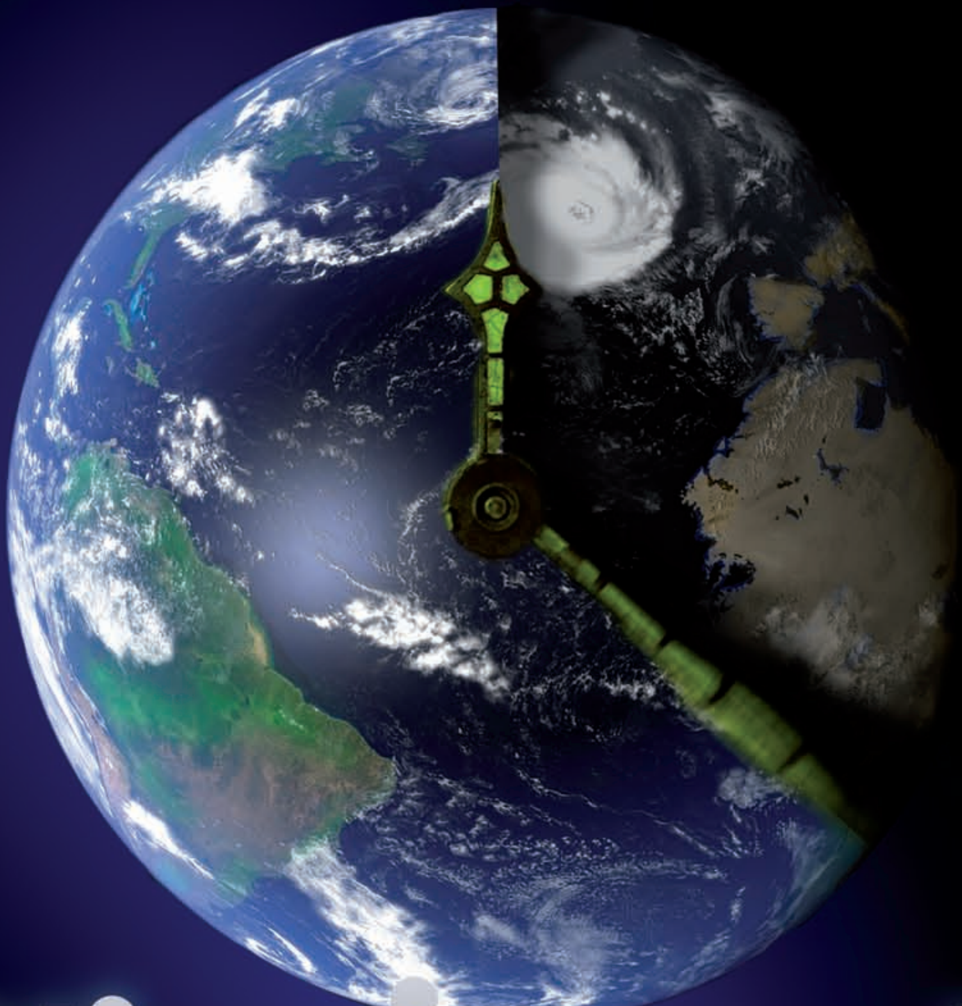

Climate LINKS

A Terrestrial Data Collection Network Complementing Satellite Observations

Final Report

Climate Links

Masters 2009

International Space University

A terrestrial data collection network complementing satellite observations

Final Report

International Space University

Masters Program 2009

The cover was designed by Diego Urbina, with input from the entire team. The graphics are intended as a visual representation of a changing Earth, as the effects of climate change become progressively more evident (drought, hurricanes, sea level rise), urging us as humankind to study this phenomenon and act. Ground, cloud, sea, and topographic textures of 3D model by NASA. Hurricane Katrina image by ESA.

The Executive Summary and the Final Report may be found on the ISU web site at http://www.isunet.edu in the "ISU Publications/Student Reports" section. Paper copies of the Executive Summary and the Final Report may also be requested, while supplies last, from:

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ABSTRACT

The ISU Masters 2009 Team Project, Climate Links: A Terrestrial Climate Data Collection Network Complementing Satellite Observations, pursues the following:

To design an integrated climate data collection, management, and distribution system featuring *in-situ* data collection complementary to satellite data collection.

The increase in the number of satellites dedicated to studying climate variables and the establishment of international programs such as GEOSS clearly show that space infrastructure plays a key role in understanding the mechanisms and effects of climate change. Although increasing amounts of climate data are being collected from space, there remains a lack of *in-situ* data collection to correlate and validate the satellite-collected data. The reason for this deficiency is that traditional methods of terrestrial data collection are often expensive and time consuming. There is also a lack in knowledge of the existence of such data by the space community.

This project envisions a comprehensive system of sensory devices for proficient users in the scientific community and non-specialized users in the public to address the above-mentioned shortcomings. The main focus of the report is to establish requirements for a pilot study in Nigeria using stationary data collection boxes (the 'GreenBox') for the systematic collection of precise and accurate data of ten essential climate variables. This integrated system includes all components required for collection, management, and distribution of the sensory data to appropriate users such as scientists and the general public. This report presents recommendations for the system architecture, implementation plan, social and political impacts, and legal consideration of such an endeavor during the pilot project in Nigeria.

FACULTY PREFACE

Mankind is now increasing its presence into a vast, hostile, and unknown universe. On the other hand, Mother Earth seems to be seriously threatened by our own actions, and this certainly limits us from embarking on a great cosmic voyage.

This year, ISU's Masters Candidates were offered a choice of two team projects: "Space and Security" and "Space Solution to Climate Change." It has been our honor to be involved with the latter project, which is composed of 26 courageous students with diverse backgrounds, skills, nationalities, and cultures. They have devoted much time and energy to the profoundly important, contemporary topic of climate change. This report is the fruit of their labors and is supplemented by an Executive Summary. They also presented and defended their research at ISU's Central Campus on May 14, 2009.

According to ISU's well-established practice, our Masters students receive only a minor level of supervision from the Faculty. Hence, a high level of self-management and independence is expected. In the case of this TP, the members quickly formed a democratic management style to accommodate all members' contributions.

It should be noted that the initial title of this team, "Space Solutions to Climate Change," alludes to an extremely broad topic of investigation. Hence, in the first part of this project, the team undertook a comprehensive literature review which was delivered to the faculty in December, 2008. Since then, they have greatly narrowed their investigation by identifying an original, useful, and interdisciplinary niche. The niche in question is the "Climate Links" project, which is presented in this report. In the midst of complicated and difficult climate change problems and issues, they have attempted to construct a practical data-gathering system which coordinates with space technologies.

The idea of the Climate Links concept resulted from the identification of gaps in contemporary climate change research. The gaps, considered by the team to be very important for better climate change understanding, are primarily a lack of data about certain aspects of climate change and insufficient public involvement and outreach. The Climate Links concept is trying to fill this gap by a proposed 'open' system that provides more data for scientists, and encourages public involvement.

We sincerely hope that this report gives its readers some new insights into tackling this critical problem on our planet. We also hope that this work will inspire some members of this team to continue climate change research upon graduation from ISU. Can you think of anything more important for humanity than to secure our future?

Yoshiki Morino
Ondrej Doule

On behalf of ISU's Resident Faculty and TAs

AUTHOR PREFACE

"Climate change can bring us together, if we have the wisdom to prevent it from driving us apart."
Margaret Becket, 2007
UN Security Council

From melting ice sheets to erratic weather patterns, it has become quite clear that climate change is happening *now*. In recent years, humanity has begun the arduous task of addressing the issue of climate change, either by attempting to mitigate it or preparing to adapt to its effects. However, whether we choose to mitigate or adapt, there remains a desperate need to better understand and predict Earth's climate.

The task of monitoring and modeling the Earth's climate is a demanding undertaking, requiring measurements from various platforms spanning the media of land, ocean, atmosphere, and space. In particular, it is vital that these platforms work together if they are to produce data needed for the precise global climate models that predict the effects of climate change. Additionally, further public involvement in the solution to climate change is needed.

In response to these gaps, the Climate Links team has proposed a system aimed at cross-correlating ground- and space-based data in order to foster more accurate climate models. At the same time, this will increase public awareness of, and participation in, the space industry's contributions to climate change. We hope that this report presents the beginnings of a successful project to aid humanity's understanding of climate change, and also stimulates awareness and support of the space industry's involvement so that future generations may reap the benefits.

The Climate Links Team

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ACRONYMS

%	percent
µm	micrometer
µA	microAmp
µV	microVolt
°	Degree
A	
AAAS	American Association for the Advancement of Science
ACDS	Attitude Control and Determination Systems
ACIM	Alternating Current Induction Motor
AFRL	Air Force Research Laboratory
AGS	Alternating Gradient Synchrotron
A-h	Amp-hour
AIR	Area's Immediate Reading
AIRS	Atmospheric Infrared Sounder
AMDAR	Aircraft Meteorological Data Relay
ATV	Automated Transfer Vehicle
AVHRR	Advanced Very High Resolution Radiometer
AWOS	Automatic Weather Observing System
B	
BCD	Basic Configurations Documents
BIS	British Interplanetary Society
BNRCC	Building Nigeria's Response to Climate Change
BPS	Biomass Production Chamber
BSRN	Baseline Surface Radiation Network
C	
CCC	California Corporations Code
CDMA	Code Division Multiple Access
CENS	Center for Embedded Networked Sensing
CEOS IDN	Committee on Earth Observation Satellites' International Directory Network
CES	Committee on Earth Studies
CFCs	Chlorofluorocarbons
cm	centimeter
CMDB	Configuration Management Database
CMS	Call Management System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COADS	Comprehensive Ocean-Atmosphere Data Set
COIN	Climate Outreach Information Network
COTS	Commercial Off The Shelf
CPSP	Communication Priority Sequence Protocol
CPU	Central Processing Unit

D

DC	Direct Current
DOPC	Direct On PC

E

ECV	Essential Climate Variable
EIA	Energy Information Administration
Envisat	Environmental Satellite
EO	Earth Observation
EPA	Environmental Protection Agency
ESA	European Space Agency

F

fAPAR	fraction of Absorbed Photosynthetically Active Radiation
FCC	Federal Communications Commission
FTP	File Transfer Protocol
FTS	Fourier Transform Spectroscopy

G

GAW	Global Atmosphere Watch
GC	Gas Chromotography
GCM	Global Climate Models
GCMD	Global Change Master Directory
GCOS	Global Climate Observation Systems
GCP	Ground Control Point
GCRIO	(US) Global Change Research Information Office
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHG	Greenhouse Gas
GIS	Geographical Information System
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System
GOS	Global Observing System
GOSAT	Greenhouse gases Observing Satellite
GOSIC	Global Observing System Information Centre
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPSRO	Global Positioning System Radio Occulation
GSM	Global System for Mobile communications
GSN	GCOS Surface Network
GTOS	Global Terrestrial Observing System

H

h	height
H_2O	Water
hPa	Pressure in hectoPascals
HST	Hubble Space Telescope
HVAC	Heating, Ventilating and Air Conditioning

I

ICT	Information, Communication, and Technology

ID	Identification
IDN-GCOS	CEOS IDN - Portal for Global Climate Observing System
IGO	Intergovernmental Organization
I/O	Input / Output
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual Property Rights
IRS	Internal Revenue Service
IT	Information Technology
ITU	International Telecommunication Union

J

JAXA	Japanese Aerospace Exploration Agency

K

kB	kilobyte
kg	kilogram
km	kilometer

L

l	length
LAI	Leaf Area Index
LAN	Local Area Network
LEED	Leadership in Energy and Environmental Design
LEO	Low Earth Orbit

M

m	meter
m/s	meters per second
m^2	Square meter
mA	milliAmp
MEMS	Micro Electro-Mechanical Systems
min	minute
mm	millimeter
MODIS	Moderate Resolution Imaging Spectroradiometer

N

N_2O	Nitrous Oxide
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
NASRDA	National Space Research and Development Agency
NCDC	National Climatic Data Center
NigeriaCAN	Nigeria Climate Action Network
NIMET	Nigerian Meteorological Agency
nm	nanometer
NOAA	National Oceanic and Atmospheric Administration
NOAA AVHRR	National Oceanic and Atmospheric Administrations Advanced Very High Resolution Radiometer
NORAD	North American Aerospace Defense Command
NPO	Non-Profit Organization
NRDC	National Research Defense Council
NSF	Nation Science Foundation
N-SMARTS	Networked Suite of Mobile Atmospheric Real-Time Sensors

NSS	National Space Society
O	
OIA	Office of Integrative Activities
OS	Operating System
P	
PC	Personal computer
PDA	Personal Digital Assistant
ppb	parts per billion
ppm	parts per million
PPP	Public Private Partnership
PV	Photo-Voltaic
Q	
QA	Quality Assurance
R	
REMAP	Research in Engineering, Media and Performance
RMSE	Root Mean Square Error
RS	Remote Sensing
RSS	Remote Sensing Systems
S	
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communication
SMC	Service Management Center
SMS	Short Message Service
SOHO	Solar and Heliospheric Observatory
SPOT	Earth observation satellite (Satellite Pour l'Observation de la Terre)
SSPS	Space Solar Power Satellites
SST	Sea Surface Temperature
SWOT	Strength Weakness Opportunity Threat
T	
TLE	Two Line Element
TM	(Landsat) Thematic Mapper
U	
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UPS	Uninterruptible Power Supply
US	United States
USD	United States Dollar(s)
USHCN	United States Climatology Network
V	
VOS	Volunteer Observing Ships
VOSClim	Volunteer Observing Ships Climatology
W	
W	Watt
w	width
W-h	Watt-hour
WIGOS	WMO Integrated Global Observing Systems

WLAN	Wireless Local Area network
WMO	World Meteorological Organization
WRMC	World Radiation Monitoring Center
X	
XHTML	Extensible Hypertext Markup Language
Y	
Z	

GLOSSARY

Term	**Definition**
Associated Data	Data collected by the device such as GNSS coordinates, time, date and sensor health readings.
Satellite Data Calibration	Finding confidence interval for satellite measurements, and redefining the satellite instrument base-line.
Climate	The average weather conditions of a particular place over a long period of time, usually at least 30 years.
Climate Change	Change in climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.
Climate Links	A terrestrial climate data collection network complementing satellite observations.
Climate Model	A quantitative method to simulate the interactions of the atmosphere, oceans, land surface, and ice.
Collection Devices	The hardware and software used to acquire measurements.
Complementary Data	ECV data not observed by satellites but that can be measured *in-situ*.
'green'	Environmentally friendly.
GreenBox	Scientific data collection device.
GreenPhone	Cellular phone data collection device.
In-situ	In a place on the ground.
Mitigation	A need for increased public participation, such that ordinary people feel connected to the problem and motivated to take action in solving it.
Mobile Platforms	Ships, trains, transport trucks, *etc*.
Monitoring	A need for coordination between terrestrial and space based data collection.
Participatory Sensing	The collection of scientific data by any concerned individual regardless of professional qualification.
Pilot Project	Phase 1 of the rollout plan of Climate Links, in Nigeria.
Processed Data	Data after validation through processing at the data center.
Product	Data and information available from Climate Links.
Prompting	Actively requesting the performance of a task.
Raw Data	Data retrieved from the device.
Rollout Plan	The method of carrying out the development of the project.
Spatial Resolution	The number of data measurements taken in a given area.
Synchronization	To take *in-situ* measurement at the same time and location as satellite observation.
Temporal Resolution	Time interval between data measurement events.
Validate	To make certain that the satellite sensors/instruments are operating properly.
Weather	The short-term state of the atmosphere with respect to variables such as temperature, humidity, cloud cover, precipitation, and wind, at a specific place and time.

1 INTRODUCTION

What is climate change? Who or what is causing it? How does it affect the global environment and what are its impacts? In the following sections of this chapter, these questions are summarized in an effort to set the context of an even more important question: What are the possible solutions?

Some current solutions are presented, with an emphasis placed on climate-related space activities. The chapter closes with a brief introduction to a potential climate change solution, Climate Links, which is the main focus of this report.

1.1 The Climate Change Problem

Various definitions of climate change exist and depend on who provides them. It is also worth making the distinction between the terms 'weather' and 'climate.' Weather is the short-term state of the atmosphere in a specific place with respect to variables such as temperature, humidity, cloud cover, precipitation, and wind. Climate, on the other hand, refers to the average weather conditions of a particular place over a long period of time, usually at least 30 years (Carter, 2007). In light of this, climate change can thus be referred to as a variation in the average weather conditions on a global scale. According to the United Nations Framework Convention on Climate Change (UNFCCC), climate change is "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (UN, 1992). This is the definition that has been adopted for this report.

The Earth's climate depends on multiple interconnected systems: the atmosphere, oceans, land, and the biosphere. In order to acquire a good understanding of climate change, the interaction and feedback mechanisms between these systems must be understood (Lucarini, 2002). Throughout the geologic history of the Earth, the global climate has cycled many times through ice ages and warming periods, with some random variations. Due to the interconnectivity of the systems listed above, it is difficult to determine the cause for each climate change event. The recent changes in climate are seemingly easier to interpret because one climate variable, carbon dioxide (CO_2), is rising faster than the others. Figure 1-1 shows past trends of atmospheric CO_2 and temperature from Antarctic ice cores over the past 400 thousand years of the Earth's history, highlighting a sharp increase in CO_2 concentrations since 1800 *AD*.

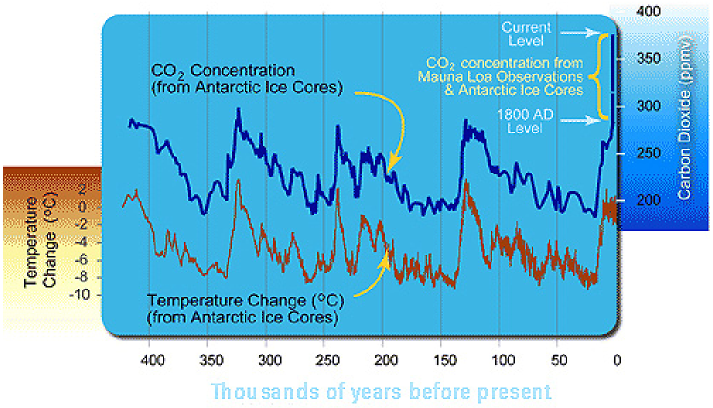

Figure 1-1: CO_2 concentration and temperature readings from the last 400,000 years (Ernst, 2009)

Changes in atmospheric concentrations greenhouse gases (GHGs) such as CO_2 are one of the drivers of climate change. Other GHGs present in the atmosphere are water vapor, methane, nitrous oxide, ozone and various chlorofluorocarbons (CFCs). These GHGs trap thermal infrared radiation in the atmosphere. As a consequence, when GHG concentrations increase over time, the average surface temperature of the Earth increases. This is known as the 'greenhouse effect.'

Changes occurring to the Earth's environment are already becoming evident. Some of these changes include rising global sea levels, melting ice sheets and glaciers, increase in the average global temperature, changes in precipitation, variations in evaporation patterns over the oceans, and a rise in intense tropical cyclone activity in the North Atlantic (NOAA, 2009). *IPCC* (2007) estimated that the annual global surface temperature rose by 0.74 ± 0.18 °C from 1905 to 2005 *AD*. As ocean temperature rises, the solubility and uptake of CO_2 decreases. On short time scales, warming may actually increase CO_2 uptake on land, but the long-term effects are not clear. Arguably, the consequences of such climate changes are not yet fully known nor quantified.

Scientists argue that both natural phenomena and human activity cause climate change. Natural factors such as the Earth's axial tilt, variability of solar activity, and cycles of glacial advance and retreat are responsible for climate variability seen in the Earth's history. Human activities, such as clearing rainforests, depleting freshwater resources, burning fossil fuels, and dramatically altering coastal habitats and marine fisheries have all been cited as factors that accelerate climate change. Nagendra *et al.* (2004) reported that anthropogenic factors in land use and cover are increasingly being recognized as serious contributors influencing global climate change.

1.2 The Impact of Climate Change on the Earth

Understanding the scope of changes made to the environment by climate change is only the beginning. This is because such transformations disturb the balance of Earth's systems, in turn leading to further changes. Climate change, therefore, affects ecosystems and biodiversity, human health and social development, business and economics, and political and technological environments.

1.2.1 Biodiversity and the Ecosystem

One area of deep concern is the possible extinction of species due to climate change. Nogues-Bravo *et al.* (2008) cited the extinction of the Woolly Mammoth as a demonstration of how climate change combined with anthropogenic effects (*e.g.* hunters) can cause irreversible consequences. Climate cycles may also impact the migration patterns of living things, in turn leading to a loss of habitat and animal food security. These changes contribute to extinction and a loss in biodiversity in a variety of ecosystems (Figure 1-2). A decrease in global biodiversity would result in a loss of irreplaceable genetic information, leading to losses in medical, agricultural, and ecosystem adaptability resources (Lucier *et al.*, 2006).

Figure 1-2: Biodiversity in ocean coral reefs is threatened due to climate change (Bergman, 2006)

1.2.2 Humans and Society

While the effects of climate change are a global phenomenon, the problems that climate change causes to people are most evident in poorer regions. Many emerging nations do not have the resources to manage the environmental impacts of flooding, changing disease vectors, and varying precipitation patterns likely to come with climate change. By the end of this century, up to one-third of a billion people are expected to need relocation as a result of changing coastal regions, an additional 290 million could be exposed to malaria, and the breakdown of agricultural systems could leave up to 600 million people facing malnutrition (Abdullahi, 2009). In an equatorial country such as Nigeria, where a majority of its land cover is prone to drought, two-thirds of its population is reliant on rain-fed agriculture, and there is 800 km of oceanic coastline, the consequences of climate change could be dire (BNRCC, 2008a).

The depletion of water resources and breakdown of agricultural systems are likely to cause not only famine and malnutrition, but also political conflicts. Societal development could change and deteriorate in regions where the once-plentiful basic necessities of life consequently become scarce. The impact throughout the world will not be uniform, and some regional inhabitants may benefit from climate change, while others may experience only negative consequences (McBean, 2004).

Population shifts and migration due to changes in local climate could create many refugees. The concept of an 'environmental refugee' is being debated worldwide. This is primarily because refugees usually migrate for more than one reason; often due to a combination of economic, environmental, political, and social factors. Still, while it is recognized that mass migrations of people can themselves cause environmental damage, environmental changes are more often the cause of migration, rather than a consequence of it (Bogardi and Renaud, 2006).

1.2.3 Economics and Business

In recent years, global climate change has evolved from a scientific issue to one that presents a new set of challenges ranging from worldwide market failures to international policy disputes (Stern, 2006). Consequently, climate change has become a major concern not only for scientists, but also businessmen, economists, and politicians. In particular, climate change is now a primary issue for many companies as the business risks and opportunities it presents become clearer.

Businesses are continually facing stricter regulations on energy efficiencies, GHG emissions, building design standards, and waste disposal strategies. Such climate change policies inevitably favor certain businesses and industries, often changing the competitive landscape of a market. It has thus become necessary for companies to consider how GHG policies affect their business objectives, as well as to anticipate future regulations and be aware of the policy options beneficial to their own business strategy (Hoffman, 2006).

For decades, companies worldwide have implemented corporate responsibility programs. Responsibility, in this context, means that companies would operate their business in a way that benefits society at large beyond any actual legal requirement (Vogel, 2005). Corporate leaders in a wide range of industries have realized that taking action concerning climate change is a responsible business decision, as it mitigates financial risks and presents competitive opportunities. This is due to increases in a combination of factors such as consumer demand for 'green' products, stakeholder demands for climate change strategies, and policy action by governments (Hoffman, 2006).

1.2.4 Politics

The Kyoto Protocol was established by the UNFCCC and entered into force in 1994. It was established to achieve: "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UN, 1992). Following the protocol, Oxfam International added that the subject of halving carbon emissions is a human rights issue. Rich countries are actually answerable for the lives and welfare of their relatively poorer counterparts, as the impacts of climate change threaten the rights of people to exist and grow (Romero, 2008). Furthermore, the emissions from coal, oil, and other fuels that are polluting the Earth's biosphere do not respect national borders. This calls for concerted efforts to work together towards formulating a common understanding to manage this issue. However, despite the convincing rhetoric by many, political will and industry lobbying are preventing useful progressive action. The Kyoto Protocol has yielded some positive results, but it is only a first step to creating a global framework for political cooperation to properly address this problem (Greenpeace UK, 2009).

1.2.5 Technology

The impact of climate change on technology development is mainly due to the changing business in, and creation of, climate-related markets. These market alterations produce both opportunities and risks, forcing businesses to anticipate and adapt to these changes if they wish to remain competitive. Climate change also creates new market opportunities for environmentally friendly technologies, as consumers and investors shift their interests towards 'green' solutions. Seizing these new opportunities has increased profits, and will become vital for the long-term survival of businesses (Lubber, 2003).

1.3 Responding to Climate Change

Responses to climate change can be divided into two categories: mitigation and monitoring. Monitoring allows for a greater understanding and predictability of climate change by tracking related environmental variables. Mitigation includes actions that attempt to decrease GHG concentrations, or to reverse or lessen the consequences of a change. Both methods are important, and are needed in combination to decrease anthropogenic causes of climate change.

1.3.1 Monitoring

Climate change monitoring allows for an understanding of the problem in order to predict changes and then find a solution. Monitoring is also used to propose, and determine the effectiveness of, mitigation strategies. The task of monitoring the global climate system is a massive undertaking achieved by utilizing resources on a variety of platforms. These platforms can be ground-, ocean-, atmosphere-, and space-based. All platform types, except for the last, measure variable data locally. This local data must be combined with other data measured elsewhere to achieve a collection of global readings. The advantage of utilizing Earth Observation (EO) satellites is that readings can be made using the same instrument to cover the entire planet.

The Global Climate Observing System (GCOS) has identified 44 Essential Climate Variables (ECVs) to be monitored by both *in-situ* and remote sensing systems. These variables are divided into the three categories shown in Appendix A and require different measurement platforms (GCOS, 2008).

When the cause of change is understood, observations should be followed up with action. The next step is to take measures to prevent further changes, and if possible, reverse negative effects.

1.3.2 Mitigation

Mitigation of climate change is a complex challenge due to a large number of factors that need to be considered. Moreover, mitigation measures have to be implemented on a global scale, which in turn complicates the issue through political, social, and economic concerns.

Large scale proposed ideas include:

- Increasing the Earth's albedo through atmospheric seeding
- Large scale carbon capture and sequestration
- Earth orbiting Sun shade systems

Some strategies supporting mitigation include:

- Intergovernmental protocols and treaties to reduce global GHG emissions
- Increased public awareness of the climate change problem
- Government incentives for the use and purchase of 'green' technologies
- Environmental education
- Promotion of sustainable development

Another challenge in climate change mitigation is that the effort made by current generations to fight the problem does not reap immediate benefit. For this reason, it is often difficult to convince decision makers to take action. Monitoring is therefore important so that trends and predictions can gain credibility in order to emphasize the importance of taking action today.

1.4 Space-based Responses to Climate Change

There are various space-based activities to monitor or mitigate climate change. These activities are meant to complement or improve upon terrestrial applications, or in some cases provide an action that cannot be achieved any other way.

1.4.1 Climate Monitoring from Space

The space industry collects a significant amount of ECV data using EO satellites. Some of the satellites carrying ECV sensors are illustrated in Figure 1-3 below.

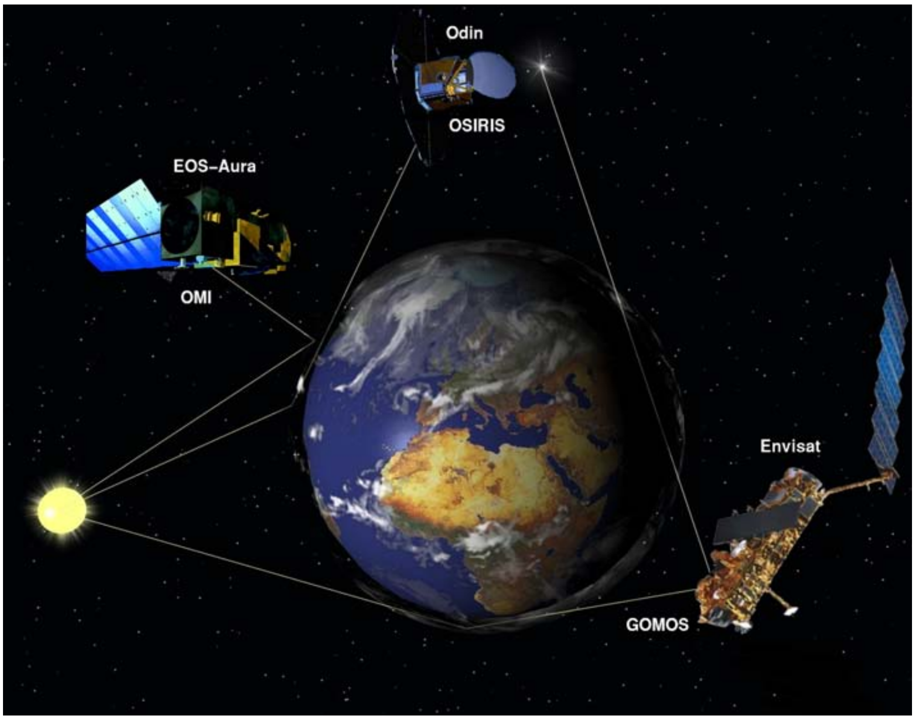

Figure 1-3: Earth observation satellites taking ECVs measurements from the space environment (Kyrola, 2006)

There are approximately 100 civilian EO satellites in orbit today that have at least one instrument capable of measuring climate-related variables. Envisat, Odin, EOS-Aura, and GOSAT are examples of EO satellites providing coverage of ECV data. There are other satellites measuring ECVs, such as the SOHO mission which collects valuable solar radiation data.

Of the 44 ECVs in Appendix A, 26 can be measured with satellite-based instruments. Three-hundred-twenty-six payloads have been identified that are, or will, monitor the ECVs shown in Figure 1-4.

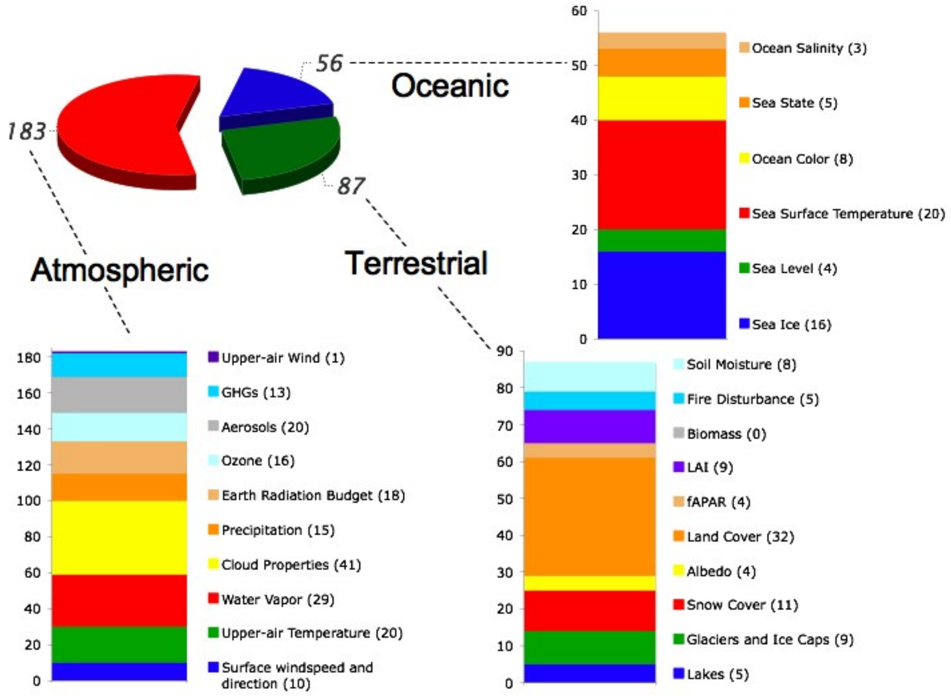

Figure 1-4: Distribution of satellite payloads measuring atmospheric, terrestrial, and oceanic ECVs (LAI: Leaf Area Index; fAPAR: fraction of Absorbed Photosynthetically Active Radiation)

One item to note in Figure 1-4 is the number of instruments listed for the measurement of biomass. While it is listed as '0', almost any EO satellite with a multi-spectral optical payload could measure this ECV. A complete list of the satellites and the ECV-monitoring instruments can be found in Appendix B.

High spatial coverage is the strength of satellite data. Measurements from a single instrument are available for a large area over a relatively short period of time. The main gaps identified in satellite measurements are low spatial resolution and infrequent re-visit time (Vaughan, 1994). These are important to validate and improve regional climate models. These gaps are being addressed by the use of ground networks, but they lack the high spatial coverage of satellite data. Thus, there is a need to complement data gathered by satellites through other means. As well, there are still 18 variables that are not measured by satellites.

An identified weakness in EO satellite climate data collection is a lack of *in-situ* data available to validate the findings. Despite an initial satellite sensor calibration, *in-situ* testing is still needed as both a confidence measure and way to find an adequate baseline. *In-situ* measurements add value in the confidence gained by independent data sets that reveal similar patterns and trends (Space Studies Board and National Research Council, 2000). These complementary data sets are needed to corroborate findings and are often used to check the validity of the sensors (Badarinath *et al.,* 2008). Complementary data sets do not necessarily measure the same variable as the satellite but rather, can also be highly coupled variables (Nevison, 2008). Temporal and spatial correlation of these data sets is needed, but heavily depends on the variable being measured. For example, data collected using both satellite and *in-situ* measurement of ozone must be done the same day, while data collected for aerosols is needed within the hour (Badarinath *et al.,* 2008).

High spatial and temporal resolutions are critical in many climate studies and are expected to become the source of error as climate models become more accurate (Space Studies Board and National Research Council, 2000). While it may seem that temporal resolution would not be a critical factor in the evolution of climate models this is not the case. The short variations in weather over a few days play a critical role in the long-term balances of energy, momentum, and water vapor in atmospheric climate systems. Of particular importance in these short-term weather variations are their usefulness in the validation of climate models (Trenberth, 1992). The combination of *in-situ* and satellite data, when input into the models, can make them more robust and accurate, adding both spatial coverage and resolution.

Finally, according to Alexander Los, the director of EKO instruments in Europe, a lack of communication between ground and space observation communities has also been determined as a gap that needs to be addressed (personal communication, April 24, 2009). For ground networks to truly be complementary to satellite networks, both groups would have to communicate amongst themselves and with scientists.

1.4.2 Space-based Mitigation Strategies

Several global scale solutions have been put forward to curb climate change using space technology. Among them are prospects of placing Space Solar Power Satellites (SSPS), and space-based sunshades.

The efficiency of solar panels is greatly enhanced in space, as there is no atmosphere attenuating incident radiation. Moreover, a satellite can be placed in an orbit such that it is view of the sun nearly constantly. With the development of wireless power transfer during the 1960s, collecting energy from space and beaming it down to Earth with a SSPS was first proposed by Peter Glaser in 1973 (Glaser, 1973). The setup costs were, and remain, prohibitive, however SSPS proposals have been reviewed at regular intervals by government panels and space agencies as technology evolves (NSSO, 2007) (Vaganov *et al.*, 2008).

Another space-based approach to mitigation is to place sunshades near the first Earth-Sun Lagrange point, L1, (Angel, 2006) or in Earth Orbit (National Academy of Sciences *et al.*, 1992) (Pearson *et al.*, 2006) to block up to 1.8 % of solar light in order to mitigate global warming. Again, due to the incredible implementation cost, such a technique is not feasible at present.

1.5 Finding a Solution

Based on the challenges stated previously, this report sets out to describe the Climate Links proposal; a high-level framework that serves both a monitoring and a mitigation need:

- **Monitoring**: A need for coordination between terrestrial and space-based data collection.
- **Mitigation**: A need for increased public participation, such that ordinary people feel connected to the problem, and motivated to take action in solving it.

The Climate Links system is a sensor network that complements satellite observations. In addition to this, the system is aimed at providing a means for communication and collaboration between the space community and *in-situ* field workers, climate scientists, and the public. The overall mission statement of the project is:

To design an integrated climate data collection, management, and distribution system featuring *in-situ* data collection complementary to satellite data.

This report, as outlined in Table 1-1, shows how the monitoring and mitigation needs can be innovatively addressed with the Climate Links system. The overall system architecture is examined in detail in the next chapter before moving on to the Nigeria pilot project in Chapters 3 through 6. The long term vision is revisited in Chapter 7 before concluding in Chapter 8.

Table 1-1: Summary of the Climate Links report structure

<table>
<tr><td>1. Introduction</td><td>The document begins by introducing the climate change problem and the context for offering space-related solutions.</td></tr>
<tr><td>2. System Overview</td><td>The Climate Links system is described along with its role in global climate monitoring and mitigation efforts.</td></tr>
<tr><td>3. System Implementation</td><td rowspan="4">A business approach and roll-out plan are proposed, beginning with a pilot project in Nigeria. This portion of the document develops the details of the pilot project including the proposed device, and data handling systems.</td></tr>
<tr><td>4. Data Collection Device</td></tr>
<tr><td>5. Data Management and Products</td></tr>
<tr><td>6. Facilitating the Pilot Project</td></tr>
<tr><td>7. Future Developments</td><td>Chapter 7 returns to the big picture and grand vision of the system and what will be included beyond the Nigerian pilot project.</td></tr>
<tr><td>8. Conclusion</td><td>The document concludes with a reminder of the purpose and value of the Climate Links system.</td></tr>
</table>

2 SYSTEM OVERVIEW

The proposed system has been designed to augment satellite Earth Observation (EO) data and to increase public awareness and participation as a method to combat climate change. This chapter describes the Climate Links system, its data collection and distribution components, how it satisfies the identified needs, and how it fits in with global efforts to monitor and mitigate climate change.

2.1 System Description

The Climate Links system adds value to satellite-based climate observations by introducing complementary data from a network of *in-situ* collection devices. The devices range from sophisticated, deployable, stationary, professional grade sensor packs, the GreenBox, to widely distributed, handheld devices, suitable for use by motivated citizens interested in 'participatory sensing,' the GreenPhone. In this context, participatory sensing refers to the collection of scientific data by any concerned individual regardless of professional qualification. Data collected by all the devices would be managed and processed in order to produce data useful for climate research scientists and public awareness initiatives.

2.1.1 Physical Architecture

The physical architecture of the Climate Links system consists of data collection devices, a data management center, and data product distribution channels. It is supported by ground- and space-based assets, which include ground communication infrastructure, the Global System for Mobile communications (GSM), EO satellites, global navigation satellites, the Global Navigation Satellite System (GNSS), and communication satellites.

This architecture would utilize existing infrastructure to efficiently implement appropriate data exchange to satisfy the system objectives. Figure 2-1 shows the hardware involved, the various space communications and the proposed devices, and the communication links to the centralized data management center.

The proposed collection devices include all of the hardware and software used to acquire measurements and link to the satellites and the data management system. The device subsets are the GreenBox, which would be available on multiple platforms as per Figure 2-1, and the GreenPhone. In the data management class, the acquired raw data would be processed in the data management center and be publicly available through a website, a user interface for acquisition and distribution. This website would allow users to upload their data directly from a GreenPhone as well as access basic maps and statistics related to the Climate Links system. Additionally, the public would be able to sign-up for 'green fact of the day' messages via the Short Message Service (SMS).

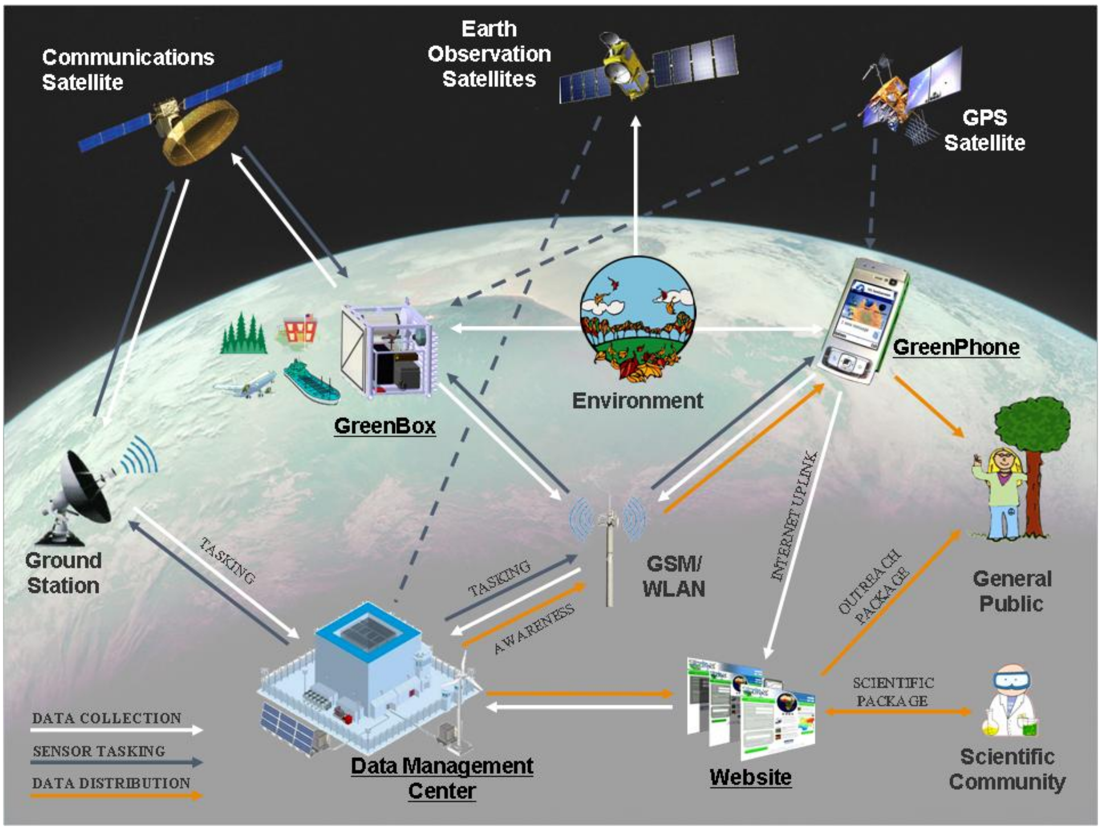

Figure 2-1: Climate Links system overview and communications

The Climate Links hardware elements can be divided into four classes: collection devices, data management system, space segment, and terrestrial communications infrastructure. These elements are listed along with their primary function in Table 2-1.

Table 2-1: High level Climate Links system elements

Class	Element	Primary Role(s)
Collection Devices	GreenBox GreenPhone	Scientific data acquisition Public involvement
Data Management System	Data management center Website	Data management Data distribution, awareness
Space Segment	Communications satellites EO satellites GNSS	Data communications Remote Sensing (RS) data acquisition Positioning
Terrestrial Communication Infrastructure	Ground Station GSM networks Internet	Data Communications

A significant space segment is necessary both as a data source in the form of EO satellites and GNSS, and as a communications link. The GNSS service will be provided in by the existing Global Positioning System (GPS), while the Thuraya network will provide satellite communications bandwidth. Existing terrestrial communications infrastructure provides the requisite connections between the data collection devices and the database through Wireless Local Area Network (WLAN), GSM networks, and the Internet.

2.1.2 Data Flow

The physical architecture of Climate Links, described in section 2.1.1, is the basis for the flow of data from the collection devices, through the data center, and finally to completed data products. Figure 2-2 illustrates these data flow paths.

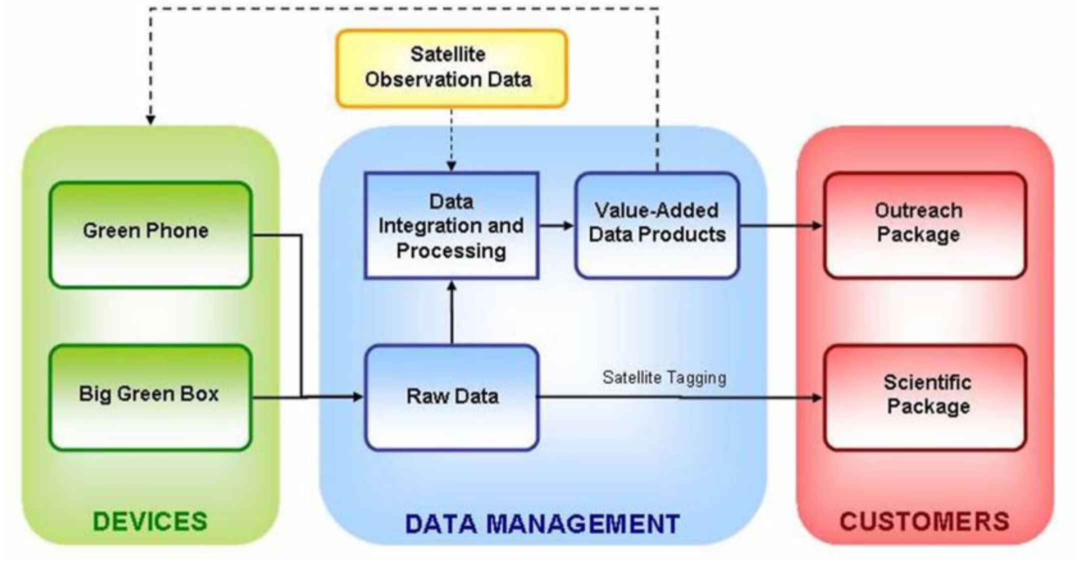

Figure 2-2: Climate Links data flow paths

As previously mentioned, the two classes of data collection devices would be the mobile GreenPhone and the autonomous GreenBox. The GreenPhone utilizes miniaturized sensors to collect data at the discretion of the user. This device is geared towards satisfying the public participatory goals of the system, but would also collect usable scientific data. The GreenBox is a mainly autonomous package of analytical grade sensors and communication equipment. This device is geared towards collecting precise, scientifically valuable data and it returns information to the data center from remote areas where mobile coverage is unavailable. Future iterations of the GreenBox could also be placed on different platforms including ships and transport trucks. The benefit of mobility is in the increased geographical coverage and fewer devices required to obtain that coverage.

Both devices collect scientifically valuable data and involve a degree of public awareness. Since each device addresses these needs to a different extent, the two are seen as complementary components. For both platforms, the data collection goals are the same: to take *in-situ* measurements that complement observations made by satellites. This may be done by synchronizing ground-based data collection with specific over-flying satellites, or by collecting data to fill gaps between satellite passes. All of the measurements taken by these devices are accumulated within the Climate Links database.

Some basic data reduction would be performed to ensure minimum quality standards, to make certain the data is tagged in time and space, and to ensure that, where appropriate, the relevant EO satellite is identified. The processed data could be used by satellite operators and research scientists to reduce data uncertainty and to validate climate models. The data may also be used to produce simplified statistics and information more suitable for public audiences. Such awareness oriented products would be processed by the Climate Links data center, and distributed via the website. Some of the data may also be distributed to GreenPhone users, giving feedback to participants.

2.2 Satisfying the Needs

The Climate Links system strives to create a comprehensive *in-situ* data collection service to improve available satellite data, to raise public awareness of climate change by increasing participation, and to improve public knowledge of the space sector's roll in addressing climate change. This section explores why these improvements are necessary and how this system can satisfy these needs. The overall effect is to improve the understanding of climate change.

2.2.1 Complementary Data Collection

The lack of appropriate *in-situ* measurements was identified as a weakness in remote sensing systems by the Committee on Earth Studies (Space Studies Board and National Research Council, 2000). Specifically, the measurement of short term evolution of greenhouse gases (GHG) is significantly enhanced by simultaneous satellite observations and ground based systems. In addition, *in-situ* data can be used to complement satellite-based observations by collecting data where and when satellites are unable to observe, improving the spatial and temporal continuity of climate datasets. Data products that combine synchronous satellite observations with *in-situ* data to produce enhanced datasets could be valuable to scientists and environmental organizations, particularly as a tool to improve climate models (Trenberth, 1992).

The 2006 Global Climate Observing System (GCOS)-107 report states that a composite system of satellite and *in-situ* measurements is needed in order to provide all the necessary observations of Essential Climate Variables (ECVs). Currently, there is no single technology that provides measurement of all the ECVs. Consequently, there is a need for the combination of various *in-situ* instruments on the ground with space-based remote sensing. Some ECVs depend on *in-situ* observations because measuring them with satellite-based instruments is not feasible (GCOS, 2006).

2.2.2 Public Involvement

In addition to supporting satellite observations, the Climate Links project promotes public awareness. One of the crucial factors limiting society's ability to address the challenges of climate change is the lack of public involvement. To a large extent, anthropogenic climate change can only be mitigated when people are motivated to change their behavior. While many people may be concerned about climate change, the problem is so vast and abstract that individuals may not feel they can make a difference (Few *et. Al.*, 2007).

Traditional public awareness campaigns tend to focus on sympathy by showing the effects of climate change on communities and wildlife in remote places such as the Arctic. Such campaigns may motivate some individuals, but since they fail to offer a direct way to help, the problem continues to be abstract, and the public remains largely removed from the issue. Moreover, the overwhelming number of these campaigns could inundate the public causing people to ignore climate change altogether (Few *et. al.,* 2007).

Awareness campaigns featuring adversely affected communities or ecosystems have proved limited in their effectiveness. People are looking for an opportunity to be involved in the solution. A powerful way to get them involved is to give them something tangible, such as a device that allows them to contribute to climate change studies. An alternative method to engage the public is to give them a way to become personally involved.

For individuals, a GreenPhone empowers them to make a direct contribution to climate change data collection. Friends, colleagues, and strangers may see these devices in use and become curious. People will see that 'ordinary' individuals can get involved in climate change monitoring and mitigation. Furthermore, companies and organizations could adopt a GreenBox to contribute to climate research by supporting the collection of important climate data.

2.2.3 Awareness of Space Solutions to Climate Change

In addition to raising climate change awareness and complementing satellite-based observations, the Climate Links system highlights the role space systems play in monitoring climate change. Promotion of the system would include a public website and text alerts on user requested climate information. Along with eventual widespread use of GreenPhones, the website will be a reminder that satellite observations are an important part of studying the climate. Using the GreenPhone will also be a way citizens can feel connected to the space industries contributions. The fact that the data collection is aimed at verifying and complementing satellite-based observations adds to the appeal, especially for space enthusiasts.

2.3 Role in Existing Climate Change Systems

It is important to understand how the Climate Links project fits into global climate monitoring efforts because the intention of Climate Links is that the data generated can be easily integrated with existing data distribution systems. This ensures that the generated data is up to current standards as well as maximize distribution to potential users.

There exist a large number of global programs with established data catalogues and proven distribution infrastructures. Some are well established, international efforts, already coordinating with the scientific user community to establish their specific needs. As a new service, the Climate Links system should integrate itself into these existing programs to accelerate the penetration of Climate Links data and services. The following sections discuss Climate Links' potential involvement with major global observing systems.

2.3.1 The Global Climate Observing System (GCOS)

During the 2002 World Summit on Sustainable Development there was a call to action to coordinate EO efforts to better understand climate change. In response, the Group on Earth Observation (GEO) was created to build a Global Observation System of Systems (GEOSS). The implementation of GEOSS is based on a ten year plan between 2005 and 2015 and is intended to benefit nine 'societal areas', one of which is climate change. The climate change subgroup of GEOSS was named GCOS, the Global Climate Observing System (GEO, 2008).

GCOS addresses the total climate system including: oceanic, hydrologic, cryospheric, atmospheric, and terrestrial, components. Components are grouped into sub systems and are characterized with the following acronyms:

- Global Ocean Observation System (GOOS)
- Global Observing System (GOS)
- Global Atmosphere Watch (GAW)
- Global Terrestrial Observing System (GTOS)

The interaction between GCOS and its various sub-systems within GEOSS is visualized inFigure 2-3. GCOS is designed as a comprehensive, long-term, user-driven structure to monitor climate systems, to assess the impacts of climate variability, and to improve the understanding of sub-systems interactions (GCOS, 2009).

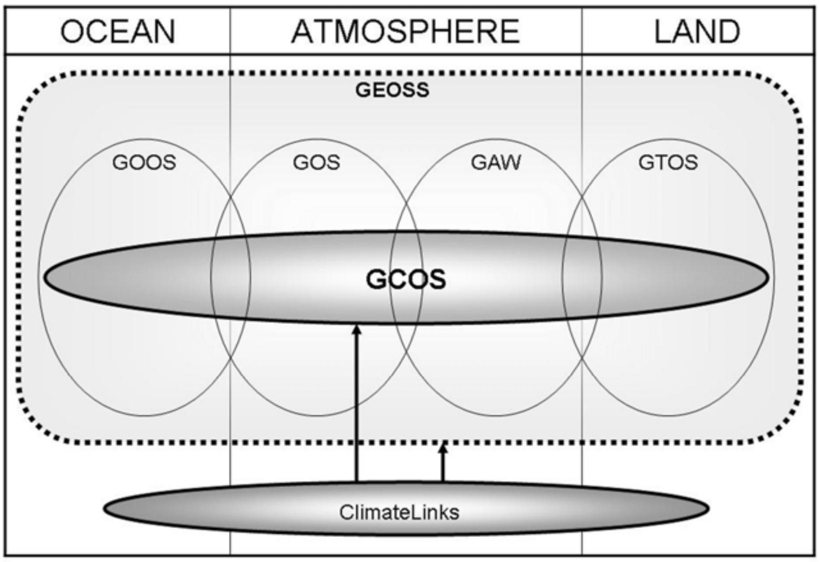

Figure 2-3: Climate Links system positioning within existing global observing systems

Climate Links can contribute to GCOS in two specific ways as depicted in Figure 2-3. First, the measurements can be fed directly into the GCOS observation network or directly into GCOS-affiliated climate models. In this role, all *in-situ* data is provided to GCOS, synchronized or otherwise, in order to increase the spatial and temporal resolution of the overall GCOS dataset. If the corresponding satellite data is available within the GCOS system, the two datasets can be linked in GCOS climate models or by scientific partners of GCOS (GEO, 2008).

A second option would be to feed climate data directly into GEOSS as shown in Figure 2-3. Since Climate Links collects *in-situ* measurements, it can augment and improve data from several sources currently feeding into GEOSS. In this role, Climate Links would provide data that can reduce uncertainties from satellite sources, as well as improve overall temporal and spatial resolution. Since GEOSS represents the unification of a large scientific community, it will be beneficial for Climate Links to register with the GEOSS Components and Services Registry, defined on the GEO webpage as: "…a formal listing and description of all the Earth observation systems, datasets, models, and other services and tools that together constitute the Global Earth Observation System of Systems" (GEO, 2008).

Similarly, Climate Links should be registered within the GEOSS Standards Registry, which contains individual systems' standards, protocols, and other specifications. This registry is concerned with standardizing the various systems within GEOSS so that they are interoperable and their information can be pooled and combined.

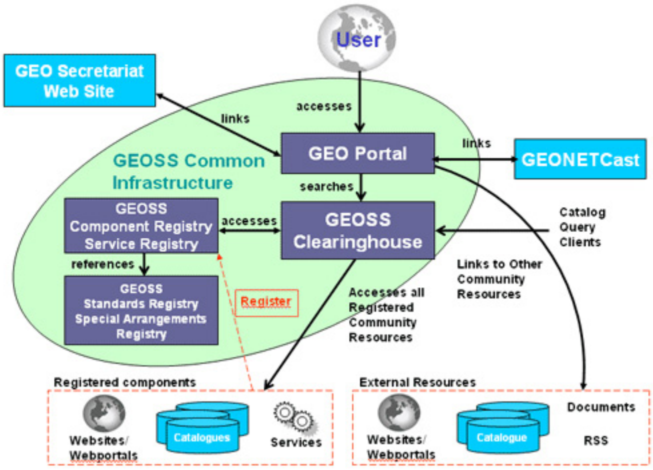

Figure 2-4: GEOSS common architecture
(GEO, 2008)

By registering in these directories and following GEOSS guidelines, Climate Links can join the GEOSS network, so that its datasets can be accessible through the GEOPortal Internet gateway and through the GEONETCast satellite telecommunications network. In Figure 2-4, the Registered Components and External Resources boxes indicate where this project would fit in the GEOSS architecture. Technically the project would remain distinct, but could be accessed through GEOSS catalogues.

2.3.2 Existing Data Distribution Channels

By integrating into GEOSS and GCOS, and providing Climate Links datasets to these communities, the distribution of the data can be simplified. Such existing data dissemination infrastructures can be used as per Figure 2-5, reaching a greater scientific audience.

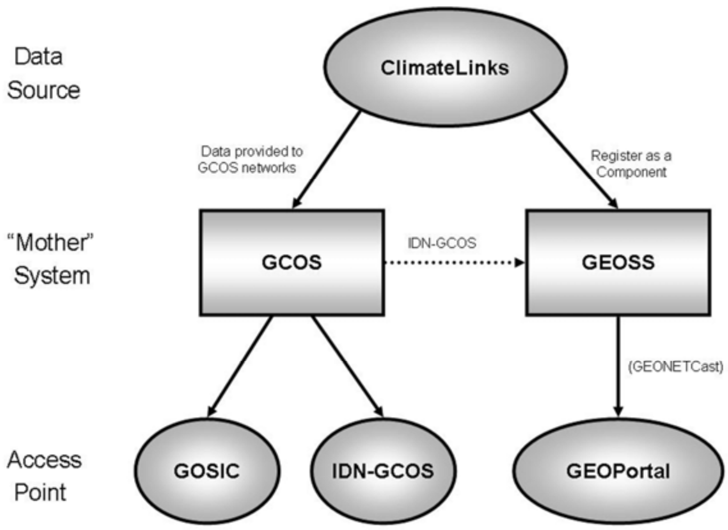

Figure 2-5: Data distribution channels provided by GEOSS and GCOS partnerships

The Global Observing System Information Center (GOSIC) is a web-based information center, hosted by NOAA, providing a single information gateway to the GCOS, GOOS, and GTOS networks. If Climate Links provides data to the GCOS observation network, its datasets and data products will be accessible through the GOSIC directories to a large community of climate scientists. Alternatively, GCOS datasets (and therefore Climate Links data) can be accessed through the Committee on Earth Observation Satellites' International Directory Network (CEOS IDN), specifically through the Portal for Global Climate Observing System (IDN-GCOS).

GEOPortal, shown in Figure 2-5, is designed to be an entry point where the various component systems of GEOSS can be accessed, along with their datasets and services. With Climate Links data available in this centralized database, marketing of the data products to the customer base (primarily the scientific community and governmental or environmental agencies) is improved. An investigation of GEOPortal shows that GCOS is registered in the GEOSS components registry, and therefore the GCOS datasets are available through the IDN-GCOS. This relationship is represented with the dashed arrow in Figure 2-5.

2.3.3 The Planetary Skin Project

Planetary Skin, a partnership between Cisco Systems and NASA, is a network of satellites, land sensors, and the Internet currently under development. It aims to create a unified measurement, reporting, and verification mechanism that reduces the current clutter of climate change monitoring. The system will be able to analyze data from integrated space- and ground-based resources, and automatically make priority-driven recommendations for tasking of additional sensors (Planetary Skin, 2009).

Planetary Skin is still in its infancy but represents an innovative partnership between private and public sectors. As a future consideration, Climate Links might be integrated into Planetary Skin as a means of enhancing its capabilities. For example, Climate Links could provide additional *in-situ* data, while Planetary Skin could use its prioritization and tasking algorithms to schedule and task Climate Links sensor instruments, enhancing the overall system accuracy.

2.4 Summary

Climate Links utilizes the existing infrastructure provided by satellite communications, GSM, WLAN, and the Internet to create a network of sensing units that allows climate data acquired in the field to be transmitted in near real-time to a data center. This data is then used to complement climate data from EO satellites, thereby providing more accurate and reliable datasets for use in climate models or by interested parties. In doing this, the Climate Links project addresses the two key problems outlined previously: the lack of *in-situ* datasets correlating to satellite measurements and the lack of active public involvement in addressing climate change. In addition the Climate Links system will bring the public closer to the work being done by space agencies, and other space players, by fostering awareness of the role space plays in monitoring the global climate.

Implementation of the Climate Links system on a global scale is relatively complex from the engineering perspective with the integration of multiple data collection devices. The following chapter provides a general description of a roll out plan starting with a preliminary study in Nigeria.

3 SYSTEM IMPLEMENTATION

The architecture outlined in the previous chapter presents an overview of the entire Climate Links system, representing the final vision of this initiative. To build such an idealistic architecture, implementation in phases is recommended. This chapter outlines these phases and presents a method, called a rollout plan, for parties interested in developing the Climate Links system. The main feature of the first phase is the development of a pilot project in Nigeria with stationary collection devices. It is possible that those interested in pursing this system are not already members of an organization. Therefore this chapter will outline the project assuming that a new initiative is necessary. The focus of this chapter is on implementation of the Climate Links system.

3.1 Rollout Plan

The recommended rollout plan for Climate Links is divided into five phases, taking the project from conception through full maturity. The implementation plan is meant to closely follow the development of the technology required. The organization undertaking the project would be primarily concerned with prototyping the devices, fundraising, and data management. Table 3-1 outlines the rollout plan and includes the major milestones in each phase.

Table 3-1: Five Phase implementation plan for the Climate Links system

Phase	Milestones
Phase 1	1. Formation of organization 2. GreenBox development 3. GreenBox manufactured in Nigeria 4. Pilot project in Nigeria 5. One-way phone application (messages to mobile phones)
Phase 2	1. Geographic expansion of GreenBox 2. Additional sensors 3. Mobile GreenBox edition
Phase 3	1. Two-way phone application 2. Establish partnership with mobile phone manufacturer 3. Prototype GreenPhone 4. Upgrade data capacity and communication infrastructure
Phase 4	1. GreenPhone release to pilot market
Phase 5	1. Geographic expansion of GreenPhone market 2. Professional GreenPhone add-on development and release 3. Complete global data availability and release

Phase 1 starts with the release of the simplest and most robust device, the GreenBox, in a single geographic location. The recommended region for this release is Nigeria, for reasons to be elaborated upon in section 3.4. Phase 1 is anticipated to take seven years, as illustrated in **Figure 3-1**. This estimated schedule allows adequate time for fundraising, product development, and the formation of partnerships needed to facilitate the entire project. The time from start of the entire project to the commencement of the pilot project in Nigeria would be two years.

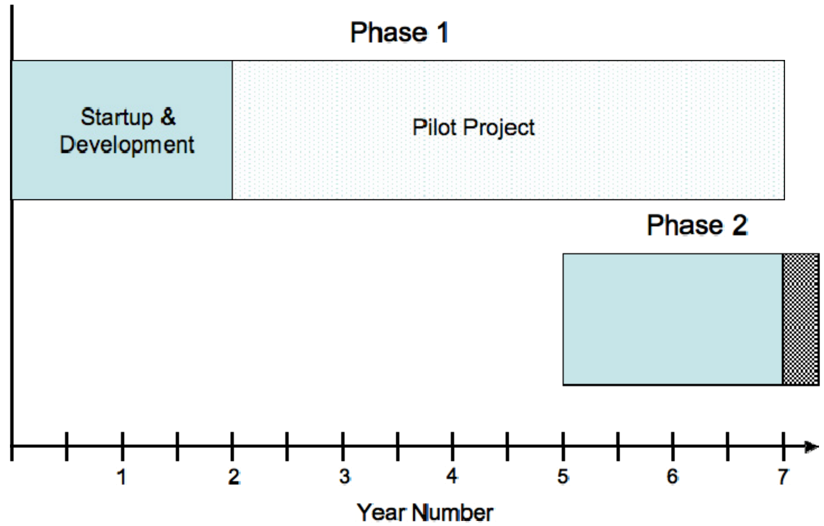

Figure 3-1: Rollout plan for Phase 1 of the Climate Links project

Project phases could be performed partly in parallel, in order to take advantage of existing resources as they become available from previous phases. For example, while the pilot project is being conducted, design staff within the organization could already be working on prototypes for GreenBoxes that would be rolled out in Phase 2. The pilot project in Nigeria is anticipated to last five years, which is reasonable compared to similar projects such as SAFE (private conversation with Ulrich Messin, 4 May 2009). This would allow enough time for implementing and proving the physical systems and the infrastructure supporting the collection and processing of raw data.

At the same time, a project website and a one-way 'green fact of the day'-type mobile phone application will be developed. The phone service would provide an avenue for public awareness, while the website would provide distribution of the data products to scientists and the general public, further increasing awareness. These web-based products are hereafter referred to as the scientific product and the awareness product.

3.2 Starting the Project

Since it cannot be assumed that an existing institution will implement this project, a comparison of four business models: For-Profit or Private company, Public Private Partnership (PPP), Intergovernmental Organization (IGO) and Non-Profit Organization (NPO) are presented in Appendix C. Most of these models take advantage of consumer and governmental preferences for 'green' technology. Upon accepting additional levels of documentation, the concern of project funding can be alleviated by the different sources open to an NPO. Furthermore, the green trend is expected to continue long enough for NPO funding sources to cover the start-up costs. Thus, an NPO is the recommended business model for the Climate Links project.

3.2.1 Details of a Climate Links NPO

An NPO exists for the general benefit of society through the provision of goods and services. It does not distribute profits to shareholders, but may employ staff and generate revenues to reinvest in the organization. In recent years, the non-profit sector has undergone explosive growth on a global scale in response to economic and climatic changes (Sargeant, 1999). Some argue this growth is coming to a halt due to the global financial crisis, as many philanthropic institutes are being forced to close programs or shutdown completely. However, climate change initiatives should continue to thrive due to worldwide recognition of its potential consequences, and assurances from major nations that have vowed to take action despite the current financial crisis (Press, 2009).

This chapter suggests incorporating the non-profit in the United States (US) for the following reasons:

- There has been an emergence of climate change initiatives in the US at regional levels. For example, 2009 marked the start of the Regional Greenhouse Gas Initiative, a market-based program in which ten states have agreed to cap and reduce greenhouse gas (GHG) emissions (Gerrard, 2007).
- The US government provides substantial funding for US-based NPOs focused on climate change (Grants.gov Program, 2009), the National Science Foundation (NSF, 2009), and the Environmental Protection Agency (EPA, 2008). The US is also home to many individuals and businesses with the financial means to support domestic and international climate change initiatives (O'Heffernan, 2007).
- US laws governing the establishment of NPOs and corporate tax exemptions are clear, well established, and easily accessible (Lutz, 2005).

3.2.2 Legal Issues of Establishing an NPO in the US

The four main legal issues to be considered by a non-profit corporation are:

1. Incorporation
2. Obtaining tax exemption status
3. Operations
4. Registering for fundraising rights

Incorporation ensures limited liability protection for stakeholders, long-term continuity of the organization, and possible tax advantages for both the corporation and donors. For incorporation, articles of incorporation and company by-laws must be established. In the US, the articles of incorporation must be filed with each state in which the NPO operates. Rules of establishing an NPO vary depending on the state (*e.g.* filing fees) (Form-A-Corp, 2007).

NPOs are subject to the same corporate formalities as for-profit organizations such as the adoption of by-laws and the documentation of meeting minutes (Form-A-Corp, 2007). Additionally, tax-exempt non-profits must follow certain rules to maintain their tax-exempt status at federal and state levels. In general, these rules oblige them to disclose information about their operations to the general public and government regulators. These practices ensure transparency to protect the public from fundraising scams. They also provide basic information to the government about the NPO to ensure regulations are being followed. Finally, these practices provide financial and operational information to donors to help them understand the workings of the organization (McNamara, 2000).

In addition to registering with the US Internal Revenue Service (IRS), most states require registration in order for a non-profit to raise funds within their borders, with requirements and fees varying from state to state. The Unified Registration Statement can be used as an alternative to registering individually in each state, however it is not accepted by all states, and most require additional paperwork and annual reports (Form-A-Corp, 2007). Raising funds is a crucial concern for NPOs and will be discussed in greater detail in Chapter 6.

3.3 Phase 1 SWOT Analysis

As with any new system development, an analysis must be performed in order to identify the Strengths, Weaknesses, Opportunities, and Threats (SWOT). A SWOT analysis for the Climate Links pilot project is summarized in Table 3-2. The strengths and weaknesses presented are of the system itself and are considered internal characteristics, while opportunities and threats are external factors that will influence the Climate Links system.

Table 3-2: SWOT analysis for the pilot project

Strength	Weakness
• Unique package and synchronization • Increase value of satellite data • Commercial Off The Shelf (COTS) components • Fulfills policy programs • Economy of scale • Worldwide support and coverage	• Needs continuous funding and investment • Unproven system • Devices development (timeline, export, *etc.*) • Device requires regular maintenance
Opportunity	**Threat**
• Expand organization and devices to more countries • Partnership with different institutions • Political opportunity • Current green trend	• Competition from similar data collection systems • Decline of green trend • Vandalism, theft, natural damage • Political instability • Resistance from GHG emitting industries

The GreenBox is designed with an innovative combination of sensors in one autonomous station. By complementing satellite data through measurement correlation, the overall value of the satellite data increases. This is a unique feature of the Climate Links system. The GreenBox is recommended to utilize COTS components, which leads to faster and cheaper development, and to the modularity of the GreenBox. This makes it possible to modify the sensors to meet new requirements for complementing satellite data. This project can take advantage of economies of scale by having a subcontractor mass-produce GreenBoxes. Finally, by manufacturing the GreenBox in Nigeria, there is a more persuasive case for the pilot project to be adopted by the Nigerian government.

One weakness of Climate Links is the continuous need for funding, a major concern for setting up the recommended NPO, and developing the devices. Although there is potential funding from governments, corporations, and individuals, the approval process is lengthy and the real amount of contribution is unknown. A major cost driver is the development and contracting of the GreenBox. Because Climate Links is a new system, credibility for the data produced must be established. The devices will require occasional calibration, repair, and replacement.

The opportunities identified are for the global expansion of the system, which is envisioned to create a range of networks to provide better climate data measurement. The suggested NPO could expand the system by establishing partnerships with institutions in the US and Nigeria like national space agencies, universities, and development programs. On an international level, there are possibilities to integrate with the Global Climate Observing System (GCOS) and the Global Earth Observation System of Systems (GEOSS), as mentioned in Chapter 2.

A threat to the system is competition from other products. Although the GreenBox is unique in the current market, there is no guarantee that another manufacturer will not introduce similar devices with cheaper prices or more advanced characteristics. Therefore, to stay competitive it is recommended that the GreenBox use an open design, so that improvements can be made to the components as required by the end user. Competition could also be in the form of companies like Leosphere, who makes instruments measuring wind, clouds, and aerosols. Additional competition may come from other research projects, such as CLOUDMap 2, a project connecting ground-based instruments with satellite measurements of cloud formation variables over Europe and North America (Muller, 2003). However, they should instead be viewed as customers or inputs to the system, since the goal is to collect ground information to supplement satellite data. Climate Links should be implemented quickly, establishing the quality of the system and its results, which would be utilized by scientists and presented to the public, in order to take advantage of the current green trend.

3.4 Pilot Project in Nigeria

It is proposed that the pilot project be carried out in Nigeria, with a mutually beneficial relationship between Nigeria and Climate Links. Climate Links can provide key contributions towards Nigeria's ability to react and adapt to climate change, while Nigeria can provide a platform for the Climate Links pilot project.

3.4.1 Responding to Climate Change

As a developing country in an equatorial region, Nigeria is particularly susceptible to the effects of climate change for many reasons. For example, its 800 km coastline would be affected by sea level rise, while almost two-thirds of its land is prone to drought and desertification. This presents a concern for the large majority of the population who depend on the coastline and arable land for survival. In fact, two-thirds of Nigeria's population depends on rain-fed agriculture and fishing activities for food, while 80 % of its population claim at least one of those activities as their primary occupation. As a nation so susceptible to the effects of climate change, participating in a project like Climate Links, which aims to improve climate impact studies, may be of particular interest (BNRCC, 2008).

In addition to answering the needs of the country, Nigeria can answer the needs of Climate Links as it provides an ideal location for the pilot project. Not only is Nigeria of particular interest to Climate Links as an area that may be greatly affected by climate change, but its territory is of manageable size such that the total number of GreenBoxes required is under 100, making it financially feasible. Moreover, the government of Nigeria appears to be eager to work with others in order to prepare for the effects of climate change, and to improve their scientific and technical capabilities. This is because they have recognized the threat of climate change to their country, and also that Nigeria currently lacks the technology, finances, and legal framework to successfully fight the potentially negative impacts on its own (BNRCC, 2008).

There are several climate change initiatives in Nigeria that could facilitate the rollout of this project. For example, the Building Nigeria's Response to Climate Change (BNRCC) project, partly funded by the Canadian government, is aimed at increasing Nigeria's ability to adapt to the current and anticipated effects of climate change. Additionally, the BNRCC works at the community level in villages most vulnerable to climate change, in order to encourage action and help Nigerians make informed, sustainable decisions. These valuable contacts may facilitate the implementation of the pilot project and also serve to illustrate the general receptiveness of the Nigerian people to such projects (BNRCC, 2008).

Moreover, there are numerous other organizations and individuals within Nigeria working to promote climate change action. Consequently, the Nigerian Climate Action Network, NigeriaCAN, was created with the specific purpose of bringing these organizations and individuals together to achieve their common goal. Its members include over twenty influential individuals and organizations, both public and private, which have functional links to various climate change initiatives in Nigeria and abroad (NigeriaCAN, 2009). This organization also works in collaboration with the Nigerian government to assist the development of climate change policies and programs. The existence of such an organization, its members, and their close relationship to the Nigerian government illustrates how addressing climate change has become a key part of Nigeria's strategy for the future.

3.4.2 Nigerian Space Activities

Nigeria became a space-faring nation in 1999 with the creation of their National Space Research and Development Agency (NASRDA). It launched its first remote sensing satellite in 2003, NigeriaSat-1, which carried a single multi-spectral optical imaging payload developed by Surrey Satellite Technology Ltd. Its successor, NigeriaSat-2, will also be a remote sensing satellite, but with superior capabilities to NigeriaSat-1. NASRDA's vision is to "pursue the development and application of space science and technology for the socio-economic benefit of the nation" (NASRDA, 2009). NASRDA has also stated that it aims to provide better ground- and satellite-based monitoring of the Earth and its environment in order to enhance its Earth monitoring activities, as well as foster international cooperation in all aspects of space science and technology. This will ensure that Nigeria benefits from global developments in the space industry (Boroffice, 2006).

3.4.3 Political Perspective

In recent years, the leaders of Nigeria have focused on making their country one of the leading economies in the world by 2020. With this goal in mind, there has been a movement towards revitalizing government investments in science and technology (UNESCO, 2008). The government agency responsible for Nigeria's policies in this sector is the Federal Ministry of Science and Technology, whose vision is:

> "To make Nigeria, in the nearest future, an acknowledged member of the fast developing Scientific and Technologically progressive nations of the world and to be Africa's leader in Scientific and Technological development" (FMST, 2008).

The Ministry's mandate is the promotion of technology acquisitions, development of scientific and technological infrastructures, and maintaining relations with international scientific and technological organizations (FMST, 2008). As Climate Links is an international and scientifically innovative endeavor, Nigeria should be particularly interested in hosting the Phase 1 pilot project.

In broader terms, Nigeria is in the process of revamping its international reputation. Historically, Nigeria has been characterized as a country affected by corruption, poverty, and political turmoil. Consequently, the Nigerian government has engaged in a series of campaigns since 2004, the most recent of which was: "Nigeria: Good people, great country." Although the Nigerian government admits that its historical problems still persist, it believes that Nigeria cannot wait until all its problems are solved before addressing its image, and that as soon as the Nigerian people's own perception improves they will be less inclined to perpetuate the stereotype (BBC, 2009). There has been recent criticism of Nigeria's image campaigns, with critics accusing Nigeria of merely painting over its problems and not actually fixing them (The Economist, 2009). By engaging in climate science in cooperation with international organizations like Climate Links, Nigeria can show its people and the rest of the world that it is taking concrete action.

From the overview of Nigeria's key policies, the goals of Climate Links appear inline with those of Nigeria, providing clear incentives for the Nigerian government to host the Climate Links pilot project.

3.4.4 Educational Benefits

This project can serve as an educational tool for Nigerian students to learn about climate change and space activities on both national and international levels. Forty-five percent of Nigeria's population is below the age of 15, and therefore the education system presents a good platform for climate change awareness initiatives for a large percentage of the Nigerian population

(FME, 2005). Indeed, a proposal in 2004 called for several new subject areas to be included into existing Nigerian curricula, among which was the topic of environmental education (FME, 2005).

The Nigerian education system consists of three levels: primary, secondary, and tertiary. Primary and secondary education lasts 12 years, but only the first nine years are mandatory. A significant decrease in enrollment at the secondary and tertiary levels make the primary years critical to pass along information. This decrease in attendance as Nigerians go from primary to secondary and tertiary education can be seen in Figure 3-2 as the percentage of students who attend (Agyeman, 2007).

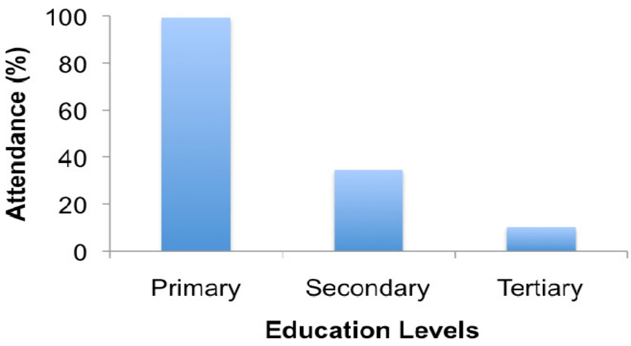

Figure 3-2: Statistics on Nigerian education attendance (Agyeman, 2007).

One way to engage Nigerian students and to encourage them to continue their education is to assign GreenBoxes to local schools so that they can have more hands-on educational experiences. For schools that have Internet access, the awareness product on the project's website can allow students to see how data from 'their' GreenBox corresponds to those in other areas of Nigeria, as well as the relationship with satellite data. By involving students in real science at an early age, Climate Links can encourage Nigerian students to continue studying and even pursue a career in science and technology sectors, thereby fostering lasting benefits for the entire country (Agyeman, 2007).

In 2007, the Ministry of Education created the Information, Communication, and Technology (ICT) department as part of a push to increase ICT projects at all levels of education. This initiative should increase the number of Nigerian schools with electricity and computers, particularly in more rural areas (Agyeman, 2007). Thus, as the Climate Links pilot project evolves, activities for the classroom can be placed on the project website for more interactive education.

Furthermore, one of the Ministry of Education's stated needs is to provide standard curriculum activities based on the Internet which can help with teacher training in ICT and the development of consistent teaching methodologies. To meet these needs, Nigeria began Technical and Vocational Educational and Training workshops, 34 of which were held in 2007 (Agyeman, 2007). Climate Links could easily be incorporated into such workshops during the implementation of the pilot project.

Finally, students outside Nigeria can also utilize the initial awareness product available on the project website to study the Nigerian climate. Graduate students from around the world can also be involved in hands-on collaborations involving the setup and maintenance of the GreenBoxes. This can be facilitated by the National Science Foundation (NSF) Office of Integrative Activities (OIA) in the US, which has created a grant to help engage scientists and engineers to become more involved in international research on the environment. The OIA feels that international environmental research is essential to research in cutting edge science and technology, and emphasizes the participation of early-career scientists and engineers in international programs (OIA, 2009).

3.4.5 Capacity and Technology Development

As of 2007, there was an estimated 860,000 computers in Nigeria with 750,000 Internet users out of a population of 140 million. Since only a small percentage of Nigerians would have access to the project's website, the immediate social benefits of this project are the technical infrastructure that would be developed to support this system. The Nigerian government is already developing partnerships with Microsoft, Intel, and CISCO to expand the country's ICT infrastructure (Agyeman, 2007). The GreenBox pilot project further presents an opportunity to increase the technical infrastructure of Nigeria while simultaneously raising awareness about climate change.

Moreover, Climate Links could work with O3b Networks, an organization tackling the current lack of Internet resources around the globe. On 24 March 2009, Direct On PC Ltd., the leading Internet provider in Nigeria, signed a multi-year, multi-million dollar contract with O3b Networks, and will launch their first telecommunication satellite in 2010 (BNET, 2009). These initiatives have the potential to facilitate the public awareness activities of Climate Links in Nigeria.

3.5 Summary

A phased rollout plan is the most suitable way to implement the Climate Links project due to the great amount of resources needed for a full-scale worldwide project. It is suggested the project be rolled out in five phases, with Phase 1 lasting for seven years.

After reviewing several business models, it was decided that an NPO would be the most suitable model since its advantages overcome its disadvantages. The proposed NPO would be based in the US and would be primarily concerned with prototyping, fundraising, and data management for the project.

A pilot project in Nigeria is suggested, because of the business advantages, the geographical location of Nigeria and its vulnerability to changes in climate, the needs of scientists who will be receiving the data from the pilot study, and potential capitalization on Nigerian development programs. Key to this pilot project is the development of the GreenBox measurement device, which is covered in detail in the following chapter.

4 GREENBOX DESIGN

As justified in the previous chapter, the focus of this report is a pilot study in Nigeria. The focus of this chapter is to outline design recommendations for the GreenBox, such that it meets the requirements for the Climate Links vision of enhancing data acquired by Earth Observation (EO) satellites. Specifically, the data being enhanced in this phase are Essential Climate Variables (ECVs) such as Greenhouse Gases (GHGs) and aerosols. GHGs and aerosols require near-simultaneous data collection for *in-situ* validation of satellite data. The GreenBox can also add value to climate and weather models through collection of additional data, and reduce the cost per ECV monitored by combining several sensors in a single device.

In this chapter, design drivers and ECVs needed for satellite data in Nigeria are presented. A survey of commercially available subsystems and sensors are then discussed. The design approach used is to provide recommendations for the GreenBox using Commercial-Off-The-Shelf (COTS) field instruments. Based on these recommended instruments, a sample design of the GreenBox is presented as an autonomous and rugged scientific device adapted for the Nigerian environment. The conceptual GreenBox design can in turn be scaled down to meet budget constraints or ground modeling needs.

4.1 Design Drivers

The initial requirement in Phase 1 of Climate Links is to support and enhance the data generated by environmental satellites such as JAXA's Greenhouse gases observing Satellite (GOSAT), which is equipped with sensors capable of measuring GHG emissions. Gases and aerosols evolve quickly on the ground; therefore a ground-based measuring device that acquires data before, during, and after the passage of such satellites will help in reducing the error margins of the satellite data (Space Studies Board and National Research Council, 2000).

For the Phase 1 pilot project in Nigeria the suggested design for the GreenBox is a rugged, semi-portable, analytical, ECV-monitoring system that integrates COTS field grade sensors. Its deployment, operation, and maintenance must be simple, as most units will be in remote areas.

Moreover, the more metadata (information about the structure, context, and meaning of the raw data) that can be measured at the same time as each ECV increases the value for climate modeling (Trenberth, 1992). This approach ensures a high level of quality so that the data will be of value for many years.

4.1.1 Climate in Nigeria

The GreenBox should be rugged enough to withstand the weather in all areas of Nigeria. As described in Figure 4-1, the GreenBox will be exposed to a range of climatic environments; from hot and humid tropical climate conditions in Lagos, to temperate dry areas such as Jos.

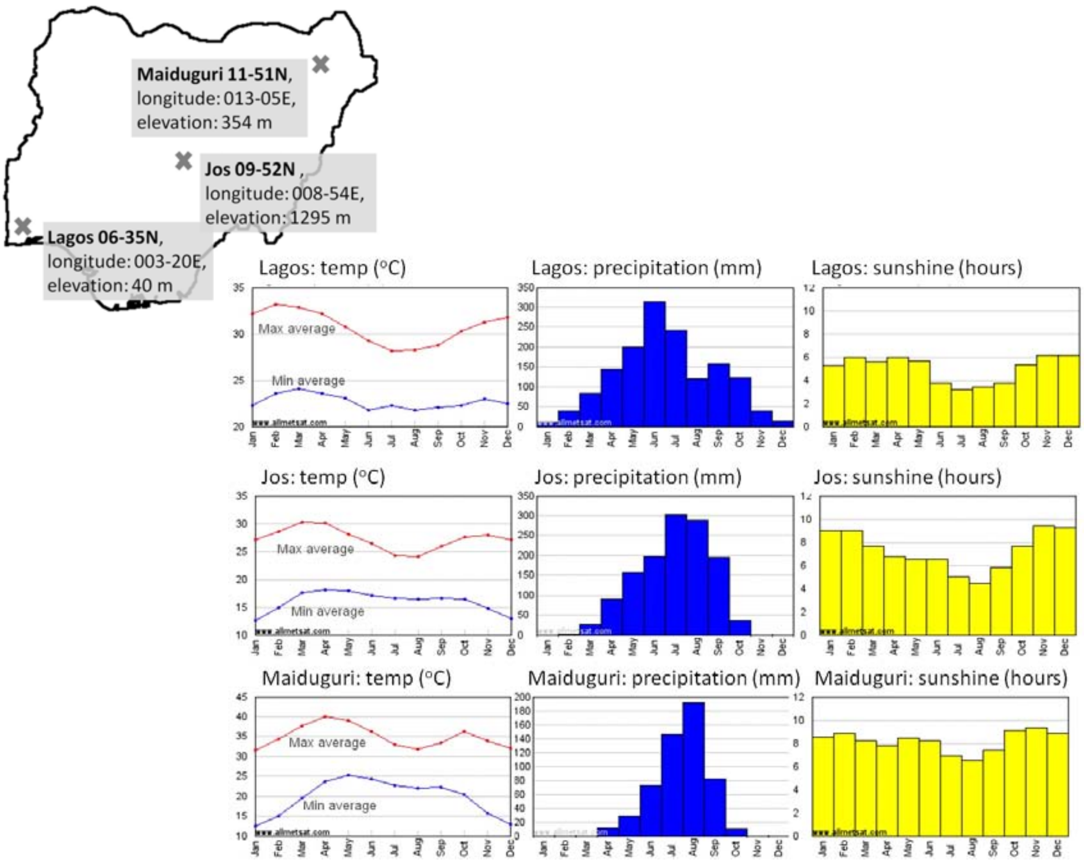

Figure 4-1: Monthly averages of climate variables for three cities in Nigeria (adapted from Allmetsat, 2009)

Maiduguri presents more continental characteristics with high average temperatures during the warmest months of 40 ºC, and an average of 12 ºC in the coolest months. Each region experiences a significant spike in precipitation from May through August, with Lagos experiencing the highest levels. High humidity during the summer months may require specialized calibration for the GreenBox sensors as well as some countermeasures, such as desiccants, to protect the electronic components (Daou *et al.*, 2006). Another practical concern will be mountainous regions such as Jos. The GreenBox will be placed in low lying areas, so shading and microclimates in these regions will have to be accounted for in the final design.

4.1.2 Essential Climate Variable Measurements

According to the Global Climate Observing System (GCOS) there are 44 ECVs broken into three subgroups: Atmospheric, Oceanic, and Terrestrial. The pilot project focuses on atmospheric ECVs and only considers variables that can be measured by a stationary platform, resulting in ten ECVs measured with eight sensors. These variables can be found in Table 4-1.

Table 4-1: Selected ECVs for Climate Links Project
(*represents ECVs not measured by satellite)

1. Carbon Dioxide	6. Surface Temperature*
2. Methane	7. Precipitation
3. Other GHGs (N_2O, CO)	8. Ground Atmospheric Pressure*
4. Aerosols (CFCs)	9. Incoming Surface Radiation*
5. Water Vapor	10. Wind Speed and Direction

4.1.3 Coverage Area

GreenBox sensor requirements and typical swath-widths of satellite data collection scans dictate that the spacing between GreenBoxes should be no larger than 1 unit every 100 km, spread as evenly as possible across the region. To cover Nigeria's approximately 924,000 km^2, this would theoretically require 93 boxes. The Baseline Surface Radiation Network (BSRN) states that boxes should not be placed in locations where vegetation cover is not uniform over at least 100 m^2 (McArthur, 2005).

Three of the estimated 93 boxes will not be placed in service, leaving only 90 deployed, as certain regions are not appropriate for the pilot study. For example, a box will not be placed in the Montane (mountain desert) region, as the change in ECVs with elevation introduces additional sources of error that are out of scope for this study (Rolland, 2003). Instead, GreenBoxes will be placed in the Savannah region at the base of the mountains. Figure 4-2 shows the vegetation coverage of Nigeria with a 100 x 100 km grid overlay.

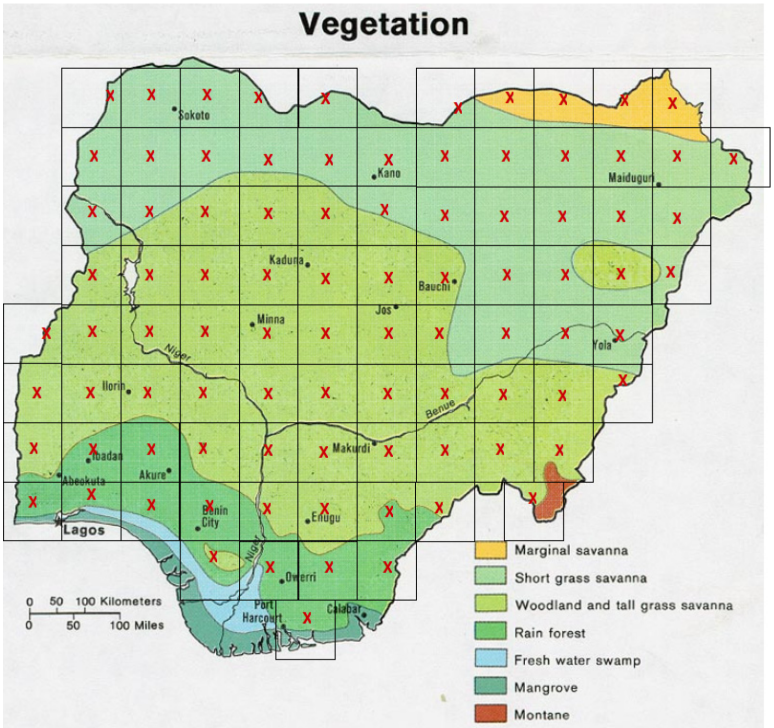

Figure 4-2: 100x100 km grid overlaid on vegetation map of Nigeria
One GreenBox should be deployed approximately in the center of each grid-square

It is recommended that 90 GreenBoxes be placed within this grid, and be distributed in the various vegetation regions in the following manner:

Marginal Savannah (desert):	4	Woodland and tall grass savannah:	43
Short Grass Savannah:	32	Rain Forest (in areas of clearing):	11

This is approximately proportional to the area of each vegetation type within the country. GreenBoxes placed in the rain forest areas will be in areas where the forest has a clearing of at least 100 m^2. Preliminary analysis using "Google Maps" indicates multiple clearings in each segment suitable for GreenBox deployment (Google Maps, 2009).

4.1.4 Selecting GreenBox Installation Sites

Choosing a site location for each of the GreenBoxes will be challenging, as the site would ideally be:

- Representative of the surrounding area (within approximately 100 km^2)
- Far from pollution sources, areas of false reflectance, and man-made phenomena that affect the microclimate
- Far from major roadways and airports
- Not sheltered by trees, buildings, *etc.*

The availability of telecommunication links should also be considered when choosing a site, as the cost of transferring data over terrestrial networks is lower than satellite communications. Although the GreenBox will be capable of withstanding harsh weather conditions, the choice of site should minimize the risk of flooding, lightning, and other extreme circumstances. The site location should also minimize the risk of theft and vandalism.

4.1.5 Data Collection

The GreenBox is designed to monitor many ECVs, so as to maximize the contribution of Climate Links to satellite data quality. Of the ten variables listed above, satellites are measuring seven: CO_2, methane, N_2O, CO, CFCs, water vapor, precipitation, wind speed and direction (See Appendix B for details of EO satellites and the ECVs monitored). In particular, the focus of Phase 1 of the project is to monitor the rapid development of airborne gases, which in turn influence climate models. It is now understood that short-term weather patterns do play a role in long-term climate modeling (Trenberth, 1992).

The GOSAT mission, launched to monitor GHGs from space, is an ideal partner project for Climate Links. Onboard GOSAT is an infrared (IR) Fourier Transform Spectroscopy (FTS) instrument to detect absorption bands of key GHGs as shown in Figure 4-3. However, due to the rapid evolution of gases, ground-based validation of the results is required (JAXA, 2009). In order for the ground validation to have any value it must be coordinated within hours of the passage of the satellite (Badarinath *et al.*, 2008).

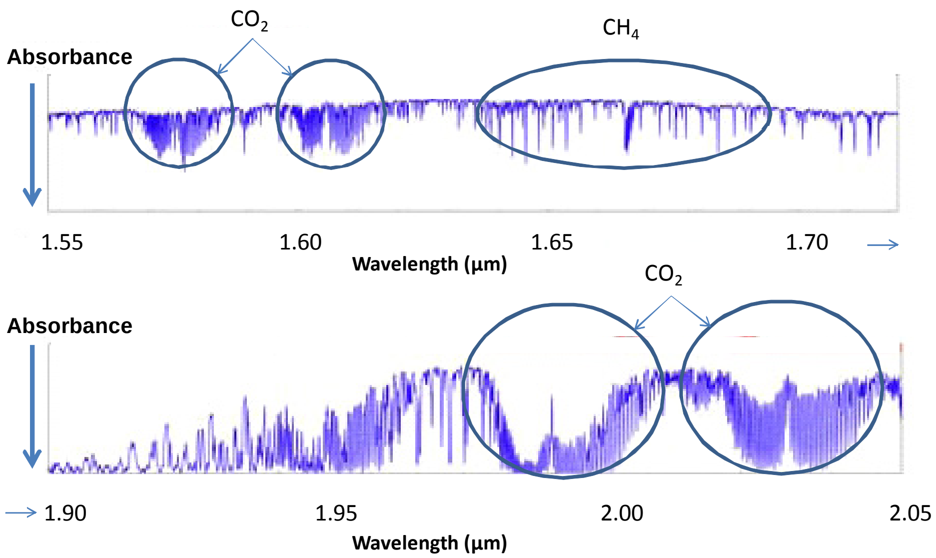

Figure 4-3: Example of GHG near-IR absorption band data acquired by the TANSO-FTS instrument (adapted from JAXA, 2009)

With the grid of GreenBoxes, the data generated by GOSAT would be enhanced, as the spectral bands would be positively identified from the ground and the associated metadata can be used to infer spectral features that may otherwise be poorly understood. Moreover, by placing the GreenBoxes in a region like Nigeria, ground validation data in other similar tropical regions further refines the value of the satellite data.

In addition to enhancing satellite data, the GreenBox also supports ground based climate modeling. Due to the expense of developing and deploying the GreenBoxes, it would be beneficial to be able to provide valuable climate monitoring data to groups such as the World Radiation Monitoring Center (WRMC), or the WMO, who study and model climate. In order to provide useful data to organizations such as these, data collected from the GreenBox would be required to be collected at a high sampling rate. For example, according to the WRMC, the baseline needed to provide useful radiation information is that "all radiation variables should be sampled at 1 Hz with an averaging time of one minute. The final output for each variable should consist of the one-minute mean, minimum, maximum, and standard deviation" (McArthur, 2005). Additionally, there is a requirement that:

> "When automatic data logging is employed to record such variables as pressure, temperature, humidity, wind speed and wind direction, providing these data at the same frequency as the radiation data is beneficial. Stations are encouraged to obtain these observations coincidentally with the radiation measurements using a one-minute sample rate to aid in understanding the energy balance of the radiation instruments and the infrared component of the radiation balance" (McArthur, 2005).

4.2 Recommended Sensors

The sensors in the GreenBox are essential to its design and the whole Nigerian pilot project within Climate Links. In order for the data collected by these sensors to be useful to users, they must meet minimum performance requirements for measuring ECVs set out by the WMO, summarized in Appendix D. Most field-grade, commercially available sensors meet or exceed these requirements, thus ensuring the dual use nature of the GreenBox while serving the purpose of Climate Links and its long-term vision.

4.2.1 Detection of Greenhouse Gases

Recent developments in portable Gas Chromatographer (GC) technology have enabled the possibility of detecting multiple ECVs rapidly and with analytical levels of sensitivity and resolution (Ohira and Toda, 2008). Current miniaturized GCs are designed for volatile organic compounds but are not suitable for GHG detection. Rather, a thermoconductivity detector is required, but development in such portable devices is only now becoming a priority. There is not yet a rugged portable thermoconductivity-measuring GC available on the market (Ohira and Toda, 2008).

However, a instrument that would satisfy the GreenBox requirements in size, weight, ruggedness, and power consumption was found in Photovac Inc.'s Voyager system (Photovac, 2007). This system has been used in several studies on volatile organic compounds, and has been operated in temperate climates similar to Nigeria and on weather stations in Costa Rica (Karl *et al.*, 2004). Tom Smith, President of Photovac Inc., indicated that the Voyager system is being adapted with a thermoconductivity detector in order to satisfy the need for a GHG detection system (personal communication, May 4, 2009). Moreover, Photovac Inc. has also developed auto-sampling and injection devices that are programmable so that they can function autonomously.

4.2.2 Humidity and Water Vapor Sensing

The most common types of electrical humidity sensors are low cost resistance and capacitive sensors. However, these devices can be inaccurate if there are pollutants in the air, and additional corrections are needed when measurements are taken below 0 ºC. Alternatives to this sensor are the chilled mirror sensors, and saturated lithium chloride sensors. Both are classified as dew-point meters. The major difficulty with the saturated lithium chloride sensor is that it requires field intervention after a power disruption. The sensor recommended for the Climate Links project is a chilled mirror dew-point sensor, due to its high accuracy.

4.2.3 Incoming Surface and Solar Radiation Detection

Pyranometers are used to evaluate broadband solar irradiance on a planar surface, by measuring the solar radiation flux in Watts per square meter, from a field of view of 180 degrees (McArthur, 2005). There are several models that could be selected for the GreenBox depending on their outer color scheme: either a completely black or a combination of black and white. Both models have been evaluated and it was found that for the purposes of the Climate Links project the uniform black option would be the most suitable (Kipp & Zonen, 2009).

Pyrgeometers are devices used to measure upwelling and downwelling components of long wave irradiance. They are sensitive to wavelengths of approximately 4.5 to 40 μm, and have a field of view of 180 degrees. The sensor needed for this application is a precision infrared radiometer (Eplab, 2009).

It is recommended that a pyranometer and a pyrgeometer are mounted on a telescoping arm slightly above the GreenBox. Ideally, these instruments would be located 30 m above the ground to allow for two of each sensor to be used for collecting the Earth's reflective radiation. This will be studied for implementation in a future phase of the project.

4.2.4 Temperature Measurement

An electrical resistance thermometer is proposed due to its automatic measurement capabilities. More specifically, a platinum resistance thermometer is the recommended temperature sensor for the autonomous GreenBox. These sensors have a wide temperature range, excellent accuracy, and have good long-term stability (WMO, 2008). This thermometer should be placed within a protective ventilated shield (a 'Stevenson Screen') to ensure it is not exposed to rain, wind, or direct sources of radiation.

4.2.5 Atmospheric Pressure

Electronic barometers consist of transducers that transform a sensor reading into a digital or analog signal. Redundancy techniques (*e.g.* one centralized microprocessor unit controlling three independently operating sensors) are used to improve accuracy of measurements and long-term stability. A high degree of accuracy is required in the measurements and therefore three pressure sensors are recommended. As electronic barometers are vulnerable to the effects of external exposure, each of the three sensors should be housed within the same 'Stevenson Screen' that as the electrical resistance thermometer. This will allow the barometer readings to be correlated with the temperature reading.

4.2.6 Precipitation Measurement

For the GreenBox, an accurate autonomous tipping-bucket rain gauge is recommended. The gauge consists of a precipitation collector balanced over a pivot. When the gauge accumulates a certain volume of water, it tips, triggering a signal that is subsequently recorded.

4.2.7 Wind Speed and Direction

The recommended model is a surface wind sensor consisting of a hemispherical cup anemometer to measure wind speed and a wind vane mounted on top of it to measure wind direction. This device consists of a set of cups that are connected to an axial. As the air flows past the cups the axial rotates at a speed proportional to the speed of the wind. Wind direction is measured using a weather vane.

The description and specifications of each sensor, and the considerations leading to its recommendation, can be found in Appendix E.

4.3 System Design

The GreenBox for Nigeria would ideally include all the sensors recommended above, in order to collect data for as many ECVs as possible. The systems to support these sensors can be seen schematically in
Figure **4-4** and include:

- Structural frame and processing module
- Computer system
- Thermal control & Humidity
- Sensors and secondary instrumentation
- Data handling and communications
- Power system

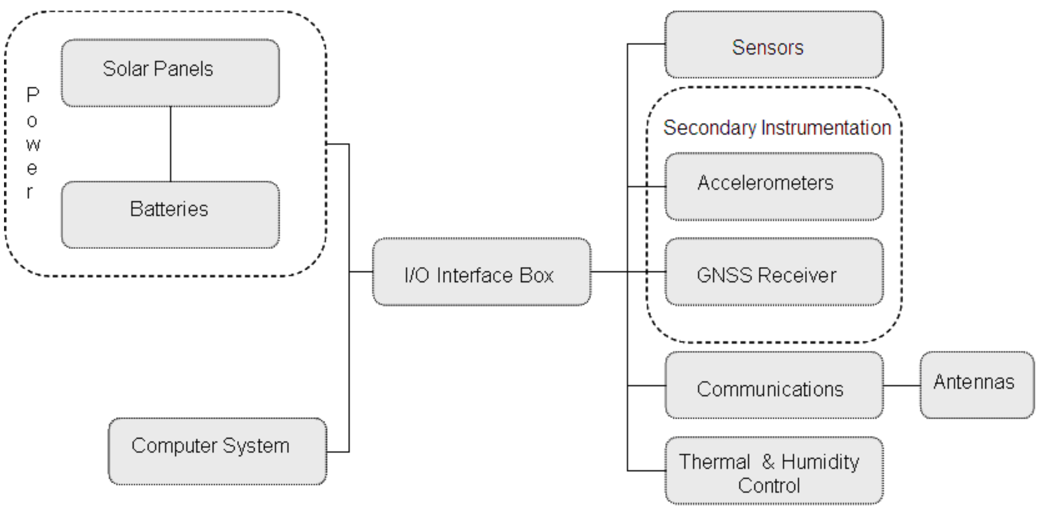

Figure 4-4: The recommended GreenBox system diagram

4.3.1 Structural Frame and Processing Module

The main structural frame provides the rigidity to the GreenBox and houses the main components, including the processing module (see next section). Figure 4-5 shows the frame and its various parts. The total dimensions for the GreenBox frame are 0.94 m (l) x 0.6 m (w) x 0.64 m (h).

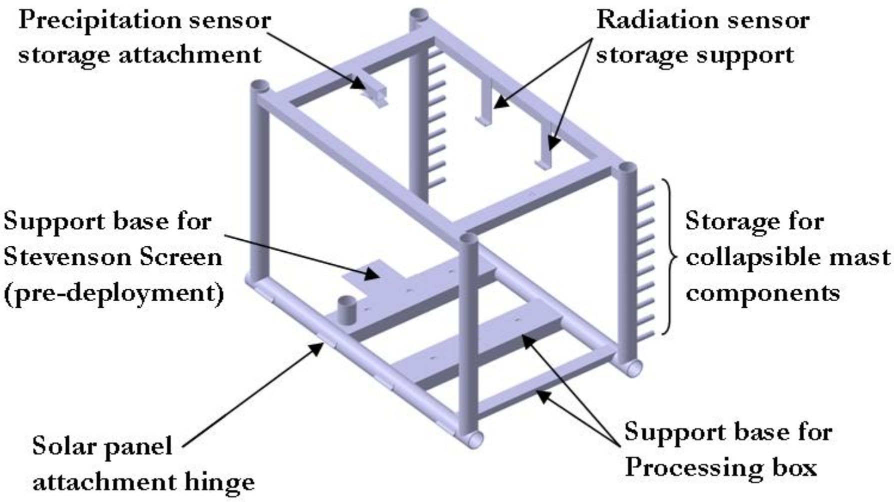

Figure 4-5: GreenBox structural frame

Within the structural frame is a permanently mounted processing module. This module houses the computer system for overall system management, integrates all sensor feeds, provides power management and thermal control, and handles data storage and communications. Figure 4-6 shows the layout of the different components within the processing module. The module should be fully enclosed, with a door for easy access during maintenance, and should be kept at a constant temperature between 25 and 30 degrees Celsius.

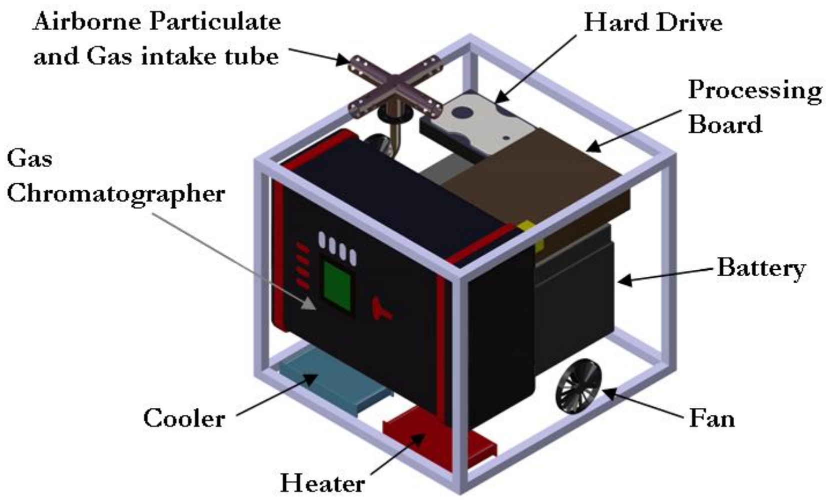

Figure 4-6: Proposed processing module schematic

4.3.2 Computer System

Computer hardware and software for the GreenBox should be robust and compatible with a standard Operating System (OS). However, much of the readily available COTS software for data management and pre-processing is built on Windows OS technology, and therefore it is recommended to use Windows-compatible equipment and programs for the main GreenBox computer system.

A specific program to manage the GreenBox hardware will also be necessary, and this will most likely have to be custom-made software due to the uniqueness of the system. The main task of this software program will be to communicate with the input/output (I/O) interface box, which connects the computer to all sensors and instrumentation, communications equipment, the power system, and thermal control system. It should also serve as a fault-monitoring program, which will survey all components to check their health status. Should a problem be detected with any subsystem, the program should try to resolve the problem and report any trouble to the data center in a recorded system events log during the next data transmission.

The I/O interface box itself will be a critical element in the GreenBox design since it will have to be compatible with the different output signals and connectors from each of the sensors and subsystems connected to it.

Finally, a program will be required to collect all the data from the sensors and perform some pre-processing of that data. The sensors will collect data once every five seconds, and the mean value and deviations collected over a minute will be calculated to ensure basic quality of the data points.

4.3.3 Primary and Secondary Instrumentation

The GreenBox should be designed to accommodate the sensors necessary for the measurement of ECVs, as well as the secondary instrumentation required to support collection of the climate data. The sensors are listed in section 4.2, while the secondary instrumentation includes:

- GNSS receiver
- Accelerometers

The secondary instruments are essential in supporting an important feature of the GreenBox, *e.g.* the ability to produce a reliable set of standardized observations. Most GreenBoxes will be almost identical, with sensors placed in the same positions and height above the ground, and facing in the same direction. To ensure an accurate and standardized data set, the GreenBox should contain accelerometers and a GNSS receiver to obtain clock signals.

The GNSS receiver should be installed in the GreenBox to ensure that synchronous measurements are taken between all of the devices within the box along with keeping the exact same time on all GreenBoxes across Nigeria. A typical GNSS receiver or clock is a COTS device with an accuracy of up to 10^{-6} s, and works anywhere on the surface of the Earth. This device should be placed on the top of the GreenBox with direct line of sight to the sky.

The GreenBox should be equipped with three microelectromechanical system (MEMS) accelerometers; one on each axis. These low-cost MEMS devices will ensure the highest quality of data gathering by alerting the user if there have been any excess vibrations while the measurements were made. If conditions during the measurement period were not within tolerances, the data can be tagged as questionable or deleted altogether.

4.3.4 Data Handling and Communications

Some of the main tasks of the computer system are to acquire data from the sensors, process them, make calculations, store the results, and then transmit them to the data center. During acquisition of data, the minimum, maximum, and standard deviation of collected data from each sensor should be recorded every minute in order to meet the requirements outlined by the WMO. Onsite data processing will reduce the data volume to be transmitted. In order to determine the amount of data produced by one station in a day, a set of mock files were made, with fictitious data from each sensor. See Appendix F for the output from this mock data collection estimation program.

Every reading includes the average, maximum, and minimum values, and the standard deviation of each sensor during the established period. The following assumptions were made:

- All the sensors except the GC will be sampled once every five seconds and statistical data for one minute will be recorded.
- The GC will gather data of all the different gases once per hour and this data will be recorded as well.

Housekeeping data is also collected every minute. Every sensor provides a status report that, in its simplest form, is a flag indicating whether the sensor is working nominally or not. This should allow a maintenance crew to know to repair a unit, as well as tag and possibly invalidate measurements taken by the box as long as a problem persists.

Based on the output from the mock program mentioned in the previous section, the total size of the data to be recorded every minute is 266 bytes, and the amount of data to be recorded every hour is 236 bytes for the gas sensors and 73 bytes for the housekeeping data. Therefore the total data for a day can be calculated as follows:

(266Bytes * 60min * 24hrs) + (236Bytes * 24hrs) + (73Bytes * 60min * 24hrs) = 493.8 kB/day.

Adding a 20 % margin, it is estimated that an average of 600 kB/day, per GreenBox, will be placed into memory for daily transmission to the data center.

This recorded data will be transmitted via WLAN/LAN, GSM or SATCOM. WLAN/LAN, although the first choice for data transmission due to its low cost, will not be used in this pilot project as it is not available in rural areas (where the GreenBox will be placed). As can be seen from Figure 4-7, GSM coverage is sporadic throughout the majority of Nigeria, but 16 of the GreenBoxes should be able to transmit their data through these networks. At 30 kbps, this would take approximately three minutes. The remaining 74 GreenBoxes will thus have to rely on SATCOM for data transfer, transmitting for eight minutes per day at approximately 10 kbps.

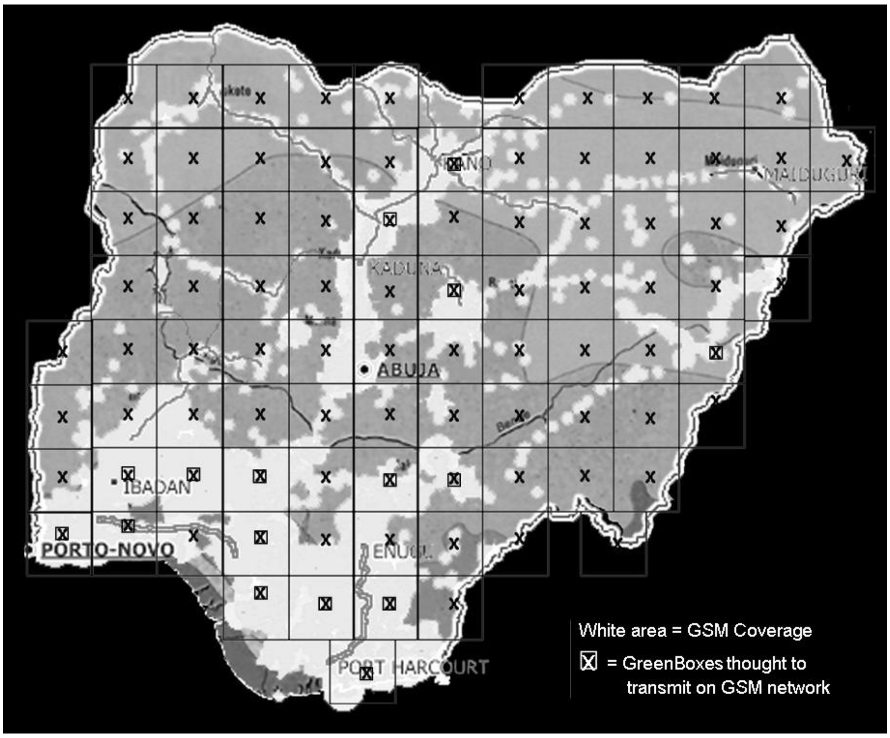

Figure 4-7: GSM coverage in Nigeria overlaid on the box placement

The antennas, transmitters, and receivers for collected data transmission to, and general communications with, the data center should be incorporated into the GreenBox design. The LAN connection would be made via a common physical Ethernet cable connection, while WLAN and GSM communications will be done via small antennas housed inside or on the outer surfaces of the processing module. The SATCOM antenna is expected to be larger, and would most likely have to be installed on the structural frame.

4.3.5 Thermal and Humidity Control

The equipment inside the GreenBox must be kept at normal operating temperatures. This is especially important for the computer system and any electronics within the processing module. As a result, heating and cooling equipment such as heaters and fans will be managed by the computer system to regulate the temperature inside. Moreover, humidity control through desiccation will ensure stability of the electronics and extend their lifetime.

4.3.6 Power

The estimated maximum power requirements for the recommended sensors and other components within the GreenBox are shown in the first table in Appendix G. The power consumption in Watts of each device was used to calculate its energy consumption during a 24 hour period. This is calculated to be 936 W-h. In order to provide this required power to a remotely located GreenBox, a photovoltaic (PV) system with battery storage is recommended. Taking into account the worst-case effective peak sunlight hours in Nigeria (estimated at 3 hours per day), three Suntech folding 140 W, 24 V panels (Energy Matters, 1999) are recommended (see Appendix G for calculation details).

With regards to energy storage, a series of batteries will also need to be included in the GreenBox. Given the power requirements of the GreenBox, and a system voltage of 24 Vdc given by the solar panel manufacturer, the electric charge needed for the battery system was calculated to be 32 A-h. Based on these requirements, it is recommended that four 12V batteries with 225 A-h capacity be used for the system (see Appendix G). The batteries must be isolated from weather variations and be kept at a constant temperature, and therefore should be located in the temperature-controlled processing module. The solar panels and batteries should be monitored via a power monitoring and conditioning system, which should ensure good electric signal quality and protection.

4.3.7 Size and Mass

In deployed configuration, the box is 2.7 m (l) x 2.4 m (w) x 10 m (h), and its mass, excluding the structural stand, and the concrete foundation for the stand, is conservatively estimated to be approximately 84kg (see Appendix H for the mass breakdown). Not included in the size and mass are the cables supporting the wind sensor mast, and a recommended fence erected around each GreenBox to discourage vandalism and theft.

4.4 GreenBox Design Overview

The GreenBox frame is designed to provide easy and safe transportation of the box using conventional transportation. The main advantage of the box is that before deployment, all the sensors and structure required for deployment are neatly packaged within the box, making it easy and convenient for stacking multiple units in a shipping truck. Due to the size and mass of the GreenBox, two to three people will be needed to deploy each device. The box was designed to be easy to install, so it is likely that only one professional with one or two assistants will be needed.

4.4.1 Pre-deployment

In its pre-deployed state, the GreenBox is only a few centimeters wider than the frame dimensions, as all components are secured within the frame with the exception of the folding solar panels that attach to the outside. The Stevenson screen is mounted on sliding arms, which are collapsed and held internally during transport. The telescoping arm that will support the radiation sensors is also dismantled and held with the frame. Finally, the removable precipitation sensor and the wind sensor are secured to the frame pending manual deployment. Figure 4-8 shows the locations of the components in this state.

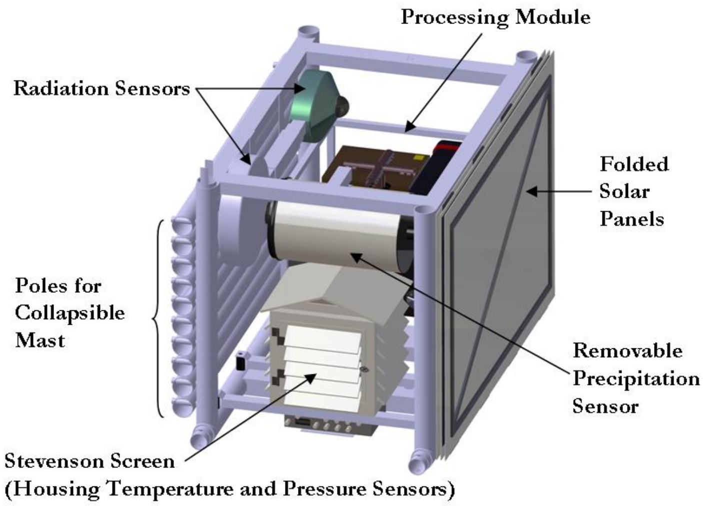

Figure 4-8: Proposed GreenBox in pre-deployed state

4.4.2 Deployment

Since each GreenBox will be deployed in a different location and the ground conditions vary, procedures for installing the structural stand will have to be determined on a case-by-case basis. The likely scenario is to secure the structural stand into a concrete foundation. The depth and width of the foundation will be determined by the soil conditions at the deployment location. Once the stand is in place, the GreenBox should be attached. Next, the individual sensors should be deployed, resulting in the configuration illustrated in Figure 4-9. The recommended order for deployment is:

1. Attach telescoping mast pieces and secure the wind sensor on top.
2. Raise mast and secure with support cables.
3. Remove the precipitation sensor from the box and secure it to the ground 2 meters away from any GreenBox component.
4. Deploy the telescoping arm with the radiation sensors.
5. Slide out the tray with the Stevenson Screen and unfold the support stand.
6. Unfold the solar panels and secure them to the support stand at the proper height (dependant on latitude of box to maximize solar array efficiency).

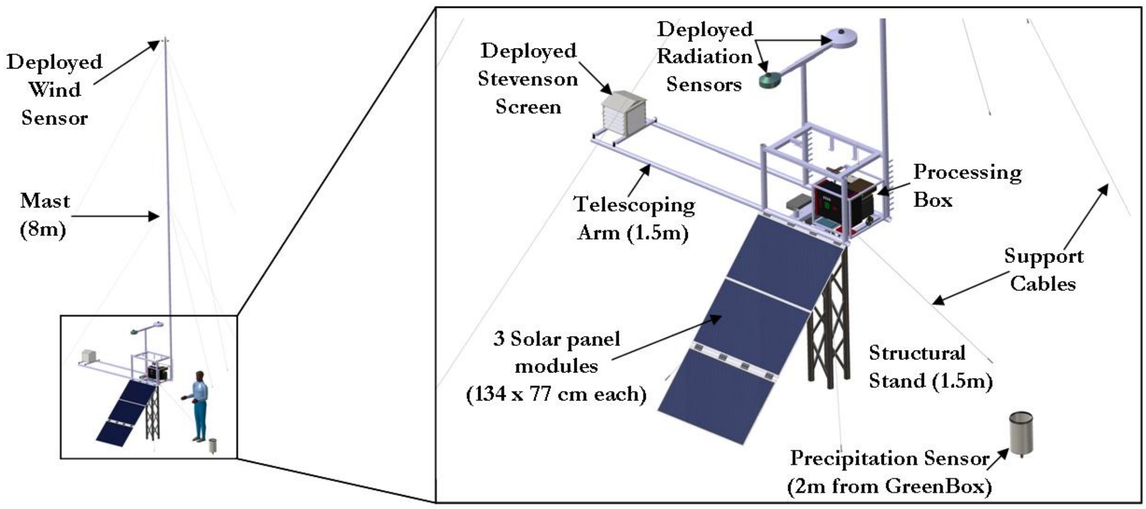

Figure 4-9: Fully deployed GreenBox

The grid of GreenBoxes would most likely consist of a mixture of these advanced devices, and a few more simplified devices that would only measure one or two ECVs. One such simplified device could be a GreenBox dedicated to monitoring only GHGs, as illustrated in Figure 4-10. This device would be significantly smaller and lighter than the full GreenBox concept.

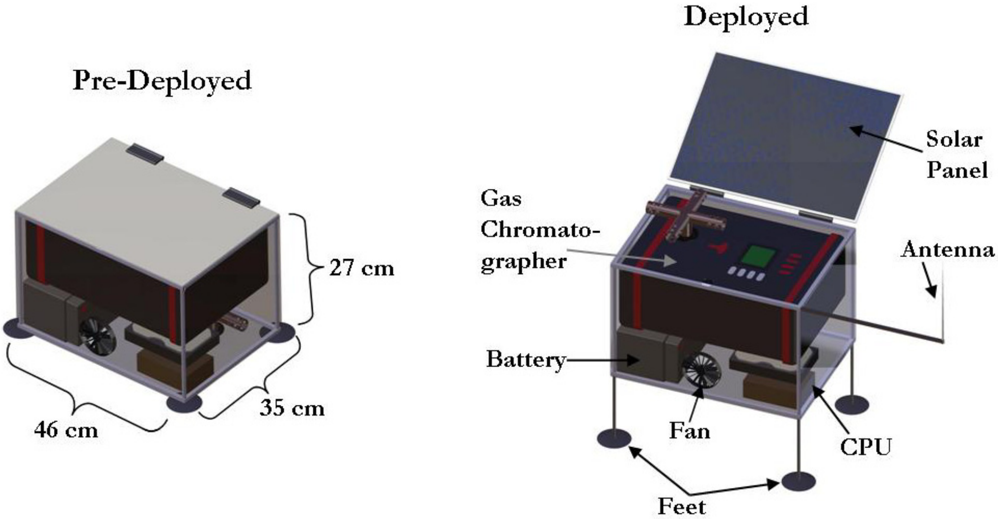

Figure 4-10: Simplified GreenBox device conceptual drawing

4.4.3 Maintenance and Lifetime

General maintenance of the GreenBox should be carried out on a monthly basis to coincide with the calibration of sensors. This general maintenance will include solar panel cleaning, battery replacement if necessary, structural inspections, and desiccant recharge. Broadly speaking, sensors will not be repaired in the field due to the remoteness of most of the sites. Also, due to the relatively low cost of most of the sensors used in the GreenBox and high staff costs, it will often be more efficient to discard faulty or broken sensors and replace them with new ones, rather than trying to repair them. Since all the sensors chosen in the GreenBox are COTS sourced, warranty agreements will be a significant factor in the overall cost of the system.

4.5 Summary

The Climate Links GreenBox provides high-quality data for augmenting satellite data, which can in turn be used for weather models, and for climate modeling. ECVs that could be measured in Nigeria were assessed, and deployment locations were suggested. Consequently, sensors to measure these ECVs were recommended, along with high-level system design requirements to support data collection. The designs presented are examples of possible configurations of the required sensors and supporting equipment. The following chapter will discuss the transmission of data to the Climate Links data center, along with the associated data management needs to process it into useful products.

5 DATA HANDLING AND INTELLIGENT SENSING

The data products from the Climate Links project are the end-result of data collection by the GreenBox devices placed throughout Nigeria. These products consist of data tailored for the scientific community and awareness products for the general public; all of which shall be made available to users via a website. Accomplishing this task requires a data management system that delivers the raw data collected by the GreenBoxes to a central data center, where processing and preparation of the data is conducted. This chapter contains the details of the resultant data products, followed by a description of the proposed data management system supporting the associated data life cycle. Considerations about the communication abilities of the data center with the devices are discussed. Finally, some strategies about intelligent management of device functionality are briefly mentioned.

5.1 Data Products

The data collected by the Climate Links project will be available for different users at differing levels of complexity. During the Nigerian pilot project only products from this location would be available. This section describes the products that Climate Links should offer to the users through a website. These products consist of data available for download by interested individuals for analysis, and the results of the analysis done using this data. The processed data will be referred to as a scientific product and the climate information on the website will be referred to as the awareness product. Hence, scientists and the public interested in Nigerian climate will have access to differing levels of data.

5.1.1 Scientific Product

The scientific product is designed to address the lack of correlation between satellite data and *in-situ* data measurements of Essential Climate Variables (ECVs). Users of this product could include scientific communities, researchers, and possibly Earth Observation (EO) satellite operators. This product provides data that has been processed and presented in a commonly practiced and accepted format.

A catalogue of all data gathered would be made available through the website to interested parties. The data could only be requested through the website. An account would have to be created by interested individuals in order to make a request for the data. After the receipt of the request, the data center would compile the required data and make it available for download. This procedure is discussed in detail in section 5.2.5. If the data contains measurements taken while an EO satellite was passing overhead, the information about the specific satellite is made available as part of the product. However, the corresponding satellite data itself would not be provided. This would encourage users to find correlations between EO and *in-situ* data being collected in Nigeria.

Since the data would be available for free to the scientists, they would be encouraged to share the information deduced from data, and their results and findings could be submitted to the data center through the website. However, this presents a sensitive issue with regard to Intellectual Property Rights (IPR). The data generated by the GreenBoxes would belong to Climate Links, while the results of a scientist's analysis would be covered under their IPR. An agreement included in the account creation process may request abstracts, articles, and images from the scientist in exchange for the data. These results would then be published on the website and act as an input to the awareness product. This method could be implemented to encourage a sense of community between climate scientists and enhance collaboration with the Climate Links project. Most importantly this would also allow the general public interested in the field of climate change to be aware of ongoing research.

5.1.2 Awareness Product

The awareness product is structured to address the lack of public knowledge about climate change, previously identified as one of the crucial needs to address climate change. It will present information directly from scientists in order to influence social, educational, public, and governmental changes. The ultimate goal is to bring the problem of climate change to a level that will influence citizen behavior. Proposed users of the public data are the general public, climate enthusiasts, and governmental and environmental agencies.

It is proposed that awareness information comes in two forms for the first phase of the system rollout. The first is the website that will display results submitted by scientists in the form of images, maps, graphs, tables, and articles as well as the ability to access the recently measured data from each device through an interactive map of the globe. The second is a subscription to a Short Message Service (SMS) sent according to selected frequency with the measurement of a few climate variables for that day and possibly interesting climate-related news. As the project becomes more established, downloadable software for smart phones would be created that can be customized to user preferences.

5.2 Data Life Cycle

Delivering the Climate Links data products to the users requires a robust data management system to handle the data throughout its life cycle. The path followed by data through capture, delivery, processing, storage, and distribution is presented in Figure 5-1.

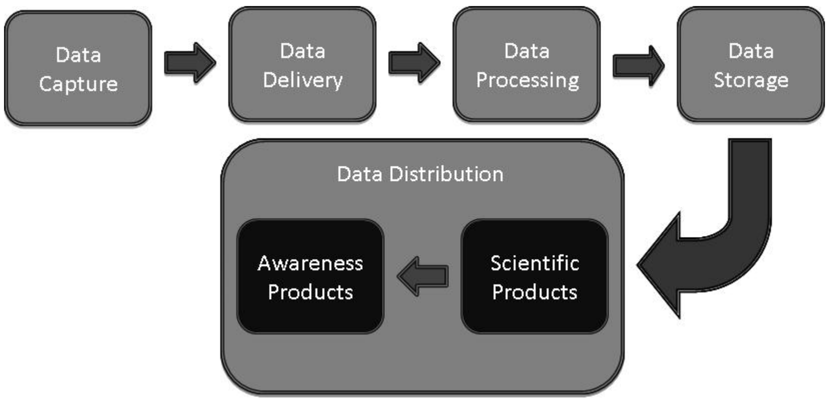

Figure 5-1: Data life cycle showing data flow from measurement to product distribution

These steps are described below in the context of the pilot project for Nigeria.

5.2.1 Capture

As described in the previous chapter detailing the GreenBox, measurements of the surrounding environment are taken by onboard sensors and coupled with associated data such as time of measurement and sensor health status information. This captured data is packaged and made ready to be sent to the data center.

5.2.2 Delivery

A GreenBox will typically take measurements at regular intervals and store a data file to be uploaded to the data center every day. To accomplish this, the use of three different network solutions is proposed depending on the local availability and costs:

- Wireless Local Area Network (WLAN) or Local Area Network (LAN)
- Global System for Mobile communications (GSM)
- Satellite Communications (SATCOM)

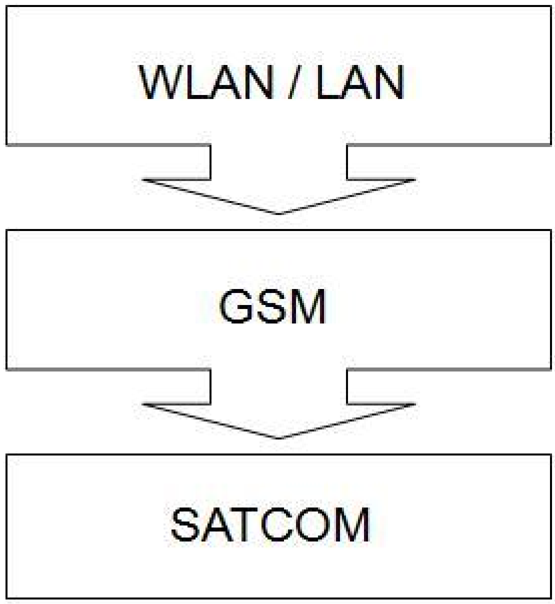

Figure 5-2: Communication Priority Sequence Protocol

The GreenBox will follow a Communication Priority Sequence Protocol (CPSP). Figure 5-2 is a graphical representation of the CPSP. By default, the GreenBox will attempt to upload its data through what is typically the least costly option, *i.e.* a WLAN or LAN connection, which is most likely to be available in urban areas. If it is unavailable, the device will attempt to upload through a GSM network. Finally, if GSM is not available, the GreenBox will try to upload via SATCOM. Failing this, the data will be stored until a connection is established through one of the mentioned networks. Various data upload service providers, together with their pricings, are listed in Table 5-1. The GreenBox is estimated to collect a maximum of approximately 600 kB of data per day, resulting in 18 MB of data per box per month.

Table 5-1: Data service provider comparison of upload rates and cost

Service Provider	Upload Rates	Pricing	18 MB/month/ box
MTN Nigeria Communications Limited (GSM)	40 kbps	1 $/MB	18 $
Thuraya Sat. Phone (SATCOM)[1]	15 kbps	5 $/MB[3]	90 $
Iridium Sat. Phone (SATCOM)[2]	2.4 kbps	0.99 $/minute	125 $

Notes: 1. (Thuraya, 2009a) 2. (Iridium, 2007) 3. (Sattrans, 2009)

In Nigeria, very few GreenBoxes would be able to use a WLAN/LAN network. The CPSP of the GreenBox would then cause it to look for a GSM network. Table 5-1 shows that usage of the local GSM operator would be most advantageous. Thuraya is the recommended SATCOM operator due to its price and upload rates in this case. Although Thuraya does not offer global coverage like Iridium, it is well-suited for the Climate Links needs in Nigeria (see Figure 5-3).

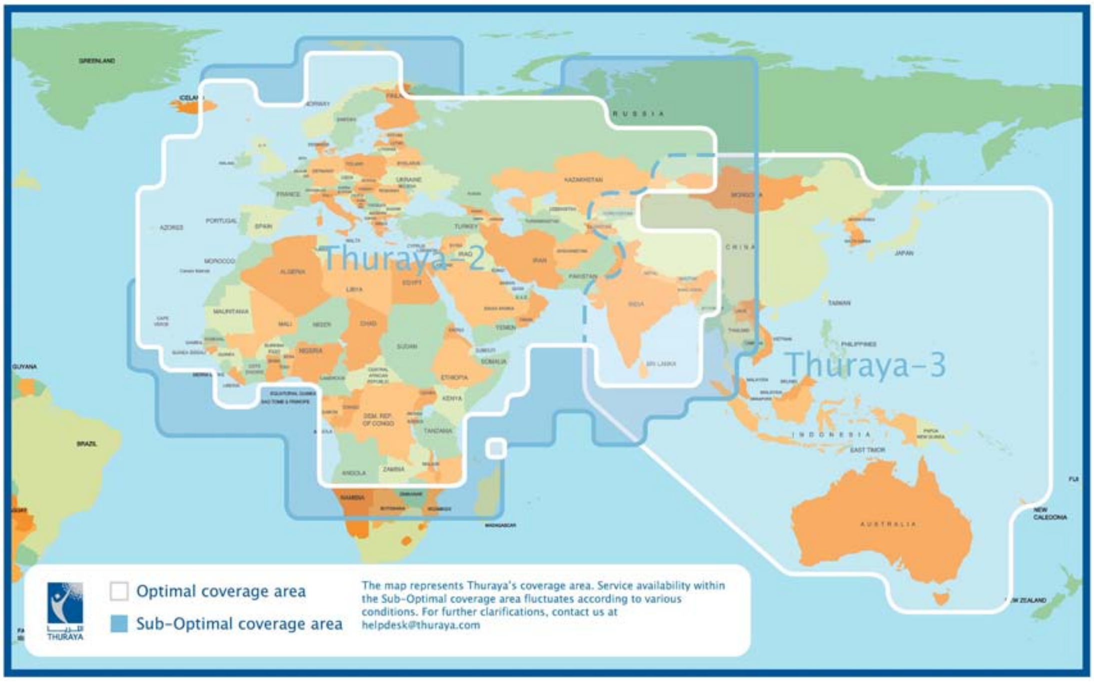

Figure 5-3: Thuraya coverage area
(Thuraya, 2009b)

5.2.3 Processing

As soon as measurements are delivered to the data center, an initial processing procedure would be required before the data is stored and organized in the database. This procedure is recommended to include rectification, filtering, classification, or validation (Günther, 1998). During the first phase of the project, the simplicity and limited volume of data sent from the GreenBox to the data center require only validation in order to avoid any undetected hazards or false alerts. Each sensor installed in the GreenBox will attach a health tag to every measurement that it performs. It is the responsibility of the data center to identify and filter out erroneous measurements through the processing procedure. These irregularities may be an indication of abnormal function of one of the sensors and can identify the need for maintenance or replacement. Another way of validating some data indirectly is to use the measurements of some sensors to extract information about the health condition of others. For instance, extreme temperature or humidity levels measured may indicate that some of the sensors are working outside their optimal conditions, and therefore would not measure accurately.

As the project scope expands towards its full deployment, the data capture procedure will become more complicated. The rectification, filtering and classification procedures will become crucial, as the volume of data grows and images are introduced. The foundation for future development and the incorporation of new features is laid out from the first phase of the project, with careful design and the greatest automation possible of the processing procedures.

5.2.4 Storage

After retrieval and processing, the data needs to be organized and stored systematically. This is an important aspect of database management since it will make the database accessible. Storage may facilitate future partnerships with data sharing portals such as the Global Climate Observation System (GCOS), as well as promote the credibility of the system to potential users. Moreover, it is important that the design of the database be flexible enough to easily include data from new sources mentioned in later phases of the rollout plan, or collaborations with other projects.

Figure 5-4 shows the delivered and processed data that is reformatted and prepared for storage. This file is stored in the database under the identification number of the GreenBox the data originated from. The method of organizing the data per the GreenBox identification number is the easiest method of organizing and keeping track of the database. In case of a failure of a box, the replacement box may have an improved sensor suit. Hence the difference between the data gathered from older generation of sensors and from the newer ones can be distinguished. Since there is a need for the database to be archived in an infrastructure accessible in the future, a procedure for migration to a new format should be established.

```
NI9550 <station identification number
9º12'00" N, 7º11'00" E <GPS coordinates
DT22.08.2009 <GPS date
TM0010:00:01:45 <GPS time

1) Sensory information: SENSORaverage;max;min;stdev
T0040,2013;0045,9000:0035,9000:0001,000 <temperature
H0040,2013;0045,9000:0035,9000:0001,000 <humidity
R0040,2013;0045,9000:0035,9000:0001,000 <pressure
WS0040,2013;0045,9000:0035,9000:0001,000 <wind speed
WDT0040,2013;0045,9000:0035,9000:0001,000 <wind direction
PAT0040,2013;0045,9000:0035,9000:0001,000 <Pyranometer
PHAT0040,2013;0045,9000:0035,9000:0001,000 <Pyrgeometer
PHBT0040,2013;0045,9000:0035,9000:0001,000 <CO2 concentration

2) Housekeeping data
NI9550, TM0010:00:01:45, TEMP10.5, ACCEL000.000
                TOK         HOK
                RO          WSOK
                WDTOK       PAOK
                PBTOK       PHATOK
                PHBTOK
```

Latitude	Longitude	Date	Time	Satellite Tag	T_{AVG}	T_{MAX}	T_{MIN}	T_{STDEV}	--
9.175833	7.180833	22.08.2009	19:45:05	-	39.2013	39.2045	39.1981	0.0020	...
9.175833	7.180833	22.08.2009	19:46:05	ENVISAT	39.2009	39.2043	39.1980	0.0018	...
9.175833	7.180833	22.08.2009	19:47:05	-	39.2001	39.2039	39.1977	0.0016	...
9.175833	7.180833	22.08.2009	19:48:05	-	39.2000	39.2037	39.1979	0.0023	...
9.175833	7.180833	22.08.2009	19:49:05	-	39.2001	39.2038	39.1981	0.0020	...
9.175833	7.180833	22.08.2009	19:50:05	-	39.2002	39.2039	39.1976	0.0022	...
9.175833	7.180833	22.08.2009	19:51:05	-	39.1998	39.2036	39.1975	0.0019	...

Figure 5-4: A sample of processed data (Top), and the reformatted file ready to be stored (Bottom)

Data centers are a core element of large-scale data collection, processing, storage and distribution systems. For the expanded global system, the data center will most likely be a dedicated building where large amounts of data will be brought together from collection devices around the world. However, in the case of the pilot project in Nigeria, the annual amount of data to be captured and stored is approximately 20 GB per year. This quantity can easily be handled by a commercial-off-the-shelf server. This server can be located in virtually any location with good connectivity to the Internet. The advanced telecommunication networks existing in urban Nigeria mean the server could be located at a university, encouraging collaboration with local researchers and students, who could assist in the maintenance of the server and handling of any problems.

5.2.5 Distribution: ClimateLinks.org

The data collected by the Climate Links system would be distributed through the project's webpage as mentioned in section 5.1. The website is recommended to be an interactive user interface that would distribute information about the Climate Links project, the data gathered by the deployed sensors, and the results from scientific analysis. The website would deliver information with the aim of reaching a wide range of audiences. This may include school aged children to university scholars. The goal of the website would be to benefit the scientific community by providing essential correlated data for analysis, as well as create awareness for social change.

It is recommended that the data center host the design, development, updating, and maintenance of the website. Authentication of information, layout, and navigation of the site should be considered as essential criteria as it is developed (Westbomke *et al.*, 2004). Standard architecture and available technologies should also be used. The website could look like the snapshot shown in Figure 5-5. The following list outlines suggestions for the design, development, and presentation of a website for effective communication (Westbomke *et al.,* 2004):

- Develop the site using Extensible Hypertext Markup Language (XHTML) to ensure optimal speed and compatibility with all browsers
- Clear and simple layout
- Easy navigation
- Simple and effective pull-down and pop-up menus
- Use English as the official language. (For global expansion, the site could be translated to other common languages)

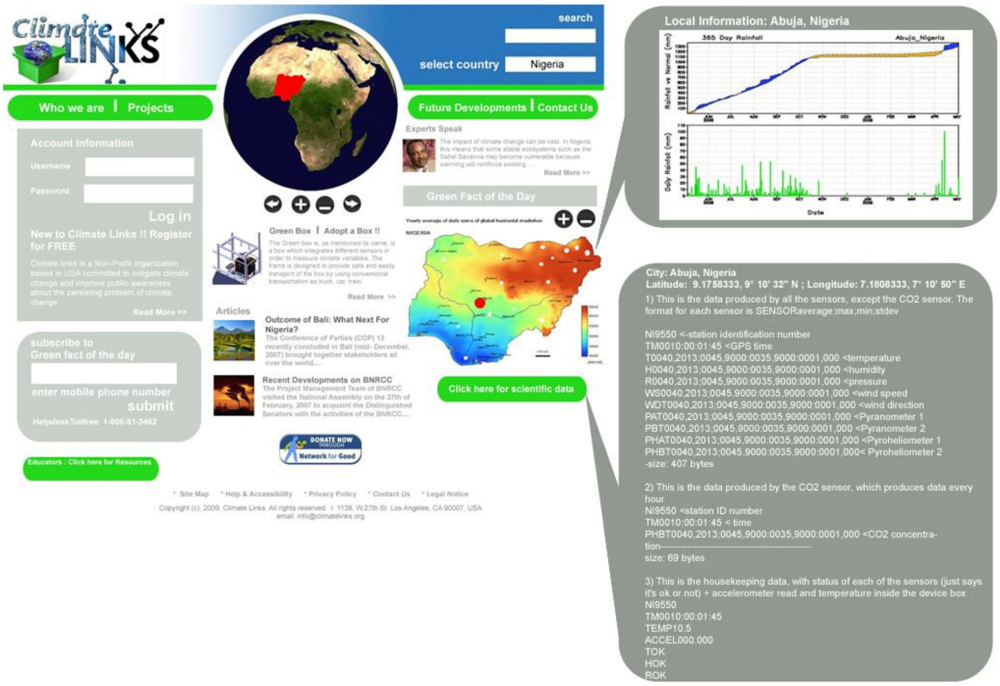

Figure 5-5: A sample image of the fully functional ClimateLinks.org

The scientific product would be accessed through the website by a search process. The users could identify the coordinates (geographical location), time, date, or the ECV(s) of interest. A snapshot of the potential query page is shown in Figure 5-6. With the identified search parameters a request would be sent to the data center. Upon receiving the request, the data center would compile the data needed for the user, and make it available for download through a file transfer protocol (FTP). To avoid overloading the FTP server data would only be made available for 72 hours.

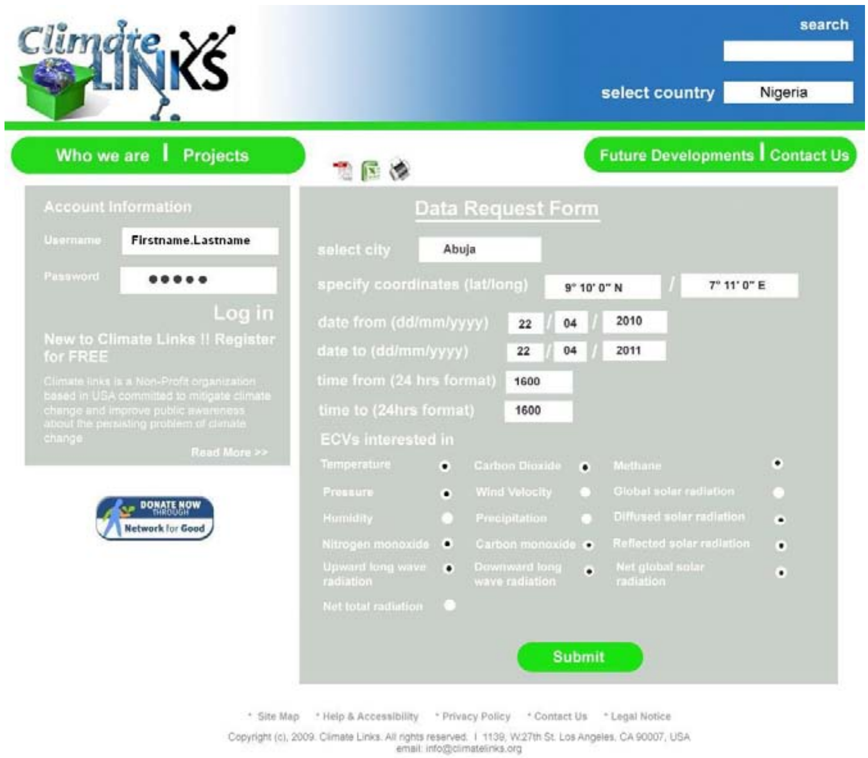

Figure 5-6: A sample snapshot of the data request page

5.3 Intelligent Sensing

The ability of the data center to communicate with and command the GreenBox is very important as the boxes can be prompted to perform various tasks that are not routine. As shown in Figure 5-7, the data center would be capable of communicating with the GreenBox through WLAN and LAN, GSM, and SATCOM using the Internet portals provided by MTN Nigeria and Thuraya. For reception of the commands from the data center the device should follow the same CPSP outlined by Figure 5-2. This method is free of charge when a contract has been established with the service provider. Communicating with the device using this method minimizes the necessary capabilities of the data center.

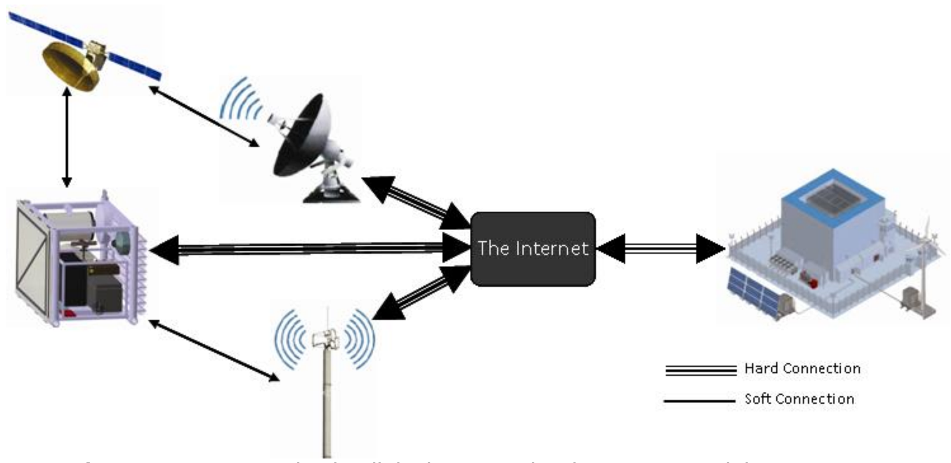

Figure 5-7: Communication links between the data center and the GreenBox
Hard connection and soft connection are the wired connection and radio connection respectively, between the shown entities

Through this capability any software update can be done remotely without on-site presence. Another advantage is that in case of anomalous weather conditions, possibly hazardous to the box, the GreenBox could be commanded to halt measurements as data measure at this time may not be useful.

5.3.1 Prompting

The primary goal of the Climate Links project is to add value to satellite imagery by performing synchronized *in-situ* measurements. Synchronicity would be accomplished as the data from the GreenBox is tagged with the name of the EO satellite that encompassed the box in its swath width during its observation. The data center would be aware of the satellite orbital parameters and would be capable of alerting devices when synchronous measurements could be made. This could lead to the device altering its measurement schedule. This process will ensure that measurements made by the device will be made at the time a satellite is taking measurements of the area around the GreenBox.

In order to accurately make synchronous measurements, the data center would need to receive updates regarding orbital changes of relevant satellites. There is publicly available data regarding the trajectories of EO satellites. A popular source of data is the North American Aerospace Defense Command, which publicly releases Two Line Elements (TLEs) which can be used to predict the position and velocity of satellites (Hoots and Roehrich, 1988). The TLE sets are updated regularly to maintain reasonable predictability. Satellite tracking software like Nova, create algorithms which take TLEs and provide prediction of the satellites' real time orbital parameters. A Nova license is of minimal cost to the user and updates are free (NLSA, 2008).

Satellites such as those belonging to the National Oceanic and Atmospheric Administration (NOAA) (Rogers *et al.*, 1997), Landsat (Nichol, 1997), and MeteoSat are EO satellites measuring ECVs over Nigeria and Africa. The Nigerian government may also wish to combine GreenBox data with NigeriaSat-1 observations, to add value to the images. They are but four examples of satellites that can be tracked using TLEs and can be used specifically for the Nigerian pilot project.

5.4 Summary

Large data collection projects such as Climate Links require several steps in the data life cycle to move data from the measuring devices to the end user. In the context of the pilot project in Nigeria, scientific and awareness products are proposed, and the data capture, delivery, processing, storage, and distribution stages that could make these products available are presented. Data center communication with the GreenBoxes are discussed incorporating the correlation of the GreenBox data with EO satellites sensing the same location at relatively the same time, instrument housekeeping data, and simultaneous data measurement.

Both a GreenBox design and the data management infrastructure are needed to complete Phase 1 of the rollout plan. Neither of these aspects, however, would be possible, in Nigeria, without cooperation with the Nigerian government. While the Climate Links project has many positive aspects, it must also meet the political and legal constraints within Nigeria. The following chapter explores these issues of promoting the rollout of this system and delves further in to the financing of such a system.

6 FACILITATING THE PILOT PROJECT

The Climate Links pilot project requires not only a strong technical infrastructure but also good business, legal and financial support. This chapter begins by demonstrating the scientific strengths that Climate Links could bring to Nigeria as a result of the technical infrastructure. It continues by outlining the costs and the fundraising strategies that could be utilized by the proposed non-profit organization to finance the Nigerian pilot project. Finally, a brief investigation into the legal and ethical difficulties of establishing Phase 1 is presented.

6.1 Scientific Benefits for Nigeria

Given the social and political benefits presented in Chapter 3, this chapter discusses the scientific benefits of Climate Links for Nigeria. Climate Links is designed to provide data to complement Earth Observation (EO) satellite data and to enhance regional and global climate models. In addition, the data may be useful for weather observations and prediction.

6.1.1 Data Correlation and West African Climate Modeling

Nigeria, as a country in West Africa, is a region where climate research needs to be improved (Messer, 2002). This can be accomplished through the use of nested regional climate models, pictured in **Figure 6-1**. The more detailed regional models, with higher spatial resolution of local climate drivers, improve global climate models. The regional models can more accurately predict, with greater confidence, precipitation from the seasonal monsoons for Nigeria and surrounding countries, thereby providing better understanding of the climate.

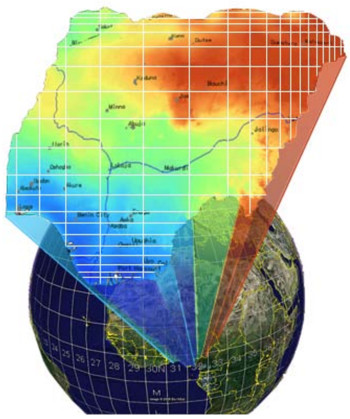

Figure 6-1: Artist's conception of regional climate models nested in a global model

Observations at a 10 to 50 km scale are needed to drive these regional models. This data is readily available from satellite observations but there are some phenomena, such as aerosol loading in the atmosphere, which cause a bias in satellite measurements (Bellouin *et al.*, 2005). Aerosol loading is a localized effect, making numerous ground stations necessary. The Climate Links GreenBoxes will provide a cross-correlation basis for filtering out the bias in the satellite measurements.

Another reason to implement the ground station network proposed by Climate Links is to provide Earth surface data when cloud cover prevents satellite instrument readings. Finally, the

GreenBox deployment in Nigeria, and the resulting synchronous satellite and ground datasets, will provide needed data for climate researchers. Results of the research will give Nigeria a better understanding of its climate, and better prepare the government and people for the effects of climate change.

6.1.2 Improving Weather Predictions

Weather forecasting through the use of GreenBox data should also be considered. The Nigerian Meteorological agency (NIMET) has installed 37 Automatic Weather Observing System (AWOS) across the country in addition to the 55 Manual Weather Observing Systems, (MWOS) and more are planned for the future (Aderinto, 2006). The Climate Links team contacted Dr. Ernest Afiesimama of NIMET and confirmed that most of the AWOS systems are now functional and that 48 fully equipped weather stations are now reporting hourly information to their head weather center (personal communication, May 6, 2009).

The AWOS and MWOS used by NIMET, show discrepancies in the data acquired. One reason is that the MWOS use analogue data systems which have some standard errors when converted to digital standard. Climate Links' GreenBoxes would be able to close the gap as it acquires data in a digital format similar to AWOS. Data reliability and authenticity are two important factors in scientific and research applications. Having two independent observing systems, which are co-located and measuring the same environmental climate variables, would offer a way to ascertain data reliability and authenticity for end users. In the case where MWOS observes along with the other two, data acquired from the other two systems could be used to calibrate the MWOS stations so that its output would meet acceptable standards. Moreover, the three observing systems working at the same time in the same location increase the density of the existing network, creating redundancy necessary for measuring the ever-changing climate variables at different special and temporal scales (Aderinto, 2006).

Because of the potential for a mutually beneficial relationship between NIMET and Climate Links, it is suggested that a partnership be formed. This cooperation could include placing the GreenBoxes or the MiniBox at AWOS or MWOS locations, so as to take advantage of the land rights granted to NIMET, and possibly also power and maintenance sharing. The grid representing the placement of GreenBoxes according to the World Meteorological Organization's (WMO's) guidelines ought to be shifted to maximize the overlap of GreenBox positions with NIMET stations. An initial overlap is shown in **Figure 6-2**.

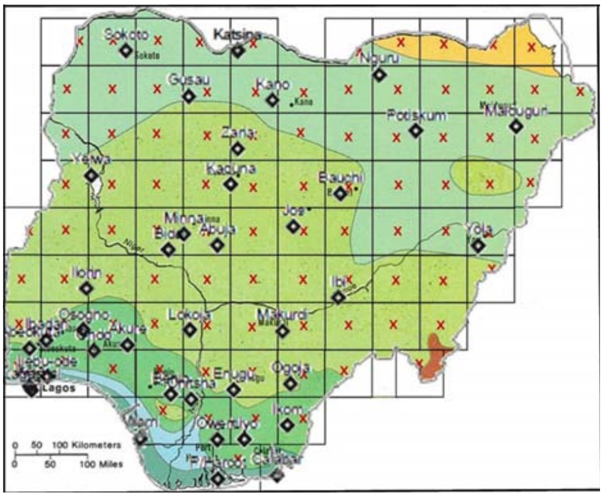

Figure 6-2: Weather stations overlay on Nigeria GreenBox map
The black diamonds are NIMET stations and the 'x's' are proposed locations for the GreenBoxes.
(Adapted from: Aderinto, 2006)

6.2 Phase 1 Costs

Many funding sources and options have been investigated in order to complete Phase 1. The nature of the suggested Non-Profit Organization (NPO) is to offer much of the system at no charge making funding crucial.

To accomplish this, the following resources will be needed:

- Human: reaching a maximum of 16 for the duration of the pilot project
  - Founders and board of directors
  - Fundraisers
  - Designers and engineers for prototyping the Green Box
  - Data center employees
  - Field Personnel
- Physical:
  - Office space – in both the US and Nigeria
  - Data server
- Financial: USD 15 million to cover the costs of Phase 1, to be raised using:
  - Government funding
  - Grants
  - Donations
  - Sponsorship
- Intangible:
  - Partnerships (for manufacturing, distribution, phone service, and other logistical issues)
  - Branding and organizational image

6.2.1 Management and Staff

An environmental NPO requires strong management and staff in order to confront the many challenges of remaining relevant in a world of competing demands. The key staff includes the director, communications manager, grant manager, technical personnel, and the field office director. This management team must know the business of environmental non-profit organizations so that they can manage the staff effectively, keep costs low, and leverage partnerships with industry and government. Total employment costs are detailed in **Table 6-1**.

Table 6-1: Estimated staff costs for Phase 1 in the US and Nigeria

Cost of Employees	1	2	3	4	5	6	7
Director	$135k	$135k	$135k	$135k	$135k	$135k	$135k
Communications Manager	$113k	$113k	$113k	$113k	$113k	$113k	$113k
Grant Manager	$90k	$90k	$90k	$90k	$90k	$90k	$90k
Office Administrator	$0k	$0k	$53k	$53k	$53k	$53k	$53k
Engineer	$90k	$90k	$90k	$90k	$90k	$90k	$90k
Technical Support	$0k	$0k	$60k	$60k	$120k	$120k	$120k
Data Management Director	$90k	$90k	$90k	$90k	$90k	$90k	$90k
IT Specialist & Web	$60k	$60k	$60k	$60k	$60k	$60k	$60k
Field Technicians	$0k	$23k	$45k	$68k	$90k	$90k	$90k
Field Office Director	$75k	$75k	$75k	$75k	$75k	$75k	$75k
Field Office Staff	$0k	$30k	$30k	$30k	$60k	$60k	$60k
Total Payroll	$653k	$705k	$840k	$863k	$975k	$975k	$975k

The fundraising and grant managers are essential for selling the project. They must establish and manage the relationships with donors in order to keep the organization financially viable. They are salaried staff because the nature of most NPOs requires funding throughout the life of the organization.

Once the pilot project has shown its potential and begins to expand to other areas of the world, new talent should be brought on board to grow into a larger organization. In addition to the key management, a support staff is required to execute the plans and strategy of the organization. The staff hiring is estimated in Table 6-2. The management and two staff members are recommended to start the organization in the first year and then more staff would be brought on to facilitate developments as the project progresses. The breakdown shown does not include the contract with a local company in Nigeria for the manufacture of the GreenBoxes.

Table 6-2: Staff Hiring

Employees	**1**	**2**	**3**	**4**	**5**	**6**	**7**
US Staff	5	6	8	8	9	9	9
U.S. Payroll	$578k	$578k	$690k	$690k	$750k	$750k	$750k
Nigeria Staff	1	3	4	5	7	7	7
Nigeria Payroll	$75k	$128k	$150k	$173k	$225k	$225k	$225k

6.2.2 Balance Sheet

The boxes are estimated to cost approximately USD 44 thousand each for the components and materials. Since the organization proposed will not own a manufacturing plant, a company will need to be contracted for the integration of the GreenBoxes. Choosing a company in Nigeria reduces shipping costs while supporting employment and technological capabilities. A concern for this contract may come from export regulations associated with any sensitive parts coming from the US. Two solutions are selecting non-sensitive components or licensing all employees of the Nigerian company.

The anticipated cost associated with Climate Links compared to the amount of funding expected is shown in Figure 6-3. The image also includes a third variable depicting the money remaining at the end of each fiscal year. As an NPO this money will be reinvested in the next year's activities, helping to lower the need for new sources of funding. The increase of net cash at the end of years four through six are in anticipation of the extra funds needed to begin Phase 2.

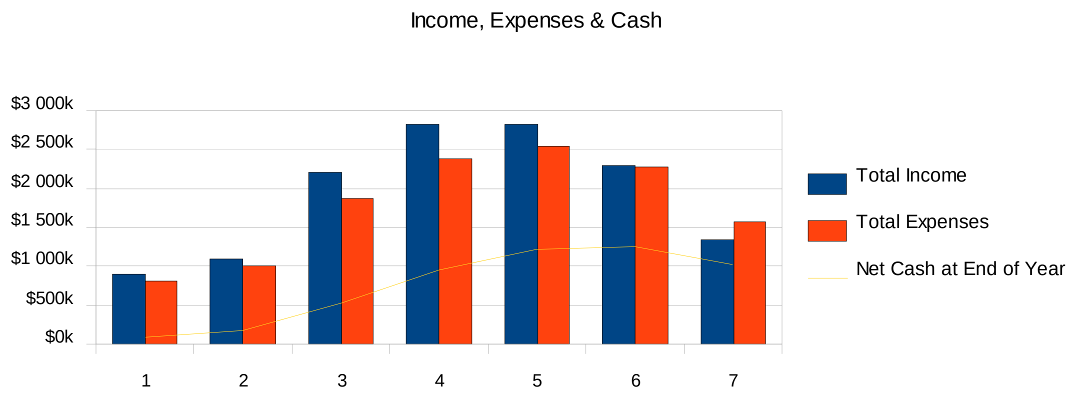

Figure 6-3: Projected costs and funds.

6.3 Funding Options

An important consideration in obtaining funding is the user base, which drives costs for the services and products offered. The goal of the NPO proposed for Climate Links is to collect data and provide it to as many users as possible, specifically scientists, researchers, and the general public. If the data products are made available free of charge, then funding for the NPO must come from other sources in order to achieve its goals.

The main sources of funds for NPOs can be categorized into four donor markets (Andreasen and Kotler, 1996):

1. Individual donations
2. Corporate donations
3. Government grants
4. Foundations and trusts

Given the global scale and technological complexity of this project, all four donor markets are considered. The following section provides a basic description of each market, as well as possible contributors specific to this project.

Non-profit corporations receiving tax-exempt status under the previously mentioned section of the IRS Tax Code must receive at least one third of their support from the general public. Individuals are a major source of donations for many NPOs, with some claiming they account for as much as 81 % of total income (Andreasen and Kotler, 1996). However, it is increasingly difficult to obtain these funds due to the growing number of NPOs, a slow growth rate in individual donations, and the current economic recession. Moreover, the donation amount depends on the nature of the cause. Fortunately, climate change currently has great philanthropic appeal. Finally, donor recognition is an important concept for long-term projects, and developing a loyal donor base is vital for sustainability (Sargeant, 1999).

Historically, corporate donations have been largely underutilized. In the US, corporate donations typically amount to less than one percent of a company's pre-tax income, even through up to five percent may be donated (Andreasen and Kotler, 1996). The Climate Links project intends to take advantage of this resource in light of trends in corporate responsibility, 'green' public relations arising from climate change policies, and increasing interest from consumers. Many corporations have declared support for green practices and reduction of GHG emissions. Such support implies that those companies may be a funding source for the project. Corporate support does not need to be limited to monetary funds as there is great value in various forms of alternative support, such as offering products and services at reduced rates.

Government agencies may prove to be the largest sources of funding for this project, since the US, Nigeria, Spain, and other nations invest heavily in scientific and environmental development. For example, the NSF has an annual budget of more than USD six billion and currently supports many projects focused on climate change. More specifically, the Pilot Climate Process and Modeling Teams grant is dedicated to improving the accuracy of climate models by bringing together field observations and modeling centers. To date, this grant has made over 500 awards, some exceeding USD one million (NSF, 2009a). Table 6-3 below summarizes several possible grants from the NSF.

Table 6-3: Possible NSF grants for the Nigerian pilot project (NSF, 2009a).

NSF Program	**Description**	**Pilot project contribution**	**Maximum Award (USD)**
Science and Technology Centers: Integrative Partnerships	This grant is for innovative research and education projects that are carried out via international collaborations and require large-scale, long-term awards. It funds research at the interfaces or disciplines or fresh approaches within disciplines.	Entire project	713,551
Pilot Climate Process and Modeling Teams	The key aim of this grant is to speed up development of global coupled climate models and reduce uncertainties in climate models.	Entire Project	Over 1,000,000
Communicating Research to Public Awareness	This grant supports projects that communicate to public audiences the process and results of current research that is being supported by any NSF directorate through informal science activities.	Public outreach website	75,000
Developing Global Scientists and Engineers	The purpose of this grant is to provide international research opportunities for US students.	Funding a US researcher in Nigeria	772,175

The EPA is another US government agency that awards grants to environmental projects. For example, the Environmental Education Grants program supports projects that "enhance the public's awareness, knowledge, and skills to help people make informed decisions that affect environmental quality" (EPA, 2008). Annual funding from this project ranges between USD two and three million, with most grants being USD 15 to 25 thousand in size.

Foundations and trusts exist to manage funds from various sources to a specific cause. For example, the Earthwatch Institute is an international NPO that raises approximately USD 15 million per year from various individuals, corporations, institutes, and governments around the world. As one of the world's largest private funds for scientific research, it places a high priority on projects that benefit the global scientific community, specifically including those for long-term climate change monitoring (Young, 2008).

Nigerian grants may come from various sectors, including:

- Federal Ministry of Education
- Federal Ministry of Science and Technology
- Federal Ministry of Information & Communications
- Federal Ministry of Environment, Housing and Urban Development

Nigeria has also been working closely with UNESCO to develop a Nigerian National Science Foundation, similar to that of the US. As of 2008, the proposal was an endowment of USD 5 billion to establish the Foundation, which would be responsible for distributing grants on a competitive basis (Waldrop, 2006). At the moment, the proposed Foundation is only a draft bill that is to be considered by the Nigerian Parliament (World of Science, 2008). However, assuming it is established within reasonable time, it could be a primary source of Nigerian funding for the Climate Links pilot project.

6.3.1 Private Donations

Donations made to a charity are made without the expectation of monetary returns. However, some top donators appreciate a feeling of importance and personal connection with their chosen project. Donor recognition can come in many forms, ranging from mass monthly newsletters to personal phone calls to high-value donors (Sargeant, 1999). One way to connect interested persons to the Climate Links system is with an adoption program. There could be various levels of cooperation: adopting a box, sponsoring the field technician who checks up on a specific area, or sponsoring the project in an entire region.

Given the philanthropic nature of the pilot project, personal donations may prove to be a source of small but consistent funding. One way to connect interested persons to this system is with an adoption program, such as adopting a box so that a school in Nigeria can engage in interactive science.

6.3.2 Technological and Industry Partnerships

Given the global scale of climate change and the continually growing number of projects addressing the issue, partnerships with existing initiatives may prove to be a considerable source of non-monetary support. One strong candidate is the Earthwatch Institute, which has been dedicated to offering volunteers the opportunity to join research teams around the world since 1971. As an active promoter of public involvement in understanding and mitigating the impacts of climate change, a partnership between Earthwatch and Climate Links would be ideal. Its interests are aligned with those of this project, and Earthwatch has already established climate change contacts and research centers around the world (Young, 2008).

Partnerships may also provide alternative support in the form of sponsorship, as corporations seek to improve their corporate responsibility. For example, as part of their corporate social responsibility program, Cisco partners with NGOs and NPOs and provides their services for the benefit of humanity (Cisco, 2009).

6.4 Legal and Ethical Considerations in Nigeria

As a part of starting a new venture, it is recommended that a thorough investigation of any ethical and legal ramifications of setting up this system be conducted. Some of the high level considerations are presented in the following sections.

6.4.1 NPOs in Nigeria

Implementation of the Climate Links system in Nigeria would require incorporation as an NPO within Nigeria. Nigerian law requires that, before obtaining a place of business or an address for service, all foreign corporations register within the Nigerian system (Federal Republic of Nigeria, 1990). This would allow for a local Climate Links presence during the pilot project and also ease some of the difficulty in applying for grants and funding available in Nigeria. NPO incorporation would also grant individual liability coverage for Nigerian counterparts.

As was demonstrated in Chapter 3, the incentives for Nigerian support for the Climate Links pilot project are numerous from a policy perspective. Obtaining the right political connections would increase this support further. Using the Building Nigeria's Response to Climate Change (BNRCC) organizational approach, the Climate links system would work closely with government agencies such as the Nigerian Meteorological Agency, National Emergency Management Agency, and State Environmental Protection Agencies (BNRCC, 2008b).

6.4.2 Data Distribution Liability

To manage potential data distribution liability issues, data provided to scientists should come with a disclaimer. Data disclaimers are common and used by organizations such as the Southeast Atlantic Coastal Ocean Observing System (SEACOOS) when supplying professional data. An example disclaimer has been adapted from the SEACOOS and can be found in **Table 6-4** (SEACOOS, 2004).

Table 6-4: Sample disclaimer for Climate Links data distribution

Scientist Data Disclaimer
The dataset enclosed within this package/transmission are only as good as the quality assurance and quality control procedures outlined by the enclosed metadata reporting statement. The user bears all responsibility for its subsequent use/misuse in any further analyses or comparisons. The Climate Links corporation does not assume liability to the Recipient or third persons, nor will Climate Links indemnify the Recipient for its liability due to any losses resulting in any way from the use of this dataset.

Such data liability and access policies are often drafted in accordance with national standards or guidelines, such as ANSI/ASQ E4 (2004). This affords a certain amount of legal protection, as such guidelines may be considered best practices. By having such a disclaimer as part of the terms and conditions that users must agree to, the Climate Links project can be protected from potential litigation as a result of data dissemination.

6.4.3 Technology Transfer

Technology transfer refers to the diffusion of technologies and technological cooperation between and within countries (Odekunle, 2008). Legal issues surrounding technology transfer include:

- Intellectual Property Rights (IPR)
- Unwillingness of developed countries to divulge environmental information
- National security
- Government policies (tariffs, trade barriers, *etc.*)

Technology transfers are generally required in the context of climate change when the effects of climate change occur faster than a population can respond. To address climate change in Nigeria there is a need for technological innovation and rapid transfer. The Climate Links system would have to verify that all technology transfers followed Nigerian and US laws.

6.4.4 Ethics

In terms of data collection in sensitive areas, freedom of information could be both a legal and ethical issue. Nigeria depends heavily on its natural resources, such as oil, and the amount of GHGs in the atmosphere near processing plants may be confidential information. Under these circumstances, the climate data would not be accessible and the locations of the GreenBoxes would have to be adjusted accordingly. This raises an ethical question of how to balance the importance of environmental research and protection with the country's economic imperatives.

6.5 Summary

The focus of the Climate Links system can help improve Nigeria's climate monitoring and technological capabilities. Beyond the primary intent to support satellite observations and to enhance regional and global climate models, the project can offer enhanced input for weather modeling and forecasting. The funding needed to hire staff and purchase the GreenBoxes are made possible through grants and support from governments, environmental groups, institutions, and private individuals. These financing avenues will hopefully expand as the project diversifies and spreads around the globe. Such future ambitions are examined in the following chapter.

7 FUTURE DEVELOPMENT

The ultimate goal of the Climate Links project is to enhance the usefulness of satellite data and promote public awareness through participation. To implement the complete Climate Links system a five-phase rollout plan is described in Chapter 3. The details of the first phase are discussed in earlier chapters, highlighting the GreenBox design, the data management requirements, the final data products, and the legal and policy consideration. This chapter discusses future developments of the GreenBox and introduces the GreenPhone concept in more detail. The results of a survey that sampled a small cross section of the Climate Links team's peer group are discussed to evaluate the reception of a GreenPhone type device. The high level future discussions of this chapter are meant to give the reader an idea as to why the expansion of the Climate Links project, beyond Phase 1, is critical to completing the vision of combining *in-situ* measurements with public participation.

7.1 Future Development of the GreenBox

The rollout plan presented in Chapter 3 recommends global expansion once the pilot project is complete. The recommended rollout strategy beyond the Nigerian pilot project begins in the equatorial regions of the world where there is a lack of useful climate data being collected (IPCC, 2007). Initial deployment in equatorial regions would expand to mid-latitudes and finally toward the poles.

The GreenBox presented in Chapter 4 is designed to work within Nigerian weather parameters. As expansion to other areas begins, slight modifications will have to be made based on geographical weather requirements. The modular design of the GreenBox, with all sensors and components removable and replaceable, allows for suitable modifications depending on climate.

The first major modification to the Phase 1 GreenBox, after making it suitable for different environments, would be to make it smaller. By making a smaller version of the GreenBox it would have the option of being mounted on, or integrated into, vehicles. The increased mobility would allow for each box to gather data over a larger geographic area. Satellite data could then be verified in more locations minimizing any location biases and maximizing the geographically varied data validation.

The GreenBox would need to be modified in order to allow it to function on mobile platforms. From the Phase 1 GreenBox, a smaller and more aerodynamic device would be developed. This would first require the development of sensors that could operate accurately while in motion. Sensor miniaturization is also important to minimize both the weight and power consumption. These mobile boxes could utilize a power source provided by the platform, as opposed to the Phase 1 edition's solar panels.

The individual platforms heavily influence the GreenBox design and must also be taken into account. For example, the GreenBox that would be placed on a ship would need to consider conditions such as high humidity, salt-water, and waterproofing. Because the GreenBox would be in motion under significantly different circumstances, speed and vibration frequencies would become design requirements. It must also be remembered that all climatic regions could be experienced by a moving platform traversing large distances.

The concept of increased device mobility and global system expansion enhances support for satellite observations while creating the necessary infrastructure for public involvement. Future changes to the GreenBox design would enhance the overall capabilities of the Climate Links system by increasing satellite verification capabilities and global coverage. A more global system could also utilize more satellites and increase the added-value to satellite data already in use.

7.2 Development of the GreenPhone

As is discussed in Chapter 2, there is not only a well-established need for *in-situ* data collection to complement remote sensing data but also a need to increase the mitigation of anthropogenic climate change. The Climate Links project takes a unique approach to these problems by including the public in climate monitoring in order to increase awareness and to begin to change destructive behavior patterns. The development of the GreenPhone as a participatory sensing device is critical to the culmination of the Climate Links system.

The GreenPhone rollout ought to allow for the maturity of technology and data management. The phases of the total rollout plan can be found in Chapter 3 and are listed in a reduced fashion for the GreenPhone in Figure 7-1. Since public participation is a main goal of the Climate Links project, a key feature of the GreenPhone application will be to prompt the user for data collection when a satellite passes overhead. This enables collection of data synchronously with a satellite pass and helps inform the public about the role of Earth observation satellites in climate monitoring. All data would be collected by the data center and processed for quality control. Finally, the website interface would make this data available for climate enthusiasts.

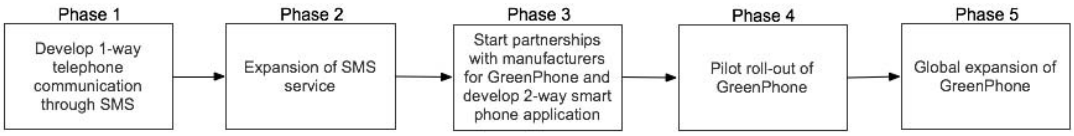

Figure 7-1: Phases of the GreenPhone development

The GreenPhone will be made available in the later phases of the rollout plan, once the infrastructure and operations for the GreenBox are well understood. The phone will most likely be developed in partnership with existing mobile phone companies, since phones with embedded sensors are under development now, rather than trying to penetrate the cell phone manufacturing markets. The GreenPhone aims to actively involve the public in climate change studies, at minimal cost, without users having to go through complicated training procedures.

7.2.1 Importance of Participatory Sensing

Increasing connectivity and affordable ubiquitous sensors are leading to a new participatory sensing movement that Climate Links could exploit to gather large datasets while increasing public awareness and activism. This movement is known as participatory sensing, sometimes called 'citizen science' or 'urban sensing'. Users of the GreenPhone would be able to monitor and measure Essential Climate Variables (ECVs), share data, and request and view relevant information. According to Lane *et al.* (2007), there are two types of 'grass-roots' sensing: participatory and opportunistic. Both need to be considered when designing the phone application.

Participatory sensing includes user-in-the-loop decision having the user actively record data when prompted by an application. System designers must consider the human as part of the system when designing such devices and applications. The system should encourage users to participate in order to generate sufficient data points. Moreover, participatory sensing provides the opportunity to add key metadata information through a carefully designed user-survey with three or four questions to help determine in which environment the sensor is functioning. This will ensure that the collected data increases in value and meaning to the scientific community.

For opportunistic sensing the phone autonomously collects data under the specific predetermined conditions. Opportunistic sensing is better suited to collecting data non-intrusively. This type of sensing could be used if the sensor technology is available. However automatic sensing may be skewed when measuring environmental variables due to proximity to the body.

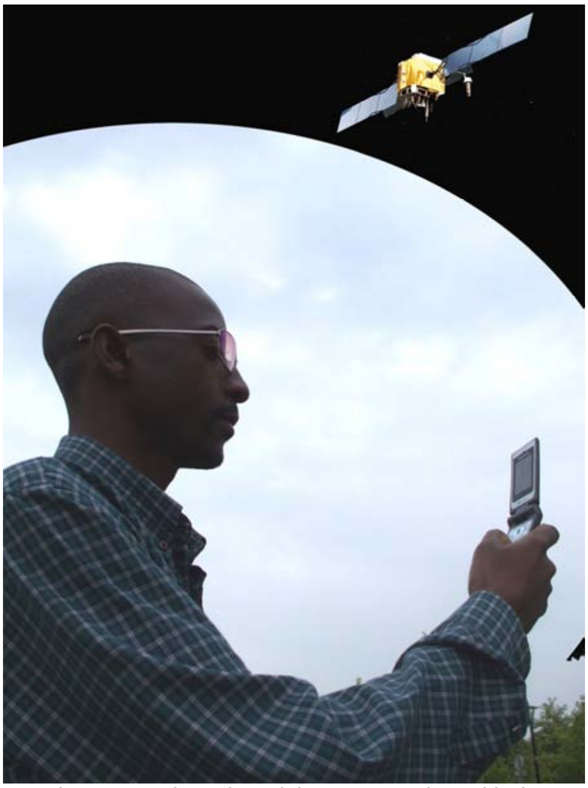

Figure 7-2: Artist conception of participatory sensing with the GreenPhone

As mobile phones become more sophisticated, they are trending away from being a simple communication device towards being a networked personal information system. The mobile phone industry represents a good method for Climate Links to personally involve many users in climate data collection. For example, in 2007, the number of subscriptions for mobile phones worldwide was 3.35 Billion (ITU, 2009). The correlation of publically collected data with satellite data involves the user in space data enhancement. **Figure 7-2** represents an artist's conception of the link between the GreenPhone user and the satellite data collection.

7.2.2 GreenPhone Design Guidelines

When designed in detail, the hardware and software application for the GreenPhone, should meet current day industry standards in terms of user interface, reliability, and programming language. There will also be particular needs such as increased autonomy, memory and power usage, and graphic interfaces. **Table 7-1** summarizes possible requirements for the GreenPhone that would allow a user to acquire climate variable data at their convenience, and when prompted for data correlation of satellite passes.

Table 7-1: Summary of GreenPhone guidelines

System	Description
Sensor	The GreenPhone would have to be equipped with a standardized high quality camera and basic climate variable measurement devices (temperature, pressure). Data must meet the data center requirements. The application will collect data only after the user has activated the sensors.
Communication	GreenPhone users should have direct communication with the data and operations center through GSM.
GNSS	The GreenPhone application will query the GNSS positioning device and append the time and position tag to all images and sensed data.
Data Management	Data storage format and organization will need to meet the standards laid out by the data center to ensure compatibility during data transmission.
Mobile to PC Connection	Downloading data from the GreenPhone to a computer to send data to the data center should an option for user. This would require installing software on the computer to download, tag, and forward the pictures to the data center.
High-Resolution Cameras	There is increased research in image recognition from mobile phone cameras (White, 2007). Climate Links would use of this information as metadata to the sensory information.

Along with the physical GreenPhone design, the supporting architecture would also be necessary. For data processing and management protocols, there would be no need for expansion or alteration. The data center would, however, be affected by the rollout of future developments. World expansion of the Climate Links initiative will include stationary devices, devices installed on moving vehicles, and potentially millions of GreenPhones participating in the project. All these devices will be collecting and transmitting large amounts of data. There would also be an increase in the communications necessary to manage the entire network of devices. At this stage, a dedicated data center may be required to retrieve, process, and store the large amounts of data. The Communication Priority Sequence Protocol (CPSC) for a public mobile device would be identical to those outlined in Chapter 5. The only exception being that public device users will not have access to satellite communications, as the public device is meant to be small in size.

7.2.3 Peer Group Analysis for GreenPhone

The Climate Link team created an online survey to assess the reaction of their peer group and to help formulate the future development of the Climate Links system. Over a three-day period, 327 participated in the survey. The questions ranged from individual interest in climate change, to their willingness to be part of citizen science campaigns. Table 7-2 summarizes the survey results.

Table 7-2: Survey results regarding Climate Links' peer group's awareness of climate change.

Survey Question	Percentage of the Total
Say that climate change is a serious problem	91 %
• Willing to support research associated with climate change	88 %
• Interested in being a "Citizen Scientist" and help in collecting climate data	61 %
• Willing to dedicate certain amount of time per day towards collecting data	57%
Interested in receiving climate data on mobile phone	
• From satellite images	18 %
• About conclusions from scientists	23 %
• About new climate statistics	27 %
• About that is location specific	32 %
Would purchase a mobile phone to collect climate data	
• Would buy a GreenPhone to collect climate data	69%
• Pay the same price as that of a normal low-end phone	44 %
• Pay the price equivalent to a communicator phone	25%
• Pay the price equivalent to an iPhone for buying the GreenPhone.	10 %
• Pay the price of a PDA, Blackberry	20%
Say that climate data is not available to public	58 %

91 % of participants stated that climate change is a serious problem and 88 % of those expressed their willingness to support research associated with climate change. 61 % of participants expressed interested in collecting climate data. It was also noted that on average, a participant would be willing to spend 20 minutes per day collecting climate data. The key findings of the survey indicate that further investigation and extensive market studies into the GreenPhone concept would be worthwhile to enhance key design features and operation.

7.2.4 SWOT Analysis

A SWOT analysis to assess the GreenPhone is provided in Table 7-3

Table 7-3: SWOT analysis for the GreenPhone

Strengths	**Weaknesses**
• Increase of social awareness • Portable device • Trendy phone • Cutting edge technology	• Cellular phone networks limited coverage • Sensor calibration • Weight and power consumption • High phone price during market entry
Opportunities	**Threats**
• Large consumer market available • Participatory sensing trend • Stimulation of phone applications market	• Rules regarding prohibited areas • Privacy issues, regarding location • Resistance from groups that emit GHG's

The GreenPhone would be able to promote awareness and responsibility, as it is a good medium to provide the public with up-to-date information regarding the climate. The GreenPhone would utilize cutting edge technology that would also be attractive to the 'high-tech' demographic.

The data collection regions could be limited by cellular network coverage. To mitigate this issue, storing data in the device and uploading it later should be possible. An easy-to-use application on the GreenPhone would be included to guide users through the calibration procedures. Regarding the weight and power consumption of the GreenPhone, the manufacture would account for sensor requirements on the phone by utilizing the latest technology. Climate Links would not be responsible for the manufacturing of the phone, but will provide input and requirements to a mobile phone manufacturer.

There is a possibility of partnership with existing mobile service operators and phone manufacturers to adopt the GreenPhone concept into their future services. Initiatives have been taken by manufacturers such as Nokia, which is promoting its Eco Sensor concept (Nokia, 2009), and Intel working with researchers at Carnegie Mellon University to develop sensor chips (Paulos, 2009). The peer group survey shows significant interest in active participation in climate change research and is evidence of the market.

Some national or local regulations might prohibit measurement around sensitive areas such as military compounds, national borders, or nuclear facilities. These restrictions might leave some gaps in the comprehensiveness of the climate data. However, it is recommended to comply with all laws and restrictions. The issue of privacy regarding sender location is an important one. This particular issue could be avoided by contractual agreements with users and ensuring that the received data in coded to ensure anonymity.

7.3 Summary

The proposed updates of the GreenBox and the introduction of the GreenPhone play an important role in the future development of the Climate Links system. The added feature of GreenBox mobility allows for the collection of climate data over wider geographic area and allows for more accurate satellite data that can be used by scientists to validate climate models.

The Climate Links system strives firstly to improve satellite data and secondly to help change the daily behavior of the public by making them more aware of their ability to impact the environment. The introduction of the GreenPhone will increase awareness by involving the public in data collection. Even more important is the fact that it brings humankind closer to the understanding of the Earths' climate mechanisms by making it possible to involve more people in data collection.

8 CONCLUSION

From the melting ice caps to the recent abrupt increase in extreme weather events it is now clear that the climate is changing. There is mounting evidence that the main driver for this change is the sharp rise in the concentration of green house gases, such as carbon dioxide and methane, in the Earth's atmosphere. Whatever the cause; natural, anthropomorphic or a combination thereof, the fact that humanity has yet to face such a global problem has already caused dramatic consequences. One solution could be to limit the emission of green house gasses; however, we seem to have reached a tipping point with the world economy's dependence on fossil fuels, deforestation and volcanic activity that a massive global initiative would be required to reverse the current trends.

Long term climate modeling remains a challenge, due to high error margins, making it difficult for decision makers to utilize predictions. Earth Observation satellites are beginning to play a more critical role in the climate modeling endeavor, with new missions (such as Jaxa's GOSAT and NASA's OCO satellites) designed specifically to study the fluctuation of carbon dioxide emissions. Observing the Earth from space allows for a global perspective which provides an overall situational awareness of atmospheric compounds. However, at the ground level, the green house gas concentration is constantly changing so satellites are limited by temporal resolution because they only capture a snapshot of the area.

The Climate Links initial proposal is to create a grid of autonomous, *in-situ* surface level climate stations called GreenBoxes. The objective is to install a grid of these GreenBoxes to enhance the ECV data already collected by satellites through synchronous data collection. The basic GreenBox would be equipped with a rugged set of sensors designed to measure fundamental green house gasses (CO_2, N_2O, CO, CH_4) and CFCs, whereas fully featured GreenBoxes would also include a full set of weather parameters. Phase one of this project focuses on the case of Nigeria: an emerging tropical country that has the ideal political and geographical characteristics for a five year study to test and validate the Climate Links system before future expansion to other areas.

Aside from better climate modelling, part of the solution to climate change is the increased public awareness on how the issue affects everybody's daily life. In Phase 1 of the Climate Links system, interested mobile phone users would be able to receive text messages updating them on the progress of Climate Links and with climate information relevant to their area. As the GreenBox technology and integration matures, and miniaturized environmental sensors become more reliable, the Climate Links project will then introduce a new mobile device, the GreenPhone which is capable of select essential climate variable measurements. With the Climate Links data infrastructure in place, the addition of the GreenPhone will open the door to participatory citizen science. GreenPhones and GreenBoxes will have the ability to be prompted by the Climate Links system to take a ground based measurement when a satellite is passing over head.

The Climate Links long term vision is a world with a seamless network of GreenBoxes continuously monitoring essential climate variables in order to enhance information obtained from EO satellites. They would be simple, reliable and rugged enough that any school group could adopt a GreenBox for educational purposes. Moreover, there are potentially millions of

GreenPhone users that will be able to measure and exchange valuable green house gas information. The Climate Links system would manage the flow of data, and would provide climate modelling professionals with precious raw data that enables them to make more accurate climate predictions far into the future.

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APPENDIX A: ESSENTIAL CLIMATE VARIABLES

This appendix outlines the ECV variables defined by GCOS (WMO, 2008).

Table A-1: Essential Climate Variables as defined by GCOS

ATMOSPHERIC	**Lower atmosphere:** Air temperature, precipitation, air pressure, surface radiation budget, wind speed, wind direction, water vapor
	Upper atmosphere: Earth radiation budget, upper-air temperature, wind speed, wind direction, water vapor, cloud properties
	Composition: Carbon dioxide, methane, ozone, other long-lived greenhouse gases (GHGs)[1], aerosols
OCEANIC	**Surface:** Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, current, ocean color, carbon dioxide partial pressure
	Sub-surface: Temperature, salinity, current, nutrients, carbon, ocean tracers/phytoplankton
TERRESTRIAL[2]	River discharge, water use, ground water, lake levels, snow cover, glaciers and ice caps, permafrost and seasonally-frozen ground, albedo, land cover, fraction of absorbed photosynthetically active radiation, leaf area index, biomass, fire disturbance, soil moisture[3]

[1] Including nitrous oxide (N2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF6), and perfluorocarbons (PFCs).

[2] Includes runoff (m3 s-1), ground water extraction rates (m3 yr-1) and location, snow cover extent (km2) and duration, snow depth (cm), glacier/ice cap inventory and mass balance (kg m-2 yr-1), glacier length (m), ice sheet mass balance (kg m-2 yr-1) and extent (km2), permafrost extent (km2), temperature profiles and active layer thickness, above ground biomass (t/ha), burnt area (ha), date and location of active fire, burn efficiency (%vegetation burned/unit area).

[3] Recognized as an emerging Essential Climate Variable (not part of the 44).

APPENDIX B: SATELLITES AND ECVs

There are 26 Essential Climate Variables (ECV) that are measurable by satellite. The following tables outline the satellites measuring or scheduled to be measuring these variables. The variables have been broken down in to the atmospheric, terrestrial and oceanic variables.

Table B-1: Terresterial ECVs monitored by satellites

Variable (Terrestrial)	**Satellite (agency, orbit, status)**	**Payload that is able to measure the variable (accuracy)**
Lake observation (surface level)	Jason-1 (NASA/CNES, MEO, iO)	Poseidon-2 Altimeter (<4.2cm)
Lake observation (surface level)	Jason-2 (NASA/CNES, MEO, iO)	Poseidon-3 Altimeter (<3.3cm)
Lake observation (surface temperature)	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]
Lake observation (surface level)	ENVISAT (ESA, LEO, iO)	RA-2 [Radar Altimeter 2]
Lake observation	Sentinel-3 (ESA, LEO, by 2012)	SRAL [Sentinel-3 Ku/C Radar Altimeter]
Glaciers/Ice caps/Ice sheets (area)	Landsat-5 (NASA, LEO, iO/restricted)	TM [Thematic mapper] (30m)
Glaciers/Ice caps/Ice sheets (area)	Landsat-7 (NASA, LEO, iO/restricted)	ETM+ [Enhanced Thematic mapper plus] (15/30m)
Glaciers/Ice caps/Ice sheets (area)	SPOT-2 (CNES, LEO, iO)	HRV [High resolution visible] (10/20m, panchromatic)
Glaciers/Ice caps/Ice sheets (area)	SPOT-4 (CNES, LEO, iO)	HRVIR [High resolution visible infra-red] (10/20m, monospectral)
Glaciers/Ice caps/Ice sheets (area)	SPOT-5 (CNES, LEO, iO)	HRG [High geometric resolution] (2.5/5/10/20m, panchromatic)
Glaciers/Ice caps/Ice sheets	ICESat (NASA, LEO, iO)	GLAS [Geoscience Laser Altimeter System]
Glaciers/Ice caps/Ice sheets	Sentinel-1 (ESA, LEO, by 2011)	C-Band SAR [Synthetic Aperture Radar]
Glaciers/Ice caps/Ice sheets	CryoSat?-2 (ESA, LEO, by 2009)	SIRAL [Synthetic Aperture Radar Interferometric Radar Altimeter]

Variable (Terrestrial)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Glaciers/Ice caps/Ice sheets	ALOS/Daichi (JAXA, LEO, iO)	PALSAR [Phased Array type L-band Synthetic Aperture Radar]
Snow cover (area)	Landsat-5 (NASA, LEO, iO/restricted)	TM [Thematic mapper] (30m)
Snow cover (area)	Landsat-7 (NASA, LEO, iO/restricted)	ETM+ [Enhanced Thematic mapper plus] (15/30m)
Snow cover (area)	SPOT-2 (CNES, LEO, iO)	HRV [High resolution visible] (10/20m, panchromatic)
Snow cover (area)	SPOT-4 (CNES, LEO, iO)	HRVIR [High resolution visible infra-red] (10/20m, monospectral)
Snow cover (area)	SPOT-5 (CNES, LEO, iO)	HRG [High geometric resolution] (2.5/5/10/20m, panchromatic)
Snow cover (parameters)	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Snow cover	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AVHHR/3 [Advanced Very High Resolution Radiometer]
Snow cover	GOES-R/S (NASA, GEO, by 2015)	ABI [Advanced Baseline Imager]
Snow cover	USGS EO-1 (NASA, LEO, iO)	ALI [Advanced Land Imager]
Snow cover	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Snow cover	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Albedo	Terra (NASA, LEO, iO)	ASTER [Advanced Spaceborne Thermal Emission and Reflection Radiometer]
Albedo	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	HIRS/4 [High resolution Infrared Radiation Sounder]
Albedo	GCOM-C1/C2/C3 (JAXA, LEO, by 2014/by 2018/by 2022)	SGLI [Second-generation Global Imager]
Albedo	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	HIRS/4 [High resolution Infrared Radiation Sounder]
Land cover (area)	Landsat-5 (NASA, LEO, iO/restricted)	TM [Thematic mapper] (30m)
Land cover (area)	Landsat-7 (NASA, LEO, iO/restricted)	ETM+ [Enhanced Thematic mapper plus] (15/30m)
Land cover (area)	SPOT-2 (CNES, LEO, iO)	HRV [High resolution visible] (10/20m, panchromatic)

Variable (Terrestrial)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Land cover (area)	SPOT-4 (CNES, LEO, iO)	HRVIR [High resolution visible infra-red] (10/20m, monospectral)
Land cover (area)	SPOT-5 (CNES, LEO, iO)	HRG [High geometric resolution] (2.5/5/10/20m, panchromatic)
Land cover (area)	Proba (ESA, LEO, iO)	HRC [High resolution camera] (5m, monochromatic)
Land cover (area)	Proba (ESA, LEO, iO)	CHRIS [Compact High Resolution Imaging Spectrometer] (18m, hyperspectral)
Land cover (change)	Aqua (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Land cover (change)	Terra (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Land cover (characterization)	Terra (NASA, LEO, iO)	MISR [Multi-angle Imaging SpectroRadiometer?]
Land cover (monitoring)	Terra (NASA, LEO, iO)	ASTER [Advanced Spaceborne Thermal Emission and Reflection Radiometer]
Land cover (characterization)	ENVISAT (ESA, LEO, iO)	ASAR [Advanced Synthetic Aperture Radar]
Land cover	ENVISAT (ESA, LEO, iO)	MERIS [Medium Resolution Imaging Spectrometer]
Land cover	Sentinel-1 (ESA, LEO, by 2011)	C-Band SAR [Synthetic Aperture Radar]
Land cover	Sentinel-2 (ESA, LEO, by 2012)	MSI [Multi Spectral Instrument]
Land cover	Sentinel-3 (ESA, LEO, by 2012)	OLCI [Ocean and Land Colour Instrument]
Land cover	EO-1 (NASA, LEO, iO)	ALI [Advanced Land Imager]
Land cover	EO-1 (NASA, LEO, iO)	Hyperion
Land cover	ALOS/Daichi (JAXA, LEO, iO)	AVNIR-2 [Advanced Visible and Near-Infrared Radiometer type 2]
Land cover	ALOS/Daichi (JAXA, LEO, iO)	PALSAR [Phased Array type L-band Synthetic Aperture Radar]
Land cover	IRS-P6/RESOURCESAT-1 (ISRO, LEO, iO)	AWiFS? [Advanced Wide Field Sensor]
Land cover	METEOR-M (Roscosmos, LEO, iO)	KMSS

Variable (Terrestrial)	**Satellite (agency, orbit, status)**	**Payload that is able to measure the variable (accuracy)**
Land cover	CBERS-2 (CAST, LEO, iO)	WFI/CCD [Wide Field Imager]
Land cover	Resurs DK (TsSKB?, LEO, iO)	ESI [Earth Surface Imager]
Land cover	EnMAP? (DLR, LEO, by 2012)	HSI [Hyperspectral Imager]
Land cover	IMS-1 (ISRO, LEO, by 2012)	Mx/HySI [Multispectral/hyperspectral camera]
Land cover	Pleiades (CNES, LEO, by 2010)	HiRI? [High Resolution Imager]
Land cover	LDCM (NASA, LEO, by 2012)	OLI [Operational Land Imager]
Land cover	Risat-1 (ISRO, LEO, by 2009)	C-Band SAR [Synthetic Aperture Radar]
Land cover	COSMO-Skymed 1/2/3/4 (ISO, LEO, iO/iO/iO/by 2010)	SAR [Synthetic Aperture Radar]
Land cover	SAOCOM (CONAE, LEO, by 2011)	SAR-L [Synthetic Aperture Radar]
Land cover	VENUS (CNES/ISA, LEO, by 2011)	VSC [Venus Superspectral Camera]
fAPAR	SPOT-4 (CNES, LEO, iO)	VEGETATION-1 (<1.7km)
fAPAR	SPOT-5 (CNES, LEO, iO)	VEGETATION-2 (<1.7km)
fAPAR	Sentinel-2 (ESA, LEO, by 2012)	MSI [Multi Spectral Instrument]
fAPAR	VENUS (CNES/ISA, LEO, by 2011)	VSC [Venus Superspectral Camera]
Leaf Area Index	SPOT-4 (CNES, LEO, iO)	VEGETATION-1 (<1.7km)
Leaf Area Index	SPOT-5 (CNES, LEO, iO)	VEGETATION-2 (<1.7km)
Leaf Area Index	Sentinel-2 (ESA, LEO, by 2012)	MSI [Multi Spectral Instrument]
Leaf Area Index	GOES-R/S (NASA, GEO, by 2015)	ABI [Advanced Baseline Imager]
Leaf Area Index	USGS EO-1 (NASA, LEO, iO)	Hyperion
Leaf Area Index	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Leaf Area Index	CBERS-2 (CAST, LEO, iO)	WFI [Wide Field Imager]
Leaf Area Index	Resurs DK (TsSKB?, LEO, iO)	ESI [Earth Surface Imager]
Leaf Area Index	VENUS (CNES/ISA, LEO, by 2011)	VSC [Venus Superspectral Camera]
Fire disturbance	Aqua (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]

Variable (Terrestrial)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Fire disturbance	ERS-2 (ESA, LEO, iO/restricted)	ATSR [Along Track Scanning Radiometer]
Fire disturbance	ENVISAT (ESA, LEO, iO)	AATSR [Advanced Along-Track Scanning Radiometer]
Fire disturbance	CBERS-2 (CAST, LEO, iO)	IR-MSS [Infrared Multi-spectral scanner]
Fire disturbance	CBERS-3/4 (CAST, LEO, 2010+)	IRS [Infrared Scanner]
Soil moisture	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Soil moisture	ENVISAT (ESA, LEO, iO)	MWR [Microwave radiometer]
Soil moisture	SMOS (ESA, LEO, by 2009)	MIRAS [Microwave Imaging Radiometer using Aperture Synthesis]
Soil moisture	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Soil moisture	NPOESS (NASA/NOAA, LEO, by 2013+)	MIS [Microwave Imager/Sounder]
Soil moisture	Risat-1 (ISRO, LEO, by 2009)	C-Band SAR [Synthetic Aperture Radar]
Soil moisture	SAOCOM (CONAE, LEO, by 2010)	SAR-L [Synthetic Aperture Radar]
Soil moisture	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/I [Special Sensor Microwave Imager]

Table B-2: Atmospheric ECVs monitored by satellite

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Surface wind speed/direction	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	ASCAT [Advanced scatterometer] (+/- 2m/s, +/- 20deg)
Surface wind speed	ERS-2 (ESA, Near-Polar LEO, iO/restricted)	AMI/WS [Active Microwave Instrument/Wind Scatterometer] (+/- 3m/s)
Surface wind speed	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Surface wind speed	ADM-Aeolus (ESA, LEO, by 2010)	ALADIN [Atmospheric Laser Doppler Instrument]
Surface wind speed	QuikSCAT? (NASA, LEO, iO)	SeaWinds?

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Surface wind speed	OceanSat?-1 (ISRO, LEO, iO)	MSMR [Multi-channel scanning microwave radiometer]
Surface wind speed	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Surface wind speed	NPOESS (NASA/NOAA, LEO, by 2013+)	MIS [Microwave Imager/Sounder]
Surface wind speed	METEOR-M (Roscosmos, LEO, iO)	KMSS
Surface wind speed	Coriolis (AFRL/NRL, LEO, iO)	WindSat?
Air temperature	CHAMP (GFZ, LEO, iO)	TRSR-2 [Turbo Rogue Space Receiver-2 (in Radio Occulation Mode)]
Air temperature	COSMIC/FORMOSAT-3 (Taiwan/USA, LEO, iO)	IGOR [Integrated GPS Occulation Receiver]
Air temperature	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]
Air temperature	Aqua (NASA, LEO, iO)	AMSU-A [Advanced Microwave Sounding Unit]
Air temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AMSU-A1/A2 [Advanced Microwave Sounding Unit]
Air temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	GRAS [Global Navigation Satellite System Receiver for Atmospheric Sounding]
Air temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	HIRS/4 [High resolution Infrared Radiation Sounder]
Air temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	IASI [Infrared Atmospheric Sounding Interferometer] (1K)
Air temperature	GOES-10/11/12/13 (NASA, GEO, iO/iO/iO/iO)	Sounder/Imager payload
Air temperature	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AMSU-A [Advanced Microwave Sounding Unit]
Air temperature	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	HIRS/4 [High resolution Infrared Radiation Sounder]
Air temperature	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	CrIMSS? [Cross-Track Infrared and Advanced Technology Microwave Sounder]
Air temperature	METEOR-M (Roscosmos, LEO, iO)	KMSS

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Air temperature	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	IRAS [Infrared Atmospheric Sounder]
Air temperature	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	MWTS [MicroWave Atmospheric Temperature Sounder]
Air temperature	SAC-C (CONAE et al, LEO, iO)	GOLPE [GPS Occultation and Passive Reflection Experiment]
Air temperature	Sabrina (ISO, LEO, by 2011)	ROSA [Radio Occultation Sounder for Atmosphere]
Air temperature	Odin (SSC/SNSB, LEO, iO)	SMR [Submillimetre Radiometer]
Air temperature	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/T-1/T-2 [Special Sensor Microwave Temperature Sounder]
Air temperature	DMSP F16/F17/F18/F19/F20 (DOD, LEO, iO/iO/iO/by 2009/by 2011)	SSM/IS [Special Sensor Microwave Imager Sounder]
Water Vapor	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]
Water Vapor	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Water vapor	Aqua (NASA, LEO, iO)	AMSU-A [Advanced Microwave Sounding Unit]
Water vapor	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AMSU-A1/A2 [Advanced Microwave Sounding Unit]
Water vapor (humidity)	Aqua (NASA, LEO, iO)	HSB [Humidity sounder for Brazil]
Water vapor (humidity)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	GRAS [Global Navigation Satellite System Receiver for Atmospheric Sounding]
Water vapor (humidity)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	IASI [Infrared Atmospheric Sounding Interferometer] (10%)
Water vapor (humidity)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	MHS [Microwave Humidity Sounder]
Water vapor	MSG-1/2/3/4 (ESA/EUMETSAT, GEO, iO/iO/by 2009/by 2011)	SEVIRI [Spinning Enhanced Visible and Infrared Imager]
Water vapor	ERS-2 (ESA, LEO, iO/restricted)	MWR [Microwave radiometer]
Water vapor	ENVISAT (ESA, LEO, iO)	MWR [Microwave radiometer]
Water vapor	Sentinel-3 (ESA, LEO, by 2012)	MWR [Microwave radiometer]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Water vapor (moisture)	GOES-10/11/12/13 (NASA, GEO, iO/iO/iO/iO)	Sounder/Imager payload
Water vapor (humidity)	NOAA-18/19 (NASA, LEO, iO/iO)	MHS [Microwave Humidity Sounder]
Water vapor	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Water vapor (moisture)	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	CrIMSS? [Cross-Track Infrared and Advanced Technology Microwave Sounder]
Water vapor (humidity)	METEOR-M (Roscosmos, LEO, iO)	KMSS
Water vapor	TRMM (NASA/JAXA, LEO, iO)	TMI [TRMM Microwave Imager]
Water vapor (profiles)	CHAMP (GFZ, LEO, iO)	TRSR [GPS TurboRogue? Space Receiver]
Water vapor	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	MWRI [Microwave Radiation Imager]
Water vapor	SAC-C (CONAE et al, LEO, iO)	GOLPE [GPS Occultation and Passive Reflection Experiment]
Water vapor	MEGHA-TROPIQUES (CNES/ISRO, LEO, by 2009+)	MADRAS [Microwave Analysis and Detection of Rain and Atmospheric Structures]
Water vapor (humidity)	MEGHA-TROPIQUES (CNES/ISRO, LEO, by 2009+)	SAPHIR [Sounder for Atmospheric Profiling of Humidity in the Intertropics by Radiometry]
Water vapor (distribution)	MTSAT-1R/2 (JMA, GEO, iO/by 2010)	VIS/IR Imager
Water vapor	Sabrina (ISO, LEO, by 2011)	ROSA [Radio Occultation Sounder for Atmosphere]
Water vapor	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/I [Special Sensor Microwave Imager]
Water vapor	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/T-1/T-2 [Special Sensor Microwave Temperature Sounder]
Water vapor	DMSP F16/F17/F18/F19/F20 (DOD, LEO, iO/iO/iO/by 2009/by 2011)	SSM/IS [Special Sensor Microwave Imager Sounder]
Water vapor	Kalpana (ISRO, GEO, iO)	VHRR [Very High Resolution Radiometer]
Cloud properties (cover)	Terra (NASA, LEO, iO)	MISR [Multi-angle Imaging SpectroRadiometer?]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Cloud properties	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Cloud properties	Aqua (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Cloud properties	Terra (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Cloud properties	Aqua (NASA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Cloud properties	Terra (NASA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Cloud properties (height, cover)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	HIRS/4 [High resolution Infrared Radiation Sounder]
Cloud properties (cover, temperature, pressure)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	IASI [Infrared Atmospheric Sounding Interferometer]
Cloud properties (temperature)	MSG-1/2/3/4 (ESA/EUMETSAT, GEO, iO/iO/by 2009/by 2011)	SEVIRI [Spinning Enhanced Visible and Infrared Imager]
Cloud properties	CLOUDSAT (NASA/CSU, LEO, iO)	CPR [Cloud Profiling Radar]
Cloud properties (vertical profiles)	CALIPSO (NASA/CNES, LEO, iO)	CALIOP [Cloud-Aerosol Lidar with Orthogonal Polarization]
Cloud properties (vertical profiles)	CALIPSO (NASA/CNES, LEO, iO)	IIR [Imaging Infrared Radiometer]
Cloud properties (height, thickness)	ICESat (NASA, LEO, iO)	GLAS [Geoscience Laser Altimeter System]
Cloud properties (temperature)	ENVISAT (ESA, LEO, iO)	AATSR [Advanced Along-Track Scanning Radiometer]
Cloud properties	ERS-2 (ESA, LEO, iO/restricted)	MWR [Microwave radiometer]
Cloud properties (water content)	ENVISAT (ESA, LEO, iO)	MWR [Microwave radiometer]
Cloud properties	Sentinel-3 (ESA, LEO, by 2012)	MWR [Microwave radiometer]
Cloud properties	EarthCARE? (ESA/JAXA, LEO, by 2012)	ATLID [Atmospheric Lidar]
Cloud properties	EarthCARE? (ESA/JAXA, LEO, by 2012)	CPR [Cloud Profiling Radar]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Cloud properties	Parasol (NASA/CNES, LEO, iO)	POLDER [Polarization and Directionality of the Earth's Reflectances]
Cloud properties	GOES-R/S (NASA, GEO, by 2015)	ABI [Advanced Baseline Imager]
Cloud properties	GOES-10/11/12/13 (NASA, GEO, iO/iO/iO/iO)	Sounder/Imager payload
Cloud properties	GCOM-C1/C2/C3 (JAXA, LEO, by 2014/by 2018/by 2022)	SGLI [Second-generation Global Imager]
Cloud properties	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Cloud properties	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Cloud properties	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	HIRS/4 [High resolution Infrared Radiation Sounder]
Cloud properties	Glory (NASA, LEO, by 2009)	APS [Aerosol Polarimetry Sensor]
Cloud properties	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	CrIMSS? [Cross-Track Infrared and Advanced Technology Microwave Sounder]
Cloud properties	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	VIIRS [Visible/Infrared Imager/Radiometer Suite]
Cloud properties (cover)	METEOR-M (Roscosmos, LEO, iO)	MSU-MR
Cloud properties	TRMM (NASA/JAXA, LEO, iO)	TMI [TRMM Microwave Imager]
Cloud properties	TRMM (NASA/JAXA, LEO, iO)	VIRS [Visible and Infrared Scanner]
Cloud properties	TRMM (NASA/JAXA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Cloud properties	GPM (JAXA/NASA/NICT, LEO, by 2013+)	GMI [GPM Microwave Imager]
Cloud properties	GPM (JAXA/NASA/NICT, LEO, by 2013+)	DPR [Dual-frequency Precipitation Radar]
Cloud properties	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	MWRI [Microwave Radiation Imager]
Cloud properties (cover)	COMS-1/2 (KARI, GEO, by 2009/by 2014)	MI [Meteo Imager]
Cloud properties	MEGHA-TROPIQUES (CNES/ISRO, LEO, by 2009+)	MADRAS [Microwave Analysis and Detection of Rain and Atmospheric Structures]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Cloud properties (distribution, motion)	MTSAT-1R/2 (JMA, GEO, iO/by 2010)	VIS/IR Imager
Cloud properties	INSAT satellites (ISRO, GEO, iO)	Radiometer payloads
Cloud properties	Kalpana (ISRO, GEO, iO)	VHRR [Very High Resolution Radiometer]
Precipitation	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Precipitation	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AMSU-A1/A2 [Advanced Microwave Sounding Unit]
Precipitation	Aqua (NASA, LEO, iO)	AMSU-A [Advanced Microwave Sounding Unit]
Precipitation	ENVISAT (ESA, LEO, iO)	AATSR [Advanced Along-Track Scanning Radiometer]
Precipitation	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]
Precipitation	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AMSU-A [Advanced Microwave Sounding Unit]
Precipitation	TRMM (NASA/JAXA, LEO, iO)	PR [Precipitation Radar]
Precipitation	TRMM (NASA/JAXA, LEO, iO)	TMI [TRMM Microwave Imager]
Precipitation	TRMM (NASA/JAXA, LEO, iO)	VIRS [Visible and Infrared Scanner]
Precipitation	GPM (JAXA/NASA/NICT, LEO, by 2013+)	GMI [GPM Microwave Imager]
Precipitation	GPM (JAXA/NASA/NICT, LEO, by 2013+)	DPR [Dual-frequency Precipitation Radar]
Precipitation	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	MWRI [Microwave Radiation Imager]
Precipitation	MEGHA-TROPIQUES (CNES/ISRO, LEO, by 2009+)	MADRAS [Microwave Analysis and Detection of Rain and Atmospheric Structures]
Precipitation	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/I [Special Sensor Microwave Imager]
Precipitation	DMSP F16/F17/F18/F19/F20 (DOD, LEO, iO/iO/iO/by 2009/by 2011)	SSM/IS [Special Sensor Microwave Imager Sounder]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Earth radiation budget (energy flux)	Aqua (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Earth radiation budget (energy flux)	Terra (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Earth radiation budget (energy flux)	Aqua (NASA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Earth radiation budget (energy flux)	Terra (NASA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Earth radiation budget	Terra (NASA, LEO, iO)	MISR [Multi-angle Imaging SpectroRadiometer?]
Earth radiation budget	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AVHHR/3 [Advanced Very High Resolution Radiometer]
Earth radiation budget	MSG-1/2/3/4 (ESA/EUMETSAT, GEO, iO/iO/by 2009/by 2011)	GERB [Geostationary Earth Radiation Budget]
Earth radiation budget	ENVISAT (ESA, LEO, iO)	MERIS [Medium Resolution Imaging Spectrometer]
Earth radiation budget	ENVISAT (ESA, LEO, iO)	MWR [Microwave radiometer]
Earth radiation budget	EarthCARE? (ESA/JAXA, LEO, by 2012)	MSI/BBR [Multi-Spectral Imager/Broadband Radiometer]
Earth radiation budget	ACRIMSAT (NASA, LEO, iO)	ACRIM-III [Active cavity Radiometer Irradiance Monitor]
Earth radiation budget	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Earth radiation budget	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	VIIRS [Visible/Infrared Imager/Radiometer Suite]
Earth radiation budget	TRMM (NASA/JAXA, LEO, iO)	CERES [Clouds and the Earth's Radiant Energy System]
Earth radiation budget	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	ERBU [Earth Radiation Budget Unit]
Earth radiation budget	MEGHA-TROPIQUES (CNES/ISRO, LEO, by 2009+)	SCARAB [Scanner for Radiation Budget]
Earth radiation budget	PICARD (CNES, LEO, by 2009)	SOVAP/PREMOS [Solar Variability PICARD/Precision Monitor Sensor]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Earth radiation budget	SORCE (NASA, LEO, iO)	SIM [Spectral Irradiance Monitor]
Ozone	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]
Ozone	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	GOME-2 [Global Ozone Monitoring Experiment-2]
Ozone	MSG-1/2/3/4 (ESA/EUMETSAT, GEO, iO/iO/by 2009/by 2011)	SEVIRI [Spinning Enhanced Visible and Infrared Imager]
Ozone	ENVISAT (ESA, LEO, iO)	GOMOS [Global Ozone Monitoring by Occultation of Stars]
Ozone	ENVISAT (ESA, LEO, iO)	MIPAS [Michelson Interferometer for Passive Atmospheric Sounding]
Ozone	ENVISAT (ESA, LEO, iO)	SCIAMACHY [Scanning Imaging Absorption Spectrometer for Atmospheric Chartography]
Ozone	ERS-2 (ESA, LEO, iO/restricted)	GOME [Global Ozone Monitoring Experiment]
Ozone	Sentinel-4 (ESA, GEO, by 2017)	Narrow Field Spectrometer
Ozone	SCISAT-1 (CSA, LEO, iO)	ACE [Atmospheric Chemistry Experiment]
Ozone	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	SBUV/2 [Solar Backscatter Ultraviolet Spectral Radiometer]
Ozone	OCO (NASA, LEO, ?/launch failure)	OCO spectrometers
Ozone	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	OMPS [Ozone mapping and profiling suite]
Ozone	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	TOM/OP [Total Ozone Mapper/Ozone Profiler]
Ozone	Odin (SSC/SNSB, LEO, iO)	OSIRIS [Optical Spectrograph and Infrared Imaging System]
Ozone	PICARD (CNES, LEO, by 2009)	SOVAP/PREMOS [Solar Variability PICARD/Precision Monitor Sensor]
Ozone	Odin (SSC/SNSB, LEO, iO)	SMR [Submillimetre Radiometer]
Aerosols	Aqua (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]
Aerosols	Terra (NASA, LEO, iO)	MODIS [Moderate Resolution Imaging Spectroradiometer]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Aerosols	Terra (NASA, LEO, iO)	MISR [Multi-angle Imaging SpectroRadiometer?]
Aerosols (vertical profiles)	CALIPSO (NASA/CNES, LEO, iO)	CALIOP [Cloud-Aerosol Lidar with Orthogonal Polarization]
Aerosols (vertical profiles)	CALIPSO (NASA/CNES, LEO, iO)	IIR [Imaging Infrared Radiometer]
Aerosols	ENVISAT (ESA, LEO, iO)	SCIAMACHY [Scanning Imaging Absorption Spectrometer for Atmospheric Chartography]
Aerosols	ENVISAT (ESA, LEO, iO)	MERIS [Medium Resolution Imaging Spectrometer]
Aerosols	ADM-Aeolus (ESA, LEO, by 2010)	ALADIN [Atmospheric Laser Doppler Instrument]
Aerosols	EarthCARE? (ESA/JAXA, LEO, by 2012)	ATLID [Atmospheric Lidar]
Aerosols	Parasol (NASA/CNES, LEO, iO)	POLDER [Polarization and Directionality of the Earth's Reflectances]
Aerosols	GOES-R/S (NASA, GEO, by 2015)	ABI [Advanced Baseline Imager]
Aerosols	SCISAT-1 (CSA, LEO, iO)	VNI [Visible/Near Infrared Imager]
Aerosols	GCOM-C1/C2/C3 (JAXA, LEO, by 2014/by 2018/by 2022)	SGLI [Second-generation Global Imager]
Aerosols	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AVHHR/3 [Advanced Very High Resolution Radiometer]
Aerosols	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Aerosols	Glory (NASA, LEO, by 2009)	APS [Aerosol Polarimetry Sensor]
Aerosols	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	IRAS [Infrared Atmospheric Sounder]
Aerosols	ISTAG (ISRO, LEO, ?)	MAPI [Multi-Angle Polarization Imager]
Aerosols	Odin (SSC/SNSB, LEO, iO)	OSIRIS [Optical Spectrograph and Infrared Imaging System]
Aerosols	ISTAG (ISRO, LEO, ?)	MAVELI [Measurements of Aerosols by Viewing Earth's Limb]
Other GHG	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]

Variable (Atmospheric)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy, if applicable)
Other GHG	Terra (NASA, LEO, iO)	MOPITT [Measurements of Pollution in the Troposphere]
Other GHG	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	GOME-2 [Global Ozone Monitoring Experiment-2]
Other GHG	ENVISAT (ESA, LEO, iO)	GOMOS [Global Ozone Monitoring by Occultation of Stars]
Other GHG	ENVISAT (ESA, LEO, iO)	MIPAS [Michelson Interferometer for Passive Atmospheric Sounding]
Other GHG	ENVISAT (ESA, LEO, iO)	SCIAMACHY [Scanning Imaging Absorption Spectrometer for Atmospheric Chartography]
Other GHG	ERS-2 (ESA, LEO, iO/restricted)	GOME [Global Ozone Monitoring Experiment]
Other GHG	Sentinel-4 (ESA, GEO, by 2017)	Narrow Field Spectrometer
Other GHG	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	OMPS [Ozone mapping and profiling suite]
Other GHG	FY-3A/3B (NSMC (China), LEO, iO/by 2010)	IRAS [Infrared Atmospheric Sounder]
Other GHG (CO)	ISTAG (ISRO, LEO, ?)	MAGIS [Measurement of Atmospheric Gases using Infrared Spectrometer]
Other GHG	Odin (SSC/SNSB, LEO, iO)	OSIRIS [Optical Spectrograph and Infrared Imaging System]
Other GHG	Odin (SSC/SNSB, LEO, iO)	SMR [Submillimetre Radiometer]
Upper Air Wind	Terra (NASA, LEO, iO)	MISR [Multi-angle Imaging SpectroRadiometer?]

Table B-3: Oceanic ECVs monitored by satellite

Variable (Oceanic)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Sea Surface Temperature	Aqua (NASA, LEO, iO)	AIRS [Atmospheric Infrared Sounder]
Sea Surface Temperature	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Sea Surface Temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AVHRR/3 [Advanced Very High Resolution Radiometer]

Variable (Oceanic)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Sea Surface Temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	HIRS/4 [High resolution Infrared Radiation Sounder]
Sea Surface Temperature	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016) (ESA, Polar LEO, iO)	IASI [Infrared Atmospheric Sounding Interferometer]
Sea Surface Temperature	MSG-1/2/3/4 (ESA/EUMETSAT, GEO, iO/iO/by 2009/by 2011)	SEVIRI [Spinning Enhanced Visible and Infrared Imager]
Sea Surface Temperature	ERS-2 (ESA, LEO, iO/restricted)	ATSR [Along Track Scanning Radiometer]
Sea Surface Temperature	ENVISAT (ESA, LEO, iO)	AATSR [Advanced Along-Track Scanning Radiometer]
Sea Surface Temperature	Sentinel-3 (ESA, LEO, by 2012)	SLST [Sea and Land Surface Temperature]
Sea Surface Temperature	GOES-R/S (NASA, GEO, by 2015)	ABI [Advanced Baseline Imager]
Sea Surface Temperature	HY-1b (CAST, LEO, iO)	COCTS/CZI
Sea Surface Temperature	OceanSat?-1 (ISRO, LEO, iO)	MSMR [Multi-channel scanning microwave radiometer]
Sea Surface Temperature	GCOM-C1/C2/C3 (JAXA, LEO, by 2014/by 2018/by 2022)	SGLI [Second-generation Global Imager]
Sea Surface Temperature	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Sea Surface Temperature	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	HIRS/4 [High resolution Infrared Radiation Sounder]
Sea Surface Temperature	NPOESS (NASA/NOAA, LEO, by 2013+)	MIS [Microwave Imager/Sounder]
Sea Surface Temperature	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	VIIRS [Visible/Infrared Imager/Radiometer Suite]
Sea Surface Temperature	COMS-1/2 (KARI, GEO, by 2009/by 2014)	MI [Meteo Imager]
Sea Surface Temperature	MTSAT-1R/2 (JMA, GEO, iO/by 2010)	VIS/IR Imager
Sea Surface Temperature	DMSP F14/F15 (DOD, LEO, iO/iO)	SSM/I [Special Sensor Microwave Imager]
Sea level	Jason-1 (NASA/CNES, MEO, iO)	Poseidon-2 Altimeter (<4.2cm)
Sea level	Jason-2 (NASA/CNES, MEO, iO)	Poseidon-3 Altimeter (<3.3cm)

Variable (Oceanic)	Satellite (agency, orbit, status)	Payload that is able to measure the variable (accuracy)
Sea level	Sentinel-3 (ESA, LEO, by 2012)	SRAL [Sentinel-3 Ku/C Radar Altimeter]
Sea level	SARAL (ISRO, LEO, by 2010)	AltiKa? [Altimeter Ka-band]
Sea surface salinity	SMOS (ESA, LEO, by 2009)	MIRAS [Microwave Imaging Radiometer using Aperture Synthesis]
Sea surface salinity	Aquarius/SAC-D (NASA/CONAE, LEO, by 2010)	Radiometers/scatterometer; PALS [Passive / Active L- and S-band radiometer]
Sea surface salinity	Risat-1 (ISRO, LEO, by 2009)	C-Band SAR [Synthetic Aperture Radar]
Sea state	ERS-2 (ESA, LEO, iO/restricted)	SAR [Synthetic Aperture Radar]
Sea state	ENVISAT (ESA, LEO, iO)	ASAR [Advanced Synthetic Aperture Radar]
Sea ice	Risat-1 (ISRO, LEO, by 2009)	C-Band SAR [Synthetic Aperture Radar]
Sea ice (parameters)	Aqua (NASA, LEO, iO)	AMSR-E [Advanced Microwave Scanning Radiometer - Earth Observing System]
Sea ice (cover)	METOP-A/B/C (ESA, Polar LEO, iO/by 2012/by 2016)	AVHHR/3 [Advanced Very High Resolution Radiometer]
Sea ice	ICESat (NASA, LEO, iO)	GLAS [Geoscience Laser Altimeter System]
Sea ice (type, concentration)	ERS-2 (ESA, LEO, iO/restricted)	SAR [Synthetic Aperture Radar]
Sea ice	ENVISAT (ESA, LEO, iO)	RA-2 [Radar Altimeter 2]
Sea ice (tracking)	ERS-2 (ESA, LEO, iO/restricted)	ATSR [Along Track Scanning Radiometer]
Sea ice (tracking)	ENVISAT (ESA, LEO, iO)	AATSR [Advanced Along-Track Scanning Radiometer]
Sea ice	Sentinel-1 (ESA, LEO, by 2011)	C-Band SAR [Synthetic Aperture Radar]
Sea ice	CryoSat?-2 (ESA, LEO, by 2009)	SIRAL [Synthetic Aperture Radar Interferometric Radar Altimeter]
Sea ice (cover, thickness)	OceanSat?-1 (ISRO, LEO, iO)	MSMR [Multi-channel scanning microwave radiometer]
Sea ice	GCOM-W1/W2/W3 (JAXA, LEO, by 2012/by 2016/by 2020)	AMSR-2 [Advanced Microwave Scanning Radiometer 2]

Variable (Oceanic)	**Satellite (agency, orbit, status)**	**Payload that is able to measure the variable (accuracy)**
Sea ice	NOAA-15/16/17/18/19 (NASA, LEO, iO/iO/iO/iO/iO)	AVHRR/3 [Advanced Very High Resolution Radiometer]
Sea ice	Sabrina (ISO, LEO, by 2011)	SAR [Synthetic Aperture Radar]
Sea ice	COSMO-Skymed 1/2/3/4 (ISO, LEO, iO/iO/iO/by 2010)	SAR [Synthetic Aperture Radar]
Sea ice	DMSP F16/F17/F18/F19/F20 (DOD, LEO, iO/iO/iO/by 2009/by 2011)	SSM/IS [Special Sensor Microwave Imager Sounder]
Ocean colour	ENVISAT (ESA, LEO, iO)	MERIS [Medium Resolution Imaging Spectrometer]
Ocean colour	Sentinel-3 (ESA, LEO, by 2012)	OLCI [Ocean and Land Colour Instrument]
Ocean colour	HY-1b (CAST, LEO, iO)	COCTS/CZI
Ocean colour	OceanSat?-1 (ISRO, LEO, iO)	OCM
Ocean colour	GCOM-C1/C2/C3 (JAXA, LEO, by 2014/by 2018/by 2022)	SGLI [Second-generation Global Imager]
Ocean colour	NPP/NPOESS (NASA/NOAA, LEO, by 2009/by 2013+)	VIIRS [Visible/Infrared Imager/Radiometer Suite]
Ocean colour	COMS-1/2 (KARI, GEO, by 2009/by 2014)	OCI [Ocean Colour Imager]
Ocean colour	SAC-C (CONAE et al, LEO, iO)	MMRS [Mulitspectral Medium Resolution Scanner]
Surface currents	ERS-2 (ESA, LEO, iO/restricted)	SAR [Synthetic Aperture Radar]
Surface currents	ENVISAT (ESA, LEO, iO)	ASAR [Advanced Synthetic Aperture Radar]
Surface currents	Sentinel-1 (ESA, LEO, by 2011)	C-Band SAR [Synthetic Aperture Radar]

APPENDIX C: BUSINESS MODEL COMPARISON

If the Climate Links project were to be started independent of an existing organization, it would require starting a new business. A comparison of four business models is presented in Table C-1

Table C-1: Business model comparison

Business Model	Strengths	Weaknesses
For-Profit Business (Pew, 2006)	- Increased business opportunities from the greater consumer demand for more environmentally friendly products (Rizk, 2005) - Venture capital is available for "green-tech" ventures - Increased profitability from developing energy efficient strategies, new products, partnerships	- Difficult to find funding - Maintaining long-term profits requires the "green" trend to persist in consumer, investment, and government markets - Ethical problems associated with profiting from an environmental, community good
Public-Private Partnership (PPP) (Blaiklock, 2005)	- Increased available funding sources: private and public - Has efficiency of the private sector - Promotes competitive markets and facilitates innovation	- Time consuming - High up-front costs for private party - Complex legal issues - Difficult corporate governance framework
Inter-Governmental Organization (IGO) (Bekker, 1994)	- International by nature - Endorsement from countries of governments involved in the IGO - Possible partnerships with other IGOs	- Based on a treaty, making establishment difficult and restricts non-member countries from participating - Possible political difficulties between member countries
Non-Profit Organization (NPO) (McNamara, 2009)	- Tax-exempt - Many funding options - Easy to set up benefit packages for employees - Independent legal entity reduces personal liability	- Must be incorporated and registered in every country in which it operates - Difficult to cover expenses through funding and the sale of products/services - Requires high levels of corporate transparency

For the Climate Links system, the risks and weaknesses associated with a for-profit endeavor outweigh the opportunity of the 'green' consumer trend. The complexities of involving both government and private sectors in this project and the long timeline weigh against the PPP business model. Because IGOs require establishment by a treaty and rely on political support, this model would take a long time to implement and was therefore eliminated from consideration. The NPO is the recommended business model.

APPENDIX D: WMO SENSOR REQUIREMENTS

The following shows the instrument(s) needed for sensing each ECV, and breaks down the requirements for each sensor in order to be compliant with the data set desired by the World Meteorological Organization (WMO).

Table D-1: Selected ECVs and the sensors required for measurement

ECV	Instrument	Sensor Requirements (BSRN, 2008)		Placement within Box
Temperature	Electrical Resistance Thermometer	Range	-80 to +60 °C	* Protected from radiation and precipitation * Offset from any heat generating source
		Resolution	0.1 °C	
		Required measurement uncertainty	0.3 °C for ≤ –40 °C 0.1 °C for > –40 °C and ≤ +40 °C 0.3 °C for > +40 °C	
		Output averaging time	1 min	
		Achievable measurement uncertainty	0.2 °C	
Precipitation	Tipping Bucket Rain Gauge	Range	0 to 500 mm	* Moderately sheltered * Ground level * 2 m from climate station
		Resolution	0.1 mm	
		Required measurement uncertainty	0.1 mm for ≤ 5 mm 2 % for > 5 mm	
		Output averaging time	N/A	
		Achievable measurement uncertainty	0.1 mm	
Atmospheric Pressure	Electronic Barometer	Range	500 to 1080 hPa	* Uniform temperature * Good Light * Draft free * Solid vertical mounting * Shielded from radiation sources * Clean & dry environment
		Resolution	0.1 hPa	
		Required measurement uncertainty	0.1 hPa	
		Output averaging time	1 min	
		Achievable measurement uncertainty	0.3 hPa	

Surface Radiation	Pyranometer		Range	310 to 2800 nm	* Viewing angle: 180° * Mounted 2m above ground * In direct sunlight
			Resolution	7 to 14 µV/W/m²	
			Required measurement uncertainty	<2 % or 5 W/m²	
			Output averaging time	1 min	
			Achievable measurement uncertainty	2 or 3 W/m²	
	Pyrgeometer		Range	3.5 to 50 µm	* Viewing angle 180° * Mounted 2m above ground * In direct sunlight * Shaded and ventilated
			Resolution	4 µV/W/m²	
			Required measurement uncertainty	5 % or 10 W/m²	
			Output averaging time	1 min	
			Achievable measurement uncertainty	2 % or 3 W/m²	
Wind Speed and Direction	Anemometer	Speed	Range	0 to 75 m/s	* Wind is representative of area * 10 m above ground * Open terrain * If on a mast, the boom must be at least three mast widths long
			Resolution	0.5 m/s	
			Required measurement uncertainty	0.5 m/s for ≤ 5 m/s 10 % for > 5 m/s	
			Output averaging time	2 and/or 10 min	
			Achievable measurement uncertainty	0.5 m/s for ≤ 5 m/s 10 % for > 5 m/s	
		Direction	Range	0 to 360°	
			Resolution	1°	
			Required measurement uncertainty	5°	
			Output averaging time	2 and/or 10 min	
			Achievable measurement uncertainty	5°	

<table>
<tr><td rowspan="5">Water Vapor</td><td rowspan="5">Chilled Mirror dew-point sensor</td><td>Range</td><td>-80 to +35 ºC</td><td rowspan="5">* Mounted outside the box
* Approximately 2 m above ground</td></tr>
<tr><td>Resolution</td><td>0.1 ºC</td></tr>
<tr><td>Required measurement uncertainty</td><td>0.1 ºC</td></tr>
<tr><td>Output averaging time</td><td>1 min</td></tr>
<tr><td>Achievable measurement uncertainty</td><td>0.5 ºC</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td rowspan="6">Airborne Gases</td><td rowspan="5">Gas Chroma-tographer

(Requirements for CO_2) **</td><td>Range</td><td>0 to 3000 ppm</td><td rowspan="5">* Protected from weather
* Placed in a chamber at a fixed temperature
* Accessible for maintenance</td></tr>
<tr><td>Resolution</td><td>1% nominal</td></tr>
<tr><td>Required measurement uncertainty</td><td>< 0.2 ppm</td></tr>
<tr><td>Output averaging time</td><td>5 to 7 minutes</td></tr>
<tr><td>Achievable measurement uncertainty</td><td>< 0.1 ppm</td></tr>
<tr><td colspan="4">** For the other airborne gases and particulates sampled by the Climate Links Project, there are no requirements or standardized ways of measuring. The precision and accuracy required will depend on the compound. However, current climate stations in the US consider the data useful as long as the readings are within 1 to 3 % of each other between data collection centers (GCOS, 2003)</td></tr>
</table>

APPENDIX E: RECOMMENDED COMMERCIALLY AVAILABLE SENSORS

The following tables describe the recommended sensors.

Table E-1: Properties of the Photovac's Voyager System (Photovac, 2007)

Operating Temperature	5 to 40 °C
Power Requirements	60 W
Detection limits	Compound specific (5 to 50 ppb)
Operating humidity	0 to 100 %
Sampling Rate	Every 5 to 7 minutes
Battery life	8 hours - continuous
Dimensions	39 cm (l), 27 cm (w), 15 cm (h)
Note: The detector for measuring green house gases will be available early 2010, the specs are for the current system designed for volatile organic compounds.	

Table E-2: Properties of the Yes Inc. Model PMH-2006 Meteorological Hygrometer (YES, 2006)

Operating Range	±50 °C
Dew/Frost Point Accuracy	Dew points: ±0.2 °C;
	Frost Points: ±0.5 °C
Sensitivity	± 0.1°C

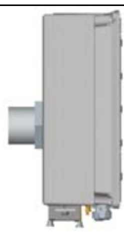


Table E-3: Properties of the Met One model 034B Surface Wind Sensor (Met One, 2002)

Temperature Range	-30 to +70 °C
Wind Speed	
Operating Range	(0 to 75 m/s)
Total Accuracy	0.1 m/s for ≤ 10.15 m/s
	±1.1 % of true for > 10.15 m/s
Wind Direction	
Operating Range	0 to 360°
Accuracy	±4°

Table E-4: Properties of the Kipp & Zonene CMP 21 Pyranometer (Kipp-Zonen, 2009)

Spectral range	310 to 2800 nm	
Sensitivity	7 to 14 μV/W/m²	
Response time	5 s	
Zero offset A	± 7 W/m²	
Zero offset B	± 2 W/m²	
Directional error (Up to 80º with 1000 W/m² beam)	± 10 W/m²	
Temperature dependence of sensitivity (-20ºC to +50ºC)	± 1 %	
Operating temp. range	-40 °C to +80 °C	
Maximum solar irradiance	4000 W/m²	
Field of view	180 °	
Dimensions	15cm (base dia.) x 7.5cm (h)	

Table E-5: Properties of EPLAB PIR Pyrgeometer (Precision Infrared Radiometer) (Eppley, 2009)

Sensitivity	4 μV/Wm²	
Impedance	700 Ohms	
Temperature Dependence	±1 % for -20 to +40 °C	
Linearity	±1 % from 0 to 700 Wm²	
Response time:	2 seconds	
Cosine	5 %	
Mechanical Vibration	OK to 20 g's	
Calibration	blackbody reference	
Dimensions	14.6cm (dia.) x 8.9cm (h)	

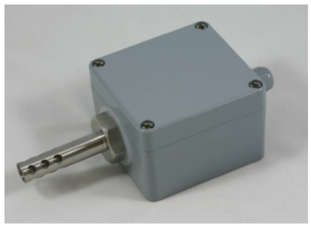
Table E-6: Properties of a Vaisala CS106 Barometric Pressure Sensor (Campbell-Scientificm 2009)

Operating Range	-40 to +60 °C	
Total Accuracy	±0.3 hPa @ +20°C ±0.6 hPa @ -20° to 40°C ±1.0 hPa @ -20° to +45°C ±1.5 hPa @ -40° to +60°C	
Long Term Stability	±0.1 hPa per year	
Current Consumption	<4 mA – Active <1 uA - Dormant	
Dimensions	9.7cm (l) x 6.8ca (w)	

Table E-7: Properties of the Yound Tipping Bucket Rain Gauge Model 52203 (R.M. Young, 2009)

Sensor Type	Tipping Bucket Rain Gauge	
Rainfall Capacity	Unlimited	
Measurement Accuracy	0.1 mm	
Operating Temperature	-20°C to +50°C	
Dimensions	18cm (dia.) x 20cm (h)	

Table E-8: Properties of a PPLL10-P Pt100 Thermistor (Process-Parameters, 2009)

Sensor Type	Platinum Resistance Thermometer—Pt100	
Operating Range	-40 to 85°C	
Sheath Material	Stainless Steel	
Measurement Accuracy	±0.27°C for –100°C 0.1°C for 0°C ±0.27°C for +100°C	
Dimensions	16cm (l) x 8cm (w) x 5cm (h)	

APPENDIX F: OUTPUT FROM MOCK DATA STORAGE PROGRAM (RUN TO CALCULATE MEMORY STORAGE NEEDS)

Data recorded every minute (266 Bytes per minute)**:**

NI9550	<station ID #
TM0010:00:01:45	<GPS time
DA01/05/2009	<GPS date
T0040.2000;0045.9000:0035.9000:0001.000	<Temperature
H0027.1500;0028.2500;0025.6000;0003.000	<Humidity
R001.200;001.3000;001.1000;000.100	<Pressure
WS001.300;0001.2000;0001.3000;0000.100	<Wind speed
WDT0023.1000;0023.0000;0023.8000;0000.100	<Wind direction
PAT01000.15;01005.00;00999.0000;0005.000	<Pyranometer
PYG0010.5694;0010.6566;0010.1000;0000.0100	<Pyrgometer

Data recorded for sensors:
Average
Minimum
Maximum
St. Deviation

Data recorded every hour (236 Bytes per hour)**:**

NI9550	<Station ID #
TM0010:00:01:45	<GPS time
DA01/05/2009	<GPS date
CS746454	<Column serial #
CR0003982	<Column run #
GCA000.0033;000.0022;000.012;000.220;000.001	<GC - CO
GCB000.0032;000.0021;000.014;000.240;000.006	<GC - N2O
GCC000.0031;000.0020;000.016;000.252;000.003	<GC - CO2
GCD000.0029;000.0019;000.018;000.225;000.002	<GC - NH4
GCE000.0028;000.0018;000.011;000.216;000.004	<GC - CFC

Data recorded for GC (each gas):
Retention time
Relative ret. time
Peak Width
Peak Area
Peak Height

Housekeeping data recorded every minute (73 Bytes per minute):

NI9550	<station ID #
TM0010:00:01:45	<GPS time
DA01/05/2009	<GPS date
TEMP25.5	<Temperature inside the box
ACCEL000.002	<Max accelerometer reading
TOK	<Temperature status
HOK	<Hygrometer status
ROK	<Barometer status
WSOK	<Wind Speed status
WDTOK	<Wind Direction status
PAOK	<Pyranometer status
PBTOK	<Pyrgeometer status
GCOK	<GC status

The total data for a day can therefore be calculated as follows:

(266Bytes * 60min * 24hrs) + (236Bytes * 24hrs) + (73Bytes * 60min * 24hrs)

= **493.8 kB/day per box**

APPENDIX G: SOLAR PANEL AND BATTERY SIZING CALCULATIONS

Table G-1:Power Requirements for the Green Box (DC Loads)

Relevant Power Loads	Qty	Power [W]	Top usage time [h]	Watt-hours
Gas Chromatographer	1	60	3	180
Thermometer	1	2.4	24	57.6
Dew-point Sensor	1	18	24	432
Barometer	3	0.1	24	7.2
Pyranometer & Pyrgeometer	2	0.1	24	4.8
Accelerometer	1	0.1	24	2.4
Rain Gauge	1	17.8	6	106.8
Anemometer	1	0.1	24	2.4
Communication System	1	2	1	2
GPS Clock receiver	1	1.2	24	28.8
Processing unit	1	2	24	48
Cooling-heating	1	8	8	64
			Total W-h	**936**

Table G-2: Solar Array Sizing

Avg. amp-hours a day	**Battery Efficiency**	**Peak Sun hrs/Day**	**Array Peak Amps**
39	0.8	3	16.25
Array Peak Amps	**Peak Amps/Module**	**Modules in Parallel**	
16.25	5.49	2.96	
DC System Voltage	**Nominal Module Voltage**	**Modules in Series**	**Total Modules**
24	24	1	2.960
1 sq meter each solar panel module = total of 3 m2			

Table G-3: Battery Sizing
(GC not included in calculation because it has battery within the unit)

AC average daily load W-hr/day	**Inverter Efficiency**	**DC avg. daily load W-hr/day**	**DC system voltage**	**Avgerage amp-hours a day**
0	1	756	24	31.50
Average Amp-hours a day	**Days of autonomy**	**Discharge Limit**	**Battery AH Capacity**	**Batteries in Parallel**
31.50	7	0.3	225	2
DC System Voltage	**Battery Voltage**	**Batteries in Series**	**Batteries in Parallel**	**Total Batteries**
24	12	2	2	4

APPENDIX H: GREENBOX MASS BUDGET

Table H-1: GreenBox mass budget

Components	Mass	Components	Mass
Frame	21	**Hardware**	18.8
Green box frame	9	Stevenson Screen	2.2
Hardware box	3	GNSS	1
Telescopic arms and body	9	Processor board	0.6
Sensors	11	Batteries	12
Temperature sensor	0.3	Solid state hard drive	0.5
Humidity	0.3	Cooler	0.5
Precipitation sensor	0.5	Heater	0.5
Barometer sensor	0.1	Fans	0.2
Albedo sensor1	0.9	Antenna	0.3
Albedo sensor2	1.3	Connectors	3.2
CO_2 Sensor + probe	6.8	**Solar panels**	22.5
Wind sensor	0.8	Solar frame (3.5 kg X 3)	10.5
Accelerometers	0.03	Solar cells	12
TOTAL (kg)			***73***
TOTAL + margin (kg)			***84***

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Bolarinwa Balogun, Nigeria
James Barth, Canada
Axel Bergman, Canada, France
Mario Ciaramicoli, Canada, Italy
Hugo André Costa, Portugal
Dohy Faied, United States, Egypt
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