Chapter 14

Digital Earth for Climate Change Research

Gensuo Jia, Li Zhang, Lanwei Zhu, Ronghan Xu, Dong Liang, Xiyan Xu
and Tao Bao

Abstract Our planet is undergoing one of the most rapid climate changes in Earth's history. The current change is particularly significant because it is most likely a consequence of human activities since the 19th century. The Digital Earth platform, which includes Earth-orbiting satellites, ground-based observations, and other technologies for collecting, analyzing and visualizing data, has enabled scientists to see our climate and its impacts at regional and global scales. The Digital Earth platform offers valuable information on the atmosphere, biosphere, hydrosphere and cryosphere to understand Earth's past and present, and it supports Earth system models for climate prediction and projection. This chapter gives an overview of the advances in climate change studies based on Digital Earth and provides case studies that utilize Digital Earth in climate change research, such as in the observation of sensitive factors for climate change, global environmental change information and simulation systems, and synchronous satellite-aerial-ground observation experiments, which provide extremely large and abundant datasets. The mapping of climate extremes and impacts improves preparedness for climate change-related risks and provides robust evidence to support climate risk management and climate change adaptation for the public, decision makers, investors, and vulnerable communities. However, Digital Earth faces the challenges of multisource data coordination and integration, requiring international partnerships between governments and other organizations to advance open data policies and practices.

Keywords Digital Earth platform · Climate change · Sensitive variables · Information and model systems · Greenhouse gases

G. Jia (✉) · X. Xu · T. Bao
Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
e-mail: jiong@tea.ac.cn

L. Zhang · L. Zhu · D. Liang
Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China

R. Xu
National Satellite Meteorological Center, Beijing, China

14.1 Introduction

Global climate change has long been recognized as the most critical issue of the 21st century. The 2016 Paris Agreement within the United Nations Framework Convention on Climate Change (UNFCCC) highlights the importance and urgency of climate action. Climate-related changes are becoming evident at various spatial and temporal scales, accompanied by a record increase in the frequency of extreme climate events and the emergence of complex environmental issues. As a result, vulnerability to climate change is expected to expand spatially, threatening larger human populations as warming continues. Understanding climate change and delivering climate information with high precision has therefore become increasingly important, especially to assist governments and decision makers in implementing appropriate mitigation and adaptation policies.

The Earth system is a complex collection of interlinked subsystems that require multidimensional, multiscale and multitemporal datasets. Understandably, challenges and uncertainties in studying climate change and its impacts are largely due to the massive amount of data that is required, and the complexity of analyses that can translate data into useful information. Earth observation for this purpose has become an invaluable resource. Earth observations, during most of the history of science, have predominantly been recorded at the ground level with limited spatial coverage. Methods such as those developed by World Weather Watch in 1963 combined a series of single surface pictures to provide global coverage but lacked network density and vertical resolution. Geophysical and biological phenomena have also been generally insufficiently sampled. However, the growing diversity and improvement of sensors and sensing platforms has greatly diversified data sources, benefiting global climate change research in the past few decades through technologies that can increasingly provide a more accurate and precise picture of biological, physical, and chemical phenomena (Table 14.1). Moreover, satellite platforms and the development of UAVs and other technologies have made multitemporal observations feasible, which have allowed for investigations into large-scale processes that were traditionally not possible. Synoptic Earth observations have changed the way we understand the planet, from the first weather satellite that revealed astonishing cloud features to their utility to verify and improve our understanding of the coupling between the El Niño-Southern Oscillation and ocean currents. They have been used to study temperatures at various altitudes, atmospheric processes, the effects of snow on water circulation, the effects of global and regional factors on sea level changes, and other phenomena. From 1960 to 2011, 514 Earth observation satellites were launched worldwide, and 200 more launches are planned by 2030 (Guo 2014). The huge amount of data collected over the years provides a rich resource of information for climate change research. However, this big data presents challenges in data collection, characterization and analysis. Therefore, there is urgent need for a Digital Earth platform that can integrate multisource spatial information into a single platform and allow for integrated investigation into Earth observation data to generate climate change information.

Table 14.1 Summary of the functions of satellites related to global change research

Satellite	Function
TIROS series, Nimbus 4 and 7, ERS-1, ERS-2, Envisat	Monitors global stratospheric ozone depletion (including Antarctica and the Arctic)
Nimbus 7, ERS-2, Envisat, Aqua, Aura, MetOp	Detects tropospheric ozone
Explorer 7, TIROS, Nimbus	Measures radiation balance
TIROS series, ATS, SMS, MetOp	Produces weather images
Meteorological satellites, including the TIROS series, GOES and POES (NOAA), MetOp (Eumetsat), ERS-1, ERS-2, Envisat	Weather forecasting
Radarsat, Landsat, Aura, Terra, Jason, ERS-1, ERS-2, Envisat	Investigates ice flows in Antarctica and Greenland
Topex/Poseidon, ERS-1, ERS-2, Envisat	Detects mid-scale sea surface topography and important variables in ocean mixtures
TIROS-N and NOAA series, ERS-1, ERS-2, Envisat	Observations of oceanic contributions to climate change
Landsat, SPOT series	Agricultural land monitoring
LAGEOS, GPS	Confirms high-precision terrestrial reference frames
GCOM	Observes Earth water and carbon dioxide
TANSAT	Monitors atmospheric carbon dioxide concentration
FY	Used in weather forecasting, climate prediction, natural disaster and environmental monitoring, and resource development

Sources NRC (2008), Guo et al. (2015)

14.2 Digital Earth and the Essential Climate Variables

Climate change is highly heterogeneous over the globe, with strong regionality. The UNFCCC provides 34 essential climate variables (ECVs) that require contributions from Earth observations from space (Table 14.2) (Guo et al. 2015). The spatial attributes of ECVs make it possible to effectively observe them through space technology (Guo et al. 2014a), and the Digital Earth platform based on space technology plays an essential role in better understanding the spatial and temporal changes in the climate.

Table 14.2 Essential climate variables (ECVs) that are feasible for global implementation and have a high impact on UNFCCC requirements

Domain		Essential climate variables
Atmospheric	Surface	Air temperature, wind speed and direction, water vapor, pressure, precipitation, surface radiation budget
	Upper-air	Temperature, wind speed and direction, water vapor, cloud properties, Earth radiation budget (including solar irradiance)
	Composition	Carbon dioxide, methane, and other long-lived greenhouse gases; ozone and aerosols, supported by their precursors
Oceanic	Surface	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean color (for biological activity), carbon dioxide partial pressure, ocean acidity
	Subsurface	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers, phytoplankton, marine biodiversity, and habitat properties
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR, leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture, terrestrial biodiversity, and habitat properties

Sources CEOS (2006), Guo et al. 2015

14.2.1 Earth Observation Data Parameters and Their Capabilities

Ground-based Earth observation systems such as rain gauge networks and radar have always been a major means of observing atmospheric structures and they are still being operated and maintained. However, satellite platforms have added valuable scientific data to monitor clouds, water vapor, precipitation, and wind at multiple spatial and temporal scales. Sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) developed by the U.S., the Medium Resolution Imaging Spectrometer (MERIS) from the European Space Agency (ESA), and the international A-Train satellite systems have provided a wealth of information on clouds, rain, and pollutants, leading to a greater understanding of cloud pollution influences (Guo et al. 2015).

The cryosphere, consisting of lakes, river ice, snow cover, glaciers, ice caps, and frozen ground (including permafrost), is one of the most important parts of the climate system. Thus, changes in the cryosphere as well as in soil moisture and salinity are very important for monitoring global climate change, managing regional water resources, and investigating water and land ecosystems and global sea levels. Data from polar-orbiting and geostationary satellites (carrying visible/near-infrared sensors), such as the Geostationary Operational Environmental Satellite System (GOES), Landsat, MODIS, MERIS, and AVHRR, have been used to monitor

the melt flow from snow cover and glaciers. This information is also valuable for the management of water resources and disasters, and has been utilized for flood disaster prediction and reservoir operation. Data from the Sea Winds scatterometers onboard the QuikSCAT satellites can monitor seasonal changes in ice, track giant icebergs, and provide daily maps of ocean ice at a 6-km resolution.

Earth observation satellites also provide hundreds of data products (Table 14.3) to monitor water quality, water color (e.g., chlorophyll, suspended solids, and turbidity) and sea surface temperatures. For example, the AVHRR, AATSR, and MODIS sensors provide data on sea surface temperatures (CEOS 2006; Guo et al. 2015). In addition, many satellites can obtain data on elevation measurements, geopotential heights, and terrain. For example, P-band synthetic aperture radar (SAR) can penetrate cloud cover and the vegetation canopy and is useful in tropical and northern forest research at high altitudes. Improved SAR such as advanced synthetic aperture radar (ASAR) and phased array L-band SAR (PALSAR) are available for agriculture, forestry, land cover classification, hydrology, and cartography.

The main characteristics of climate change are the trends in temperature, precipitation, polar ice cover, and sea level. A new generation of satellite systems and advanced sensors such as Suomi NPP, GPM, OSTM/Jason-2, ICESat-2, and SWOT

Table 14.3 Remotely sensed oceanographic parameters, their observational category, and representative sensors

Parameter	Observational category	Satellite/Sensor
Bio-optical	Visible to near-infrared	ENVISAT/MERIS, AQUA/MODIS, OrbView-2/SeaWiFS
Bathymetry	Visible to near-infrared	Landsat, SPOT, IKONOS
Sea surface temperature	Thermal infrared microwave radiometers	POES/AVHRR, GOES/Imager DMSP/SSM/I, TRMM/TMI
Sea surface roughness, wind velocities, waves and tides	Microwave scatterometers and altimeters Synthetic aperture radar	ERS-1 & -2/AMI QuikSCAT, RADARSAT-1
Sea surface height and wind speeds	Altimeters	Topex/Poseidon, Jason-1
Sea ice	Visible to near-infrared microwave radiometers, scatterometers and altimeters Synthetic aperture radar	POES/AVHRR DMSP/SSM/I ERS-1 & -2/AMI RADARSAT-1
Surface currents, fronts, and circulation	Visible to near-infrared, thermal infrared microwave scatterometers and altimeters	POES/AVHRR, GOES/Imager Topex/Poseidon, Jason-1
Surface objects-ships, wakes, and flotsam	Synthetic aperture radar	RADARSAT-1, ENVISAT/ASAR

Source Brown et al. (2007), Guo et al. 2015

have further improved our capability for space-based observation of these key parameters related to climate change. In addition to the space-based data, in situ data from ground measurements and reanalysis data are used to provide information on key indicators of climate change. The Copernicus Climate Change Service (C3S) compiles all the information obtained by the Copernicus environmental satellites, air and ground stations, and sensors to provide comprehensive pictures of the past, present, and future climate of Earth.

14.2.2 Heterogeneous Changes in Temperature

Heatwaves and rising temperatures have gained prominence in the context of global warming. Digital Earth technology is relatively mature for monitoring global land and sea surface temperatures, although the algorithms and retrieval accuracy need to be further improved, and satellite LST measurements have uncertainties caused by data accuracy and inconsistencies between sensors. Nevertheless, satellite measurements have been very useful in monitoring surface temperatures and detecting extreme temperature events.

Thermal infrared surface temperatures from satellite platforms are frequently integrated into data assimilation systems and reanalysis data systems for climate parameters, including NCEP/NCAR and NCEP/DOE, ERA-40, and JRA-25, which effectively improves the accuracy and reliability of datasets. The most widely used global land surface temperature datasets are the monthly data measured by the AVHRR thermal infrared band (4, 5) since 1982, the 8-day composite data derived from the MODIS thermal infrared band since 2000, the daily global LST and SST data provided by ENVISAT from the ESA, and the LST measured by Aster at small scales. The geostationary satellite system operated by the United States, Europe, China, Japan, and others provide low- and middle-latitude LST data at one-minute intervals. In addition, SeaWiFS, FY-2/4 and FY-3 can acquire LST data. The Suomi NPP satellite launched in 2012 carries a 750-meter spatial resolution Visible Infrared Imaging Radiometer Suite (VIIRS) sensor, and its surface temperature data quality was an improvement (Guillevic et al. 2014).

The monitoring and impact assessment of heat waves based on multisource thermal infrared remote sensing data have made important progress in recent years. Since the heat wave in central Europe in 2003, most large-scale heat wave events have been successfully monitored, including the large-area heat wave in southern Asia in the summer of 2010, the continued high-temperature anomaly in eastern Asia during the spring of 2013, the extreme low-temperature event that lasted several weeks in central and eastern North America in the winter of 2014, and the persistent heat wave that swept over southern Asia and western Europe in the spring and summer of 2015. Progressive improvement of Digital Earth's thermal environment platform that integrates multisensor and multiresolution spatial data can provide automatic and more accurate extreme temperature information, and support government decision making and public information services.

14.2.3 Heterogeneous Changes in Precipitation

The accuracy of precipitation estimation has improved over the years with satellite-based sensors. Satellite systems allow for continual monitoring and observation of precipitation on a global scale, which was only possible at fixed intervals with limited spatial coverage using conventional ground-based observation systems. Infrared sensors onboard geostationary satellites, passive microwave sensors carried by the polar-orbiting satellites, and active radar onboard the TRMM satellite and its successors have collected a huge wealth of data on precipitation over the years. The establishment of Global Precipitation Measurement (GPM) realized a satellite constellation with coordinated, seamless observation of global precipitation, indicating a new era of “digital precipitation”. GPM is an independent and complex project consisting of a core satellite and approximately eight other satellites. Its precipitation observation can reach a radius of 5 km, covering 90% of the global land and ocean surface at three-hour intervals, and can distinguish rainfall, snow, ice and other precipitation forms. It is much more advanced than the previous generation of TRMM.

Geostationary meteorological satellites such as FY-2, GOES, GMS, Meteosat, and MTSAT have seen improvements in multichannel scanning and real-time performance and have high spatial and temporal resolutions (from one-hour intervals to half-hour intensive observation, and 5-km and 1.25-km spatial resolution at nadir for the infrared and visible and near-infrared spectral channels, respectively). This makes them more effective in monitoring hazardous weather systems. Therefore, comprehensive application of multiple channels such as thermal infrared, visible light, near-infrared, and water vapor channels is an essential component of the Digital Earth platform for extreme precipitation monitoring.

14.2.4 Extreme Climate Events

Extreme climate events refer to serious deviation of the climate from its average state, including phenomena that are statistically less significant. Extreme climate events generally include high-temperature heat waves, extreme snow, strong tropical storms, floods, meteorological droughts, and natural fires. Space-based observation of extreme climate events consists of real-time warning and monitoring, rapid postdisaster assessment, and disaster risk reduction. This requires high spatial and temporal resolution satellite information and an efficient operational platform. This is both a challenge and an opportunity for Digital Earth. For instance, regarding disaster risk, the combination of multisource satellite data, land use data, and topographic data makes it possible to rapidly assess flood risk at the watershed and regional scales (Reager et al. 2014). Cold winter events have occurred frequently in Eurasia in the last 10 years, and extreme low temperatures have been record-breaking. Mori et al.

(2014) added Arctic sea ice data and SST to climate models and found that the reason for most cold winters is Arctic Oscillation (AO).

Digital Earth technology has shown great potential in disaster monitoring, emergency response, disaster assessment, and reconstruction. Disaster reduction is the most effective aspect of the Digital Earth platform, which can perform all-weather, all-day dynamic detection. Meteorological satellites, radar satellites, and high-resolution visible and near-infrared Earth observation satellites can be used to monitor rainfall, floods, and droughts in real time for emergency response. The Digital Earth platform can support rapid analysis of the statistics and distribution of flooded areas, flooded land use categories, and the number of people affected, especially when satellite data is combined with digital thematic maps such as administrative, land use, population, and socioeconomic maps.

14.3 Interactions Between Climate and Society Through Space and Time

14.3.1 *Greenhouse Gas Exchange*

The current global climate change is mainly attributed to rapidly increasing atmospheric concentrations of two greenhouse gases, carbon dioxide (CO₂) and methane (CH₄). Most of the body of research on greenhouse gases has focused on CO₂ rather than CH₄, which is a more potent greenhouse gas. The lack of high spatial and temporal resolution datasets on continuous flux is a major reason for the limited knowledge on CH₄ exchange (Holgerson and Raymond 2016). In the case of CO₂, the scientific community still lacks a detailed understanding. For example, according to existing ground measurements, 40–50% of the carbon dioxide produced by human activities remains in Earth's atmosphere, and the remaining 50–60% is considered to be absorbed by the ocean and ground vegetation. However, scientists do not know exactly where the carbon dioxide is stored, how this storage process occurs, and whether this process can limit the increase in carbon dioxide in the atmosphere. To date, spatiotemporal pattern studies of terrestrial carbon sources and carbon sinks based on space technology have been mainly achieved through satellite-based visible light and near-infrared band indexes. The 8-km inverted AVHRR continuous vegetation index data is the longest time series, since 1982, and the accuracy of the sixth generation of the MODIS (C6) vegetation index data has been greatly improved. In addition, Landsat, MERIS, VIIRS, SPOT Vegetation, and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) data are available.

A key parameter for monitoring the temporal and spatial patterns of terrestrial carbon sources and carbon sinks is the fraction of absorbed photosynthetically active radiation (FAPAR), which largely determines the total gross primary production (GPP) or carbon assimilation capacity. To date, more than six different global FAPAR spatial databases have been released, inverted from MODIS, MERIS, SeaWiFS,

MODIS-TIP, SPOT-VEG, and AVHRR time series data; however, the data are highly uncertain. A systematic evaluation of more than 800 ground sample datasets revealed that they differed greatly between continents and biomes, and all were insensitive to vegetation coverage and needed further improvement (Pickett-Heaps et al. 2014). Chinese scholars have made costrengthening observations among 25 field flux stations and driven vegetation productivity models with flux data, satellite-based vegetation indexes, surface albedo, and soil moisture indexes, which have significantly improved the estimation of FAPAR and GPP on a regional scale (Wang et al. 2010). A recent improvement was the use of chlorophyll fluorescence data from the GOME satellite to drive vegetation productivity models and monitor global crop photosynthesis (Guanter et al. 2014).

The Orbital Carbon Observing Satellite (OCO-2) is a satellite launched by the United States in 2014 to monitor the global space-time distribution of carbon dioxide. It is mainly used to observe the carbon dioxide level of the Earth's atmosphere and to understand the role of humans in global climate changes caused by greenhouse gas emissions. The satellite carries a three-channel spectrometer for accurate measurements. OCO-2 collects approximately 8 million accurate global carbon dioxide measurements every 16 days, with a measurement accuracy of one in a million. With instruments such as spectrometers carried on satellites, scientists can dynamically measure carbon dioxide from different sources in the atmosphere and monitor the adsorption of carbon dioxide by oceans and forests. The acquisition of such a dynamic global carbon dioxide map will help reduce errors and improve the accuracy of forecasts for global warming.

Prior to this, in 2009, JAXA (Japan) launched GOSAT, the first satellite dedicated to detecting the concentration of greenhouse gases such as atmospheric CO₂. The satellite was equipped with high-precision observation equipment that used greenhouse gases such as carbon dioxide and methane to absorb infrared rays of a specific wavelength, and estimated the concentration of greenhouse gases by observing the infrared rays reflected from the surface. The goal of GOSAT was to observe the distribution of global CO₂ and CH₄, with a measurement precision of 2–3 ppm for CO₂ and approximately 15 ppb for CH₄, to capture the spatial variation in the carbon flux each year. GOSAT was equipped with thermal infrared and near-infrared sensors to obtain carbon observations as well as cloud and aerosol images. As the infrared rays pass through the atmosphere, a gas that forms a greenhouse effect, such as carbon dioxide, causes a specific wavelength to be absorbed, and the concentration of the gas can be calculated from these data. TanSat, launched by China, has further improved our ability to detect atmospheric CO₂ and other greenhouse gases.

Many countries including China are actively planning to launch satellites for the special detection of atmospheric CO₂ and other greenhouse gases. Integrating spatial data from these different sources with station observation data on the Digital Earth platform will greatly enhance the accuracy of detection and the technical support for climate change research.

14.3.2 Connectivity and Teleconnection in the Earth System

The Earth system as a whole, its components, and the various regional subsystems are connected and closely related. For example, in ocean-air interactions, the transfer of energy between the two is a teleconnection. We are gradually recognizing the importance of teleconnections in the climate system. For example, variability in the El Niño-Southern Oscillation (ENSO) model across the equatorial Pacific is linked to widespread distribution of floods, droughts, and forest fires in often arid or semiarid areas such as East Africa, tropical and subtropical Australia, and North America within the mid-latitudes and the western coast of South America. Another good example comes from Mori et al. (2014), who showed that most cold winters are attributed to AO changes caused by Arctic sea ice.

Studying and understanding teleconnections is an important challenge and an undertaking that can greatly benefit from utilization of the Digital Earth platform's capabilities of macroscopic multiparameter data integration to enable discovery of hidden and underlying connections in the Earth system and reveal the mechanisms to improve predictions of climate and weather. Various aspects remain to be identified and can benefit from the Digital Earth platform. For example, regarding ENSO and the North Atlantic Oscillation (NAO), we know relatively little about the teleconnection between the stratosphere and the Earth's surface. A strong vortex is formed over the polar region in winter, and the vortex intensity changes. When the vortex is strong, a tightly stable cycle is concentrated in the stratosphere, with little connection to the troposphere and the Earth's surface. When the vortex is weak, the control is not very stable, and it can generate a large-scale dynamic process. Therefore, it can be transmitted to the surface of the Earth through the convective top layer. It causes unusually cold weather at high latitudes, for example, in Scandinavia. When the Arctic vortex weakens, cold air flows outwards and downwards. Another example is the study by Zhang et al. (2019), which showed that the mean winter visibility throughout most of eastern China is negatively correlated with the preceding Antarctic Oscillation (AAO), especially in northern China. It emphasizes the important roles of sea surface temperature warming or cooling tendencies in the northwestern southern Indian Ocean (NSIO) and provides possible pathways through which NSIO warming may influence the atmosphere of northern China.

14.4 Impacts and Response

14.4.1 Ecosystems

Currently, the spatial data used to analyze the response of large-scale ecosystems to climate change are mainly acquired from long-term time series data from medium- and coarse-resolution optical satellite sensors such as AVHRR, MODIS, SPOT, VIIRS, SeaWiFS, and MERIS, which have inconsistencies between the sensors and

their time spans (Guay et al. 2014). Several released global data series are generally based on the records of a single sensor. There are few data series from multisource data fusion and integration. However, satellite data often contain uncertainties caused by biases in different sensors and retrieval algorithms as well as inconsistencies between continuing satellite missions with the same sensor. Undetected drifts in sensor sensitivity have been cited as the main reason for the apparent spectrum of change. If the procedures for merging data from different time series are not well-developed and calibrated, the uncertainties can potentially be high in combined datasets. An integrated vegetation index dataset based on system calibration and data fusion is an important requirement for the Digital Earth platform.

Due to the complexity of ecosystem dynamics in the context of climate change, traditional methods based on single-satellite data have great limitations. By integrating and comparing multiple satellite datasets and ground observation data, the Digital Earth platform can dynamically and effectively display and analyze the trends of climate-related parameters.

14.4.2 Water Cycle and Water Resources

The global water cycle involves transformation, flow, and redistribution, and the redistribution of global and regional energy and regulation of the climate. The Earth observation system can quantitatively monitor many key parameters of the global water cycle, including various forms of precipitation (such as rainfall, hailstones, ice rain, and snow), atmospheric water vapor, surface evaporation, vegetation canopy transpiration, surface water, snow, continental glaciers, sea ice, soil moisture, and surface runoff.

Using the Digital Earth platform, global hydrology cycle models can be developed to reveal the controlling factors of terrestrial water cycling and trends in water resource patterns. It is expected to lead to a revolutionary solution to a series of key issues in Earth's multiple spheres of interactions from the perspective of Earth system dynamics, including global ocean-atmospheric interaction, land-atmospheric interaction and the boundary layer process, ocean-land correlation, and coastal ecosystem evolution.

14.4.3 Coastline, Urban Areas, and Infrastructure

Smajgl et al. (2015) employed remote sensing land use data, digital elevation data, and high-resolution climate models to simulate the scenario of a regional sea level rise of 30 cm by 2050. The study predicted that urban floods and sea water backflow would be severe downstream of the Greater Mekong Subregion and that the land use structure would change significantly.

The urban heat island effect accompanies the expansion of human settlements and is closely related to regional climate change. As the most active region of economic growth and urbanization, the urban heat island phenomenon in Asia, especially in China, has become an important issue in regional climate change. The Digital Earth system provides comprehensive spatial information about urban areas (Hu et al. 2015), human activity intensity (Zhou et al. 2014), and thermal infrared land surface temperature. It provides a scientific platform for research on urban heat islands at different spatial and temporal scales. Regarding the potential contributions of infrastructure to a warming climate, researchers have examined the impacts of urban expansion on the trends in air temperature by investigating the changes in urban land use around meteorological stations and analyzing the relationship between the rate of urban expansion and air temperature magnitudes (He et al. 2013). Urban heat islands can influence land-atmospheric energy exchange, the turbulence regime of atmospheric flow, and the microclimate, and can accordingly modify the boundary layer processes over urban canopy and downstream areas. Research showed that estimation of key urban morphology parameters using high- and medium-resolution satellite data and intense field measurement along urban-rural transects can improve the performance of regional climate models in capturing critical climate effects over large and rapidly expanding urban clusters (Jia et al. 2015; Feng et al. 2014; Wang et al. 2012).

14.5 Multisource Digital Earth for Studying Climate Change Phenomena

Earth is a large, complex system, broadly grouped into three subsystems: the atmosphere, oceans, and land surface. Climate change involves understanding changes in one of these subsystems and understanding how these systems interact, their impacts on one another, and the consequences of changes in any one of them or their subsystems. This requires rich scientific datasets quantifying sensitive climate factors, which is not possible without integration of data from multiple sources. These multisource datasets have been collected over the years through synchronous satellite-aerial-ground observation experiments (Fig. 14.1).

Multisource datasets allow for comprehensive, continuous, and diverse information on the Earth's surface. Similarly, multisensor remote sensing datasets enable dynamic (and in some cases real-time or near real-time) monitoring of Earth's systems. It has played a fundamental role in supporting modern data-driven scientific innovation. Effective use of multiplatform Earth observation data with multiple sensors helps avoid and mitigate issues related to information extraction and inversions that arise from the use of a single sensor.

These datasets have enabled researchers to explore new theories by developing new methodologies and assimilation models that can incorporate multi-source/multisensor, heterogeneous spatial data to acquire precise information on

Fig. 14.1 Synchronous satellite-aerial-ground observation experiments on the Qinghai-Tibetan Plateau (revised from Guo et al. 2015)

sensitive climate factors and develop simulation platforms to understand regional climate change patterns. Multisensor Earth observations also provide long-term, stable spatial data for scientific research, compensating for uneven spatiotemporal observations, and play a fundamental supporting role in global change research.

The National Basic Research Program of China (973 Program) launched the project “Earth Observation for Sensitive Variables of Global Change: Mechanisms and Methodologies” on January 1, 2009. This was the first research project on Earth observation techniques for global change research in China. The project highlighted sensitive variables in terrestrial, oceanic and atmospheric systems based on big data from Earth observation from multiple platforms and multiband sensors, focusing on the development of new theories, technologies, and methods in these fields. The research scheme of the project is shown in Fig. 14.2. During the project, the new concept of moon-based Earth observation for global change monitoring was also widely discussed and considered as an efficient way to map the solid earth dynamics and radiation budget at the top of the atmosphere (Guo et al. 2014b, 2018).

Fig. 14.2 Research scheme for the “Earth observation for sensitive variables of global change: mechanisms and methodologies” project (Guo et al. 2015)

14.5.1 Glaciers

Glaciers provide unique records and feedback that influence global climate change and are closely related to temperature, precipitation, and the material balance. The glaciers on the Tibetan Plateau have retreated considerably since the 1970s, and this rate of retreat has accelerated in recent years. In general, the retreat rate for glaciers covering less than 1 km² is faster than those of larger glaciers, but there are significant spatial differences. For example, glacial retreat was observed to be the fastest in the Himalayas and slower in the central plateau (Yao et al. 2003). It has been suggested that the retreat of the Himalayan glaciers is much more serious than expected (Ma et al. 2010). Consequently, with the rapid melting of glaciers, lakes supplied by the glacier melt water, such as Nam Co Lake (the highest lake on the central Tibetan Plateau), have expanded between 1976 and 2009 (Zhang et al. 2011; Guo et al. 2015).

A method for extracting glacier thickness has been developed based on interferometric synthetic aperture radar (InSAR) data and elevation data from the Geoscience Laser Altimeter System instrument aboard the Ice, Cloud, and land Elevation satellite (ICESat/GLAS14). As a result of calculations using the ICESat data along with the Shuttle Radar Topography Mission digital elevation model (SRTM DEM), a reduction of 0.63 m per year (water equivalent) was observed in the thickness of the Naimona'nyi glacier between 2000 and 2009 (Zong et al. 2013). This lies between the material balance of 0.56 m per year (water equivalent) and the glacier thickness

reduction of 0.65 m per year (water equivalent) measured by GPS (Li et al. 2012). In general, glacial shrinkage decreases toward the interior plateau from the Himalayas, and the minimum degree of shrinkage occurs in the Pamir mountain range (Yao et al. 2012; Guo et al. 2015).

14.5.2 *Lakes*

Large fluctuations in lake surface area in a short time significantly influence water cycles and the local ecological environments. Studies have been conducted on lake areas, in addition to water level monitoring in different regions of the Tibetan Plateau using Landsat and ICESat data. Since 2003, a large spatial variation in lake area on the Tibetan Plateau has been observed, with a shrinkage of lakes in southern Tibet and an expansion trend for lakes in the Qiangtang region (Liao et al. 2013). In the Qaidam Basin, Qinghai Lake showed an expansion trend, and the annual rate of change in water volume in spring was greater than that in autumn. Gyaring Lake in the eastern Tibetan Plateau also showed an expansion trend that mirrored that of Qinghai Lake (Liao et al. 2013). Glacial melt is the dominant driver of the recent lake expansions on the Tibetan Plateau. By investigating detailed changes in the surface area and levels of lakes across the Tibetan Plateau from Landsat/ICESat data, Li et al. (2014) found a spatial pattern in the lake changes from 1970 to 2010 (especially after 2000). They observed a southwest-northeast transition from shrinking, to stable, to rapidly expanding lakes, which suggests a limited influence of glacial melt on lake dynamics. The plateau-wide pattern of lake area changes is related to precipitation variations and is consistent with the pattern of permafrost degradation induced by rising temperatures (Li et al. 2014; Guo et al. 2015).

14.5.3 *Vegetation*

The plant phenological period is closely related to climate change, and phenological changes influence the carbon balance of terrestrial ecosystems by affecting ecosystem productivity. The alpine vegetation on the Tibetan Plateau is extremely sensitive to global change. Zhang et al. (2013), Wang et al. (2015) used MODIS to analyze the response and driving factors of space observations of plant greenness and phenology (Fig. 14.3). Zhang et al. (2013) found that the normalized difference vegetation index (NDVI) showed a gradual increasing trend in the plateau during the growing seasons from 2000 to 2009. On the western Tibetan Plateau, the continuous decrease in precipitation resulted in a delay in the alpine grassland phenology; in the eastern part of the plateau, the precipitation continued to increase, resulting in an advance in the grassland phenology (Wang et al. 2015). In addition, Liu et al. (2014) found that the spring phenology of the grasslands on the Tibetan Plateau exhibited a stronger

Fig. 14.3 Trends in **a** the growing season NDVI, **b** the start of the season, and **c** the end of the season on the Tibetan Plateau during 2000–2009 (Zhang et al. 2013; Wang et al. 2015; Guo et al. 2015)

response to changes in temperature at higher elevations than at lower elevations (Guo et al. 2015).

The remote sensing and monitoring of C_3 and C_4 grass species and their responses to climate change are mainly focused on the high-precision extraction of plant functional types and the transformation response of the grassland type to global climate change and human factors. In the U.S. Great Plains, vegetation with different functional types usually shows similar temporal trends in NDVI but different phenological characteristics (Wang et al. 2013). The onset of the growing season for C_3 grasses is earlier than that for C_4 grasses, and the growing season of C_3 grasses is longer. However, under mild weather conditions, C_3/C_4 short grasses have similar onsets of season dates and growing season lengths compared with C_3/C_4 tallgrasses (Wang et al. 2013). In northern China, a study by Guan et al. (2012) showed that temperate grassland was mainly occupied by C_3 species, yet C_4 species made an important contribution to the grassland biomass.

The fraction of photosynthetically active radiation (fPAR) is an important physiological parameter that reflects the growth of vegetation and is a key parameter for terrestrial ecosystem models and for reflecting global climate change (Fig. 14.4). Peng et al. (2012) found that the spatial variation in the global fPAR was affected

Fig. 14.4 Spatial patterns of global fPAR: **a** annual average fPAR in 2006, and **b** average fPAR in the latter half of August 2006. (Guo et al. 2015)

by the vegetation types as well as changes in the seasonal cycles. Temperature, precipitation and extreme drought have different effects on the fPAR. Climate change, deforestation, reforestation, and other human activities also significantly impact the fPAR in regions such as southeast Asia and the Three-North Shelter Forest area in China (Guo et al. 2015).

14.5.4 Radiation

(1) Impacts of aerosols on cloud cover and the regional radiation forcing effect

Based on satellite remote sensing data from aerosol-cloud-radiation and trace gases and meteorological observations, Xia (2010, 2012) analyzed long-term trends in the sunshine duration (SSD) and surface solar radiation and focused on the possible impacts of clouds on solar radiation in China over the last 50 years. The results indicated that the SSD and total cloud cover (TCC) showed a significant decreasing trend; however, with low-level cloud cover (LCC), a slight increasing trend was observed (Xia 2010). Short-term variability in the SSD is mainly determined by the amount of cloud cover, but the long-term change in the TCC cannot account for the decreasing trend in the SSD. Regarding the impacts of aerosols on clouds, Xia (2012) found that the data are inconsistent with the expectation that larger decreasing trends in cloud cover should be observed in regions with higher aerosol loading. Therefore, the aerosol effect on decreasing cloud cover in China does not appear to be supported by the results of their study (Guo et al. 2015).

(2) Spatiotemporal characteristics of land surface solar radiation in China

The land surface solar radiation in China and its temporal trends were calculated and the results demonstrate that previous studies overestimated the downward trend in land surface solar radiation in China (Tang et al. 2011). However, the aerosol abundance from human activities was still negligible on the Tibetan Plateau, and the decrease in solar radiation over the plateau was larger in magnitude than that for the rest of China after the 1970s. Further research revealed that the solar radiation on the Tibetan Plateau had continually decreased over the preceding 30 years due to the increasing water vapor and deep convective clouds. These increases were found to be connected to the warming climate and the enhanced effective convection energy of the Tibetan Plateau (Tang et al. 2011; Guo et al. 2015).

14.6 Digital Earth to Inform Climate Adaptation, Mitigation, and Sustainable Development

Effective strategies for climate change adaptation and mitigation require a comprehensive understanding of various underlying factors, including natural science, economics, society, and ethics. This makes climate change one of the most complex and challenging issues of modern times. Climate prediction and climate change projection are highly relevant to policy makers, investors, and vulnerable communities. The Digital Earth platform allows for investigations into many important processes that control the climate system, incorporates spatial dimensions at higher resolutions into the climate change context, and enables intuitive visual support for decisions and innovative actions. Strong visual and virtual demonstrations, supported by the Digital Earth platform, can help translate complex data into communicable information to support governments in decision and policy development and public information services.

Decades of Earth observation information is critical to improving predictions at different scales of climate projections. However, the existing remote sensing products have defects such as noise and time and space discontinuity (Brown et al. 2006; Jia et al. 2006). These defects severely constrain land surface processes and climate change simulations that are driven by spatial data parameters, and therefore reduce the reliability of climate change predictions and projections. It is necessary to synthesize multisensor remote sensing data to obtain high-quality and spatiotemporally continuous land surface observation data. The synthesis processes face the challenges of multisensor remote sensing data coordination and validation (Guo et al. 2015). These processes can greatly benefit from the Digital Earth data framework.

In addition to climate-sensitive environmental parameters, socioeconomic parameters characterize the demographic, socioeconomic, and technological driving forces underlying anthropogenic greenhouse gas emissions that have driven recent climate change and are key in the assessment of climate impacts, adaptation, and vulnerability. Conversely, the sensitivity, vulnerability, and adaptive capacity of socioeconomic systems also depend on their responses to climate change. The IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations recommend the use of socioeconomic scenarios, with and without climate change, to assess climate impacts and adaptive responses. This adds a layer of complexity to predicting future scenarios and is only possible in the integrative environment provided by the Digital Earth platform. The challenges in implementing socioeconomic scenarios in Digital Earth include compatible scales that match the socioeconomic and satellite data, and rational assumptions that represent the evolution of key socioeconomic drivers.

The Digital Earth platform can also support the implementation of the UN Sustainable Development Goals (SDGs) by providing a conducive platform for information and data sharing, access, and use, and as a multisource data fusion platform. In the near future, Earth science will extensively make use of large amounts of data to monitor and predict continuously changing climatic environments. The Digital Earth platform can handle the challenge of geographical big data and the new emerging

threats from climate change more systematically and specifically (Elder et al. 2016; Guo et al. 2017). This greatly enhances preparedness, rapid response, and adaptation to extreme events (such as extreme weather events) and facilitates understanding of the climate and projection of climate change.

In addition to geographical big data, a new form of geo-referenced data from the internet and social media, when combined with newly available observational, reanalysis, or other data sources on the Digital Earth platform, can potentially expand the scope of climate change studies greatly and increase the spatial and temporal scales addressed. For example, by using data from social networking sites, smart phones, and online experiments, we can assess the vulnerability to weather events and the impacts of local and national policies and programs in real time (Hernandez 2017).

Digital Earth has great potential for increasing our understanding of global climate change and its impacts on various dimensions. It is a powerful platform for policy support in climate change adaptation and mitigation. New developments in emerging technologies such as “big Earth data”, citizen science, the blockchain, and artificial intelligence further enhance the power of Digital Earth to support studies and actions on climate change.

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Gensuo Jia is a professor at CAS Institute of Atmospheric Physics and the Director of START Regional Center for East Asia. He serves as coordinating lead author of IPCC Special Report on Climate Change and Land (SRCCL). He has broad research interests in terrestrial ecology and atmospheric sciences, including remote sensing of land surface processes, ecosystem-climate interactions, climate extremes, and climate change impacts.

Li Zhang is a Professor in Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences. She researches remote sensing applications for land-surface dynamics and coastal environment. She serves as the Steering Committee Member of the GEO Blue Planet. She has published over 110 scientific papers.

Lanwei Zhu is an associate professor, Institute of Remote Sensing and Digital earth, Chinese Academy of Sciences. She researches nature heritage change, coral reefs change and bleaching monitoring based on remote sensing.

Ronghan Xu is an associate professor at the National Satellite Meteorological Center, China Meteorological Administration (CMA). Her researches focus on climate change and extremes, land use/cover change, urban heat island, and thermal infrared remote sensing. She served as a lead author of global environmental outlook youth edition.

Dong Liang received B.Sc. and M.Sc. degrees in applied mathematics from the University of Hull, U.K. (2006), and Mälardalen University, Sweden (2009). He is pursuing a Ph.D. in cartography and GIS at the University of Chinese Academy of Sciences, with a focus on Big Earth Data and polar remote sensing.

Xiyun Xu is an associate professor at the Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS). Her research fields cover land-atmosphere interactions, climate change, and climate effects of land use/cover change. She serves as a chapter scientist of IPCC Special Report on Climate Change and Land (SRCCL).

Tao Bao is an assistant professor at the Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS). He researches changing soil and vegetation processes under climate change, land-atmosphere carbon flux, and interactive changes of climate and ecosystems in polar regions using field and satellite observations.

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