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Monitoring Climate Change using Satellite-observed Earth's Surface Temperature: A Review

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***Abstract*—** Anthropogenic influence on climate modification is currently apparent more than ever, and this is comprehensible from the measurements of various climate variables such as the Earth's surface temperature. The investigation of climate variables is a challenging task as no one technique can reliably produce the essential data at both fine and broad scales. Accurate observations of surface temperature are traditionally available from functional ground-based weather stations. Unfortunately, this network of stations is not dense enough in terms of spatial extent for a detailed spatial assessment of the temperature field. However, the application of the satellite-based observation method makes it possible for multi-scale and instantaneous observations with a consistent temporal revisit concerning the Earth's processes. Therefore, this review is primarily focused on monitoring climate change using surface temperature data from satellite remote sensing. Recent papers that were published in the English language between 2013 and 2022 were accessed and used for the review. The research specifically emphasized the global temperature trend, and Earth's surface temperature observation including Land Surface Temperature, and Sea Surface Temperature. Summarily, it was shown that the satellite-based temperature time-series data is important for studying the climate system. Also, the current Earth Observation System and many proposed satellite systems will enhance assessment regarding the Essential Climate Variables. Thus, satellite remote sensing is a potent tool for comprehending the Earth's surface temperature and climate change.

***Keywords*—** Air temperature; Anthropogenic; GHG; LST; Satellite; SST; Weather station

I. INTRODUCTION

There are glaring signs that the global ecosystem is at risk and requires urgent attention. Natural and anthropogenic factors are gradually impacting the biophysics, biochemistry and biogeography of the Earth [1]. For instance, many available researches in the literature demonstrate that natural processes usually influence climate change. Also, anthropogenic emission of excess greenhouse gases (GHGs) into the atmosphere, predominantly carbon dioxide (CO2) and methane (CH4) is known to be the cause of contemporary climate change [2-4].

Human-induced GHG emission is mainly from the combustion of fossil fuel, agriculture, cement production, and deforestation/forest degradation. These anthropological activities increase the heat-trapping GHG levels in the Earth's atmosphere, thereby increasing the Earth's average temperature. Of course, the Earth's mean surface temperature has risen by nearly 1 °C (1.8 °F) with a substantial effect on the Earth's climate system. The time-series air temperature (Ta) data has been significant as input for climate modelling [5]. In other words, long-term past temperature records form the basis for climate change studies [6]. It is used to examine the numerous extreme weather and alteration in climate occurrences since the past decades. This comprises alterations in land and ocean average temperature, hot extremes in most settled areas, rise in sea levels, upsurge in heavy precipitation, and the likelihood of drought, and rainfall deficits in some areas [7, 8].

Global temperature alterations are an essential aspect of global climate change study. The temperature data obtained from weather stations are of great importance in the estimation of the world's average temperature for more than a century. The ground-based measurements are necessary for comprehending specific habitat alterations and effects on populations, but they are labour-intensive and limited in scale [9]. Specifically, the customary approach of estimating temperature using weather stations is limited in some terrain conditions [10], and also time-consuming. Nevertheless, employing sophisticated satellite remote sensing has greatly enhanced temperature measurements especially by generating the Land Surface Temperature (LST).

The LST is simply the land radiating temperature acquired from solar radiation [12] or satellite sensor [11] measurements. It has a direct link to surface energy changes (or surface energy budget), evapotranspiration and water stress [13-17], and surface longwave emission [18]. Thus, LST is vital for understanding climatological and hydrological processes in a changing climate [19-21]. Apart from deriving LST, a functioning satellite Sea Surface Temperature (SST) observation has been available since 1981. Thus, SST with in situ observations forms the modern-era SST observing system [22].

By and large, remote sensing affords the appropriate data source for diverse topographic and climatic conditions. It deals with the collection of information on features, areas, or occurrences by analyzing the data acquired through a device situated far away from the features, areas, or occurrences being investigated. These methods can vary from the manual examination of aerial photos to the computer-enhanced analysis of non-visible energy acquired by satellite systems [23]. It can provide high spatial coverage and rapid observations when compared to the in-situ weather stations. Therefore, it can be used for acquiring surface temperature over a large area consistently and accurately [24].

This paper is organized into five sections. The first section introduces the problem. The second section provides a literature review. Section three deals with the methods used in the study. Section four presents and discusses the results achieved in the review. Section 5 concludes the study.

II. Related Work

The Earth's temperature is essential for climate change assessment. Zhang et al. [25] suggested that the revised data on surface temperature offer a more reliable view of climate tendencies per decade from 0.070 °C in v4 to 0.073 °C in v5 throughout 1880–2018. Consequently, many efforts have been dedicated to the Earth's surface temperature studies in the recent past. In this regard, remote sensing affords a distinctive technique for obtaining surface temperature information at the scales. For instance, Cowtan and Way [26] provided a hybrid form of the global surface temperature using satellite data. They reconstruct SAT series covering about 16 % of the world including parts of Africa, South America, and the Polar Regions with result showing increase from 0.046 to 0.119 °C per decade between 1997 and 2012.

Dara et al. [27] assessed the LST in parts of the Chenab basin, Jammu and Kashmir. They used Landsat imageries (ETM+ and TM), and Terra ASTER data to estimate the influence of the variation in spatial resolution of Landsat-based generated LSTs. Additionally, radiometric resolution impact was compared between the LST images generated from the ETM+ and ASTER. It was concluded that the spatial resolution influence has been assessed effectively because both ETM+ and ASTER systems have similar characteristics.

Koner [28] studied the coast and near-coast of California, Bengal, and Chesapeake within the Pacific, Indian, and Atlantic Oceans respectively. The study concentrated on the quality and availability of swath-processed day SSTs from MODIS-AQUA. Besides the in-situ validation based on iQuam (in-situ SST quality monitor), indirect validation was equally conducted by comparing diverse SST products.

III. Materials and Methods

A literature search was conducted to gather research materials that are relevant to this study. This was done through electronic records, with a specific focus on monitoring climate change using satellite-observed Earth's Surface Temperature. Through specific search terms, the researcher collected papers published between 2013 and 2022. The search terms include 'monitoring climate change', 'satellite remote Sensing' AND 'Earth's Surface Temperature'. Furthermore, search terms and criteria for the inclusion/exclusion of papers were formulated.

Some research materials were eliminated as they are not related to the subject matter while others that are connected to the topic were included with regards to their significance, reliability, and influence. The included papers were read thoroughly, reviewed in full detail, and examined. Subsequently, the significant information were summarized with respect to the search terms used in gathering the papers.

IV. Results and Discussion

4.1 Global Temperature Trend

Anthropogenic influence such as the combustion of fossil fuel and the destruction of forest resources is seriously influencing global environmental change. It has caused the concentration of atmospheric GHGs to increase [2, 29] by about 40 per cent since the industrial era [30]. The current estimate of CO_2 concentration in the atmosphere is roughly 415 ppm [31], which is 54 per cent higher than the pre-industrial level of 270 ppm [32]. The consequence of this high concentration of CO_2 and other GHGs is contemporary global warming [33, 34-36] or a rise in global temperature (see figure 1). The knowledge of this development was initially acquired through analysis of anomalies in near-surface air temperature time-series from weather station data. In other words, measurement is typically conducted against a reference value.

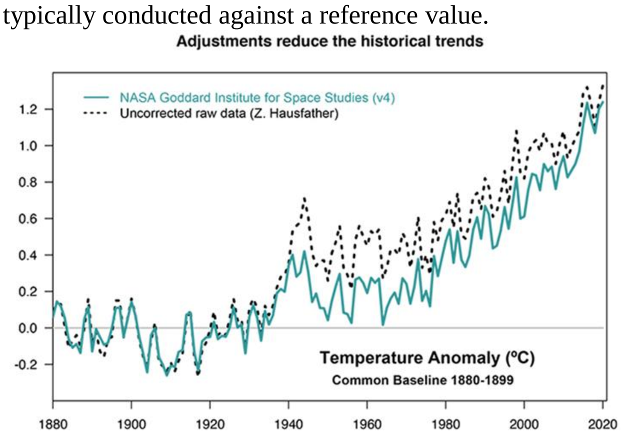

Figure 1. Global temperature trend. Source: Madge [37]

Apart from the weather forecast, the Earth's surface temperature measurements form the core of climate change assessment [6, 38]. It is a major biophysical variable that impacts virtually all biotic and several abiotic processes [39]. Hence its observation is important for scientific discussions and political decisions.

The global average temperature is rising since industrialization and it is likely to increase by approximately 5 °C at the end of the 21st century if urgent action is not taken to sustain the present GHGs emission rates. The global temperature observations may have begun in 1850; the reconstructions of earlier temperatures based on climate proxies however suggest that the highest temperature over a long period may occur in current years [40]. Also, the global yearly mean temperature between 1880 and 2021 based on NOAA data shows that 2016 is the warmest year among the ten warmest years in the record (see table 1).

Table 1. The 10 warmest years between 1880 and 2021

Rank	Year	Anomaly °C	Anomaly °F
1	2016	1.00	1.80
2	2020	0.98	1.76
3	2019	0.95	1.71
4	2015	0.93	1.67
5	2017	0.91	1.64
6	2021	0.84	1.51
7	2018	0.83	1.49
8	2014	0.74	1.33
9	2010	0.72	1.30
10	2013	0.68	1.22

Source: NOAA National Centres for Environmental Information [41]

Though all the pledges made under the 2015 Paris agreement may be redeemed, global warming will still go above 3 °C at the close of the century [42]. The global mean temperature record (i.e. land plus ocean surfaces) from various autonomously created datasets shows decadal warming at 1.09 °C between 2011 and 2020 [43]. Another data computed by a linear trend indicates warming at 0.85 °C from 1880 to 2012, and about 0.72 °C from 1951 to 2012 [see 44].

Generally, the analyses of surface temperature from several autonomous organizations across the world show a similar upward trend. The independent computation of average yearly global temperature is carried out mostly by NASA and NOAA with minor variances in their results. The reason for the variance is that NASA's computations are inferred to account for Polar Regions, which is characterized with sparse distribution of stations whereas NOAA profoundly depends on the polar station data [45].
The IPCC report indicates that the increase in LST is quicker compared to SST. Their averages were 1.59 °C and 0.88 °C respectively between 1850–1900 and 2011–2020 [43]. The linear rise in temperature between 1980 and 2020 for land and sea surface temperature has increased from 0.18 °C to 0.20 °C per decade [46]. The influence of LULC change on this rising temperature is confirmed, yet, it is unlikely to be above 10 per cent (see [40]). Also, the mean global temperature change by decades indicates persistent climate change with every previous year indicating higher surface temperature than any prior 10 years since 1850. Recent records show that 2012-2021 present the highest temperatures in the instrumental temperature record. Beginning from 2015, every year is warmer than any year before it since 1850 [see 47]. Also, a decadal estimate indicates a 40 % probability of a year exceeding 1.5 °C between 2021 and 2025 periods [see 48]. Similarly, the datasets gathered by the World Meteorological Organization (WMO) show the mean global temperature of almost 1.11 (± 0.13) °C in 2021 exceeding the pre-industrial levels. This makes 2021 the 7th sequential year from 2015 to 2021 when the global temperature has been more than 1°C higher than the pre-industrial level. However, the global temperature was somewhat repressed in 2021 as a result of the cooling influence of La Niña in the tropical Pacific.

4.2 Observation of the Earth's Surface Temperature

The rising temperature affects the global economy and humankind. For instance, it culminated in the loss of about 302 billion working hours in 2019, which is 52 per cent more than in 2000 [49]. Thus, an accurate assessment of the spatiotemporal distribution and variability of surface temperature is essential for planning. Meteorological devices located at some stations are traditionally used for obtaining air temperature (Ta) information. This information is normally extended to other places where devices are not positioned using various spatial interpolations. In this case, discrete data based on a group of sample points serve the purpose of input data for predicting the value of unknown points through mathematical methods. Many researchers have employed different spatial interpolation methods for extending the value of surface temperature across the globe including simple regression (see [50]), spline (see [51]), and geostatistics such as kriging (see [52]). Regrettably, the outcomes of interpolation do not show the complete spatial variability of the air temperature. Also, these interpolation approaches would create large errors, especially for different underlying surfaces [53]. Thus, meteorological re-analysis products are preferable as they afford high temporal and finer spatial resolutions as compared to other gridded data products of air temperature. Yet, temperature values derived from re-analysis are still modelled and not observations [54].

Generally, surface temperature measured from in-situ devices is highly reliable and accurate at a local scale for climate studies. The case is however not the same for regional or global scale. The reason is that in-situ stations are sparse and unevenly distributed [55, 56], and thus lack representative measurements from certain areas of the Earth [57, 58]. Hence there can be bias in the temperature estimation [59]. Besides, variations in topography and station's location geometry frequently affect the interpolation accuracy [60, 61]. However, evidence in the literature show that satellite remote sensing provides a consistent way for large-scale air temperature estimation with more details. For instance, Liu et al. [62] used remote sensing to evaluate the air temperature over Northwest China. They compared the results with the in-situ observations, which indicate an R^2 of 0.77 and RMSE of 0.31K.

Remote sensing uses different platforms and sensors to achieve large-scale work with cheap and faster results in contrast to the traditional technique. Some of the recently used satellite products for retrieval of surface temperatures through TIR measurement are presented in table 2. Thermal Infrared (TIR) remote sensing captures the radiation emitted from the ground to estimate the surface temperature. It is noteworthy that satellite-based temperature observations are extrapolations of the atmospheric temperature at different heights over land and sea surfaces.

Table 2: satellite products for retrieval of surface temperatures

Satellites Sensors	Authors
AVHRR	[63]
MODIS	[64, 65]
Landsat (TM, ETM+, OLI/ TIRS)	[66-68]
ASTER	[69, 70]
VIIRS	[71-74]
AASTR	[75-77]
AIRS	[78]
SEVERI	[79, 80]

In a real sense, satellites measure radiances in different wavelength channels and not temperature directly. The radiances are then mathematically inverted to get indirect temperature inferences. By and large, satellite-based measurement of Earth's surface temperature can be done by the observations of LST and SST as discussed in the following subsections.

4.2.1 Land Surface Temperature

LST is the land radiative temperature generated from thermal infrared radiation that is emitted by the Earth's surface. It is essentially a measure of the Earth's surface hotness in a specific place. Consistent LST assessments are very important for a sufficient comprehension of surface energy budget and land-atmosphere relations [81-84]. The reason is that it is one of the fundamental parameters of the processes in the physics of land-surface. Unfortunately, spatiotemporal inconsistency of LST at the regional scale is impacted by factors such as vegetation cover properties, surface thermal characteristics, topography, incoming solar energy and climatological conditions. Thus, it is imperative to develop quantitative models that may define the link between the spatiotemporal changeability of LST and the cause of the change.

Satellite sensors can be effectively and consistently used to measure LST globally. This can be achieved from two broad types of sensors including TIR and microwave (MW). TIR remote sensing is important for measuring temperatures and energy fluxes [85] as they produce higher spatial resolution and retrieval accuracy. For instance, Balewa and Korme [86] evaluated the spatial-temporal patterns of LST over Bahir Dar city between 1987 and 2017 using Landsat imageries. The result indicate an increase of the average temperature from 34.5 °C in 1987 to 37.57 °C in 2002 and declined to 34.57 °C in 2017.

Infrared-based observations are constrained to clear-sky situations only. Therefore, MW remote sensing is preferable due to its potential to remove atmospheric contamination [see 87]. However, LST retrieved from passive microwave under certain circumstances may accumulate larger uncertainties as compared to the infrared-based estimates. Thus, both TIR and MW satellite data are usually integrated to achieve all-weather high-resolution LST satellite products [88].

The MODIS-LST is a more suitable data for diverse uses [89]. It appears to be the most commonly used satellite data for Earth's surface temperature estimation as demonstrated by many studies (e.g., [90-96]). However, many other available products similar to the MODIS-LST have been successfully utilized (see table 2). Normally, LST is not numerically equal to surface Ta [97]. Ta at the Earth's surface cannot be estimated from remote sensing data accurately. But, LST has a strong relationship with Ta [98] and serves as a source of data for Ta retrieval over a region or large area [99, 100]. This can be achieved by using a statistical method, temperature-vegetation index, and energy-balance modelling.

4.2.2 Sea Surface Temperature

Sea Surface Temperature is a vital variable used for many climatology and ecology applications. Being at the ocean-atmosphere boundary, SST is essential for interchange of heat, moisture, momentum, and gases between the ocean and atmosphere [101, 102]. Measurement results indicate that SST in all the oceans has been rising in the last 5 decades, which is similar to the near-surface air temperature. The regional inconsistency of SST is connected with that of other climate variables, like rainfall. These have resulted in enhanced knowledge about the significance of the oceans in global climate.

The in-situ approach has been used for the measurement of SST with high precision for many decades. But, the application of satellite-based approach to examine global temperature trends now predominates. Recent research provides a comprehensive outline of the modern improvement in remote sensing utilization of SST measurements (see [103]). SST can be generated from both infrared (IR) satellites [104] and microwave observations with different and complementary properties. Nonetheless, the IR-based measurements are affected by aerosols and cloud cover persistence because wavelengths cannot measure the surface through clouds. Accordingly, measurements from the passive microwave sensors are essential substitutes for Infrared measurements because they are not affected by non-precipitating clouds or aerosols. Additionally, integration of Infrared and microwave SST data with in situ data provides a method for generating global temperature fields accurately (e.g., [105]).

V. CONCLUSION AND FUTURE SCOPE

Although the ground-based approach for temperature observations is highly accurate, it has a major constraint — its view is limited. Each piece of surface-based data may be joined to produce large maps; the data is a representation of one location. Additionally, surface observations are comparatively dense in certain regions while they are scanty in others like Africa, portions of South America, and the oceans. This review has shown how satellite remote sensing offers a distinctive vantage point for acquiring the information needed to predict and investigate the weather and climate. More importantly, because satellites are orbiting the planet for years, they can make consistent measurements over long periods. SST products derived from satellites can complement the in-situ network, offering finer and more comprehensive spatiotemporal sampling.

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