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A review of applications of satellite earth observation data for global societal benefit and stewardship of planet earth

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ABSTRACT

Remotely sensed data can be used to understand and devise measures to address important global issues such as climate change, disaster and disease outbreak. National Aeronautics and Space Administration (NASA) is one of the largest producer and gatekeeper of satellite earth observation (EO) data that plays a crucial role in ensuring that these resources are used for solving global societal problems. However, the extent of remote sensing application is highly disparate in different parts of the world. This paper provides a general overview of key societal applications that have been enabled globally with the use of EO data. It also summarizes the impact of various NASA-supported programs for promoting applications on the targeted beneficiary communities. The themes addressed here are land cover/land use mapping, carbon biomass assessment, food security, disaster management, water resources, ocean management and health and air quality. The paper also argues for capacity building that is crucial to building sustainable solutions when using EO data for science-based decision making.

1. Introduction

Remote sensing is the science of obtaining information without physically being in contact with it. This process involves detection and measurement of radiation at different wavelengths reflected or emitted from distant objects or materials, by which they may be identified and categorized by class/type, substance, and spatial distribution. Through various remote sensing platforms such as satellites and aircraft, supplemented by surface and subsurface measurements and mapping, Earth's physical, chemical, and biological systems can be obtained, which is collectively known as Earth Observation (EO) [2].

The capacity of satellite remote sensing and satellite technology is distributed quite disproportionately in the world. As of November 2015, only 74 countries have been able to make satellite launches independently or with the help of others (see Fig. 1; [4]. Out of the satellite launches since 1962, more than 320 have been EO satellites launched worldwide covering the atmosphere, oceans, land, and other Earth systems. The United States, Russia, France, Italy, and Germany are at the forefront of the EO satellite launches. They are followed by China, India, Canada, Brazil, Argentina, South Africa, Nigeria, and Australia [7].

The history of earth observation began in 1840s, during the era of geographical exploration, when pictures were taken from cameras secured to the tethered balloons for the purpose of topographic mapping. It took a further 100 years for earth observations to evolve to a platform based in space called satellites. In 1958, the National Aeronautics and Space Administration (NASA) was established. Much of the technological advances in human and robotic space flight had already started in response to the early Soviet space achievements [13,14]. Initially, a lot of the applications were defense-centric. Later, NASA missions like Environmental Science Services Administration (ESSA) and Synchronous Meteorological Satellites (SMS) came on board to improve meteorology and weather science. The first major land monitoring camera system from the sky, called Landsat mission, was launched in 1972. It has produced over 2 million images since the first launch. In 2008, a new era of open-access satellite data began when the US Geological Survey (USGS) publicly released its Landsat archive, dating back from the 1970s. Currently, this is believed to be the world's largest collection of Earth imagery [2]. This availability of open source data has also helped developing countries that are not capable of launching or maintaining their own EO satellite but are in dire need of remotely sensed data to solve problems.

NASA has been an important catalyst for international cooperation in changing the mindset of how and why humans need “space” as the final frontier for stewardship of Planet Earth [13,14]. When the National Research Council (NRC) completed its first decadal survey in 2007 for Earth science and applications for NASA and National Oceanic and Atmospheric Administration (NOAA), and USGS, it highlighted the need of the U.S. government to work in concert with private sector, academe, the public, and its international partners in renewing the EO systems and restoring leadership in Earth and science applications. That survey set a new agenda for satellite EO missions in which practical societal benefits were of an equal importance as were the efforts in acquiring new knowledge about Earth.

Fig. 2 shows select programs that NASA launched in the past 5 years that have direct societal benefits associated with its science focus area. The goal of all these missions are to find answers to how the global earth system changing, how will it change in the future, and how does the Earth system respond to natural and human induced changes – all driven by the need to make planet earth a more sustainable place for humans to live with other forms of flora and fauna [13,14] (see Fig. 3).

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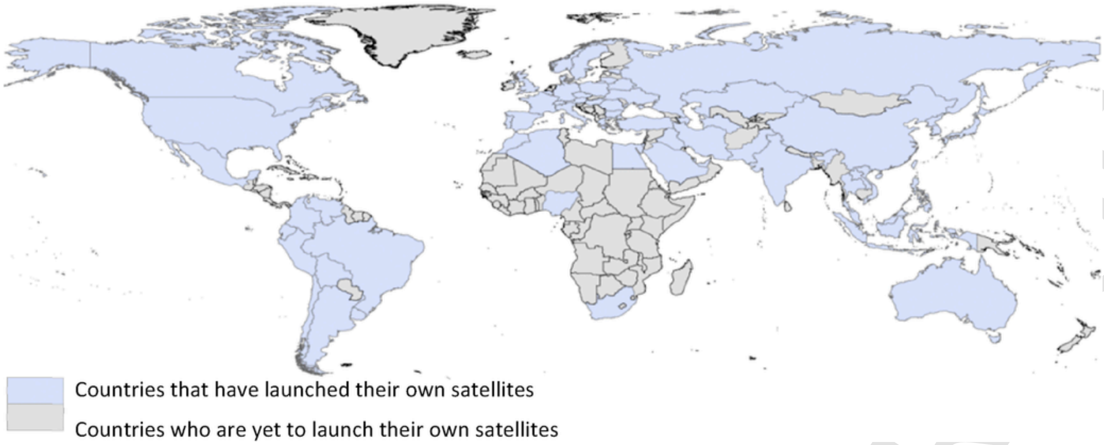

Fig. 1. As of November 2015, 74 countries have launched their own satellites indigenously or with the help of others. Map was compiled from various data sources in the public domain.

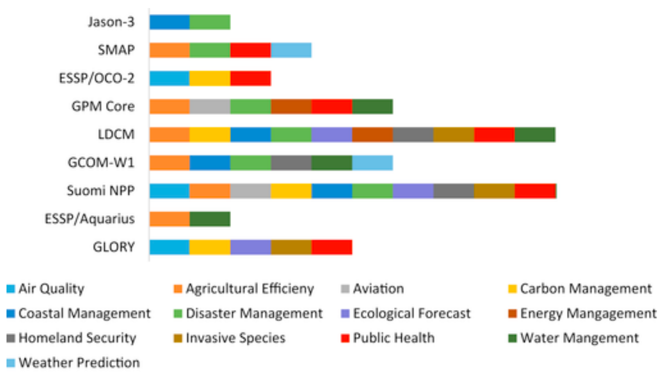

Fig. 2. Select NASA missions[1] from 2010 to 2016 that has direct application on societal benefits listed above. Data adapted from http://eospso.nasa.gov/files/mission_profile.pdf [13,14].

However, greater access to remote sensing data has not necessarily translated to greater utilization of the EO data to its full potential for the global society. Although remote sensing data has great potential for science-based decision-making on critical areas such as disaster management, global environment, and management of natural resources, not all users (policy makers, academic institutions, organizations in various countries) have the necessary technical background and knowledge to understand, download, and manipulate the data according to their needs. This is especially the case for developing nations where the potential of EO for the societal applications is yet to be appreciated in its full merit. These are the countries where EO data are a clear surrogate for traditional methods of gathering data that are cost intensive or fundamentally impossible.

To realize the fullest potential of EO data, various international organizations have developed programs to help make the use of remote sensing data more widespread. SERVIR (Spanish for “to serve”) is one such program that has played a major role in spurring programs that use remotely sensed data for various critical programs in developing countries. It was originally established in 2004 as a joint venture between NASA and the U.S. Agency for International Development (USAID). SERVIR provides satellite-based EO data and science applications to help developing nations in providing critical information in order to assess environmental threats and damages from natural disasters. It first started in Central America, expanded to East Africa in 2008, to Hindu-Kush-Himalaya (HKH) in 2010. In 2015, the Lower Mekong region was also brought under the SERVIR umbrella in partnership with Asian Disaster Preparedness Center (ADPC) where the application is primarily focused on disaster risk management (DRM) and disaster risk reduction (DRR).

After the first decadal survey [3], programs were identified to enable better interaction between satellite mission scientists and relevant communities from the initial development phase so that mission data products were of maximum value. One such program is the Early Adopter (EA) program by NASA Applied Sciences Program (ASP). Subsequently, the first Early Adopter Program was developed for NASA's Soil Moisture Active Passive Mission (SMAP) in 2010. The goal of EA program is to facilitate feedback on mission products during pre-launch, and to accelerate the use of these products during post-launch by providing specific support to Early Adopters who commit to engage in applied research [5]. Most of the Early Adopters are currently from academic institutions, international organizations and government entities in developed countries. However, if the Early Adopter Program reaches out to all the planned decadal survey missions, it is likely to evolve more quickly and ultimately benefit research and decision-making in developing countries as well.

2. Current state of the art on satellite EO-based applications

As apparent from the trajectory of EO data applications to date, NASA's remote sensing data users encompass a broad spectrum from developed and developing countries, governmental and academic institutions, and national and regional level decision makers. The motivation of NASA satellite missions now extends beyond mere curiosity or pure research that were mostly focused around developed countries in the 20th century. Today's problems that are most threatening to the planet take the form of scarcity of food, water, human health, disasters, habitat endangerment and climate change. Because of widespread globalization, economies are more intertwined and therefore transcend political boundaries. Therefore, developed and developing countries now have a common stake in managing these global issues and resources like food, water, energy and natural environment. For example, the effects of a bad crop year in South America might be felt well beyond its

1. Acronym List: Soil Moisture Active- Passive (SMAP), Earth System Science Pathfinder (ESSP)/Orbiting Carbon Observatory (OCO), Global Precipitation Measurement (GPM) Core, Landsat Data Continuity Mission (LDCM), Global Change Observation Mission-Water (GCOM-W), Suomi National Polar Orbiting Partnership (NPP).

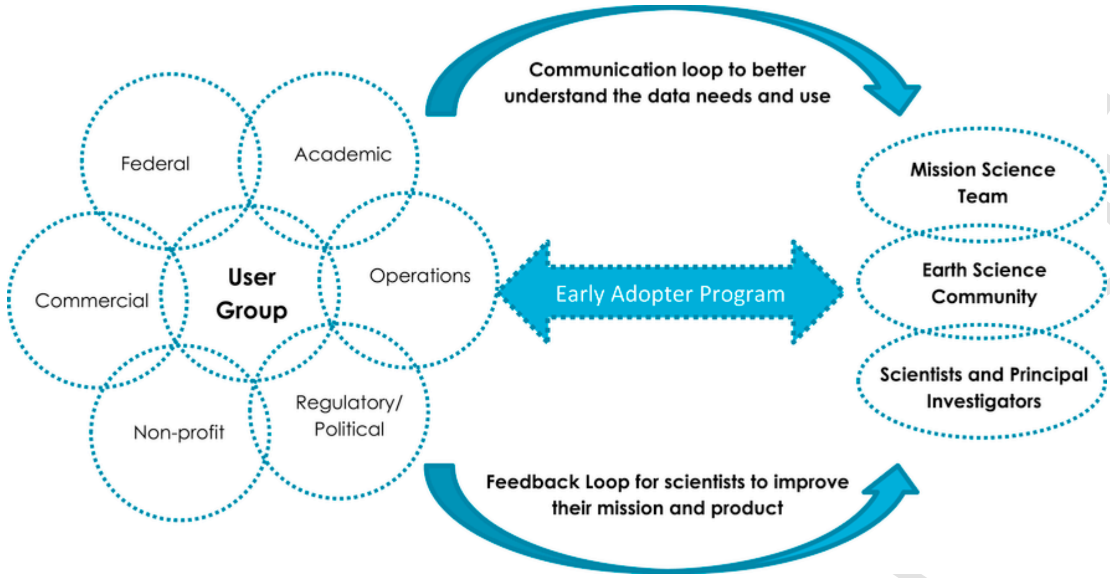

Fig. 3. Early Adopter Program Schematic. Adapted from (Escobar et al., 2014).

geographical boundaries to faraway countries that import crops from the region. Remote sensing and the vantage of space can help achieve these common goals of today's globalized community by providing a common data resource and global-view infrastructure that can be used for making various critical decisions.

This paper explores various areas where EO applications that have been successfully implemented. The focus is more on developing countries where use of remote sensing technology is relatively new but is highly sought after. For many developing countries, remote sensing is the only method via which one can get access to data that are otherwise impossible to collect. Remotely sensed EO data therefore provides that opportunity for these communities to make science-based decisions and take advantage of the cutting edge technologies that are otherwise inaccessible. There has been a steep learning curve for many application communities and there are many lessons learned so far. However, there is a lack of collaborative efforts among many developing countries (i.e., in the spirit of 'south to south' cooperation) in addressing similar problems. There is also a gap between the available technology on hand and the much needed technologically-able workforce who can mobilize the resources to societal benefits. Although use of remote sensing EO has evolved in different parts of the world at varying speeds, almost all communities face similar challenges when it comes to effectively executing programs that use remote sensing for decision making. For example, lack of capacity in terms of workforce or technological infrastructure to store the data is still a major challenge in many developing countries regardless of how advanced their programs are. Therefore, capacity building is one of the most significant aspects of ensuring that EO technology is utilized to its full potential for global societal benefit.

2.1. Specific examples of successful satellite EO application

Earth observation data relevant to land cover, weather, disaster management, and agriculture are the ones that are widely used around the world, particularly in developing nations. For example, Tropical Rainfall Measuring Mission (TRMM) and now the Global Precipitation Measurement Mission (GPM) provide precipitation estimates that are widely used for weather forecasting and its impact on agriculture. With the recent launch of Soil Moisture Active Passive (SMAP) mission, high resolution global soil moisture data will soon be available for worldwide use with potential application in operational meteorology, disaster management, and food security. Similarly, highest resolution topographic data generated from NASA's Shuttle Radar Topography Mission (SRTM) has been released globally with successful applications in hydrology, land cover analysis, carbon biomass assessment to name a few. Out of all satellite missions, Landsat images are perhaps one of the most commonly used EO data resource. Following subsections explores some of the most successful applications of satellite EO data focusing particularly in developing countries. The perceived impact of these applications is also briefly discussed.

2.1.1. Land cover/land use mapping

Land-use and land cover (LULC) maps can be a powerful tool in understanding the cause and effects of climate change in hydrology, biodiversity, carbon dynamics, population, migration and urbanization. The LULC maps can demonstrate visual data in an effective manner that help mobilize both the decision makers and the grassroots towards a more sustainable use of resources. For many developing countries that are new to using EO data, LULC mapping projects can serve as a baseline project and a good starting point for building remote sensing capacity. For example, in Eastern Africa, a three-year project was implemented in joint collaboration between NASA-SERVIR and USAID across nine countries of Malawi, Rwanda, Tanzania, Zambia, Namibia, Botswana, Ethiopia, Uganda, and Lesotho [16]. This project produced baseline land cover maps using Landsat images and also implemented capacity building efforts within the participating countries. The main purpose of the maps developed under this project was to support national processes in reporting to the United Nations Framework Convention on Climate Change (UNFCCC) on greenhouse emission estimates. Apart from government agencies within Africa, this project brought together strategic partners in the United States and rest of Africa and was therefore deemed successful.

For LULC mapping, Landsat imagery is particularly advantageous because of its spatio-temporal consistency and reliability with data collected over the last four decades. Because it is freely available and is readily accessible with reasonable internet connection, it is especially preferred in developing countries [16]. However, when using Landsat images, image corrections may be necessary to interpret the data accurately as there could be issues with image resolution and quality. For example, atmospheric conditions like haze and cloud cover during image acquisition can compromise the quality of the data. In the absence of such corrections, and whenever possible, it is important to support the imagery data with field observations and other resources like google earth for better accuracy. Once the data is compiled, it is essential to properly define the classification themes for consistency across board. This is especially critical in a large scale projects where there are multiple agencies/countries and stakeholders involved.

2.1.2. Carbon biomass assessment

Forest biomass is a critical indicator of carbon sequestration. The amount of carbon sequestered by a forest can be inferred from its biomass accumulation because approximately 50% of forest dry biomass is carbon [17]. Landsat Imagery, Shuttle Radar Topography Mission (SRTM) and International Space Station SERVIR Environmental Research and Visualization System (ISERV) are few resources that provide images of earth that are used in carbon biomass assessment. These technologies can be used for approximating carbon stocks by estimating tree trunk diameter via tree crown area. These methods are currently being used by the Climate Action Reserve, a premier carbon offset registry of North American carbon market, to provide forest owners with a platform to market carbon stored in their forest. Similarly, in the international arena, the UN-REDD Program is the United Nations collaborative initiative on Reducing Emissions from Deforestation and Forest Degradation (REDD) in developing countries. The REDD program supports 64 partner countries across Africa, Asia-Pacific, Latin America, and the Caribbean. In many developing countries, the REDD program is the emerging driving factor in developing EO applications since these programs rely on robust and transparent national forest monitoring systems. REDD program is expected to be pivotal for EO applications especially in Mesoamerica as it effectively monitors forest fire, one of the primary cause of forest degradation [18].

Even with the availability of EO data, the application of EO technology in biomass assessment is at early stages of application in many regions. Regions like Hindu Kush Himalayan (HKH) region have a lot of potential for carbon sequestration because of its diverse land mass but limited efforts have been made to assess its true potential in sequestering the carbon. This is mostly because the traditional methods of determining forest landmass are both time and cost intensive, and the new methods using EO data is still in its primary phase. Although resources such as annual tree cover and global change monitoring systems using Landsat data are readily available, these data often need significant improvement for regional application. Recently, the International Center for Integrated Mountain Development (ICIMOD) in collaboration with NASA-SERVIR program have developed programs to facilitate collaboration among the regional member countries in order to develop periodic national land cover change databases in the region using remote sensing technologies [12].

There is an absence of multi-scale and cost effective carbon monitoring across political boundaries that support REDD strategies for forest based vulnerability and adaptation planning [12]. This is especially the case in HKH and Lower Mekong region. Very limited research has been carried out to assess the relationship between cascading effects of land cover changes with hydro-meteorological hazard occurrence and the subsequent long term impacts on environment, especially through the loss of ecosystem services [6]. The quantification of carbon fluxes of forest land is a difficult task due to changing carbon dynamics. Forest cover change rapidly especially in remote communities that heavily depend on forest resources for fuel, grazing, and timber. It is often difficult to monitor such changes happening in micro scale unless there is high resolution EO data that is able to detect other parameters such as soil moisture and thermal information. Many communities still do not have the capacity to do such complex analyses that allows for gathering accurate information. Therefore, there is a critical need to invest in capacity building in order to implement a standardized methodological framework for baseline forest assessment system using multiple scale monitoring protocols.

2.1.3. Agriculture and food security

The impacts of food security are felt most seriously in developing countries where people practice subsistence farming. According to World Health Organization (WHO), food security is built on three pillars –availability of food on a consistent basis, access to sufficient resources to obtain nutritious diet, and appropriate use based on knowledge of basic nutrition as well as adequate water and sanitation. In addition to the market-driven impacts on food security, many of those at risk rely upon adequate weather conditions for subsistence agricultural activities. High food prices coupled with an unfavorable conditions during growing season can be devastating for subsistence farmers. This is where accurate monitoring of growing season conditions can significantly help mitigate the effects of food security in the developing world. These assessments are done using remotely sensed monitoring data for precipitation, crop water requirements, and vegetation indices [11]. For example, MODIS satellite data is now used in developing vegetation indices that provide consistent spatial and temporal comparisons of vegetation properties used to track drought conditions that may threaten subsistence agriculture [15].

Programs with sensors tailored for agricultural system with small farm holdings, mixed crop conditions, rain fed-system experiencing temperature stress, and land degradation are some of the areas where satellite EO data can help. In addition, programs that have country specific technologies and modeling frameworks that integrate local farming knowledge and traditional production systems must be implemented in conjunction with scientific data and technical skills. This can be achieved if EO community engages with the diverse stakeholders to develop an integrated platform that would then enable them to combine and add value to the diverse EO domains.

The agriculture sector is affected not just by the changing climatic patterns, but also by globalization, socio-economic transformation, land use conflicts, and the changing dynamics as the result of growth in population such as migration, and war. Especially in areas with harsh climate, rough terrain, and short growing seasons, the issue of food insecurity is more prominent. To develop strategies against these issues, countries like Afghanistan, Bangladesh and Pakistan have made major strides in implementing crop monitoring programs with the help of data gathered from national space agencies with the help of Famine Warning Systems Network (FEWSNET). The FEWSNET is a USAID funded program that collaborates with international, regional, and national partners to provide timely and rigorous early warning and vulnerability information on emerging and evolving food security issues. In Nepal and Myanmar however, crop monitoring is still in a preliminary stage. However, recent efforts of NASA-SERVIR program for developing national crop and drought monitoring systems in conjunction with food security programs is an effort in the right direction [12]. In an effort to enhance global crop assessment decision support, NASA is also working together with the U.S. Department of Agriculture (USDA) and Foreign Agricultural Service (FAS) in integrating NASA soil moisture products through implementation of data assimilation tools.

Many communities are still lacking in strategic and operational capacity at the local level. The limited technological knowledge on the user end makes it harder to interpret data collected by remote sensing. Therefore, it is important to devise programs that serve as the intermediaries between ones who are collecting data (scientists and engineers) and ones who are using the data (i.e., farmers). In other words, public outreach post data collection and analysis is crucial.

2.1.4. Disaster management

The effects of climate change are especially pronounced among the already marginalized populations increasing their vulnerability to unpredictable weather patterns, floods, droughts, and rising sea levels. Warnings and mitigation strategies are important both on national and regional levels for short, medium, and long term time-scales ready to be executed during times of disasters. However, these strategies are often a challenge to deliver without having robust ground observation data. This is where satellite EO data has a unique potential to contribute where ground observation data is limited or unavailable. Maps showcasing the spatial extent of disaster, and assessing the pre- and post-disaster effects are some of the most simplistic ways that remote sensing technology can help with disaster management efforts. Other sophisticated applications include using water extent data from instruments like Moderate Resolution Imaging Spetroradiometer (MODIS) and near-real-time precipitation data to model potential flood inundation and ultimately improve flood management.

The following subsections provide an overview of the most common remote sensing data application for disaster management - landslide, flood, and earthquake. Apart from these, there are many other types of disasters like forest fire, hurricane, typhoon, and volcanic eruption where EO data is crucial.

2.1.4.1. Landslide

A systematic inventory of landslide events over the globe is valuable for estimating human and economic losses, quantifying the relationship between landslide occurrences and climate variations and for predicting disasters in the future [8]. Resources like Global Landslide Catalog (Fig. 4) developed by NASA provide an inventory of the effects of landslides around the world including the associated number of fatalities. Complex technologies are currently being explored to provide a more in-depth understanding of conditions that induce landslides. Sensors like optical remote sensing such as MODIS, Shuttle Radar Topography Mission (SRTM), Soil Moisture Active Passive (SMAP), and Synthetic Aperture Radar techniques are being used to assess landslide density, areal extent, frequency, and other variables important in assessing the vulnerability of an area to landslides such as soil moisture, slope, aspect, etc.

Another available resource is the susceptibility map developed using Landslide Hazard Assessment Situational Awareness (LHASA) model [20]. LHASA provides a relative indication of landslide susceptibility across 700,000 square kilometers. Although originally developed for the Central America region, it is being applied in a prototype form in Nepal and Peru. The model combines the indication of susceptibility with variables such as rainfall intensity to predict the probability for a landslide. However, due to its coarse spatial resolution it has limited applicability for local emergency for which high resolution data is often required.

2.1.4.2. Flood

Most of the collaborations and responses related to flood are limited to emergency response during flood events through international space charter in this region [12]. This is mostly because there seems to be a significant lag in providing reliable climate forecasts in order to prepare for and prevent damages associated with flood. The Global Flood Working Group (GFWG) comprised of top experts on flood studies have argued for a product that uses satellite remote sensing data to predict flood inundation areas [20]. Apart from this, the remote sensing data itself have been unreliable at times due to the mountainous terrain of the region. Rainfall pattern in mountainous terrain are affected by orographic influence which is not adequately captured by the current remote sensing technologies.

In Hindu Kush Himalaya (HKH) region, online multi-scale disaster information and risk assessment database has been developed as part of NASA-SERVIR Himalaya Program. Although databases and spatial delineation of flood risk zones have been prepared across the region to support planning efforts, these risk reduction metrics and databases are not being utilized on operational levels. Bangladesh on the other hand has a relatively sophisticated flood management program that uses the satellite radar altimetry satellites to measure the river flow discharges. The radar altimetry also uses water elevation of wide rivers to help predict the flood forecasting downstream. Lower Zambezi River Basin (ZRB) is another area where satellite EO data are being used for flood relief services. Although there are local flood forecasting efforts in the area, these efforts currently have no integrated flood warning system and are not integrated with real time data. In the area, the only source of accurate and reliable flood maps are developed by NASA funded programs using MODIS data.

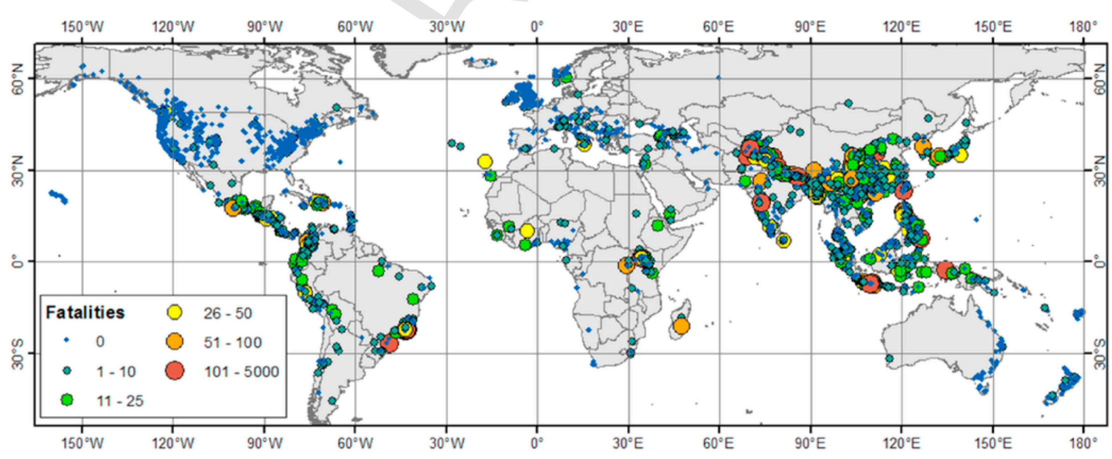

Fig. 4. Global Landslide Catalog (2007–2015) developed by NASA with nearly 7000 events and associated fatalities [20]. Figure Source: Reprinted from *Earth Science Satellite Applications* with kind permission from Springer Publications.

2.1.4.3. Earthquake

An example of earthquake disaster response where remote sensing technology proved to be a valuable resource was during the 2015 earthquake in Nepal of magnitude 7.8 and several aftershocks that followed it. After the earthquake, mappers from different agencies such as ICIMOD, NASA-SERVIR, International Charter, and other international agencies came together for a combined effort to develop tools for earthquake response [20]. Because these types of partnerships take time to develop, it is important to look into the future and have these organizational infrastructures built in place prior to crisis so that it is readily available when the disaster strikes without warning.

2.1.5. Water resources

Trans-boundary water basin management and water security are the key challenges that water resource management is facing today in both developed and developing countries. Therefore, solutions to water resources issues involving EO data have also been developed in different scales. In Africa, a NASA SERVIR project was developed with the intention of finding a better balance between water abstractions for human use and other ecosystems. This project supported basin-level water management by developing monitoring and forecasting tools using EO and meteorological forecasts with rainfall-runoff hydrology models [10].

In United States, the California drought has affected its 38 million residents and costs have exceeded $2.2 billion in 2014 alone. This has also provided an opportunity to utilize EO data to support monitoring and response to drought. As a response to this, United States Drought Monitor (USDM) NASA EO mission was launched specifically for integrating various datasets to illustrate the onset and extent of drought conditions. Remote sensing applications and decision support system has been utilized in monitoring water supplies stored in snowpacks, drought impacts on agricultural production and groundwater depletion. These ongoing efforts ensure that these capabilities are sustained beyond the current drought, and that they become a standard operational toolset available to water managers in California and other regions around the world that are vulnerable to drought [20].

2.1.6. Health and air quality

Use of remote sensing technology in monitoring and forecasting conditions that directly or indirectly affect health and air quality is still in its infancy. Consistent with the 2007 decadal survey, remote sensing technology has been advancing its applications in air quality and health in infectious and vector-borne diseases and environmental health issues. These applications include mitigation of health-related hazards, implementation of air quality standards, policy, regulations for economic and human welfare and the understanding the effects of climate change on public health and air quality to support managers and policy makers in planning and preparations.

Some of the challenges related to using remote sensing data for Health and Air Quality (HAQ) applications include gathering optical data in cloudy conditions, determining the vertical distribution of particulates affecting air quality, determining the human exposure to pollutants at higher spatial resolution, and lack of real-time environmental data such as air quality for use in warning systems. The HAQ program of NASA ASP in the context of EO application can be helpful in understanding the relationships between climate change and human health and on improving predictability of health epidemics.

Application of remote sensing in studying communicable diseases like cholera has been an emerging research area with more accurate datasets over the last few decades [1]. For example, satellite remote sensing data was successfully used to capture the changes in hydroclimatic conditions related to infamous cholera outbreak of 2008 in Zimbabwe [9]. It has been found that satellite data measurements of climatic and environmental variables such as precipitation, temperature, terrestrial water storage, vegetative cover, and costal chlorophyll can be meaningful predictors over a range of space and time scales. Such satellite EO data can be effective in developing a cholera prediction model with several months' lead time. Once it is understood how the occurrence and spreading of diseases are affected by climate, the predictability of disease and timing of intervention can be augmented by hydrologic data retrieved from EO systems.

2.1.7. Ecosystems and oceans

Since 1970s, scientists have implemented airborne remote sensing (ARS) using balloons, helicopters, and airplanes to study and manage fisheries. The scale and scope of satellite EO data now allows for the implementation of near-real time ecosystem and forecast models that can be applied to ocean management. Ocean management includes measuring sea surface temperature (Fig. 5), ocean color, sea surface salinity, ocean currents, and sea surface height, to name a few. Analyses of in-situ biological data paired with SRS data can be one of the most powerful means to determine habitat preferences on large spatial scales. Satellite EO data provides planners and managers with quantifiable information on biotic and abiotic conditions which is a key element for marine reserve designs (Kacev and Lewison, 2016). In developed countries like United States and Australia, commercial fishers rely on satellite EO data to help find productive fishing grounds in efficient manner. Many countries have allocated public funds to provide SRS data to fishermen with an intention of reducing fishing costs and increasing productivity as it reduces the search time by as much as 50%. For example, EO data have saved salmon and albacore fisheries in Pacific Northwest upwards of $500,000 per year (Kacev and Lewison, 2016). In addition, the ability of remote optical sensors to pick out boats in remote reserves can minimize the impact of illegal fishing.

Key players like NOAA and NASA have conducted programs to identify specific ways to incorporate earth science satellite observations, data, and associated models to fisheries management. The spatial and temporal scale of features such as ocean currents, eddies, and fronts that are essential for understanding marine ecosystems are often difficult to study with traditional ARS methods. Satellite platforms, however, have the capacity to monitor these dynamic ocean features on larger scales with high resolution satellite data and images. For example, satellite EO data can aid in Marine Protected Areas (MPA) monitoring at large spatial and temporal scales without the need for expensive ship time. In addition, the use of fishery logs, fishery-independent surveys in combination with SRS data is used to study and predict fish distributions. For example, by integrating a merged satellite EO product and data from PSAT deployments, new insights on migration pathways for yellowfin tuna have been identified in the Caribbean Sea and the Gulf of Mexico. (Kacev and Lewison, 2016).

Another application of EO data is to avoid or minimize bycatch, the incidental catch of unused or unmanaged species. For example, satellite EO data paired with sophisticated predictive ocean models integrating oceanographic and telemetry data have been developed to forecast the presence of high-risk bycatch species like the Bluefin tuna in Australia, guiding dynamic spatiotemporal fisheries restriction decisions. Dynamic ocean management combines technological advances to utilize and share near real-time environmental and biological data to promptly communicate fisheries conditions to a broad stakeholder community (managers, industry, fishermen, and conservation organizations). These types of approaches can allow managers and fishermen to rapidly adjust fishing practices, efforts, and locations in response to changing conditions. The development and effective application of

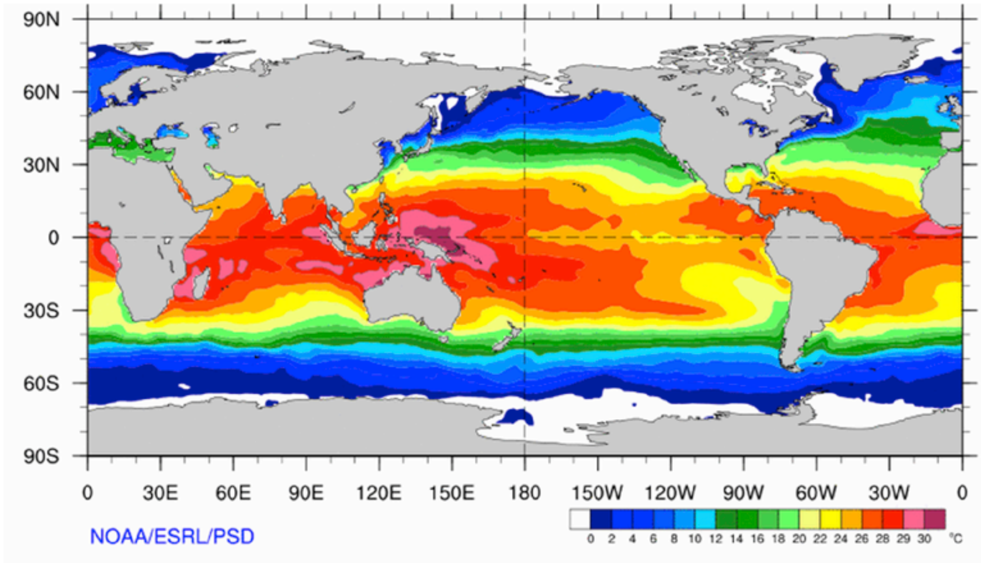

Fig. 5. Global weekly average of sea surface temperatures recorded from January 30, 2011 to February 5, 2011. Source: Earth System Research Laboratory Physical Sciences Division (Kacev and Lewison, 2016) reprinted with kind permission from Springer Publication.

these dynamic tools is reliant on robust high resolution ocean data, making continued availability of satellite EO data critical to the innovation of fisheries and other sectors of ocean management.

Satellite EO data applications in this area are focused more in developed countries and therefore there is tremendous potential in starting such programs in many developing countries where fishing is the primary source of livelihood. Although traditional fishing methods practiced for multiple generations are invaluable, with climate change many ecosystems, including that of underwater ecosystem, are behaving out of the norm. This is where satellite EO data application could play a vital role in ensuring that fish farmers can fish in a more efficient manner.

3. What are the key components for successful application of satellite EO data?

Although getting access to data is the most important first step, there are many other key foundations like institutional capacity, technological competency, and executional control that govern the extent to which any new technology is utilized. Following are a list of key components that usually ensure a successful implementation of programs using EO data for global societal benefit.

3.1. Capacity building

Capacity building is the process of training the workforce to advance their knowledge by exposing them to new technologies and infrastructures that improve resource management skills and capabilities. Capacity is the key challenge that all countries, particularly developing ones, face when it comes to EO data application. Capacity building is an iterative and dynamic process that requires modification according to the new technology, problem being addressed, regions, and pre-existing infrastructure and personnel skill level. There have been cases where capacity building efforts have flourished in diverse government and non-government institutions around the world when sufficient thought was put into the design of application with stakeholder input. It is clear from the previous examples that capacity building must continue and scaled further for globalization of public access to satellite EO data in a manner that results in sustainable uptake by stakeholders for societal benefit and address key challenges facing the world today.

3.2. Technological competency

Biggest hurdle in developing useful applications to help solve existing challenges include effectively translating products intended for scientific research questions into tangible applications that can drive stakeholder decision making. Challenges to this translation are often related not just to increased technical capacity, but also to institutional, organizational, and resource capacity. In order to address this, continuous efforts must be made on different levels in collaboration key partners of the region. For example, the satellite EO capacity building effort of NASA ASP in Pakistan developed in collaboration with University of Washington and Pakistan Council of Research in Water Resources (PCRWR) is an example where the success of professional training of stakeholder staff in research institutions became clear. This type of consistent partnerships can help close the capacity gap between the countries who have advanced remote sensing technologies and ones where EO data use is relatively new.

3.3. Political stability and will to address challenges

For developing and developed countries alike, political stability is crucial for planning and executing any type of large scale projects involving the uptake of satellite EO data. Institutional agencies and government bodies must be formed to facilitate access to, and application of, EO data. These infrastructures must work in collaboration with international agencies like NASA, SERVIR, and International Charters to develop programs both for short term and long term needs. Only when EO applications are integrated with policies and strategies of a community or a country's political institution will it achieve full potential. It is important that political leaders understand the value of investing in programs that enable scientists and engineer to find new ways to solving problems rather than resorting to traditional methods that are often time and cost sensitive.

4. Conclusion

Remote sensing EO technology is a powerful tool that has changed the way we think and solve problems related to the environmental and sustainable stewardship of our planet. Global scale problems like global warming and climate change cannot be solved with only a few countries having access to EO data and devise methods to mitigate it. The broader scientific community must understand that remote sensing EO technology fills that gap by providing an opportunity for all countries, and all human beings, even ones that might not have the ability to collect important data, to be part of a local solution for global problems. Since the last decadal survey by the National Research Council a decade ago, NASA ASP and in particular the Capacity building program, has been at the in the forefront of accelerating and globalizing societal benefit of satellite EO data around the world. Many programs developed by NASA and other international organizations have played critical role in ensuring that these resources are being utilized in developing countries. It is clear from this article that there have been many success stories where satellite EO data has been used for important applications like disaster management and improved agricultural production for food security. However, much more needs to be done to ensure that countries around the world and their citizens can benefit from a sustainable uptake of observations of earth from space. For example, there have been many uses of EO data for disaster management but very little has been done for disaster prevention. There are many lessons to be learned from the past ASP projects that can be implemented and scaled up in the future. In addition to investing in capacity building and increasing technical competency, it is important that the policy makers understand the importance of satellite EO data in making decisions supported by scientific evidence. When remote sensing EO technology is integrated with an environmental decision making strategy, solutions are more efficient and more sustainable. For all these fundamental reasons, the broader scientific community must continue to support programs that enable application of satellite EO data for global societal benefit and stewardship of our planet.

Uncited reference

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