Chapter 1
An Introduction to Satellite-Based Applications and Research for Understanding Climate Change

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Abstract The use of satellite data in applications has changed as the environmental community has become more sophisticated deriving products from the remotely sensed measurements. This introduction summarizes the changes from the first satellites where the images were used to improve cloud forecasts to the international coordination groups that have formed to improve collaboration and data sharing of satellite observations. This introduction also addresses some of the key challenges associated with using satellite data for both weather and climate; the challenges include calibration, derived products, trend uncertainty, and measurement quality. A short discussion of subsequent future issues is briefly discussed as satellite measurement calibration reaches maturity.

Keywords Satellite • Applications • Research • Calibration • Collaboration • Climate • Trend • Uncertainty

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1.1 Introduction

Climate change is one of most important issues facing the world today. With the Arctic polar ice extent at near record minimums and new temperature records being set in many regions of the world, the need to understand how our planet is responding to environmental change is critical for society. Although some progress was made toward understanding the changes in weather, the understanding of changes in oceans and land over time is still in a formative stage. A description of climate observations in support of the Global Climate Observing System can be found in Thomas R. Karl's (ed) (1996) book: *Long-Term Climate Monitoring by the Global Climate Observing System*. As better quality global observations of the Earth are collected from satellites, the opportunity to gain insight into the dynamic processes driving our planet and the long-term trends will improve. Even though there are thousands of surface observations, rawinsondes, buoys, and other in situ measurements from ships and aircraft, the observations are limited in global coverage, particularly over the oceans and the polar caps. Measurements over the sparsely observed oceans and polar caps are needed to understand how the various regions of our planet are connected. The land regions where we live are impacted by changes in the oceans and the polar caps. For example, if the polar caps continue to melt, sea level rise will affect islands and coastlines – inundating some to such an extent that the inhabitants must live elsewhere. Changes in temperature will affect precipitation, evaporation, and crop growth, leading to economic impacts and potential disruptions in global food supply. It is vital that a fundamental understanding of how our planet works be developed so accurate predictions of environmental change can be provided. This will allow the world's decision makers to make tough choices relative to both global and regional consequences. To garner an improved understanding about how our environment functions, a comprehensive set of global observations are required. Satellites can help provide those observations and eliminate the data sparse coverage in many regions of the world like the oceans, deserts, and polar caps.

1.2 Satellites and Changes over Time

Satellite observations play a crucial role filling the gaps in the data sparse regions and helping to understand the connections between different regions of the world. The observations will provide information about how the Earth exchanges energy between the tropics and the poles and how the heat exchange impacts global atmospheric circulation patterns as well as the weather and climate trends around the globe. Satellites are relatively new on the global monitoring scene with only about 30 years of modern observations. Progress is being made in understanding the spaceborne observations, how they relate to our collection of in situ observations, and how they can be used to predict changes in our environment.

In the early years, the first satellites were successful if the imagery had sufficient contrast and clarity to be used for cloud pattern analysis. One of the first publications on satellite data applications was the *Environmental Science Services*

Administration (ESSA) Technical Report, from the *National Environmental Satellite Center* (NESC) on the Application of Meteorological Satellite Data in Analysis and Forecasting (Anderson et al. 1969). In the introductory chapter, the wisdom of the early satellite scientist pioneers was captured in the following quotes on page 1:

> Since the advent of the operational ESSA weather satellites in 1966, routine use of satellite cloud photographs has increased steadily. Meteorologists worldwide now depend on these data to supplement conventional observations and rely completely on satellite cloud observations where other data are not available. The problem of "sparse data" areas has been greatly alleviated since weather satellites now provide analysts with a timely view of the cloud conditions over all parts of the earth. Even so, the advantages of the satellite data are not limited to isolated areas but also provide additional intelligence over areas where the conventional observations are dense.
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> If the maximum value of these data is to be realized, correct interpretation of the cloud photographs is essential. This technical report furnishes guidance in the interpretation of satellite cloud photographs and presents the latest relationships as determined by research and study in this field.

The ESSA Technical Report authors further comment:

> Future research with improved satellite data will undoubtedly result in the determination of new concepts and a better understanding of the relationships between the satellite data and the dynamics of the atmosphere.

The pioneers of environmental satellite applications had a vision for the use of satellite data and understood the value of training and educating others in the use of the new satellite data. By training others, the value of the satellite data and its benefits to society would be recognized. Twenty-five years after the Anderson publication, similar issues of training and educating users as well as gaining an improved understanding of the satellite measurements were identified by Stanley Kidder and Thomas VonderHaar in their 1995 book entitled *Satellite Meteorology: An Introduction* (Kidder and Vonder Haar 1995). In the preface to their book, they write:

> We place special emphasis on the physical understanding of measurements from space because it is this understanding which will allow both the useful application of current techniques and the development of future techniques. We also tend to emphasize operational techniques over experimental techniques. We do this in the belief that most readers will not do their own information or parameter retrievals from raw satellite data; they will use parameters retrieved by others. Most often these parameters will be retrieved using operational, near real-time methods. A thorough exploration of the operational techniques is therefore important.

Note the shift in approach from the first scientists who were involved in all aspects of the satellite program and its development – a team of scientific jack-of-all-trades. The early scientists helped in the instrument design, worked closely with the instrument engineers, and performed their own data analysis which led to developing "operational products" for the community of users. From their scientific analyses, the scientists taught others how to use the information to monitor the Earth to make better weather forecasts. As the use of satellites for monitoring the Earth became more routine, a core group of scientific specialists was developed who also train users on the benefits of the routine operational products. By 1995, the field of satellite meteorology had grown dramatically, and the value of satellite data had proven its worth to multiple communities eager to take advantage of the satellite measurements and the information derived from them.

1.3 International Satellite Collaboration and Coordination

The complexity of the world's satellite systems and programs led to the development of coordinating groups to better leverage satellite resources and share their data. The Group on Earth Observations (GEO) was formed from a call to action by the 2002 World Summit on Sustainable Development. The World Summit recognized that international collaboration was critical for exploiting the growing potential of Earth observations to support decision making in an increasingly complex world. GEO is a voluntary partnership of governments and international organizations. It provides a framework where partners can develop new strategies and projects and coordinate their investments.

To improve efforts to apply satellite observations, GEO coordinates efforts to build a Global Earth Observation System of Systems (GEOSS). GEOSS will provide a broad range of societal benefits including reducing the loss of life and property, improving human health, managing energy resources, adapting to climate variability and change, improving water resource management and weather forecasts, protecting coastal marine and marine ecosystems, supporting sustainable agriculture, and monitoring and conserving biodiversity. GEOSS coordinates numerous complex issues. This crosscutting approach avoids duplication, encourages synergies between systems, and ensures substantial economic, societal, and environmental benefits.

GEOSS provides decision-support tools to a wide variety of users. GEOSS is a global and flexible network of content providers allowing decision makers to access an extraordinary range of information at their desk. This "system of systems" links together observing systems around the world. It promotes common technical standards, so satellite data from the numerous instruments can be fused into integrated data sets. The "GEOPortal" offers users a single Internet access point for data, imagery, and analytical software packages. It connects users to existing databases of observations, tools, and software. It provides reliable, up-to-date information critical for the work of decision makers, planners, and emergency managers. Users with limited or no access to the Internet will be able to use satellite information available via the "GEONETCast" telecommunication satellite network where data is broadcast to field systems with small portable antennas (information on GEO and GEOSS is derived from http://www.earthobservations.org/about_geo.shtml).

Another key satellite group, the Committee on Earth Observation Satellites (CEOS), was established in 1984. CEOS coordinates civil spaceborne Earth observations. Members enhance international coordination and data exchange for societal benefit and represent space agencies as well as national and international organizations. Members participate in planning and related CEOS activities through a variety of working groups; one is related to climate applications.

CEOS established a Working Group on Climate (WGClimate) to coordinate and encourage collaborative climate monitoring activities between the world's major space agencies. The Working Group's mandate is to facilitate the implementation and exploitation of the Essential Climate Variable (ECV) time series through coordination of CEOS member activities (information on CEOS is derived from http://www.ceos.org).

Using the satellite observations and coordinating the satellite constellation is fundamental to managing the Earth observations. However, the use of the observations is impacted by the data formats and communications pathways and extends to various user communities. The World Meteorological Organization (WMO) is a specialized agency of the United Nations which helps facilitate international coordination. It originated from the International Meteorological Organization (IMO), founded in 1873. The WMO was established in 1950. It became the specialized agency of the United Nations (UN) in 1951 for meteorology (weather and climate), operational hydrology, and related geophysical sciences. The WMO is the UN system's authoritative voice on the state and behavior of the Earth's atmosphere, its interaction with the oceans, the climate, and the distribution of water resources. WMO provides the framework for international cooperation and collaboration.

As weather, climate, and the water cycle recognize no country boundaries, global level international cooperation is essential for developing meteorological and hydrological applications to reap the observational benefits. WMO membership consists of 189 member states and territories. WMO facilitates the free and unrestricted exchange of data and information. It also promotes products and services relating to the safety and security of society, economic welfare, and the protection of the environment. WMO contributes to policy formulation at national and international levels. For weather, climate, and water-related hazards, which account for nearly 90% of all natural disasters, WMO's programs provide information for advance warnings that save lives and reduce property and environmental damage (information on WMO is derived from www.wmo.int).

Studies show that every dollar invested in meteorological and hydrological services produces an economic return many times greater. The world of satellite observations has come a long way from the first observations taken nearly 50 years ago.

Systems for the routine collection of data on the state of the climate system are the bedrock for generating climate services. The requirements and standards for observing systems and their component instruments for measuring the state of the climate system are described fully in the relevant WMO manuals and in a range of documents developed by the Global Climate Observing System (GCOS). The needs for climate data are not the same across all applications. Climate change detection and attribution need high-quality, homogeneous, long-term data. For this purpose, the GCOS baseline systems, especially the GCOS Surface Network (GSN) and the GCOS Upper-Air Network (GUAN), are the essential benchmarks for ensuring the overall homogeneity of the global/regional databases. The GCOS Climate Monitoring Principles provide the "Gold Standard Rules" for planning, developing and operating observing systems. WMO is now implementing the WMO Integrated Global Observing System (WIGOS) as an all-encompassing approach to the improvement and evolution of meteorological and related observing systems.

Given the change in emphasis of satellite programs, their coordination internationally, and the expanding satellite constellation coordination, it is no surprise that the satellite research and applications community has changed substantially. This book discusses selected analyses and research findings in application areas of interest to the environmental satellite community and its users. The wide range of satellite products, the need for specialization in specific areas of endeavor, and the expanding interest in new or improved satellite and model forecast capabilities mean that today's satellite scientists, product specialists, and the climate community are collaborating more than any point in the past. Future expectations include a greater and more rapid information exchange.

Partnerships similar to ones described in the various coordinating organizations foster the continuation of the original principles listed in the two publications cited earlier, for example, to train and educate others about the satellite measurements and the products with the result being (a) the development of new satellite-based concepts and (b) a better understanding of the dynamics of our planet as reflected in the atmosphere, the oceans, on the land, and in space.

1.4 Modern Satellite Era

Twenty-five years after the first environmental satellites, the scientific roles changed. Kidder and VonderHaar emphasized providing satellite-derived "operational products" to users over the research or experimental products. The community of users had expanded greatly thanks to a plethora of satellite-based products and services that provided capabilities which had become routinely used.

Today, approximately 45 years after the first ESSA satellites, one can see animating loops of satellite images routinely on the television weather broadcasts. Users can obtain specialized satellite-derived products that display the cloud patterns, vegetation indices, sea surface temperatures, cloud track winds, snow cover, precipitation, and over 450 other specialized satellite-based products that help decision makers mitigate the impacts of the weather and climate on the economy. Users can obtain these satellite products freely from the National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite Data and Information Service (NESDIS), and other international centers around the globe. Near real-time updates about the status of instruments used by NOAA operationally can be found at http://www.star.nesdis.noaa.gov/icvs/.

The modern satellite and environmental scientists are becoming specialists in particular niche areas like winds, precipitation, vegetation, crop yields, drought identification, satellite data assimilation into the forecast models, and satellite calibration. As the satellite capabilities advanced, ensuring the stability of the instruments and tracking their individual calibration contributed to the higher-fidelity satellite products developed by the mid-1990s. Today, the problem of satellite calibration continues to evolve and has become more complex. It involves not only the United States constellation of operational environmental satellites but the environmental satellite data from our international partner's satellites as well as the National Aeronautics and Space Administration's (NASA) environmental research satellites. Satellite calibration has grown into a specialized field where the calibration is no longer ensuring the accuracy of individual satellite instruments but a calibrated constellation of satellites and their instruments. To support our understanding of climate, instrument stability and cross-satellite calibration have become essential components for developing products capable of supporting climate services including monitoring climate trends. Accurate calibration is required to meet the needs of today's users, and access to this more accurate data has expanded the user community to include climate scientists. To support new requirements for more tailored products and services, an international Global Space-based Inter-Calibration System (GSICS) working group coordinates the activities of participating nations to improve the overall calibration of all the satellites in the international constellation. The GSICS Working Group was established in 2005 by the WMO and the Coordinating Group for Meteorological Satellites (CGMS) for the purpose of monitoring, improving, and harmonizing the quality of observations from operational weather and environmental satellites of the Global Observing System (GOS). The goal is to provide consistent accuracy among space-based observations worldwide for climate monitoring and weather forecasting. (Information about the US GSICS Coordination Center and its international role was derived from http://www.star.nesdis.noaa.gov/smcd/GCC/index.php and http://gsics.wmo.int/).

1.5 Using Satellite Data to Understand Climate

With the intercalibrated satellite data as the global foundation data source, an improved understanding of the environment can be derived from the information. Understanding the movement of water in the Earth system is important for many applications of satellite data. Passive microwave observations and the products derived from them are routinely available and widely used in meteorological analyses and forecasting applications requiring rainfall, total precipitable water (TPW), and snowfall rate products, for example. These measurements and products form the foundation for initializing satellite and climate models. Ferraro et al. (2010) provides a summary of example applications within NOAA. However, simply generating satellite-based products is not sufficient. For climate purposes, the measurements must be stable and consistent across the period of the observations. For snow and snow cover, Romanov (2011) shows how the tools developed for monitoring global snow cover could be used to support agricultural applications with specific application in Ukraine to assess crop yield impacts.

To address the needs of the climate community, improved calibration is the essential stepping stone. Intercalibration techniques were the first step and compared a reference satellite instrument with another satellite instrument. In Yang et al. (2011), intercalibration was accomplished between the Defense Meteorological Satellite Program Special Sensor Microwave Imagers (SSM/I) on F13 and F15 and the Tropical Rainfall Monitoring Mission (TRMM). The reduced biases for total precipitable water (TPW) products were significant. Intersensor TPW biases were reduced by 75% over the global ocean and 20% over the tropical ocean. In addition, intersensor calibration reduced biases by 20.6, 15.7, and 6.5% for oceanic, land, and global precipitation, respectively (Yang et al. 2011). The removal of biases between measuring systems is extremely important for assessing accurate climate trends and establishing measurement uncertainties.

Global climate change signals as small as a few percent per decade critically depend on accurately calibrated level 1B (L1B) data and the derived Fundamental Climate Data Records (FCDRs). Detecting small climate changes over decades is a major challenge and also impacts the retrieval of geophysical parameters from satellite observations. Without dependable FCDRs and their derivative Thematic Climate Data Records (TCDRs), the trends calculated from the measurements will be questioned. Cao et al. (2008) analyzed the consistency of calibrated reflectance from the operational L1B data between AVHRR on NOAA-16 and NOAA-17 and between NOAA-16/AVHRR and Aqua/MODIS, based on the recent Simultaneous Nadir Overpass (SNO) observation time series. The SNO approach advanced the science of satellite calibration to a higher level of accuracy and reliability and now includes the intercalibration between polar and geostationary measurements. Even so, the measurement uncertainty is still too high relative to the trends being monitored. As a consequence, a more stable calibration source has been sought: the Moon. The Moon is thought to be a reliable and stable calibration reference for studying climate change from satellites (Cao et al. 2009). However, having a quality FCDR does not guarantee the same or equivalent quality TCDR or derived trend.

To calculate confident trends, Zou et al. (2009) developed a calibrated data set based on the SNO approach for the Microwave Sounding Units (MSU) on NOAA satellites 10 through 14 over the period from 1987 to 2006. This intercalibrated data set reduced intersatellite biases by an order of magnitude compared to prelaunch calibration and resulted in a well-merged time series for the MSU channels 2, 3, and 4, which represent the deep layer temperature of the mid-troposphere (T2), tropopause (T3), and the lower stratosphere (T4). From Zou et al.'s (2009) data set, the trend patterns revealed the tropical mid-troposphere warmed at a rate of 0.28 $\pm$ 0.19 K per decade, while the Arctic atmosphere warmed two to three times faster than the global average. Even with this improved trend calculation, there is appreciable regional variability not demonstrated in this single number.

Liu and Weng (2009) also reported findings about the warming trend in the troposphere and the cooling trend in the stratosphere. However, Liu and Weng's (2009) analysis presents evidence that the lower stratosphere has warmed slightly since 1996 and the warming trend in the lower stratosphere may be related to a possible recovery of stratospheric ozone concentration. This points out that even with highly calibrated data, the debate over climate trends will likely change from data quality to one of improving our understanding of the dynamic effects. In this regard, Qin et al. (2012) analyzed MSU brightness temperatures to estimate the global climate trend in the troposphere and stratosphere using a new adaptive and temporally local data analysis method – Ensemble Empirical Mode Decomposition (EEMD). Using EEMD, a nonstationary time series is decomposed into a sequence of amplitude-frequency-modulated oscillatory components and a time-varying trend. The data from the NOAA-15 satellite over the time period from October 26, 1998 to August 7, 2010 shows that most trends derived from microwave channels are nonlinear in the Northern Hemisphere with a few channel exceptions. Although the decadal trend variation of the global average brightness temperature is no more than 0.2 K, the regional decadal trend variation could be different by plus or minus 3 K in the high latitudes and over high terrain.

While the calibration is improving for the core measurements, Cao et al. (2009) pointed out there are still significant uncertainties in determining the long-term climate trends using indices such as the Normalized Difference Vegetation Index (NDVI). This is partly due to the lack of stability in measurements required for climate change detection and partly due to the nonphysical derivation of the NDVI from measured radiances. Using calibrated AVHRR (Advanced Very High Resolution Radiometer) data from 1982 to 2007, complex trends in both the growing season amplitude and seasonally integrated vegetation greenness in southwestern North America can be observed. Zhang et al. (2010) show greenness measurements from 1982 to 2007 with an increasing trend in grasslands but a decreasing trend in shrublands. Also, vegetation growth appears to be a function of both the rainfall amount and the dry season length. The average global temperature over the past 100 years increased 0.74°C according to the 2007 Intergovernmental Panel on Climate Change Report. The period after 2000 was the warmest and includes the two warmest years (2007 and 2010) since the 1880s. A warmer world is expected to have tendencies toward higher temperature variability increasing the risk of summer droughts, which should affect larger areas, last longer, be more intense and produce more devastating impacts on the environment and economy. Due to data sparse ground observing stations, the assessment of agricultural impacts has been performed using satellite data. Drought affects the largest number of people in the world and has the largest economic impacts. The Vegetation Health Index has both a temperature and moisture component to distinguish the effects of the dominant variables (temperature and moisture/rainfall) for a particular region. Using the new indices, drought intensity and the area covered appear to be increasing as the temperature warms (Kogan et al. 2013). During the most recent decade, the global drought analysis indicates that 17–35% of the world experienced droughts from moderate to exceptional intensity, 7–15% severe to exceptional, and 2–6% the most exceptional droughts, an increase over earlier periods. Two droughts, 2010 in Russia and 2011 in the USA, stand out by their intensity, affected area, and substantial economic consequences (Kogan et al. 2013).

Climate products will continue to evolve with time. They will incorporate a greater variety of both satellite and in situ data. The combined use of the most modern measurements to understand current trends while leveraging our knowledge and understanding of the older in situ observations combined with modeled physics to allow an improved assessment of past climate changes is the future trend. An example of this type of project is the monthly reconstruction of precipitation project (Smith et al. 2010) which covers 1900 until the present. This reconstruction attempts to resolve interannual and longer time scales as well as spatial scales larger than 5° over the entire globe using both direct and indirect correlations. A key advantage for this type reconstruction is that it evaluates global precipitation variations for periods much longer than the satellite period of record, which begins in 1979 for routine use in NOAA operational models. In the future, the multisource fusion of the in situ observations with remotely sensed measurements and detailed model physics will allow the investigation of climate change to a level well beyond today's capability. However, the unfolding debate over whether the model physics is accurate will become the central scientific debate as the observations become more reliable with lower uncertainties through better calibration. Since models have many physical pathways with differing and complex physics, it will take a substantial period of time to assess which model physics components should be used. As the environmental research community successfully achieves their goals by improving the satellite data and its applications, the climate trends will not only be a debate about the observations but also the model-dependent physics used to facilitate understanding the climate as well. The question of climate trends will shift in the level of detail along with our understanding of the climate.

1.6 Book Overview

With the goal of adding an incremental improvement to our climate understanding, the chapters in this text have been grouped into the following four areas:

1.6.1 Part I Overview of Satellite-Based Measurements and Applications

This section addresses the vitally important calibration of satellite instruments and their data since accurate calibration is the key to high-quality climate products and services. With high-quality calibration, the data can be used to support climate change studies and large-scale atmospheric trends and improve our understanding of the forcings that drive the global atmospheric systems. As one looks to the future, the development of new instruments and their potential value to society need to be addressed. Calibration will be essential for using the satellite observations effectively.

1.6.2 Part II Atmospheric and Climate Applications

Precipitation and temperature are two very important measurements for understanding how our climate will change and how it will affect different regions. Using the microwave and precipitation measurements, a set of papers addresses global precipitation monitoring, the development of a historical precipitation record, and suitable methods for developing atmospheric temperature climate data records for better monitoring climate trends.

1.6.3 Part III Hydrological and Cryospheric Applications

The movement of water and variations in the ice caps are critical to understanding how our planet is changing. Given the dramatic decline in the Northern Hemisphere ice extent over the last decade, it is important to understand changes in the Arctic. With global warming as a contributor to the declining ice extent, it may also impact the intensity of hurricanes and the amount of tropical rainfall. Changes in the sea surface temperatures influence the development of hurricanes and evaporation and precipitation patterns around the globe. These important topics are covered in this section recognizing their potential for significant impacts globally and on coastal communities.

1.6.4 Part IV Land Surface and Ecological Applications

With changes in global temperature and precipitation as key drivers, their impacts are investigated using satellite data to develop products and analyses for monitoring climate trends. The impacts of temperature and precipitation on vegetation growth, health, and trends will be paramount. As temperatures increase, a global migration of plants, animals, and sea creatures is expected. A relatively recent ecological related development is the pioneering work to detect sentinel species migration and change from satellites.

This suite of chapters discusses key topics and findings that those interested in satellite remote sensing will find appealing. The chapters touch on the most pressing problem areas for helping to make effective decisions about sustaining our environment and mitigating the consequences of climate change.

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