Environmental Geodesy: state of the art

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Abstract
With ever increasing global population, intense pressure is being exerted on the Earth's resources leading to severe changes in its land cover (e. g., deforestation), diminishing biodiversity and natural habitats, dwindling freshwater supplies, and changing weather and climatic patterns (e. g., global warming, changing sea level). Environmental monitoring techniques that provide such information are under scrutiny from an increasingly environmentally conscious society that demands the efficient delivery of such information at a minimal cost. Environmental changes vary both spatially and temporally, thereby putting pressure on traditional methods of data acquisition, some of which are very labour intensive, such as animal tracking for conservation purposes. With these challenges, conventional monitoring techniques, particularly those that record spatial changes call for more sophisticated approaches that deliver the necessary information at an affordable cost. One direction being followed in the development of such techniques involves Environmental Geodesy, which can act as stand-alone method, or to complement traditional methods. This contribution looks at its current state of the art.

1 Introduction

Although the environment has remained at the forefront of scientific interest for well over four decades, see, e. g. Lein (2012), it was not until the last two decades that remote sensing of the environment using geodetic methods started gaining momentum. This has largely been fuelled by the launching of modernized satellites that enable the environment to be measured, mapped, and modelled. The advent of these satellites have given birth to „***Environmental Geodesy***“, which can be viewed as the branch of geodesy that applies geodetic techniques to sense the environment and provide information that contribute towards its effective management by supporting appropriate policies and decision making (e. g. Awange, 2012, 2018; Awange and Kiema, 2013).

Geodetic techniques that are useful in sensing the environmental include: Satellite laser ranging (SLR) that are useful in monitoring mass redistribution, e. g., postglacial and also in calibrating altimetry satellites; interferometric synthetic aperture radar (InSAR) that are finding use in monitoring land subsidence and oil leaks; satellite altimetry, used in monitoring the melting polar ice; very long baseline interferometry (VLBI), that are useful in plate tectonic studies, etc. Of these methods, perhaps the most revolutionary techniques that have pushed geodesy to the forefront of sensing the environment are the satellites gravity measurements from CHAMP (CHAllenging Mini-satellite Payload), GRACE (Gravity Recovery And Climate Experiment) and GOCE (Gravity field and the steady state-of-the ocean circulation explorer (see Fig. 1.1).

Apart from the gravimetric sensing satellites, GNSS (Global Navigation Satellite System) satellites such as GPS (Global Positioning System) are playing an increasingly crucial role in tracking low earth orbit-

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ing (LEO) remote sensing satellites at altitudes below 3000 km with accuracies of better than 10 cm, see e. g., Yunck et al. (1990).

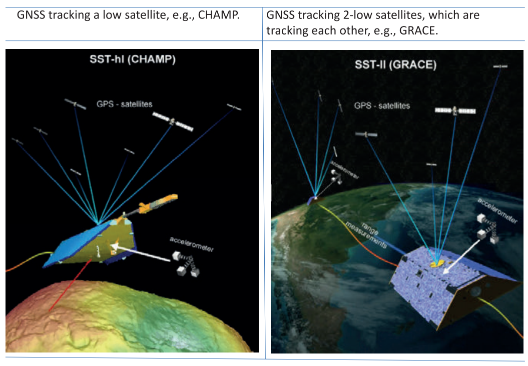

Figure 1.1: Left: SST-hl realized with CHAMP (©GFZ Potsdam ([2.2]). Right: A combination of ll-SST and hl-SST realized with GRACE and GNSS satellites (©GRACE - CSR Texas ([2.2]). Figures modified by D. Rieser (Rieser, 2008)).

2 Environmental sensing

2.1 GNSS-environmental sensing

Never before has there been a tool that in its application spans all the four dimensions of relevance to mankind (position, navigation, timing and the environment). Global Navigation Satellite Systems (GNSS), a satellite microwave (L-band) technique, is such a tool that has widely been used for positioning (both by military and civilians), navigation, timing, and is now revolutionizing the art of monitoring our environment in ways never fathomed before (Awange, 2018).

Over the years, research efforts have been dedicated to modelling atmospheric refraction in order to improve on GNSS positioning accuracy by accounting for the excess path delay (see, e. g. Awange, 2018). In the last two decades, however, GNSS space and ground based remote sensing methods have increasingly become essential tools for measuring atmospheric parameters. Geodetic remote sensing satellites employ a precise global network of GNSS ground receivers operating in concert with receivers onboard the LEO (Low Earth Orbiting) satellites, with all estimating the satellites' orbits, GPS orbits, and selected ground locations simultaneously (Yunck et al., 1990). GNSS radio occultation (GNSS-RO) takes place when a transmitting satellite, setting or rising behind the Earth's limb, is viewed by a LEO satellite as illustrated in Fig. 2.1.

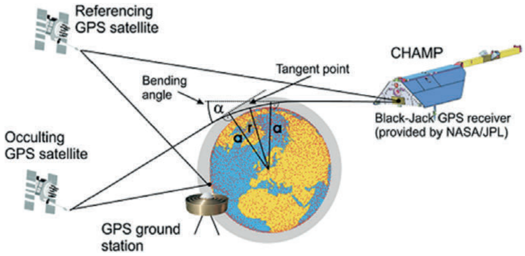

Figure 2.1: GNSS radio occultation. Use is made of (i) an occulting satellite, (ii) a non-occulting GNSS satellite and (iii) a ground-based GNSS station to determine the bending angle α from which the vertical profiles of temperature and pressure are determined. Source: Wickert (2002).

GNSS satellites send radio signals that pass through successively deeper layer of the Earth's atmosphere and are received by LEO satellites. These signals are bent and retarded, causing a delay in their arrival at the LEO. Figure 2.1 shows the occultation geometry where the signal transmitted from a GNSS to a LEO satellite passes through dispersive layers of the ionosphere and atmosphere, and in so doing senses them. As the signal is bent, the total bending angle, α, an impact parameter, a, and a tangent radius, r_t, define the ray passing through the atmosphere. The *refraction angle* is accurately measured and related to the atmospheric parameters; temperature, pressure and water vapour via the refractive index i (see Awange, 2018, for more details). A visual examination of Fig. 2.2 indicates that the COSMIC RO temperature profile agrees very well with its corresponding radiosonde profile with almost no deviation from the radiosonde data.

In a sister approach, also known as the GNSS-reflection (GNSS-R) remote sensing, the microwave signals reflected from various surfaces are received and processed to extract useful environmental information about those surfaces. The possibility of using GNSS reflected signals for sensing sea surface heights was proposed by Martín-Neira (1993), who used fixed-platform experiments to demonstrate that GNSS-reflection altimetry performed to an accuracy of ~20 m over the ocean, 450 m above Crater Lake, and 10 m over a pond (see e. g. Lowe et al., 2002, and the references therein). According to Lowe et al. (2002), such GNSS altimetry would involve an orbiting receiver that obtains position and timing information from the GNSS constellation as usual, but measures ocean height using the arrival time of GNSS signals reflected from the surface. The advantage over monostatic radar altimeters is that the receiver could produce about 10 simultaneous measurements (∼ 20 when Galileo becomes fully operational), distributed over an area thousands of km across-track (Lowe et al., 2002). Studies of GNSS-reflections from space include (e. g. Lowe et al., 2002). Applications of GNSS-R remote sensing include water reservoir level and ocean monitoring, soil moisture monitoring, where the observations relating to the flux of water to- and from- the land surface can be gleaned from GNSS multipath measurements of, e. g., snow depth and soil moisture (Larson et al., 2008, 2009; Yang et al., 2009). The advantages of GNSS-R remote sensing over traditional satellite scatterometry and radar altimetry together with their use in sensing vegetation changes are discussed in Awange (2018).

2.2 Geodetic sensing of gravity variations

Two types of gravity field variation exists. The *first* is the long-term, also known as mean gravity field, which is due to the static part of the gravity field. The variation is constant over a very long time interval. Its study is useful in understanding the solid structure of the Earth, ocean circulation, and in achieving a universal height measuring system. In this respect, GOCE satellite products are used to map changes in gravity using state-of-the-art gradiometer with improved accuracy, see e. g., Hirt et al. (2011). GOCE data is expected to benefit other studies such as those concerned with earthquakes, changes in sea level, and volcanoes[1]. The *second* type of variation of the Earth's gravity field is associated with those processes that occur over shorter time scales, such as atmospheric circulation or the hydrological cycle. This is known as the *time-varying gravity field* and is the component which enables the monitoring of, for example, variations in water resources and the melting of the polar ice. By removing the effects of the other processes that cause changes in the gravity field, changes in *terrestrial water storage* can thus be inferred from the observed temporal changes in the terrestrial gravity field.

At the broadest conceptual level, LEO satellites' gravity field missions observe (either directly or indirectly) gradients in the Earth's external gravitational field. This is essentially done through differential measurements between two or more points, thus largely eliminating spatially correlated errors. When done from space, two approaches can be used, e. g., Awange et al. (2009) and Rummel et al. (2002):

1) Satellite-to-satellite tracking (SST), or
2) A dedicated gravity gradiometer on board a satellite, coupled with SST.

The SST methods can use either low-low inter-satellite tracking (ll-SST, see Fig. 1.1, right), where two LEO satellites track one another and additional observations in terms of high precision ranges and range rates between the two satellites are taken, or high-low inter-satellite tracking (hl-SST, see Fig. 1.1, left), where high-Earth orbiting satellites (notably GPS) track a LEO satellite. The low-low mode, compared to the high-low mode, has the advantage of signal amplification leading to a higher resolution of the obtained gravity variations, up to the medium wavelength spectrum

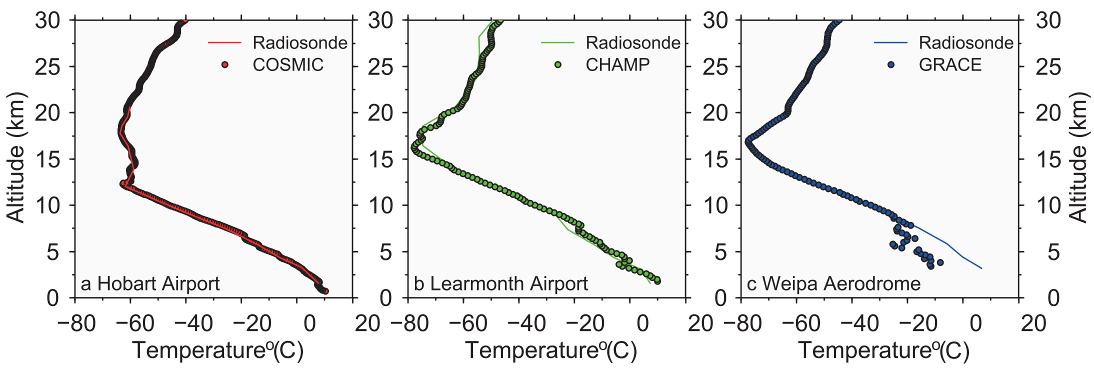

Figure 2.2: GNSS-RO soundings observed on (a) 20 December 2006 over Hobart Airport [42.84°S, 147.50°E] using COSMIC RO data, (b) 14 June 2005 over Learmonth Airport in Western Australia [22.24°S, 114.09°E] using CHAMP RO data and (c) on 8 September 2006 over Weipa Aero using GRACE data [12.68°S, 141.92°E]. Source: Khandu et al. (2010).

[1] see, e. g., http://www.esa.int/esaCP/SEMV3FO4KKF_Germany_0.html

of a few hundred km in spatial extent (Awange et al., 2009). Taking this further, a combination of ll-SST and hl-SST is conceptually better still, as is demonstrated by the GRACE mission (Fig. 1.1, right) with a baseline length between the two satellites of about 220 km.

In order to detect temporal gravity field variations at smaller spatial scales, the satellite(s) being tracked must be in as-low-as-possible orbits (close to the mass source), with the satellites being as free as possible from the perturbing effects of atmospheric drag (Awange et al., 2009). In addition, so-called dealiasing models (for correcting short-term - 6 hours - variations due to atmosphere and ocean mass variations) have to be used to mitigate the propagation of unwanted signals (e. g., leakage from the oceans) into the derived gravity solutions (e. g. Schrama and Visser, 2007).

The GRACE mission, launched on 17th of March 2002, consisted of two near-identical satellites following one another in nearly the same orbital plane (about 400 km altitude) separated by a distance of 220 km; the so-called tandem formation (see Fig. 1.1, right). The ll-SST was measured using K-band ranging, coupled with hl-SST tracking of both satellites by GNSS (GPS; Fig. 1.1, right). GNSS receivers were placed on GRACE satellites to measure occulted signals, and also to determine the orbital parameters of GRACE satellites required in order to determine gravity changes. On-board accelerometers monitored orbital perturbations of non-gravitational origin.

The Earth's gravity field is mapped by making accurate measurements of changes in the distance between the satellites, using GNSS and a microwave ranging system. These changes in the distances between the two satellites occur due to the effect of the gravity (mass concentration) of the Earth. As the lead satellite passes through a region of mass concentration, it is pulled away from the trailing satellite (Fig. 1.1, right). As the trailing satellite passes over the same point, it is pulled towards the lead satellite thus changing the distance between the satellites.

Time-variable gravity field solutions are obtained by the exploitation of GRACE observation data over certain time intervals, i.e., every month or less. There are a number of institutions delivering GRACE products, each applying their own processing methodologies and, often, different background models. The process causing gravity variations that are being studied by GRACE include (Ramillien et al., 2004);

- changes due to surface and deep currents in the ocean leading to more information about ocean circulation (e. g. Chambers et al., 2005; Wahr et al., 2002),
- changes in groundwater storage on land masses, relevant to water resource managers (e. g. Rodell and Famiglietti, 1999),
- exchanges between ice sheets or glaciers and the oceans, needed for constraining the mass balance of the global ice regime and sea level change, e. g., Baur et al. (2009) and Velicogna (2009), see also Sect. 3.4.
- air and water vapour mass change within the atmosphere, vital for atmospheric studies, e. g., Boy and Chao (2005) and Swenson and Wahr (2002), and
- variations of mass distribution within the Earth arising from, e. g., on-going glacial-isostatic adjustments and earthquakes, e. g., Barletta et al. (2008) and Tregoning et al. (2009).

The GRACE satellites have now been deactivated. However, plans are underway to launch a GRACE follow-on mission given the excellent results that have been delivered so far. The follow up mission may use lasers to measure inter-satellite distances, instead of the traditional microwave, and thus improve the measuring accuracy.

2.3 Satellite altimetric sensing of the environmental

Satellites altimetry (Fig. 2.3) operates in two steps:

- *First*, the precise orbit of the satellite, i.e., its position, is determined. Through this, its *height* above the Earth is obtained.
- *Second*, range measurements are made by obtaining the time an emitted signal (radar or laser) travels to the Earth's surface and reflected back to the satellite.

GNSS contributes to the *first step* where height is determined. This is achieved through GNSS receiver onboard the space satellites that enables monitoring of ranges and timing signals from GNSS satellites. The observed GNSS ranges provide precise and continuous tracking of the spacecraft, thereby delivering its position $\{\phi, \lambda, h\}$ at any time. The height component h is useful in determining the measured height (see Fig. 2.3).

In the *second step*, the Earth's surface heights (e. g., ocean surface, glaciers, and ice sheets) are measured using ranges from the space altimetry satellite to the surface of interest. Satellite altimeters send microwave signals to the Earth's surface and measures the time taken by the reflected signals to travel back upon which the distance from the satellite to the Earth's surface is derived. Since the signals pass through the atmosphere from and to the satellites, they are affected by the atmosphere and as such, atmospheric corrections have to be made. The sea surface height is then obtained by subtracting the measured ranges in step 2 from the GNSS-derived satellite heights in step 1 (Fig. 2.3).

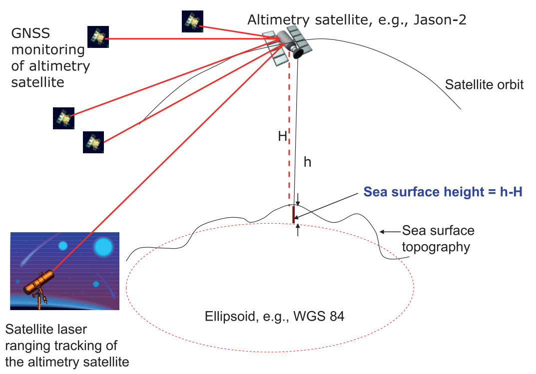

Figure 2.3: GNSS in support of monitoring changes in sea level through the determination of the altimetry satellites' precise orbit. From the precise orbital parameters, the height component h is useful in determining changes in sea level through the difference $\{h - H\}$, where H is measured by multiplying the speed of light with the time taken by the signals to travel from and to the satellite divided by 2, since the same distance is covered twice.

3 State of the art

The last two decades has seen the widening application of Environmental Geodesy. This section highlights a few examples.

3.1 Weather and climate change monitoring

Global Navigation Satellite Systems (GNSS), a general term for the US-based Global Positioning System (GPS), Russian's GLObal NAvigation Satellite System (GLONASS), China's Beidou or Compass, and the European Galileo satellite systems is a satellite tool currently providing location (spatial) data, remote sensing of the Earth's atmosphere (temperature and pressure) and surface (see Sect. 2.1), assisting in precise orbit determination of low earth orbiting environmental satellites (see Sect. 2.3), and supporting the tracking of elusive fresh underground and surface waters (see Sect. 2.2), among many other uses.

Its spatial data are also integrable with other remote sensing, socio-economic, and field survey data through geographical information systems (GIS) to provide highly continuous real-time spatio-temporal dataset that are of enormous benefit to the emerging field of *geosensor-network* environmental monitoring (e. g. Awange, 2012, 2018; Awange and Kiema, 2013).

The last two decades has seen the emergence of GNSS remote sensing techniques that are capable of monitoring changes in the global tropopause height and in so doing, contribute to monitoring *global warming* (see Fig. 3.1).

With all GNSS satellites (GPS, Galileo, GLONASS and Beidou) becoming operational, multi-signals are now available that are capable of remotely sensing the Earth's atmosphere and surface providing highly precise, continuous, all-weather and near real time environmental monitoring data. In this regard, the refracted GNSS signals (i.e., occulted GNSS signals or GNSS-meteorology) are now emerging as sensors of climate variability while the reflected signals (GNSS-Reflectrometry or GNSS-R) are increasingly finding applications in determining, e. g., soil moisture content, ice and snow thickness, ocean heights, and wind speed and direction of ocean surface among others. More recently, GNSS-meteorology is finding use in monitoring climate variability and the associated impacts of global teleconnections across most developing countries in the southern hemisphere where poor reliability of radiosonde records imposes serious challenges in understanding the structure of upper-tropospheric and lower-stratospheric (UTLS) region, i.e., the tropopause (see Fig. 3.2). The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission launched in April 2006 has overcome many observational limitations inherent in conventional atmospheric sounding instruments to provide millions of RO signals.

A recent study by Khandu et al. (2016a) examined the interannual variability of UTLS temperature over the Ganges-Brahmaputra-Meghna (GBM) River Basin in South Asia using monthly averaged COSMIC radio occultation (RO) data, together with two global reanalyses. Comparisons between August 2006 and December 2013 indicated that MERRA (Modern-Era Retrospective Analysis for Research Application) and ERA-Interim (European Centre for Medium-Range Weather Forecasts reanalysis) were warmer than COSMIC RO data by 2°C between 200 hPa and 50 hPa levels but these warm biases with respect to COSMIC RO data were found to be consistent over time. The UTLS temperature showed considerable inter-annual variability from 2006-2013 in addition to warming (cooling) trends in the troposphere (stratosphere). The cold (warm) anomalies in the upper troposphere (tropopause region) were found to be associated with warm ENSO (El Niño Southern Oscillation) phase, while quasi-biennial oscillation (QBO) was negatively (positively) correlated with temperature anomalies at 70 hPa (50 hPa) level. PCA (Principal Component Analysis) decomposition of tropopause temperatures and heights over the GBM basin indicated that ENSO accounts for 73% of the inter-annual variability with a correlation of 0.77 with Niño3.4 index whereas the quasi-biennial oscillation (QBO) explained about 10% of the variability. The largest tropopause anomaly associated with ENSO occurs during the winter, when ENSO reaches its peak. The tropopause temperature (height) increased (decreased) by about 1.5°C (300 m) during the last major El Niño event of 2009/2010. In general, a decreasing (increasing) trend in tropopause temperature (height) between 2006 and 2013 was found.

3.2 Agriculture and animal telemetry

Increasing recognition and application of GNSS-supported unmanned aircraft vehicles (UAV)/drones in agriculture (e. g., through the determination of water holding capacity of soil) highlights the new challenges facing GNSS. Frank Veroustraete (2015) puts it candidly:

> *„A lot is happening lately on the subject of drone applications in agriculture and precision farming. From the ability to image, recreate and analyze individual leaves on a corn plant from 120 meters height, to getting information on the water-holding capacity of soils to variable-rate water applications, agricultural practices are changing due to drones delivering agricultural intelligence for both farmers and agricultural consultants“.*

For example, *GNSS-based radio telemetry* is a modern method for observing animal movements, thereby moving the burden of making observations from the

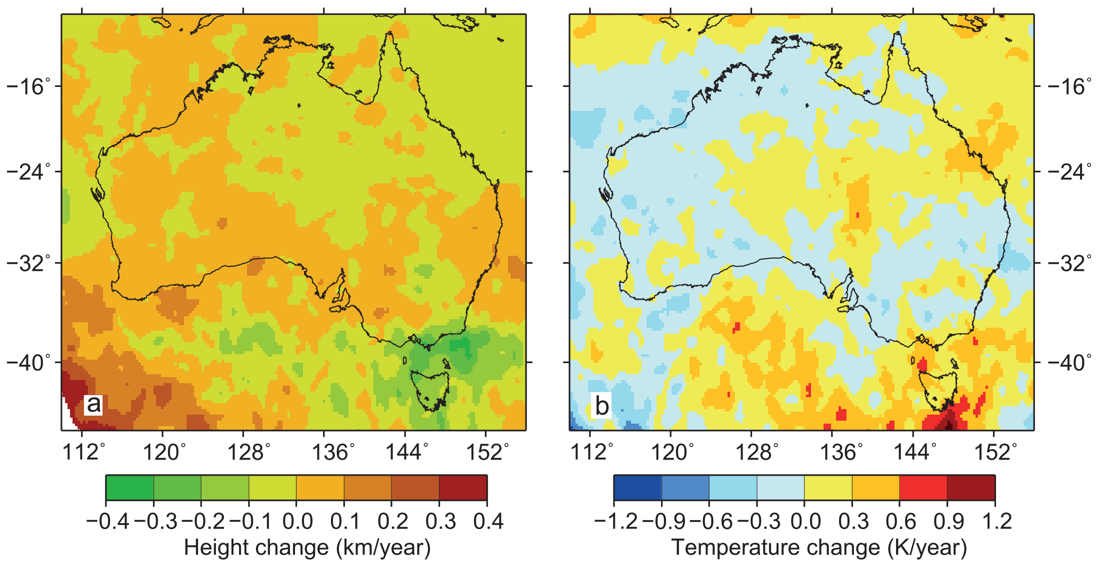

Figure 3.1: Rate of change in (a) the tropopause heights and (b) tropopause temperatures between September 2001 and April 2008. Source: Khandu et al. (2010).

observer (i.e., researcher) to the observed (i.e., animal), and in so doing alleviating the difficulties associated with personal bias, animal reactions to human presence, and animal habits that make most of them secretive and unseen (Cagnacci et al., 2010). This method provides large, continuous, high-frequency data about animal movement, data which, if complemented by other information dealing with animal behaviour, physiology, and the environment itself, contributes significantly to our knowledge of the behaviour and ecological effects of animals, allowing the promotion of quantitative and mechanistic analysis (Cagnacci et al., 2010).

3.3 Monitoring water storage changes and impacts of agricultural drought

The GRACE satellites had been recognized as having the potential to provide the first space-based estimate of changes in terrestrial water storage. In essence, it is a tool that now assist water managers in conserving and controlling the utilization of dwindling water resources in a sustainable way. Water is arguably one of the most precious resource in the world, therefore, it is logical to try to monitor its distribution as efficiently as possible, and GRACE offers one such opportunity, see e. g., Awange et al. (2008) and Khandu et al. (2016b). This is because one of the environmentally important signals detected by GRACE is the temporal gravity field variation induced by changes in the distribution of water on and below the Earth's surface, i.e., hydrology, e. g., Awange et al. (2009). Satellite altimetry provides the possibility of monitoring sea or lake surface heights as was demonstrated for Lake Naivasha (Awange et al., 2013). GNSS also plays a major role in providing location-based information for monitoring groundwater wells, and source of water pollutants as discussed in Awange (2018). Recent applications to drought monitoring are reported e. g., in Chen et al. (2009) and Agutu et al. (2017) while its use in characterizing geological properties that influence hydrological patterns are discussed in Awange et al. (2014)

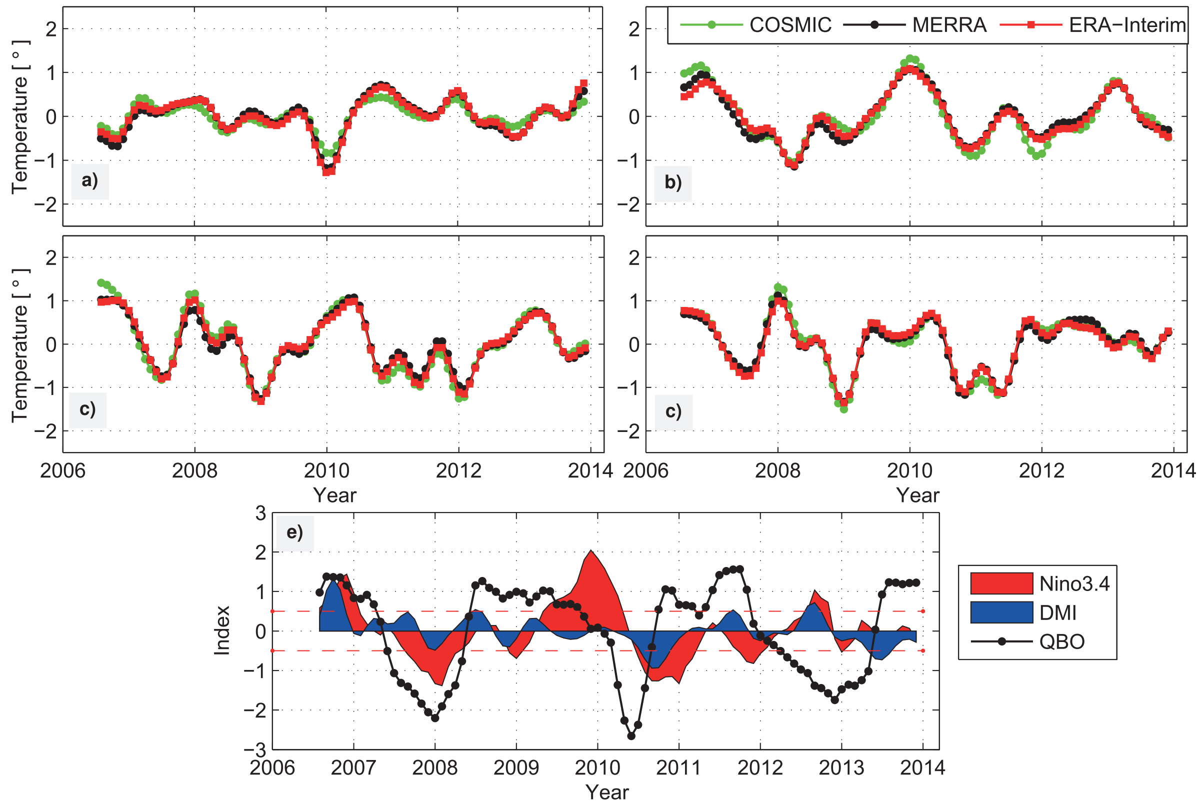

Figure 3.2: Interannual variability of temperature (°C) at (a) 200 hPa, (b) 100 hPa, (c) 70 hPa, and (d) 50 hPa from August 2006 to December 2013 based on COSMIC RO, MERRA, and ERA-Interim. (e) Ocean-atmospheric indices: Niño3.4, DMI, and QBO are also plotted for reference. Source: Khandu et al. (2016a)

and Hu et al. (2017). Forootan et al. (2016) pushed the boundary by employing GRACE to study rainfall and teleconnection linkage over Australia, Ndehedehe et al. (2017) looked at the influence of global teleconnections on West Africa's total water storage while Khaki and Awange (2018) used of remotely sensed GRACE, TRMM and soil moisture products to enhance hydrological model's study of climate induced water storage changes over South America.

3.4 Monitoring cryospheric changes

The cyrosphere, the subsystem of the Earth characterized by the presence of snow, ice, and permafrost, is fundamental to changes occurring in the Earth's environment, e. g., global warming as a result of the melting snow cover, glaciers, and sea ice that produces more warming due to decreased albedo associated with the greater extent and duration of the dark surface (Slaymaker and Kelly, 2007). Some of the occurrences in the Earth's polar region (Greenland and Antarctic) could have far reaching consequences on the environment and as such, require constant monitoring, which can be achieved through remote sensing using of satellite altimetry such as NASA's ICESat-2 (ice, cloud, and land elevation satellite) and GRACE satellites, e. g., Baur et al. (2009) and Velicogna (2009).

For instance, the Greenland and Antarctic ice sheets are reported to be losing mass at an increasing rate. Fast flowing outlet glaciers and ice streams carrying most of the mass flux from the interiors of the vast Greenland and Antarctic ice sheets toward the ocean have accelerated dramatically, the sea ice that covers the Arctic Ocean has decreased in areal extent far more rapidly than climate models have predicted and has thinned substantially, some of the thick and ancient ice shelves that fringe the Antarctic Peninsula have disintegrated, triggering the acceleration of the outlet glaciers that feed them, see Abdalati et al. (2010, and the references therein).

Abdalati et al. (2010) list the following consequences as the possible likely outcome of the behavior of ice sheets and sea ice changes to society:

- The melting ice sheets from Greenland and Antarctic are thought to contain enough ice to raise sea level by about 7 and 60 m, respectively.
- Sea ice exhibits a major influence on the Earth's planetary energy budget, influencing global weather and climate; and the Arctic ice cover is especially sensitive to and a strong driver of climate change, in large part due to the positive albedo feedbacks associated with melting ice.

GNSS contributes to glaciology measurements as evidenced by the performance of GPS where it has had a remarkable impact on the study of glacier volume, flow, and history in the last few years, leading to improvements in measurements of gross flow velocities, rates of surface snowfall, and isostatic adjustment associated with glacial mass change. In particular, RT-GPS (real-time GPS) can contribute to a better understanding of the dynamics of glaciers by allowing researchers to collect and analyze glacier flow data along with the ocean and atmospheric data (Hammond et al., 2010).

4 Concluding remarks

Geodetic sensing of the environment is a new and active area of research. The data that has been collected so far has provided several environmental (atmospheric) properties that were hitherto difficult to fathom. The new technique clearly promises to contribute significantly to environmental studies. When the life span of the various missions (e. g., GRACE) is reached, thousands of data sets will have been collected that will help to unravel some of the complex nature of atmospheric and environmental phenomenon. From the analysis of water vapour trapped in the atmosphere and tropopause temperature, climate change studies will be significantly enhanced. These are discussed in detail in Awange (2012, 2018) and Awange and Kiema (2013, 2018) leading to the question; should it ideally not be called „Environmental Geoinformatics (see e. g. Awange et al., 2016, where the techniques have been used for drought analysis in Brazil)" ?

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