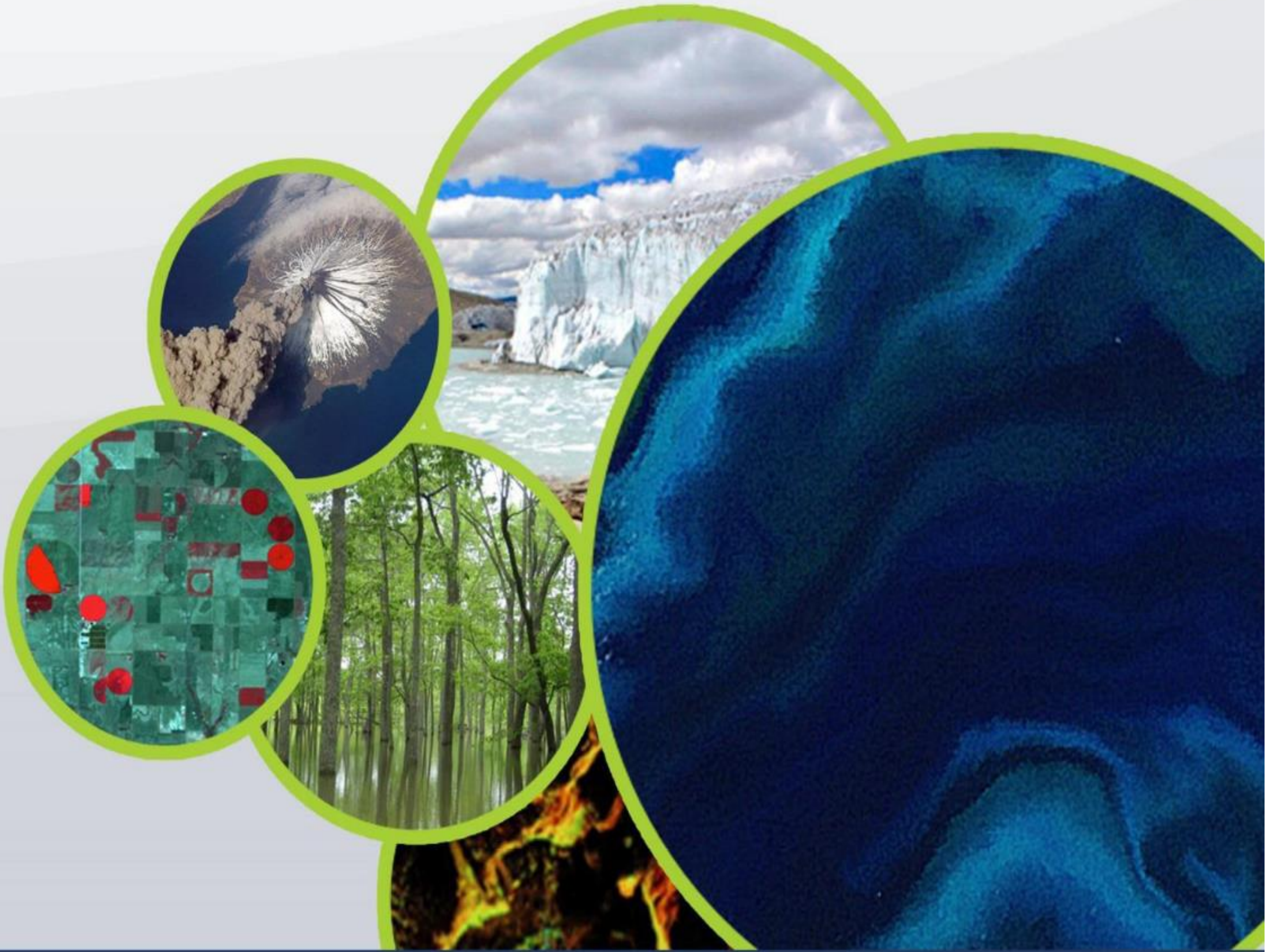
Committee on Earth Observation Satellites



Current and future sea surface temperature missions: Towards 2050

White Paper of the CEOS Sea Surface Temperature Virtual Constellation

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Executive Summary

Sea surface temperature (SST) is a key variable for understanding, monitoring and predicting interactions between the ocean and the atmosphere. Its influence covers a wide range of temporal (from seconds to multi-decadal) and spatial (from a few microns to ocean scale) resolutions. It has a direct or indirect impact on a wealth of application areas.

The provision of daily maps of SST is now a mature and sustained service. Activities are coordinated by the Group for High Resolution SST (GHRSST) and the Committee for Earth Observing Satellites (CEOS) SST Virtual Constellation (SST-VC). This white paper sets out a basis for optimising components of the SST-VC.

Key challenges related to provision of Fiducial Reference Measurements (FRM) and data management are highlighted. One urgent need, for sustained continuity of passive microwave SST determination using a 6.9 GHz channel in an operational (redundant) context, is identified.

Please reference this document as:

CEOS SST-VC (2020), Current and future sea surface temperature missions: Towards 2050, available from www.ceos.org, pp 33.

1 Introduction

1.1 Purpose and scope

The purpose of this document is to provide guidelines for development and optimisation of the Sea Surface Temperature (SST) satellite constellation and its individual missions over the next 25 years to meet its major operational and science objectives. Maximizing the synergy between missions and improving the efficiency of the global SST constellation is essential as no one mission will satisfy all scientific and operational needs.

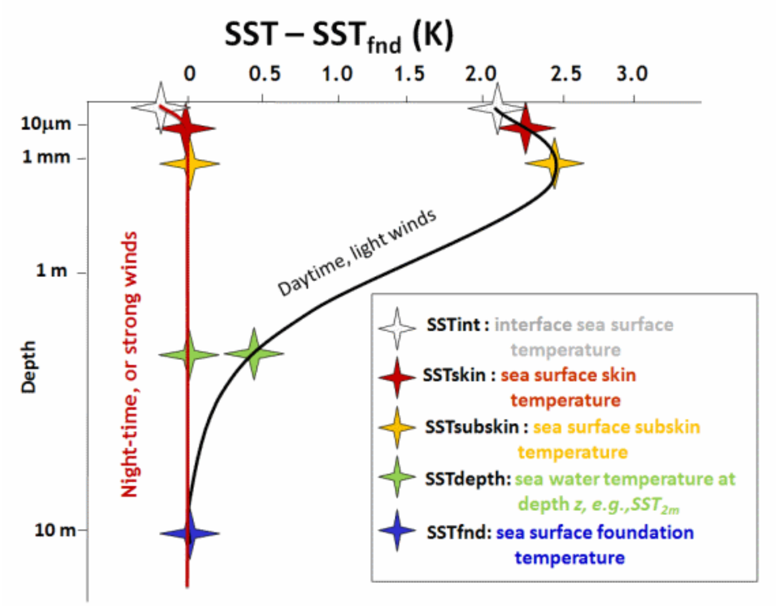
The document is built on the strong heritage from the use of SST missions developed by space agencies. A review of the first 50-years of remote sensing of SST can be found in Minnett et al. (2019). This document does not attempt to document all SST requirements since the agencies themselves work directly with their user communities to define the specific requirements for their respective missions. Instead, this document gathers in one place the needs of various user communities, indicates which known options (instrument, orbit, etc.) best satisfy those needs, and provides a summary table of SST requirements across different application areas. As such the document focuses on the main components of the constellation and not on the generation of SST products themselves, which is coordinated by the Group for High Resolution SST (GHRSST). Ongoing research and development challenges in this area are summarised in O'Carroll et al. (2019).

The document is organised as follows:

- Section 1: Introduction to SST, purpose and scope of the document
- Section 2: Summarises and collates user needs for SST
- Section 3: Gives an overview of SST and its measurement systems
- Section 4: Details the current SST constellation
- Section 5: Describes necessary activities necessary to maintain and enhanced SST constellation
- Section 6: Summary and conclusions
- Section 7: References

1.2 What is SST?

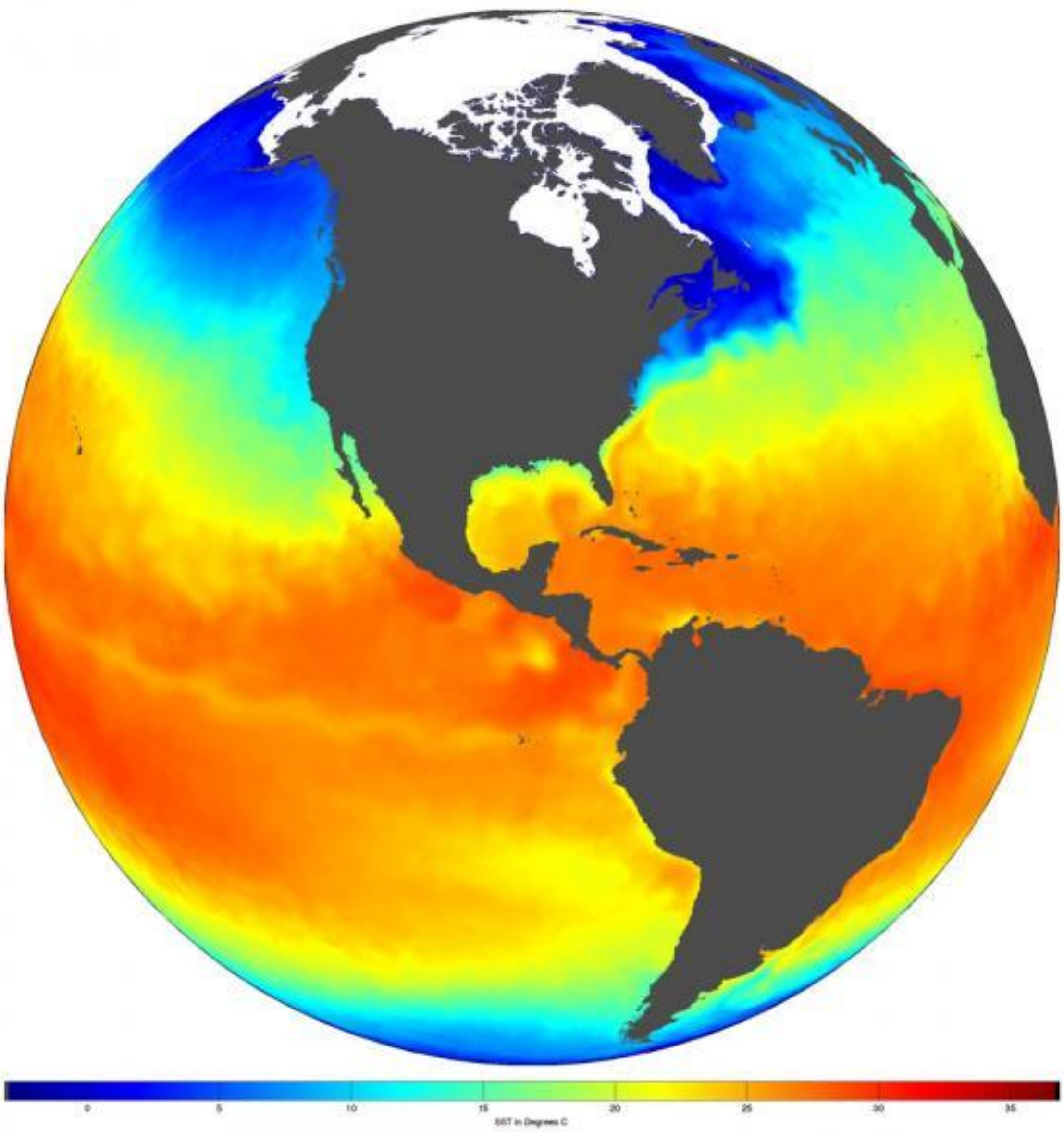
SST is a challenging parameter to define precisely as the upper ocean (~10 m) has a complex and variable vertical temperature structure that is related to ocean turbulence and air-sea fluxes of heat, moisture and momentum. A theoretical framework is therefore required to understand the information content and relationships between measurements of SST made by different satellite and in situ instruments, especially if these are to be merged together. The definitions of SST developed by the GHRSST Science Team achieve the closest possible coincidence between what is defined and what can be measured, considering current scientific knowledge and understanding of the near surface thermal structure of the ocean.



The figure above presents a schematic diagram that summarises the definition of SST in the upper 10 m of the ocean and provides a framework to understand the differences between complementary SST measurements. It encapsulates the effects of dominant heat transport processes and time scales of variability associated with distinct vertical and volume regimes of the upper ocean water column (horizontal and temporal variability is implicitly assumed).

1.3 The role of SST in the Earth System

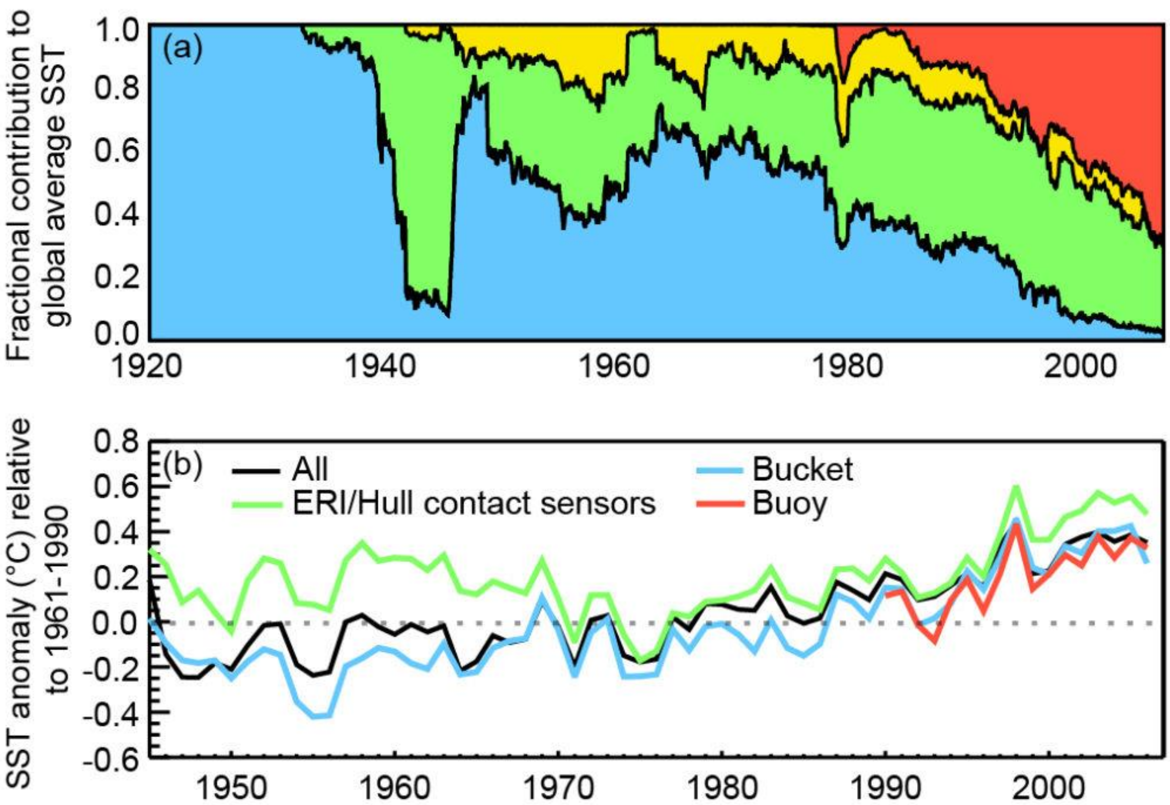
SST is a key variable in both oceanographic and atmospheric studies. It is the lower boundary condition for atmospheric numerical models, essential in their ability to support accurate forecasts. For example, warm ocean temperatures feed hurricanes, and thus accurate knowledge of SST (and the heat potential under the surface) helps forecast their path and intensity. Ocean temperatures, as reflected in SST, influence fish feeding and reproductive behaviour. Temperature 'fronts', where there is a strong gradient in temperature (often extending several tens of metres vertically), encourage the growth of plankton and thus attract fish to feed on the plankton, or on other fish; at such fronts, fish display reproductive behaviour such as changing vertical position and forming schools. Ocean temperatures affect corals, and SST is used to evaluate coral bleaching. Eddies are the storms of the sea carrying trapped ocean properties, and they can be recognized in SST as well as in sea surface height. SST is a central factor in studies of air sea fluxes, and as an indicator for interannual variability as well as climate variation. The onset of the well-known El Niño / La Niña cycles can be easily recognized in SST.



SST is a critical parameter for weather and climate research as well as oceanography. Indeed, SST is one of the oldest and best documented Essential Climate Variables (ECV). The global SST distribution is directly related to the sources and sinks of heat at the surface. The factors which contribute to an increase in SST are incoming shortwave radiation from the Sun, incoming longwave radiation from the atmosphere, conduction of warmer air toward cooler water, gain of latent heat through condensation and movement (advection) of warmer water into the region. The factors which contribute to a decrease in SST are the emission of longwave radiation from the surface to the atmosphere, conduction of warmer water toward cooler air, loss of latent heat through evaporation and movement (advection) of cooler water into the region. Naturally, the SST will increase if the net effect of these processes is such that the ocean surface receives more energy than it loses.

1.4 Measurement of SST over time

Records of SST date back to the 1850's with the more recent period (1982 onwards) being enhanced with SST from satellites, which provide a truly global perspective. SST can be measured by several different methods with traditional methods involving temperature sensors either located on a ship's hull or water intake, or lowered from a ship (or measuring temperature from a bucket of seawater). The figure below, showing part of this variability over time, is taken from the IPCC 5th Assessment WG-I Report (IPCC, 2013). Here blue represents SST observations from buckets, green ship engine room intake (ERI) and hull contact sensors, yellow represents unknown sensors and red drifting and moored buoys.



Over the past few decades other platforms became available: not only satellites but also drifting buoys, gliders, Argo floats, etc. Each technique has strengths and limitations. For example, satellites measure SST indirectly, by measuring the amount of radiation emitted by the sea surface at different wavelengths, either in the thermal infrared or the microwave part of the spectrum. Ship engine intake SST may be biased warm due to contamination from the ship's heat, or cold because it measures at depth. Different methods not only have different accuracies but sample the "surface" differently, requiring clarification of their depth sampling characteristics as well as an understanding of the vertical profile of temperature near the surface. A summary of the sampling and accuracy properties of various methods is given in the following table (updated from Robinson and Donlon, 2003), where SST_{skin} denotes skin SST and SST_{depth} denotes SST at a defined depth.

Instrument	Spatial	Time sampling	Depth sampling	Performance sampling
In Situ				
Research vessel	Precise; very sparse	Continuous	SST_{depth} at many z; SST_{skin}	0.1 K
Buoy: hull mounted thermistor or PRT	Distributed; sparse	1 hr - 1 day	SST_{depth} at z = 0.3 - 1.5 m	0.2 K
Voluntary observing ship reports (VOS)	Track-limited; fairly sparse	1 day	SST_{depth} at z = 1 - 7 m	0.5 - 1.0 K
Ship-of-opportunity, autonomous sensors	Track-limited; sparse	1 hr	SST_{depth} at z = 1 - 7 µm; SST_{skin}	0.1 - 0.2 K
Satellite				
Polar orbiting IR radiometer	Global; 1 km, cloud-limited	12 hr; cloud-limited	SST_{skin} (z ~ 10 µm)	0.1 - 0.5 K
Polar-orbit microwave radiometer	Global; 25 km	12 hr - 2 days	SST_{skin} (z < 1mm)	0.5 - 1.0 K
Geostationary orbit IR radiometer	45S - 45N; 2-6 km	10 - 30 min; cloud-limited	$SST_{subskin}$ (z ~ 10 µm)	0.3 - 0.5 K

1.5 CEOS SST-VC and GHRSST

The Group for High Resolution SST (GHRSST) grew out of a Pilot Project of the Global Ocean Data Assimilation Experiment (GODAE), 1997-2008. It is composed of an international Science Team of researchers and operational practitioners with the aim of coordinating research and operational developments in satellite-derived SST worldwide. It is organized into Technical Advisory Groups and Task Teams focused on particular problems or activities. Data processing through Regional and Global Data Assembly Centres, combining satellite and Numerical Weather Prediction (NWP) fields in common data formats for ease of access and analysis.

The CEOS SST-VC serves as the formal link between GHRSST and the broader CEOS community. At the highest level, the SST-VC provides a means for CEOS to present its needs and requirements to GHRSST and for GHRSST to present its needs directly to CEOS, the global community of space agencies. In addition, there are several thematic connections between GHRSST and CEOS that take place at the working group level (e.g. between the GHRSST Climate Data Record Technical Advisory Group and the CEOS Working Group on Climate). GHRSST provides an existing vibrant and fully coordinated community from which CEOS can directly benefit.

2 User Needs for SST

2.1 Summary of SST application areas

The vast array of applications that benefit from satellite-based SST products cover a wide range of temporal and spatial scales. Time scales associated with ocean processes include sub-hourly, diurnal, multi-day, intra-seasonal, seasonal, annual, interannual, decadal, and longer-term trends. Associated spatial scales cover a large range from a 100 m up to global scale.

Specific processes and phenomena include:

- The diurnal warming and cooling cycle
- Surface expression of internal waves
- Regional air-sea interaction processes including synoptic events, intra-seasonal processes (especially in the tropical and coastal regions), fluxes near fronts, and convection and mixing in mode and deep-water formation regions
- Open ocean fronts; regional to basin-scale fluxes of heat, evaporation, and precipitation associated with the seasonal cycle, trade wind, and monsoon regimes
- Seasonal to interannual basin and global-scale processes such as El Niño Southern Oscillation (ENSO)
- Decadal variability such as the Pacific Decadal Oscillation (PDO); and global change-induced trends.

For the coastal regions (and in lakes) applications include upwelling, sub-mesoscale eddies and fronts, jets and filaments, and the impact of biogeochemical, pollutant and river inflow processes on both dynamics and optical properties. In many cases the effects of coastal processes extend well offshore and influence open ocean conditions. In addition to covering the full range of spatial and temporal scales, the phenomena and processes have associated space/time signatures and amplitudes that vary regionally.

Sea Surface temperature (SST) is therefore of interest for many user communities, including:

- Aquaculture
- Atmospheric research
- Aviation
- Climate variability and change
- Coastal users (recreational and coast guard)
- Commercial shipping
- Coral reef protection
- Ecosystems
- Fisheries
- Habitats
- Hazardous spill mitigation
- Hurricane research
- Media (TV, Film, News)
- Naval operations

- Ocean forecasting
- Ocean research
- Power plant outflow monitoring
- Recreational boating
- Recreational fishing
- Sailing and Racing
- Search and Rescue
- Seasonal Forecasting
- Teleconnection studies
- Tourism
- Weather Forecasting

In the next section, we present some example applications across five domains. This review of applications is not intended to be comprehensive and instead is intended to highlight the diversity of the many applications of SST.

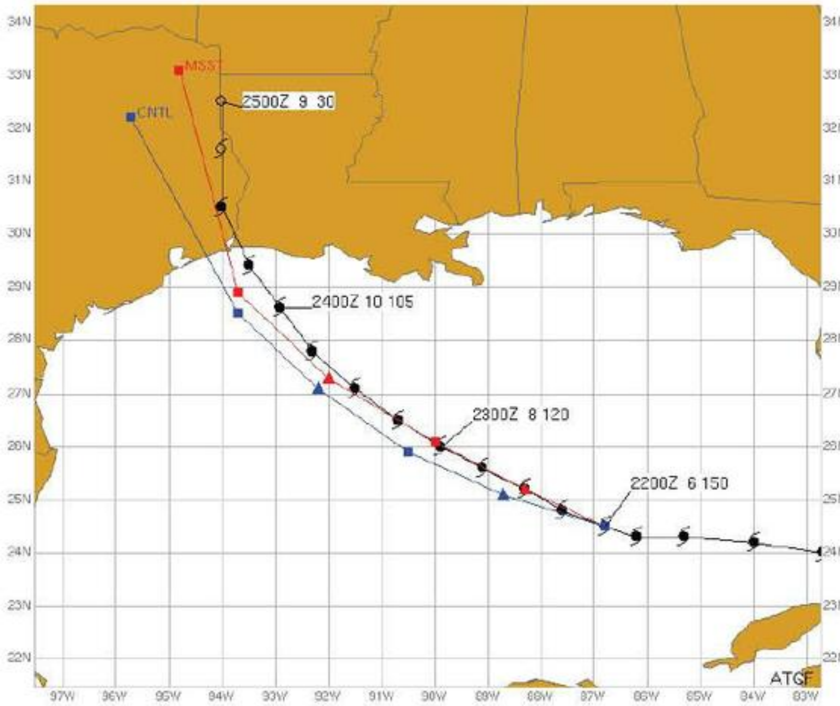
2.2 Specific applications of satellite SSTs

2.2.1 Operational Forecasting

Knowledge of the three-dimensional structure of the oceans requires the combined use of satellite observations, in-situ observations and ocean numerical models through assimilation techniques. Due to limitations in coverage regarding the in-situ measurements, and the systematic errors in Numerical Weather Prediction (NWP) models, observations are required for SST, radiative short-wave and long-wave fluxes. SST (and sea-ice) in particular affect the behaviour of the overlying atmosphere and vice versa and so SST (and sea-ice) provide boundary conditions for NWP and Numerical Ocean Prediction (synoptic meteorology/oceanography). Together with near-surface wind vectors and ice cover observations, these parameters can be used for the modelling of heat and momentum exchange. Such a coherent set of information can then be used for characterizing the ocean surface and the energy fluxes through it. SST as a boundary condition is becoming more important as international centres are now moving to coupled Ocean-Atmosphere model systems.

NWP uses current weather conditions as input into mathematical models of the atmosphere to predict the weather. Consequently, NWP systems need to be regularly updated with the latest SST and sea-ice observations to ensure an accurate forecast. Daily analyses of both SST and sea-ice extent and concentration are required by many operational NWP systems. SST affects the formation and subsequent evolution of tropical cyclones, convection and thunderstorms, cyclogenesis, sea fog and sea breezes. It can also help upper air forecasters at the World Aviation Forecast Centre to monitor areas more likely to develop Cumulonimbus activity which can produce significant threat to aircraft.

A comparison of two SST tracks forecasts for Hurricane Rita, on 22 September 2005 is shown in the following figure (Gentemann, 2019). The black line and symbols denote the actual storm track. The difference between the two tracks is the one indicated by the red line uses an SST analysis that has incorporated microwave SST data.

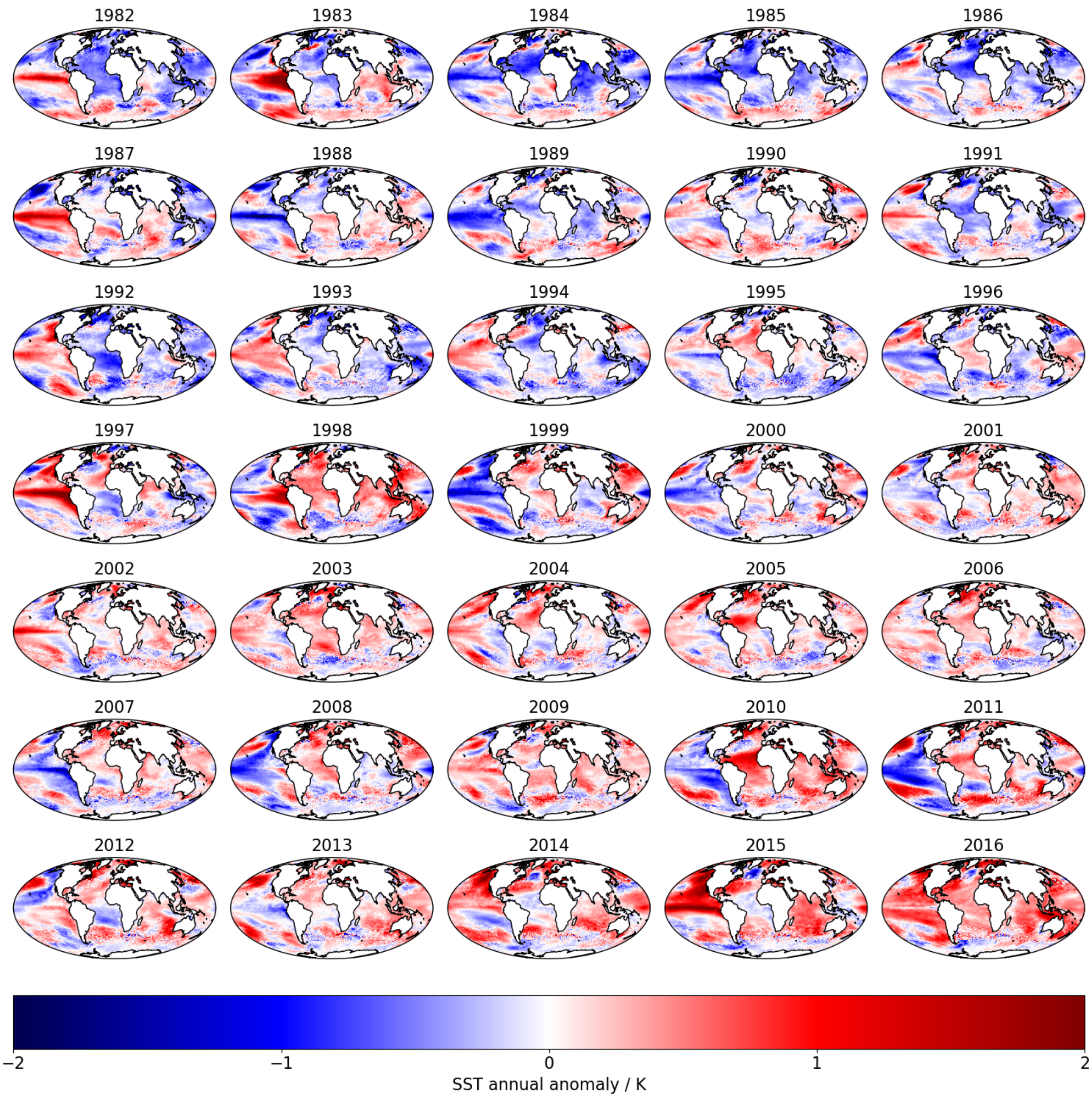


Operational numerical prediction ocean model systems providing forecasts of currents, temperature and salinity fields are used for a variety of operational applications including coral reef management, tide predictions, marine sanctuary and estuary management, diving operations, naval applications, oil and chemical spill drift forecasts, search and rescue operations, offshore oil drilling operations, cable laying and ship routing. Today, a dozen numerical ocean modelling systems routinely operate in the nine countries that participated in the Global Ocean Data Assimilation Experiment (GODAE) (Dombrowsky et al. 2009). They range from regional high-resolution systems that include tides, to global eddy-resolving systems that provide estimates of the ocean state, updated regularly (from daily to monthly), providing forecasts from a few days to one month ahead (Dombrowsky et al. 2009; https://www.godae-oceanview.org/).

Several operational centres routinely issue seasonal forecasts of the Earth's climate for timeframes from a month to a year using coupled ocean-atmosphere models, which require near-real-time knowledge of the state of the global ocean (Balmaseda et al. 2009; MacLachlan et al., 2014; Hudson et al., 2017). Seasonal forecasting systems are based on coupled ocean-atmosphere general circulation models that predict SSTs and their impact on atmospheric circulation. The aim of seasonal forecasts is to predict climate anomalies (e.g. temperature, rainfall, frequency of tropical cycles) for the forthcoming seasons (Balmaseda et al. 2009). The strongest relationship between SST patterns and seasonal weather trends are found in tropical regions (Beggs, 2010).

2.2.2 Climate Monitoring and Research

Teleconnection patterns relate SST anomalies with anomalies in ocean currents, atmospheric circulation, and respective rainfall anomalies. SST related teleconnections include the El Niño Southern Oscillation, the Madden-Julian Oscillation and with implications for the Monsoon, the Arctic/North Atlantic Oscillation, and rainfall over large parts of the globe. Such large-scale climate anomalies have economic consequences for agriculture and fishing and determine the severity or frequency of natural hazards such as tropical cyclones, droughts, floods and fires.

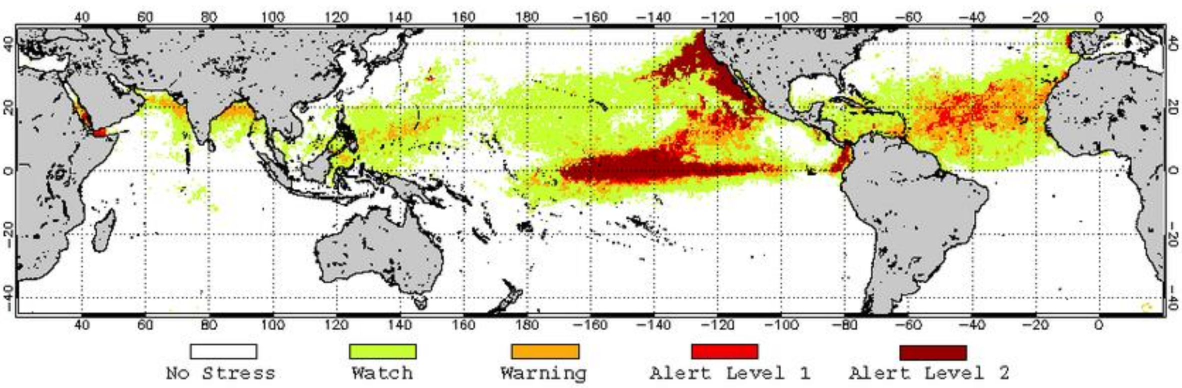


In situ observations of subsurface ocean temperature have been used to monitor long-term changes in the global SST since the late 1800's. However, these have been limited spatially, and available SST analyses of in situ data are of relatively coarse resolution, typically monthly on a 5 degree grid (e.g. HadSST4, ERSST v5). Since 1982, SST observations from infrared radiometers on polar-orbiting satellites have also been used to monitor multi-decadal trends (e.g. Reynolds et al., 2007). However, satellite SST data alone have not been used as a major resource for estimating climate change because of their strong time-varying biases which are hard to completely remove. Recent efforts by the ESA Climate Change Initiative (CCI) SST Project (http://www.esa-sst-cci.org) have produced a > 30 year satellite record of consistent SST at high spatial resolution (~ 5 km) with target accuracy of 0.1°C even in periods of elevated stratospheric aerosol. Annual-mean sea surface temperature anomalies for thirty-five calendar years form the SST_CCI v1.1 dataset is shown in the previous figure (with permission, CC-BY 4.0, Corlett, GK, 2019, http://doi.org/10.1038/s41597-019-0236-x).

2.2.3 Marine biology and Fisheries

Marine biology applications are especially interested in classifying habitats using SST; thus, they need information about fronts, coastal areas, and upwelling regions, and the seasonal and inter-annual variability of these features. They require information on effective feature resolution and need to be warned of possible pitfalls in interpretation of areas with resolution changes. They need to be alerted to or provided with information concerning clouds, the possible linkage of clouds to fronts, as well as explanations about the technical cloud clearing information. Biology users might need some introduction about SST measured from space, and to be pointed to the concept of foundation temperature. They might benefit from using SST together with salinity or ocean colour.

Coral bleaching results from the loss of symbiotic algae, known as zooxantheallae, from coral tissues during times of stress, often due to temperatures higher than the coral colony's tolerance level (Glynn, 1993). NOAA's Coral Reef Watch[1] Program's satellite data provide current reef environmental conditions to quickly identify areas at risk for coral bleaching. Continuous monitoring of sea surface temperature at global scales provides researchers and stakeholders with tools to understand and better manage the complex interactions leading to coral bleaching. When bleaching conditions occur, these tools can be used to trigger bleaching response plans and support appropriate management decisions. An example of NOAA Coral Reef Watch 50 km Bleaching Alert Area (based on satellite SST data) for October 1997 is shown below (Eakin et al., 2014)



[1] http://coralreefwatch.noaa.gov/satellite/index.html

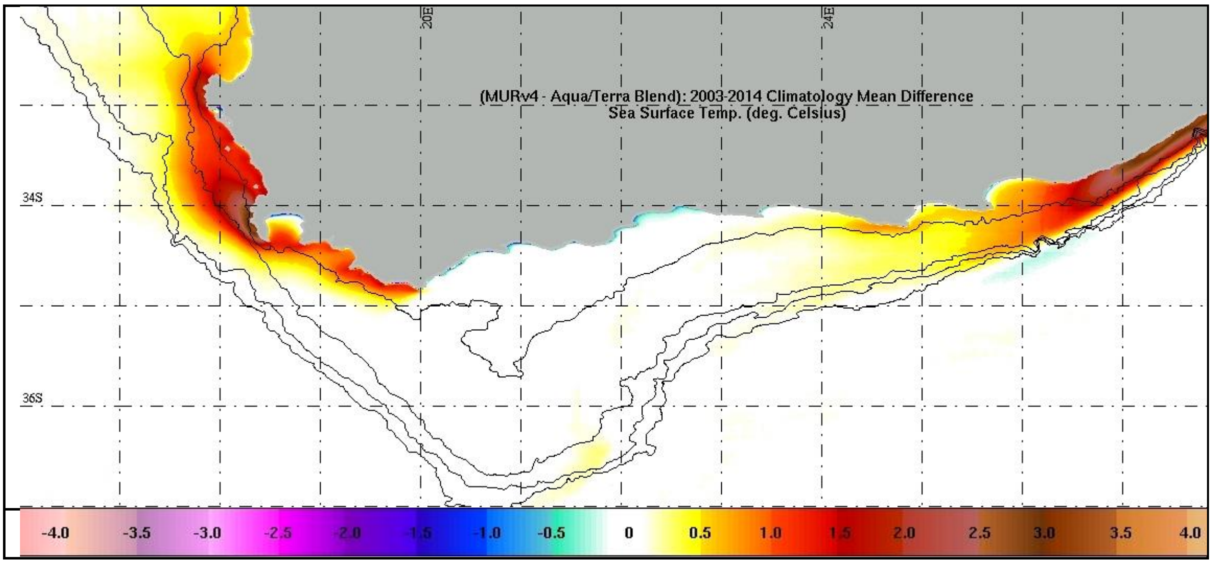
Different species of fish are known to be sometimes found at certain temperature ranges. Near real time SST maps derived from satellite data can help inform where good fishing locations might be (e.g. http://www.fishtrack.com and https://www.satfish.com). For example, SST is one of the most important environmental parameters used by longline fisheries to locate good fishing areas (Beverly, 2011). Pelagic fish such as albacore tuna (*Thunnus alulunga*), bigeye tuna (*Thunnus obesus*), skipjack tuna (*Katsuwonus pelamis*), striped marlin (*Tetrapturus audax*), swordfish (*Xiphias gladius*), and yellowfin tuna (*Thunnus albacores*) have preferences for waters with certain temperature ranges. The importance of ocean temperature is true for both horizontal and vertical temperature ranges, but longline fishermen are more interested in horizontal, or surface, temperatures when searching for fish (Beverly, 2011).

Frontal zones are also interesting to the fishing industry because baitfish and predator fish often accumulate near them, often on the warm side of the frontal zone. In this case, the location of the front, rather than absolute temperature, is of greater interest.

2.2.4 Coastal and Inland waters

The application of SST products in coastal areas presents several issues. Coastal areas such as those off California and Peru have extended periods of times of cloud cover. Infrared sensors provide coverage at ~1 km but cannot retrieve SSTs though clouds. Microwave sensors have all-weather capability (except for significant rain events) but are limited by their >25 km resolution. This coarse resolution can be limiting in applying SSTs in coastal areas where major upwelling events can occur in areas much closer than 25 km. Cloud clearance and uncertainty information is particularly important to coastal and inland waters SST applications. Regional products have been developed that combine data from multiple sensors to produce reliable daily average SSTs at the 1km resolution required to study frontal structures in coastal upwelling zones. Although the combination of IR SST data from multiple sensors within the Earth Observation constellation significantly reduces the undesirable data gaps cause d by cloud presence, seasonal variability in cloud cover will still considerably reduce successful SST retrievals.

A global 1 km resolution gap-free SST analysis is available from NASA JPL in the Multi-scale Ultra-high Resolution (MUR) daily SST analysis (https://mur.jpl.nasa.gov). This analysis has been assessed in highly dynamic coastal regions such as the Peruvian Coastal Upwelling System (Vazquez-Cuervo et al., 2013) and Benguela Coastal Upwelling System.



The figure above illustrates the mean difference between MUR and valid SST retrievals from a daily average 1km MODIS Aqua/Terra product over a 12 year period. Less than 0.1 °C differences between the products indicate that MUR effectively captures highly variable frontal zones associated with the central Agulhas Bank and the edge of the Agulhas Current. Cloud clearance and uncertainty information is particularly important to coastal and inland waters SST applications. The rigorous application of the standard SST cloud identification tree often compromises the successful retrieval of SST in upwelling zones and this is reflected in MUR data as a warm bias. Regional cloud identification algorithms developed by the GHRSST user community has successfully demonstrated an improved retrieval of SST values within the Benguela upwelling cells. Cloud clearance and uncertainty information is particularly important to coastal and inland waters SST applications. For this, coastal applications will benefit from better use of existing ultra-high resolution IR data, such as that from Landsat, in addition to a new generation of high resolution infrared radiometers.

2.2.5 Recreational

Forecasts of ocean currents from general ocean circulation models can be very helpful to recreational boaters. Nowcasts of ocean currents can also be obtained from combining information about sea surface height anomaly from satellite altimeters with satellite SST data (e.g. http://oceancurrent.imos.org.au).

Observations and forecasts of SST can be helpful to recreational users who expect to immerse themselves in the ocean. However, as these in-water human activities generally occur in close proximity to the coast, it would be helpful to be able to quantify how accurate the high-resolution satellite SST analyses are within a few kilometres of land. Currently, commercial surfing information web sites such as Surfline (http://www.surfline.com) use the MUR 1 km gap-free SST analyses, based on infra-red and microwave satellite SST data, to provide SST information for recreational beach users.

2.3 Summary of user needs

Operational systems need timely, accurate, reliable, and robust SST products in consistent, well-described formats (Beggs, 2010). Climate monitoring and research generally need less timely but more accurate and stable SST products. For other applications (such as fishing, boating, surfing, search and rescue, and oil spill management), spatial coverage and accurate location of ocean features may be more important than SST accuracy or stability. Specific needs of each user group are summarised in the table below, based on Beggs (2010) and WMO (2019).

Application	**Horizontal Resolution (km)**	**Temporal Resolution (hours)**	**Delivery Timeliness (hours)**	**Uncertainty (°C)**	**Stability (°C/yr.)**
Numerical Weather Prediction - Global - Regional	 5 1	 3 1	 3 0.5	 0.3 0.3	 - -
Ocean Forecasting - Coastal Ocean - Open Ocean	 < 1 5 - 10	 1 < 6	 1/12 1	 < 0.1 < 0.1	 - -
Seasonal and Interannual Forecasting	10 100	24 24	24 24	< 0.1 < 0.25	0.01
Climate Monitoring and Research	10	24	24	0.1	0.01
Climate Modelling Research	50	24	30 days	0.5	
Coral Reef Management Systems	< 1	1 and 24	24	< 0.3	0.03
Fisheries	< 1	1 and 24	< 3	0.5	-
Coastal and Inland Waters	< 1	1 and 24	1	< 0.3	-
Recreational	< 1	24	1	0.5	-

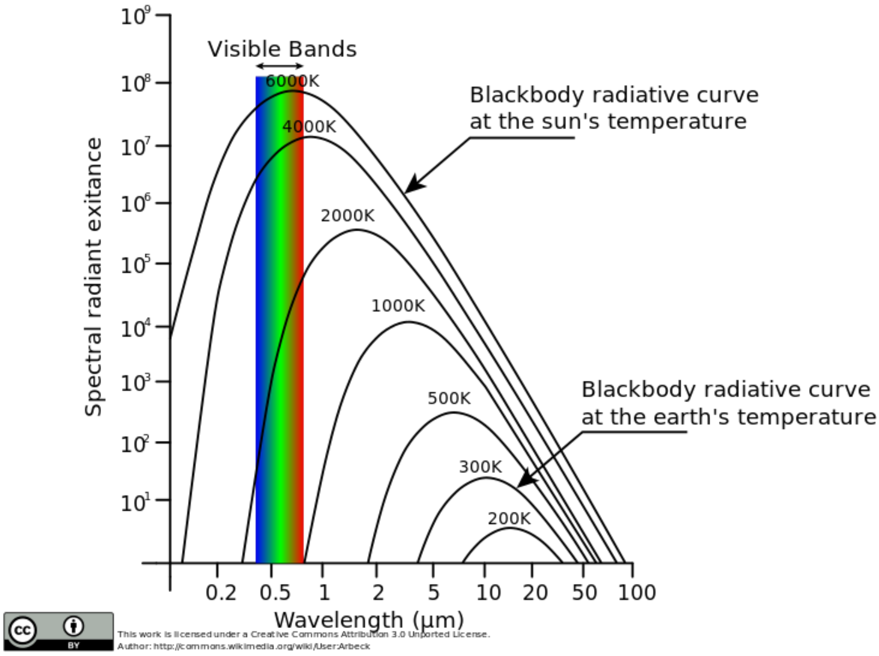
Summary of key applications and their SST target requirements.

3 Remote Sensing of SST

The measurement of SST from remote sensing relies on the fact that all matter emits radiation according to Planck's law for temperatures above absolute zero. The Earth has an average temperature of around 300 K giving a peak emission signal in the spectral region between 8 µm and 10 µm. The emitted signal can then be measured by a radiometer on a remote platform. For satellites, the emitted signal has traversed the atmosphere, where it is modified by emission and absorption from trace gases and scattering from clouds and aerosols.

To detect SST change, one can measure the intensity of electromagnetic radiation arriving from the ocean to the satellite. Since all objects with a temperature greater than absolute zero emit electromagnetic radiation, there are two equations which allows one to predict the temperature remotely:

1. Stefan-Boltzmann's Law: Hotter objects emit more total energy per unit area than colder objects.
2. Wein's Displacement Law: The hotter the radiating body, the shorter the wavelength of maximum radiation.



Most of Earth's objects (from land, the oceans, and clouds) emit radiation in the longer wavelengths of the thermal infrared spectrum. Satellite sensors can detect and measure the amount of infrared radiation from the Earth's surface. From the amount of emitted infrared radiation, scientists can then calculate the temperature of the land and ocean surfaces and of the atmosphere. Since the ocean, land, atmosphere, and clouds have relatively similar temperatures, these sources emit energy primarily in the infrared portion of the electromagnetic spectrum. Satellites can detect emission in the infrared region from surface (skin) emissions, direct cloud emissions, direct atmospheric emissions, and reflected cloud or atmosphere emissions.

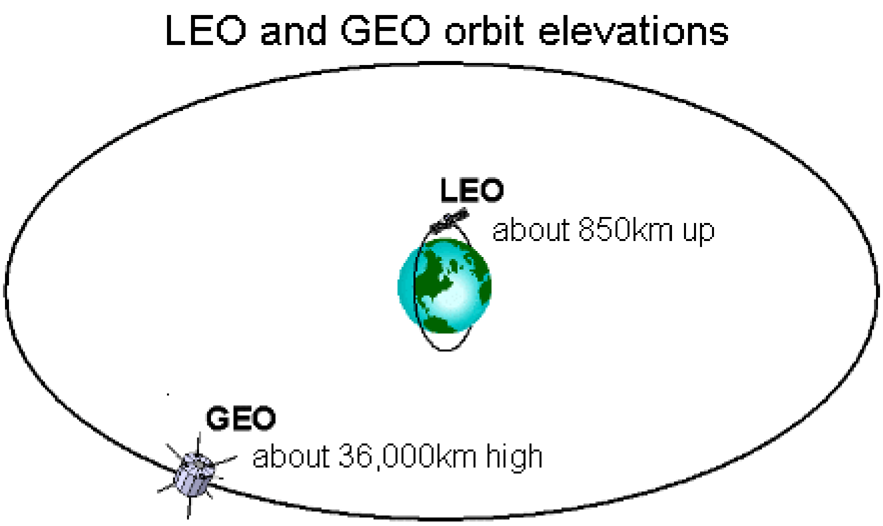
As much of the radiation from the surface is attenuated by the atmosphere, space-borne instruments operate at wavelengths where the atmosphere is mostly transparent. Also, they usually use two or more spectral channels to account for attenuation by the atmosphere. There are usable atmospheric windows in the IR and microwave parts of the spectrum. IR radiometers are more accurate and have higher spatial resolution, but they are limited to cloud free regions and are more sensitive to variable clear-sky atmospheric conditions. Microwave radiometers can sense the surface through clouds, but have lower spatial resolution, are less accurate, and are sensitive to surface roughness and rain.

3.1 Complementarity of low-Earth and geostationary orbits

Remote sensing satellites can exploit any Earth orbit but predominantly fly in three main types:

- Low Earth orbit (LEO) polar Sun synchronous
- LEO polar non Sun synchronous drifting
- Geostationary Earth orbit (GEO)

These are shown schematically in the following image.

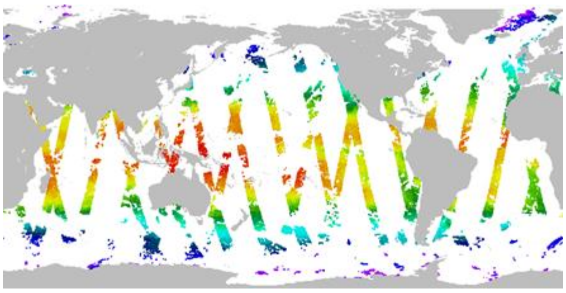


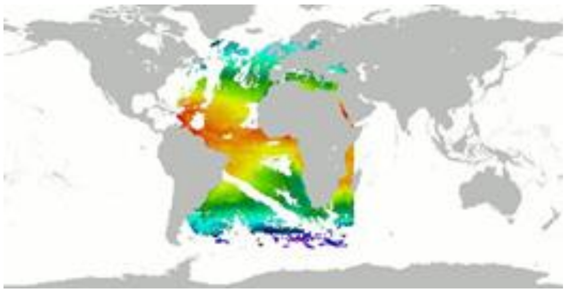
For the measurement of SST each type of orbit offers unique sampling of the Earth's surface. When exploited simultaneously a combination of these meet many user needs. Polar Sun-synchronous orbits offer complete global coverage but with often only once or twice views of the earth per day at most. In addition, the Earth is sampled at the same local solar time each day. Polar drifting orbits offer reduced global coverage, mainly in the tropics, but allow for increased sampling within a diurnal cycle. Geosynchronous orbits offer a limited amount of total coverage with only the full Earth disk being sampled but have the advantage of being located over the same longitude so that they can sample the full diurnal cycle, typically every 30 minutes or better.

3.2 SST estimation from infrared satellite radiances

Radiometers operating at IR wavelengths have two channels centred near 11 µm and 12 µm and one or more channels centred ~3.7-3.9 µm (during night-time only). The surface temperature is determined using two or more different channels compensating for variable absorption mostly due to atmospheric water vapour. Examples, of daily data from a LEO IR (left) and an hourly GEO IR (right, located over 0-degree meridian) sensor are shown below.

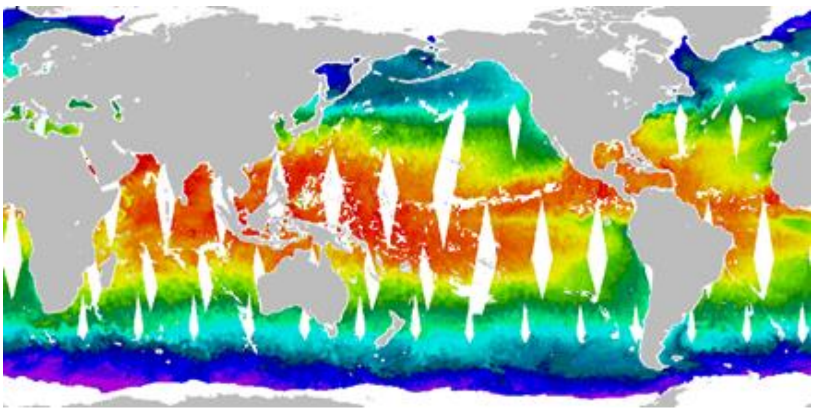
LEOs provide data with high spatial resolutions of < 1 km, and GEOs provide data with high spatial/temporal resolutions of ~2 km/~10-15 min.. Instruments should also ideally have channel(s) in the region around 8.9 µm to facilitate SST retrieval in the presence of atmospheric aerosols. Instruments using dual-view observation geometry provide much better accuracy due to variable path-lengths, thus correcting for the uncertainties in SST estimates caused due to atmospheric water vapour and aerosol.





3.3 SST estimation from passive microwave satellite radiances

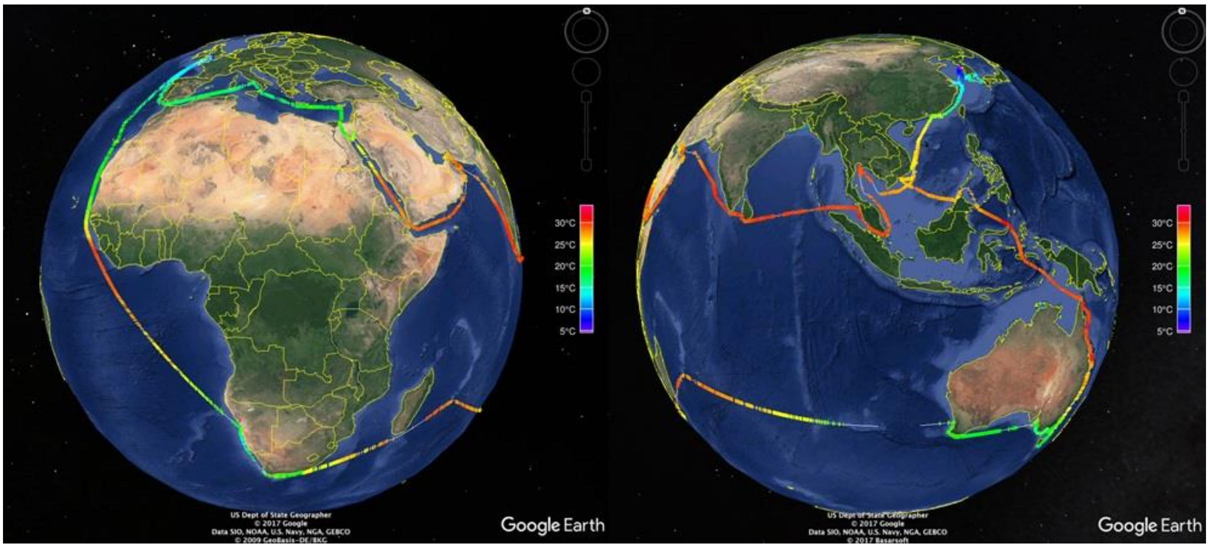
Due to the lower signal of the Planck radiation curve for a mean Earth temperature in microwave regions, the retrieval of SST is more challenging. Microwave radiometers used for measuring SST have channels around 7 and/or 10 GHz, and in addition to those, 23 and 37 GHz channels are used for correction of atmospheric and wind effects. At these frequencies non-precipitating clouds are largely transparent and atmospheric water vapour has a negligible impact on observations at the lower end of the frequency range. However, microwave radiometers cannot "see through" rain and they are also affected by radio frequency interference from TV broadcasts and other communications.



An example of daily data from a PMW sensor is shown in the previous figure. Global SST provision requires a channel around 7 GHz which has sensitivity to SST of all temperature zone and is least affected by atmospheric water vapour and sea surface wind speed supported by additional channels to allow computation of surface roughness (emissivity) and atmospheric water vapour impacts.

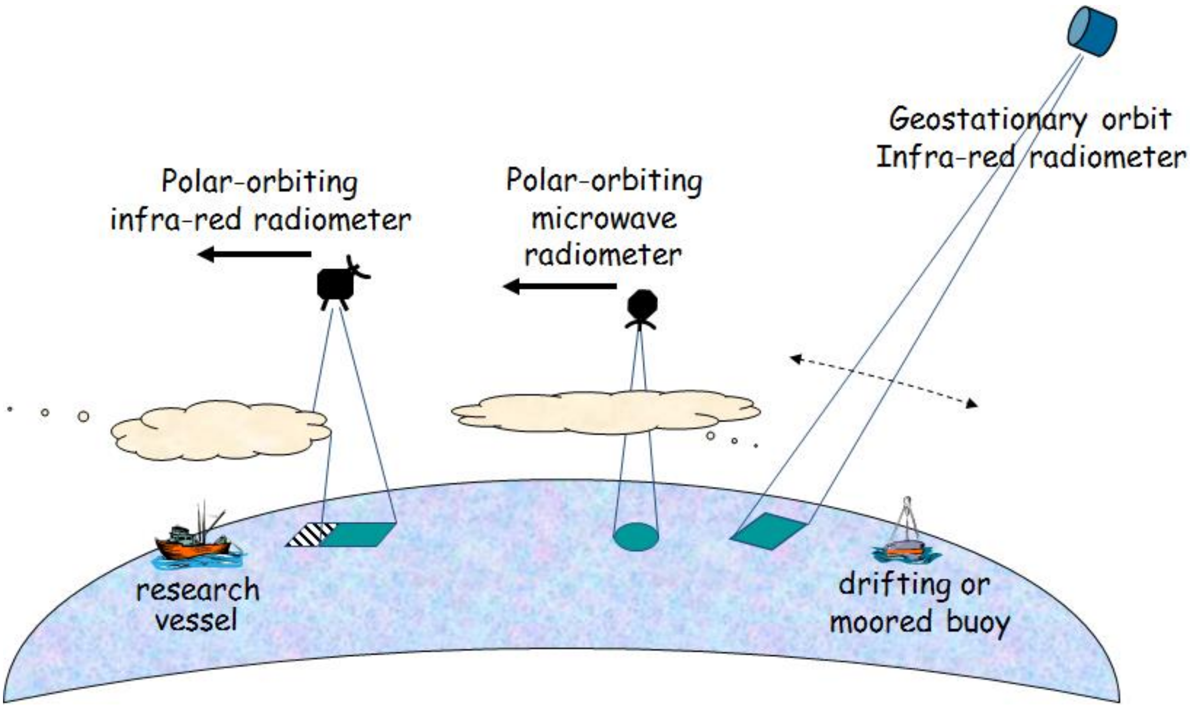
3.4 Fiducial reference measurements

Apart from the satellite data, the high quality SST observations require in situ data as a reference source for tying together all available data from various platforms. Fiducial Reference Measurements (FRM) are a suite of independent, fully characterised and traceable ground measurements (Donlon et al, 2015). They enable independent validation reports and satellite measurement uncertainty estimation, throughout the entire duration of a satellite mission. An example of a single cruise track of a ship-borne radiometer providing FRM is shown in the figure below.



4 The SST Virtual Constellation

To meet user requirements an SST measurement system requires an optimal combination of measurements from LEO and GEO infrared and passive microwave radiometers on satellites, with complementary reference measurements from in situ platforms. This concept is shown schematically in the figure below (courtesy Ian S. Robinson).



4.1 Composition of the constellation

The virtual constellation is ideally coordinated internationally to ensure continual full global coverage at necessary spatial and temporal resolutions with appropriate levels of operational redundancy. The nature of satellite orbits means there is no optimal combination of orbit to meet both the spatial and temporal requirements defined by the users. So, the system would ideally:

- Allow for daily sampling across the global oceans at a spatial resolution < 10 km.
    - Be comprised of multi-spectral radiometers operating in the IR region and multi-frequency radiometers operating in the microwave region, in low Earth orbit.
    - Be comprised of one high-accuracy dual-view multi-spectral radiometer operating in the IR region in low Earth orbit.

- Allow for sub-daily (< 3 hr) temporal sampling of the diurnal cycle of SST across the global oceans.

- Be augmented with a series of multi-spectral infrared radiometers in geostationary Earth orbit.
- A series of sensors in GEO would be arranged to ensure complete coverage across all longitudes. Ideally a constellation of 6 geostationary instruments is required to provide global coverage at satellite zenith angles amenable to quantitative SST estimation.

- Provide a measure of SST at a clearly defined depth. For infrared radiometers, this is defined at the skin-SST; for microwaves radiometers, this is defined as the sub-skin SST.
- Higher spatial resolution sampling (1 km or less) is required for coastal and regional applications such as marginal ice zones.

4.1.1 Performance characteristics

The following table gives a summary of the SST constellation target performance needs, updated from Donlon et al. (2010). Areas where targets are not met by the current constellation are highlighted in italics with the current capability.

Constellation element	Radiometer wavebands/data sources	Accuracy	Nadir spatial resolution	Swath width	Coverage /revisit	Availability/Latency
Ocean in situ SST system	Contact thermometry and thermal infrared radiometers.	0.05 K *(0.1 to 1.0 K)*	Point source	N/A	Providing global sample of SST and atmospheric structure and in oceanic areas characterised by strong temperature gradients. *Better sampling in polar regions and Southern Ocean.* *Reporting hourly together with measurement depth.*	< 1 hour
Wide swath Infrared imager	Thermal IR channels within the ~3.7-12 µm waveband for SST measurement, near-IR and visible channels for cloud flagging.	0.1 K *(0.3 K)*	0.25 - 1 km	>2000 km	Day and night global coverage by each satellite	< 3 hours
Dual view SST reference sensor	Thermal IR channels within the ~3.7-12 µm waveband for SST measurement, near-IR and visible channels for cloud flagging, each	0.1 K	0.5 km *(1 km)*	>500km	Daily global coverage	< 3 hours

	with dual view along track scanning capability.					
Wide swath Microwave Radiometer	For global coverage ~7 GHz is needed. 10 GHz also has sensitivity to SST but limited to higher SSTs. 23-37 GHz channels are required for corrections for wind, water vapor, precipitation etc.	0.3 K *(0.5 K)*	10 km *(30-50 km)*	>1500 km	Day and night global coverage	< 3 hours
Geostationary constellation of infrared imagers	Thermal IR channels within the ~3.7 - 12 µm waveband for SST measurement, near-IR and visible channels for cloud flagging.	0.5 K	1 km *(2-5 km)*	Full Earth disk from 36000 km altitude	Sample interval < 30 min	< 1 hour

4.1.2 New missions

All new satellite SST missions can join the constellation to ensure long-term continuity of data for users. Agencies are however requested to consider the constellation when planning new missions. To facilitate joining the constellation agencies are encouraged to:

- Provide their missions and system requirements documents to the CEOS SST-VC.
- Work with the CEOS SST-VC and interact with their project teams on mission requirements, and design, performance budgets, and Cal/Val activities.
- Provide timely acquisition and distribution to data users of Near-Real-Time (NRT) and Short Time Critical (STC) SST products in GHRSST L2P format to support operational applications.

Specific requirements in term of sampling and performances for both components are defined in following sections.

4.2 Cal/Val and Fiducial Reference Measurement needs

To provide information on data quality on new SST missions to users, agencies are encouraged to:

- Adopt the Observing CEOS Quality Assurance for Earth Observation data (QA4EO). The approach should be used by Space Agencies working together with inter-Governmental agencies, in situ data providers, and the scientific SST community when defining, implementing, and operating a sustained SST validation program.

- Include a NRT verification phase intended to qualify the system with respect to operational objectives.

- Allow for a science verification phase, with a minimum duration of 6 months after launch for recurring missions, 9 months when new technology is used or when there is no overlap with a previous mission, intended to qualify the system with respect to the science requirements.

- Confirm the calibration/verification accuracy of the SST products and their uncertainties is compatible with expected error budget specifications.

- Document and make available the mission's Cal/Val plans.

- Publish a report on Cal/Val activities for users, including a revised error budget, any derived calibration, and updated ground-processing algorithms.

- Provide pixel level uncertainties in the form of Sensor Specific Error Statistics (SSES) describing SST uncertainty for individual satellite.

- Work towards providing pixel level modelled uncertainties together with their documented error model.

In support of Cal/Val the SST community of producers and users should establish and maintain:

- A programme of in situ measurements, both thermometers on buoys, ships, and subsurface vehicles and radiometers on ships and platforms that can be used for validating the different satellite products. This should include both Fiducial Reference Measurements (FRM) and established in situ data with multi-purpose functionality.

- A forum in which sets of quality metrics relevant to specific uses of SST data are defined and regularly reviewed (consistent with QA4EO).

- Match-up databases (MDB) which relate satellite-derived SST products with in situ / FRM measurements of SST.

- A generic system to acquire better feedback from data assimilation systems (e.g., observation weights rejection statistics) to ascertain how much influence different SST observational products, have on the observing system models.

As well as satellite data, the SST virtual constellation has needs for fiducial reference measurements (FRM). Key components include:

- Space Agencies working together with inter-Governmental agencies, in situ data providers, and the scientific SST community take steps to define, implement and operate a sustained validation program for all satellite radiometers producing SST for the lifetime of the mission. Space Agencies and in situ data providers should consider sustained validation of their SST products as a fundamental component of each satellite mission and in situ platform for the entire mission/instrument duration.

4.3 Data and Service Components of the Constellation

An effective constellation for SST requires not only specific platforms and instruments on orbit, but also a set of data management components, adoption of community data processing standards, adherence to a common framework for data distribution, and a set of community-based services and tools to effectively deliver on its mission. Through these data management components and services, the full value of the constellation will be achieved. These aspects are described in the following sections.

4.3.1 Data Management Components

A set of data management components is essential to ensure that the constellation can effectively meet user requirements. These components include data product processing services, FRM in situ calibration and validation components as described previously, data exchange services between agencies and with users, and collaborative workspaces where users can bring their applications to the data without the need to download many terabytes of data to their own local systems. These services must be scalable and flexible, evolving to leverage advances in technologies and standards. Interoperability at the interfaces between all systems in the constellation must be ensured, and both reproducibility and traceability to international SI standards enabled. Without these systems in place, the constellation will not be able to deliver the data needed in an integrated and useful fashion.

4.3.2 Data Processing Standards

Agencies are encouraged to adopt GHRSST standard levels of data processing, use them in their SST product generation systems, and to create their products to conform to the GHRSST Data Specification (GDS). Through the wide adoption of these standards, international collaboration, scientific advances, and improved products have been enabled. GHRSST focuses its data specifications on Level 2, Level 3, and Level 4 processing levels, and has refined the widely-used definitions of these levels to remove the ambiguity that can exist in other definitions in use around the world. These definitions are given below, and are expected to slowly evolve over time as technologies and standards evolve:

Level 2 Pre-Processed (L2P):

- Geophysical variables derived from Level 1 source data at the same resolution and location as the Level 1 data, typically in a satellite projection with geographic information. These data form the fundamental basis for higher-level GHRSST products and require ancillary data and uncertainty estimates. No adjustments to input SST have been made.

Level 3 Uncollated (L3U), Collated (L3C), and Super-collated (L3S). L3 GHRSST products do not use analysis or interpolation procedures to fill gaps where no observations are available:

- L3U: L2 data granules remapped to a space grid without combining any observations from overlapping orbits

- L3C: SST measurements combined from a single instrument into a space-time grid. Multiple passes/scenes of data can be combined. Adjustments may be made to input SST data.

- L3S: SST measurements combined from multiple instruments into a space-time grid. Multiple passes/scenes of data are combined. Adjustments may be made to input SST data.

Level 4 (L4):

- Data sets created from the analysis of lower level data that results in gridded, gap-free products. SST data generated from multiple sources of satellite data using optimal interpolation are an example of L4 GHRSST products

4.3.3 Data Distribution Expectations

Agencies are encouraged to make their data accessible through the GHRSST Regional/Global Task sharing Framework (R/GTS) to ensure full utilization of the data products. Currently, the R/GTS framework organizes a coordinated system of Regional Data Assembly Centres, which produce GHRSST-compliant datasets and send them to a Global Data Assembly Centre in near real time for consolidated user access. The data are then sent to the Long-Term Stewardship and Reanalysis Facility (LTSRF) for long term preservation and redistribution to an even wider range of users.

RDACs are operated at centres around the world and maintained by a host of agencies and organizations. The GDAC is maintained at the NASA Physical Oceanography DAAC (PO.DAAC) and the LTSRF at the NOAA National Centers for Environmental Information (NCEI). The structure of this framework is currently evolving to become a more distributed network, where data discovery services are centralized but the data products themselves are provided directly by their national and regional systems.

Agencies providing data via the R/GTS framework should distribute their SST products in a timely and well-documented manner to users:

- NRT operational data products should be provided to users within 3 hours of collection to support operational services.

- Documentation of the various products should be distributed including the format of the files, definition of all the parameters and flags, the way to use these data, and the algorithms used to generate these data.

- L4 SST producers should provide a user-oriented document following a standard template that describes each analysis product and the choices and assumptions that have been made for the analysis procedure. The document should highlight the strengths and weaknesses of the analysis output to help users use these data in the most appropriate manner.

4.3.4 Community Services Expectations

To optimize the utility of the constellation data, a set of community-based services are needed. These community services to support include:

- An international reference match-up database that applies the same control and process methodologies to the match-up process between satellite and in situ SST measurements and supporting input data is developed, maintained and operated to allow a fair, consistent and up-to-date estimation of errors on satellite SST retrieval. Such a common database is best constructed following the systematic re-processing of satellite data as part of a Climate Data Record development activity and should be consistent with the CEOS QA4EO process.

- A GHRSST Multi Product Ensemble (GMPE) capability which includes quantitative data outputs in a GHRSST format for use by the general ocean community, considers higher spatial resolutions for the system grid specification, includes automated procedures for statistical analysis of the ensemble and the creation of regional GMPE tools for specific and challenging regions (e.g., Tropical Pacific, Bay of Bengal and Indian Ocean, Indonesia, Arctic Ocean, Great Lakes). These services could be distributed across multiple centres.

- Online data quality monitoring of near real time products

Considerations for space agencies up to 2050:

- Inclusion of data management procedures and documentation as a component of the constellation, to fully manage and exploit the full value of the constellation.

- Documentation, review, and ongoing maintenance of requirements, to be flexible, evolvable and scalable.

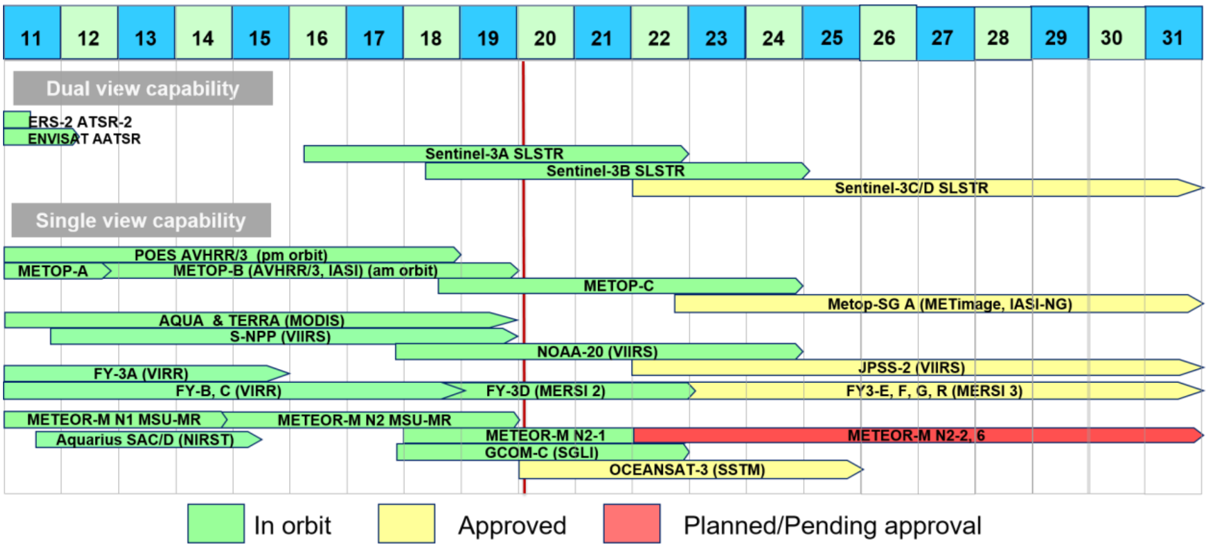
- Adaptations to big data needs: facilitating the possibility to bring processing, applications and algorithms to data, the development of advance sub-setting capability for users, and improved data cataloguing and search facilities.

- Data should be fully reproducible and reprocessable at all levels, and achieve documented SI traceability at the lowest data level.

5 Current & planned capability and gap analysis

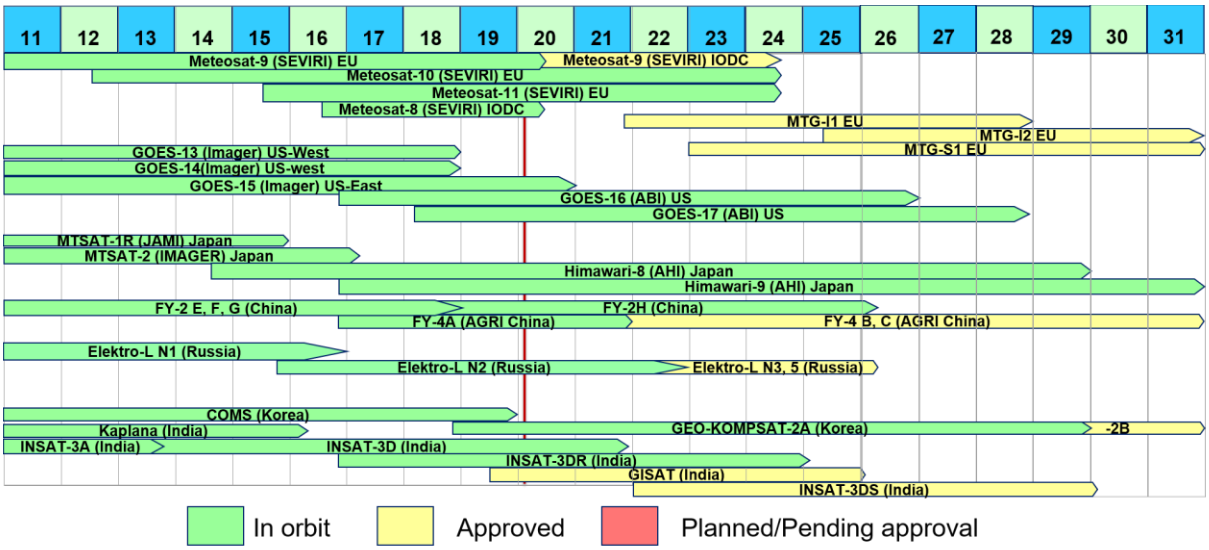
5.1 Low Earth orbit infrared

The current situation of the LEO IR constellation for SST is summarised in the figure below:



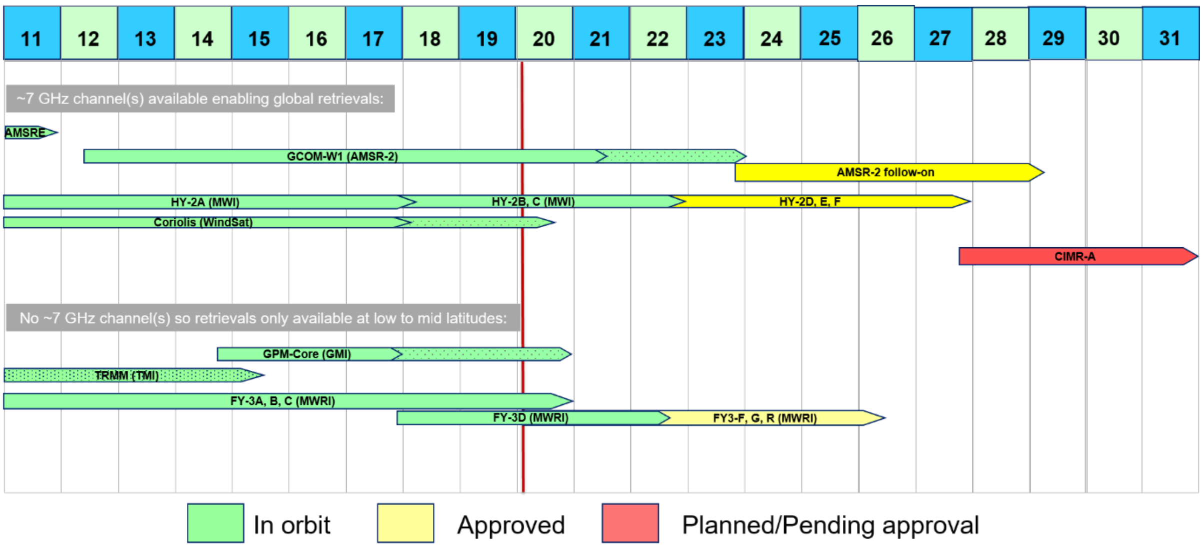
5.2 Geostationary Earth Orbit Infrared

The current situation of the GEO IR constellation for SST is summarised in the figure below:



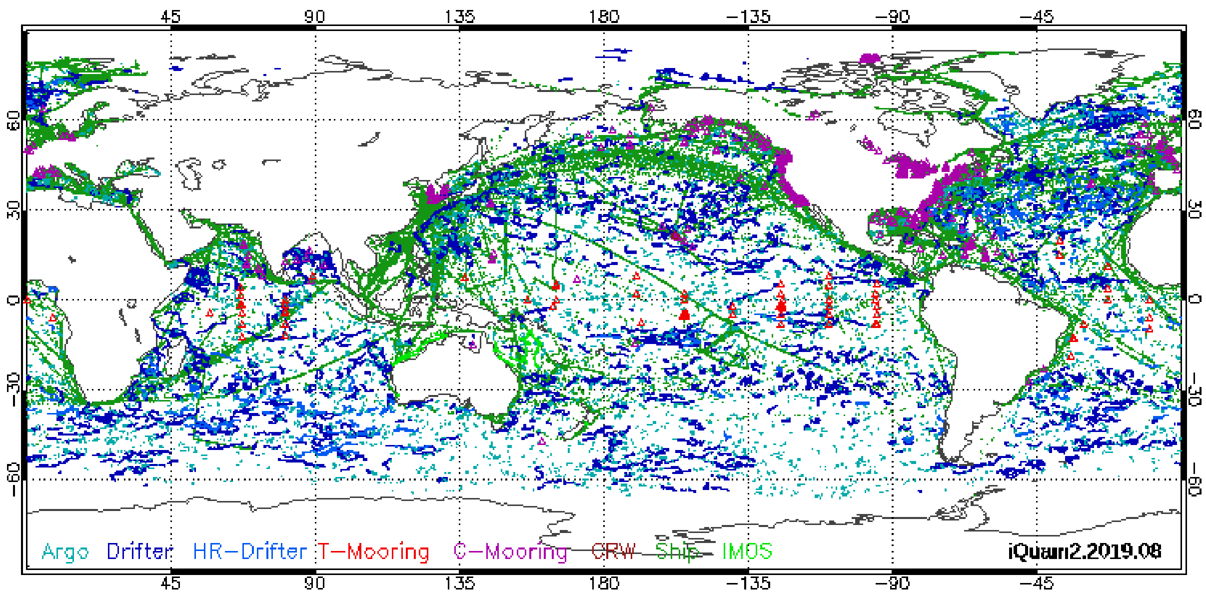
5.3 Microwave Radiometer

The current situation of the PMW constellation for SST is summarised in the figure below:



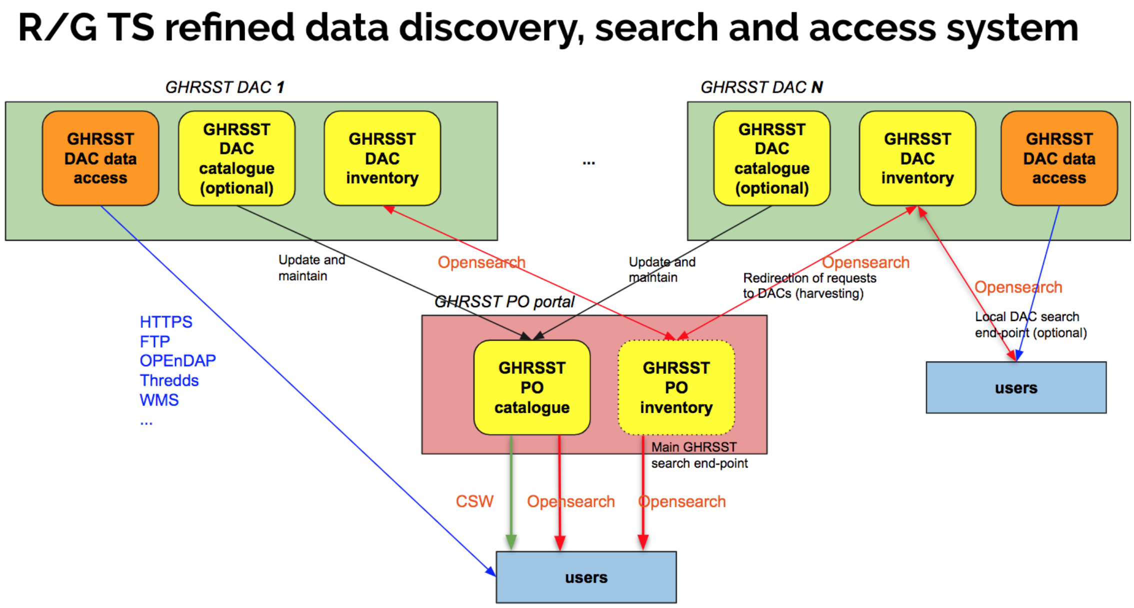
5.4 In situ

The CEOS community should continue to work with the various in situ data providers to provide necessary data for validation and integration of the satellite products. A key part of this is the provision of FRM with well prescribed uncertainty information. Efforts to provide such data in currently sparse regions should be increased. An example of the August 2019 coverage of in situ data from the NOAA iQuam v2.1 system (https://www.star.nesdis.noaa.gov/sod/sst/iquam2) is shown below.



5.5 Gaps in Data Management Services

The rapidly growing number and volume of SST products and diversified production sources means there is a need to provide a single one-stop catalogue for data discovery and access. A key part of this will be a refinement of the GHRSST R/G TS as shown in the figure below.



Tools to facilitate data visualisation and quality control monitoring should continue to be supported and expanded.

5.6 Urgent Needs

To support a sustainable high-resolution SST measurement system one issue that needs urgent attention has been identified:

- **Sustained continuity of Microwave Radiometer SST using a 6.9 GHz channel in an operational (redundant) context.**

This issue was first highlighted in the GHRSST Ocean Observations 2009 community white paper (Donlon et al., 2009), which was written prior to the cessation of AMSR-E SSTs in October 2011.

Since that date we have had the launch of AMSR2 on GCOM-W in May 2012. However, continuation of observation and a redundant capability for global SSTs is still needed. Two new missions are currently being planned to address this need:

1. JAXA has started Phase A of AMSR2 follow-on (AMSR3) since September 2018 and is preparing for the Project Approval Review scheduled in autumn 2019. Sensor

specification of AMSR3 is almost equivalent to AMSR2 except additional high-frequency channels for snowfall retrievals and numerical weather prediction. AMSR3 will share the satellite bus with follow-on mission of the Greenhouse-gases Observation SATellite-2 (GOSAT-2), and its orbit will be 666 km altitude (30 km lower than GCOM-W) and 13:30 LT in Ascending node (same as GCOM-W).

2. The Copernicus Imaging Microwave Radiometer (CIMR) is now under development and full information can be found at http://cimr.eu. CIMR will deploy a wide-swath (>1900 km) conically scanning multi-frequency microwave radiometer and will operate in synergy with the EUMETSAT MetOp-SG(B) mission so that in the polar regions (> 65 °N and > 65 °S) collocated and contemporaneous measurements between CIMR and MetOp-SG(B) will be available within +/-10 minutes.

6 Summary

This document summarises the components and future needs of the CEOS SST-VC. The SST-VC provides a key link between the GHRSST community and the CEOS community to ensure the required components are available. The work of both CEOS and GHRSST has ensured the SST-VC is currently strong and viable. Despite that strength, one urgent need has been identified and additional challenges for the provision of FRM and in situ data management to ensure smooth operation of the SST-VC are highlighted.

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The CEOS Sea Surface Temperature Virtual Constellation:

http://ceos.org/ourwork/virtual-constellations/sst/