capabilities. Satellite coverage of tropical regions is hampered by cloud cover and low revisit rates of sun-synchronous orbits. For instance, with a revisit period of 16 days, Landsat typically obtains less than one cloud-free scene a year in certain parts of the Amazon region. Lower inclination satellites would provide much better coverage. A SAR satellite in near equatorial LEO, for example, would provide images in cloudy conditions several times per day. A weather satellite in near equatorial LEO would provide near continuous high resolution storm tracking in support of U.S. military operations in tropical latitudes, though subject to more challenging illumination, thermal and radiation environment requirements.

**Table 3. Summary of Climate Change Impacts by Latitude and Associated NSS Needs.**

Color code for table entries:

**Red = Relative near-term (10-20 years) and/or with impacts and instability severe enough likely to involve U.S. military in disaster relief and/or peace keeping operations.**

**Yellow = Longer term (> 20 years) and/or less severe impacts with less likelihood (but still possible) involvement of U.S. military.**

**Blank = Impact unlikely to involve U.S. military either because impacts are mild or because government stability or resources not stressed.**

Impact of Climate Change	Tropical Latitudes	Mid Latitudes	Polar Latitudes
Sea Level Rise	Military/Civil Comm/Nav Interoperability	Military/Civil Comm/Nav Interoperability	
Cryosphere Melt			Arctic Comm; Ice & Traffic Surveillance; Search & Rescue Support
Storms/Increased Precipitation	Storm Tracking; Military/Civil Comm/Nav Interoperability	Storm Tracking; Military/Civil Comm/Nav Interoperability	
Flooding	Flood Prediction/Sensing; Military/Civil Comm/Nav Interoperability	Flood Prediction/Sensing; Military/Civil Comm/Nav Interoperability	
Reduced Regional Precipitation	Weather Prediction	Weather Prediction	
Heat Waves	Weather Prediction	Weather Prediction	
Winds	Weather Prediction; Wind/Launch Advisory	Weather Prediction; Wind/Launch Advisory	
Wildfires	Fire Detection/Tracking; Military/Civil Comm/Nav Interoperability	Fire Detection/Tracking; Military/Civil Comm/Nav Interoperability	
Drought	Weather Prediction; Military/Civil Comm/Nav Interoperability	Weather Prediction; Military/Civil Comm/Nav Interoperability	
Degraded Air Quality	Pollutant Sensing	Pollutant Sensing	
Disease Spread			
Ecosystem Impacts	Bio Imaging	Bio Imaging	Bio Imaging
Crop/Farm/Fish Failures	Weather Prediction; Bio Imaging	Weather Prediction; Bio Imaging	Weather Prediction; Bio Imaging
Climate Intervention		Stratospheric Aerosol Sensing	

### *Improved Communication, Surveillance & Search & Rescue Coverage of the Arctic Region*

The opening of Arctic waters due to melting ice presents both opportunities in terms of new trade channels and increased access to oil and gas reserves, and challenges related to patrolling open waters, competition for energy resources and territorial claims. Seasonal summertime opening of the Arctic would cut 7000 km/4000 nm off of sea routes between Europe and Asia and produce a dramatic increase in ship traffic, including tourism. An ice-free Arctic will also open up fossil fuel exploitation (an estimated 40% of world's oil and gas reserves are located in the Arctic region). Russia, Denmark, Norway, Canada and the U.S. have all staked resource claims in the Arctic. Most military communications satellites don't cover the polar regions, and with tight budgets and no firm requirements, military polar communications requirements are currently a low priority. Search and rescue capability is also needed, as cruise ships are already visiting the Arctic region, which are often an 8-hour helicopter flight away from any source of assistance.

In a recent report to Congress, DoD officials say the Arctic is a place they and the services are paying attention to because of rapid climate change there that likely will open the area to greater human inhabitation and traffic, as well as possible threats to U.S. interests [14]. Thus, military and Coast Guard operations in the Arctic will require satellite point-to-point and broadband communications, as well as improved ice and traffic surveillance, and search and rescue support. A small constellation of GIO or HEO satellites could meet those needs. These issues are discussed in detail in our 2009 AIAA paper, entitled, "Future Space System Support to U.S. Military Operations in an Ice-Free Arctic: Broadband Satellite Communications Considerations" [15].

### *Improved Environmental Monitoring*

Improved weather prediction models, methods and technologies (with combined space and ground based elements) will help mitigate the detrimental effects of climate change-induced severe and variable weather. Near continuous high resolution storm tracking in support of U.S. military operations will become increasingly important, especially in tropical latitudes.

DMSP, POES (or follow-on JPSS) and the European Metop provide 3-hour updates for forecasts at mid- and higher-latitudes. Measurements include: water vapor, sea ice, cloud cover, land/sea/air temperature and, for VIIRS on DWSS, ozone. However, many of the greenhouse gas, radiation budget, soil moisture, air quality, biosphere and land use parameters are not measured.

GPS is also an important contributor to climate monitoring. It provides frequent, global signals for a global network of ground and LEO occultation, limb sounding and reflectometer instruments that measure such parameters as total water vapor, temperature and water vapor sounding, and sea state. The sea state in turn provides a vital

correction to the microwave brightness temperature measured by radiometers, which is used together with temperature measurements by IR radiometers to determine sea surface salinity. The salinity is related to climatological factors such as ice melt, and ocean circulation impacting climate.

Under the Kyoto Protocol, countries self-report inventories of their anthropogenic emissions based on land-use surveys (often supported by satellite imagery), in situ monitoring stations (if available), and various proxy measures and computer models. Based on studies of current reporting systems (such as for sulfur dioxide), experts suspect that significant under-reporting of GHG emissions is likely occurring [16]. If emission limits are tightened under future GHG treaties, independent verification of nations' emissions reports will become increasingly important and technically challenging.

Satellite remote sensing is used for land-use monitoring and the commercial remote sensing industry is developing improved protocols and algorithms for monitoring compliance with land use provisions of future GHG treaties. Accurately measuring urban and power plant emissions using satellites is a far greater challenge, however. NASA's Orbiting Carbon Observatory (OCO), which failed to launch in February 2009, offered higher precision than any current CO<sub>2</sub>-sensing satellite but would have sampled only 7 to 12 percent of the land surface with a revisit period of 16 days. OCO's successor, OCO-2, is currently scheduled to launch in 2013 [17].

Lack of technical means and protocols for verifying compliance with future GHG treaties has become a stumbling block in negotiations on carbon-reduction targets, as evidenced by the disagreement between U.S. and Chinese negotiators at the 2010 climate treaty meeting in Copenhagen. Independent verification is also seen as necessary for GHG trading markets to ensure that an offset purchased by a buyer results in an actual cut in emissions [16][17]. However, given the inherent technical limitations of satellite sensors and nations' political concerns about satellites collecting information that can also be used to assess economic resources or national security it appears unlikely that remote sensing satellites alone will be adequate for independent treaty verifications.

## **4. CONCLUSION**

In conclusion, gradual but significant climate change is very likely. Sea levels are rising, with a 3 to 4 foot rise likely, but a worst case scenario predicting as much as a 20 foot rise by the end of this century (a 3- to 4-foot sea level rise puts 10 million people out of homes). In general, governments, relief agencies, and populations need to prepare for drought, water and food crises, rising sea levels, massive storms, and flooding. These climate-induced crises around the world will result in mass migrations to more habitable areas [4].

Military and international partnership satellites currently provide important contributions to meteorological, climate and disaster monitoring, navigation and communications. However, new satellite capabilities and orbits may be needed to support future environmental monitoring and military activities arising due to environmental changes, especially in regions not currently adequately covered. The DoD may need to partner with commercial (e.g., communications satellite providers), civil (e.g., NASA and NOAA), and international (e.g., ESA) programs in order to provide these new capabilities.

Military DMSP and GPS space systems currently make critical contributions to meteorological and climate monitoring, and their continuing contributions are a vital part of international partnerships. European and other national navigation systems also enhance GPS globally and regionally. Similarly, the international DMC constellation provides important disaster monitoring and response support capability. However, the revisit times of existing sun-synchronous constellations in tropical regions is deficient for support to meteorological, disaster monitoring and climatological needs. This deficiency is amplified by the projected impacts of climate change on these low latitude regions. It appears that these deficiencies could be most efficiently met by replicating DMSP/POES/Metop and DMC satellites in low-inclination LEO orbits, using the pattern of international cooperation, with more contribution by those countries affected.

Polar regions are also increasingly impacted by climate change, and growing needs for communications and other satellite coverage in both polar regions could be met by a small constellation of polar-inclined GEO or HEO satellites, similar in design to Intelsat or even WGS military satellites. Again, this could be an international cooperative constellation supported by those nations involved in science, traffic, exploration, etc. in polar regions.

Finally, it should be mentioned that research has begun on various schemes to synthetically increase the earth's albedo as a potential improvised measure to mitigate the impacts of global warming in case emission reductions are not sufficient or if the climate response is more extreme than anticipated. Future international agreements regarding development, testing, and implementation of such schemes will not be enforceable without effective means of monitoring and verification, which will likely become a DoD responsibility. A previous paper ("Feasibility of Space-Based Monitoring for Governance of Solar Radiation Management Activities" [18]) addresses the feasibility of space-based remote-sensing systems for detecting and monitoring particle injection into the upper atmosphere. Preliminary findings suggest that reliable detection of small clandestine tests from space will be very challenging. This conclusion has important implications for future treaty negotiations, which may need to consider alternative methods of monitoring such activities. As with nuclear test monitoring, detecting clandestine particle-injection

experiments and development activities will require a combination of techniques involving extensive ground, space and other means. However, given the need for improved understanding of the role of aerosols in the stratosphere, as well as for applications such as the monitoring of volcano dust for airline safety, the impetus may exist for the development of a multifunction system of space-based sensors to serve these various objectives.

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Agency)

*CONUS* = Contiguous United States

*DoD* = Department of Defense

*DMC* = Disaster Monitoring Constellation

*DMSP* = Defense Meteorological Satellite Program

*DWSS* = Defense Weather Satellite System

*EO-1* = Earth Observing 1 Satellite (NASA)

*EOS* = Earth Observing System

*ERS* = European Remote Sensing Satellite

*ESA* = European Space Agency

*ETM* = Enhanced Thematic Mapper (Landsat)

*EUMETSAT* = European Organisation for the Exploitation of Meteorological Satellites

*GOES* = Geostationary Operational Environmental Satellite

*GEO* = Geosynchronous Earth Orbit

*GIO* = Geosynchronous Inclined Orbit

*GOME* = Global Ozone Monitoring Experiment

*GPS* = Global Positioning System

*HEO* = High Earth Orbit

*HRVIR* = High Resolution Visible & Infrared instrument

*HYDROS* = Hydrosphere State Satellite mission (NASA)

*JPSS* = Joint Polar Satellite System

*LEO* = Low Earth Orbit

*MetOp* = Polar Meteorological Satellites (EUMETSAT)

*MODIS* = Moderate Resolution Imaging Spectroradiometer

*NASA* = National Aeronautics and Space Administration

*NGDC* = National Geophysical Data Center

*NOAA* = National Oceanic and Atmospheric Administration

*NSS* = National Security Space

*OLS* = Operational Linescan System (NGDC/NOAA)

*OMI* = Ozone Monitoring System (NASA)

*POES* = Polar Operational Environmental Satellite

*SAR* = Synthetic Aperture Radar

*SCIAMACHY* = Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (ESA's EnviSat)

*SMOS* = Soil Moisture & Ocean Salinity Satellite (ESA)

*SPOT* = Satellite Pour l'Observation de la Terre (CNES)

*SSO* = Sun Synchronous Orbit

*SSMIS* = Special Sensor Microwave/Image System

*TOMS* = Total Ozone Mapping Spectrometer (NASA)

*TRMM* = Tropical Rainfall Measuring Mission (NASA)

*UARS* = Upper Atmosphere Research Satellite

*VIIRS* = Visible Infrared Imager Radiometer Suite (NASA)

*WGS* = Wideband Global SATCOM System

## ACRONYMS

*AIRS* = Atmospheric Infrared Sounder

*ALI* = Advanced Land Imager

*AMSR* = Advanced Microwave Scanning Radiometer

*AMSU* = Advanced Microwave Sounding Unit

*ASTER* = Advanced Spaceborne Thermal Emission & Reflection Radiometer

*CNES* = Centre National d'Etudes Spatiales (French Space

## BIOGRAPHIES



**Leslie Wickman, Ph.D.**, currently works as a Senior Engineering Specialist at The Aerospace Corporation, as well as director of the Center for Research in Science (CRIS) at Azusa Pacific University (APU). She is an internationally respected research scientist and engineering consultant. For more than a decade Leslie was an engineer for Lockheed Martin Missiles & Space in Sunnyvale, Ca., where she worked on NASA's Hubble Space Telescope and International Space Station Programs, receiving commendations from NASA for her contributions and being designated as Lockheed's Corporate Astronaut. She has also worked as a consulting research scientist with The RAND Corporation on the technical and political aspects of various national defense issues, particularly involving fighter pilot training. Her current projects include research on global climate change and national security issues, assessment of current and future space mission technologies and their applications, human factors issues in extreme environments, and sustainable environmental systems. Leslie has lectured extensively around the world on satellite servicing, astronaut operations, mission planning, and space physiology issues, as well as topics in science and theology. She is also a dedicated athlete, playing competitive beach volleyball and women's professional football. Leslie holds a master's degree in aeronautical and astronautical engineering as well as a doctoral degree in human factors and biomechanics from Stanford University. She earned a bachelor's degree in political science, graduating with honors from Willamette University, in Salem, Oregon.



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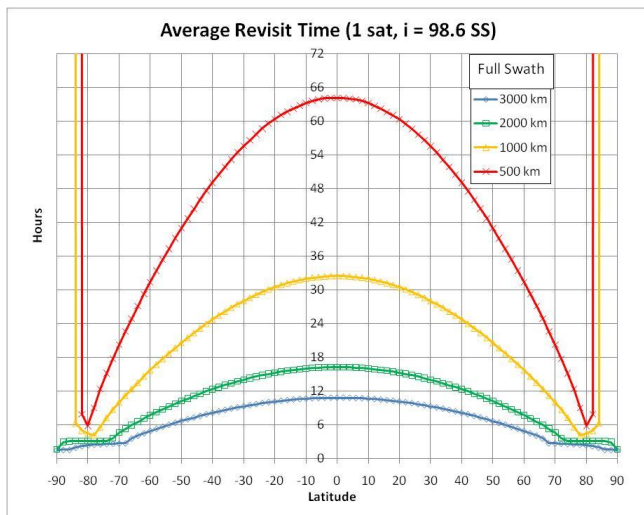
## ACKNOWLEDGEMENTS

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## APPENDIX A

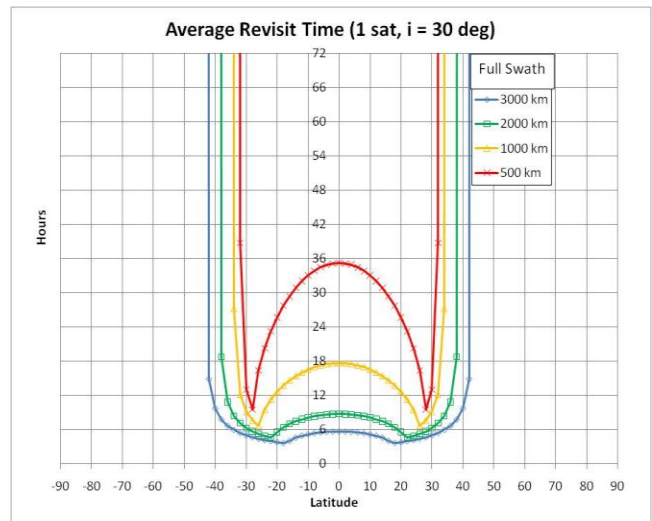
### Satellite Coverage Characteristics

This section is a brief overview of remote sensing satellite orbits and coverage characteristics. Most remote sensing satellites are in sun-synchronous (SS) or near-polar orbits, which cover a wide range of latitudes and provide consistent diurnal conditions. Figure A1 shows that a single SS satellite at 800km altitude, with 500km swath, has an average revisit time of 6 hours at 80 degree latitude (but never covers the poles), and 64 hours at the equator. These revisit times may be adequate for monitoring slowly-varying climate observables. Reduced revisit times required for meteorological, disaster or other shorter-timescale phenomena require wider collection swaths, multiple satellites, and/or specialized orbits. Increasing the swath width to 3000km, characteristic of meteorological (e.g., DMSP) satellites, reduces single-satellite average revisit to 3 hours at the poles and 10 hours at the equator, for example. The 3-satellite DMSP/POES/MetOP constellation in 3 planes achieves 3-hour maximum revisit outside the tropics.



**Figure A1 - Sun-synchronous revisit.**

Reducing orbital inclination to 30 deg. (Figure A2) provides 35- hour revisit at the equator, which is typical of the TRMM spacecraft designed for tropical meteorology. An equatorial (0 deg. inclination) orbit would achieve 100-minute (orbit period) revisit over a swath width about the equator. Hybrid constellations, such as a combination of SS and low-inclination, can achieve the best of both types of coverage (high and low latitude), and may be more cost-effective than simply proliferating SS orbits.



**Figure A2 - Low-inclination revisit.**

Even shorter revisit times or continuous coverage are possible from higher orbits, such as geosynchronous equatorial and inclined orbits (GEO, GIO), and the highly eccentric orbits (HEO) such as Molniya and Tundra. They all suffer reduced resolution and sensitivity with their large ranges, and require higher power for communications. GEO orbits do not provide polar coverage, with GOES and Intelsat being examples. GIO, Molniya and Tundra orbits can provide high latitude and polar coverage, as exemplified by various communication satellites. HEO orbits do, however, suffer life-shortening effects of radiation belt traversal.