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Article

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Sea Surface Temperature intercomparison in the framework of the Copernicus

Climate Change Service (C3S)

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25 **Abstract**

26 A joint effort between the Copernicus Climate Change Service (C3S) and the Group
27 for High Resolution Sea Surface Temperature (GHRSST) has been dedicated to an
28 intercomparison study of eight global gap-free Sea Surface Temperature (SST)
29 products to assess their accurate representation of the SST relevant to climate
30 analysis. In general, all SST products show consistent spatial patterns and temporal
31 variability during the overlapping time period (2003-2018). The main differences
32 between each product are located in western boundary current and Antarctic

33 Circumpolar Current regions. Linear trends display consistent SST spatial patterns
34 among all products and exhibit a strong warming trend from 2012 to 2018 with the
35 Pacific Ocean basin as the main contributor. SST discrepancy between all SST
36 products is very small compared to the significant warming trend. Spatial power
37 spectral density shows that the interpolation into 1° spatial resolution has negligible
38 impacts on our results. The global mean SST time series reveals larger differences
39 among all SST products during the early period of the satellite era (1982-2002) when
40 there were fewer observations, indicating that the observation frequency is the main
41 constraint of the SST climatology. The maturity matrix scores, which present the
42 maturity of each product in terms of documentation, storage, and dissemination but
43 not the scientific quality, demonstrate that ESA-CCI and OSTIA SST are well
44 documented for users' convenience. Improvements could be made for MGDSSST and
45 BoM SST. Finally, we have recommended that these SST products can be used for
46 fundamental climate applications and climate studies (e.g. El Nino).

47

48 **1. Introduction**

49 Sea surface temperature (SST) as one of the Essential Ocean Variables (EOVs), and
50 the Essential Climate Variables (ECVs), plays a crucial role in heat, freshwater, and
51 momentum flux exchange at the ocean-atmosphere interface. The variation of SST at
52 different temporal and spatial scales modulates the atmospheric lower boundary
53 layer (e.g. Renault et al., 2019) eventually driving small and large-scale changes at
54 interannual to decadal time scales in the atmosphere (Perlin et al., 2014, McPhaden,
55 2012). Additionally, the SST changes can influence the biogeochemical marine
56 environment, contributing to modulating the primary production and related carbon
57 absorption in the ocean (Behrenfeld et al, 2006). Besides its importance for assessing
58 and monitoring the state of the global climate system, SST is widely used as
59 boundary conditions in weather and climate operational forecast systems (Robinson
60 2012) and as initial conditions in ocean operational forecast systems (Le Traon et al.,
61 2019). Therefore, assessing the quality of SST data is critical from several
62 perspectives, from operational to climate studies, marine environment and related
63 services.

64

65 SST observations are mainly obtained from low-Earth orbit infrared and microwave
66 satellite imagery and geostationary infrared imagery, and from various in situ
67 platforms including moored and drifting buoys, Argo floats, ships of opportunity,
68 autonomous sailing drones, and radiometers (O'Carroll et al., 2019). All these
69 instruments provide observations characterized by different representativeness,
70 resolution, and accuracy. Different retrieval methods and reanalysis techniques are
71 thus applied to obtain temporally and spatially consistent long-term SST products
72 with global coverage (Minnett et al, 2019).

73

74 The Group for High-Resolution Sea Surface Temperature (GHR SST, www.ghrsst.org;
75 Donlon et al, 2009) is an international initiative aimed at coordinating the provision
76 of SST products developed and distributed by different agencies and research
77 institutes. Among GHR SST products, level 4 data (L4) provide gap-free SST maps at
78 regional and global scales, obtained with different algorithms that combine and
79 interpolate satellite based SST data, acquired by a variety of different sensors,

80 sometimes also including in situ observations. Different interpolation techniques and
81 related configurations (e.g. observation/background error correlation scales),
82 interpolation grid size, input data bias-correction, and the sampling adopted by
83 GHRSSST data providers induce a significant diversity among L4 SST products (Dash
84 et al., 2012). Understanding the consistency and discrepancy of the different SST L4
85 products will not only help data providers to improve their algorithms, but also
86 represents an important step to inform users about the characteristics of the
87 different products, helping them to select the one that may better suit their
88 applications.

89

90 Several previous global SST analysis intercomparison studies have already been
91 performed, among which, most noticeably, the Global Climate Observing System
92 (GCOS) SST-Sea Ice intercomparison project
93 (<https://www.nodc.noaa.gov/SatelliteData/ghrsst/intercomp.html>), and the GMPE
94 (Group for High-Resolution SST, GHRSSST, Multi-Product Ensemble) system,
95 performed as a contribution to GHRSSST activities. The initial work by Martin et al.

96 (2012) and Dash et al. (2012), which were focused on a relatively short time series
97 over the satellite period (for the year 2010), has recently been extended to
98 intercompare longer-term analyses over the overlapping period of 1991 to 2010
99 (Fiedler et al., 2019a). A much shorter period (one year) is considered in the
100 intercomparison of satellite-based analyses performed by Okuro et al. (2014), while a
101 comparison study on the historical SST datasets based on in situ data alone is
102 described in Yasunaka and Hanawa (2011). With the recent reprocessing of several
103 global high resolution daily L4 products from the start of the operational satellite
104 SST era (1981) to recent years, it is now timely to perform an intercomparison of
105 additional SST analyses over a significantly longer period.

106

107 In the framework of the European Copernicus Climate Change Service (C3S), an
108 Independent Assessment of Essential Climate Variables (ECVs) present in the C3S
109 Climate Data Store (CDS) is foreseen. The C3S CDS distributes and provides access
110 to quality-assured climate dataset and tools in the clouds for users. The independent
111 assessment aims to evaluate the quality, usability and consistency of available ECVs

112 for different applications, ranging from scientific studies (e.g. on climate change), to
113 commercial and private sector uses. SST is one of the ECVs considered in the
114 assessment framework of C3S and the intercomparison of SST products available in
115 the CDS will help the users to understand the quality of different SST products and
116 choose the right one for their specific applications.

117

118 The study presented hereafter represents the joint effort between the GHR SST
119 Analysis Intercomparison Task Team ([https://www.ghrsst.org/about-ghrsst/task-](https://www.ghrsst.org/about-ghrsst/task-teams/)
120 [teams/](https://www.ghrsst.org/about-ghrsst/task-teams/)) and the C3S SST assessment activities. The objective of this study is to
121 evaluate the basic characteristics and the maturity of eight state of the art global
122 SST analysis products; to describe how SST climatology and variability is represented
123 in each SST product, and to understand the consistency and discrepancy between all
124 these long-term eight SST analyses available in or outside of CDS (some of the SST
125 products are provided in GHR SST L4 format), and eventually to provide guidance on
126 which product might be better suited for users' applications.

127 The paper is organized as follows: Section 2 introduces the characteristics of SST
128 analysis products included in this study, the basic diagnostics are presented in
129 section 3, and the data maturity of all SST products is described in section 4, and
130 finally, the summary of the evaluation and the recommendations to users are
131 discussed in sections 5 and 6.

132

133 **2. Datasets**

134 Currently, two global SST analysis datasets are distributed through the CDS, namely
135 European Space Agency (ESA) Climate Change Initiative (ESA CCI) version 2.1 and
136 European Centre for Medium-Range Weather Forecasts Atmospheric Reanalysis
137 version 5 (ERA5). They are compared here with a selection of six state of the art SST
138 analyses distributed outside the CDS, obtained from different input data and analysis
139 system configurations. These are:

- 140 · Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) (Rayner et
141 al., 2003);

- 142 · UK MetOffice Operational Sea Surface Temperature and Sea Ice Analysis
- 143 (OSTIA) system (Good et al., 2020)
- 144 · NOAA Daily OISST v2.1 daily reanalysis also referred to as Reynolds SST
- 145 (Reynolds et al., 2007; Banzon et al., 2016; Huang et al., 2020);
- 146 · Multi-scale Ultra-high Resolution 0.25 deg. (MUR25) SST analysis v.4.2
- 147 (Chin et al., 2017);
- 148 · Merged satellite and in situ data Global Daily Sea Surface Temperature
- 149 (MGDSST) (Sakurai et al., 2005; Kurihara et al., 2006);
- 150 · Australian Bureau of Meteorology Global Monthly SST Analysis (BoM
- 151 Monthly SST) (Smith et al., 1999).

152

153 These eight datasets combine satellites and in many cases in situ temperature
154 measurements to generate gap-free (optimally interpolated) SST fields at the global
155 scale. All these datasets are specifically designed to provide accurate high spatial
156 and temporal resolution SST estimates that can be used in operational applications
157 such as assimilation and/or boundary conditions in numerical weather prediction

158 models (e.g., MGSST and OSTIA SST), and/or analysed for climate applications (e.g.
159 HadISST1, NOAA Daily OISST analysis, MUR25, BoM Monthly SST). Some of the
160 selected datasets, namely ESA CCI v2.1, OSTIA, NOAA Daily OISST v2.1, MUR25 and
161 BoM Monthly are provided in GHRSSST L4 format (GHRSSST Science Team, 2012).

162

163 Below, we detail the characteristics of all the SST products included in this
164 intercomparison study.

165

166 **2.1 ESA-CCI SST**

167 The ESA CCI SST dataset (version 2.1) provides global daily SST estimates based on
168 observations acquired from different satellite sensors covering the period from
169 September 1981 to December 2018 (at the time of the study). The CCI SSTs are
170 designed to provide a stable, low-bias climate data record derived from different
171 infrared sensors, i.e., the Advanced Very-High-Resolution Radiometer (AVHRR),
172 Advanced Along Track Scanning Radiometer (AATSR) and Sea and Land Surface

173 Temperature Radiometer (SLSTR) series of sensors (Merchant et al., 2019, 2014).
174 These data are provided at different processing levels: single-sensor data on the
175 native swath grid (Level-2); uncollated single-sensor (Level-3U) and collated multi-
176 sensor (Level-3C) gridded data; and blended multi-sensor and optimally interpolated
177 (Level-4) data.

178 The ESA CCI Level-4 product considered here consists of gap-free (optimally
179 interpolated) maps of daily average SST at 20 cm depth at $0.05^\circ \times 0.05^\circ$ latitude-
180 longitude grid (approximately 5x5 km at the equator). The Level-4 data have been
181 produced by running the OSTIA system (Donlon et al., 2012) using CCI Level-3U
182 SSTs as inputs, no in situ data are included. Estimates of standard uncertainty
183 (considered as the standard deviation of the estimated error distribution) are
184 provided for every SST at all product levels. The evaluated global median uncertainty
185 is 0.18 K (Merchant et al., 2019). The multiannual stability of the whole time series,
186 evaluated relative to drifting buoy measurements, is within 0.003K/year (Merchant et
187 al., 2019). Given the high temporal and spatial resolution and the performance

188 statistics, this dataset gives an accurate representation of SST spatio-temporal
189 variability of relevance to climate applications. Target applications of the ESA CCI
190 SST dataset include climate and ocean model assessment; accurate definitions of
191 climatic indices; quantification of climate variability and its impacts on weather
192 extremes (including marine heatwaves), marine ecosystems, and related services.

193

194 **2.2 ERA5**

195 The ERA5 SST dataset is produced by ECMWF to be used for ERA5 atmospheric
196 reanalysis (Hirahara et al., 2016). It consists of hourly global gap-free SST data at
197 $0.25^{\circ} \times 0.25^{\circ}$ latitude-longitude grid covering the period from 1979 to the present.
198 ERA5 SST data are based on the HadISST2 (Kennedy et al., 2016) product from 1979
199 to August 2007, and the daily operational OSTIA (Donlon et al., 2012) product from
200 September 2007 to present. The HadISST1 version 2 was developed by the UK Met
201 Office Hadley Centre, and its "pentad" dataset consists of spatially complete, 5-daily
202 mean fields on a 0.25° spatial resolution grid. OSTIA is a high resolution ($0.05^{\circ} \times 0.05^{\circ}$)

203 operational daily product developed by the UK MetOffice and distributed through
204 the Copernicus Marine Environment Monitoring Service (CMEMS). These two SST
205 datasets are aggregated into one continuous data record and interpolated onto the
206 ERA5 model grid (Dee et al., 2011) to be used as boundary conditions for ERA5
207 atmospheric reanalysis. There are two types of Sea Surface Temperature in ERA5
208 including Sea Surface Skin Temperature and Sea Surface Temperature. In this study
209 we have used monthly ERA5 Sea Surface Temperature. ERA5 SST is calculated as
210 the SST from an ocean model with increment as the difference between OSTIA SST
211 and the ocean analysis. Since the input of SST comes from both OSTIA and
212 HadISST2, the ERA5 SST is a mixture of SST in the absence of diurnal variation,
213 "foundation SST" (OSTIA), and SST at indeterminate depth, "SSTdepth" (HadISST2),
214 following the SST definitions in Minnett and Kaiser-Weiss (2012). Here we give the
215 SST type as SSTdepth for ERA5 SST.

216 **2.3 HadISST1**

217 Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST1) is available
218 at <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. This dataset
219 includes a combination of monthly globally-complete fields of SST and sea ice
220 concentration on a 1°x1° latitude-longitude grid from 1870 to present. HadISST1
221 data have been produced using SST measurements from the Met Office Marine Data
222 Bank (MDB), mainly ship tracks, and a blend of in situ and adjusted satellite-derived
223 SSTs for 1982-onwards. A bias adjustment of the satellite SST data is performed by
224 subtracting the in situ fields from the AVHRR fields. Specifically, the difference fields
225 are smoothed using a moving window average with a radius of 2224 km (20 degrees
226 of latitude). The smoothed bias fields are then subtracted from the monthly AVHRR
227 SST (see Appendix C in Rayner et al. 2003 for further details).

228

229 In order to enhance data coverage, monthly median SSTs for 1871-onward from the
230 Comprehensive Ocean-Atmosphere Data Set (COADS) (now ICOADS) were also used
231 where MDB data were not available. Information on sea ice concentrations is also

232 included in the HadISST product. This information is derived from several sources
233 that include digitized sea ice charts and satellite data. Temperatures are
234 reconstructed using a two-stage reduced-space optimal interpolation procedure
235 (Kaplan et al., 1997), followed by superposition of quality-improved gridded
236 observations onto the reconstructions to restore local detail (Rayner et al., 2003).

237

238 **2.4 NOAA (Daily OISST)**

239 The NOAA Daily OISST v2.1 dataset (Reynolds et al., 2007; Banzon et al., 2016;
240 Huang et al., 2020), also known as the “Reynolds” Daily Optimum Interpolation SST
241 analysis, consists of global daily spatially-complete SST data on a 0.25°x0.25°
242 latitude-longitude grid from 1981 to present (<https://www.nodc.noaa.gov/oisst>). This
243 dataset is routinely produced by NOAA/NESDIS/NCEI and publicly provided at
244 [https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-](https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/)
245 [interpolation/v2.1/](https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/).

246 GHRSSST GDS2 L4 format (GHRSSST Science Team, 2012) files are also available from
247 1981 to 2015 from https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-
248 v2.0 and 2016 to present from https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-
249 L4-GLOB-v2.1.

250

251 The NOAA optimal interpolation analysis uses both in situ and satellite-derived SST
252 data. Satellite SSTs are estimated from NOAA/AVHRR and MetOp/AVHRR
253 observations. This dataset also utilizes the in situ ICOADS dataset to correct the
254 residual satellite SST biases. OISST has been updated from v2.0 to v2.1 from January
255 2016 onward. The updates include the following five aspects: (a) MetOp-B replaces
256 NOAA-19 while MetOp-A remains unchanged, (b) freezing-point temperature
257 replaces ice-SST regression in SST proxy in ice-covered oceans, (c) the estimated
258 ship SST bias is reduced from 0.14°C to 0.01°C, (d) ship and buoy observations from
259 ICOADS-D R3.0.2 are used instead of NCEP GTS receipts, and (e) Argo observations
260 above 5 m depth are included. The Argo observations were first used as

independent data to validate the improvements in the updates from (a) to (d), and the Argo observations were finally included in OISST in (e).

2.5 MUR25

The Multi-scale Ultra-high Resolution 0.25 degree. (MUR25) SST analysis (v.4.2) is a global daily spatially-complete SST dataset on a $0.25^{\circ} \times 0.25^{\circ}$ grid covering the period from mid-2002 to present. The analyzed SST is representative of the foundation temperature (namely, the temperature free, or nearly free, of any diurnal cycle (Minnett and Kaiser-Weiss, 2012). This dataset is a reprocessed version of the MUR dataset v.4.1 (Chin et al., 2017), which provides global daily spatially-complete SST analyses at 0.01° spatial resolution. MUR25 is provided by NASA's Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO.DAAC) and is available at <https://podaac.jpl.nasa.gov/dataset/MUR25-JPL-L4-GLOB-v04.2>. The MUR L4 analysis is built by using only nighttime SST observations derived from different types of satellite sensors, which include microwave and infrared

276 measurements from, e.g., Advanced Microwave Scanning Radiometer (AMSR) for
277 Earth Observing System (AMSR-E) and NOAA/AVHRR observations. In addition,
278 MUR25 ingests in situ SST measurements from the NOAA iQuam data set (Xu and
279 Ignatov, 2014) to improve the estimate of the foundation temperature, and ice
280 concentration data from the EUMETSAT Ocean and Sea Ice Satellite Application
281 Facility (OSI SAF), which are used for an improved SST parameterization in the polar
282 regions. Satellite and in situ data are combined using MRVA, a meshless multi-scale
283 interpolation method which uses wavelets as basis functions in order to build the
284 daily MUR SST analysis (Chin et al., 2017).

285

286 **2.6 MGDSST**

287 The Merged satellite and in situ data Global Daily SST (MGDSST) analysis dataset
288 provides global daily spatially-complete SST fields on a 0.25°x0.25° latitude-
289 longitude grid covering the period from 1982 to present. This dataset is derived
290 from infrared satellite sensors (NOAA/AVHRR and MetOp/AVHRR), microwave

291 satellite sensors (Coriolis/WINDSAT, GCOM-W1/AMSR-2), and in situ temperature
292 measurements (from buoys and ships). This dataset is provided by The Japanese
293 Meteorological Agency (JMA) and is available at
294 https://ds.data.jma.go.jp/gmd/goos/data/rrtdb/jma-pro/mgd_sst_glb_D.html.
295 SSTs from the microwave sensor AQUA/AMSR-E are used in the analysis from May
296 2002 through 5th October, 2011. In the reanalysis data, SSTs under sea ice are
297 determined according to the statistical relation between sea-ice concentration and
298 SST. The lowest SST is -1.8 degree Celsius where the sea-ice concentration is 100%.
299 Additional information is provided by Kurihara et al. (2006) and Sakurai et al. (2005).
300

301 **2.7 BoM Monthly**

302 The Monthly Optimal Interpolation (OI) SST Analysis is the global monthly spatially
303 complete SST dataset on a 1°x1° grid produced by the Australian Bureau of
304 Meteorology (BoM), covering the period of 1994 to present (Smith et al., 1999),
305 formed by averaging the BoM Weekly OI SST analyses over each month. In this

306 study, we use the GHRSSST version 1 L4 format files of this dataset covering the
307 period 2002 to present (Beggs and Pugh, 2009). The SST observations are obtained
308 from in situ SST observations from drifting and moored buoys, ships, Argo floats,
309 Conductivity Temperature Depth (CTD) and Expendable Bathythermographs (XBTs),
310 and satellite-derived SST from infrared AVHRR sensors aboard NOAA Polar-Orbiting
311 Environmental Satellites (POES) and ESA/EUMETSAT MetOp satellites. Weekly OI
312 analyses of the in situ data are used to correct for biases in the satellite data (Smith
313 et al., 1999), similar to the method used in the NOAA Weekly 1°x1° OISST v2
314 (Reynolds et al., 2002). The resulting outputs of the Weekly and Monthly OI
315 analyses of in situ and satellite data are therefore SST values of indeterminate depth,
316 SSTdepth.

317 At high latitudes, the BoM weekly analysis system uses the daily sea-ice
318 concentration analysis from NOAA/NCEP
319 (<https://polar.ncep.noaa.gov/seaice/Analyses.shtml>) to constrain the SST, by setting
320 SST at a given grid point to -1.8°C if the concentration of NCEP ice data in that grid

321 cell is greater than 50 per cent. Until 12 March 2008, the 0.5° resolution sea-ice
322 analysis was used and after that date, the 1/12° resolution sea-ice analysis
323 (Grumbine, 1996).

324 Maps of these weekly and monthly SST analyses are available at
325 <http://www.bom.gov.au/marine/sst.shtml>, and they are used operationally by BoM to
326 generate El Niño indices, monitor the Indian Ocean Dipole and produce SST
327 anomaly maps for climate applications
328 (<http://www.bom.gov.au/climate/enso/#tabs=Sea-surface>). The BoM Weekly and
329 Monthly OI SST analysis GHR SST L4 format files are available on request
330 (<http://www.bom.gov.au/climate/data-services/data-requests.shtml>). It should be
331 noted that higher resolution (0.25°x0.25°) global daily OI SST analyses have been
332 produced operationally at the Bureau of Meteorology since 2008 (Zhong and Beggs,
333 2008; <http://www.bom.gov.au/marine/sst.shtml>) but these only cover the period 2008
334 to present so were not included in this study.

335

2.8 UK Met Office OSTIA SST

The UK Met Office OSTIA (Good et al., 2020) system is a daily global SST product with a resolution of $1/20^\circ$ (approximately 5-6km). Monthly and seasonal frequency datasets are also available. The version of OSTIA SST we use in this study is the CMEMS reprocessed SST analysis based on the OSTIA configuration reported in Good et al. (2020), covering the period 1 October 1981 to 31 December 2018. This OSTIA reanalysis is formed by the combination of satellite SST data provided by the GHRSSST project with additional AATSR, SLSTR and AVHRR data from ESA CCI SST v2.1, C3S projects, and in situ observations from the HadIOD by using NEMOVAR, a variational assimilation (Fiedler et al., 2019b), instead of the optimal interpolation algorithm (Martin et al., 2007, Donlon et al., 2012). Note that ESA CCI SST v2 and V2.1 only differ in the file specification, but no scientific differences. Bias correction is performed for all the input satellite data (except the satellite data in the reference dataset) by carrying out match-ups between satellite and reference measurements. The depth of the SST analysis represents the sub-skin temperature immediately

351 before sunrise also referred to as foundational SST that is free of diurnal variability
352 (Donlon et al., 2012). The OSTIA reanalysis is publicly available from
353 https://resources.marine.copernicus.eu/?option=com_csw&task=results?option=com_csw&view=details&product_id=SST_GLO_SST_L4_REP_OBSERVATIONS_010_011.
354
355 In order to verify the accuracy of reprocessed SST analysis, near-surface Argo data
356 that are not included in SST analysis are used as independent data for quality
357 assessment as shown in CMEMS quality information documentation of OSTIA SST
358 ([https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-](https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-011.pdf)
359 [011.pdf](https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-011.pdf)). Note that the drifting buoy SSTs used for validation are ingested into the
360 analyses, however the validation process uses OSTIA background fields without data
361 assimilating buoy SSTs to compare with drifting buoys from analysis day plus 1 day
362 to avoid the validation data independence issue.

363 OSTIA SST has been used as boundary conditions for operational forecast models at
364 the UK Met Office and European Centre for Medium-range Weather Forecasting
365 (ECMWF) and is also part of the CMEMS project. The validation, assessment activities

366 update regularly through the CMEMS project, the data, and relevant documentations
367 are available at
368 [https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=](https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SST_GLO_SST_L4_REP_OBSERVATIONS_010_011)
369 [SST_GLO_SST_L4_REP_OBSERVATIONS_010_011](https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SST_GLO_SST_L4_REP_OBSERVATIONS_010_011).

370

371 **3 Basic diagnostics**

372

373 In order to compare the selected datasets (see Section 2) especially against global
374 SST climatology, all the SST products need to be mapped on a common temporal
375 and spatial resolution (regular 1°x1° latitude-longitude grid.). Apart from HadISST1,
376 the majority of the SST products have higher resolution than 1°x1° and the
377 advantage of high resolution is to resolve small scale ocean processes. The
378 interpolation from higher resolution to low resolution may exclude the impacts of
379 important small-scale signals in the SST products. Before we present the basic
380 diagnostics such as mean climatology and variability, we have performed spatial

381 spectral analysis (Section 3.1.1 - methods and Section 3.2.1 - results) to quantify the
382 impact of interpolation to the common 1°x1° resolution we have performed in our
383 basic diagnostics.

384

385 The grid of HadISST1 has been chosen as the reference grid (at 1°x1° nominal
386 resolution). The HadISST1 land-sea mask has then been applied to all products. In
387 addition, a sea-ice mask was built from HadISST1 and used as a common sea-ice
388 mask for all datasets.

389

390 To homogenize the datasets' temporal and spatial resolution we have used CDO
391 (Climate Data Operator) command line operators (see the user guide at
392 <https://code.mpimet.mpg.de/projects/cdo/embedded/cdo.pdf>). In particular, we have
393 chosen a bilinear interpolation for gridding all datasets on the HadISST1 spatial grid.

394

395 For all the selected SST products, the overlapping period is 2003-2018 (Figure 1) and
396 the intercomparison of all SST products are performed for the period 2003-2018,

397 when observations are abundant compared to the beginning of the satellite era.
398 Recent period increased quantities of observations ingested in the SST analysis may
399 reduce the spread of ensemble SST products produced with different algorithms. In
400 order to understand deeper the discrepancy and consistency between all the SST
401 analyses produced with different algorithms, similar intercomparison diagnostics of
402 SST products (ESA-CCI, ERA5, OSTIA, NOAA OISST, MGD SST and HadISST1) that
403 have the common period from 1982-2018 (Figure 1) are also carried out for the
404 earlier period of the satellite era (1982-2002) when the observations are scarce
405 compared to the later period of the satellite era.

406

407 In this section, we first introduce the methodologies we applied to produce the
408 basic diagnostics, and the spatial spectral analysis method used to investigate the
409 impact of spatial resolution is also presented. Then we present the results generated
410 by these diagnostics in terms of intercomparison for the period 2003-2018, and the
411 intercomparison of SST products that cover the period 1982-2002 is presented at
412 the end of this section.

413

414 **3.1 Statistical Methods**

415 A set of basic diagnostics have been defined to evaluate the similarity and
416 disagreements between selected SST datasets, as detailed in the following
417 subsections. Some of these metrics, such as the mean climatology, quantify the
418 long-term mean spatial distribution (climatology) of the SST for each single dataset
419 and can be used to qualitatively evaluate the capability of SST in representing the
420 climatological spatial patterns and the temporal variability of globally averaged
421 SSTs . Other metrics, such as difference, root-mean-square difference (RMSD), and
422 correlation, measure the distance between a single product and a "reference". The
423 latter can be either a previously validated dataset (if available) or any other dataset
424 that is arbitrarily chosen as reference. In this report, we have taken the median of all
425 datasets (hereafter the Ensemble median) as a reference and used it to measure the
426 difference among different SST products. Finally, we choose a specific case study of
427 the El Niño Southern Oscillation (ENSO) Nino3.4 Index to evaluate the capability of

428 representing ENSO events in all SST products. Nino3.4 is the average SST anomaly in
429 the region bounded by 5°N to 5°S, from 170°W to 120°W.

430 **3.1.1 Spatial Spectral Analysis**

431 The spectral analysis method we adopted in this study is the Multitaper Power
432 Spectral Density Estimate (MTM) (Thomson, 1982), which is a very useful tool for the
433 analysis of relatively short and noisy series that may contain both broadband and
434 line components. Different from several other techniques, MTM multiplies the data
435 by a small set of orthogonal tapers rather than a single taper to minimize the
436 spectral leakage due to the finite length of the series.

437 MTM power spectral estimates were performed using the pmtm matlab function
438 (<https://www.mathworks.com/help/signal/ref/pmtm.html>). For more details please
439 refer to Ghil et al. (2002) Section 3.4.

440

441 We have chosen four datasets, ESA-CCI and OSTIA with the original spatial
442 resolution of 0.05° and MGD SST and NOAA Daily OISST (Reynolds 0.25 x 0.25° SST)

443 with the original resolution of 0.25° all covering the same period 1982-2018 with
444 daily frequency. Meanwhile, we chose the Pacific equator pixel line, spanning from
445 Indonesian to South America as the study region (0°N, 120°E-80°W). For each
446 dataset the spatial power spectral density has been estimated on a daily basis over
447 the common period (1982-2018) and then time averaged. The detailed results and
448 discussion are given in Section 3.2.1.

449 **3.1.2 Trend analysis**

450

451 SST trends have been estimated by using the X-11 seasonal adjustment procedure
452 (see e.g. Pezzulli et al., 2005). Given X_t is the input time series (namely, an SST time
453 series), the X-11 procedure generates the following decomposition:

$$454 \quad X_t = T_t + S_t + I_t$$

455

456 where T_t is the trend component, S_t the seasonal component and I_t the irregular
457 component, which accounts for the residual irregular variations such as sub-annual

458 fluctuations. The decomposition is obtained through iterative application of different
459 running means, which have the effect of a low-pass filter for T_t estimation and a
460 seasonal filter for S_t estimation.

461 In addition, the Mann-Kendall test is used to assess whether a monotonic upward or
462 downward trend in T_t exists (against the null hypothesis of no trend), Sen's method
463 is applied to estimate the slope of T_t , i.e. the trend (as the median of the slopes of
464 all pairs of sample points), and a bootstrap procedure is used to estimate the 95%
465 confidence interval of the trend (Mann, 1945; Sen, 1968; Kendall, 1975; Efron and
466 Tibshirani, 1993).

467

468 **3.2 Results**

469

470 **3.2.1 Spatial Spectrum Analysis**

471 In order to verify the suitability of our choice of interpolation, we have performed
472 spatial power spectral analysis (section 3.1.1) based on the chosen SST products

473 (Figure 2). With rapid growth of computing power and storage capacity, along with
474 advancement of scientific knowledge and users' needs, spatial resolution of SST gap-
475 free analyses has increased dramatically to resolve smaller scale features in the
476 ocean. The spatial resolution of SST products used in this study spans from 1° to
477 0.05° , meaning that the highest resolution is 20 times the lowest resolution. In the
478 high resolution SST products, the meso-scales might be resolved, by contrast in the
479 low resolution SST products only large scale features are represented.

480

481 All of the SST products we chose for the spectral analysis cover the same period
482 from 1982 to 2018 with daily frequency. OSTIA and ESA-CCI SST have the original
483 spatial resolution of 0.05° and MGDSST and NOAA Daily OISST have the spatial
484 resolution of 0.25° . If the power spectra gradient becomes flat at a certain
485 wavelength it means that the analysis carried out at a wavelength shorter than this
486 certain wavelength contains only noise. The power spectrum density of these four
487 datasets shows that even though all of these SST products have higher grid
488 resolution than the chosen common grid, 1° , the power density of all SST products

489 starts to decline at spatial wavelengths greater than their grid-resolution. The
490 prominent differences between NOAA OISST and MGD SST are most likely due to
491 different background correlation length scales being used in the optimal
492 interpolation and different methodology used to correct satellite-based observations.
493 For high resolution datasets, the 0.05° products, the power density significantly
494 declined after ~ 100 km (wavenumber 10^{-2}), which is close to 1° spatial resolution
495 near the equator and the gradient becomes flat at wavelengths ~ 70 km. It means
496 that the signals within a wavelength of 100 km are noise, with no physical meaning
497 in 0.05° SST products, and that also applies to 0.25° resolution SST products. Similar
498 results were shown in Fiedler et al. (2019a) that in the Gulf Stream regions for the
499 2017 northern winter the spectral density of SST starts to depart from the
500 $\omega^{-11/3}$ cascade of SST field (equivalent to kinetic energy power spectrum cascade of
501 $\omega^{-5/3}$ based on Le Traon et al., 1990; 2008) at wavelengths around 90 km. This
502 confirms that the interpolation to 1° does not undermine the interpretation of
503 results presented in our study.

504

505 Additionally, the diagnostics performed in the following sections mainly focus on the
506 general features (mean climatology and long-term temporal variability) of the
507 representation of all the SST products. We believe the interpolation of all SST
508 products to 1° brings minor issues to the interpretation of the results. Certainly, the
509 intercomparison between all the SST products in terms of specific details, for
510 example, the representation of the Gulf Stream and meso-scale features are not in
511 the scope of this study. Related activities are underway and will be presented by the
512 GHRSSST SST Analysis Intercomparison Task Team in the near future.

513

514 **3.2.2 Mean and Variability (2003-2018)**

515 In terms of the basic diagnostics, we have first calculated the mean climatology of
516 the global SST distribution of the eight selected SST datasets during 16 years from
517 2003 to 2018 plus the median of all the eight SST products, i.e., the climatology of
518 the ensemble median (Figure 3). In all eight cases, the average correctly reveals the
519 dominant latitudinal spatial SST pattern: higher at the tropics, milder at middle
520 latitudes and lower in the polar regions. Regions impacted by occasional or

521 persistent presence of sea ice are flagged, i.e., only complete years have been
522 considered for the average estimate in each grid point.

523

524 A first qualitative inspection of the eight mean SST fields suggests that all products
525 reproduce a very similar spatial distribution of SST with minor differences not
526 appreciable from Figure 3. Considering a confidence level of 95%, the eight global
527 mean SST estimates for the period 2003 to 2018 range in an interval between
528 20.02°C and 20.17°C. The ensemble median obviously falls close to the middle of
529 this range (i.e., 20.12 °C).

530 In order to have a further investigation of the consistency and discrepancy between
531 all SST products, we calculated the difference between each SST product and the
532 ensemble median displayed in Figure 4. Considering a 95% confidence interval, the
533 global mean difference between each single product and the ensemble median
534 ranges between -0.05 and 0.1 °C with relevant spatial variability (Figure 4). In fact,
535 differences are more pronounced in the Southern ocean where distances between

536 single product values and the ensemble median reach values higher than 1°C. This is
537 particularly evident in the case of HadISST1 data. In general, higher difference areas
538 correspond to the western boundary current systems such as the Gulf Stream
539 Current, the Kuroshio Current in the Northern Hemisphere, Brazil currents in the
540 Southern Atlantic Ocean, and the Antarctic Circumpolar Current (ACC), where eddies
541 are extremely active. In some datasets, especially ESA-CCI SST, MGD SST and OSTIA,
542 the greatest differences from the ensemble median are also located within eastern
543 boundary currents which represent the main upwelling systems, e.g., Peru-Chilli,
544 Benguela, North West-African coast and along the southern Saudi Arabia coast.
545 These discrepancies could be due to mismatch in the position of the main streams,
546 especially the eddy representation in different SST products. Along the coast, the
547 disagreement may come from the interpolation methodology implemented in
548 different SST datasets by data providers. Especially regions where upwelling is active
549 add difficulties to retrieving satellite observations for representing SST patterns and
550 variability. For the case of ESA CCI SSTs, it has been shown that cool biases off the
551 North West-African coast and in the Arabian Sea arise from influences of mineral

552 dust aerosol on IR retrievals of SST, and a large-scale adjustment (not used here) for
553 the dust-related biases has been devised (Merchant and Embury, 2020).

554 The RMSD is defined as the square root of the average squared difference between
555 the SST value of each dataset and the ensemble median, which is an absolute
556 measure of the distance between each single product value and the ensemble
557 median. Considering the 95% confidence interval, the global average RMSD ranges
558 from 0.02 to 0.18 °C. Extreme RMSD values (Figure 5) are concentrated in the
559 Southern ocean and correspond to the ACC, as also evidenced by the mean
560 difference (Figure 4), particularly evident in HadISST1 data. These higher RMSD
561 values are also observed in correspondence to large differences between each SST
562 product and the ensemble median that are mainly located in the western boundary
563 currents, namely, the Gulf Stream in the North Atlantic Ocean and the Kuroshio
564 Current in the North Pacific Ocean, and the ACC regions.

565 The spatial distribution of the Pearson correlation coefficient (Figure 6) highlights the
566 different behavior of HadISST1 with respect to the other seven products. In

567 particular, in the southern ocean region, the correlation falls down to values as low
568 as 0.5 or even less. Similar but less extended discrepancies are also observed for
569 BoM, NOAA Daily OISSTs, ESA-CCI, MUR25, ERA5, OSTIA and MGDSSST. In particular,
570 ESA-CCI seems well representative of the ensemble median. MUR25, ERA5, MGDSSST
571 and OSTIA are well representative of the ensemble median as well but with slightly
572 higher discrepancies than other SST products. However, the low correlation
573 especially along the coastal regions could be due to the interpolation method
574 adopted during the SST production by data providers because it is still a challenge
575 to correctly retrieve satellite observations at the coastal upwelling regions where SST
576 is highly variable.

577 The temporal variability of globally averaged monthly mean SSTs (Figure 7) clearly
578 exhibits the annual oscillation around the mean value of 20.12 °C (Figure 3). This
579 oscillation has an amplitude of about 0.6 °C as a result of the opposite seasonal
580 cycle in the southern and northern hemispheres. SST anomalies from 2003 to 2018
581 (Figure 8) are obtained by subtracting from all SST products the annual cycle of the

582 ensemble median, i.e., the mean of each month over the whole period (2003-2018).
583 Two main periods are observed with distinct mean values: the first period before
584 2012 where the temperature oscillates around a constant mean value of about
585 20.1°C and a second period where a positive (warming) trend is observed. All the
586 eight datasets show temperatures that vary coherently over all time scales but with
587 relative absolute biases in the range from zero to 0.4 °C.

588

589 **3.2.3 Global linear trends (2003-2018)**

590 Global SST trend maps have been computed for each product over the common 16
591 years period from 2003 to 2018 (Figure 9). All the datasets exhibit a global mean
592 warming SST trend ranging from 0.012 (HadISST1) to 0.022 (MGDSST) °C/year, with
593 an average value of 0.019 °C/year (ensemble median). Within the 95% confidence
594 interval, these results are close to the global ocean warming trend of 0.011 °C/year
595 from 1980 to 2005 reported in the last IPCC report (Pachauri et al., 2014) and the
596 differences are due to the different calculating period. The prominent warming

597 trends shown in all SST products are located in the subtropical North Atlantic Ocean,
598 South Indian Ocean, eastern tropical Pacific Ocean close to the American continent.
599 Especially at the Gulf Stream area all SST products (apart from HadISST1 which has
600 slightly weaker signals compared to other dataset) exhibit distinguished warming
601 trends for the period of 2003 to 2018.

602 In the North Atlantic Ocean, between 40 and 70 °N, negative trends are observed in
603 the sub polar gyre region extending up to the coastal areas of Ireland. A second
604 common negative trend area is present in the Southern Ocean at longitudes
605 centered around the Drake Passage. In the tropical Atlantic Ocean, a large area of
606 negative trends is observed only in ERA5 and a smaller area in BoM, OSTIA and
607 HadISST1. For all the other products this area is characterized by no significant
608 trends (i.e., areas where, given the $p=0.05$ limit, the null hypothesis cannot be
609 refuted) with few sparse negative trend points.

610

611 The Mediterranean Sea shows an evident positive trend in all products in contrast
612 with a close to zero trend region in the adjacent northeast Atlantic Ocean. This is in
613 agreement with what was recently published by Pisano et al. (2020) who observe
614 that, after 1990, SST in the Mediterranean Sea continues to increase in contrast with
615 the adjacent areas of the Atlantic Ocean where a pause of the general warming
616 trend occurred. The larger area of positive SST trends is present in the Indian Ocean.
617 Intense (positive) trends cover more uniformly and densely the reddish areas in ESA
618 CCI, MUR, NOAA OISST and MGDSST data, while a more patchy and less intense
619 positive trend coverage is observed in ERA5, BoM, OSTIA and HadISST1 data.

620 Besides a bias that separates the curves by a maximum of 0.2°C, the trend
621 component of the eight spatially averaged global SST time series (Figure 10a),
622 obtained using the X-11 procedure with a 2-year low-pass filter (section 3.1.2),
623 shows a very similar behaviour for all the products. The time evolution of the trend
624 component reveals an apparently neutral period until 2011 included with a single
625 maximum centered on the year 2009. After this period, a continuous warming phase

626 is observed with an increase of the temperature of nearly 0.3°C , that is, about
627 $0.06^{\circ}\text{C}/\text{year}$ which is consistent with the signal observed in the time series anomalies
628 (Figures 7 and 8).

629 In order to understand better the contribution to the significant warming trends for
630 the period of 2012-2018 observed in all SST products, we have calculated the SST
631 trend component in different ocean basins, i.e. Pacific Ocean (Figure 10b), Atlantic
632 Ocean (Figure 10c) and Indian Ocean (Figure 10d). Quantitatively, the warming
633 trends for the period 2012-2018 ranges from $0.036^{\circ}\text{C}/\text{year}$ (BoM) to $0.062^{\circ}\text{C}/\text{year}$
634 (MUR25) with $0.049^{\circ}\text{C}/\text{year}$ in the ensemble median. The major contributor to this
635 warming trend comes from the Pacific Ocean where warming trends span from
636 $0.045^{\circ}\text{C}/\text{year}$ (BoM) to $0.084^{\circ}\text{C}/\text{year}$ (MUR25) with $0.064^{\circ}\text{C}/\text{year}$ in the ensemble
637 median. The contribution from the Atlantic ($0.02^{\circ}\text{C}/\text{year}$ from BoM to $0.52^{\circ}\text{C}/\text{year}$
638 from MUR25) is smaller compared to the Pacific Ocean, and the warming trends in
639 the Indian Ocean from 2012 to 2018 are relatively very small (from $0.002^{\circ}\text{C}/\text{year}$,
640 MGDSST to $0.030^{\circ}\text{C}/\text{year}$, BoM), which are evidently exhibited in Figure 10d.

641

642 **3.2.4 Intercomparison during the early period (1982-2002)**

643 In this section, we present the intercomparison of all SST products covering the
644 period 1982-2002. First we have shown the global mean SST time series (Figure 11)
645 that covers the time period originally obtained in each SST product allows us to
646 detect the consistency and disagreement between all SST products for a longer
647 period to fully take advantage of SST products which covers the period beyond 2003
648 and 2018. As we have discussed, all the SST products are very similar to the period
649 of 2003-2018 when there are abundant observations. On the contrary, during the
650 period of early satellite era (1982-2002), the disagreement between all the SST
651 products is larger compared to the later period (2003-2018), which may be due to
652 fewer observations ingested in the SST analysis.

653 To quantify the consistency and discrepancy of SST products for the early satellite
654 era (1982-2002) we have calculated the mean climatology (Figure 12) for all SST
655 products which cover the period back to 1982 (Figure 1), including ESA-CCI, OSTIA,

ERA5, NOAA OISST, MGDSSST and HadISST1 and the differences between each member with the ensemble median (Figure 13). The mean climatology of SST during the period of 1982-2002 spans the range from 19.76°C (NOAA OISST) to 20.05°C (HadISST1) with the ensemble median as 19.79°C. The differences of each member relative to the ensemble median for the period of 1982-2002 range from 0.03°C to 0.26°C that is much higher than that during the period of 2003-2018 which range from 0.01°C to 0.1°C. The discrepancy of all SST products (Figure 13) are located in the areas that are similar to the period of 2003-2018 (Figure 4), but with amplified signals. However, in some SST products, the differences relative to the ensemble median change signs. For example, during the period of 2003-2018 the MGDSSST mean climatology is higher than the ensemble median in the eastern Indian Ocean. On the contrary, the mean climatology differences between MGDSSST and the ensemble median became negative during the period of 1982-2002. ERA5 SST is based on OSTIA SST, however, there are differences between them because ERA5 is forced by SST from an ocean model with increment based on the difference

671 between ocean analysis and OSTIA, which contains information from the OSTIA SST
672 but is not exactly identi.

673 These results are consistent with what is shown in Figure 11 that during the early
674 period of the satellite era (1982-2002, fewer SST observations) all the SST products
675 have larger differences compared to the later period (2003-2018, more SST
676 observations), indicating that observation number is the main factor to constrain the
677 climatology of all the SST products developed with different algorithms. The total
678 number of valid in situ SST observations from drifting buoys, ships, Argo floats and
679 moorings, used for bias-correcting satellite SST ingested into ERA5, HadISST1, OSTIA,
680 Daily OISST and BoM Monthly, indeed increases over time (Xu and Ignatov, 2014;
681 <https://www.star.nesdis.noaa.gov/socd/sst/iqum>).

682 In 2002, the microwave radiometer AMSR-E, which measures ocean brightness
683 temperatures through clouds, commenced operation on Aqua satellite. This
684 improvement in spatial coverage is another important factor affecting SST data

685 ingested into OSTIA, ERA5, MGDSSST and MUR25, and it is notable that all SST
686 products studied converge more after 2003 compared to before 2003.

687

688

689 **3.2.5 Niño 3.4 Index**

690

691 In order to have a deeper evaluation of the quality of the SST for climate studies, we
692 investigated the capability of representing the climate modes in all SST products for
693 the period of 1982-2018 in order to include more ENSO events, here the Nino3.4
694 index (Trenberth 2020). Niño 3.4 is one of the most used indexes to monitor the
695 occurrence and variability of El Niño and la Niña events, defined as the average
696 equatorial SST anomalies across the Pacific in the region 5°S-5°N, 170W°-120W°.
697 Figures 14 show the time evolution of the Niño 3.4 index during the 1982-2018
698 "common period" for each product time series after applying a 5-month running
699 mean filter.

700 All products give evidence of the very strong El Niño events in the period selected.
701 The procedure used here to independently compute the Niño 3.4 index for all the
702 data sets is the same applied by Trenberth (2020). The time evolution of the Niño
703 3.4 SST anomaly is nearly identical for all the products with minor differences (Figure
704 14). The three strong El Niño events that occurred during this investigation period,
705 namely 1982-1983, 1997-1998, and 2015-2016, are reproduced, with a similar
706 intensity, by all products. Moreover, the larger intensity of the El Niño positive
707 anomalies with respect to the negative La Niña events confirms the asymmetry
708 hypothesis of Monahan and Dai (2004).

709

710 **4. Data Maturity Matrix**

711 The concept of the data maturity matrix is to evaluate the basic characteristics of a
712 dataset initiated by the World Meteorological Organization (WMO) to develop
713 technical guidance and standards for collecting, processing, and managing datasets.
714 The assessment of the maturity of the individual dataset is essential to guarantee

715 and further improve the documentation, storage, and dissemination of datasets that
716 are applicable for users (Peng et al., 2019).

717 The System Maturity Matrix (SMM) for Climate Data Records (CDRs) is first
718 developed in the Coordinating Earth Observation Data Validation for Reanalysis for
719 Climate Services project (CORE-CLIMAX) (Su *et al.*, 2018). The objective is to
720 develop a tool to evaluate different aspects of the CDRs combining scientific and
721 engineering views. (EUMETSAT, 2014). In the SMM framework assessments are made
722 in six major category areas and a score of 1 to 6 is assigned that reflects the
723 maturity of the CDR with respect to a specific category;

724

- 725 1. Software readiness
- 726 2. Metadata
- 727 3. User documentation
- 728 4. Uncertainty characterization
- 729 5. Public access, feedback, and update

730 6. Usage

731 However, the assessment of maturity can only reflect aspects of process maturity. It
732 does not interpret the scientific quality of a dataset. For example, a mature product
733 may not be scientifically reliable thus the maturity matrix only provides the
734 assessment of fitness-of-purpose of a given product for climate service practitioners
735 in terms of the categories mentioned above.

736 Additionally, the SMM scores recognize that at the early evaluation stage in the life
737 cycle of the product the low scores in some of the categories do not demonstrate
738 the possible future maturity of the dataset. Instead, low SMM scores indicate a
739 recently released and evolving product at a less mature stage being made available
740 to users.

741 In the context of the C3S_511 project, the aim of our assessment is to evaluate the
742 maturity of the dataset instead of the whole CDRs. We have adopted the SMM
743 methodology of the CORE-CLIMAX for our use to evaluate individual datasets. We
744 defined our matrix as the Maturity Matrix (MM) since we evaluate the dataset

745 instead of the system of the dataset. Not all the categories from CORE-CLIMAX are
746 included because some of them are not suitable for our usage. A guidance
747 document is developed in the framework of C3S_511 project , and the assessment
748 scores given in this study are based on our guidance document
749 ([https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+M](https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+Maturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control)
750 [aturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control](https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+Maturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control)). The MM, as
751 important as the scientific quality, provides data providers important information in
752 which aspects they need to improve their dataset for potential easy access and
753 usage for users.

754 The MM of ESA-CCI and ERA5 SST (Table 2), showing that ESA-CCI SST is much
755 more mature compared to ERA5 SST in terms of documentation, uncertainty
756 characterization, and usage. As we mentioned above, low MM scores do not suggest
757 the scientific quality of ERA5 SST is lower than ESA-CCI SST. However, in terms of
758 the documentation of the dataset, ESA-CCI SST is much more advanced than ERA5
759 SST.

760 In this study we have extended the evaluation of the MM to the dataset outside of
761 CDS (Table 2). Due to the length limit, detailed defensible traces to score MM for
762 SST products are given in the Appendix. In terms of metadata, MGDSST has a lower
763 score because it is provided in text format not following any standards with limited
764 global attributes. The rest of the SST analysis products follow the NetCDF format
765 and CF compliance with detailed information on Metadata. Compared with other
766 datasets, BoM, MGDSST and MUR25 lack user documentation including the formal
767 description of scientific methodology, validation report and product user guide. A
768 formal user guide is not found for HadISST1 either. Very few SST products (OSTIA
769 and ESA-CCI SST) have automated quality monitoring in terms of the uncertainty
770 characterisation category. Thanks to GHR SST activities, all GHR SST L4 products
771 follow internationally agreed GHR SST specifications, which provide uncertainty
772 calculations. Several SST analysis products (HadISST1, MGDSST, BoM and ERA5)
773 have very limited validation, standards or uncertainty quantification documentation.
774 All SST products are publicly available via the online portal, except that BoM SST is
775 available on request from the data provider via their website. However, the

776 versioning, user feedback, and updates to records in the category of public access to
777 SST products are not fully developed for BoM and MGD SST. All SST products except
778 ERA5 are widely used in multiple research fields, and most of them either support
779 decision support systems or usage and benefits of the SST products are emerging.

780 Overall, most of the SST products are well documented and user friendly. As we
781 mentioned before, this scoring does not judge the scientific quality of the SST
782 product. However, the low scoring of some products might give data providers
783 important information to improve the documentation of their products in order to
784 make the product more user friendly.

785

786 **5. Summary of evaluations**

787 SST is an essential climate variable (ECV) to assess the state of the global climate
788 system and monitor its variations on interannual and (multi)decadal timescales.

789 Accurate SST observations at high spatial and temporal resolution over a long-term

790 period are needed to evaluate the present state of the oceans and the impact of
791 global surface warming.

792 In this report, eight different SST datasets have been analyzed and intercompared
793 for the overlapping period from 2003-2018. The ESA CCI SST v.2.1 and ERA5
794 reanalysis are available through the C3S Climate Data Store while the remaining six
795 datasets (OSTIA, HadISST1, NOAA Daily OISST, MUR, MGDSST, BoM) are provided
796 outside the CDS. All these datasets provide global gap-free (optimally interpolated)
797 SST maps but at different spatial and temporal resolutions. Then, to be comparable,
798 all the datasets have been gridded to a common grid (i.e., $1^\circ \times 1^\circ$) and averaged to a
799 common temporal frequency (i.e., monthly) over the overlapping period from 2003
800 to 2018. Finally, the average of the median of all the datasets (namely, the Ensemble
801 median) has been defined in order to analyze differences among these datasets.

802 In general, all the SST datasets show consistent climatological spatial patterns
803 (section 3.2). The global monthly mean and anomaly SST time series of these
804 datasets show very good agreement. When compared to the Ensemble median,

805 higher differences (in terms of mean difference, root-mean-square difference and
806 correlation) are found in correspondence to the main current systems, such as the
807 Gulf Current, the Kuroshio Current and the Antarctic circumpolar current. These
808 discrepancies are due to the different retrieval methods used to derive the spatially-
809 complete SST analyses. Differences can originate from several factors: interpolation
810 technique and related configuration (e.g. observation/background error correlation
811 scales), interpolation grid size, input data bias-correction and, if present, the
812 correction applied to obtain the foundation temperature or the temperature at 0.2
813 m. As an example, OSTIA, MUR25, MGDSSST and ERA5 (via OSTIA from 2007
814 onwards) are the only L4 analyses included in the study that ingested microwave SST
815 data. Since these datasets (OSTIA, MUR25, MGDSSST and ERA5) would ingest possibly
816 cooler daytime SST observations over cloudy regions, they may therefore exhibit
817 slightly cooler biases after 2002 compared with the other analyses that ingest only
818 infrared SST observations and in situ data. This effect may be offset in some
819 analyses, such as BoM Monthly and NOAA Daily OISST v2.1, where in situ data at 0.2
820 m to several meters depth are used to bias-correct the infrared AVHRR SST data.

821 However, on average, the Taylor diagram confirms the very close similarity between
822 the different datasets.

823 All the datasets reproduce very similar spatial patterns of global SST trends (section
824 3.3). In addition, global mean warming trends as estimated from all the datasets are
825 consistent (within the 95% confidence interval) with the global ocean warming trend
826 as reported in the last IPCC report, estimated at 0.011 °C/year from 1980 to 2005.

827 The linear trend in different basins shows that the main contributor from 2012 to
828 2018 is the Pacific Ocean.

829

830 The global mean SST time series for the whole period originally covered by all the
831 SST products reveals that the disagreement between all SST products is larger in the
832 early period (1982-2002) of the satellite era during which fewer observations are
833 available compared to the later period (2003-2018) of the satellite era. Specifically,
834 the difference between each ensemble member and the ensemble median ranges
835 from 0.03°C to 0.26°C during the early period (1982-2002) and from 0.01°C to 0.1°C

836 during the later period (2003-2018), respectively. It indicates that the observations
837 ingested into each SST analysis plays a significant role in constraining the SST
838 climatology. Satellite sensor improvements (e.g., the launch of AMSR-E in 2002 that
839 could measure ocean brightness temperatures through clouds) is another important
840 factor affecting SST quality after 2003. Note that the impact of natural variability on
841 SST climatology is embedded in the analysis, that is, it is difficult to differentiate
842 from the constraint of SST observations on the SST climatology. Additionally, the
843 discrepancy between each product due to algorithms, observations ingested etc. is
844 very small compared to the significant warming trends shown in the linear trends
845 and time series.

846

847 Finally, the tropical Pacific region has been selected, as a test case, to assess the
848 capability of the different SST products, with a longer common temporal period, to
849 capture the main modes of variability of a well-known climate oscillatory mode, e.g.
850 ENSO. This analysis confirmed the close similarity of all the five datasets selected
851 and their capability to reproduce, in the same way, the main components of the

852 tropical Pacific region space and time variability at time scales compatible with the
853 length of the selected time series.

854

855 The maturity matrix score of all SST products (Table 2), that aims to demonstrate the
856 maturity of data documentation during the life cycle of one product, shows that
857 most of SST products are user friendly and provide sufficient information. Low scores
858 of some SST products (Table 2) indicate a direction where data providers could
859 improve their products in terms of data documentation, storage and dissemination
860 for users. Thanks to the GHRSSST effort, all GHRSSST products are well documented
861 for their uncertainty characteristics (GHRSSST Science Team, 2012).

862

863 **6. Recommendations to users**

864 All the datasets presented here provide state-of-the-art spatially-complete SST
865 products at the global scale. These datasets are characterized by different spatial

866 and temporal resolutions and temporal coverage that can fulfil the requirements of
867 a large variety of users.

868 Intercomparison results and a test case analysis suggest these datasets provide an
869 accurate representation of the SST spatio-temporal variability. These datasets can
870 then be used for fundamental climate applications compatible with the length of
871 each time series, such as long-term monitoring of SST changes (e.g., trends) and
872 comparison to or initialization of numerical models. Other target applications include
873 the use of these datasets in the definition of climatic indices, assessment and
874 monitoring of weather extreme events (including marine heatwaves) and their
875 impact on marine ecosystem, and related services.

876

877 In this study we have interpolated all SST products into 1 degree and monthly
878 frequency in order to facilitate intercomparison studies. However, to understand
879 which dataset is suitable for specific case studies where spatial and/or temporal
880 resolution are critical, such as the separation of the Gulf Stream and the diurnal

881 cycle of the SST products, specific intercomparison studies are required. Indeed, in
882 the framework of the GHRSSST intercomparison team, several such intercomparison
883 tasks are ongoing and scientific findings will be available in the near future.

884

885 Finally, users are strongly encouraged to consider also the type of SST offered by
886 each producer and to distinguish between, e.g., skin SST, subskin or SSTdepth, and
887 foundation SST according to the specific application for which the data are intended
888 to be used. For example, in conditions of high insolation and low surface ocean
889 mixing skin SST is strongly impacted by diurnal warming, SST at 0.2 m depth
890 somewhat impacted, SSTdepth below 1 m minimally impacted and foundation SST
891 has no diurnal signature (Gentemann et al., 2009; Minnett and Kaiser-Weiss, 2012).
892 In our study, we have used SSTdepth, foundation SST and SST at 0.2 m depth, which
893 appears to have had minor impacts on the results.

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900 The BoM Monthly OI SST analysis GHR SST L4 format files were provided by the
901 Australian Bureau of Meteorology and are available on request from
902 <http://www.bom.gov.au/climate/data-services/data-requests.shtml>.

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906 authors declare no conflict of interest.

907

908 **Data Availability Statement**

909 The download website of all datasets used in this study has been included in the
910 manuscript in section 2.

911

912 **Appendix**

913 This section provides defensible traces for Maturity Matrix Score given to all SST
914 products shown in Table 2 based on the guidance document

915 ([https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+M](https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+Maturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control)
916 [aturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control](https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+Maturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control)) developed within
917 the C3S independent assessment project (C3S_511).

918

919 1. ESA-CCI SST

920 Metadata

921 *Standard* (Score: 6/6)

922 The ESA CCI SST data files follow the GHR SST Data Specification v2.0 (GDS) and are
923 provided in NetCDF-4 format CompactFlash (CF)-1.5 compliant. Files specifications

924 are fully detailed in the ESA CCI Product User Guide (PUG). The NetCDF files contain
925 detailed metadata describing the data by means of global attributes, which are
926 applicable to the whole file, and variable attributes, which apply to a specific data
927 field.

928

929 *Collection Level (Score: 6/6)*

930 The ESA CCI SST data files follow the GHR SST Data Specification v2.0 (GDS). Global
931 attributes provide all information available on the data and relative references. In
932 addition the Product Specification Document (PSD) with detailed information of
933 Metadata is available.

934

935 User Documentation

936 *Formal description of scientific methodology (Score: 6/6)*

937 The formal description of the ESA CCI SST product is detailed in the Algorithm
938 Theoretical Background Document (ATBD), published by the data provider, which
939 describes and justifies the algorithms used for obtaining SST estimates. A synthesis

940 of the formal ATBD is also available in the CDS. In addition, the ESA CCI SST dataset
941 has been published in Nature Scientific Data (Merchant et al., 2019).

942

943 *Formal validation report* (Score: 6/6) For the formal validation report of the ESA CCI
944 SST L4 product users can refer to Merchant et al. (2019), Product User Guide (PUG),
945 and Climate Assessment Report (CAR).

946

947 *Formal product user guide* (Score: 6/6)

948 The formal product user guide ESA CCI SST product is published by the data
949 provider (PUG). A synthesis of the formal user product guide is also available in the
950 CDS.

951

952 Uncertainty Characterization

953 *Standards* (Score: 6/6)

954 Uncertainty characterization follows the internationally agreed GHR SST standard
955 specifications, which are detailed in the GHR SST Data Specification v2.0 (GDS)
956 document.

957

958 *Validation* (Score: 6/6)

959 A detailed and comprehensive validation of the ESA CCI SST L4 product is provided
960 in the Product User Guide (PUG), Climate Assessment Report (CAR), and in Merchant
961 et al. (2019). The validation of the ESA CCI SST L4 product is based on different
962 procedures, from automated and visual inspection to comparison of SST data with
963 co-located in situ measurements.

964

965 *Uncertainty quantification* (Score: 6/6)

966 Uncertainty in the ESA CCI SST L4 data at each location (i.e., the analysed_sst field in
967 the NETCDF file) is quantified and provided (i.e., in the analysis_error field) through
968 an analysis quality methodology. The methodology used to derive the uncertainty is
969 based on the optimal interpolation theory and described in the ATBD and PUG,

970 giving comprehensive information of validation of the quantitative uncertainty
971 estimates and error covariance.

972

973 *Automated Quality monitoring* (Score: 6/6)

974 The identification of valid observations for SST estimation and algorithms used in
975 the preparatory preprocessing are described in the ATBD and PUG. Moreover, a
976 confidence level on a scale 0 to 5 is provided for each SST as a quality indicator,
977 following the international GHRSSST conventions. Five indicates the highest
978 confidence. Quality levels 4 and 5 should be used for climate applications.
979 Automated check is implemented to valid the data quality (Merchant et al., 2019).

980

981 Public access, feedback and update

982 *Public Access/Archive* (Score: 5/6)

983 The ESA CCI SST dataset v2.0 is available on the data provider's website. Detailed
984 information available in the PUG. However, the source code is not publically
985 available.

986

987 *Version* (Score: 6/6)

988 The version is fully established by the data provider.

989

990 *User feedback* (Score: 6/6)

991 The ESA CCI SST dataset v2.0 is also provided through the CMEMS and is part of

992 GHR SST. Within CMEMS, a Multi-Year Product Quality Working Group is established

993 with the aim of periodically assessing the status of the CMEMS climate data records,

994 including ESA CCI SST, integrating users' needs and feedback. Feedback from users

995 are also included in the Climate Assessment Report (CAR). In addition, ESA CCI data

996 provider provides an email contact to collect users' feedback.

997

998 *Updates to record* (Score: 6/6)

999 Currently the ESA CCI SST dataset v2.0 covers the period from late-1981 to 2018.

1000 Updates through to the near-present are expected this year (2020). Extensions are

1001 expected to be produced by the Copernicus Climate Change Service (C3S) with only

1002 ~5 days delay to real time

1003

1004 Usage

1005 *Research* (Score: 6/6)

1006 The ESA CCI SST dataset v.2.0 is very recent. However, it has already been used in

1007 some research publications.

1008

1009 *Decision support system* (Score: 6/6)

1010 ESA-CCI SST is part of the ESA Climate Change Initiative, and one of the essential

1011 climate variables. The objective of ESA-CCI SST is to establish a long term data

1012 record to monitor the global climate system required by UNFCCC (<http://cci.esa.int/>)

1013 for decision making.

1014

1015 2. ERA5 SST

1016 Metadata

1017 *Standard* (Score: 6/6)

1018 ERA5 SST data can be downloaded from the CDS in both GRIB and NetCDF formats.

1019 The native data format is GRIB, but they can be converted to NetCDF format

1020 through the CDS. In NetCDF global attributes reference to CF-1.6 conventions is

1021 made. This represents a mature state-of-the-art metadata standard according to

1022 guidance.

1023

1024 *Collection Level* (Score 5/6)

1025 The standardized attributes on the collection level of the dataset are sufficient to

1026 understand the data's origins without further documents, including standardized

1027 information on how to obtain raw data and its preprocessing procedures.

1028 Note: The collection level in this case includes the ECMWF confluence wiki.

1029 (<https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation>)

1030

1031 User Documentation

1032 *Formal description of scientific methodology* (Score 6/6)

1033 The scientific description is comprehensive and publicly available in the form of a
1034 scientific report/ATBD and elibrary of ECMWF. The description is kept up to date
1035 with the updated dataset. There is also a peer reviewed methodological journal
1036 paper published.

1037

1038 *Formal validation report* (Score: 3/6)

1039 There is no formal validation report for ERA5 SST. The ERA5 documentation available
1040 at confluence wiki can be regarded as a user guide but does not have any clear
1041 version number with a publication date and is a document that is changing. Due to
1042 the nature of ERA5 being in development it makes sense to have an evolving
1043 documentation, but the creation of a formal product validation report in the future
1044 is recommended. An assessment report evaluating HadISST2 and OSTIA SST datasets
1045 (from which ERA5 SST is built) is available (Hirahara 2016).

1046

1047 *Formal product user guide* (Score 6/6)

1048 There is a regularly updated comprehensive formal Product User Guide (PUG) for the
1049 dataset publicly available.

1050 Note: In this case the confluence wiki is regarded as the Product User Guide (PUG).

1051

1052 Uncertainty Characterization

1053 Standards (Score 3/6)

1054 Uncertainty information follows standard nomenclature.

1055 Note: In this case the ensemble members are regarded as uncertainty measures.

1056

1057 *Validation* (Score: 3/6)

1058 A formal validation report of ERA5 SST is not available. However, an assessment
1059 report evaluating HadISST2 and OSTIA SST datasets (from which ERA5 SST is built) is
1060 available (Hirahara 2016), and users can refer to HadISST2 and OSTIA
1061 documentation.

1062

1063 *Uncertainty quantification* (Score 3/6)

1064 A comprehensive uncertainty quantification of systematic and random effects is
1065 available.

1066 Note: In this case the ensemble members are regarded as uncertainty measures.
1067

1068 *Automated quality monitoring* (Score 2/6)

1069 There is no automated quality monitoring documented for the dataset.

1070 Note: Although there is no automated quality monitoring documented, data
1071 assimilation itself could be regarded as a quality check.

1072

1073 Public access, feedback and updates

1074 *Access and Archive* (Score 5/6)

1075 The dataset is publicly available. The different versions of data including
1076 documentation and source code is archived by the data provider. Source code is not
1077 publically available.

1078

1079 *Version Control* (Score 6/6)

1080 There is full information on version control of documentation, data and/or metadata
1081 available for the dataset. The documented version control information is fully
1082 traceable from the files.

1083 Note: In this case the version control is referring to the confluence wiki.

1084

1085 *User Feedback (Score 6/6)*

1086 There is a public reach-out/feedback form/contact point for collecting feedback for
1087 the dataset. There are regular events, groups, 2-way feedback mechanisms, etc.
1088 organized by the data provider. The established feedback fed back into data
1089 production is documented, including third party international data quality
1090 assessment results.

1091

1092 *Updates to Record (Score 6/6)*

1093 There are regular operational updates available for the dataset, depending on the
1094 availability of input data and including improved methodology.

1095

1096 Usage

1097 *Research* (Score: 3/6)

1098 Although ERA5 reanalysis has been largely used in many research publications, it

1099 seems that there are few relevant publications based on ERA5 SST data (as e.g.

1100 Wang et al., 2020). This could arise from the prevalent use of ERA5 in atmospheric

1101 research.

1102

1103 *Decision support system* (Score: 1/6)

1104 To the evaluators' knowledge the product is not used yet for the decision support

1105 system. .

1106

1107 3. OSTIA SST

1108 Metadata

1109 *Standard* (Score: 6/6)

1110 The OSTIA SST data files are provided in NetCDF-4 format CF-1.5 compliant through

1111 CMEMS and the Recommended GHR SST Data Specification (GDS). File specifications

1112 are fully detailed in the OSTIA Product User Manual (PUM) available in CMEMS. The
1113 NetCDF files contain detailed metadata describing the data by means of global
1114 attributes, which are applicable to the whole file, and variable attributes, which apply
1115 to a specific data field.

1116

1117 *Collection Level* (Score: 6/6)

1118 Global attributes provide all information available on the data and relative
1119 references. In addition the Product User Manual (PUM,) with detailed information on
1120 Metadata is available.

1121

1122 User Documentation

1123 *Formal description of scientific methodology* (Score: 6/6)

1124 The formal description of the OSTIA product is detailed in the peer-reviewed paper
1125 (Good et al., 2020), published by the data provider, which describes and justifies the
1126 algorithms used for obtaining SST estimates. A synthesis of the Product User Manual
1127 (PUM) is also available in the CMEMS.

1128

1129 *Formal validation report* (Score: 6/6)

1130 For the formal validation report of the OSTIA product users can refer to the Quality
1131 Information Document (QUID) available in the CMEMS service.

1132

1133 *Formal product user guide* (Score: 6/6)

1134 The formal product user guide OSTIA product is published by the data provider
1135 (PUM) as a peer-reviewed journal article Good et al. (2020). A synthesis of the formal
1136 user product guide (PUM) is also available in the CMEMS.

1137

1138 Uncertainty Characterization

1139 *Standards* (Score: 6/6)

1140 Uncertainty characterization follows the internationally agreed GHR SST standard
1141 specifications, which are detailed in the GHR SST Data Specification v2.0 (GDS)
1142 document (GHR SST Science Team, 2012).

1143

1144 *Validation* (Score: 6/6)

1145 A validation of the OSTIA product is provided in the Quality Information Document
1146 through CMEMS. The validation of the OSTIA SST product is based on comparison
1147 of SST data with co-located in situ measurements.

1148

1149 *Uncertainty quantification* (Score: 6/6)

1150 Uncertainty in the OSTIA data at each location (i.e., the analysed_sst field in the
1151 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an
1152 analysis quality methodology. The methodology used to derive the uncertainty is
1153 produced using a special "observation influence" analysis (Good et al., 2020).

1154

1155 *Automated Quality monitoring* (Score: 6/6)

1156 Automatic quality is monitored during the production of the SST product. The real-
1157 time OSTIA SST analysis is routinely validated by the UK MetOffice against the
1158 GHRSSST Multi-product ensemble (<http://ghrsst-pp.metoffice.gov.uk/ostia->

1159 website/gmpe-monitoring.html) and Argo SST ([http://ghrsst-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)

1160 [pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)).

1161

1162 Public access, feedback and update

1163 *Public Access/Archive* (Score: 5/6)

1164 The OSTIA SST is available on the CMEMS website. Detailed information available in
1165 the PUM. However, the source code is not publically available.

1166

1167 *Version* (Score: 6/6)

1168 The version is fully established by the data provider.

1169

1170 *User feedback* (Score: 6/6)

1171 The OSTIA is provided through the CMEMS and is part of GHR SST. Within CMEMS, a
1172 Multi-Year Product Quality Working Group is established with the aim of periodically
1173 assessing the status of the CMEMS data records, including OSTIA, integrating users'
1174 needs and feedback.

1175

1176 *Updates to record* (Score: 6/6)

1177 Currently the OSTIA SST dataset covers the period from late-1981 to 2018. Updates

1178 through to the near-present are expected this year (2020). Extensions are expected

1179 to be produced by the CMEMS with only ~5 days delay to real time

1180

1181 Usage

1182 *Research* (Score: 6/6)

1183 The current version of OSTIA SST is very recent. However, it has already been used

1184 in some research publications.

1185

1186 *Decision support system* (Score: 6/6)

1187 OSTIA SST is part of the CMEMS project and the information derived from SST

1188 products is used in the CMEMS ocean state report for decision making.

1189

1190 4. BoM

1191 Metadata

1192 *Standard* (Score: 6/6)

1193 The BoM SST files are provided in the GHRSSST Data Specification version 1.7 NetCDF
1194 classic format CF-1 (Beggs and Pugh, 2009) on request from the data providers. The
1195 NetCDF files contain detailed metadata describing the data by means of global
1196 attributes, which are applicable to the whole file, and variable attributes, which apply
1197 to a specific data field.

1198

1199 *Collection Level* (Score: 5/6)

1200 Global attributes provide all information available on the data and relative
1201 references. However, the reference shown in the Metadata (Beggs and Pugh, 2009) is
1202 not accessible at the moment of writing this report although it is available by
1203 request from library@bom.gov.au.

1204

1205 User Documentation

1206 *Formal description of scientific methodology* (Score: 4/6)

1207 The formal description of the BoM Monthly OI SST is published in a conference
1208 paper (Smith et al., 1999) and a peer-reviewed paper (Beggs et al., 2011), however
1209 the peer-reviewed paper focuses on the BoM higher resolution daily 1/12 degree
1210 regional analyses available from 2006, which uses a modified version of the Fortran
1211 "SIANAL" code used to produce the original BoM Weekly and Monthly OI SST
1212 analyses.

1213

1214

1215 *Formal validation report* (Score: 2/6)

1216 BoM Monthly OI 1 degree L4 SST is part of the GHR SST suite of L4 products, and
1217 intercomparison of the BoM higher resolution daily SST analyses with other SST
1218 products have been published in peer reviewed journals (Beggs et al., 2011; Dash et
1219 al., 2012; Martin et al., 2012). However, the only previously published comparison of
1220 the lower resolution BoM Weekly 1 degree OI SST analysis with other SST analysis
1221 products is in a BoM Operations Bulletin (Zhong and Beggs, 2008).

1222

1223 *Formal product user guide* (Score: 4/6)

1224 The description of the BoM Monthly OI SST analysis methodology is published in
1225 Smith et al. (1999) and Beggs et al. (2011), and a user guide is provided (Beggs and
1226 Pugh, 2009). However, (Beggs and Pugh, 2009) is not accessible at the moment of
1227 writing this report although it is available by request from library@bom.gov.au.

1228

1229

1230 Uncertainty Characterization

1231 *Standards* (Score: 6/6)

1232 Uncertainty characterization follows the internationally agreed GHR SST standard
1233 specifications (analysis_error), which are detailed in the GHR SST Data Specification
1234 v2.0 (GDS) document (GHR SST Science Team, 2012).

1235

1236 *Validation* (Score: 5/6)

1237 No validation report is found for BoM SST. However, BoM is part of the GHR SST
1238 community and intercomparison activities of the BoM Daily Global SST analyses have
1239 been performed in the framework of GHR SST (Dash et al., 2011; Martin et al., 2011).

1240 Although routine verification of the BoM Global Daily 0.25 degree OI SST analysis
1241 (GAMSSA) are performed by UK MetOffice (<http://ghrsst-pp.metoffice.gov.uk/ostia->
1242 [website/gmpe-argo-stats.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)) and NOAA/NESDIS/STAR
1243 (<https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4>), there are no routine
1244 verifications of the BoM Monthly or Weekly OI SST analyses.

1245

1246

1247 *Uncertainty quantification* (Score: 6/6)

1248 Uncertainty in the BoM data at each location (i.e., the analysed_sst field in the
1249 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an
1250 analysis quality methodology (Beggs et al., 2011).

1251

1252 *Automated Quality monitoring* (Score: 1/6)

1253 No Automatic quality is provided.

1254

1255 Public access, feedback and update

1256 *Public Access/Archive* (Score: 4/6)

1257 BoM Monthly SST product is available on request from the data provider website for
1258 both real-time and archived GHRSSST L4 files.

1259

1260 *Version* (Score: 2/6)

1261 No information is found for the version control for BoM SST.

1262

1263 *User feedback* (Score: 3/6)

1264 Data providers collect and evaluate feedback from the scientific community through
1265 the data provider's website, but no feedback mechanisms set up from data
1266 providers.

1267

1268 *Updates to record* (Score: 5/6)

1269 BoM Daily, Weekly and Monthly SST analyses are published in real time for climate
1270 monitoring on the BoM website.

1271

1272 Usage

1273 *Research* (Score: 4/6)

1274 The BoM Weekly and Monthly SST analyses have been used by the BoM for
1275 research, especially climate studies.

1276

1277 *Decision support system* (Score: 6/6)

1278 BoM Monthly SST is an operational SST analysis which serves for climate monitoring
1279 that is an essential service of the Australian Government Bureau of Meteorology.

1280

1281 5. MGDSSST

1282 Metadata

1283 *Standard* (Score: 3/6)

1284 The MGDSSST is provided in the txt format and variable attributes are limited.

1285

1286 *Collection Level* (Score: 2/6)

1287 There is limited information about standard attributes, but extra information
1288 published in the data provider's website is needed to use and understand the data.

1289

1290 User Documentation

1291 *Formal description of scientific methodology* (Score: 3/6)

1292 Limited information is provided on the data provider's website, but the method is
1293 documented in two non peer-reviewed reports

1294

1295 *Formal validation report* (Score: 4/6)

1296 No JMA validation report is found for MGD SST at the time of writing this report.

1297 However, MGD SST was compared with other SST analyses and independent

1298 observations in Martin et al. (2012) and Fiedler et al. (2019a) for the periods 2010

1299 and 1992 to 2011. The UK MetOffice routinely compares MGD SST with the GHR SST

1300 Multi-product ensemble ([http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)

1301 [monitoring.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)) and Argo SST ([http://ghrsst-pp.metoffice.gov.uk/ostia-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)

1302 [website/gmpe-argo-stats.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)).

1303

1304 *Formal product user guide* (Score: 3/6)

1305 Limited product user guide from the data provider.

1306

1307 Uncertainty Characterization

1308 *Standards* (Score: 1/6)

1309 No information is available at this stage.

1310

1311 *Validation* (Score: 6/6)

1312 MGDSST is part of the GHRSSST and intercomparison with other SST products has

1313 been performed and published in peer-review journals (Fiedler et al., 2019a; Martin

1314 et al., 2012).

1315

1316 *Uncertainty quantification* (Score: 1/6)

1317 No uncertainty quantification is found.

1318

1319 *Automated Quality monitoring* (Score: 2/6)

1320 No automatic quality is monitored during the production of the SST product.

1321

1322 Public access, feedback and update

1323 *Public Access/Archive* (Score: 4/6)

1324 The MGDSSST is publicly accessible from the data provider's website and brief

1325 information of the data is provided in the data provider's website.

1326

1327 *Version* (Score: 2/6)

1328 No information is found for the version control.

1329

1330 *User feedback* (Score: 3/6)

1331 Data providers collect and evaluate feedback from the scientific community through

1332 the data provider's website.

1333

1334 *Updates to record* (Score: 4/6)

1335 MGDSSST is published in real time for climate monitoring and Numerical Weather

1336 Prediction on the data provider's website.

1337

1338 Usage

1339 *Research* (Score: 6/6)

1340 The data has already been used in some research publications.

1341

1342 *Decision support system* (Score: 6/6)

1343 MGDSST is an operational SST analysis which serves for climate monitoring and

1344 Numerical Weather Prediction that is an essential service of the Japanese

1345 Meteorological Agency (JMA).

1346

1347 6. MUR25

1348 Metadata

1349 *Standard* (Score: 6/6)

1350 The MUR25 SST is provided in NetCDF format. The NetCDF files contain detailed

1351 metadata describing the data by means of global attributes, which are applicable to

1352 the whole file, and variable attributes, which apply to a specific data field.

1353

1354 *Collection Level* (Score: 6/6)

1355 Global attributes provide all information available on the data and relative
1356 references.

1357

1358 User Documentation

1359 *Formal description of scientific methodology* (Score: 6/6)

1360 The formal description of the MUR25 product is detailed in the peer-reviewed
1361 journal (Chin et al., 2017), published by the data provider.

1362

1363 *Formal validation report* (Score: 4/6)

1364 No formal validation report is available, however, the validation is performed in the
1365 peer-reviewed paper (Chin et al., 2017). Additional validation of the 1km product
1366 occurred with direct comparisons with the Saildrone autonomous vehicle with the
1367 published article. The validation focused on an exemplary coastal area, the
1368 California/Baja Coast.

1369

1370 *Formal product user guide* (Score: 2/6)

1371 No formal product user guide is available for MUR25 SST.

1372

1373 Uncertainty Characterization

1374 *Standards* (Score: 6/6)

1375 Uncertainty characterization follows the internationally agreed GHR SST standard

1376 specifications, which are detailed in the GHR SST Data Specification v2.0 (GDS)

1377 document.

1378

1379 *Validation* (Score: 6/6)

1380 Intercomparison of MUR25 has been performed in the framework of GHR SST.

1381

1382 *Uncertainty quantification* (Score: 6/6)

1383 Uncertainty in the MUR25 data at each location (i.e., the analysed_sst field in the

1384 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an

1385 analysis quality methodology.

1386

1387 *Automated Quality monitoring* (Score: 4/6)

1388 No automatic quality monitoring is found for MUR25 SST product, but the 1 km
1389 resolution version of the MUR SST analysis is routinely validated with the GHR SST
1390 Multi-product ensemble ([http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)
1391 [monitoring.html](https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4); <https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4>). Since
1392 Argo SST are ingested into MUR25 they are not useful for verification.

1393

1394 Public access, feedback and update

1395 *Public Access/Archive* (Score: 5/6)

1396 The MUR25 SST is published in the data provider's archive center. However, source
1397 code is not publically available.

1398

1399 *Version* (Score: 6/6)

1400 The version is fully established by the data provider.

1401

1402 *User feedback* (Score: 6/6)

1403 Public contact information is given in the data provider's website for users to give
1404 feedback. Users can give all feedback through the Physical Oceanography

1405 Distributed Active Archive Center (PO.DAAC) user services and forum. All feedback

1406 is publicly available.

1407

1408 *Updates to record* (Score: 5/6)

1409 Regular updates are available from the data provider. There is no immediate

1410 production of interim data products.

1411

1412 Usage

1413 *Research* (Score: 6/6)

1414 The MUR25 is used in research in multiple fields.

1415

1416 *Decision support system* (Score: 3/6)

1417 No decision support system is found for MUR25 SST, however use is occurring and

1418 benefits are emerging.

1419

1420 7. NOAA Daily OISSTv2.1 SST

1421 Metadata

1422 *Standard* (Score: 6/6)

1423 The NOAA Daily OISST data files are provided in NetCDF-4 format CF-1.0 compliant
1424 data provider's website. The NetCDF files contain detailed metadata describing the
1425 data by means of global attributes, which are applicable to the whole file, and
1426 variable attributes, which apply to a specific data field.

1427

1428 *Collection Level* (Score: 6/6)

1429 Global attributes provide all information available on the data and relative
1430 references.

1431

1432 User Documentation

1433 *Formal description of scientific methodology* (Score: 6/6)

1434 The formal description of the NOAA Daily OISST v2.1 is provided in the data
1435 provider's website (<https://www.ncdc.noaa.gov/oisst>), third party data resource
1436 website (https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-v2.1) and is

1437 also detailed in several peer-reviewed papers (Reynolds et al., 2007; Banzon et al.,
1438 2016; Huang et al., 2020), published by the data provider, which describe and justify
1439 the algorithms used for obtaining SST estimates.

1440

1441 *Formal validation report* (Score: 6/6)

1442 Formal validation report of NOAA Daily OISST is along with data access.

1443

1444 *Formal product user guide* (Score: 6/6)

1445 The formal product user guide is provided in the peer review journal (Banzon et al.,
1446 2016).

1447

1448 Uncertainty Characterization

1449 *Standards* (Score: 6/6)

1450 Uncertainty characterization follows the internationally agreed GHR SST standard
1451 specifications, which are detailed in the GHR SST Data Specification v2.0 (GDS)
1452 document.

1453

1454 *Validation* (Score: 6/6)

1455 A validation of NOAA Daily OISST is provided through peer-review journals (Dash et
1456 al., 2012; Martin et al., 2012; Banzon et al., 2016; Fiedler et al., 2019a; Huang et al.,
1457 2020).

1458

1459 *Uncertainty quantification* (Score: 6/6)

1460 Uncertainty in the NOAA Daily OISST data at each location (i.e., the analysed_sst
1461 field in the NETCDF file available from
1462 https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-v2.1) is quantified and
1463 provided (i.e., in the analysis_error field) through an analysis quality methodology.

1464

1465 *Automated Quality monitoring* (Score: 4/6)

1466 The Daily OISST v2.1 SST analyses are validated in near real-time against the
1467 GHRSSST Multi-Product Ensemble by NOAA/STAR at

1468 <https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4>. Since Argo SST are
1469 ingested into Daily OISST v2.1 they are not useful for verification.

1470

1471 Public access, feedback and update

1472 *Public Access/Archive* (Score: 5/6)

1473 The data is publicly accessible through the data provider's website and also other
1474 data portals with documentation. No source code is available publically.

1475

1476 *Version* (Score: 6/6)

1477 The version is fully established by the data provider.

1478

1479 *User feedback* (Score: 3/6)

1480 Contact information of the data provider is publicly available for user feedback.

1481

1482 *Updates to record* (Score: 6/6)

1483 Data providers regularly update the data record.

1484

1485 Usage

1486 *Research* (Score: 6/6)

1487 The NOAA Daily OISST is widely used in multiple research fields.

1488

1489 *Decision support system* (Score: 3/6)

1490 No decision support system is found for NOAA Daily OISST, however use is

1491 occurring and benefits are emerging.

1492

1493 8. HadISST1

1494 Metadata

1495 *Standard* (Score: 6/6)

1496 The HadISST1data files are provided in NetCDF classic format CF compliant through

1497 the data provider's website. The NetCDF files contain detailed metadata describing

1498 the data by means of global attributes, which are applicable to the whole file, and

1499 variable attributes, which apply to a specific data field.

1500

1501 *Collection Level* (Score: 6/6)

1502 Global attributes provide all information available on the data and relative
1503 references.

1504

1505 User Documentation

1506 *Formal description of scientific methodology* (Score: 6/6)

1507 The formal description of the HadISST1 is detailed in the peer-reviewed journal
1508 (Rayner et al., 2003), published by the data provider, which describes and justifies
1509 the algorithms used for obtaining SST estimates.

1510

1511 *Formal validation report* (Score: 6/6)

1512 Formal validation report is published in a peer reviewed journal.

1513

1514 *Formal product user guide* (Score: 3/6)

1515 No formal product user guide is provided. Product information is provided on the
1516 data provider's website.

1517

1518 Uncertainty Characterization

1519 *Standards* (Score: 1/6)

1520 No information is available at this stage.

1521

1522 *Validation* (Score: 6/6)

1523 The validation is available through peer reviewed journal paper.

1524

1525 *Uncertainty quantification* (Score: 1/6)

1526 No uncertainty quantification is found.

1527

1528 *Automated Quality monitoring* (Score: 1/6)

1529 No automatic quality is monitored during the production of the SST product.

1530

1531 Public access, feedback and update

1532 *Public Access/Archive* (Score: 5/6)

1533 The data is published through the data provider's website, but no source code is
1534 publically available.

1535

1536 *Version* (Score: 6/6)

1537 The version is fully established by the data provider.

1538

1539 *User feedback* (Score: 3/6)

1540 Contact information of the data provider is given for collecting user feedback.

1541

1542 *Updates to record* (Score: 6/6)

1543 The data is regularly updated by the data provider.

1544

1545 Usage

1546 *Research* (Score: 6/6)

1547 HadISST1 has been widely used in multiple research fields.

1548

1549 *Decision support system* (Score: 6/6)

1550 Up to now no decision support system is found for HadISST1, however, influence on

1551 decision making is demonstrated.

1552

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1838 **Figures:**

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Dataset	Institution	Type of product	Time Range	Observation input	Type of SST	Horizontal Grid spacing	Vertical resolution	Temporal resolution	Main Reference
ESA CCI SST (v.2.0)	Met Office	SST analysis	1981-2018	IR	SST at 0.2 m	global 0.05°x0.05°	surface	daily	Merchant et al. (2019)
ERA5	ECMWF	SST analysis	1979-2018	IR + MW + in situ	SSTdepth	global 0.25°x0.25°	surface	hourly	Hirahara et al. (2016)
HadISST1	Met Office	SST analysis	1870-2018	IR + in situ	SSTdepth	global 1°x1°	surface	monthly	Rayner et al. (2003)
NOAA Daily OISST v2.1	NOAA	SST analysis	1981-2018	IR + in situ	SST at 0.2 m	global 0.25°x0.25°	surface	daily	Huang et al., (2020)
MUR25 (v.4.2)	PODACC	SST analysis	2003-2018	IR + MW + in situ	Foundation SST	global 0.25°x0.25°	surface	daily	Chin et al. (2017)
MGDSST	Japanese Met. Agency (JMA)	SST analysis	1982-2018	IR + MW + in situ	SSTdepth	global 0.25°x0.25°	surface	daily	Sakurai et al. (2005)
BoM Monthly SST	Australian Bureau of Met. (BoM)	SST analysis	2002-2018	IR + in situ	SSTdepth	global 1°x1° (weekly/monthly)	surface	weekly/monthly	Smith et al. (1999)
OSTIASST	UK MeOffice	SST analysis	1981-2018	IR + MW + in situ	Foundation SST	0.05°x0.05°	surface	daily/weekly/monthly	Good et al., 2020

1841

1842 Table 1. Descriptive product comparison summary for the described products from
1843 sections 2. Input observations are derived from satellite infrared (IR) and/or
1844 microwave (MW) sensors and/or in situ measurements.

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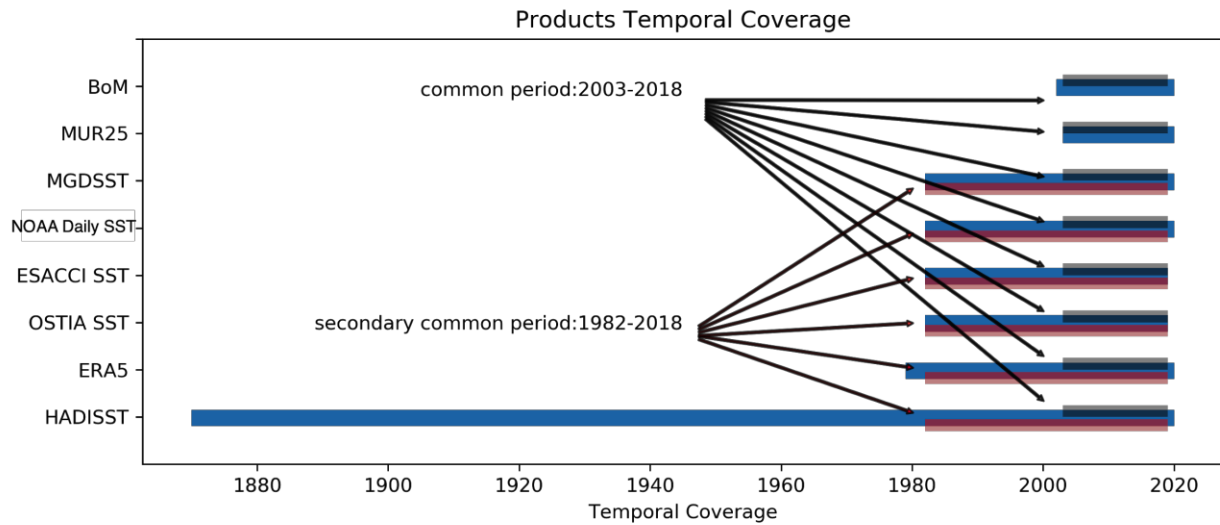
Name	ESA CCI SST	ERA5 SST	OSTIA	BoM	MGDSST	MUR25	NOAA Daily OISST	HadISST1
C3S_511 MM Category								
Metadata								
Standards	6	6	6	6	3	6	6	6
Collection level	6	5	6	5	2	6	6	6
User Documentation								
Formal description of scientific methodology	6	6	6	4	3	6	6	6
Formal validation report	6	3	6	2	4	4	6	6
Formal product user guide	6	6	6	4	3	2	6	3
Uncertainty Characterisation								
Standards	6	3	6	6	1	6	6	1
Validation	6	3	6	5	6	6	6	6
Uncertainty quantification	6	3	6	6	1	6	6	1
Automated quality monitoring	6	2	6	1	2	4	4	1
Public Access, feedback, and update								
Public Access/Archive	5	5	5	4	4	5	5	5
Version	6	6	6	2	2	6	6	6
User feedback mechanism	6	6	6	3	3	6	3	6
Updates to record	6	6	6	5	4	5	6	6
Usage								
Research	6	3	6	4	6	6	6	3
Decision support system	6	1	6	6	6	3	3	6

1849

1850 Table 2. Maturity Matrix for all SST products

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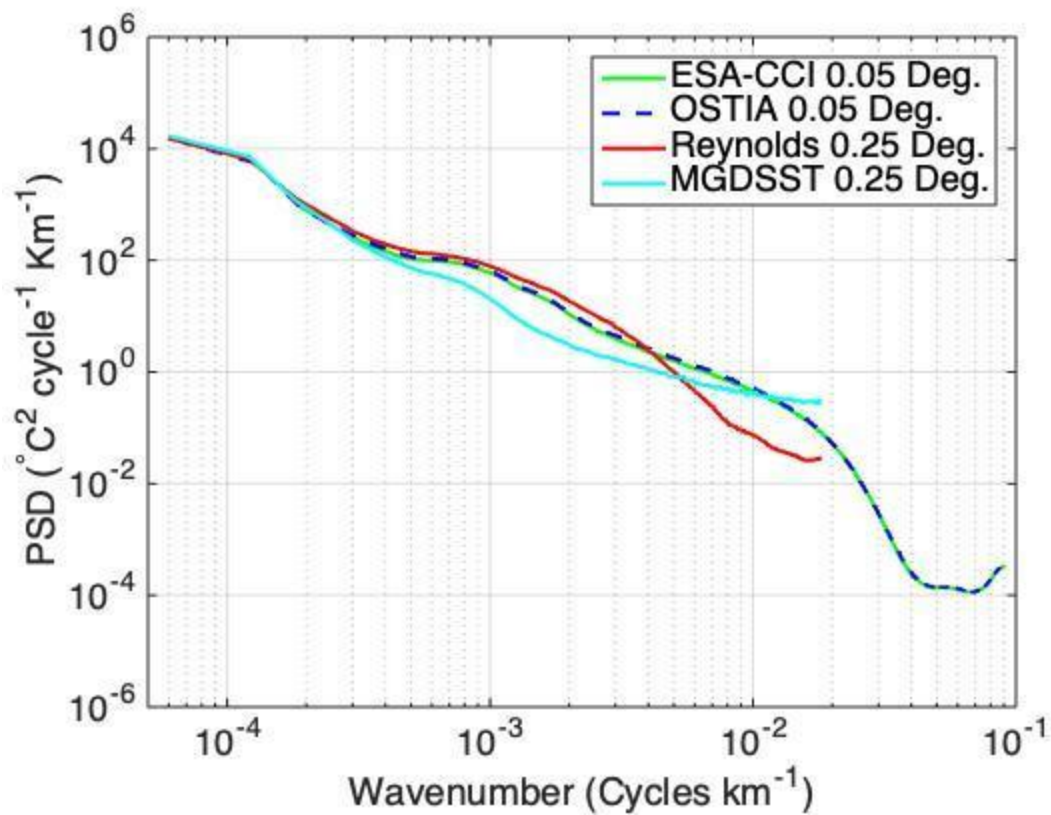
1854 Figure 1. Temporal range (years) covered by each SST dataset. The common period

1855 for all datasets is highlighted (2003-2018) and the secondary common period is

1856 1982-2018 with less SST products included.

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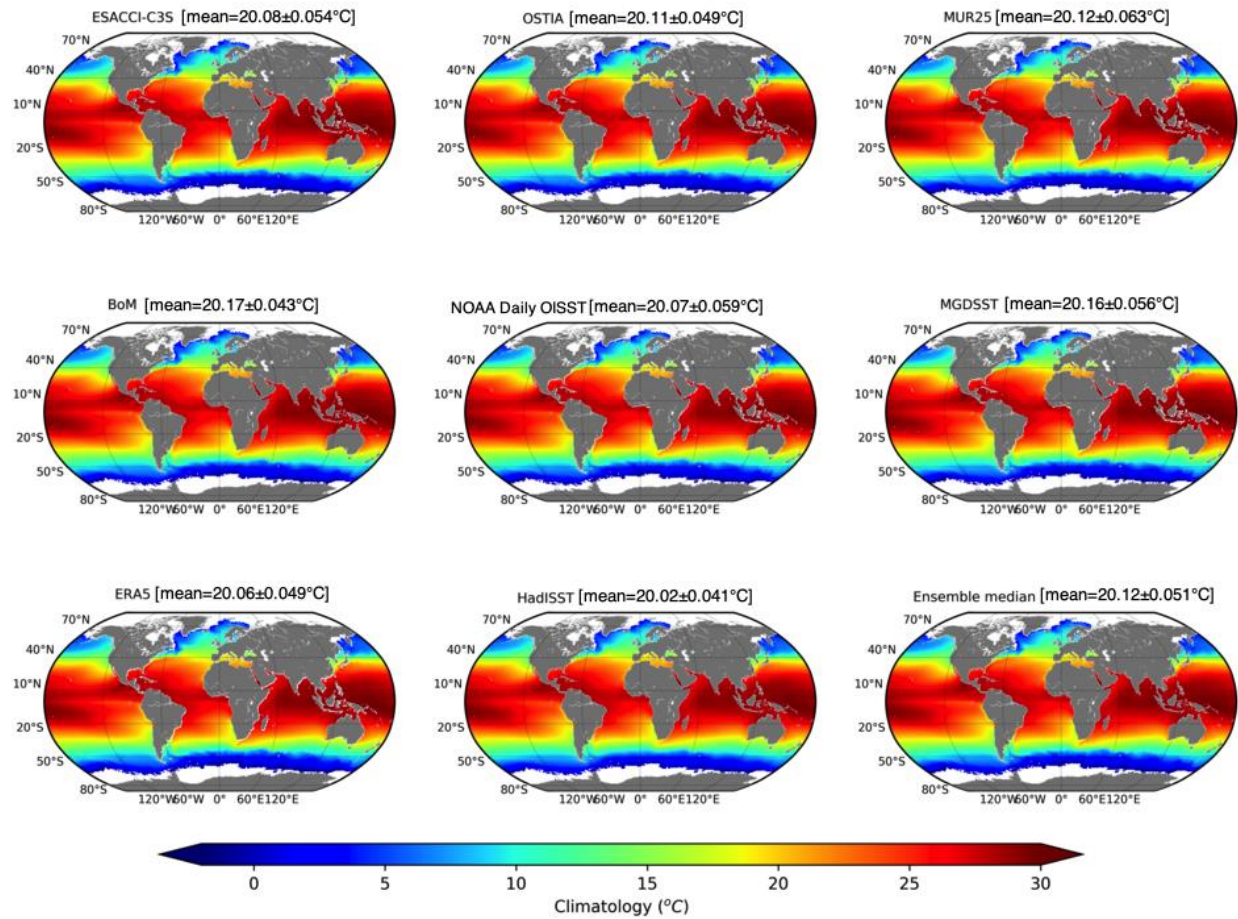
1861 Figure 2. Power Spectral Density at the equator in the Pacific Ocean (0°N , 120°E -

1862 80°W) for ESA-CCI (green), OSTIA (dashed dark blue), NOAA Daily OISST (Reynolds

1863 0.25 Degree. red) and MGDSST (cyan) based on the daily temporal and original

1864 spatial resolution for the period 1982-2018

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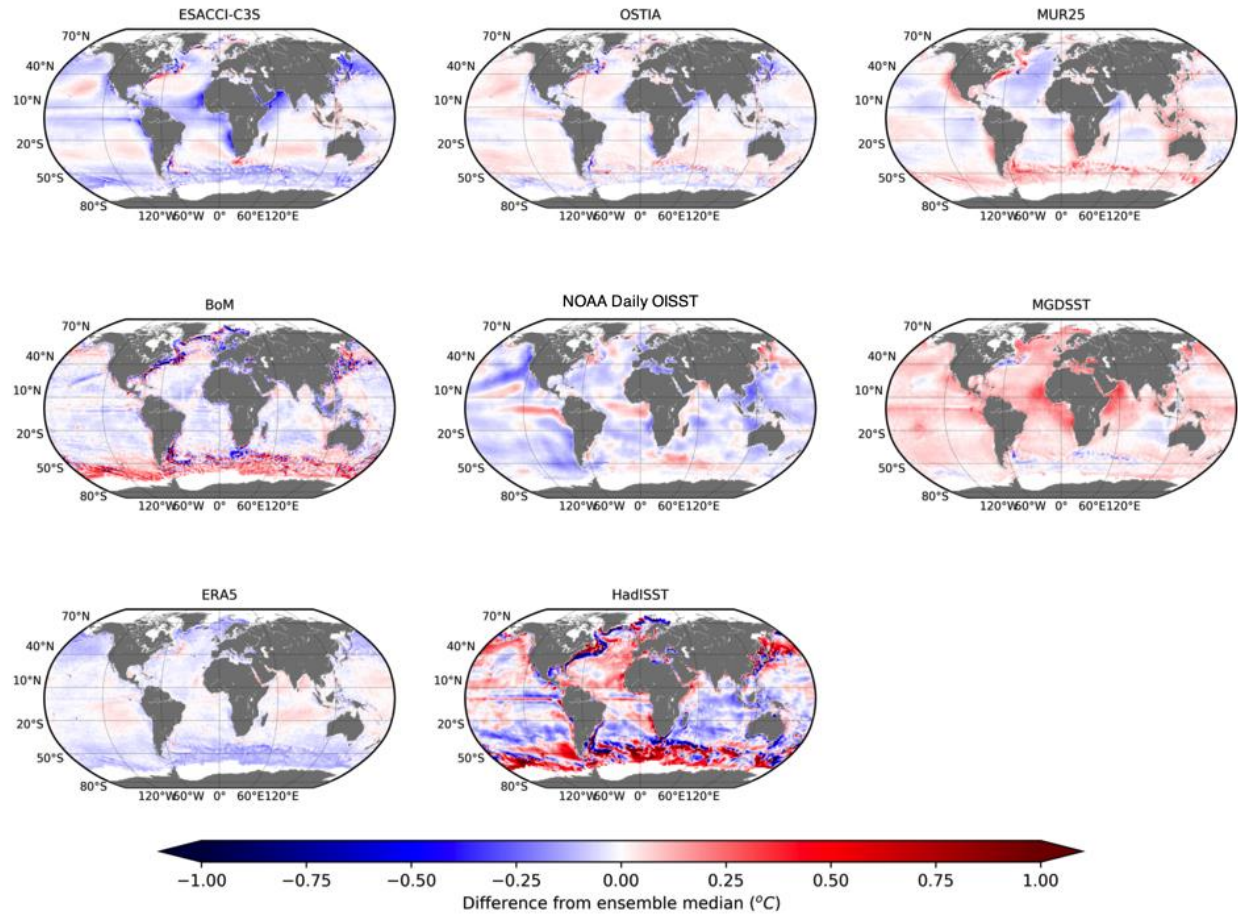


1866

1867 Figure 3. Global SST climatologies for the period 2003-2018. Global SST average

1868 value and its 95% confidence interval is also shown.

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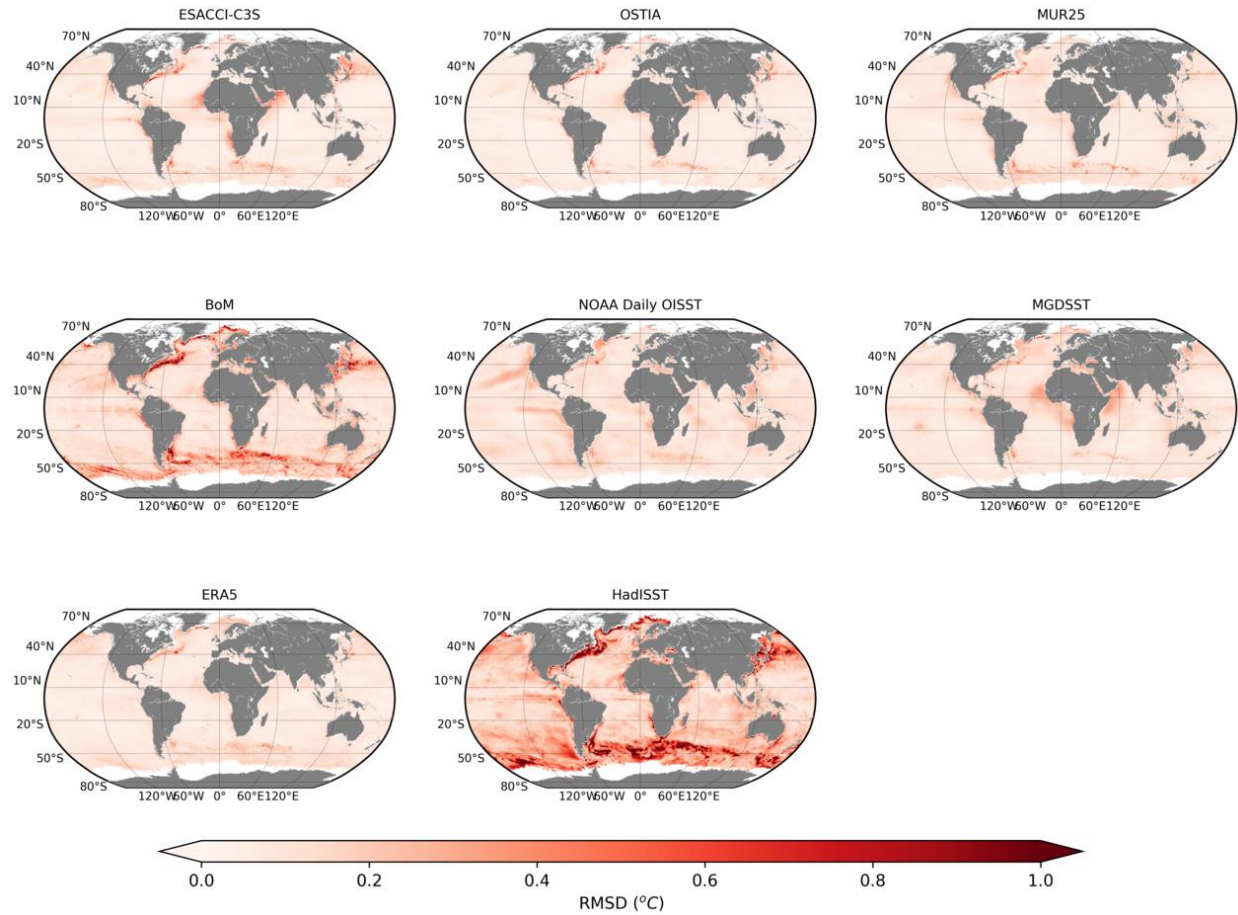


1870

1871 Figure 4 The difference between each SST product and the ensemble median for the
 1872 period of 2003-2018

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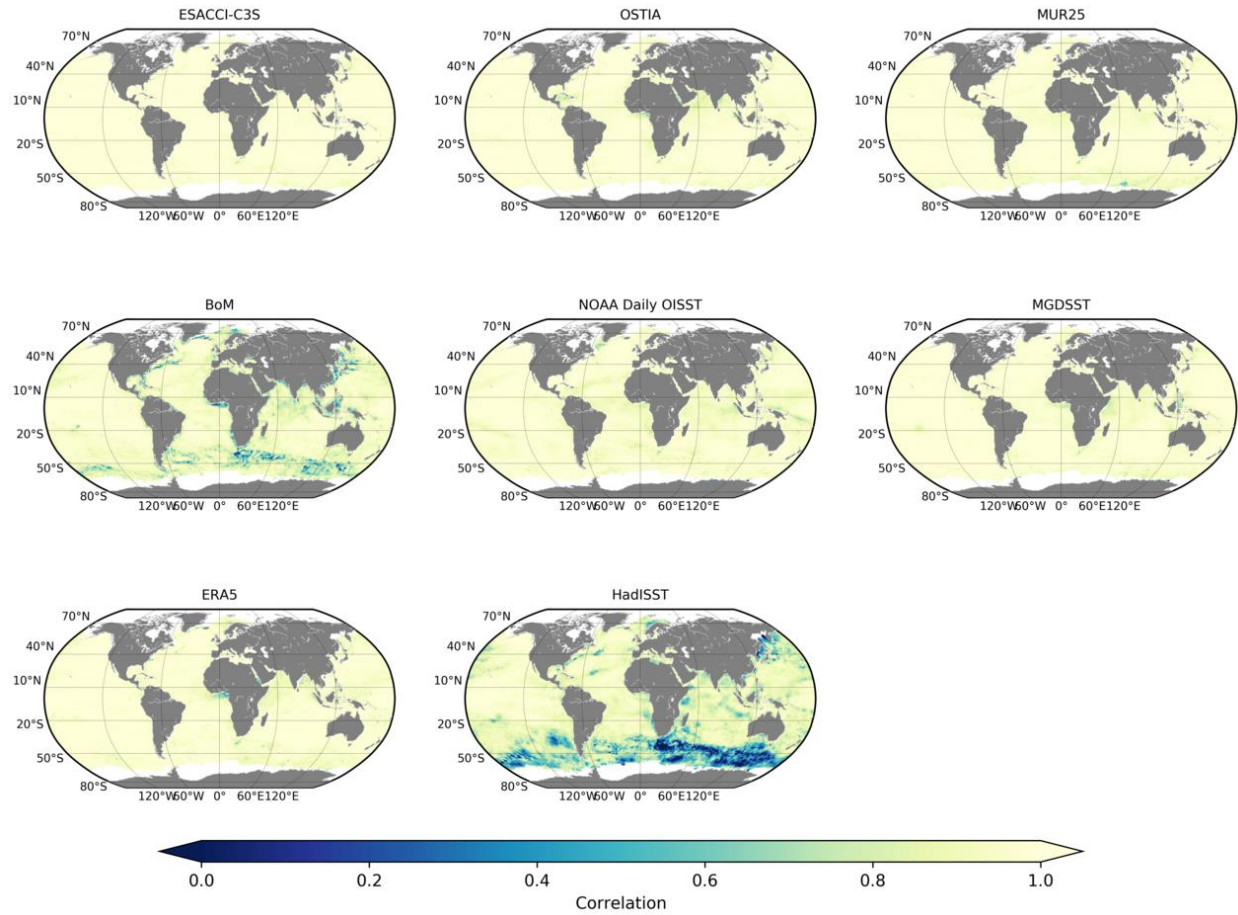


1875

1876 Figure 5 The RMSD between each SST product and the ensemble median for the

1877 period of 2003-2018

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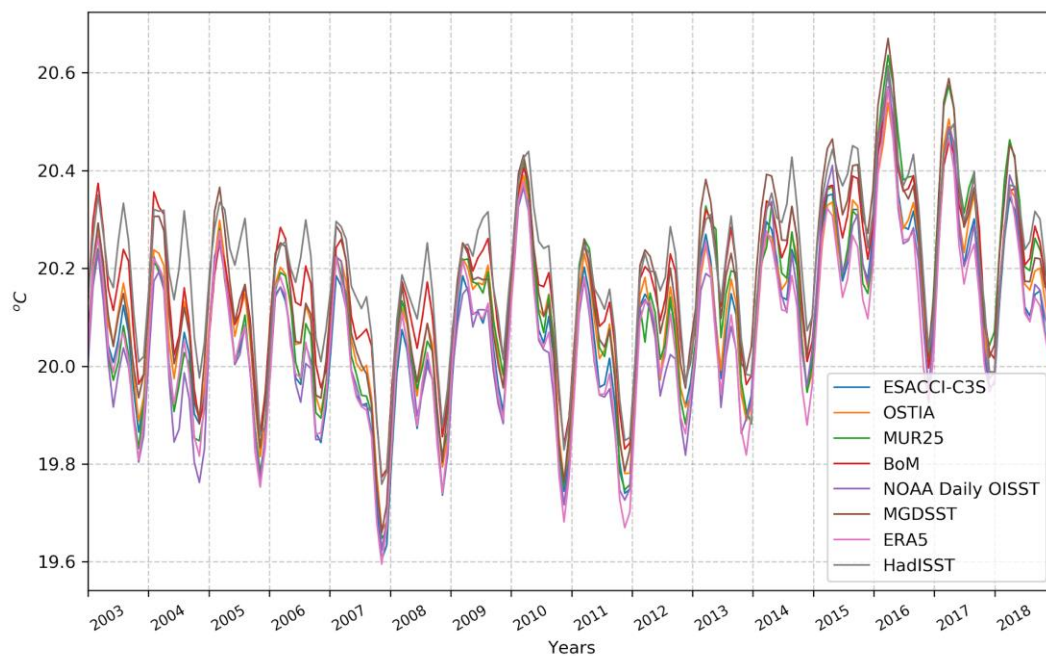
1879

1880 Figure 6 The correlation between each SST product and the ensemble median for
 1881 the period of 2003-2018

1882

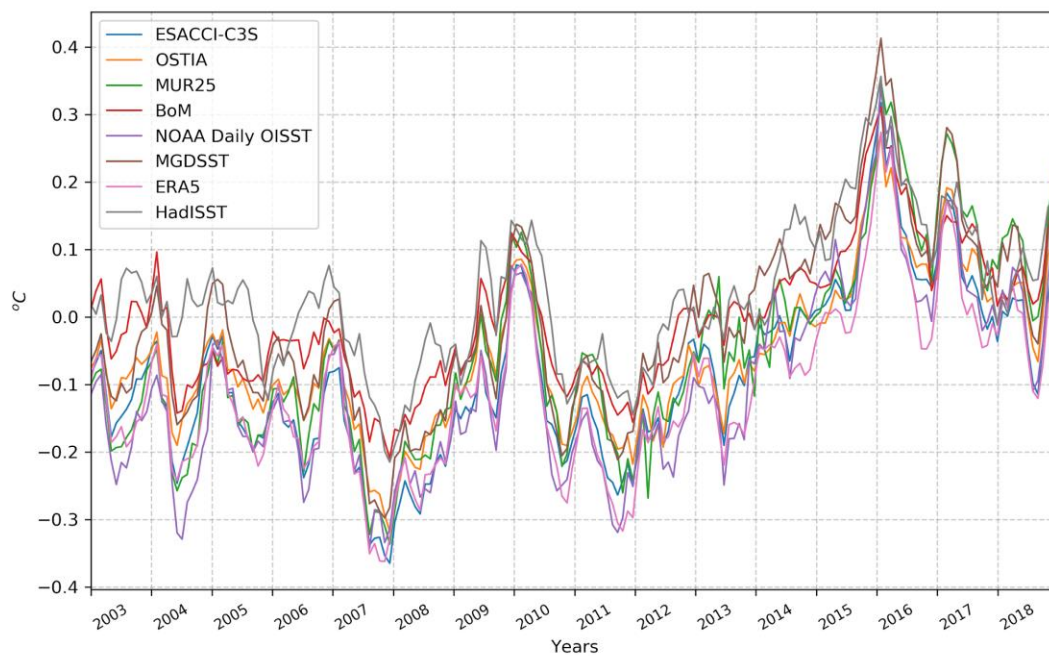
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1886 Figure 7 Global monthly mean SST time series from 2003 to 2018.

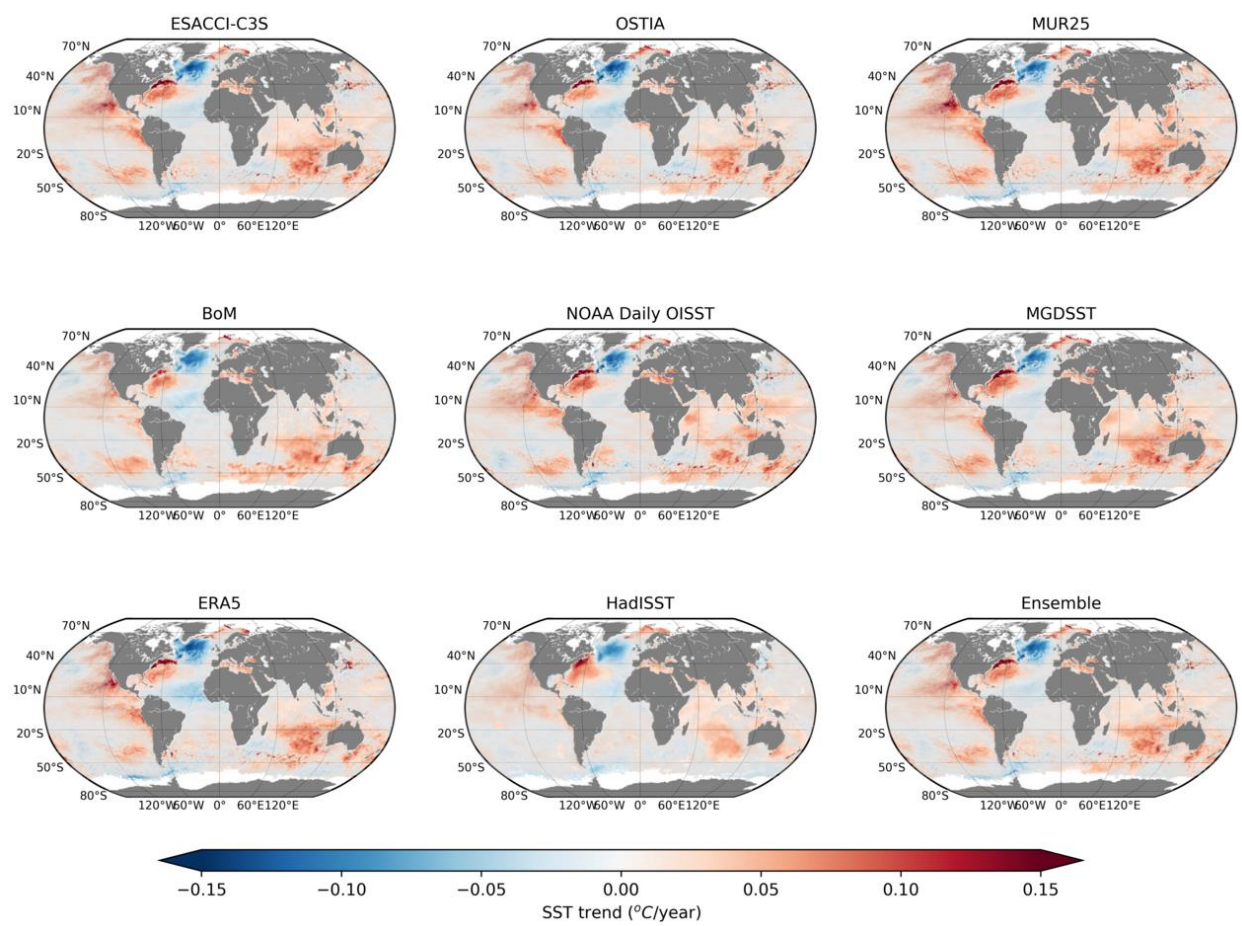


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1888 Figure 8. Global SST monthly anomalies time series, obtained by subtracting the
1889 climatology of the ensemble median to all the SST ensemble members from 2003 to
1890 2018.

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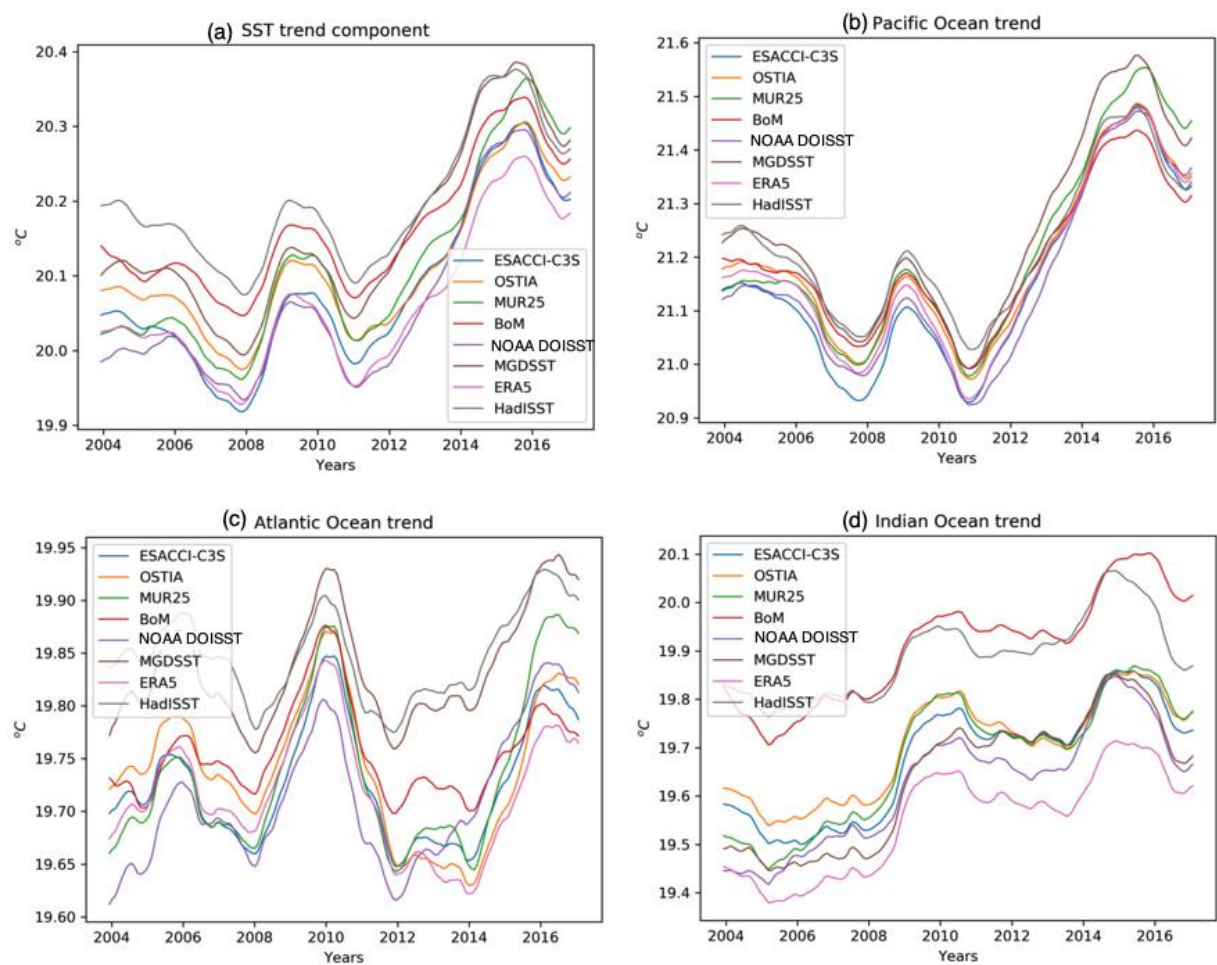
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1895 Figure 9. Global linear trend maps (2003-2018) ($^{\circ}\text{C}/\text{year}$) of each ensemble member
 1896 and ensemble median. Areas with no significant (95% significance level) trends are
 1897 covered by grey points.
 1898



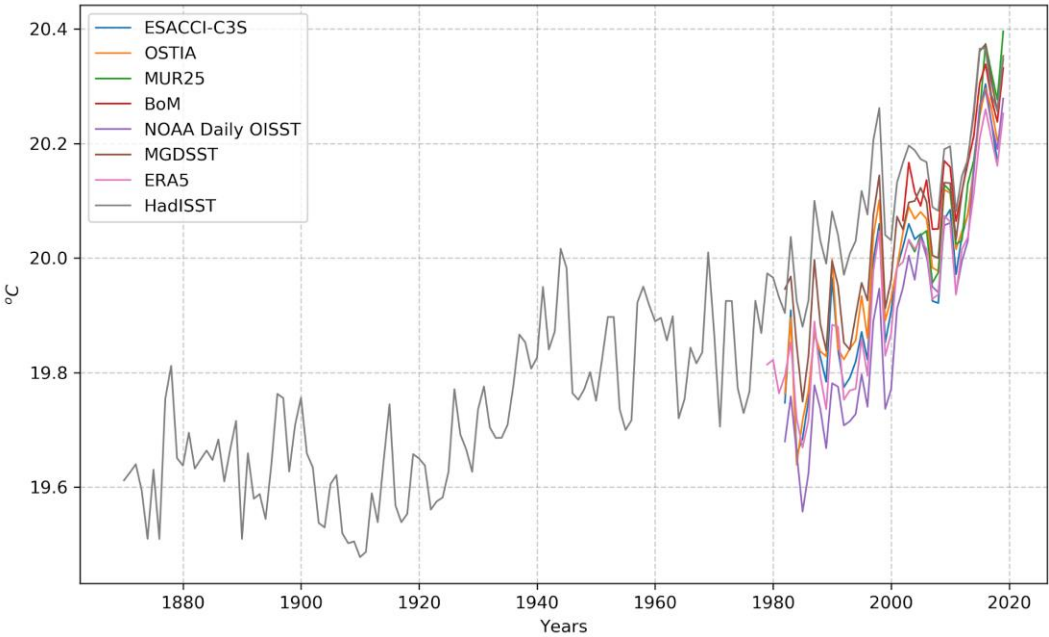
1899
 1900 Figure 10. (a) Global average SST trend component deduced from the global
 1901 average monthly mean time series (Figure 3.2.2) using the X-11 procedure (section

1902 3.1.2), the same calculation but for (b) the Pacific Ocean basin (c) Atlantic Ocean

1903 basin and (d) Indian Ocean Basin for the period of 2003-2018.

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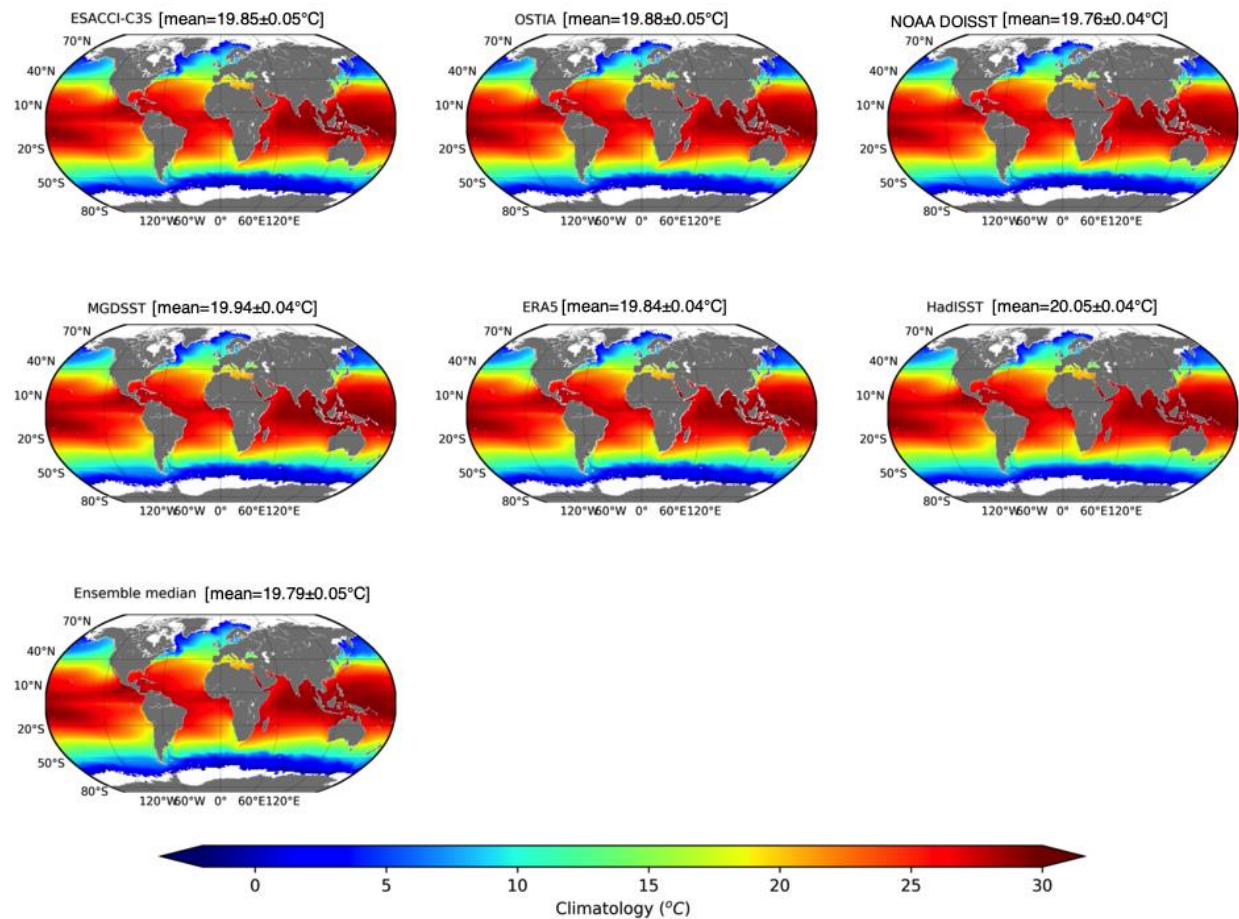


1906

1907 Figure 11. Global monthly mean SST time series for all the ensemble members for

1908 the whole covered period originally obtained in each SST product.

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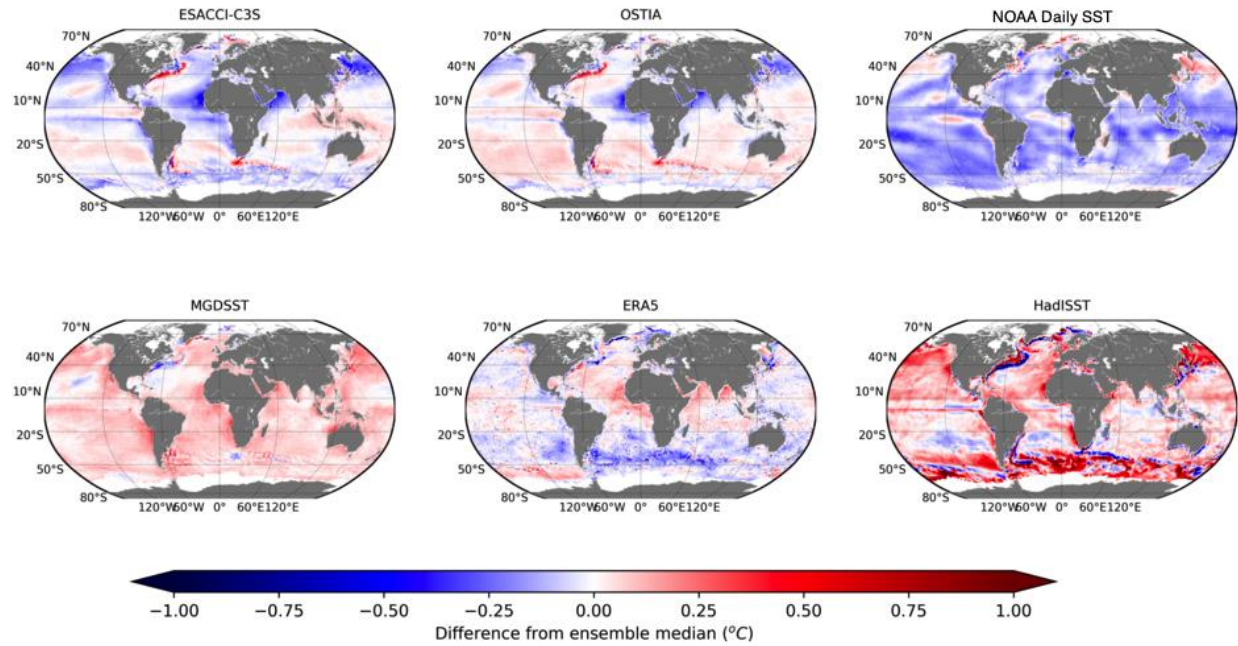


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1911 Figure 12 Global SST climatologies for the period 1982-2002. Global SST average

1912 and its 95% confidence interval is also shown in brackets above each map.

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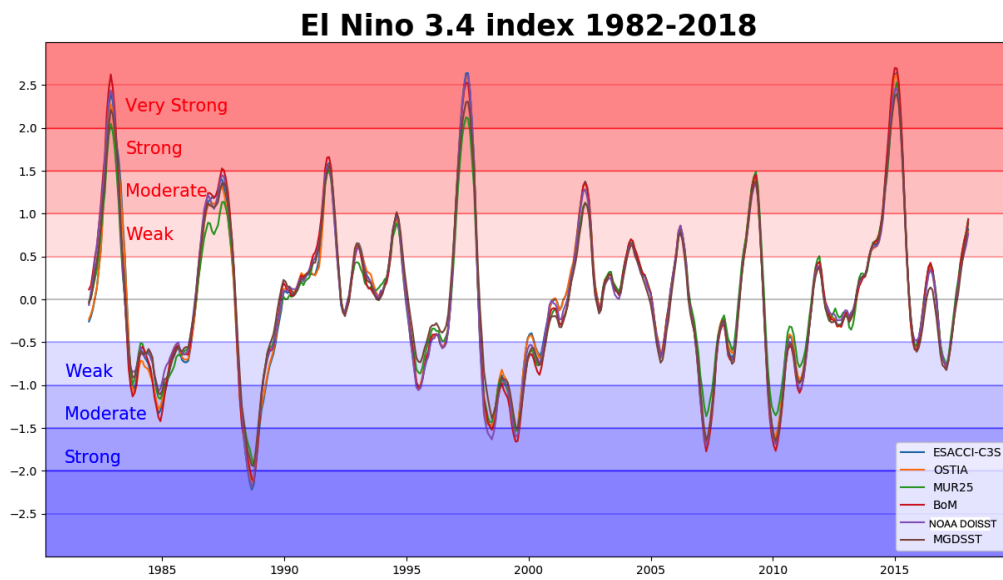
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1916 Figure 13 The difference between each SST product and the ensemble median for

1917 the period of 1982-2002

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1920

1921 Figure 14 Intercomparison between El Niño 3.4 time series of the five SST products:

1922 HadISST1, ERA5, ESA CCI SST, MGDSST, NOAA OISST.

1923

Sea Surface Temperature intercomparison in the framework of the Copernicus

Climate Change Service (C3S)

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Simon Good⁸, Boyin Huang⁹, Christopher J. Merchant¹⁰, Toshiyuki Sakurai¹¹, Rosalia
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Abstract

A joint effort between the Copernicus Climate Change Service (C3S) and the Group
for High Resolution Sea Surface Temperature (GHR SST) has been dedicated to an
intercomparison study of eight global ~~and~~-gap-free Sea Surface Temperature (SST)
products to assess their accurate ~~-~~representation of the SST relevant to climate
analysis. In general, all SST products show consistent ~~climatological~~-spatial patterns
and temporal variability during the overlapping time period (2003-2018). The main
differences between each product ~~are~~is located in western boundary current-~~regions~~

33 and Antarctic Circumpolar Current (~~ACC~~) regions. ~~L-Global~~ linear trends display
34 consistent SST spatial patterns among all ~~-the~~ products and ~~exhibitevidencing~~ a
35 strong warming trend from 2012 to 2018 with the Pacific Ocean basin as the main
36 contributor. SST discrepancy between all SST products is very small compared to the
37 significant warming trend. Spatial ~~p~~Power spectral density shows that the
38 interpolation into 1° spatial resolution has negligible impacts on our results. The
39 global mean SST time series reveals larger differences among all SST products
40 during the early period of the satellite era (1982-2002) when there were ~~fewerless~~
41 observations ~~compared to the latter period~~, indicating that the observation
42 ~~frequencies are-is~~ the main constraint of the SST climatology. The maturity matrix
43 scores, which present the maturity of each product in terms of documentation,
44 storage, and dissemination but not the scientific quality, ~~-of a dataset-~~ demonstrate
45 that ESA-CCI and OSTIA SST are well documented for users' convenience.
46 Improvements could be made for MGD SST and BoM SST. Finally, we have
47 recommended ~~to users~~ that these SST products can be used for fundamental climate
48 applications and climate studies (e.g. El Nino).

49

50 **1. Introduction**

51 Sea surface temperature (SST) as one of the Essential Ocean Variables (EOVs), and
52 the Essential Climate Variables (ECVs), plays a crucial role in heat, freshwater, and
53 momentum flux~~xx~~e exchange at the ocean-atmosphere interface. The variation of SST
54 at different temporal and spatial scales modulates the atmospheric lower boundary
55 layer (e.g. Renault et al., 2019) eventually driving small and large-scale changes at
56 interannual to decadal time scales in the atmosphere (Perlin et al., 2014, McPhaden,
57 2012). Additionally, the SST changes can influence the biogeochemical marine
58 environment, contributing to modulating the primary production and related carbon
59 absorption in the ocean (Behrenfeld et al, 2006). Besides its importance for assessing
60 and monitoring the state of the global climate system, SST is widely used as
61 boundary conditions in weather and climate operational forecast systems (Robinson
62 2012) and as initial conditions in ocean operational forecast systems (Le Traon et al.,
63 2019). Therefore, assessing the quality of SST data is critical from several

64 perspectives, from operational to climate studies, marine environment and related
65 services ~~preservation~~.

66

67 SST observations are mainly obtained from low-Earth orbit infrared and microwave
68 satellite imagery and geostationary infrared imagery, and from various in situ
69 platforms including moored and drifting buoys, Argo floats, ships of opportunity,
70 autonomous sailing drones, and radiometers (O'Carroll et al., 2019). All these
71 instruments provide observations characterized by different representativeness,
72 resolution, and accuracy. Different retrieval methods and reanalysis techniques are
73 thus ~~applied in to~~ applied to obtain temporally and spatially consistent long-term
74 SST products with global coverage (Minnett et al, 2019).

75

76 The Group for High-Resolution Sea Surface Temperature (GHR SST, www.ghrsst.org;
77 Donlon et al, 2009) is an international initiative aimed at coordinating the provision
78 of SST products developed and distributed by different agencies and research
79 institutes. Among GHR SST products, level 4 data (L4) provide gap-free SST maps at

80 regional and global scales, obtained with different algorithms that combine and
81 interpolate satellite based SST data, acquired by a variety of different sensors,
82 sometimes also including in situ observations. Different interpolation techniques and
83 related configurations (e.g. observation/background error correlation scales),
84 interpolation grid size, input data bias-correction, and the sampling adopted by
85 GHRSSST data providers induce a significant diversity among L4 SST products (Dash
86 et al., 2012). Understanding the consistency and discrepancy of the different SST L4
87 products will not only help data providers to improve their algorithms, but also
88 represents an important step to inform users about the characteristics of the
89 different products, helping them to select the one that may better suit their
90 applications.

91
92 Several previous global SST analysis intercomparison studies have already been
93 performed, among which, most noticeably, the Global Climate Observing System
94 (GCOS) SST-Sea Ice intercomparison project
95 (<https://www.nodc.noaa.gov/SatelliteData/ghrsst/intercomp.html>), and the GMPE

96 (Group for High-Resolution SST, GHRSSST, Multi-Product Ensemble) system,
97 performed as a contribution to GHRSSST activities ~~under the umbrella of the SST~~
98 ~~Analysis Intercomparison Task Team of GHRSSST~~. The initial work by Martin et al.
99 (2012) and Dash et al. (2012), which were focused on a relatively short time series
100 over the satellite period (for the year 2010), has recently been extended to
101 intercompare longer-term analyses ~~analyses~~ over the overlapping period of 1991 to
102 2010 (Fiedler et al., 2019a). A much shorter period (one year) is considered in the
103 intercomparison of satellite-based analyses performed by Okuro et al. (2014), while a
104 comparison study on the historical ~~sea surface temperature~~ SST datasets based on in
105 situ data alone is described in Yasunaka and Hanawa (2011). With the recent
106 reprocessing of several global high resolution daily L4 products from the start of the
107 operational satellite SST era (1981) to recent years, it is now timely to perform an
108 intercomparison of additional SST analyses over a significantly longer period.
109
110 In the framework of the European Copernicus Climate Change Service (C3S), an
111 Independent Assessment of Essential Climate Variables (ECVs) present in the C3S

112 Climate Data Store (CDS) is foreseen. The C3S CDS distributes and provides access
113 to quality-assured climate dataset and tools in the clouds for users. -The
114 independent assessment aims to evaluate the quality, usability and consistency of
115 available ECVs for different applications, ranging from scientific studies (e.g. on
116 climate change), to commercial and private sector uses. SST is one of the ECVs
117 considered in the assessment framework of C3S and the intercomparison of SST
118 products available in the CDS will help the users to understand the quality of
119 different SST products and choose the right one for their specific applications.

120

121 The study presented hereafter represents the joint effort between the GHRSSST SST
122 Analysis I intercomparison Itask Iteam ([https://www.ghrsst.org/about-ghrsst/task-](https://www.ghrsst.org/about-ghrsst/task-teams/)
123 [teams/](https://www.ghrsst.org/about-ghrsst/task-teams/)) and the C3S SST assessment activities. The objective of this study is to
124 evaluate the basic characteristics and the maturity of eight states of the art global
125 SST analysis products; to describe how SST climatology and variability is represented
126 in each SST product, and to understand the consistency and discrepancy between all
127 these long-term eight SST analyses available in or outside of CDS (some of the SST

128 products are provided in GHR SST L4 format), and eventually to provide guidance on
129 which product might be better suited for users' applications.

130 The paper is organized as follows: Section 2 introduces the characteristics of SST
131 analysis products included in this study, the basic diagnostics are presented in
132 section 3, and the data maturity of all SST products is described in section 4, and
133 finally, the summary of the evaluation and the recommendations to users are
134 discussed in sections 5 and 6.

135

136 **2. Datasets**

137 Currently, two global SST analysis datasets are distributed through the CDS, namely

138 [European Space Agency \(ESA\) Climate Change Initiative \(ESA CCI\)](#) version 2.1 and

139 [European Centre for Medium-Range Weather Forecasts Atmospheric Reanalysis](#)

140 [version 5 \(ERA5\)](#). They are compared here with a selection of six state of the art SST

141 analyses distributed outside the CDS, obtained from different input data and analysis

142 system configurations. These are:

- 143 · Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) (Rayner et
144 al., 2003);
- 145 · UK MetOffice Operational Sea Surface Temperature and Sea Ice Analysis
146 (OSTIA) system (Good et al., 2020)
- 147 · NOAA Daily OISST v2.1 daily reanalysis also referred to as Reynolds SST
148 (Reynolds et al., 2007; Banzon et al., 2016; Huang et al., 2020);
- 149 · Multi-scale Ultra-high Resolution 0.25 deg. (MUR25) SST analysis v.4.2
150 (Chin et al., 2017);
- 151 · Merged satellite and in situ data Global Daily Sea Surface Temperature
152 (MGDSST) (Sakurai et al., 2005; Kurihara et al., 2006);
- 153 · Australian Bureau of Meteorology Global Monthly SST Analysis (BoM
154 Monthly SST) (Smith et al., 1999).

155

156 These eight datasets combine satellite and in many cases in situ temperature
157 measurements to generate gap-free (optimally interpolated) SST fields at the global
158 scale. All these datasets are specifically designed to provide accurate high spatial

159 and temporal resolution SST estimates that can be used in operational applications
160 such as assimilation and/or boundary conditions in numerical weather prediction
161 models (e.g., MGD SST and OSTIA SST), and/or analysed for climate applications (e.g.
162 HadISST1, NOAA Daily OISST analysis, MUR25, BoM Monthly SST).Some of the
163 selected datasets, namely ESA CCI v2.1, OSTIA, NOAA Daily OISST v2.1, MUR25 and
164 BoM Monthly are provided in GHR SST L4 format (GHR SST Science Team, 2012).

165

166 Below, we detail the characteristics of all the SST products included in this
167 intercomparison study.

168

169 **2.1 ESA-CCI SST**

170 The ESA CCI SST dataset (version 2.1) provides global daily SST estimates based on
171 observations acquired from different satellite sensors covering the period from
172 September 1981 to December 2018 (at the time of the study). The CCI SSTs are
173 designed to provide a stable, low-bias climate data record derived from different

174 infrared sensors, i.e., the Advanced Very-High-Resolution Radiometer (AVHRR),
175 Advanced Along Track Scanning Radiometer ((A)ATSR) and Sea and Land
176 Surface Temperature Radiometer (SLSTR) series of sensors (Merchant et al., 2019,
177 2014). These data are provided at different processing levels: single-sensor data on
178 the native swath grid (Level-2); uncollated single-sensor (Level-3U) and collated
179 multi-sensor (Level-3C) gridded data; and blended multi-sensor and optimally
180 interpolated (Level-4) data.

181 The ESA CCI Level-4 product considered here consists of gap-free (optimally
182 interpolated) maps of daily average SST at 20 cm depth at 0.05° x 0.05° latitude-
183 longitude grid (approximately 5x5 km at the equator). The Level-4 data have been
184 produced by running the Operational Sea Surface Temperature and Sea Ice Analysis
185 ~~(OSTIA)~~ system (Donlon et al., 2012) using CCI Level-3U SSTs as inputs, no in situ
186 data are included. Estimates of standard uncertainty (considered as the standard
187 deviation of the estimated error distribution) are provided for every SST at all
188 product levels. The evaluated global median uncertainty is 0.18 K (Merchant et al.,

189 2019). The multiannual stability of the whole time series, evaluated relative to
190 drifting buoy measurements, is within 0.003K/year (Merchant et al., 2019). Given the
191 high temporal and spatial resolution and the performance statistics, this dataset
192 gives an accurate representation of SST spatio-temporal variability of relevance to
193 climate applications. Target applications of the ESA CCI SST dataset include climate
194 and ocean model assessment; accurate definitions of climatic indices; quantification
195 of climate variability and its impacts on weather extremes (including marine
196 heatwaves), marine ecosystems, and related services.

197

198 **2.2 ERA5**

199 The ERA5 ~~Sea Surface Temperature (SST)~~ dataset is produced by ECMWF to be used
200 for ERA5 atmospheric reanalysis (Hirahara et al., 2016). It consists of hourly global
201 gap-free SST data at 0.25°x0.25° latitude-longitude grid covering the period from
202 1979 to the present. ERA5 SST data are based on the HadISST2 (Kennedy et al.,
203 2016) product from 1979 to August 2007, and the daily operational OSTIA (Donlon

et al., 2012) product from September 2007 to present. The HadISST1 version 2 was developed by the UK Met Office Hadley Centre, and its "pentad" dataset consists of spatially complete, 5-daily mean fields on a 0.25° spatial resolution grid. OSTIA is a high resolution (0.05°x0.05°) operational daily product developed by the UK MetOffice and distributed through the Copernicus Marine Environment Monitoring Service (CMEMS). These two SST datasets are aggregated into one continuous data record and interpolated onto the ERA5 model grid (Dee et al., 2011) to be used as boundary conditions for ERA5 atmospheric reanalysis. There are two types of Sea Surface Temperature in ERA5 including Sea Surface Skin Temperature and Sea Surface Temperature. In this study we have used monthly ERA5 Sea Surface Temperature. ERA5 SST is calculated as the SST from an ocean model with increment as the difference between OSTIA SST and the ocean analysis. Since the input of SST comes from both OSTIA and HadISST2, the ERA5 SST is a mixture of SST in the absence of diurnal variation, "foundation SST" (OSTIA), and SST at indeterminate depth, "SSTdepth" (HadISST2), following the SST definitions in Minnett and Kaiser-Weiss (2012). Here we give the SST type as SSTdepth for ERA5 SST.

220 2.3 HadISST1

221 Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST1) is available
222 at <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. This dataset
223 includes a combination of monthly globally-complete fields of SST and sea ice
224 concentration on a 1°x1° latitude-longitude grid from 1870 to present. HadISST1
225 data have been produced using SST measurements from the Met Office Marine Data
226 Bank (MDB), mainly ship tracks, and a blend of in situ and adjusted satellite-derived
227 SSTs for 1982-onwards. A bias adjustment of the satellite SST data is performed by
228 subtracting the in situ fields from the AVHRR fields. Specifically, the difference fields
229 are smoothed using a moving window average with a radius of 2224~~radius-2224~~ km
230 (20 degrees of latitude). The smoothed bias fields are then subtracted from the
231 monthly AVHRR SST (see Appendix C in Rayner et al. 2003 for further details).

232

233 In order to enhance data coverage, monthly median SSTs for 1871-onward from the
234 Comprehensive Ocean-Atmosphere Data Set (COADS) (now ICOADS) were also used

235 where MDB data were not available. Information on sea ice concentrations ~~isare~~ also
236 included in the HadISST product. This information is derived from several sources
237 that include digitized sea ice charts and satellite data. Temperatures are
238 reconstructed using a two-stage reduced-space optimal interpolation procedure
239 (Kaplan et al., 1997), followed by superposition of quality-improved gridded
240 observations onto the reconstructions to restore local detail (Rayner et al., 2003).

241

242 **2.4 NOAA (Daily OISST)**

243 The NOAA Daily OISST v2.1 dataset (Reynolds et al., 2007; Banzon et al., 2016;
244 Huang et al., 2020), also known as the “Reynolds” Daily Optimum Interpolation SST
245 analysis, consists of global daily spatially-complete SST data on a 0.25°x0.25°
246 latitude-longitude grid from 1981 to present (<https://www.nodc.noaa.gov/oisst>). This
247 dataset is routinely produced by NOAA/NESDIS/NCEI and publicly provided at
248 [https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-](https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/)
249 [interpolation/v2.1/](https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/).

250 GHRSSST GDS2 L4 format (GHRSSST Science Team, 2012) files are also available from
251 1981 to 2015 from https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-
252 v2.0 and 2016 to present from https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-
253 L4-GLOB-v2.1.

254
255 The NOAA optimal interpolation analysis uses both in situ and satellite-derived SST
256 data. Satellite SSTs are estimated from NOAA/AVHRR and MetOp/AVHRR
257 observations. This dataset also utilizes the in situ ICOADS dataset to correct the
258 residual satellite SST biases. OISST has been updated from v2.0 to v2.1 from January
259 2016 onward. The updates include the following five aspects: (a) MetOp-B replaces
260 NOAA-19 while MetOp-A remains unchanged, (b) freezing-point temperature
261 replaces ice-SST regression in SST proxy in ice-covered oceans, (c) the estimated
262 ship SST bias is reduced from 0.14°C to 0.01°C, (d) ship and buoy observations from
263 ICOADS-D R3.0.2 are used instead of NCEP GTS receipts, and (e) Argo observations
264 above 5 m depth are included. The Argo observations were first used as

independent data to validate the improvements in the updates from (a) to (d), and the Argo observations were finally included in OISST in (e).

2.5 MUR25

The Multi-scale Ultra-high Resolution 0.25 degree. (MUR25) SST analysis (v.4.2) is a global daily spatially-complete SST dataset on a 0.25° x 0.25° grid covering the period from mid-2002 to present. The analyzed SST is representative of the foundation temperature (namely, the temperature free, or nearly free, of any diurnal cycle [\(Minnett and Kaiser-Weiss, 2012\)](#). This dataset is a reprocessed version of the MUR dataset v.4.1 (Chin et al., 2017), which provides global daily spatially-complete SST analyses at 0.01° spatial resolution. MUR25 is provided by NASA's Jet Propulsion Laboratory (JPL) Physical Oceanography Distributed Active Archive Center (PO.DAAC) and is available at <https://podaac.jpl.nasa.gov/dataset/MUR25-JPL-L4-GLOB-v04.2>. The MUR L4 analysis is built by using only nighttime SST observations derived from different types of satellite sensors, which include microwave and infrared

measurements from, e.g., [Advanced Microwave Scanning Radiometer \(AMSR\) for Earth Observing System](#) (AMSR-E) and NOAA/AVHRR observations. In addition, MUR25 ingests in situ SST measurements from the NOAA iQuam [data set \(Xu and Ignatov, 2014\)](#) project to improve the estimate of the foundation temperature, and ice concentration data from the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF), which are used for an improved SST parameterization in the polar regions. Satellite and in situ data are combined using MRVA, a meshless multi-scale interpolation method which uses wavelets as basis functions in order to build the daily MUR SST analysis (Chin et al., 2017).

2.6 MGSST

The Merged satellite and in situ data Global Daily ~~Sea Surface Temperature~~SST (MGSST) analysis dataset provides global daily spatially-complete SST fields on a 0.25°x0.25° latitude-longitude grid covering the period from 1982 to present. This dataset is derived from infrared satellite sensors (NOAA/AVHRR and MetOp/AVHRR),

295 microwave satellite sensors (Coriolis/WINDSAT, GCOM-W1/AMSR-2), and in situ
296 temperature measurements (from buoys and ships). This dataset is provided by The
297 Japanese Meteorological Agency (JMA) and is available at
298 https://ds.data.jma.go.jp/gmd/goos/data/rrtdb/jma-pro/mgd_sst_glb_D.html.
299 SSTs from the microwave sensor AQUA/AMSR-E are used in the analysis from May
300 2002 through 5th October, 2011. In the reanalysis data, SSTs under sea ice are
301 determined according to the statistical relation between sea-ice concentration and
302 SST. The lowest SST is -1.8 degree Celsius where the sea-ice concentration is 100%.
303 Additional information is provided by Kurihara et al. (2006) and Sakurai et al. (2005).

304

305 **2.7 BoM Monthly**

306 The Monthly Optimal Interpolation (OI) SST Analysis is the global monthly spatially
307 complete SST dataset on a 1°x1° grid produced by the Australian Bureau of
308 Meteorology (BoM), covering the period of 1994 to present (Smith et al., 1999).
309 [formed by averaging the BoM Weekly OI SST analyses over each month.](#) In this

310 study, we use the GHR SST version 1 L4 format files of this dataset covering the
311 period 2002 to present (Beggs and Pugh, 2009). ~~Each Monday a weekly SST analysis~~
312 ~~on a 1°x1° grid is formed from optimally interpolated SST observations collected~~
313 ~~over the preceding week (Monday to Sunday) (Smith et al., 1999). The BoM monthly~~
314 ~~OI SST analysis is formed on the first Monday of each month from an average of the~~
315 ~~weekly OI SST analyses for the preceding calendar month, where the middle date of~~
316 ~~each weekly analysis falls within that month (Beggs and Pugh, 2009).~~ The SST
317 observations ~~used to derive the global weekly and monthly SST analyses~~ are
318 obtained from in situ SST observations from drifting and moored buoys, ships, Argo
319 floats, [Conductivity Temperature Depth \(CTD\)](#) and Expendable Bathythermographs
320 (XBTs), and satellite-derived SST from infrared AVHRR sensors aboard NOAA Polar-
321 Orbiting Environmental Satellites (POES) and ESA/[EUMETSAT](#) MetOp satellites.
322 Weekly OI analyses of the in situ data are used to correct for biases in the satellite
323 data (Smith et al., 1999), similar to the method used in the NOAA Weekly 1°x1°
324 OISST v2 (Reynolds et al., 2002). [The resulting outputs of the Weekly and Monthly](#)

325 [OI analyses of in situ and satellite data are therefore SST values of indeterminate](#)
326 [depth, SSTdepth.](#)

327 At high latitudes, the BoM weekly analysis system uses the daily sea-ice
328 concentration analysis from NOAA/NCEP
329 (<https://polar.ncep.noaa.gov/seaice/Analyses.shtml>) to constrain the SST, by setting
330 SST at a given grid point to -1.8°C if the concentration of NCEP ice data in that grid
331 cell is greater than 50 per cent. Until 12 March 2008, the 0.5° resolution sea-ice
332 analysis was used and after that date, the $1/12^{\circ}$ resolution sea-ice analysis
333 (Grumbine, 1996).

334 Maps of these weekly and monthly SST analyses are available at
335 <http://www.bom.gov.au/marine/sst.shtml>, and they are used operationally by BoM to
336 generate El Niño indices, monitor the Indian Ocean Dipole and produce SST
337 anomaly maps for climate applications
338 (<http://www.bom.gov.au/climate/enso/#tabs=Sea-surface>). The BoM Weekly and
339 Monthly OI SST analysis GHRSSST L4 format files are available on request

(<http://www.bom.gov.au/climate/data-services/data-requests.shtml>). It should be noted that higher resolution (0.25°x0.25°) global daily OI SST analyses have been produced operationally at the Bureau of Meteorology since 2008 (Zhong and Beggs, 2008; <http://www.bom.gov.au/marine/sst.shtml>) but these only cover the period 2008 to present so were not included in this study.

345

346 2.8 UK Met Office OSTIA SST

347 The UK Met Office ~~Operational Sea Surface Temperature and Sea Ice Analysis~~
348 ~~OSTIA~~ (Good et al., 2020) system is a daily global SST product with a resolution of
349 1/20° (approximately 5-6km). Monthly and seasonal frequency datasets are also
350 available. The version of OSTIA SST we use in this study is the ~~Copernicus Marine~~
351 ~~Environment Monitoring Service (CMEMS)~~ reprocessed SST analysis based on the
352 OSTIA configuration reported in Good et al. (2020), covering the period 1 October
353 1981 to 31 December 2018. This OSTIA reanalysis is formed by the combination of
354 satellite SST data provided by the GHRSSST project with additional ~~(A)~~ATSR, SLSTR

355 and AVHRR data from ESA CCI SST v2.1,1 ~~(note that ESA CCI SST v2 and V2.1 only~~
356 ~~differ in the file specification, but no scientific differences)~~ and C3S projects, and in
357 situ observations from the HadIOD by using NEMOVAR, a variational assimilation
358 (Fiedler et al., 2019b), instead of the optimal interpolation algorithm (Martin et al.,
359 2007, Donlon et al., 2012). Note that ESA CCI SST v2 and V2.1 only differ in the file
360 specification, but no scientific differences. Bias correction is performed for all the
361 input satellite data (except the satellite data in the reference dataset) by carrying out
362 match-ups between satellite and reference measurements. The depth of the SST
363 analysis represents the sub-skin temperature immediately before sunrise also
364 referred to as foundational SST that is free of diurnal variability (Donlon et al., 2012).
365 The OSTIA reanalysis is publicly available from
366 https://resources.marine.copernicus.eu/?option=com_csw&task=results?option=com_csw&view=details&product_id=SST_GLO_SST_L4_REP_OBSERVATIONS_010_011.
367
368 In order to verify the accuracy of reprocessed SST analysis, ~~drifting buoys and near-~~
369 surface Argo data that are not included in SST analysis are used as independent

370 data for quality assessment as shown in ~~Copernicus Marine Environment Monitoring~~
371 ~~Service (CMEMS)~~ quality information documentation of OSTIA SST
372 ([https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-](https://resources.marine.copernicus.eu/documents/QUID/CMEMS-SST-QUID-010-011.pdf)
373 011.pdf). Note that the drifting buoy SSTs used for validation are ingested into the
374 analyses, however the validation process uses OSTIA background fields without data
375 assimilating buoy SSTs -to ~~compareed with-to~~ drifting buoys from analysis day plus
376 1 day to ~~,as the time offset between the background fields and these drifting buoys~~
377 avoids the validation data independence issue.

378 OSTIA SST has been used as boundary conditions for operational forecast models at
379 the UK Met Office and European Centre for Medium-range Weather Forecasting
380 (ECMWF) and is also part of the CMEMS project. The validation ~~_and-~~ assessment
381 activities update regularly through the CMEMS project ~~_and-~~ the data ~~_and-~~ relevant
382 documentations are available at
383 [https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=](https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SST_GLO_SST_L4_REP_OBSERVATIONS_010_011)
384 SST_GLO_SST_L4_REP_OBSERVATIONS_010_011.

385

386 **3 Basic diagnostics**

387

388 In order to compare the selected datasets (see Section 2) especially against global
389 SST climatology, all the SST products need to be mapped on a common temporal
390 and spatial resolution (regular $1^\circ \times 1^\circ$ latitude-longitude grid.). Apart from HadISST1,
391 the majority of the SST products have higher resolution than $1^\circ \times 1^\circ$ and the
392 advantage of high resolution is to resolve small scale ocean processes. The
393 interpolation from higher resolution to low resolution may exclude the impacts of
394 important small-scale signals in the SST products. Before we present the basic
395 diagnostics such as mean climatology and variability, we have performed spatial
396 spectral analysis (Section 3.1.1 - methods and Section 3.2.1 - results) to quantify the
397 impact of interpolation to the common $1^\circ \times 1^\circ$ resolution we have performed in our
398 basic diagnostics.

399

400 The grid of HadISST1 has been chosen as the reference grid (at 1°x1° nominal
401 resolution). The HadISST1 land-sea mask has then been applied to all products. In
402 addition, a sea-ice mask was built from HadISST1 and used as a common sea-ice
403 mask for all datasets.

404

405 To homogenize the datasets' temporal and spatial resolution we have used CDO
406 (Climate Data Operator) command line operators (see the user guide at
407 <https://code.mpimet.mpg.de/projects/cdo/embedded/cdo.pdf>). In particular, we have
408 chosen a bilinear interpolation for gridding all datasets on the HadISST1 spatial grid.

409

410 For all the selected SST products, the overlapping period is 2003-2018 (Figure 1) and
411 the intercomparison of all SST products are performed for the period 2003-2018,
412 when observations are abundant compared to the beginning of the satellite era.

413 ~~Recent period increased quantities of observations ingested~~ The richness of
414 ~~observation numbers used~~ in the SST analysis may reduce the spread of ensemble
415 ~~help all the~~ SST products produced with different algorithms converge. In order to

416 understand deeper the discrepancy and consistency between all the SST analyses
417 produced with different algorithms, similar intercomparison diagnostics of SST
418 products (ESA-CCI, ERA5, OSTIA, NOAA OISST, MGD SST and HadISST1) that have the
419 common period from 1982-2018 (Figure 1) are also carried out for the earlier period
420 of the satellite era (1982-2002) when the observations are scarce compared to the
421 later period of the satellite era.

422
423 In this section, we first introduce the methodologies we applied to produce the
424 basic diagnostics, and the spatial spectral analysis method used to investigate the
425 impact of spatial resolution is also presented. Then we present the results generated
426 by these diagnostics in terms of intercomparison for the period 2003-2018, and the
427 intercomparison of SST products that cover the period 1982-2002 is presented at
428 the end of this section.

429

430 **3.1 Statistical Methods**

431 A set of basic diagnostics have been defined to evaluate the similarity and
432 disagreements between selected SST datasets, as detailed in the following
433 subsections. Some of these metrics, such as the mean climatology, quantify the
434 long-term mean spatial distribution (climatology) of the ~~sea-surface-temperature~~SST
435 for each single dataset and can be used to qualitatively evaluate the capability of
436 SST in representing the climatological spatial patterns and the temporal variability of
437 globally averaged SSTs . Other metrics, such as difference, root-mean-square
438 difference (RMSD), and correlation, measure the distance between a single product
439 and a "reference". The latter can be either a previously validated dataset (if available)
440 or any other dataset that is arbitrarily chosen as reference. In this report, we have
441 taken the median of all datasets (hereafter the Ensemble median) as a reference and
442 used it to measure the difference among different SST products. Finally, we choose a
443 specific case study of the El Niño Southern Oscillation (ENSO) Nino3.4 Index to
444 evaluate the capability of representing ENSO events in all SST products. Nino3.4 is
445 the average ~~sea-surface-temperature~~SST anomaly in the region bounded by 5°N to
446 5°S, from 170°W to 120°W.

447 3.1.1 Spatial Spectral Analysis

448 The spectral analysis method we adopted in this study is the Multitaper Power
449 Spectral Density Estimate (MTM) (Thomson, 1982), which is a very useful tool for the
450 analysis of relatively short and noisy series that may contain both broadband and
451 line components. Different from several other ~~spectra~~ techniques, MTM
452 ~~multiplies~~multiply the data by a small set of orthogonal tapers rather than a single
453 taper to minimize the spectral leakage due to the finite length of the series.

454 ~~MTM requires, as input, to fix number of tapers (k) and the integer bandwidth~~
455 ~~parameter (p) that imply a choice of a bandwidth equal to $2pf$, in which f is the~~
456 ~~Rayleigh frequency $f=1/(NDT)$, N is the number of samples and DT is the sampling~~
457 ~~interval. As in many other practical cases the selection of p and k represents a~~
458 ~~classical trade off between spectral resolution, defined by the selection of p , and the~~
459 ~~need of a variance reduction related to the number of tapers k that pre-multiply~~
460 ~~the series. Note that the choice $p=1$ and $k=1$ is simply the single tapered discrete~~
461 ~~Fourier transform.~~

462 MTM power spectral estimates were performed using the pmtm matlab function
463 (<https://www.mathworks.com/help/signal/ref/pmtm.html>). ~~setting the time-~~
464 ~~halfbandwidth product p equal to 2. This is equivalent to the choice resolution p=2~~
465 ~~and number of tapers, k=(2*p-1)=3 in the SSA-MTM toolkit~~
466 (<https://dept.atmos.ucla.edu/tcd/documentation>). ~~We preferred to use the matlab~~
467 ~~function rather than the University California Los Angeles (UCLA) toolkit because we~~
468 ~~needed to recursively compute spectra on a daily basis for time series of several~~
469 ~~years before applying a time average and this was not feasible with the very user~~
470 ~~friendly toolkit that requires to process individually each series.~~ For more details
471 please refer to Ghil et al. (2002) Section 3.4.

472

473 We have chosen four ~~representative~~ datasets, ESA-CCI and OSTIA with the original
474 spatial resolution of 0.05° and MGSST and NOAA Daily OISST (Reynolds 0.25 x
475 0.25° SST) with the original resolution of 0.25° all covering the same period 1982-
476 2018 with daily frequency. Meanwhile, we chose the Pacific equator ~~pixel~~~~pixels~~ line,
477 spanning from Indonesian to South America as the study region (0°N, 120°E-80°W).

478 For each dataset the spatial power spectral density has been estimated on a daily
479 basis over the common period (1982-2018) and then time averaged. The detailed
480 results and discussion are given in Section 3.2.1.

481 **3.1.2 Trend analysis**

482
483 ~~Sea surface temperature~~SST trends have been estimated by using the X-11 seasonal
484 adjustment procedure (see e.g. Pezzulli et al., 2005). Given X_t is the input time series
485 (namely, an SST time series), the X-11 procedure generates the following
486 decomposition:

487
$$X_t = T_t + S_t + I_t$$

488
489 where T_t is the trend component, S_t the seasonal component and I_t the irregular
490 component, which accounts for the residual irregular variations such as sub-annual
491 fluctuations. The decomposition is obtained through iterative application of different

492 running means, which have the effect of a low-pass filter for T_t estimation and a
493 seasonal filter for S_t estimation.

494 In addition, the Mann-Kendall test is used to assess whether a monotonic upward or
495 downward trend in T_t exists (against the null hypothesis of no trend), Sen's method
496 is applied to estimate the slope of T_t , i.e. the trend (as the median of the slopes of
497 all pairs of sample points), and a bootstrap procedure is used to estimate the 95%
498 confidence interval of the trend (Mann, 1945; Sen, 1968; Kendall, 1975; Efron and
499 Tibshirani, 1993).

500

501 **3.2 Results**

502

503 **3.2.1 Spatial Spectrum Analysis**

504

505 ~~With rapid growth of computing power and storage capacity, along with~~
506 ~~advancement of scientific knowledge and users' needs, spatial resolution of SST gap-~~
507 ~~free analyses has increased dramatically to resolve smaller scale features in the~~

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ocean. The spatial resolution of SST products used in this study spans from 1° to 0.05°, meaning that the highest resolution is 20 times smaller than the lowest resolution. In the high resolution SST products, the meso-scales might be resolved, by contrast in the low resolution SST products only large scale features are represented.

In order to verify the suitability of our choice of interpolation, we have performed spatial power spectral analysis (section 3.1.1) based on the chosen SST products (Figure 2). With rapid growth of computing power and storage capacity, along with advancement of scientific knowledge and users' needs, spatial resolution of SST gap-free analyses has increased dramatically to resolve smaller scale features in the ocean. The spatial resolution of SST products used in this study spans from 1° to 0.05°, meaning that the highest resolution is 20 times smaller than the lowest resolution. In the high resolution SST products, the meso-scales might be resolved, by contrast in the low resolution SST products only large scale features are represented.

524

525 All of the SST products we chose for the spectral analysis cover the same period

526 from 1982 to 2018 with daily frequency. OSTIA and ESA-CCI SST have the original

527 spatial resolution of 0.05° and MGDSSST and NOAA Daily OISST have the spatial

528 resolution of 0.25°. If the power spectra gradient becomes flat at a certain~~at certain~~

529 wavelength it means that the analysis carried out at a wavelength shorter than this

530 certain wavelength contains only noise. The result~~The power spectrum density of~~

531 these four datasets shows that even though all of these SST products have higher

532 grid resolution than the chosen common grid, 1°, the power density of all SST

533 products starts to decline at spatial wavelengths greater than their grid-resolution.

534 The prominent differences between NOAA OISST and MGDSSST are mostly likely due

535 to different background correlation length scales being used in the optimal

536 interpolation and different methodology used to correct satellite-based

537 observations~~Argo SSTs ingestion in NOAA OISST and different methodology to~~

538 correct satellite based observations. For high resolution datasets, the 0.05° products,

539 the power density ~~is~~ significantly declined after by ~80 ~100 km (wavenumber 10⁻²).

540 which is close to 10.7° spatial resolution near the equator and the gradient becomes
541 flat at wavelengths ~70 km. It means that the signals within a wavelength of 100 km
542 are noise,s with no physical meaning in 0.05° SST products, and that also applies to
543 0.25° resolution SST products. —Similar results were shown in Fiedler et al. (2019a)
544 that in the Gulf Stream regions for the 2017 northern winter the spectral density of
545 SST starts to depart from the $\varpi^{-11/3}$ cascade of SST field (equivalent to kinetic
546 energy power spectrum cascade of $\varpi^{-5/3}$ based on Le Traon et al., 1990; 2008) at
547 wavelengths around 90km. This confirms that the interpolation to 1° does not
548 undermine the interpretation of results presented in our study.

549
550 Additionally, the diagnostics performed in the following sections mainly focus on the
551 general features (mean climatology and long-term temporal variability) of the
552 representation of all the SST products. W-that we believe the interpolation of all SST
553 products to 1° brings minor issues to the interpretation of the results. Certainly, the
554 intercomparison between all the SST products in terms of specific details, for
555 example, the representation of the Gulf Stream and meso-scale features are not in

the scope of this study. Related activities are ~~underway~~undergoing and will be presented by the GHR SST SST Analysis Intercomparison Task Team in the near future.

3.2.2 -Mean and Variability (2003-2018)

In terms of the basic diagnostics, we have first calculated the mean climatology of the global SST distribution of the eight selected SST datasets during 16 years from 2003 to 2018 plus the median of all the eight SST products, i.e., the climatology of the ensemble median (Figure 3). In all eight cases, the average correctly reveals the dominant latitudinal spatial SST pattern: higher at the tropics, milder at middle latitudes and lower in the polar regions. Regions impacted by occasional or persistent presence of sea ice are flagged, i.e., only complete years have been considered for the average estimate in each grid point.

A first qualitative inspection of the eight mean SST fields suggests that all products reproduce a very similar spatial distribution of SST with minor differences not

572 appreciable from Figure 3. Considering a confidence level of 95%, the eight global
573 mean SST estimates for the period 2003 to 2018 range in an interval between
574 20.02°C and 20.17°C. The ensemble median obviously falls close to the middle of
575 this range (i.e., 20.12 °C).

576 In order to have a further investigation of the consistency and discrepancy between
577 all SST products, we calculated the difference between each SST product and the
578 ensemble median displayed in Figure 4. Considering a 95% confidence interval, the
579 global mean difference between each single product and the ensemble median
580 ranges between -0.05 and 0.1 °C with relevant spatial variability (Figure 4). In fact,
581 differences are more pronounced in the Southern ocean where distances between
582 single product values and the ensemble median reach values higher than 1°C. This is
583 particularly evident in the case of HadISST1 data. In general, higher difference areas
584 correspond to the western boundary current systems such as the Gulf Stream
585 Current, the Kuroshio Current in the Northern Hemisphere, Brazil currents in the
586 Southern Atlantic Ocean, and the Antarctic Circumpolar Current ~~Antarctic~~

587 ~~Circumpolar Current~~-(ACC), where eddies are extremely active. In some datasets,
588 especially ESA-CCI SST, ~~and~~ MGSST and OSTIA, the greatest differences from the
589 ensemble median are also located ~~within~~ eastern boundary currents ~~which~~
590 represent the main upwelling systems, e.g., ~~Peru~~-Chilli, Benguela, North West-
591 African coast and along the southern Saudi Arabia coast. These discrepancies could
592 be due to ~~the~~ mismatching in the position of the main streams, especially the eddy
593 representation in different SST products. Along the coast, the disagreement may
594 come from the interpolation methodology implemented in different SST datasets by
595 data providers. Especially regions where upwelling is active add difficulties to
596 retrieving satellite observations for representing SST patterns and variability. For the
597 case of ESA CCI SSTs, it has been shown that cool biases off the North West-African
598 coast and in the Arabian Sea arise from influences of mineral dust aerosol on IR
599 retrievals of SST, and a large-scale adjustment (not used here) for the dust-related
600 biases has been devised (Merchant and Embury, 2020).

601 The RMSD is defined as the square root of the average squared difference between
602 the SST value of each dataset and the ensemble median, which is an absolute
603 measure of the distance between each single product value and the ensemble
604 median. Considering the 95% confidence interval, the global average RMSD ranges
605 from 0.02 to 0.18 °C. Extreme RMSD values (Figure 5) are concentrated in the
606 Southern ocean ~~and that~~ corresponds to the ~~Antarctic Circumpolar Current~~ACC, as
607 also evidenced by the mean difference (Figure 4), particularly evident in HadISST1
608 data. These higher RMSD values are also observed in correspondence ~~to~~of the large
609 differences between each SST product and the ensemble median that are mainly
610 located in the western boundary currents, namely, the Gulf Stream in the North
611 Atlantic Ocean and the Kuroshio Current in the North Pacific Ocean, and the ACC
612 ~~currents~~ regions.

613 The spatial distribution of the Pearson correlation coefficient (Figure 6) highlights the
614 different behavior of HadISST1 with respect to the other seven products. In
615 particular, in the southern ocean region, the correlation falls down to values as low

616 as 0.5 or even less. Similar but less extended discrepancies are also observed for
617 BoM, ~~and~~ NOAA Daily OISSTs, ESA-CCI, MUR25, ERA5, OSTIA and MGDSSST. In
618 particular, -ESA-CCI seems well representative of the ensemble median. MUR25,
619 ERA5, MGDSSST and OSTIA are well representative of the ensemble median as well
620 but with slightly higher discrepancies than other SST products. However, the low
621 correlation especially along the coastal regions could be due to the interpolation
622 method adopted during the SST production by data providers because it is still a
623 challenge to correctly retrieve satellite observations at the coastal upwelling regions
624 where SST is highly variable.

625 The temporal variability of globally averaged monthly mean SSTs (Figure 7) clearly
626 exhibits the annual oscillation around the mean value of 20.12 °C (Figure 3). This
627 oscillation has an amplitude of about 0.6 °C as a result of the opposite seasonal
628 cycle in the southern and northern hemispheres. SST anomalies from 2003 to 2018
629 (Figure 8) are obtained by subtracting from all SST products the annual cycle of the
630 ensemble median, i.e., the mean of each month over the whole period (2003-2018).

631 Two main periods are observed with ~~distinguished~~distinct mean values: the first
632 period before 2012 where the temperature oscillates around a constant mean value
633 of about 20.1°C and a second period where a positive (warming) trend is observed.
634 All the eight datasets show temperatures that vary coherently over all time scales
635 but with relative absolute biases in the range from zero to 0.4 °C.

636

637 **3.2.3 Global linear trends (2003-2018)**

638 Global SST trend maps have been computed for each product over the common 16
639 years period from 2003 to 2018 (Figure 9). All the datasets exhibit a global mean
640 warming SST trend ranging from 0.012 (HadISST1) to 0.022 (MGDSST) °C/year, with
641 an average value of 0.019 °C/year (ensemble median). Within the 95% confidence
642 interval, these results are close to the global ocean warming trend of 0.011 °C/year
643 from 1980 to 2005 reported in the last IPCC report (Pachauri et al., 2014) and the
644 differences are due to the different calculating period. The prominent warming
645 trends shown in all SST products are located in the subtropical North Atlantic Ocean,

646 South Indian Ocean, eastern tropical Pacific Ocean close to the American continent.
647 Especially at the Gulf Stream area all SST products (apart from HadISST1 which has
648 slightly weaker signals compared to other dataset) exhibit distinguished warming
649 trends for the period of 2003 to 2018.

650 In the North Atlantic Ocean, between 40 and 70 °N, negative trends are observed in
651 the sub polar gyre region extending up to the coastal areas of Ireland. A second
652 common negative trend area is present in the Southern Ocean at longitudes
653 centered around the Drake Passage. In the tropical Atlantic Ocean, a large area of
654 negative trends is observed only in ERA5 and a smaller area in BoM, OSTIA and
655 HadISST1. For all the other products this area is characterized by no significant
656 trends (i.e., areas where, given the $p=0.05$ limit, the null hypothesis cannot be
657 refuted) with few sparse negative trend points.

658
659 The Mediterranean Sea shows an evident positive trend in all products in contrast
660 with a close to zero trend region in the adjacent northeast Atlantic Ocean. This is

661 in agreement with what was recently published by Pisano et al. (2020) who observe
662 that, after 1990, SST in the Mediterranean Sea continues to increase in contrast with
663 the adjacent areas of the Atlantic Ocean where a pause of the general warming
664 trend occurred. The larger area of positive SST trends is present in the Indian Ocean.
665 Intense (positive) trends cover more uniformly and densely the reddish areas in ESA
666 CCI, MUR, NOAA OISST and MGDSST data, while a more patchy and less intense
667 positive trend coverage is observed in ERA5, BoM, OSTIA and HadISST1 data.

668 Besides a bias that separates the curves by a maximum of 0.2°C, the trend
669 component of the eight spatially averaged global SST time series (Figure 10a),
670 obtained using the X-11 procedure with a 2-year low-pass filter (section 3.1.2),
671 shows a very similar behaviour for all the products. The time evolution of the trend
672 component reveals an apparently neutral period until 2011 included with a single
673 maximum centered on the year 2009. After this period, a continuous warming phase
674 is observed with an increase of the temperature of nearly 0.3°C, that is, about

0.06°C/year which is consistent with the signal observed in the time series anomalies (Figures 7 and 8).

In order to understand better the contribution to the significant warming trends for the period of 2012-2018 observed in all SST products, we have calculated the SST trend component in different ocean basins, i.e. Pacific Ocean (Figure 10b), Atlantic Ocean (Figure 10c) and Indian Ocean (Figure 10d). Quantitatively, the warming trends for the period of 2012-2018 ranges from 0.036°C/year (BoM) to 0.062°C/year (MUR25) with 0.049°C/year in the ensemble median. The major contributor to this warming trend comes from the Pacific Ocean where warming trends span from 0.045°C/year (BoM) to 0.084°C/year (MUR25) with 0.064°C/year in the ensemble median. The contribution from the Atlantic (0.02°C/year from BoM to 0.52°C/year from MUR25) is smaller compared to the Pacific Ocean, and the warming trends in the Indian Ocean from 2012 to 2018 are relatively very small (from 0.002°C/year, MGDSSST to 0.030°C/year, BoM), which are evidently exhibited in Figure 10d.

3.2.4 Intercomparison during the early period (1982-2002)

In this section, we present the intercomparison of all SST products covering the period 1982-2002. ~~First we have shown t~~The global mean SST time series (Figure 11) that covers the time period originally obtained in each SST product allows us to detect the consistency and disagreement between all SST products for a longer period to fully take advantage of SST products which covers the period beyond 2003 and 2018. As we have discussed, all the SST products are very similar ~~to for~~ the period of 2003-2018 when there are abundant observations. On the contrary, during the period of early satellite era (1982-2002), the disagreement between all the SST products is larger compared to the later period (2003-2018), which may be due to ~~fewerless~~ observations ingested in the SST analysis.

To quantify the consistency and discrepancy of SST products for the early satellite era (1982-2002) we have ~~calculated~~~~performed~~ the mean climatology (Figure 12) for all SST products which cover the period back to 1982 (Figure 1), including ESA-CCI, OSTIA, ERA5, NOAA OISST, MGSST and HadISST1 and the differences between

705 each member with the ensemble median (Figure 13). The mean climatology of SST
706 during the period of 1982-2002 spans the range from 19.76°C (NOAA OISST) to
707 20.05°C (HadISST1) with the ensemble median as 19.79°C. The differences of each
708 member relative to the ensemble median for the period of 1982-2002 range from
709 0.03°C to 0.26°C that is much higher than that during the period of 2003-2018
710 which range from 0.01°C to 0.1°C. The discrepancy of all SST products (Figure 13)
711 are located in the areas that are similar to the period of 2003-2018 (Figure 4), but
712 with amplified signals. However, in some SST products, the differences relative to the
713 ensemble median change signs. For example, during the period of 2003-2018 the
714 MGDSSST mean climatology is higher than the ensemble median in the eastern
715 Indian Ocean. On the contrary, the mean climatology differences between MGDSSST
716 and the ensemble median became negative during the period of 1982-2002. ERA5
717 SST is based on OSTIA SST, however, there are differences between them because
718 ERA5 is forced by SST from an ocean model with increment based on the difference
719 between ocean analysis and OSTIA, which contains information from the OSTIA
720 SST but is not exactly identical to the same.

721 These results are consistent with what is shown in Figure 11 that during the early
722 period of the satellite era (1982-2002, ~~fewer~~less SST observations) all the SST
723 products have larger differences compared to the later period (2003-2018, more
724 SST observations), indicating that observation numbers is the main factor to
725 constrain the climatology of all the SST products developed with different
726 algorithms.— The total number of valid in situ SST observations from drifting buoys,
727 ships, Argo floats and moorings, used for bias-correcting satellite SST ingested into
728 ERA5, HadISST1, OSTIA, Daily OISST and BoM Monthly, ~~number~~ indeed increases
729 over time (Xu and Ignatov, 2014; <https://www.star.nesdis.noaa.gov/socd/sst/iqum>).
730 In 2002, the microwave radiometer AMSR-E~~the Advanced Microwave Scanning~~
731 Radiometer (AMSR) for Earth Observing System (EOS) started to be in operation on
732 Aqua and Terra satellites, which measures ocean brightness temperatures through
733 clouds, commenced operation on Aqua satellite. This improvement in spatial
734 coverage of sensors in the satellite sensors is another important factor affecting on
735 SST data quality ingested into OSTIA, ERA5, MGSST and MUR25, and it is notable

that all SST products studied converge more after ~~year~~ 2003 compared to ~~that~~
before ~~year~~ 2003.

3.2.5 Niño 3.4 Index

In order to have a deeper evaluation of the quality of the SST for climate studies, we investigated the capability of representing the climate modes in all SST products for the period of 1982-2018 in order to include more ENSO events, here the Nino3.4 index (Trenberth 2020). Niño 3.4 is one of the most used indexes to monitor the occurrence and variability of El Niño and la Niña events, defined as the average equatorial SST anomalies across the Pacific in the region 5°S-5°N, 170W°-120W°. Figures 14 show the time evolution of the Niño 3.4 index during the 1982-2018 “common period” for each product time series after applying a 5-month ~~running~~moving ~~mean~~average filter.

751 All products give evidence of the very strong El Niño events in the period selected.

752 The procedure used here to independently compute the Niño 3.4 index for all the

753 data sets is the same applied by Trenberth (2020). The time evolution of the Niño

754 3.4 SST anomaly is nearly identical for all the products with ~~very~~ minor differences

755 (Figure 14). The three strong El Niño events that occurred during this investigation

756 period, namely 1982-1983, 1997-1998, and 2015-2016, are reproduced, with a

757 similar~~the same~~ intensity, by all products. Moreover, the larger intensity of the El

758 Niño positive anomalies with respect to the negative La Niña events confirms the

759 asymmetry hypothesis of Monahan and Dai (2004).

760

761 **4. Data Maturity Matrix**

762 The concept of the data maturity matrix is to evaluate the basic characteristics of a

763 dataset initiated by the World Meteorological Organization (WMO) to develop

764 technical guidance and standards for collecting, processing, and managing datasets.

765 The assessment of the maturity of the individual dataset is essential to guarantee

766 and further improve the documentation, storage, and dissemination of datasets that
767 are applicable for users (Peng et al., 2019).

768 The System Maturity Matrix (SMM) for Climate Data Records (CDRs) is first
769 developed in the Coordinating Earth Observation Data Validation for Reanalysis for
770 Climate Services project (CORE-CLIMAX) (Su *et al.*, 2018). The objective is to
771 develop a tool to evaluate different aspects of the CDRs combining scientific and
772 engineering views. (EUMETSAT, 2014). In the SMM framework assessments are made
773 in six major category areas and a score of 1 to 6 is assigned that reflects the
774 maturity of the CDR with respect to a specific category;

775

- 776 1. Software readiness
- 777 2. Metadata
- 778 3. User documentation
- 779 4. Uncertainty characterization
- 780 5. Public access, feedback, and update

6. Usage

However, the assessment of maturity can only ~~reflectspeak about aspects~~
~~aspects~~ of process maturity. It does not interpret the scientific quality of a dataset.

For example, a mature product may not be scientifically reliable thus the maturity matrix only provides the assessment of fitness-of-purpose of a given product for climate service practitioners in terms of the categories mentioned above.

Additionally, the SMM scores ~~should be recognized~~ recognize that at the early evaluation stage in the life cycle of the product the low scores in some of the categories do not demonstrate the possible future maturity of the dataset. Instead, low SMM scores indicate a recently released and evolving product at a less mature stage being made available to users.

In the context of the C3S_511 project, the aim of our assessment is to evaluate the maturity of the dataset instead of the whole CDRs. We have adopted the SMM methodology of the CORE-CLIMAX for our use to evaluate individual datasets. We defined our matrix as the Maturity Matrix (MM) since we evaluate the dataset

796 instead of the system of the dataset. Not all the categories from CORE-CLIMAX are
797 included because some of them are not suitable for our usage. A guidance
798 document is developed in the framework of C3S_511 project , and the assessment
799 scores given in this study are based on our guidance document
800 (<https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+M>
801 [aturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control](https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+M)). The MM, as
802 important as the scientific quality, provides data providers important information in
803 which aspects they need to improve their dataset for potential easy access and
804 usage for users.

805 The MM of ESA-CCI and ERA5 SST (Table 2), showing that ESA-CCI SST is much
806 more mature compared to ERA5 SST in terms of documentation, uncertainty
807 characterization, and usage. As we mentioned above, low MM scores do not suggest
808 the scientific quality of ERA5 SST is lower than ESA-CCI SST. However, in terms of
809 the documentation of the dataset, ESA-CCI SST is much more advanced than ERA5
810 SST.

811 In this study we have extended the evaluation of the MM to the dataset outside of
812 CDS (Table 2). Due to the length limit, detailed defensible traces to score MM for
813 SST products are given in the Appendix. In terms of metadata, MGDSSST has a lower
814 score because it is provided in text format not following any standards with limited
815 global attributes. The rest of the SST analysis products follow the NetCDF format
816 and CF compliance with detailed information on Metadata. Compared with other
817 datasets, BoM, MGDSSST and MUR25 lack user documentation including the formal
818 description of scientific methodology, validation report and product user guide. A
819 formal user guide is not found for HadISST1 either. Very few SST products (OSTIA
820 and ESA-CCI SST) have automated quality monitoring in terms of the uncertainty
821 characterisation category. Thanks to GHRSSST activities, all GHRSSST L4 products
822 follow internationally agreed GHRSSST specifications, which provide uncertainty
823 calculations. Several SST analysis products (HadISST1, MGDSSST, BoM and ERA5)
824 have very limited validation, standards or uncertainty quantification documentation.

825 All SST products are publicly available via [the](#) online portal, except that BoM SST is
826 available on request from the data provider via their website. However, the

827 versioning, user feedback, and updates to records in the category of public access

828 ~~toef~~ SST products are not fully developed for BoM and MGD SST. All SST products

829 except ERA5 are widely used in multiple research fields, and most of them either

830 support decision support systems or usage and benefits of the SST products are

831 emerging.

832 Overall, most of the SST products are well documented and user friendly. As we

833 mentioned before, this scoring does not judge the scientific quality of the SST

834 product. However, the low scoring of some products might give data providers

835 important information to improve the documentation of their products in order to

836 make the product more user friendly.

837

838 **5. Summary of evaluations**

839 ~~Sea Surface Temperature (SST)~~ is an essential climate variable (ECV) to assess the

840 state of the global climate system and monitor its variations on interannual and

841 (multi)decadal timescales. Accurate SST observations at high spatial and temporal

842 resolution over a long-term period are needed to evaluate the present state of the
843 oceans and the impact of global surface warming.

844 In this report, eight different SST datasets have been analyzed and intercompared
845 for the overlapping period from 2003-2018. The ESA CCI SST v.2.1 and ERA5
846 reanalysis are available through the C3S Climate Data Store while the remaining six
847 datasets (OSTIA, HadISST1, NOAA Daily OISST, MUR, MGDSST, BoM) are provided
848 outside the CDS. All these datasets provide global gap-free (optimally interpolated)
849 SST maps but at different spatial and temporal resolutions. Then, to be comparable,
850 all the datasets have been gridded to a common grid (i.e., 1°x1°) and averaged to a
851 common temporal frequency (i.e., monthly) over the overlapping period from 2003
852 to 2018. Finally, the average of the median of all the datasets (namely, the Ensemble
853 median) has been defined in order to analyze differences among these datasets.

854 In general, all the SST datasets show consistent climatological spatial patterns
855 (section 3.2). The global monthly mean and anomaly SST time series of these
856 datasets show very good agreement. When compared to the Ensemble median,

857 higher differences (in terms of mean difference, root-mean-square difference and
858 correlation) are found in correspondence to the main current systems, such as the
859 Gulf Current, the Kuroshio Current and the Antarctic circumpolar current. These
860 discrepancies ~~can be~~are due to the different retrieval methods used to derive the
861 spatially-complete SST analyses. Differences can originate from several factors:
862 interpolation technique and related configuration (e.g. observation/background error
863 correlation scales), interpolation grid size, input data bias-correction and, if present,
864 the correction applied to obtain the foundation temperature or the temperature at
865 0.2 m. As an example, OSTIA, MUR25, MGDSST and ERA5 (via OSTIA from 2007
866 onwards) are the only L4 analyses included in the study that ingested microwave SST
867 data. Since these datasets (OSTIA, MUR25, MGDSST and ERA5) would ingest possibly
868 cooler daytime SST observations over cloudy regions, they may therefore exhibit
869 slightly cooler biases after 2002 compared with the other analyses that ingest only
870 infrared SST observations and in situ data. This effect may be offset in some
871 analyses, such as BoM Monthly and NOAA Daily OISST v2.1, where in situ data at 0.2
872 m to several meters depth are used to bias-correct the infrared AVHRR SST data.

873 However, on average, the Taylor diagram confirms the very close similarity between
874 the different datasets.

875 All the datasets reproduce very similar spatial patterns of global SST trends (section
876 3.3). In addition, global mean warming trends as estimated from all the datasets are
877 consistent (within the 95% confidence interval) with the global ocean warming trend
878 as reported in the last IPCC report, estimated at 0.011 °C/year from 1980 to 2005.

879 The linear trends in different basins show~~ss~~ that the main contributor from 2012 to
880 2018 is the Pacific Ocean.

881
882 The global mean SST time series for the whole period originally covered by all the
883 SST products reveals that the disagreement between all SST products is larger in the
884 early period (1982-2002) of the satellite era during which ~~fewerless~~ observations are
885 available compared to the later period (2003-2018) of the satellite era. Specifically,
886 the difference between each ensemble member and the ensemble median ranges
887 from 0.03°C to 0.26°C during the early period (1982-2002) and from 0.01°C to 0.1°C

888 during the later period (2003-2018), respectively. It indicates that the observations
889 ingested into ~~each~~ the SST analysis plays a significant role in constraining the SST
890 climatology. ~~The Satellite sensor improvements in the satellite (e.g., the~~
891 ~~launch~~ operation of AMSR-EOS in 2002 that could measure ocean brightness of
892 temperatures through clouds) is another important factor affecting ~~on the~~ SST quality
893 after 2003. ~~Noted~~ that the impact of natural variability on SST climatology is
894 embedded in the analysis, that is, ~~it is~~ difficult to differentiate from the constraint of
895 SST observations on the SST climatology. Additionally, the discrepancy between each
896 product due to algorithms, observations ingested etc. is very small compared to the
897 significant warming trends shown in the linear trends and time series.

898
899 Finally, the tropical Pacific region has been selected, as a test case, to assess the
900 capability of the different SST products, with a longer common temporal period, to
901 capture the main modes of variability of a well-known climate oscillatory mode, ~~i.e.~~ e.g.
902 ~~the El Niño Southern Oscillation (ENSO)~~. This analysis confirmed the close similarity
903 of all the five datasets selected and their capability to reproduce, in the same way,

904 the main components of the tropical Pacific region space and time variability at time
905 scales compatible with the length of the selected time series.

906
907 The maturity matrix score of all SST products (Table 2), that aims to demonstrate the
908 maturity of data documentation during the life cycle of one product, shows that
909 most of SST products are user friendly and provide sufficient information. Low scores
910 ~~of some SST products (Table 2), which do not indicate low scientific quality of the~~
911 ~~dataset, but shows~~indicate a direction where data providers could improve their
912 products in terms of data documentation, storage and dissemination for users.

913 Thanks to the ~~Group for High Resolution SST (GHRSSST)~~ effort, all GHRSSST products
914 are well documented for their uncertainty characteristics (GHRSSST Science Team,
915 2012).

916

917 **6. Recommendations to users**

918 All the datasets presented here provide state-of-the-art spatially-complete SST
919 products at the global scale. These datasets are characterized by different spatial
920 and temporal resolutions and temporal coverage that can fulfil the requirements of
921 a large variety of users.

922 Intercomparison results and a test case analysis suggest these datasets provide an
923 accurate representation of the SST spatial-temporal variability. These datasets can
924 then be used for fundamental climate applications compatible with the length of
925 each time series, such as long-term monitoring of SST changes (e.g., trends) and
926 comparison to or initialization of numerical models. Other target applications include
927 the use of these datasets in the definition of climatic indices, assessment and
928 monitoring of weather extreme events (including marine heatwaves) and their
929 impact on marine ecosystem, and related services.

930

931 In this study we have interpolated all SST products into 1 degree and monthly
932 frequency in order to facilitate intercomparison studies. However, to understand
933 which dataset is suitable for specific case studies where spatial and/or temporal
934 resolution are critical, such as the separation of the Gulf Stream and the diurnal
935 cycle of the SST products, specific intercomparison studies are required. Indeed, in
936 the framework of the GHRSSST intercomparison team, several such intercomparison
937 tasks are ongoing and scientific findings will be available in the near future.

938

939 Finally, users are strongly encouraged to consider also the type of SST offered by
940 each producer and to, distinguish between, e.g., skin SST, subskin or SSTdepth, and
941 foundation SST according to the specific application for which the data are ~~meant~~
942 intended to be used. For example, skin SST in conditions of high insolation and low
943 surface ocean mixing skin SST is- strongly impacted by diurnal warmingcontains
944 diurnal cycle, but SST at 0.2 m depth somewhat impacted, SSTdepth below 1 m
945 minimally impacted and foundation SST has no diurnal signature~~do not have the~~

946 ~~diurnal cycle involved~~ [\(Gentemann et al., 2009; Minnett and Kaiser-Weiss, 2012\)](#). In
947 our study, we have used SSTdepth, foundation SST and SST at 0.2 [m depth](#), which
948 [appears to](#) have [had](#) minor impact~~ss~~ on the ~~interpretation of the~~ results.

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961 authors declare no conflict of interest.

962

963 **Data Availability Statement**

964 The download website of all datasets used in this study has been included in the
965 manuscript in section 2.

966

967 **Appendix**

968 This section provides dDefensible traces for Maturity Matrix Score given to all SST
969 products shown in Table 2 based on the guidance document
970 (<https://confluence.ecmwf.int/display/CKB/Guidance+document+on+applying+the+M>
971 aturity+Matrix+as+part+of+the+Evaluation+and+Quality+Control) developed within
972 the C3S independent assessment project (C3S_511).

973

974 1. ESA-CCI SST

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975 Metadata

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976 *Standard* (Score: 6/6)

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977 The ESA CCI SST data files follow the GHR SST Data Specification v2.0 (GDS) and are

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978 provided in NetCDF-4 format CompactFlash (CF)-1.5 compliant. Files specifications

979 are fully detailed in the ESA CCI Product User Guide (PUG). The NetCDF files contain

980 detailed metadata describing the data by means of global attributes, which are

981 applicable to the whole file, and variable attributes, which apply to a specific data

982 field.

983

984 *Collection Level* (Score: 6/6)

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985 The ESA CCI SST data files follow the GHR SST Data Specification v2.0 (GDS). Global

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986 attributes provide all information available on the data and relative references. In

987 addition the Product Specification Document (PSD) with detailed information of

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988 Metadata is available.

989

990 User Documentation

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991 *Formal description of scientific methodology* (Score: 6/6)

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992 The formal description of the ESA CCI SST product is detailed in the Algorithm

993 Theoretical Background Document (ATBD), published by the data provider, which

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994 describes and justifies the algorithms used for obtaining ~~sea surface temperature~~ SST

995 estimates. A synthesis of the formal ATBD is also available in the CDS. In addition,

996 the ESA CCI SST dataset has been published in Nature Scientific Data (Merchant et

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997 al., 2019).

998 *Formal validation report* (Score: 6/6)

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1000 For the formal validation report of the ESA CCI SST L4 product users can refer to

1001 Merchant et al. (2019), Product User Guide (PUG), and Climate Assessment Report

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1002 (CAR).

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1004 *Formal product user guide* (Score: 6/6)

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1005 The formal product user guide ESA CCI SST product is published by the data
1006 provider (PUG). A synthesis of the formal user product guide is also available in the
1007 CDS.

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1008
1009 Uncertainty Characterization

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1010 *Standards* (Score: 6/6)

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1011 Uncertainty characterization follows the internationally agreed GHR SST standard
1012 specifications, which are detailed in the GHR SST Data Specification v2.0 (GDS)
1013 document.

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1014
1015 Validation (Score: 6/6)

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1016 A detailed and comprehensive validation of the ESA CCI SST L4 product is provided
1017 in the Product ~~Product~~-User Guide (PUG), Climate Assessment Report (CAR), and in
1018 Merchant et al. (2019). The validation of the ESA CCI SST L4 product is based on
1019 different procedures, from automated and visual inspection to comparison of SST
1020 data with co-located in situ measurements.

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1021

1022 *Uncertainty quantification* (Score: 6/6)

1023 Uncertainty in the ESA CCI SST L4 data at each location (i.e., the analysed_sst field in

1024 the NETCDF file) is quantified and provided (i.e., in the analysis_error field) through

1025 an analysis quality methodology. The methodology used to derive the uncertainty is

1026 based on the optimal interpolation theory and described in the ATBD and PUG,

1027 giving comprehensive information of validation of the quantitative uncertainty

1028 estimates and error covariance.

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1029

1030 *Automated Quality monitoring* (Score: 6/6)

1031 The identification of valid observations for ~~sea surface temperature~~SST estimation

1032 and algorithms used in the preparatory preprocessing are described in the ATBD

1033 and PUG. Moreover, a confidence level on a scale 0 to 5 is provided for each SST as

1034 a quality indicator, following the international GHR SST conventions. Five indicates

1035 the highest confidence. Quality levels 4 and 5 should be used for climate

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1036 applications. Automated check is implemented to valid the data quality (Merchant et
1037 al., 2019).

1039 Public access, feedback and update

1040 *Public Access/Archive* (Score: 56/6)

1041 The ESA CCI SST dataset v2.0 is available on the data provider's website. Detailed
1042 information available in the PUG. However, the source code is not publically
1043 available.

1045 *Version* (Score: 6/6)

1046 The version is fully established by the data provider.

1048 *User feedback* (Score: 6/6)

1049 The ESA CCI SST dataset v2.0 is also provided through the ~~Copernicus Marine~~
1050 ~~Environment Monitoring Service (CMEMS)~~ and is part of GHR SST. Within CMEMS, a
1051 Multi-Year Product Quality Working Group is established with the aim of periodically

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1052 assessing the status of the CMEMS climate data records, including ESA CCI SST,
1053 integrating users' needs and feedback. Feedback from users are also included in the
1054 Climate Assessment Report (CAR). In addition, ESA CCI data provider provides an
1055 email contact to collect users' feedback.

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1057 *Updates to record* (Score: 6/6)

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1058 Currently the ESA CCI SST dataset v2.0 covers the period from late-1981 to 2018.
1059 Updates through to the near-present are expected this year (2020). Extensions are
1060 expected to be produced by the Copernicus Climate Change Service (C3S) with only
1061 ~5 days delay to real time

1062

1063 Usage

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1064 *Research* (Score: 6/6)

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1065 The ESA CCI SST dataset v.2.0 is very recent. However, it has already been used in
1066 some research publications.

1067

1068 *Decision support system* (Score: 6/6)

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1069 ESA-CCI SST is part of the ESA Climate Change Initiative, and one of the essential

1070 climate variables. The objective of ESA-CCI SST is to establish a long term data

1071 record to monitor the global climate system required by UNFCCC (<http://cci.esa.int/>)

1072 for decision making.

1073

1074 2. ERA5 SST

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1075 Metadata

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1076 Standard (Score: 6/6)

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1077 ERA5 SST data can be downloaded from the CDS in both GRIB and NetCDF formats.

1078 The native data format is GRIB, but they can be converted to NetCDF format

1079 through the CDS. In NetCDF global attributes reference to CF-1.6 conventions is

1080 made. This represents a mature state-of-the-art metadata standard according to

1081 guidance.

1082

1083 *Collection Level* (Score 5/6)

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1084 The standardized attributes on the collection level of the dataset are sufficient to
1085 understand the data's origins without further documents, including standardized
1086 information on how to obtain raw data and its preprocessing procedures.

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1087 Note: The collection level in this case includes the ECMWF confluence-wiki
1088 confluence
1089 wiki. (<https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation>)

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1090 User Documentation

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1091 *Formal description of scientific methodology* (Score—5 6/6)

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1092 The scientific description is comprehensive and publicly available in the form of a
1093 scientific report/ATBD and elibrary of ECMWF. The description is kept up to date
1094 with the updated dataset. There is also a peer reviewed methodological journal
1095 paper published.

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1096 ~~Note: In this case the confluence-wiki is regarded as the scientific report/ATBD and~~
1097 ~~also elibrary of ECMWF.~~

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1098
1099 *Formal validation report* (Score: 3/6)

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1100 There is no formal validation report for ERA5 SST. The ERA5 documentation available
1101 at confluence wiki can be regarded as a user guide but does not have any clear
1102 version number with a publication date and is a document that is changing. Due to
1103 the nature of ERA5 being in development it makes sense to have an evolving
1104 documentation, but the creation of a formal product validation report in the future
1105 is recommended. An assessment report evaluating HadISST2 and OSTIA SST datasets
1106 (from which ERA5 SST is built) is available (Hirahara 2016).

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1108 *Formal product user guide* (Score 6/6)

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1109 There is a regularly updated comprehensive formal Product User Guide (PUG) for the
1110 dataset publicly available.

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1111 Note: In this case the confluence wiki is regarded as the Product User Guide (PUG).

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1113 Uncertainty Characterization

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1114 Standards (Score 3/6)

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1115 Uncertainty information follows standard nomenclature.

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1116 Note: In this case the ensemble members are regarded as uncertainty measures.

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1118 *Validation* (Score: 3/6)

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1119 A formal validation report of ERA5 SST is not available. However, an assessment

1120 report evaluating HadISST2 and OSTIA SST datasets (from which ERA5 SST is built) is

1121 available (Hirahara 2016), and users can refer to HadISST2 and OSTIA

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1122 documentation.

1123

1124 *Uncertainty quantification* (Score 3/6)

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1125 A comprehensive uncertainty quantification of systematic and random effects is

1126 available.

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1127 Note: In this case the ensemble members are regarded as uncertainty measures.

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1129 *Automated quality monitoring* (Score 2/6)

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1130 There is no automated quality monitoring documented for the dataset.

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1131 Note: Although there is no automated quality monitoring documented, data
1132 assimilation itself could be regarded as a quality check.

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1133
1134 Public access, feedback and updates

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1135 *Access and Archive* (Score 56/6)

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1136 The dataset is publicly available. The different versions of data including
1137 documentation and source code is archived by the data provider. Source code is not
1138 publically available.

1140 *Version Control* (Score 6/6)

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1141 There is full information on version control of documentation, data and/or metadata
1142 available for the dataset. The documented version control information is fully
1143 traceable from the files.

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1144 Note: In this case the version control is referring to the confluence wiki.

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1146 *User Feedback* (Score 6/6)

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1147 There is a public reach-out/feedback form/contact point for collecting feedback for
1148 the dataset. There are regular events, groups, 2-way feedback mechanisms, etc.
1149 organized by the data provider. The established feedback fed back into data
1150 production is documented, including third party international data quality
1151 assessment results.

1152

1153 *Updates to Record* (Score 6/6)

1154 There are regular operational updates available for the dataset, depending on the
1155 availability of input data and including improved methodology.

1156

1157 Usage

1158 *Research* (Score: 3/6)

1159 Although ERA5 reanalysis has been largely used in many research publications, it
1160 seems that there are few relevant publications based on ERA5 SST data (as e.g.
1161 Wang et al., 2020). This could arise from the prevalent use of ERA5 in atmospheric
1162 research.

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1163

1164 *Decision support system* (Score: 1/6)

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1165 To the evaluators' knowledge the product is not used yet for the decision support
1166 system. ~~this DSS.~~

1167
1168 3. OSTIA SST

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1169 Metadata

1170 *Standard* (Score: 6/6)

1171 The OSTIA SST data files are provided in NetCDF-4 format CF-1.5 compliant through

1172 ~~Copernicus Marine Environment Monitoring Service (CMEMS)~~ and the

1173 Recommended GHRSSST Data Specification (GDS)-. File specifications are fully

1174 detailed in the OSTIA Product User Manual (PUM) available in CMEMS. The NetCDF

1175 files contain detailed metadata describing the data by means of global attributes,

1176 which are applicable to the whole file, and variable attributes, which apply to a

1177 specific data field.

1178

1179 *Collection Level* (Score: 6/6)

1180 Global attributes provide all information available on the data and relative

1181 references. In addition the Product User Manual (PUM,) with detailed information on

1182 Metadata is available.

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1184 User Documentation

1185 *Formal description of scientific methodology* (Score: 6/6)

1186 The formal description of the OSTIA product is detailed in the peer-reviewed paper

1187 (Good et al., 2020), published by the data provider, which describes and justifies the

1188 algorithms used for obtaining ~~sea surface temperature~~SST estimates. A synthesis of

1189 the Product User Manual (PUM) is also available in the CMEMS.

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1191 *Formal validation report* (Score: 6/6)

1192 For the formal validation report of the OSTIA product users can refer to the Quality

1193 Information Document (QUID) available in the CMEMS service.

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1195 *Formal product user guide* (Score: 6/6)

1196 The formal product user guide OSTIA product is published by the data provider

1197 (PUM) as a peer-reviewed journal article Good et al. (2020). A synthesis of the formal

1198 user product guide (PUM) is also available in the CMEMS.

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1200 Uncertainty Characterization

1201 *Standards* (Score: 6/6)

1202 Uncertainty characterization follows the internationally agreed GHRSSST standard

1203 specifications, which are detailed in the GHRSSST Data Specification v2.0 (GDS)

1204 document (GHRSSST Science Team, 2012).

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1206 *Validation* (Score: 6/6)

1207 A validation of the OSTIA product is provided in the Quality Information Document

1208 through CMEMS. The validation of the OSTIA SST product is based on comparison

1209 of SST data with co-located in situ measurements.

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1211 Uncertainty quantification (Score: 6/6)

1212 Uncertainty in the OSTIA data at each location (i.e., the analysed_sst field in the
1213 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an
1214 analysis quality methodology. The methodology used to derive the uncertainty is
1215 produced using a special "observation influence" analysis (Good et al., 2020).

1216

1217 Automated Quality monitoring (Score: 6/6)

1218 Automatic quality is monitored during the production of the SST product. The real-
1219 time OSTIA SST analysis is routinely validated by the UK MetOffice against the
1220 GHR SST Multi-product ensemble ([http://ghrsst-pp.metoffice.gov.uk/ostia-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)
1221 [website/gmpe-monitoring.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)) and Argo SST ([http://ghrsst-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)
1222 [pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)).

1223

1224 Public access, feedback and update

1225 Public Access/Archive (Score: 5/6)

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1226 The OSTIA SST is available on the CMEMS website. Detailed information available in
1227 the PUM. However, the source code is not publically availaible.
1228

1229 Version (Score: 6/6)

1230 The version is fully established by the data provider.
1231

1232 User feedback (Score: 6/6)

1233 The OSTIA is provided through the ~~Copernicus Marine Environment Monitoring~~
1234 ~~Service (CMEMS)~~ and is part of GHR SST. Within CMEMS, a Multi-Year Product
1235 Quality Working Group is established with the aim of periodically assessing the
1236 status of the CMEMS data records, including OSTIA, integrating users' needs and
1237 feedback.
1238

1239 Updates to record (Score: 6/6)

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1240 Currently the OSTIA SST dataset covers the period from late-1981 to 2018. Updates
1241 through to the near-present are expected this year (2020). Extensions are expected
1242 to be produced by the CMEMS with only ~5 days delay to real time

1243

1244 Usage

1245 *Research* (Score: 6/6)

1246 The current version of OSTIA SST is very recent. However, it has already been used
1247 in some research publications.

1248

1249 *Decision support system* (Score: 6/6)

1250 OSTIA SST is part of the CMEMS project and the information derived from SST

1251 products is used in the CMEMS ocean state report for decision makingers.

1252

1253 4. BoM

1254 Metadata

1255 *Standard* (Score: 6/6)

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1256 The BoM SST files are provided in the GHR SST Data Specification version 1.7 NetCDF
1257 classic format CF-1 (Beggs and Pugh, 2009) on request from the data providers. The
1258 NetCDF files contain detailed metadata describing the data by means of global
1259 attributes, which are applicable to the whole file, and variable attributes, which apply
1260 to a specific data field.

1261 *Collection Level* (Score: 5/6)
1262 Global attributes provide all information available on the data and relative
1263 references. However, the reference shown in the Metadata (Beggs and Pugh, 2009) is
1264 not accessible at the moment of writing this report although it is available by
1265 request from library@bom.gov.au.

1266 User Documentation
1267 *Formal description of scientific methodology* (Score: 4/6)
1268 The formal description of the BoM Monthly OI SST is published in a conference
1269 paper (Smith et al., 1999) and a peer-reviewed paper (Beggs et al., 2011), however
1270
1271

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1272 the peer-reviewed paper focuses on the BoM higher resolution daily 1/12 degree
1273 regional analyses available from 2006, which uses a modified version of the Fortran
1274 "SIANAL" code used to produce the original BoM Weekly and Monthly OI SST
1275 analyses.

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1278 *Formal validation report* (Score: 22/6)

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1279 BoM Monthly OI 1 degree L4 SST is part of the GHRSSST suite of L4 products, and
1280 intercomparison of the BoM higher resolution daily SST analyses with other SST

1281 products have been published in peer reviewed journals (Beggs et al., 2011; Dash et

1282 al., 2012; Martin et al., 2012). However, the only previously published comparison of

1283 the lower resolution BoM Weekly 1 degree OI SST analysis with other SST analysis

1284 products is in a BoM Operations Bulletin (Zhong and Beggs, 2008).

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1286 *Formal product user guide* (Score: 4/6)

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1287 The description of the BoM Monthly OI SST analysis methodology is published in

1288 Smith et al. (1999) and Beggs et al. (2011), and a user guide is provided (Beggs and

1289 Pugh, 2009). However, (Beggs and Pugh, 2009) is not accessible at the moment of
1290 writing this report although it is available by request from library@bom.gov.au.
1291 However, the product user guide is not up to date for the current version of the SST
1292 we have used.

1294 Uncertainty Characterization
1295 *Standards* (Score: 6/6)
1296 Uncertainty characterization follows the internationally agreed GHR SST standard
1297 specifications (analysis_error), which are detailed in the GHR SST Data Specification
1298 v2.0 (GDS) document (GHR SST Science Team, 2012).

1300 *Validation* (Score: 53/6)
1301 No validation report is found for BoM SST. However, BoM is part of the GHR SST
1302 community and intercomparison activities of the BoM Daily Global SST analyses have
1303 been performed in the framework of GHR SST (Dash et al., 2011; Martin et al., 2011).
1304 Although routine verification of the BoM Global Daily 0.25 degree OI SST analysis

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1305 (GAMSSA) are performed by UK MetOffice (<http://ghrsst-pp.metoffice.gov.uk/ostia->
1306 [website/gmpe-argo-stats.html](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-argo-stats.html)) and NOAA/NESDIS/STAR
1307 (<https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4>), there are no routine
1308 verifications of the BoM Monthly or Weekly OI SST analyses.

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1310

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1311 *Uncertainty quantification* (Score: 6/6)

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1312 Uncertainty in the BoM data at each location (i.e., the analysed_sst field in the
1313 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an
1314 analysis quality methodology (Beggs et al., 2011).

1315

1316 *Automated Quality monitoring* (Score: 1/6)

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1317 No Automatic quality is provided.

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1318

1319 Public access, feedback and update

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1320 *Public Access/Archive* (Score: 4/6)

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1321 BoM Monthly SST product is available on request from the data provider website for
1322 both real-time and archived GHRSSST L4 files.

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1324 *Version* (Score: 2/6)

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1325 No information is found for the version control for BoM SST.

1326
1327 *User feedback* (Score: 3/6)

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1328 Data providers collect and evaluate feedback from the scientific community through
1329 the data provider's website, but no feedback mechanisms set up from data
1330 providers:-

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1332 *Updates to record* (Score: 5/6)

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1333 BoM Daily, Weekly and Monthly SST analyses are published in real time for climate
1334 monitoring on the BoM website.

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1336 Usage

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1337 *Research* (Score: 4/6)

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1338 The BoM Weekly and Monthly SST analyses have been used by the BoM for
1339 research, especially climate studies.

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1341 *Decision support system* (Score: 6/6)

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1342 BoM Monthly SST is an operational SST analysis which serves for climate monitoring
1343 that is an essential service of the Australian Government Bureau of Meteorology.

1345 5. MGDSSST

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1346 Metadata

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1347 *Standard* (Score: 3/6)

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1348 The MGDSSST is provided in the txt format and variable attributes are limited.

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1350 *Collection Level* (Score: 2/6)

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1351 There is limited information about standard attributes, but extra information
1352 published in the data provider's website is needed to use and understand the data.

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1354 User Documentation

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1355 *Formal description of scientific methodology* (Score: 34/6)

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1356 Limited information is provided on the data provider's website, but the method is
1357 documented in two non peer-reviewed reports

1358

1359 *Formal validation report* (Score: 4/6)

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1360 No JMA validation report is found for MGD SST at the time of writing this report.

1361 However, MGD SST was compared with other SST analyses and independent

1362 observations in Martin et al. (2012) and Fiedler et al. (2019a) for the periods 2010

1363 and 1992 to 2011. The UK MetOffice routinely compares MGD SST with the GHR SST

1364 Multi-product ensemble (<http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe->

1365 monitoring.html) and Argo SST (<http://ghrsst-pp.metoffice.gov.uk/ostia->

1366 website/gmpe-argo-stats.html).

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1368 *Formal product user guide* (Score: 3/6)

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1369 Limited product user guide from the data provider.

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1370

1371 Uncertainty Characterization

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1372 *Standards* (Score: 1/6)

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1373 No information is available at this stage.

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1375 *Validation* (Score: 6/6)

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1376 MGD SST is part of the GHR SST and intercomparison with other SST products has

1377 been performed and published in peer-review journals (Fiedler et al., 2019a; Martin

1378 et al., 2012).

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1380 *Uncertainty quantification* (Score: 1/6)

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1381 No uncertainty quantification is found.

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1383 *Automated Quality monitoring* (Score: 2/6)

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1384 No automatic quality is monitored during the production of the SST product.

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1386 Public access, feedback and update

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1387 *Public Access/Archive* (Score: 4/6)

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1388 The MGDSST is publicly accessible from the data provider's website and brief
1389 information of the data is provided in the data provider's website.

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1391 *Version* (Score: 2/6)

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1392 No information is found for the version control.

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1394 *User feedback* (Score: 3/6)

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1395 Data providers collect and evaluate feedback from the scientific community through
1396 the data provider's website.

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1398 *Updates to record* (Score: 4/6)

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1399 MGDSST is published in real time for climate monitoring and Numerical Weather
1400 Prediction on the data provider's website.

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1402 Usage

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1403 *Research* (Score: 6/6)

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1404 The data has already been used in some research publications.

1405

1406 *Decision support system* (Score: 6/6)

1407 MGDSST is an operational SST analysis which serves for climate monitoring and

1408 Numerical Weather Prediction that is an essential service of the Japanese

1409 Meteorological Agency (JMA).

1410

1411 6. MUR25

1412 Metadata

1413 *Standard* (Score: 6/6)

1414 The MUR25 SST is provided in NetCDF format. The NetCDF files contain detailed

1415 metadata describing the data by means of global attributes, which are applicable to

1416 the whole file, and variable attributes, which apply to a specific data field.

1417

1418 *Collection Level* (Score: 6/6)

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1419 Global attributes provide all information available on the data and relative
1420 references.

1421 User Documentation

1423 *Formal description of scientific methodology* (Score: 6/6)

1424 The formal description of the MUR25 product is detailed in the peer-reviewed
1425 journal (Chin et al., 2017), published by the data provider.

1426
1427 *Formal validation report* (Score: ~~4~~3/6)

1428 No formal validation report is available, however, the validation is performed in the
1429 peer-reviewed paper (Chin et al., 2017). Additional validation of the 1km product
1430 occurred with direct comparisons with the Saildrone autonomous vehicle with the
1431 published article. The validation focused on an exemplary coastal area, the
1432 California/Baja Coast.

1433
1434 *Formal product user guide* (Score: 2/6)

1435 No formal product user guide is available for MUR25 SST.

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1437 Uncertainty Characterization

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1438 *Standards* (Score: 6/6)

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1439 Uncertainty characterization follows the internationally agreed GHRST standard

1440 specifications, which are detailed in the GHRST Data Specification v2.0 (GDS)

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1441 document.

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1443 *Validation* (Score: 6/6)

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1444 Intercomparison of MUR25 has been performed in the framework of GHRST.

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1446 *Uncertainty quantification* (Score: 6/6)

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1447 Uncertainty in the MUR25 data at each location (i.e., the analysed_sst field in the

1448 NETCDF file) is quantified and provided (i.e., in the analysis_error field) through an

1449 analysis quality methodology.

1450

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1451 *Automated Quality monitoring* (Score: 4/6)

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1452 No automatic quality monitoring is found for MUR25 SST product, but the 1 km
1453 resolution version of the MUR SST analysis is routinely validated with the GHR SST
1454 Multi-product ensemble ([http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-](http://ghrsst-pp.metoffice.gov.uk/ostia-website/gmpe-monitoring.html)
1455 [monitoring.html](https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4); <https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4>). Since
1456 Argo SST are ingested into MUR25 they are not useful for verification.
1457
1458 Public access, feedback and update
1459 *Public Access/Archive* (Score: 56/6)
1460 The MUR25 SST is published in the data provider's archive center. However, source
1461 code is not publically available.
1462
1463 *Version* (Score: 6/6)
1464 The version is fully established by the data provider.
1465
1466 *User feedback* (Score: 6/6)
1467 Public contact information is given in the data provider's website for users to give
1468 feedback. Users can give all feedback through the Physical Oceanography

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1469 Distributed Active Archive Center (PO.DAAC) user services and forum. All feedback
1470 is publicly available.

1471

1472 *Updates to record* (Score: 5/6)
1473 Regular updates are available from the data provider. There is no immediate
1474 production of interim data products.

1475
1476 Usage
1477 *Research* (Score: 6/6)
1478 The MUR25 is used in research in multiple fields.

1479
1480 *Decision support system* (Score: 3/6)
1481 No decision support system is found for MUR25 SST, however use is occurring and
1482 benefits are emerging.

1483

1484 7. NOAA Daily OISSTv2.1 SST

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1485 Metadata

1486 *Standard* (Score: 6/6)

1487 The NOAA Daily OISST data files are provided in NetCDF-4 format CF-1.0 compliant

1488 data provider's website. The NetCDF files contain detailed metadata describing the

1489 data by means of global attributes, which are applicable to the whole file, and

1490 variable attributes, which apply to a specific data field.

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1492 *Collection Level* (Score: 6/6)

1493 Global attributes provide all information available on the data and relative

1494 references.

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1496 User Documentation

1497 *Formal description of scientific methodology* (Score: 6/6)

1498 The formal description of the NOAA Daily OISST v2.1 is provided in the data

1499 provider's website (<https://www.ncdc.noaa.gov/oisst>), third party data resource

1500 website (https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-v2.1) and is

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1501 also detailed in several peer-reviewed papers (Reynolds et al., 2007; Banzon et al.,
1502 2016; Huang et al., 2020), published by the data provider, which describe and justify
1503 the algorithms used for obtaining ~~sea surface temperature~~SST estimates.

1505 *Formal validation report* (Score: 6/6)
1506 Formal validation report of NOAA Daily OISST is along with data access.

1507
1508 *Formal product user guide* (Score: 6/6)
1509 The formal product user guide is provided in the peer review journal (Banzon et al.,
1510 2016).

1511
1512 Uncertainty Characterization
1513 *Standards* (Score: 6/6)
1514 Uncertainty characterization follows the internationally agreed GHRSSST standard
1515 specifications, which are detailed in the GHRSSST Data Specification v2.0 (GDS)
1516 document.

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1518 *Validation* (Score: 6/6)

1519 A validation of NOAA Daily OISST is provided through peer-review journals (Dash et
1520 al., 2012; Martin et al., 2012; Banzon et al., 2016; Fiedler et al., 2019a; Huang et al.,
1521 2020).

1522
1523 *Uncertainty quantification* (Score: 6/6)

1524 Uncertainty in the NOAA Daily OISST data at each location (i.e., the analysed_sst
1525 field in the NETCDF file available from
1526 https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-v2.1) is quantified and
1527 provided (i.e., in the analysis_error field) through an analysis quality methodology.

1528

1529 *Automated Quality monitoring* (Score: 4/6)

1530 The Daily OISST v2.1 SST analyses are validated in near real-time against the
1531 GHRSSST Multi-Product Ensemble by NOAA/STAR at

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1532 https://www.star.nesdis.noaa.gov/socd/sst/squam/analysis/l4. Since Argo SST are
1533 ingested into Daily OISST v2.1 they are not useful for verification.

1534

1535 Public access, feedback and update

1536 *Public Access/Archive* (Score: 56/6)

1537 The data is publicly accessible through the data provider's website and also other

1538 data portals with documentation. No souce code is available publically.

1539
1540 *Version* (Score: 6/6)

1541 The version is fully established by the data provider.

1542
1543 *User feedback* (Score: 36/6)

1544 Contact information of the data provider is publicly available for user feedback.

1545

1546 *Updates to record* (Score: 6/6)

1547 Data providers regularly update the data record.

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1548

1549 Usage

1550 *Research* (Score: 6/6)

1551 The NOAA Daily OISST is widely used in multiple research fields.

1552

1553 *Decision support system* (Score: 3/6)

1554 No decision support system is found for NOAA Daily OISST, however use is

1555 occurring and benefits are emerging.

1556

1557 8. HadISST1

1558 Metadata

1559 *Standard* (Score: 6/6)

1560 The HadISST1 ~~OISST~~ data files are provided in NetCDF classic format CF

1561 compliant through the data provider's website. The NetCDF files contain detailed

1562 metadata describing the data by means of global attributes, which are applicable to

1563 the whole file, and variable attributes, which apply to a specific data field.

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1565 Collection Level (Score: 6/6)

1566 Global attributes provide all information available on the data and relative
1567 references.

1568

1569 User Documentation

1570 Formal description of scientific methodology (Score: 6/6)

1571 The formal description of the HadISST1 is detailed in the peer-reviewed journal
1572 (Rayner et al., 2003), published by the data provider, which describes and justifies
1573 the algorithms used for obtaining ~~sea surface temperature~~SST estimates.

1574

1575 Formal validation report (Score: 6/6)

1576 Formal validation report is published in a peer reviewed journal.

1577

1578 Formal product user guide (Score: 3/6)

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1579 No formal product user guide is provided. Product information is provided on their

1580 the data provider's website.

1581

1582 Uncertainty Characterization

1583 Standards (Score: 1/6)

1584 No information is available at this stage.

1585

1586 Validation (Score: 6/6)

1587 The validation is available through peer reviewed journal paper.

1588

1589 Uncertainty quantification (Score: 1/6)

1590 No uncertainty quantification is found.

1591

1592 Automated Quality monitoring (Score: 1/6)

1593 No automatic quality is monitored during the production of the SST product.

1594

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Public access, feedback and update

Public Access/Archive (Score: 56/6)

The data is published through data provider's website, but no source code is
publically available.

Version (Score: 6/6)

The version is fully established by the data provider.

User feedback (Score: 36/6)

Contact information of the data provider is given for collecting user feedback.

Updates to record (Score: 6/6)

The data is regularly updated by the data provider.

Usage

Research (Score: 6/6)

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1611 HadISST1 has been widely used in multiple research fields.

1612

1613 *Decision support system* (Score: 6/6)

1614 Up to now no decision support system is found for HadISST1, however, influence on
1615 decision making is demonstrated.

1616

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1898 **Figures:**

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Dataset	Institution	Type of product	Time Range	Observation input	Type of SST	Horizontal Grid spacing	Vertical resolution	Temporal resolution	Main Reference
ESA CCI SST (v.2.0)	Met Office	SST analysis	1981-2018	IR	SST at 0.2 m	global 0.05°x0.05°	surface	daily	Merchant et al. (2019)
ERA5	ECMWF	SST analysis	1979-2018	IR + MW + in situ	---	global 0.25°x0.25°	surface	hourly	Hirahara et al. (2016)
HadISST1	Met Office	SST analysis	1870-2018	IR + in situ	---	global 1°x1°	surface	monthly	Rayner et al. (2003)
NOAA Daily OISST V8.1	NOAA	SST analysis	1981-2018	IR + in situ	SST at 0.2 m	global 0.25°x0.25°	surface	daily	Huang et al., (2020)
MUR25 (v.4.2)	PODACC	SST analysis	2003-2018	IR + MW + in situ	Foundation SST	global 0.25°x0.25°	surface	daily	Chin et al. (2017)
MGDSST	Japanese Met. Agency (JMA)	SST analysis	1982-2017	IR + MW + in situ	---	global 0.25°x0.25°	surface	daily	Sakurai et al. (2005)
BoM Monthly SST	Australian Bureau of Met. (BoM)	SST analysis	2002-2018	IR + in situ	SST at 0.2 m	global 1°x1° (weekly/monthly)	surface	weekly/monthly	Smith et al. (1999)
OSTIASST	UK MetOffice	SST analysis	1981-2018	IR + MW + in situ	Foundation SST	0.05°x0.05°	surface	daily/weekly/monthly	Good et al., 2020

Dataset	Institution	Type of product	Time Range	Observation input	Type of SST	Horizontal Grid spacing	Vertical resolution	Temporal resolution	Main Reference
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HadISST1	Met Office	SST analysis	1870-2018	IR + in situ	SSTdepth	global 1°x1°	surface	monthly	Rayner et al. (2003)
NOAA Daily OISST v2.1	NOAA	SST analysis	1981-2018	IR + in situ	SST at 0.2 m	global 0.25°x0.25°	surface	daily	Huang et al., (2020)
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OSTIASST	UK MetOffice	SST analysis	1981-2018	IR + MW + in situ	Foundation SST	0.05°x0.05°	surface	daily/weekly/monthly	Good et al., 2020

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Dataset	Institution	Type of product	Time Range	Observation input	Type of SST	Horizontal Grid spacing	Vertical resolution	Temporal resolution	Main Reference
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ERA5	ECMWF	SST analysis	1979-2018	IR + MW + in situ	SSTdepth	global 0.25°x0.25°	surface	hourly	Hirahara et al. (2016)
HadISST1	Met Office	SST analysis	1870-2018	IR + in situ	SSTdepth	global 1°x1°	surface	monthly	Rayner et al. (2003)
NOAA Daily OISST v2.1	NOAA	SST analysis	1981-2018	IR + in situ	SST at 0.2 m	global 0.25°x0.25°	surface	daily	Huang et al., (2020)
MUR25 (v.4.2)	PODACC	SST analysis	2003-2018	IR + MW + in situ	Foundation SST	global 0.25°x0.25°	surface	daily	Chin et al. (2017)
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OSTIASST	UK MetOffice	SST analysis	1981-2018	IR + MW + in situ	Foundation SST	0.05°x0.05°	surface	daily/weekly/monthly	Good et al., 2020

1903 Table 1. Descriptive product comparison summary for the described products from
1904 sections 2. Input observations are derived from satellite infrared (IR) and/or
1905 microwave (MW) sensors and/or in situ measurements.

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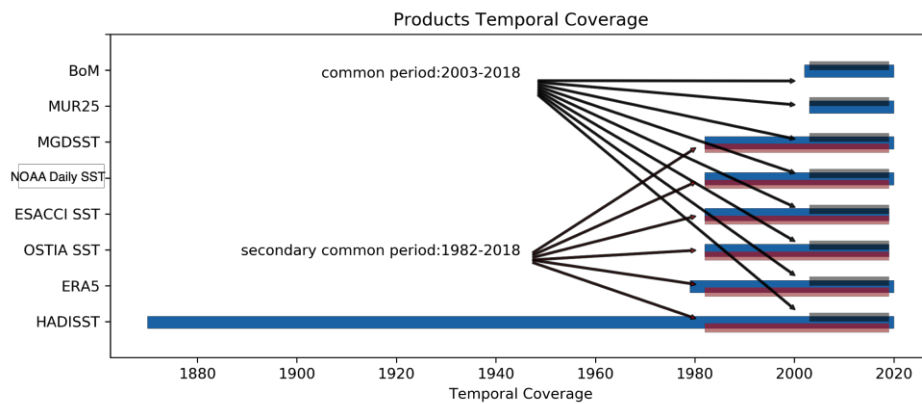
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Name	ESA CCI SST	ERAS SST	OSTIA	BoM	MGDSST	MUR25	NOAA Daily OISST	HadISST1
C3S_511 MM Category								
Metadata								
Standards	6	6	6	6	3	6	6	6
Collection level	6	5	6	5	2	6	6	6
User Documentation								
Formal description of scientific methodology	6	5	6	4	4	6	6	6
Formal validation report	6	3	6	2	4	3	6	6
Formal product user guide	6	6	6	4	3	2	6	3
Uncertainty Characterisation								
Standards	6	3	6	6	1	6	6	1
Validation	6	2	6	2	6	6	6	6
Uncertainty quantification	6	3	6	6	1	6	6	1
Automated quality monitoring	6	2	6	1	2	4	4	1
Public Access, feedback, and update								
Public Access/Archive	6	6	6	4	4	6	6	6
Version	6	6	6	2	2	6	6	6
User feedback mechanism	6	6	6	3	3	6	6	6
Updates to record	6	6	6	5	4	5	6	6
Usage								
Research	6	3	6	4	6	6	6	6
Decision support system	6	1	6	6	6	3	3	6

Name	ESA CCI SST	ERAS SST	OSTIA	BoM	MGDSST	MUR25	NOAA Daily OISST	HadISST1
C3S_511 MM Category								
Metadata								
Standards	6	6	6	6	3	6	6	6
Collection level	6	5	6	5	2	6	6	6
User Documentation								
Formal description of scientific methodology	6	6	6	4	3	6	6	6
Formal validation report	6	3	6	2	4	4	6	6
Formal product user guide	6	6	6	4	3	2	6	3
Uncertainty Characterisation								
Standards	6	3	6	6	1	6	6	1
Validation	6	3	6	5	6	6	6	6
Uncertainty quantification	6	3	6	6	1	6	6	1
Automated quality monitoring	6	2	6	1	2	4	4	1
Public Access, feedback, and update								
Public Access/Archive	5	5	5	4	4	5	5	5
Version	6	6	6	2	2	6	6	6
User feedback mechanism	6	6	6	3	3	6	3	6
Updates to record	6	6	6	5	4	5	6	6
Usage								
Research	6	3	6	4	6	6	6	3
Decision support system	6	1	6	6	6	3	3	6

Table 2. Maturity Matrix for all SST products



1914

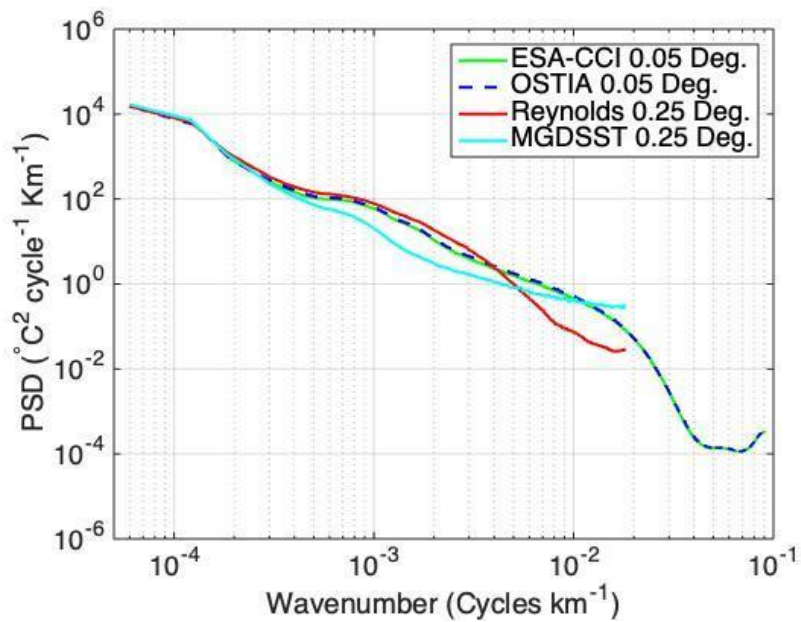
1915 Figure 1. Temporal range (years) covered by each SST dataset. The common period

1916 for all datasets is highlighted (2003-2018) and the secondary common period is

1917 1982-2018 with less SST products included.

1918

1919

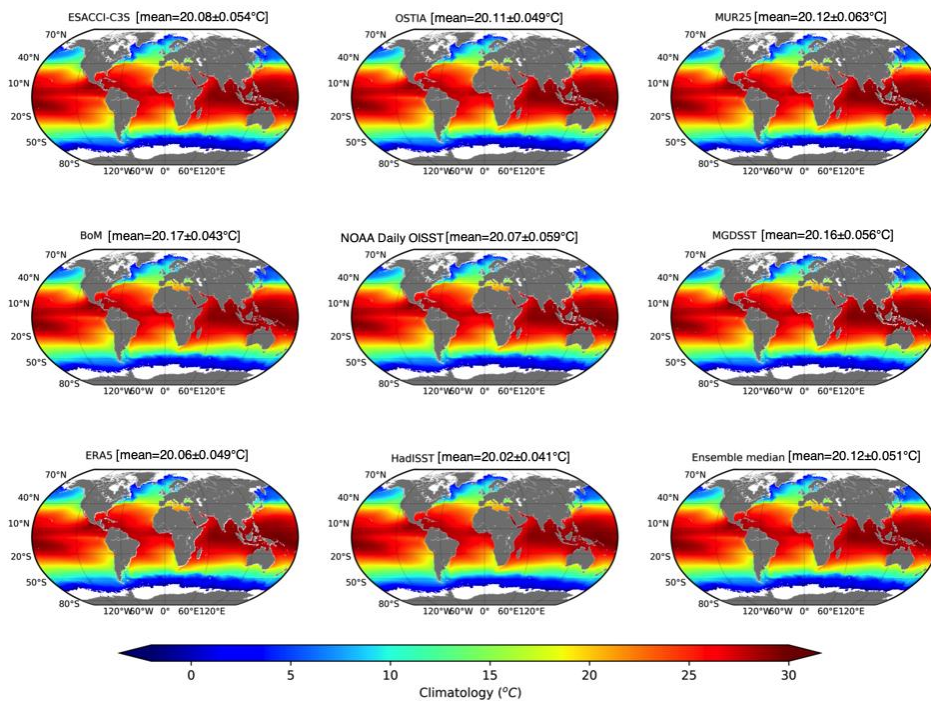


1920

1921

1922 Figure 2. Power Spectral Density at the equator in the Pacific Ocean (0°N, 120°E-
 1923 80°W) for ESA-CCI (green), OSTIA (dashed dark blue), NOAA Daily OISST (Reynolds
 1924 0.25 Degree. red) and MGDSST (cyan) based on the daily temporal and original
 1925 spatial resolution for the period 1982-2018

1926

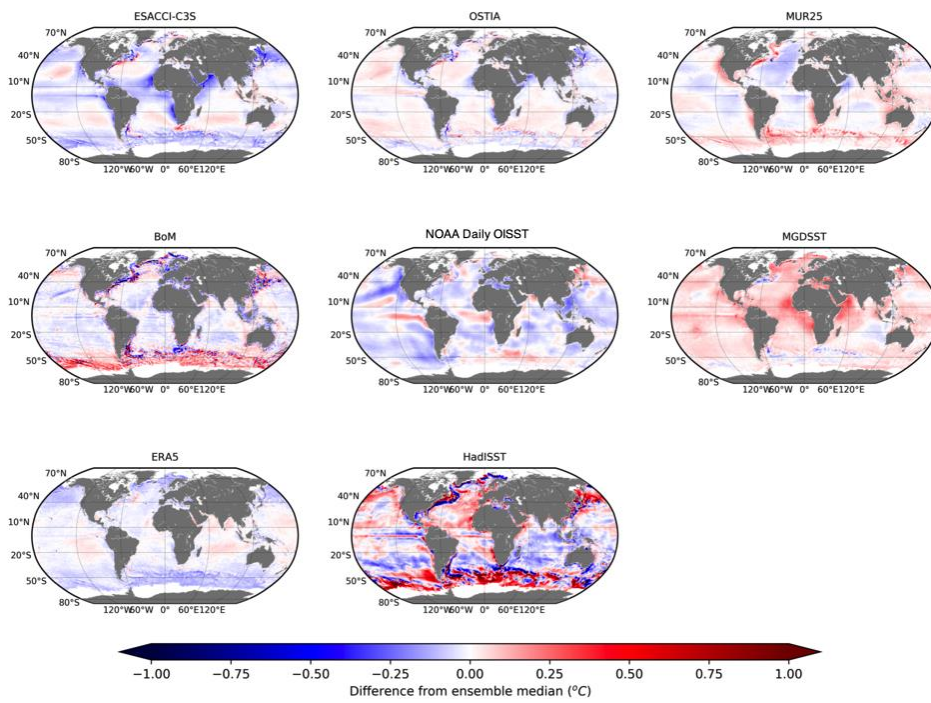


1927

1928 Figure 3. Global SST climatologies for the period 2003-2018. Global SST average

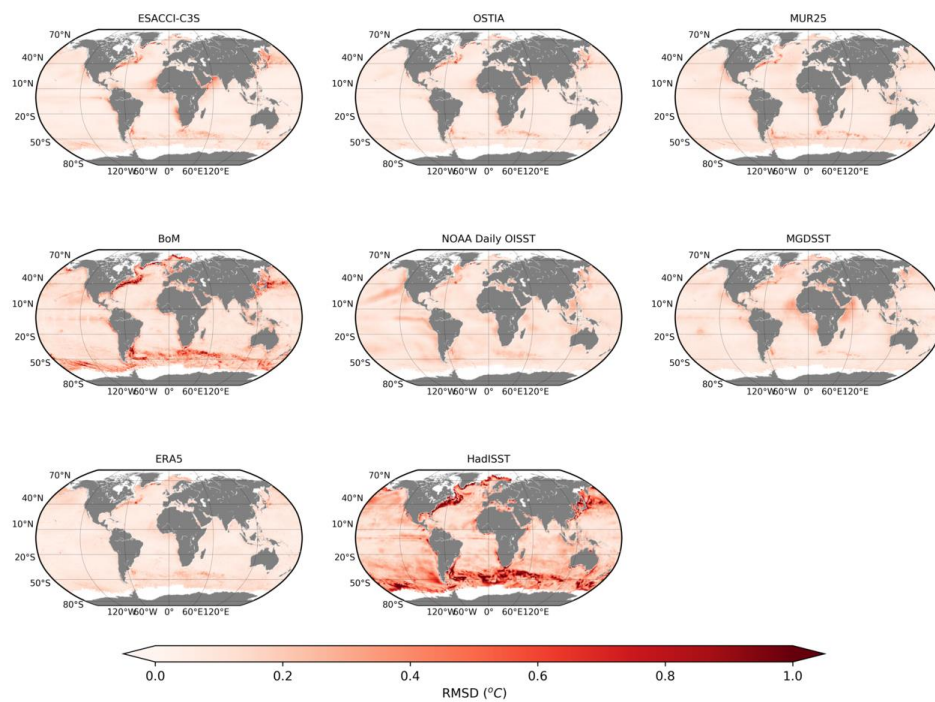
1929 value and its 95% confidence interval is also shown.

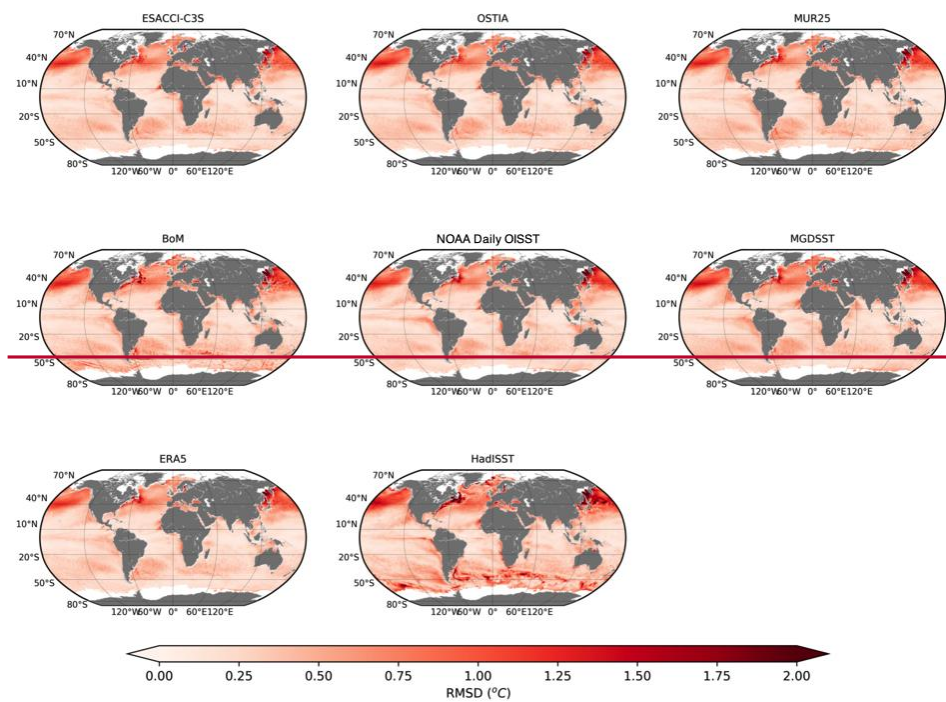
1930



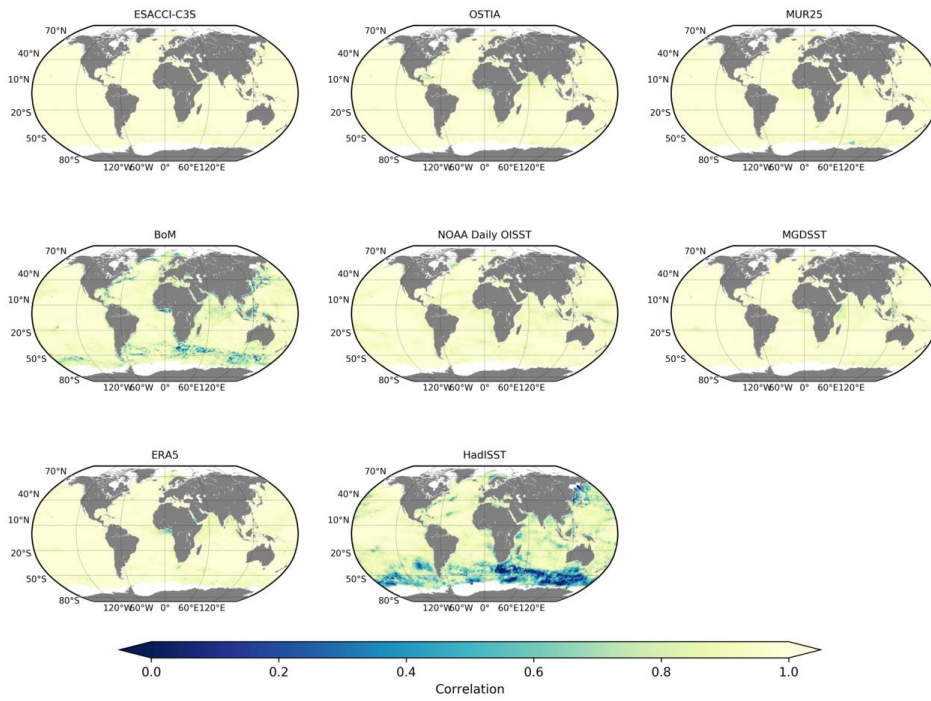
1931
 1932 Figure 4 The difference between each SST product and the ensemble median for the
 1933 period of 2003-2018

1934
 1935





1937
 1938 Figure 5 The RMSD between each SST product and the ensemble median for the
 1939 period of 2003-2018



1941

1942 Figure 6 The correlation between each SST product and the ensemble median for

1943 the period of 2003-2018

1944

1945

1946

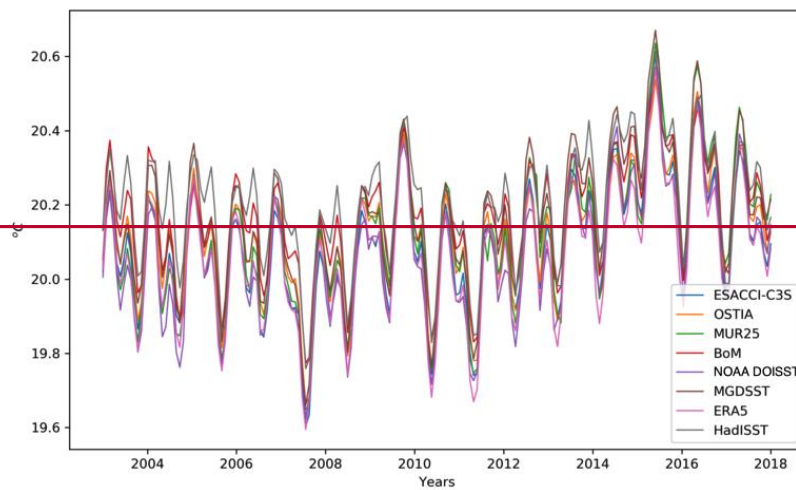
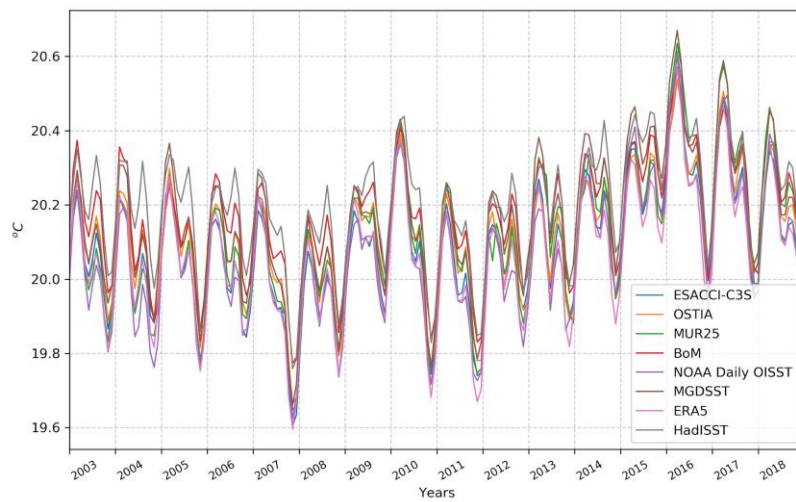
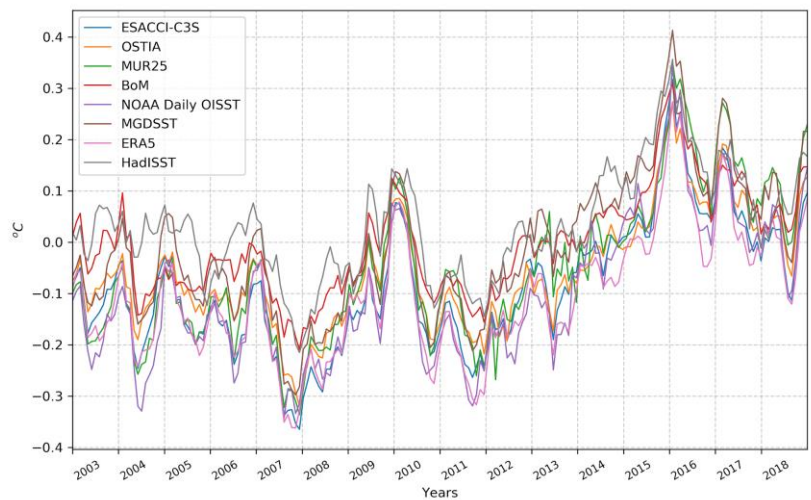
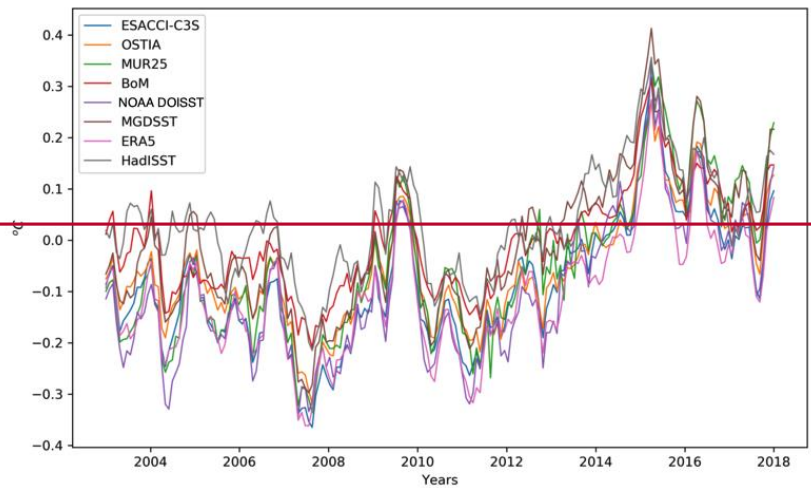


Figure 7 Global monthly mean SST time series from 2003 to 2018.

1950



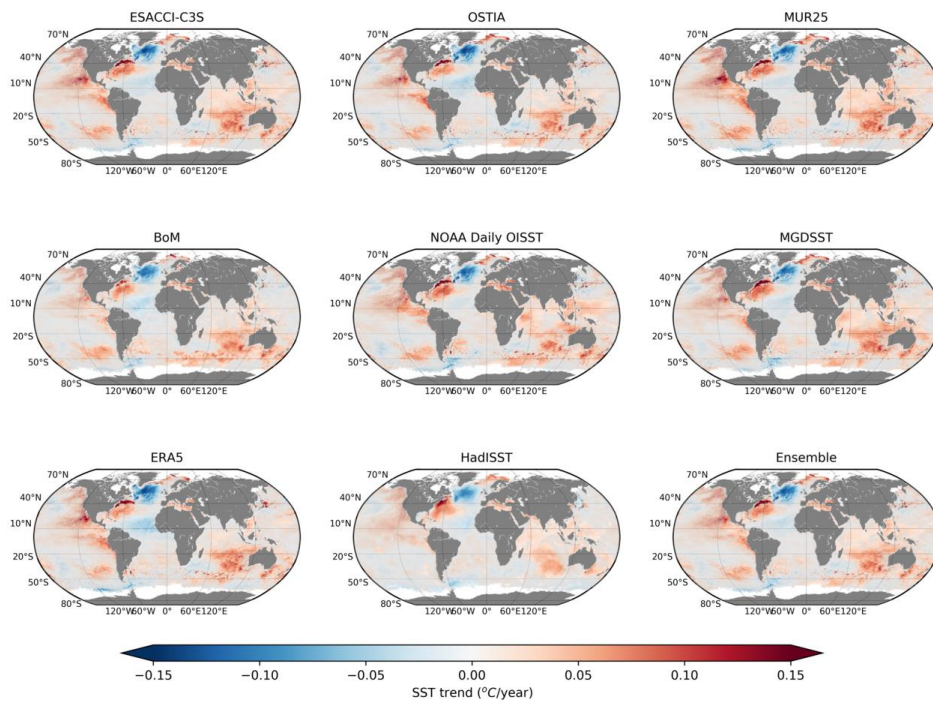
1951

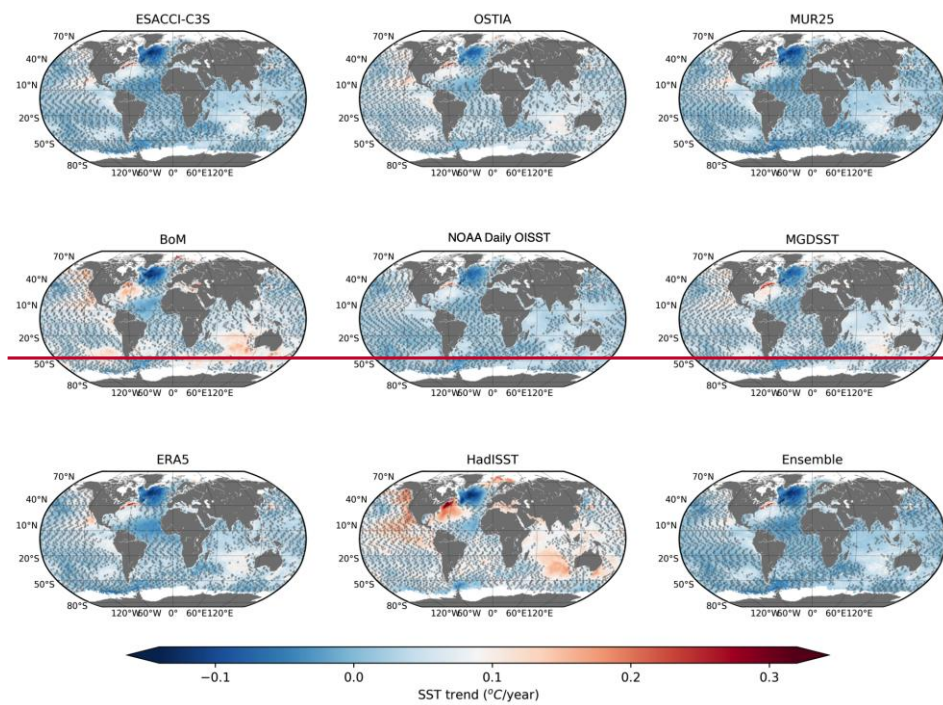


1952 Figure 8. Global SST monthly anomalies time series, obtained by subtracting the
1953 climatology of the ensemble median to all the SST ensemble members from 2003 to
1954 2018.

1955

1956





1958

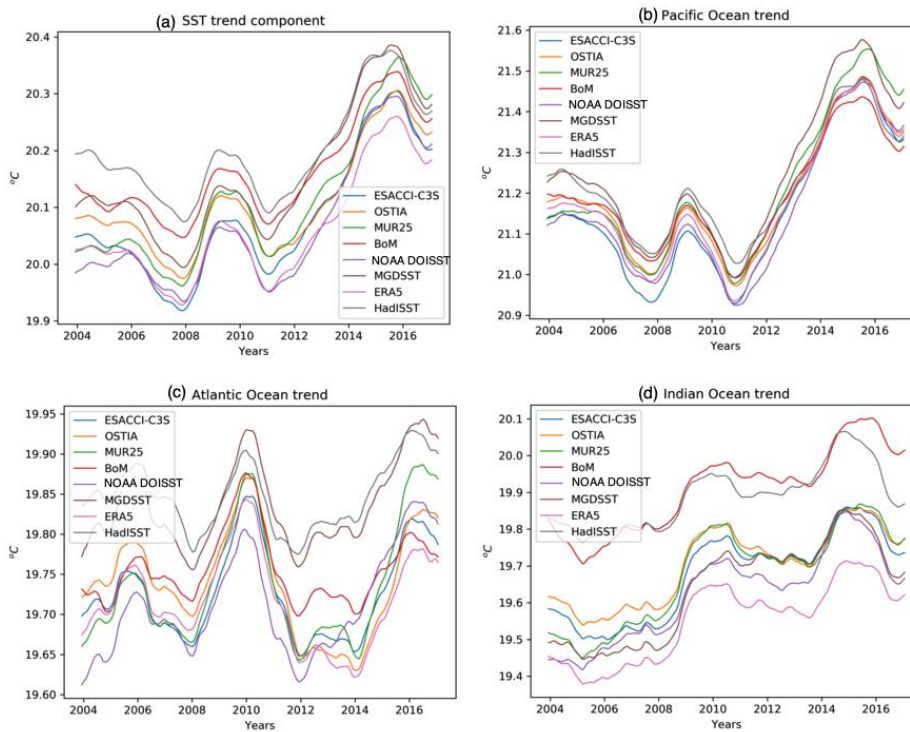
1959

1960 Figure 9. Global linear trend maps (2003-2018) ($^{\circ}\text{C}/\text{year}$) of each ensemble member

1961 and ensemble median. Areas with no significant (95% significance level) trends are

1962 covered by grey points.

1963

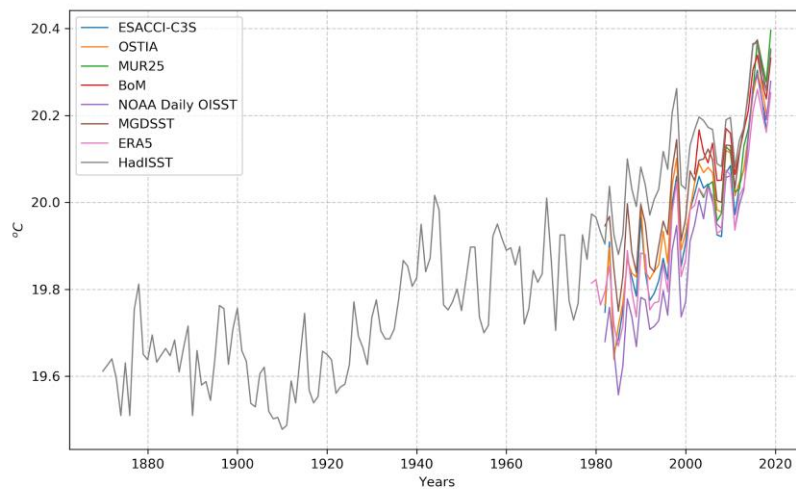


1964

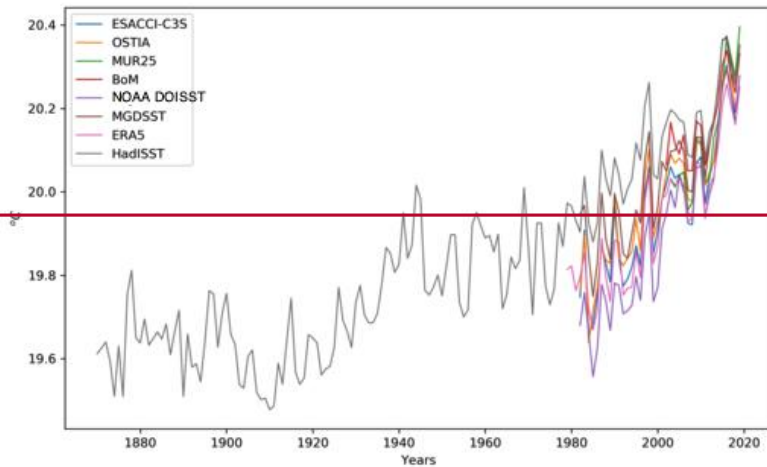
1965 Figure 10. (a) Global average SST trend component deduced from the global
 1966 average monthly mean time series (Figure 3.2.2) using the X-11 procedure (section
 1967 3.1.2), the same calculation but for (b) the Pacific Ocean basin (c) Atlantic Ocean
 1968 basin and (d) Indian Ocean Basin for the period of 2003-2018.

1969

1970



1971

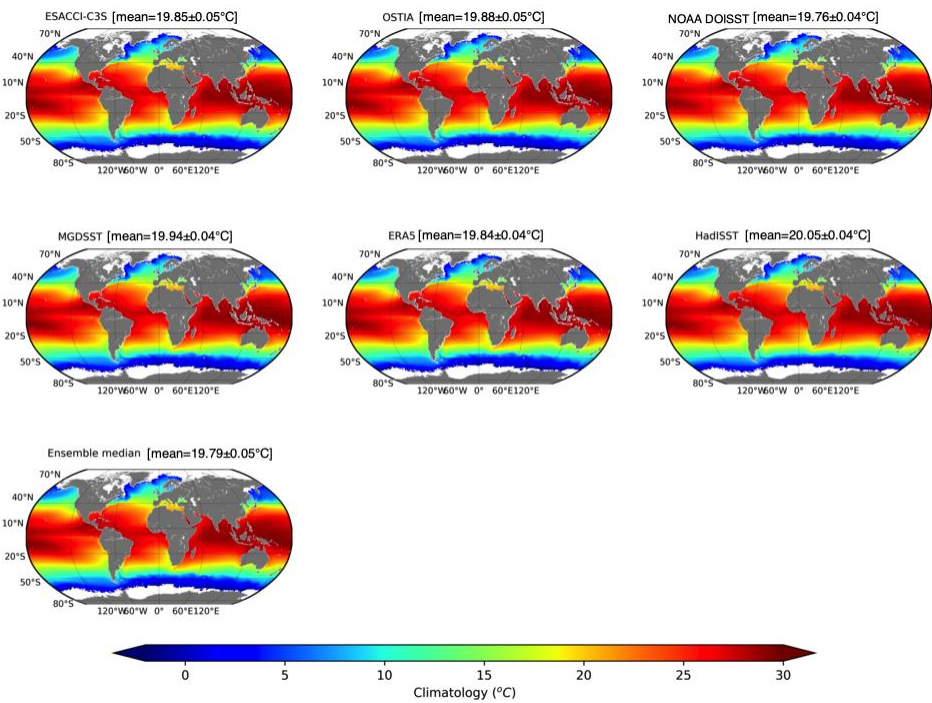


1972

1973 Figure 11. Global monthly mean SST time series for all the ensemble members for

1974 the whole covered period originally obtained in each SST product.

1975

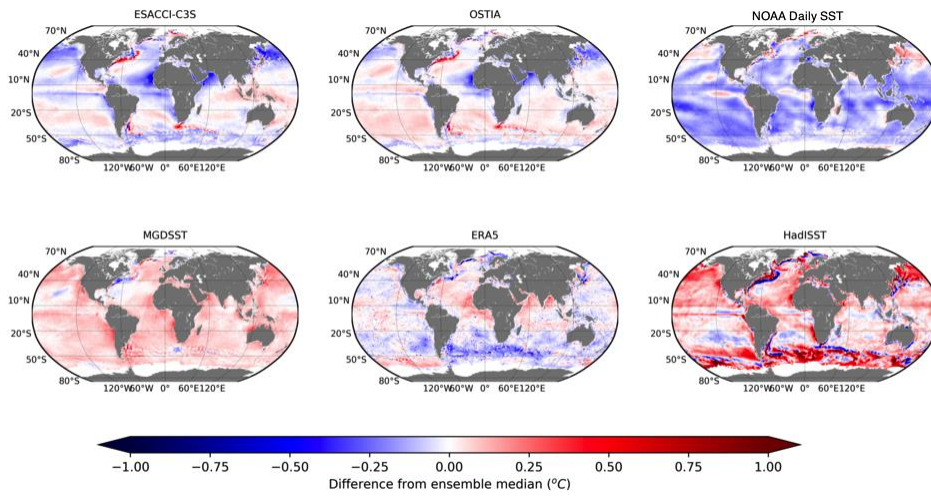


1976

1977 Figure 12 Global SST climatologies for the period 1982-2002. Global SST average

1978 and its 95% confidence interval is also shown in brackets above each map.

1979



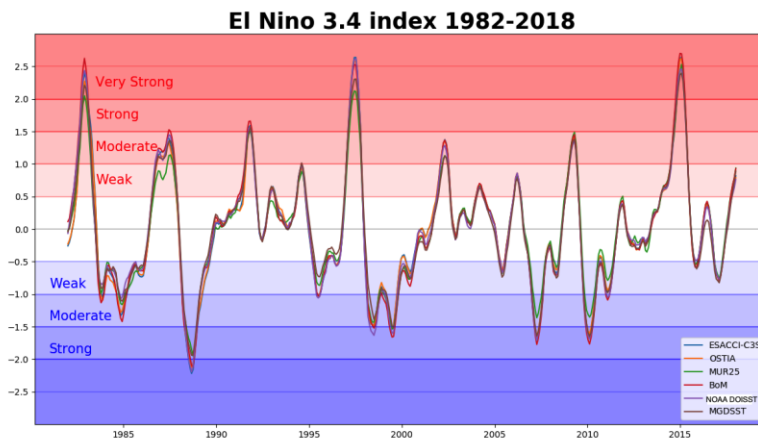
1980

1981

1982 Figure 13 The difference between each SST product and the ensemble median for

1983 the period of 1982-2002

1984



1985

1986 Figure 14 Intercomparison between El Niño 3.4 time series of the five SST products:

1987 HadISST1, ERA5, ESA CCI SST, MGDST, NOAA OISST.

1988