

## REVIEW

# Geodetic Techniques for Climate-Induced Surface Deformation: A Global Review

Chang Yu <sup>1</sup>, Tiexin Lv <sup>2\*</sup>

<sup>1</sup> Jilin Earthquake Agency, Changchun 130117, China

<sup>2</sup> Changchun Jirun Jingyue Hospital, Changchun 130110, China

## ABSTRACT

Climate change is causing extensive and quantifiable surface deformation by moving mass in the cryosphere, hydrosphere, atmosphere, and oceans. These deformations can give a great deal of information on the dynamics of the Earth system and interactions between climate processes and solid Earth processes. Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), satellite gravimetry, and other supplementary techniques have become important tools to be used to monitor and quantify these deformations. The insight of this review is the understanding of the mechanisms that cause deformation on the surface due to climate change, the strengths and weaknesses of the modern geodetic observation methods, and the way in which these geodetic observations are reconciled with the Earth's response models and climate simulations. Polar, alpine, hydrologically sensitive, and coastal case studies demonstrate that geodesy can be used globally in climate change studies. Although there has been a lot of improvement, there have been many problems in signal separation, data coverage, and uncertainties in models, but new emerging technologies are promising solutions. A combined climate/geodetic observing system will be critical in enhancing long-term monitoring and in further developing the knowledge on how the Earth responds to climate change.

**Keywords:** Climate Change; Surface Deformation; Geodesy; GNSS; InSAR

### \*CORRESPONDING AUTHOR:

Tiexin Lv, Changchun Jirun Jingyue Hospital, Changchun 130110, China; Email: m15590292766@163.com

### ARTICLE INFO

Received: 19 December 2025 | Revised: 7 January 2026 | Accepted: 10 January 2026 | Published Online: 28 January 2026  
DOI: <https://doi.org/10.30564/jees.v8i1.12961>

### CITATION

Yu, C., Lv, T., 2026. Geodetic Techniques for Climate-Induced Surface Deformation: A Global Review. Journal of Environmental & Earth Sciences. 8(1): 224–241. DOI: <https://doi.org/10.30564/jees.v8i1.12961>

### COPYRIGHT

Copyright © 2026 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (<https://creativecommons.org/licenses/by-nc/4.0/>).

## 1. Introduction

Climate change has become a dominant force that defines the contemporary system of the Earth. Not only does it impact atmospheric and oceanic processes, but it also has mechanical effects on the solid Earth. The melting ice sheets and glaciers, terrestrial water storage, degradation of permafrost, and the rise of the sea level result in mass wasting and massive redistribution of mass, which is measurably deforming the surface of the Earth. Such deformities are very small, and they can be hidden in most instances. Nevertheless, they give critical data concerning the magnitude, spatial arrangement, and temporal dynamics of processes triggered by climate. Climate-related surface deformation measurement and interpretation is thus important in earth system science, in enhancing future change projections, as well as in risk evaluation in human and natural systems<sup>[1,2]</sup>.

Climatic forcing of the surface leads to a deformation of the surface of the lithosphere and mantle primarily by elastic and viscoelastic response to surface loading and unloading. The polar regions and the high mountain areas lose their cryospheric masses, resulting in crustal uplift and horizontal movement. Moreover, annual and sub-annual indicators of deformation can also be seen due to the cyclic accretion and melting of snow. Vertical and horizontal motions of the surface of the Earth are also measurable by changes in hydrological loading caused by precipitation, droughts, floods, and groundwater recharge. In permafrost, the growing temperatures change the thermal and mechanical properties of frozen ground. The changes may result in subsidence, decreased heave, and the development of thermokarst<sup>[3]</sup>. Additional loading effects occur in the coastal areas due to the increase in the sea level and the redistribution of the ocean mass. These effects are in combination with tectonic activity and sediment compaction. Combined with other climate-sensitive indicators of deformations, these can give a global view of the coupling between the solid Earth and climate processes. They also provide a special observational perspective on the current environmental change<sup>[1,4-6]</sup>.

Geodetic methods have developed over the past few decades. With the developments, the ability to observe and understand deformation of the surface with much greater accuracy and space coverage has been enhanced significantly. Space-based as well as ground-based geodetic observations

are now routinely used to measure at the level of millimetre to sub-millimetre level and over periods such as days to decades. Global Navigation Satellite Systems (GNSS) offer surface position change measurements (in three dimensions) at distinct points. These observations can be used to identify both long-term trends and seasonal changes. The Interferometric Synthetic Aperture Radar (InSAR) provides high spatial resolution in the fields of deformation. This is what makes it especially handy in the determination of localized subsidence, uplift, and spatially heterogeneous climate forcing responses. Gravity Recovery and Climate Experiment (GRACE) and GRACE follow-on satellite missions also provide a direct measure of changes in mass distribution, which completes the measurements on deformation. Such data are useful in the separation of signals of loading-induced deformation among other geodynamic processes. These methods combined create an effective observational system to study the surface deformation caused by climate on the regional and global levels<sup>[7,8]</sup>.

Geodetic observations are important in making a connection between solid Earth geophysics and climate science. Geodetic data, unlike most conventional climate measurements, directly measure the mechanical response of the Earth to the redistribution of mass. This gives a self-contained limitation of estimations of ice mass stability, groundwater stores, and ocean loading. As an example, to check and enhance the estimation of the current loss of ice-sheet mass, uplift rates beyond the glacier-covered regions have been employed. Likewise, hydrological loading deformation signals have enhanced our knowledge on variability of large-scale water cycles. Geodesy can therefore be used as a monitoring instrument and also as a way of testing and checking climate and Earth systems models.

Although these improvements have been made, it is still difficult to understand climate-driven deformation. Surface motions that are observed do not generally indicate a single process. These are tectonic deformation, glacial isostatic adjustment due to ice ages in the past, and anthropogenic processes like groundwater pumping, and current climatic driving forces. Such contributions can only be separated through a combination of multi-sensor geodetic measurements together with the physical theory of Earth rheology and surface loading. Other problems are caused by disproportional observational cover, especially in mountainous areas and poles. Problems

regarding reference frame and long-term stability of geodetic records are also problematic for analysis. These issues can be overcome by tackling them to exploit geodetic observations during the study of climate change<sup>[9–11]</sup>.

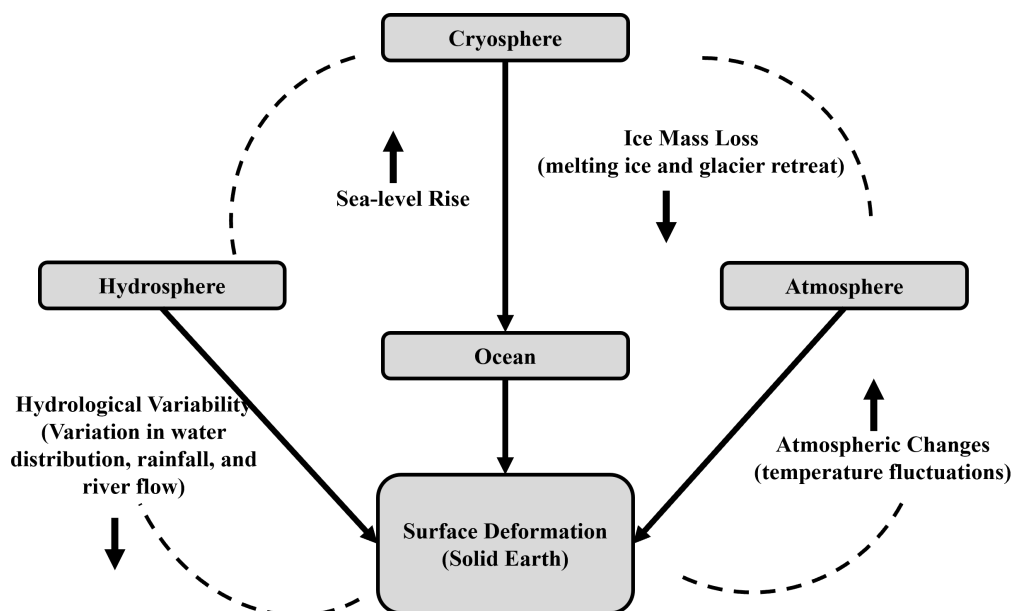
A growing literature is available on climate-related deformation in particular areas or depending on the particular techniques. Nevertheless, there are not many complete syntheses comprising the physical processes, observational techniques, and their extensive applications across the world. As the satellite missions evolve, as well as the networks of satellites and the methods of data analysis, the necessity to generalize the existing knowledge grows. The strengths and limitations of the current methodological approaches should also be considered, and the priorities of future research should be identified. This synthesis is especially up-to-date. The topicality of climate-induced deformation to the problems of society is growing, particularly in relation to natural hazards evaluation, the structure of infrastructure, and coastal zone and water resources management<sup>[1,12]</sup>.

The purpose of this review is to provide an up-to-date synthesis of geodetic methods for measuring and understanding climate-driven surface deformation on a global scale. We focus on the physical processes linking climate and surface deformation, the strengths and limitations of key geodetic observation techniques, and the integration of observations with models to improve understanding of Earth system re-

sponses to climate change. By evaluating global and regional applications and highlighting major challenges and future directions, this article aims to demonstrate the central role of geodesy in climate research. It also provides an interdisciplinary perspective that connects climate science, geophysics, and environmental monitoring.

## 2. Climate-Driven Mechanisms of Surface Deformation

The surface deformation caused by climate is a concern of the redistribution of mass and energy in the Earth system and the mechanical response of the lithosphere. In contrast to the plate boundary-driven deformation, which is mainly governed by plate boundary and lithospheric stresses, climate-driven deformation is predominated by surface and near-surface processes that apply time-varying loads on the lithosphere. They are processes that operate at a large spectrum of spatial and time scales, including seasonal to multi-decadal, and are strongly associated with cryosphere, hydrosphere, atmospheric, and ocean changes<sup>[13–15]</sup>. **Figure 1** illustrates the interaction between key climate processes and surface deformation. The physical mechanisms involved in the deformation due to climate are important to understand the geodetic observations and also to isolate the climatic signal on top of other geodynamic processes.



**Figure 1.** Diagrammatic illustration of climate-induced surface deformation.

## 2.1. Cryospheric Forcing

The cryosphere is one of the largest sources of surface deformation caused by climate. Modern glacier recession and loss of the mass of ice sheets (through the rise in air and ocean temperatures) cause the lithosphere to be unloaded and result in measurable crustal and horizontal motions. This elastic behavior happens almost immediately after the mass has lost, whereas long-term viscoelastic adaptation shows the tardy reaction of the mantle to surface loading. Geodetic surveys in polar latitudes, like in Greenland and the Antarctic, have found the uplift of ice mass (several millimeters per year), which is related to the rapid loss of ice mass, to establish independent limits on ice-sheet behavior and its contribution to global sea-level<sup>[16,17]</sup>.

Cyclical deformation signals are also produced by seasonal snow build-up and melt, and can be determined moving forward through continuous geodetic measurements. Such seasonal loading is especially strong in high-latitude and mountainous areas in which snowpacks vary and cause annual vertical movements of the order of a few millimeters. However, seasonal cryospheric responses, though small when compared to the mass loss of ice on a long-term basis, are useful in the test of surface loading models and in the validation of hydrological and climatic simulations<sup>[18]</sup>.

A major complicating element of cryospheric areas is the glacial isostatic adjustment (GIA), which is the continuous viscoelastic reaction of the Earth to ice loading and unloading since the last glacial peak. GIA produces long-wavelength uplift and subsidence patterns that will mask or bias estimates of present-day climate-induced deformation if not properly accounted for. Proper modeling of GIA is hence the key to isolating the contemporary cryospheric signal of geodetic data<sup>[19]</sup>.

## 2.2. Hydrological Loading and Terrestrial Water Storage

The other significant cause of surface deformation caused by climate is variations in the terrestrial water storage. Precipitation, evapotranspiration, snowmelt, and runoff vary to cause surface water, soil moisture, and groundwater redistribution, which results in elastic crustal deformation. These effects of hydrological loading are highly dependent on climatic variability and extremes, including drought and

flood events, and can create displacements horizontally on the scale of cryosphere processes<sup>[20]</sup>.

Hydrological loading results in typical patterns of annual deformation that are commonly noticed in GNSS time series at seasonal time scales. Long-term subsidence or uplift. Long-lasting climatic anomalies, like extended droughts, may occur at interannual to decadal scales as water storage is fully emptied or is replenished. Hydrological indications of climate interact with human action in most of the geographical properties, especially groundwater abstraction, to make attribution of recorded deformation to climate-only forcing more difficult<sup>[21]</sup>.

The hydrological processes are spatially heterogeneous, and this is a challenge to both observation and modeling. Localized deformation signals that can be detected using InSAR might result from localized variations in groundwater, whereas GNSS networks and satellite gravimetry are more effective at capturing more general variations in soil moisture and surface water. These complementary observations are important to describe the entire range of hydrologically-induced deformation<sup>[22]</sup>.

## 2.3. Permafrost Degradation and Thermal Processes

High sensitivity to climate warming, the permafrost regions are prone to climatic warming, and permafrost degradation has presented itself as a major process of surface deformation in high latitude and high-altitude regions. Increasing the ground temperatures decreases the mechanical strength of frozen soils and causes the ice-containing permafrost to thaw, causing the ground to sink, decrease the frost heave, and form thermokarst. These processes are commonly heterogeneous in space, nonlinear in time, and are indicative of the changes in soil composition, ice content, vegetation, and the local climate conditions<sup>[23]</sup>.

Short-term signals of deformation are brought about by seasonal freeze-thaw themselves, with long-term warming creating progressive subsidence that may accumulate over years to decades. InSAR has been especially successful in imaging the permafrost-related process of deformation at a high spatial resolution, whereas the GNSS observations have been used to constrain a vertical motion over the long term. The implication of permafrost-related deformation on infrastructure stability, ecosystem dynamics, and carbon

release is significant, and the overall importance of these processes can be highlighted beyond the scope of geophysical observations<sup>[24]</sup>.

## 2.4. Oceanic and Coastal Loading

The alteration of ocean mass and sea level is another cause of surface deformation in climate conditions, especially in the coastal and near-shore areas. Increased loading on the margins of the continents due to global sea-level rise, caused by the expansion of the thermosphere and the influx of melting ice and ice sheets in the form of meltwater, causes the elastic subsidence of the crust. There are deformation signals that are spatially varied at the regional scales due to the redistribution of ocean masses related to currents, winds, and atmospheric pressure variations<sup>[25]</sup>.

The problem of coastal deformation is further complicated by the contacts with the compaction of sediments,

tectonic processes, and human activities, including land reclamation and groundwater extraction. To make accurate estimations of relative sea-level change and coastal vulnerability, it is important to be able to separate the climate-driven effects of ocean loading from these other contributions. Oceanographic and climate data, together with geodetic observations, are very important in the quantification of such interactions. Surface deformation caused by climate is a complicated interaction of cryospheric, hydrological, and permafrost processes, as well as oceanic processes, with each having a different spatial and temporal pattern. Detailed knowledge of these processes is the basis of understanding geodetic measurements and making a future step forward in applying geodesy to climate change studies<sup>[26,27]</sup>. **Table 1** outlines the main processes of climate that cause surface deformation, with the focus on the various geodetic observation techniques used in individual processes.

**Table 1.** Major Climate-Driven Surface Deformation Mechanisms.

Climate Process	Mechanism	Primary Deformation Type	Geodetic Observations	Example Locations
<b>Cryospheric Forcing</b>	Ice mass loss (glacier/ice sheet retreat)	Uplift, horizontal motion, seasonal deformation	GNSS, InSAR, gravimetry	Greenland, Antarctica, Himalayas, Andes
<b>Hydrological Loading</b>	Variations in groundwater, soil moisture, snowmelt	Vertical displacement, subsidence, uplift	GNSS, InSAR, gravimetry	California Central Valley, Ganges–Brahmaputra Delta
<b>Permafrost Degradation</b>	Thawing of permafrost, reduction in frost heave	Ground subsidence, thermal expansion, thermokarst	InSAR, GNSS	Siberia, Alaska, Canada, Northern Europe
<b>Oceanic and Coastal Loading</b>	Sea-level rise, ocean mass redistribution	Coastal subsidence, uplift, sediment compaction	InSAR, GNSS, gravimetry	Nile Delta, Mekong Delta, Bangladesh

## 3. Geodetic Observation Techniques for Climate-Induced Surface Deformation

Geodetic observation methods are used to give the basic measurements necessary to detect and quantify the surface deformation caused by processes related to climate change. The latest geodesy uses a combination of both space and ground-based techniques to attain high accuracy, long-term stability and a wide spatial coverage. All of the methods have distinct sensitivities to the deformation signals and mass redistribution, and combining them is critically important in surfacing the entire range of climate-induced surface motions<sup>[1,28–30]</sup>. This section is a review of the major geodetic methods used in the study of climate deformation, with the focus on the capabilities, limitations, and common uses of geodetic methods (**Table 2**).

### 3.1. Global Navigation Satellite Systems (GNSS)

Global Navigation Satellite Systems (GNSS), such as Global Positioning System (GPS), GLObal NAVigation Satellite System (GLONASS), Galileo, and BeiDou, deliver positioning of fixed stations in three-dimensional mode with millimeter resolution in a continuous fashion. Continuous GNSS (GNSS) networks are especially efficient in identifying long-term trends and seasonal changes of the surface deformation due to the loading processes triggered by climatic changes. Vertical GNSS elements are the most sensitive to terrestrial water storage, snow loading, and loss of ice mass, and horizontal ones give great restriction on the subsequent motions of lateral elastic unloading and viscoelastic changes<sup>[31]</sup>.

The use of GNSS has become very popular in measuring uplift in polar areas associated with loss of mass in

ice-sheets, seasonal deformation associated with hydrological and snow loading, and long-term subsidence related to depletion of groundwater and thawing of permafrost. The advantages of GNSS are its temporal continuity and capability to operate in absolute positioning; this allows building sta-

ble reference frames and long-term records of deformation. The GNSS measurements are, however, spatially sparse in comparison to remote sensing methods, and network density also differs greatly between regions, making them incapable of resolving localized deformation patterns.

**Table 2.** Major Geodetic Techniques Used to Monitor Climate-Induced Surface Deformation.

Technique	Observational Principle	Spatial Resolution	Temporal Resolution	Strengths	Limitations	Common Applications
<b>GNSS (Global Navigation Satellite Systems)</b>	Measures precise 3-D ground displacement using satellite ranging and carrier-phase observations	Point measurements (station-based)	Continuous to daily	High temporal resolution; millimeter-level vertical accuracy; long-term stability	Sparse spatial coverage; requires stable ground stations; infrastructure and maintenance costs	Monitoring tectonic and climate-related deformation, glacier mass changes, glacial isostatic adjustment, groundwater extraction, and coastal subsidence
<b>InSAR (Interferometric Synthetic Aperture Radar)</b>	Uses phase differences between repeated SAR satellite images to detect surface deformation	High (meters to tens of meters)	Days to weeks, depending on satellite repeat cycle	Excellent spatial coverage; high spatial resolution; capable of detecting small deformation signals	Sensitive to atmospheric delays; decorrelation in vegetated or snow-covered areas; requires reference points	Glacier flow monitoring, permafrost thaw subsidence, volcanic deformation, and land subsidence in coastal and urban regions
<b>Satellite Gravimetry (GRACE/GRACE-FO)</b>	Measures temporal variations in Earth's gravity field to infer mass redistribution	Coarse (≈300–400 km)	Monthly	Direct measurement of mass change; useful for large-scale hydrological and cryospheric processes	Low spatial resolution; signal leakage and filtering effects; requires modeling corrections	Ice sheet mass balance, groundwater depletion, large-scale hydrological changes, sea-level mass contributions
<b>Altimetry (Satellite Radar/Laser Altimetry)</b>	Measures surface elevation changes using radar or laser from satellites	Moderate (10–1,000 m along track)	Weeks to months	Direct elevation measurements are useful over oceans and ice sheets	Limited coverage between satellite tracks; sensitivity to surface roughness	Ice sheet elevation change, glacier thinning, sea-level rise monitoring
<b>Leveling and Tide Gauges</b>	Ground-based measurements of relative vertical motion and sea level	Local	Periodic (months to years)	High vertical precision at specific sites	Limited spatial coverage; labor-intensive; reference stability required	Coastal subsidence studies, sea-level monitoring, and validation of satellite observations

### 3.2. Interferometric Synthetic Aperture Radar

InSAR is now one of the most effective instruments of surface deformation mapping with high spatial resolution. InSAR can be used to image line-of-sight surface displacement on a millimeter to centimeter scale (over much larger extents) by taking advantage of the phase difference between successive radar acquisitions. The InSAR methods used to determine deformation histories over several years include time-series InSAR methods (Persistent Scatterer (PS-InSAR) and Small Baseline Subset (SBAS) techniques.

The InSAR system is especially used in fields where the study is of particular interest to climate-related studies,

such as subsidence due to groundwater loss, thaw settlement in permafrost areas, glacier movement and subduction, and deformation in deltaic and coastal systems. Spatial coverage of InSAR is high, which is an advantage over the GNSS measurements, which are point-based measurement, enabling the gradients of deformations to be mapped in detail, as well as local features<sup>[32–34]</sup>.

InSAR is not without limitations; despite its benefits, it suffers various limitations that are associated with the temporal decorrelation, atmospheric delays, and also geometric limitations, especially in densely vegetated, snow-covered, or rapidly changing surfaces. These effects will usually have

to be carefully processed and combined with other geodetic data to remove them and achieve credible deformation estimates.

### 3.3. Satellite Gravimetry

The satellite gravimetry offers a completely different, though complementary, view on the surface deformation caused by climate effects by directly monitoring the changes in the Earth's gravity field due to mass redistribution. The Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On, have made the observation of changes in ice mass, terrestrial water storage, and ocean mass both regionally and globally possible in time.

Despite the fact that satellite gravimetry does not directly determine the surface deformation as such, it is necessary to use satellite gravimetry to determine geodetic displacement signals through constraining the degree and spatial pattern of the surface loading. As an example, the mass loss of ice masses determined by gravimetry can be used to predict patterns of elastic uplift determined by GNSS, and changes in terrestrial water storage derived using gravimetry can justify seasonal and interannual deformation signals. The main constraints of satellite gravimetry are its comparatively low spatial resolution and leakage of the signal, which limit the satellite gravimetry to small-scale processes<sup>[35,36]</sup>.

### 3.4. Satellite Laser Ranging and DORIS

Satellite Laser Ranging (SLR) and Doppler Orthography and Radio positioning Integrated by Satellite (DORIS) systems have also been used to study climate deformation by offering precise orbit determination and independent determinations of the positions of the stations. The techniques are important in the maintenance and validation of international geodetic reference frames necessary to provide the consistency of deformation measurements over a long period of time. SLR, especially, is very sensitive to the large-scale vertical movement, and it can be useful in testing the trends based on the GNSS, as well as in tracking the global-scale deformation of mass redistribution. In spite of their small spatial resolution in relation to that of the GNSS and InSAR, SLR and DORIS deliver valuable complementary constraints and strengthen the stability of the multi-method geodetic

studies<sup>[37]</sup>.

### 3.5. Emerging and Complementary Techniques

The latest development in complementary geodetic methodologies has added to the observation tool of climate-induced deformation studies. High-resolution topography data can be obtained through airborne and terrestrial LiDAR, photogrammetric techniques, and applied to identify changes to surface elevation related to glacier thinning, permafrost degradation, and coastal erosion. Site-specific observations using unmanned aerial (UAV) surveys are flexible and offer an alternative to ground-based and satellite measurements, providing a coverage gap. New methods of seafloor geodesy allow the monitoring of both vertical and horizontal movement beneath the ocean in coastal and offshore settings, which are important to the study of the effects of ocean loading and relative sea-level change. Although these approaches remain in their inception and are short in spatial coverage, they are good prospects for future studies<sup>[1,38]</sup>.

Contemporary geodetic methods of observation have complementary capabilities of identifying surface deformation on a broad spatial and temporal scale that is caused by climate. The GNSS, InSAR, satellite gravimetry, and auxiliary techniques integration has given a complete observational framework that is paramount in developing the understanding of climate solid Earth interactions.

## 4. Integration of Geodetic Observations and Physical Modeling

The realization of climate-induced surface deformation is based on accurate geodetic measurements as well as on how these measurements are combined with physical models that characterize the surface loading and Earth's mechanical response. Since the signals of deformation typically observed are an overprint of many processes acting at varying scales (spatially and in time), powerful modeling frameworks are necessary when it comes to assigning surface motion to particular climate-driven processes. In this section, the main methods of introducing geodetic data into Earth response models, data fusion methods, and techniques of climate-related simulations are examined<sup>[1]</sup>.

#### 4.1. Elastic and Viscoelastic Earth Response Models

Climate processes that result in surface mass redistribution cause deformation of the lithosphere and underlying mantle by elastic and viscoelastic responses. At the short-period scale, the response of the Earth may frequently be assumed to be elastic, and the displacement of the surface is proportional to the load being applied and is also determined by the Green functions that are based upon the elastic models of Earth. These models are very common in the prediction of deformation related to seasonal snow loads, hydrological variability, and modern loss of ice mass.

At a longer time scale, especially in areas where the ice used to cover them, viscoelastic processes become important. The late mantle response to the historic ice loading and unloading is reflected in glacial isostatic adjustment and has to be considered when interpreting the current geodetic signals. Viscoelastic Earth models include rheology factors like lithospheric thickness and mantle viscosity, which are rather uncertain. Differences in these parameters can give significant differences in predicted deformation, which underlines the necessity of geodetic constraints to improve the structure model on Earth<sup>[39,40]</sup>.

#### 4.2. Separation of Climatic, Tectonic, and Anthropogenic Signals

One of the primary issues in the climate deformation research is to distinguish between climate-related signals and the tectonic motion and human-induced deformation. Tectonic processes tend to cause long-term deformation, which is consistent, and climate signals tend to be seasonal to interannual. Nonetheless, the distinction may be complicated by spatial pattern and timescale overlaps, especially in areas where tectonic, groundwater, and climatic forcing co-exist. Signal separation is very effective using multi-technique geodetic observations. Time series of the GNSS system can be deconstructed into linear trends, seasonal variations, and transient signals, whereas InSAR can provide the spatial context, which could be used to detect localized anthropogenic deformation. Gravimetry of satellites provides an additional constraint to the change of mass and helps assign contri-

butions of displacements on the surface-to-surface loading and not tectonic forcing. Isolation of climate-related components is usually done using statistical methods, including time-series decomposition and spectral analysis<sup>[41,42]</sup>.

#### 4.3. Joint Inversion and Data Fusion Approaches

A combination of several geodetic data sets using joint inversion and data fusion approaches has gained more significance in enhancing the integrity and solution to deformation estimates. Using a combination of GNSS, InSAR, and gravimetry data will allow researchers to take advantage of the complementary capabilities of each method, namely, temporal continuity, spatial density, and mass sensitivity, respectively.

Joint inversion schemes tend to deal with the concurrent determination of surface loads, Earth rheological parameters, and fields of deformation. This type of method minimizes ambiguity and enhances the separation of overlapping signals, especially in areas with intricate deformation profiles. Data fusing algorithms also reduce the drawbacks of single techniques, including the low spatial resolution of GNSS or the low resolution of satellite gravimetry<sup>[43]</sup>. **Figure 2** illustrates the process of integrating multiple geodetic data sets with Earth system models.

Several studies illustrate the success of multi-technique geodetic integration in isolating components of deformation due to climate in complicated settings. As an example, in Greenland, combined studies of continuous GNSS, satellite gravimetry (GRACE/GRACE-FO), and InSAR-based deformation of the crust have made it possible to decouple modern elastic crustal uplift due to modern ice mass loss and longer-term viscoelastic uplift due to glacial isostatic adjustment. Using the estimates of mass change obtained by gravimetry and high-resolution patterns of deformation obtained by GNSS and InSAR analyses, researchers have been in a position to not only place constraints on the amount and location of contemporary ice-sheet mass loss, but also to provide estimates of mantle viscosity and lithospheric structure. This combined method has largely unified any ambiguities in approximations of the contribution of Greenland to the rise of the sea level around the world.

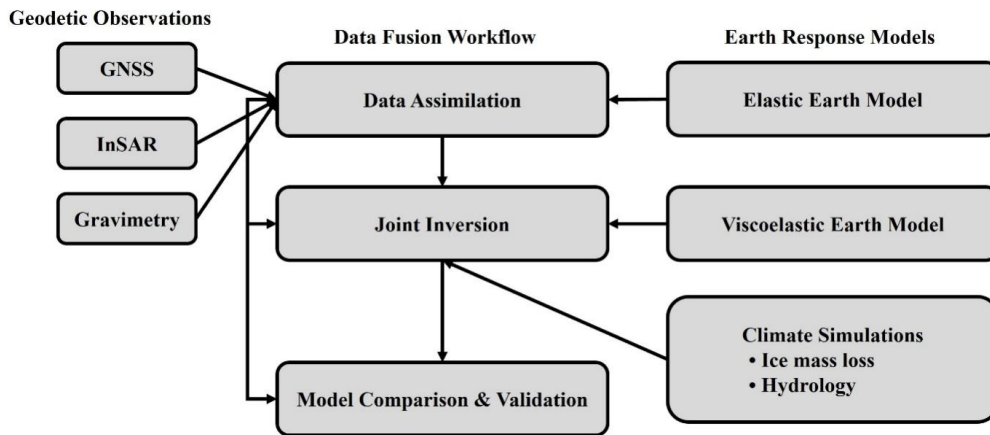


Figure 2. Schematic: Example of Data Fusion and Model Integration.

A second example is in hydrologically sensitive areas of the continents, where simultaneous analysis of GNSS vertical series of displacements, GRACE-derived terrestrial water storage anomalies, and InSAR-based deformation map has been employed to isolate seasonal and interannual hydrological loading signals. Multi-sensor integration has enabled the identification of variability of water storage due to climate changes and long-term subsidence due to groundwater extraction in large sedimentary basins like the Central Valley of California and the North China Plain. These studies prove that the complementary spatial and temporal sensitivity characteristics of various geodetic methods form a strong framework for the measurement of surface deformation caused by climatic conditions<sup>[44,45]</sup>.

#### 4.4. Coupling with Climate, Cryospheric, and Hydrological Models

Geodetic measurements are becoming more incorporated into the climate, cryospheric, and hydrological models in order to enhance the comprehension of processes in the Earth system. Measurements of deformation can be used to independently confirm estimates of model physics of ice mass balance, snow water equivalent, and terrestrial water

storage. On the other hand, climate and hydrological models provide spatially and temporally resolved loading estimates that could be utilized in estimating geodetic deformation. Data assimilation models are a viable future direction of the complete coupling of geodetic observations with Earth system models. Through the use of deformation data in model simulations, a constraint of poorly known parameters, uncertainty reduction, and better prediction can be achieved. These coupled strategies prove to be especially useful in the estimation of future climatic effects on surface deformation or in the creation of operational monitoring systems<sup>[28]</sup>.

A combination of a set of geodetic measurements and physical models is critical in the interpretation of surface deformation due to climate change, and also to assign the measured signals to processes. The development of Earth response modeling and multi-sensor data fusion, and the integration with climate models, is making it possible to analyze more completely and accurately the climatic interactions between the solid Earth and the atmosphere<sup>[46]</sup>. **Table 3** presents an overview of common geodetic data integration techniques with physical Earth models and discusses the associated uncertainties and challenges in climate deformation studies.

Table 3. Data Integration and Model Uncertainty in Climate Deformation Studies.

Geodetic Data	Modeling Approach	Uncertainties/Challenges	Solutions/Approaches
GNSS	Elastic and viscoelastic Earth response models	Spatial gaps in data, temporal decorrelation	Improve network density, joint inversion with InSAR, GRACE
InSAR	Surface loading and geodynamic models	Atmospheric delays, temporal decorrelation, reference frame errors	Time-series processing, integration with GNSS
Satellite Gravimetry	Mass redistribution models (e.g., ice loss and water storage)	Coarse spatial resolution, signal leakage	Combine with higher-resolution techniques like InSAR
Climate and Hydrological Models	Terrestrial water, cryospheric, and climate system models	Uncertainty in model parameters, lack of data in key regions	Data assimilation, ensemble modeling approaches

## 5. Global and Regional Applications of Geodetic Observations

The geodetic surveys on the surface deformations due to climate have escalated at a rapid pace in the past two decades and provided information previously unavailable regarding the interactions between climate and the solid Earth in various geographical and environmental settings. There

are space and time variations of deformation that have been achieved through climatic forcing and interaction of human activity between polar ice sheets to densely populated river deltas recorded by geodetic measurements. This section is an overview of some of the typical uses of geodesy in the analysis of the global and regional impacts of climatic changes on different scales<sup>[47]</sup>. **Table 4** shows a summary of the main points and highlights the application of geodetic techniques.

**Table 4.** Global and Regional Applications of Geodetic Observations.

Region/Environment	Observed Climate Process	Deformation Type	Geodetic Techniques	Key Findings/Applications
<b>Polar Regions (Greenland, Antarctica)</b>	Ice sheet mass loss, seasonal snowmelt	Uplift, horizontal motion, seasonal deformation	GNSS, InSAR, gravimetry	Documenting ice sheet contribution to sea-level rise, understanding GIA effects
<b>High-Mountain Regions (Himalayas, Andes)</b>	Glacier retreat, seasonal hydrological variability	Vertical displacement, seasonal uplift/subsidence	GNSS, InSAR	Monitoring glacier dynamics, assessing water resource availability
<b>Permafrost Regions (Siberia, Alaska)</b>	Permafrost thaw, freeze-thaw cycles	Subsidence, thermokarst formation	InSAR, GNSS	Quantifying thaw-induced ground motion, infrastructure impacts
<b>Coastal Deltas (Mississippi, Mekong, Nile)</b>	Sea-level rise, sediment compaction	Coastal subsidence, uplift	GNSS, InSAR, gravimetry	Assessing relative sea-level change, coastal vulnerability

### 5.1. Polar Regions

The most powerful predictors of the impact of climate are found in polar areas, where the mass of ice sheets is increased. In some places, meltdown and recession of ice have been observed because of continuous GNSS systems in Greenland and Antarctica to uplift the crust by several millimeters annually. The observations provide independent information on the ice mass balance and have been important to test estimates of the ice mass balance by satellite altimetry and gravimetry. In addition to the long-term trends, seasonal deformation is also registered by the geodetic measurements through snowfall and melting, which gives an idea of what is occurring at the surface when it comes to the mass balance. The use of a combination of GNSS, InSAR, and gravimetry has provided a step forward in separating the modern ice mass loss and glacial isostatic adjustment, which has been a decisive step in achieving the real measurements of sea-level rise. These applications focus on polar climate research and measurement of global cryophilic change, the subject of geodesy<sup>[48,49]</sup>. **Figure 3** shows observed surface deformation in polar regions, such as Greenland and Antarctica.

Although there has been major progress made in the study of polar deformation, there are gaps in knowledge. Es-

pecially, the low density of the continuous GNSS stations in specific regions of the Antarctic and the low spatial resolution of the gravimetry data limit the ability to determine accurately whether the current ice mass loss or the signal of glacial isostatic adjustment is present. Better models of Earth rheology and expanded geodetic networks are thus required to better measure polar mass balance and its role in increasing sea-level on Earth.

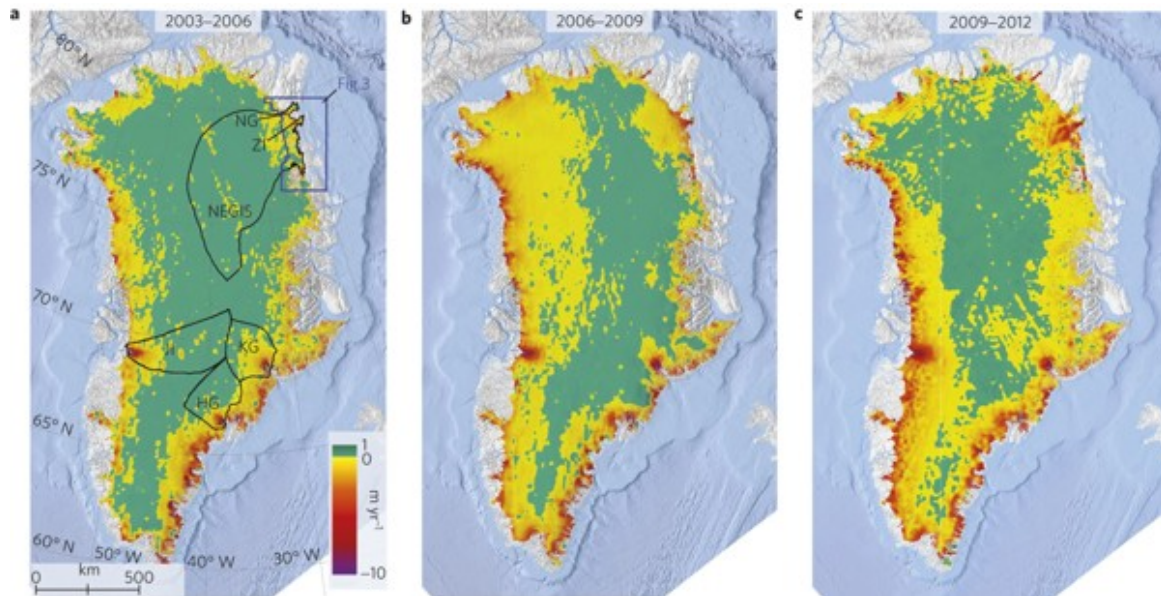
### 5.2. High-Mountain and Alpine Regions

The high mountain regions are extremely prone to climatic change and have a significant water source within the region. Geodetic techniques have been significantly employed in mountain ranges, such as the Himalayas, Andes, Alps, and the Rockies, to determine the extent of the shrinking of glaciers, seasonal snow, surface, and surface-related deformations. The seasonal, as well as the long-term uplift related to the hydrological variability and the loss of glacier mass, may be observed using GNSS.

Through InSAR, it has become possible to map spatially heterogeneous deformation in the mountainous terrain, like glacier flow, ice thinning, and subsidence caused by permafrost. The said observations are particularly helpful

in the regions where in situ measurements are scarce or logistically challenging. Observations of high mountain geodetic may serve to improve the connection between the

glaciers and the climatic conditions and establish the foundation of the future of water availability and the geohazard risks<sup>[50]</sup>.



**Figure 3.** Surface Deformation Observed in Polar Regions (Greenland). (a) Rates of ice surface elevation change (in meters per year) from April 2003 to April 2006; (b) April 2006 to April 2009; (c) April 2009 to April 2012.

Source: Modified from Khan et al. <sup>[49]</sup>.

Nevertheless, several high-mountainous areas are not well monitored as the terrain conditions are hard to reach, infrastructure is inadequate, and geodetic networks are limited. A better spatial resolution of GNSS observations and a higher acquisition rate of satellites is required as a means of resolving both the short-term glacier and hydrological processes, and also to put into better perspective the correlation between the mass loss of glaciers and crustal deformation.

### 5.3. Continental Interiors and Hydrologically Sensitive Regions

Terrestrial water storage variations induced by climate in the continental interiors cause a strong influence on the deformation of the surface. GNSS networks have been claimed to record detailed seasonal deformation with reference to precipitation and seasonal fluctuations in soil moisture, but the long-term patterns have shown persistent climatic anomalies, such as drought. These measurements are complemented by InSAR measurements to solve localized subsidence, which is attributed to groundwater depletion and recharge.

Large sedimentary basins and agricultural areas are

some examples of notable areas where climate variability and water management activities interact. Such works of geodetic measurements have improved actualization of the connection between climate, hydrology, and solid earth deformation, which has shown the importance of such components and the role of both climatic and anthropogenic aspects in the deformation studies<sup>[51]</sup>.

An ongoing issue with such environments is that it is difficult to separate climate-induced hydrological loading processes and anthropogenic processes, including groundwater extraction and land-use change. The future studies will need a combined study of the geodetic measurements with the hydrological models and better measurements of the in situ water storage to be able to attribute the deformation signals to the particular processes.

### 5.4. Coastal Zones and Delta Systems

Coastal and river deltas are also other examples of environments that are likely to be deformed as a result of climate change, since it involves the interactions of sea-level rise, sediment compaction, and changes in hydrological loading.

It has been observed by the use of InSAR and GNSS that extremely subsiding activity is taking place within the major delta system of the Mississippi, Mekong, and Nile, as well as the Ganges-Brahmaputra deltas. Climate-related processes associated with the decline in sediment supply and altering hydrologic regimes contribute to subsidence in many cases as a result of human activities.

It is therefore significant to measure the relative change

in the sea level of the coastal areas, and this is achieved by geodetic measurements. The geodesy will be able to provide priceless information about the dangers of the coast, the structure of infrastructures, and the methods of adapting to the changes in climate by dividing the minor and major contributors to the total process of the coastal deformation<sup>[52,53]</sup>.

Figure 4 illustrates an InSAR-derived deformation map of a coastal delta region (Ganges–Brahmaputra).

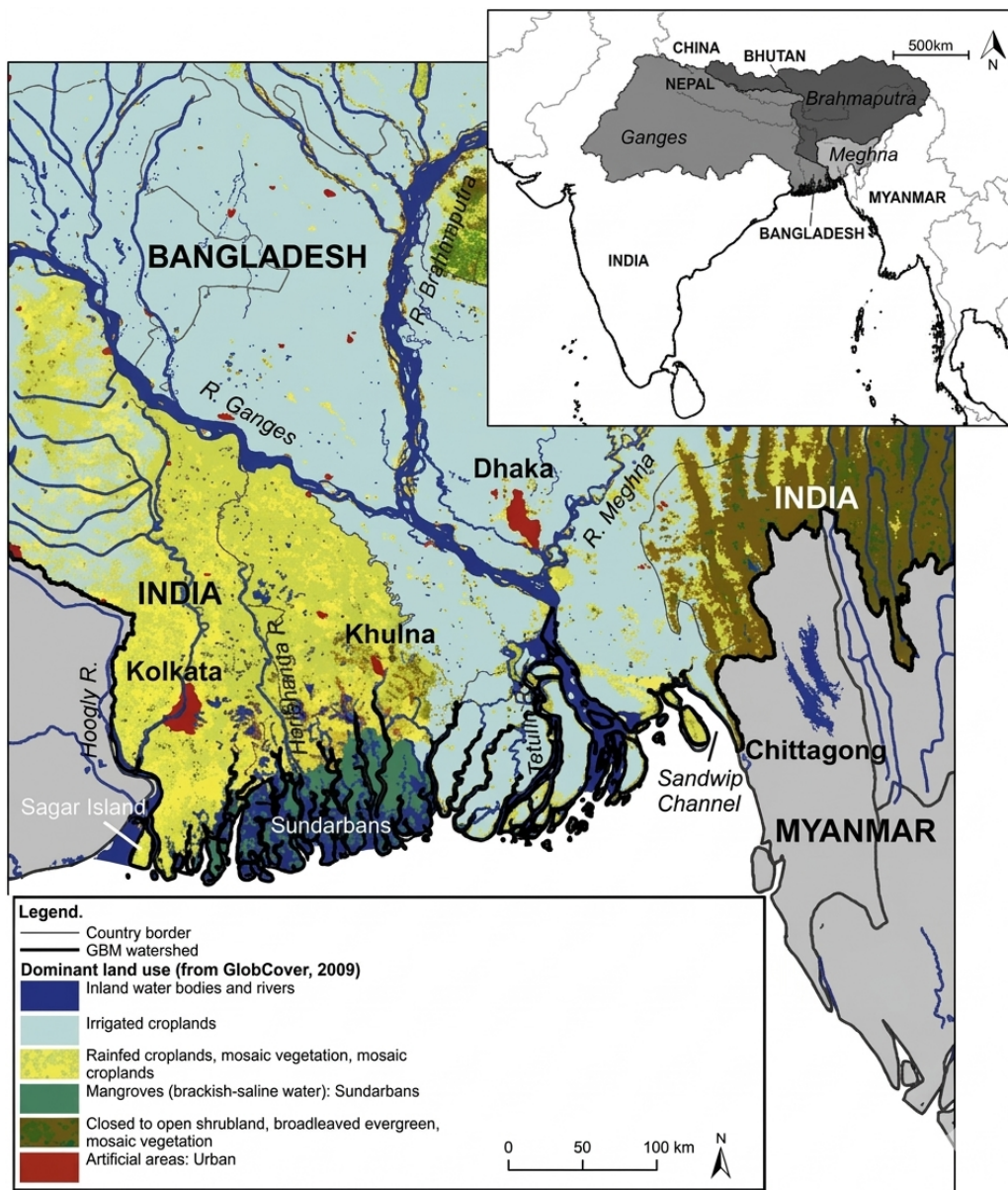


Figure 4. InSAR-derived Deformation Map of Coastal Delta (Ganges–Brahmaputra).

Source: Modified from Brown and Nicholls<sup>[53]</sup>.

However, it is still difficult to measure the relative roles of climate-driven ocean loading, sediment compaction,

tectonics, and human activities in most coastal areas. Monitoring deformations at high-resolution levels will be critical,

along with enhanced sediment and hydrologic models, which will be critical in the accurate evaluation of future coastal subsidence and relative sea-level change.

### 5.5. Permafrost and High-Latitude Environments

The high latitudes with areas under permafrost have made it difficult to respond to the warming of the climate. The studies of InSAR have been used to give maps of large-scale subsidence in permafrost thaw areas, but GNSS can be used to measure trends over longer durations and seasonal freeze-thaw cycles. Through these applications, the spatial scale of permafrost degradation and the rate have been improved, and their implication on the landscape stability and infrastructure have been created. Other uses of permafrost geodetic include studies in the larger climate sciences because permafrost geodetic cannot permit the release of carbon and ecosystem reorganization coupled with warming permafrost. As the Arctic continues to warm, geodesy may gain more and more significance as a technique of monitoring permafrost deformation<sup>[54]</sup>.

Overall, the multi-usefulness and usefulness of geodetic methods in the monitoring of the surface deformation brought about by climate in various environments have been shown by the global and regional applications. Geodesy is a major component in interdisciplinary climate change research, providing quantitative, spatially resolved quantities of how the Earth responds to climate forcing.

Although more observational capabilities are becoming possible, the spatial variability and nonlinear behavior of permafrost degradation are not very well constrained. The further establishment of high-resolution InSAR time series and increased ground-based geodetic observations are required to improve the measurement of thaw-induced deformation and its effects on infrastructure stability and the change of the Arctic ecosystem.

## 6. Challenges, Uncertainties, and Future Directions

Although considerable advances have been made in the observation and interpretation of surface deformation due to climate, many challenges and uncertainties prevent the complete utilization of geodetic observations. These

issues are due to both observational and conceptual issues of the Earth system process. The question of how to deal with them is critical in enhancing the accuracy, reliability, and applicability of geodetic insights in climate change research.

### 6.1. Signal Attribution and Process Separation

The distinction between the climatic signals and the tectonic and anthropogenic as well as long-term geodynamic processes is one of the most important problems of the research on the deformations caused by climate. The deformation which is seen at the surface through geodetic methods is often a summation of a number of contributions with overlapping spatial modes and temporal nature. As an illustration, long-term uplift in glaciated regions indicates the current loss of ice mass as well as glacial isostatic preequilibrium, and subsidence in the basins of the sediments may be due to a combination of extraction of groundwater, compaction of the sediments, and climate-related fluctuation in hydrology. Proper attribution entails extensive modeling and the combination of various sets of data. Nevertheless, ambiguities in Earth rheology, estimates of surface loading of the Earth and the boundary conditions of the past create uncertainties in interpreting geodetic signals. Interest in creating strong methods of disentangling these contributions is a still-developing field<sup>[28]</sup>.

### 6.2. Observational Limitations and Data Gaps

Geodetic networks are not evenly distributed throughout the world, with high-density GNSS networks where the world's modernized areas are, and low-density areas where numerous polar and high-mountain and developing areas are often characterized by climate effects most of all. Although spatially extensive, InSAR coverage is impacted by temporal decorrelation, atmospheric delays, and snow-covered areas or thick vegetative limitations. Coarse spatial resolution and signal leakage are limitations to satellite gravimetry, which, despite its invaluable role in determining changes in mass, is limited by these weaknesses.

There is another problem with the long-term consistency of observations. Artificial trends or discontinuities may be introduced in deformation time series caused by variations in satellite missions, instrumentation, processing strategies, or reference frames. The continuity and inter-mission consis-

tency are essential to identify subtle climate-caused signals at decadal periods<sup>[55]</sup>.

### 6.3. Modeling Uncertainties

Physical models that relate loading of surfaces to deformation rely on assumptions regarding the structure and rheology of the Earth that are typically poorly defined. Lithostatic thickness, mantle viscosity, and subsequent lateral heterogeneity may also play a major role in influencing predicted deformation patterns. Similarly, uncertainty in climate, cryospheric, and hydrological models influences the estimates of the surface loading, especially where there is a limited amount of observational data. To enhance model fidelity, the geophysical constraints need to be enhanced in quality, and the Earth system, climate, and geodetic modeling communities need to be brought closer to one another. Attempts to quantify uncertainties are increasingly being made using sensitivity analyses and ensemble modeling methods; however, additional attempts are required to bridge the systematic propagation of uncertainties between loading models and predicted deformation<sup>[56]</sup>.

### 6.4. Emerging Opportunities and Technological Advances

In the future, there are a number of developments that can provide promising opportunities to overcome the existing limitations. Advanced SAR and gravimetry missions are being planned as the next generation of satellites that have the potential to deliver better spatial resolution, temporal sampling, and measurement. The use of wider GNSS systems and the incorporation of affordable sensors can help to increase coverage in data-deficient areas. The development of data analysis techniques (machine learning and artificial intelligence) brings in new opportunities for identifying subtle cues of deformation, automatic time-series analysis, and the combination of large, heterogeneous data sets. These methods might be especially useful in Near-Real-Time monitoring and early warning applications<sup>[57]</sup>.

### 6.5. Toward an Integrated Climate Geodetic Observing System

One of the major directions of the future is an initiative that will create a unified, global climate-geodetic observ-

ing system, which will combine various geodetic methods with climate and environmental measurements. A system like this would promote long-term and consistent monitoring of surface deformation due to climate and interdisciplinary research. This endeavor will need open data policies, standardized methodologies of processing, and collaboration among countries. As much as geodetic methods have contributed a lot to the knowledge on the surface deformation caused by climate, it is important to consider the remaining aspects of the issue of signal attribution, geodetic coverage, and model uncertainty issues. The future of climate-geodetic research will be based on a strong focus on further technological development and interdisciplinary integration<sup>[58,59]</sup>.

In order to promote the engagement of geodetic measurements in climate studies, several real collaborative projects might be transformative. The coordinated global monitoring program of key coastal delta systems (the combination of continuous GNSS networks, regular satellite InSAR measurements, and hydrological measurements) would be one of the priorities. The target of such a program could be highly vulnerable areas such as the Ganges-Brahmaputra, Mekong, Nile, and Mississippi deltas, where the sea-level rise due to climate change is combined with subsidence due to sediment compaction and groundwater exploitation. The implementation of a standardized monitoring system would allow to maintain the consistency of long-term deformation measurements and enhance the measurements of relative sea-level change and coastal risk.

An open-access data assimilation platform to retrieve the geodetic observations into the Earth system models is the second priority. This platform would enable previous data streams on GNSS displacement, InSAR displacement maps, and satellite gravimetry-obtained mass change forecasts to be uniformly integrated into the forthcoming climate, cryospheric, and hydrological computerized applications. An initiative of this kind would enable interdisciplinary cooperation between geodesists, climate scientists, and model developers and enhance the simulation of redistribution of surface mass and solid Earth responses in the context of the Earth system.

## 7. Conclusions

Surface deformation due to climate is an essential expression of the interaction between the climate and the solid

Earth. The climate change occurring through the redistribution of mass in the cryosphere, hydrosphere, atmosphere, and oceans is already causing quantifiable and, in most places, increasing deformation of the surface of the Earth. Geodetic methods have become essential instruments in the observation of the processes, which can give precise, continuous, and spatially comprehensive measurements, reflecting the response of the solid Earth to climatic forcing over a large spectrum of spatial and time scales.

This review has generalized the physical processes of climate-induced surface movements and evaluated the performance of the large geodetic observation methods, such as GNSS, InSAR, satellite gravimetry, and other auxiliary techniques. With a combination of these observations with elastic and viscoelastic Earth models and climate, cryospheric, and hydrological simulations, geodesy can provide special information concerning the process of mass redistribution that is impossible to derive using any one of the observational systems. Applications in polar regions, high-mountain settings, intra-continental interiors, permafrost settings, and sensitive coastal regions indicate that geodetic measurements are globally applicable to the measurement of climate effects and their interactions with tectonic and human activities.

Though major steps have been made, much remains to be done to distinguish overlapping deformation signals, minimize observational and modeling uncertainties, and even to have consistent global coverage. To overcome these difficulties, further evolution of multi-sensor data integration approaches, increased constraints on Earth rheology and surface loading, and increased networks of observation in data-sparse areas will be needed. With the advent of the next-generation satellite missions, improved GNSS structures, and improved data analytics, the role of geodesy in climate change studies is being presented as never before.

In the future, the development of an integrated climate-geodetic observing system, achieved through international collaboration and the availability of open data, will be essential in long-term monitoring of the deformation of surfaces due to climate change. With climate change still transforming the Earth system, geodetic observations will become a more central point of scientific development, hazard assessment, and evidence-based adaptation and mitigation.

## Funding

This work was funded by the 2025 Jilin Provincial Earthquake Administration Youth Science and Technology Development Project (JZQ-202503).

## Institutional Review Board Statement

Not applicable.

## Informed Consent Statement

Not applicable.

## Data Availability Statement

All data supporting the findings of this study are included in the article. No new data were created or analyzed in this study.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

- [1] Bürgmann, R.B., Chanard, K., Fu, Y., 2023. Climate- and weather-driven solid-earth deformation and seismicity. *Earth ArXiv*. DOI: <https://doi.org/10.31223/X5SH5M>
- [2] Huggett, R.J., 2012. *Climate, Earth Processes and Earth History*. Springer Science & Business Media: Berlin, Germany.
- [3] Zhong, S., Watts, A., 2013. Lithospheric deformation induced by loading of the Hawaiian Islands and its implications for mantle rheology. *Journal of Geophysical Research: Solid Earth*. 118(11), 6025–6048.
- [4] Pan, Y., Ding, H., Li, J., et al., 2022. Transient hydrology-induced elastic deformation and land subsidence in Australia constrained by contemporary geodetic measurements. *Earth and Planetary Science Letters*. 588, 117556.
- [5] Khan, M.N., Aslam, M.A., Muhsinah, A.B., et al., 2023. Heavy metals in vegetables: Screening health risks of irrigation with wastewater in Peri-Urban areas of Bhakkar, Pakistan. *Toxics*. 11(5), 460.
- [6] Aslam, M.A., Abbas, M.S., Mustaqeem, M., et al., 2024. Comprehensive assessment of heavy metal contamination in soil-plant systems and health risks from wastewater-irrigated vegetables. *Colloids and Surfaces*

- C: Environmental Aspects. 2, 100044.
- [7] Montillet, J.-P., Kermarrec, G., Forootan, E., et al., 2024. How big data can help to monitor the environment and to mitigate risks due to climate change: A review. *IEEE Geoscience and Remote Sensing Magazine*. 12(2), 67–89.
- [8] Maciejewska, A., Maciuk, K., 2025. Research using GNSS (Global Navigation Satellite System) products—A comprehensive literature review. *Journal of Applied Geodesy*. 19(4), 555–574.
- [9] Khan, M.N., Aslam, M.A., Zada, I., et al., 2023. Statistical analysis and health risk assessment: Vegetables irrigated with wastewater in Kirri Shamozai, Pakistan. *Toxics*. 11(11), 899.
- [10] Mazza, D., Cosentino, A., Romeo, S., et al., 2023. Remote sensing monitoring of the Pietrafitta earth flows in southern Italy: An integrated approach based on multi-sensor data. *Remote Sensing*. 15(4), 1138.
- [11] Zhu, X., 2024. *Geodetic Applications in Geophysics: (1) Mechanical Modeling and Spatial Geodesy of the Southeastern Tibetan Plateau (2) Orientation and Transfer Function of Borehole Tiltmeters* [PhD Thesis]. Université de Montpellier: Montpellier, France; University of Chinese Academy of Sciences: Beijing, China.
- [12] Sonali, P., Nagesh Kumar, D., 2020. Review of recent advances in climate change detection and attribution studies: A large-scale hydroclimatological perspective. *Journal of Water and Climate Change*. 11(1), 1–29.
- [13] Yadav, M., Gosai, H.G., Singh, G., et al., 2023. Major impact of global climate change in atmospheric, hydro-spheric and lithospheric context. In: Singh, P., Ao, B., Yadav, A. (Eds.). *Global Climate Change and Environmental Refugees: Nature, Framework and Legality*. Springer: Cham, Switzerland. pp. 35–55.
- [14] Watts, A.B., Zhong, S.J., Hunter, J., 2013. The behavior of the lithosphere on seismic to geologic timescales. *Annual Review of Earth and Planetary Sciences*. 41, 443–468.
- [15] Burov, E., 2009. Thermo-mechanical models for coupled lithosphere-surface processes: Applications to continental convergence and mountain building processes. In: Cloetingh, S., Negendank, J. (Eds.). *New Frontiers in Integrated Solid Earth Sciences*. Springer: Dordrecht, The Netherlands. pp. 103–143.
- [16] Liu, S., Wu, T., Wang, X., et al., 2021. Changes in the global cryosphere and their impacts: A review and new perspective. *Sciences in Cold and Arid Regions*. 12(6), 343–354.
- [17] Yu, G.-A., Yao, W., Huang, H.Q., et al., 2021. Debris flows originating in the mountain cryosphere under a changing climate: A review. *Progress in Physical Geography: Earth and Environment*. 45(3), 339–374.
- [18] Oestreicher, N., 2018. *Geodetic, Hydrologic and Seismological Signals Associated with Precipitation and Infiltration in the Central Southern Alps, New Zealand* [Master's Thesis]. Victoria University of Wellington: Wellington, New Zealand.
- [19] Whitehouse, P.L., 2018. Glacial isostatic adjustment modelling: historical perspectives, recent advances, and future directions. *Earth Surface Dynamics*. 6(2), 401–429.
- [20] Li, X., Long, D., Scanlon, B.R., et al., 2022. Climate change threatens terrestrial water storage over the Tibetan Plateau. *Nature Climate Change*. 12(9), 801–807.
- [21] White, A.M., Gardner, W.P., Borsa, A.A., et al., 2022. A review of GNSS/GPS in hydrogeodesy: Hydrologic loading applications and their implications for water resource research. *Water Resources Research*. 58(7), e2022WR032078.
- [22] Gao, H., Sabo, J.L., Chen, X., et al., 2018. Landscape heterogeneity and hydrological processes: A review of landscape-based hydrological models. *Landscape Ecology*. 33(9), 1461–1480.
- [23] Shan, W., Hu, Z., Guo, Y., et al., 2015. The impact of climate change on landslides in southeastern of high-latitude permafrost regions of China. *Frontiers in Earth Science*. 3, 7.
- [24] Zhang, Z., Lin, H., Wang, M., et al., 2022. A review of satellite synthetic aperture radar interferometry applications in permafrost regions: Current status, challenges, and trends. *IEEE Geoscience and Remote Sensing Magazine*. 10(3), 93–114.
- [25] Cazenave, A., Nerem, R.S., 2004. Present-day sea level change: Observations and causes. *Reviews of Geophysics*. 42(3). DOI: <https://doi.org/10.1029/2003RG000139>
- [26] Huang, Y., Jin, P., 2018. Impact of human interventions on coastal and marine geological hazards: A review. *Bulletin of Engineering Geology and the Environment*. 77, 1081–1090.
- [27] Tabari, M.M.R., Eilbeigi, M., 2025. Evaluating and determining the mechanism of land subsidence susceptibility under excessive overexploitation of groundwater and problematic sediments. *Environment, Development and Sustainability*. DOI: <https://doi.org/10.1007/s10668-025-06977-9>
- [28] Jin, S., van Dam, T., Wdowinski, S., 2013. Observing and understanding the Earth system variations from space geodesy. *Journal of Geodynamics*. 72, 1–10.
- [29] Raucoules, D., Le Cozannet, G., Wöppelmann, G., et al., 2013. High nonlinear urban ground motion in Manila (Philippines) from 1993 to 2010 observed by DInSAR: Implications for sea-level measurement. *Remote Sensing of Environment*. 139, 386–397.
- [30] Ramya, A., Poornima, R., Karthikeyan, G., et al., 2023. Climate-induced and geophysical disasters and risk reduction management in mountains regions. In: Sharma, S., Kuniyal, J.C., Chand, P. (Eds.). *Climate Change Adaptation, Risk Management and Sustainable Practices in the Himalaya*. Springer: Cham, Switzerland.

- pp. 361–405.
- [31] Tan, S., 2018. *GNSS Systems and Engineering: The Chinese Beidou Navigation and Position Location Satellite*. John Wiley & Sons: Singapore.
- [32] Lu, Z., Kwoun, O., Rykhus, R., 2007. Interferometric synthetic aperture radar (InSAR): Its past, present and future. *Photogrammetric Engineering and Remote Sensing*. 73(3), 217–221.
- [33] Pepe, A., Calò, F., 2017. A review of interferometric synthetic aperture RADAR (InSAR) multi-track approaches for the retrieval of Earth’s surface displacements. *Applied Sciences*. 7(12), 1264.
- [34] Rott, H., 2009. Advances in interferometric synthetic aperture radar (InSAR) in Earth system science. *Progress in Physical Geography*. 33(6), 769–791.
- [35] Flechtner, F., Reigber, C., Rummel, R., et al., 2021. Satellite gravimetry: A review of its realization. *Surveys in Geophysics*. 42(5), 1029–1074.
- [36] Chen, J., 2019. Satellite gravimetry and mass transport in the Earth system. *Geodesy and Geodynamics*. 10(5), 402–415.
- [37] Barasa, B.P.M., 2020. *Evaluation of Satellite Laser Ranging Errors Associated with Pressure Sensor Height Offsets [Master’s Thesis]*. University of Pretoria: Pretoria, South Africa.
- [38] Thiéblemont, R., Cozannet, G.L., Nicholls, R.J., et al., 2024. Assessing current coastal subsidence at continental scale: Insights from Europe using the European Ground Motion Service. *Earth’s Future*. 12(8), e2024EF004523.
- [39] Beuchert, M.J., Podladchikov, Y.Y., 2010. Viscoelastic mantle convection and lithospheric stresses. *Geophysical Journal International*. 183(1), 35–63.
- [40] Vauchez, A., Tommasi, A., Barruol, G., 1998. Rheological heterogeneity, mechanical anisotropy and deformation of the continental lithosphere. *Tectonophysics*. 296(1–2), 61–86.
- [41] Isioye, O.A., 2017. *An Investigation of Ground-based GNSS Atmospheric Remote Sensing Techniques for Weather and Climate Monitoring in Nigeria [PhD Thesis]*. University of Pretoria: Pretoria, South Africa.
- [42] Diamantidis, P.-K., 2023. *Combination of Space-Geodetic Techniques in the Era of VGOS and Multi-GNSS [PhD Thesis]*. Chalmers Tekniska Hogskola: Gothenburg, Sweden.
- [43] Yan, H., Dai, W., Liu, H., et al., 2022. Fusion of spatially heterogeneous GNSS and InSAR deformation data using a multiresolution segmentation algorithm and its application in the inversion of slip distribution. *Remote Sensing*. 14(14), 3293.
- [44] Hasan, M.F., 2022. *Integrating Remote Sensing and Model-Based Datasets in a Machine Learning Model to Map Global Subsidence Associated with Groundwater Withdrawal [Master’s Thesis]*. Missouri University of Science and Technology: Rolla, MO, USA.
- [45] Tang, W., Zhao, X., Li, J., et al., 2025. Investigation of land subsidence in the Fenhe River Basin, northern China, using Sentinel-1 InSAR time series analysis, to support hazard mitigation and groundwater management. *Natural Hazards*. 121(17), 20683–20711.
- [46] Bishop, M.P., Olsenholler, J.A., Shroder, J.F., et al., 2004. Global Land Ice Measurements from Space (GLIMS): Remote sensing and GIS investigations of the Earth’s cryosphere. *Geocarto International*. 19(2), 57–84.
- [47] Angermann, D., Pail, R., Seitz, F., et al., 2022. *Mission Earth: Geodynamics and Climate Change Observed through Satellite Geodesy*. Springer: Berlin, Germany.
- [48] Van der Veen, C., 2002. Polar ice sheets and global sea level: How well can we predict the future? *Global and Planetary Change*. 32(2–3), 165–194.
- [49] Khan, S.A., Kjær, K., Bevis, M., et al., 2014. Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change*. 4(4), 292–299.
- [50] Beniston, M., 2003. Climatic change in mountain regions: A review of possible impacts. *Climatic Change*. 59(1), 5–31.
- [51] Zhang, H., Zhan, C., Xia, J., et al., 2022. Responses of vegetation to changes in terrestrial water storage and temperature in global mountainous regions. *Science of the Total Environment*. 851(Part 2), 158416.
- [52] Kuenzer, C., Renaud, F.G., 2012. Climate and environmental change in river deltas globally: Expected impacts, resilience, and adaptation. In: Renaud, F.G., Kuenzer, C. (Eds.). *The Mekong Delta System: Interdisciplinary Analyses of a River Delta*. Springer: Dordrecht, The Netherlands. pp. 7–46.
- [53] Brown, S., Nicholls, R.J., 2015. Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of the Total Environment*. 527–528, 362–374.
- [54] Xue, Z., Zhao, S., Zhang, B., 2024. Study on Soil Freeze–Thaw and Surface Deformation Patterns in the Qilian Mountains Alpine Permafrost Region Using SBAS-InSAR Technique. *Remote Sensing*. 16(23), 4595.
- [55] Wenzel, D., Kasten, A., Berdermann, J., et al., 2017. The German ISWI instruments SOFIE and GIFDS. In *Proceedings of the United Nations/United States of America Workshop on the International Space Weather Initiative: The Decade after the International Helio-physical Year 2007*, Boston, MA, USA, 31 July–4 August 2017.
- [56] Vyalov, S.S., 2013. *Rheological Fundamentals of Soil Mechanics*. Elsevier: Amsterdam, The Netherlands.
- [57] L’Abbate, M., et al., 2015. Compact SAR and micro satellite solutions for Earth observation. In *Proceedings of 31st Space Symposium*, Colorado Springs, CO, USA, 13–16 April 2015.

- [58] Rank, J., Pace, V.L., Frese, M., 2004. Three avenues for future research on creativity, innovation, and initiative. *Applied Psychology*. 53(4), 518–528.
- [59] Dvir, R., Dvir, R., Schwartzberg, Y., et al., 2006. The future center as an urban innovation engine. *Journal of Knowledge Management*. 10(5), 110–123.