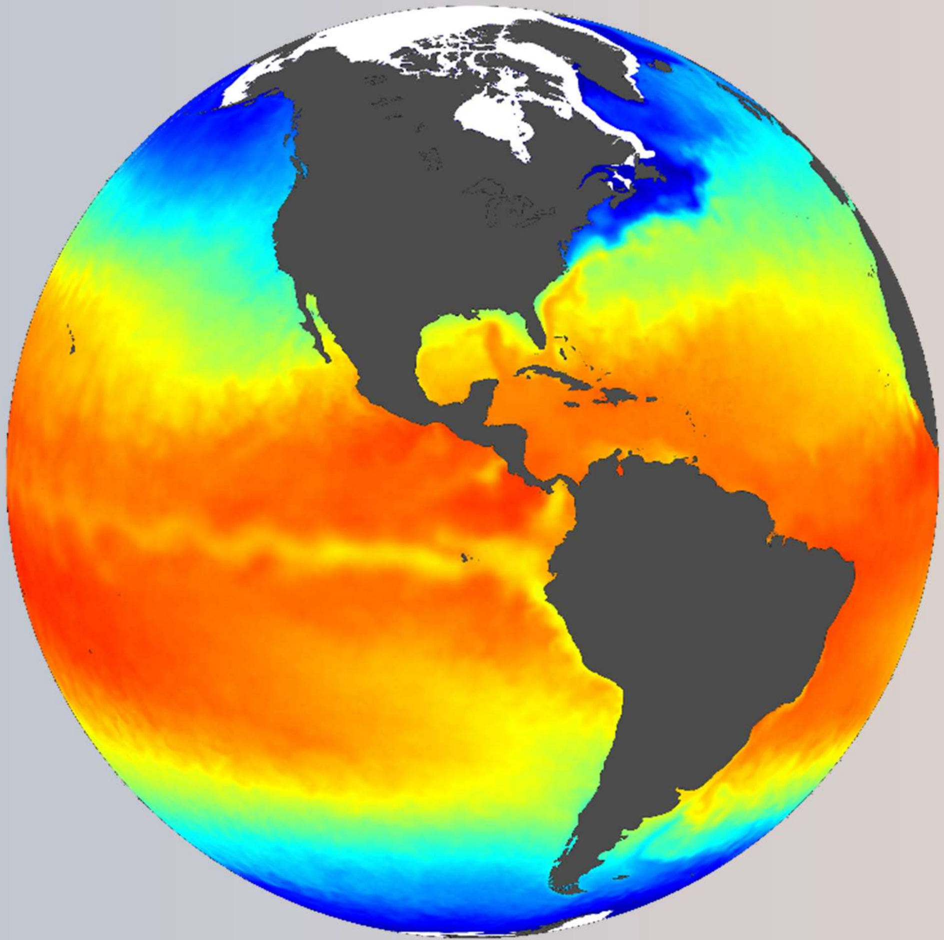


To provide operational users and the science community with the SST measured by the satellite constellation

Processing Levels

Peter Minnett

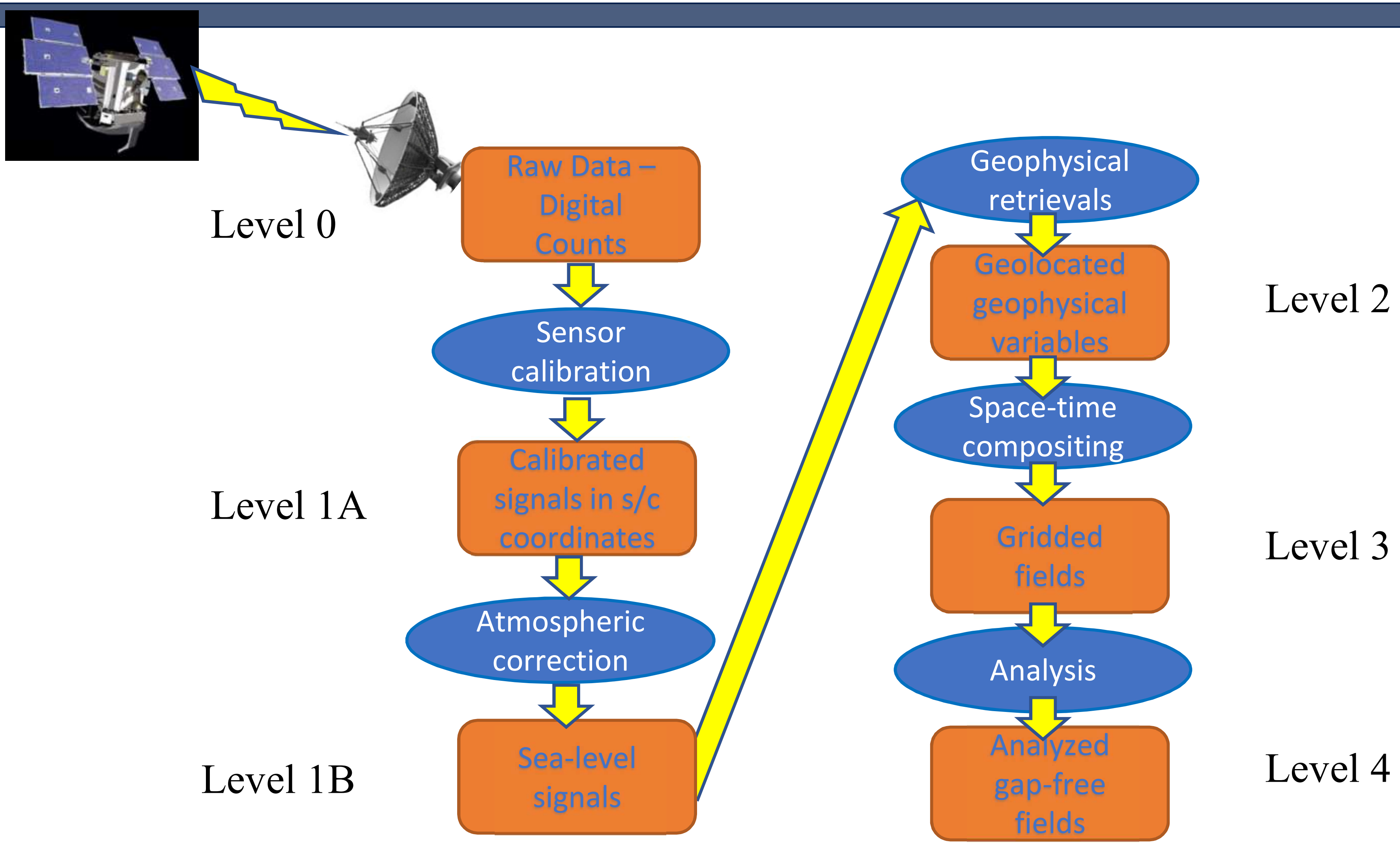
GHRSST
Group for High Resolution Sea Surface Temperature

CEOS Committee on Earth Observation Satellites
Sea Surface Temperature Virtual Constellation

Why data levels?

- Satellite data products are processed at various levels ranging from Level 0 to Level 4.
- Level 0 products are raw data at full instrument resolution, as transmitted to ground.
- At higher levels, the data are converted into more useful parameters and formats.
- But no unique data level definitions.....
- Often modified to suit a particular sensor or mission.

Satellite data flow



NASA's Definitions

Level 0

Reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g., synchronization frames, communications headers, duplicate data removed.

Level 1A

Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and geo-referencing parameters, e.g., satellite ephemeris, computed and appended but not applied to the Level 0 data.

Level 1B

Level 1A data that have been processed to sensor units (not all instruments have Level 1B data products).

Level 2

Derived geophysical variables at the same resolution and location as the Level 1 source data.

Level 3

Variables mapped on uniform space-time grids, usually with some completeness and consistency.

Level 4

Model output or results from analyses of lower level data, e.g., variables derived from multiple measurements.

Parkinson, C., Ward, A., & King, M. (2006). Earth science reference handbook: a guide to NASA's earth science program and earth observing satellite missions. National Aeronautics and Space Administration, 277pp. http://eospso.gsfc.nasa.gov/sites/default/files/publications/2006 ReferenceHandbook.pdf

CEOS conventions applied to SMOS

CEOS (Committee on Earth Observation Satellites) conventions and have been specifically tailored to the SMOS mission.

Raw data

These are SMOS Payload data in their original format (CCSDS packets) comprised of instrument observation data and housekeeping telemetry, as received from the satellite.

Level 0 data products

These are SMOS payload data in so-called Source Packets with added Earth Explorer product headers. They are chronologically sorted by Source Packet type: Observation Data and Housekeeping Telemetry.

Level 1A data products

These are the SMOS reformatted and calibrated observation and housekeeping data in engineering units. Scientific SMOS Level 1A products are the so-called calibrated visibilities between the individual antenna receivers prior to applying image reconstruction, and in full polarization. They come in pole-to-pole (half orbit) time-based segments.

CEOS conventions applied to SMOS

Level 1B data products

The SMOS Level 1B products are the output of the image reconstruction of the SMOS observation measurements and consist of Fourier components of brightness temperatures in the antenna polarization reference frame.

Level 1C data products

Geographically sorted, multi-incidence angle brightness temperatures at the top of the atmosphere, geolocated in an equal-area grid system. Two different Level 1C products are generated according to the surface type: one containing only sea and the other only containing land pixels. Two sets of information are available: pixel-wise and snapshot-wise. For each Level 1C product there is also a browse product containing brightness temperatures averaged for an incidence angle of 42.5°.

CEOS conventions applied to SMOS

Level 2 data products

Level 2 products are of two separate types and available only for their respective geographical areas (land/sea):

Soil Moisture swath products: these contain not only the soil moisture retrieved, but also a series of ancillary data derived from the processing (nadir optical thickness, surface temperature, roughness parameter, dielectric constant and brightness temperature retrieved at top of atmosphere and on the surface) with their corresponding uncertainties.

Ocean Salinity swath products: these contain three different ocean salinity values derived from three retrieval algorithms using different assumptions for the surface roughness correction and the brightness temperature retrieved at the top of atmosphere and on the sea surface (with their corresponding uncertainties).

Level 3 and 4 data products

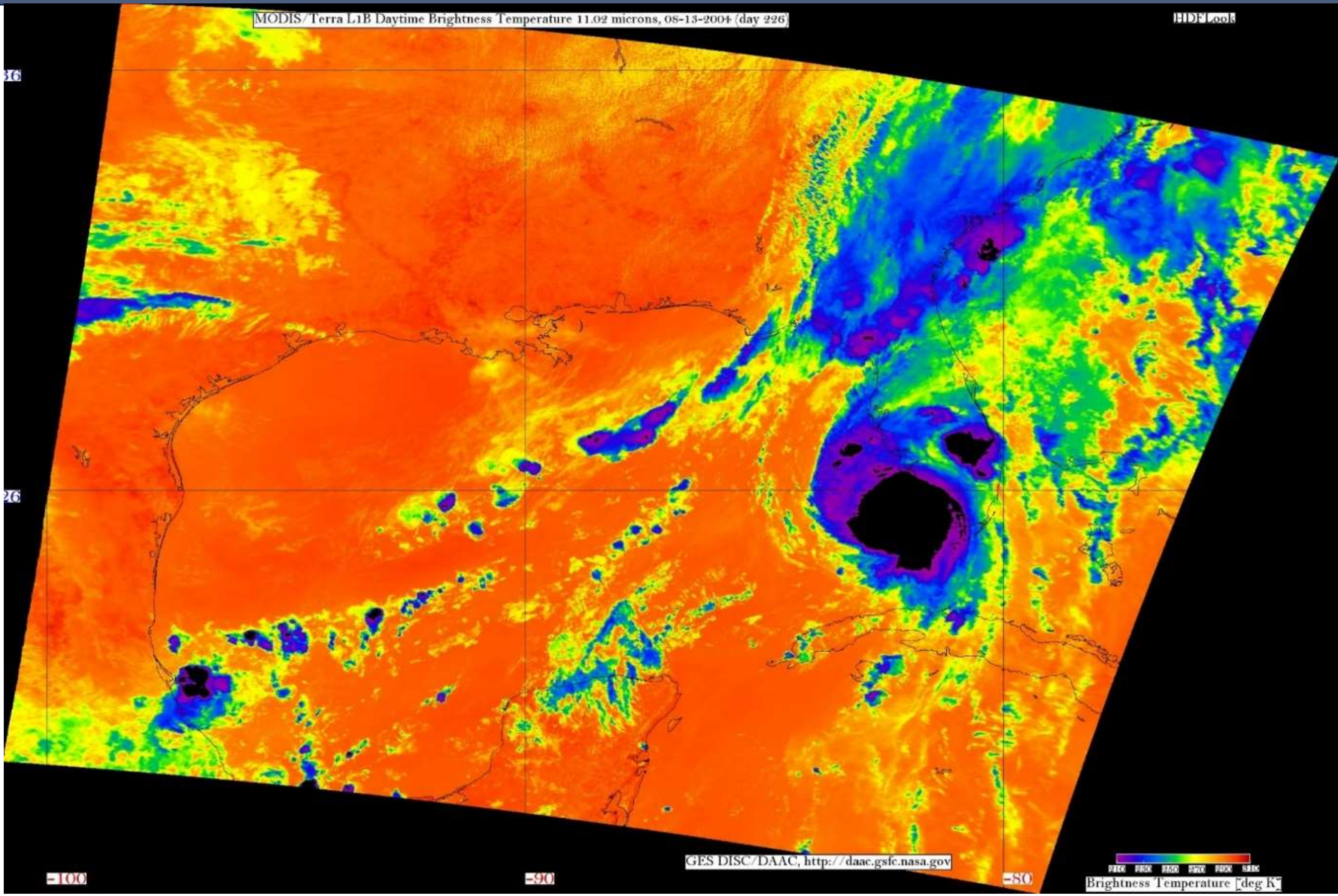
ESA's mandate for the provision of data products ends at level 2. For Sea Surface Salinity and Soil Moisture level 3 and 4 data products see the national French and Spanish processing entities: Centre Aval de Traitement des Données SMOS (CATDS) and SMOS CP34.

https://earth.esa.int/web/guest/-/data-types-levels-formats-7631

Level 0

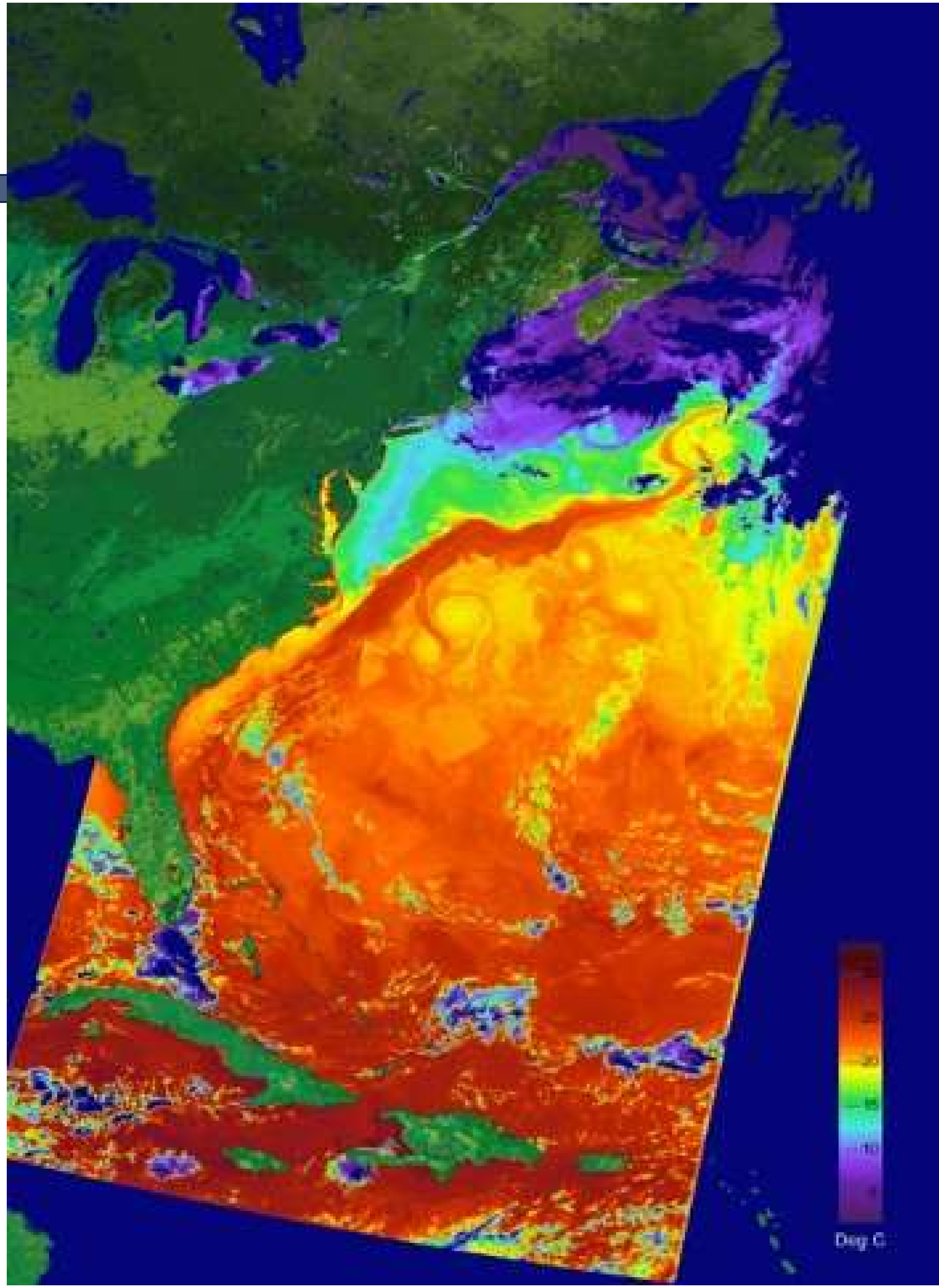
Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e.g., synchronization frames, communications headers, duplicate data) removed.

MODIS L1B


MODIS/Terra L1B Daytime Brightness Temperature 11.02 microns, 08-13-2004 (day 226)
HDFLook
36
26
-100
-90
-80
GES DISC/DAAC, http://daac.gsfc.nasa.gov
Brightness Temperature [deg K]

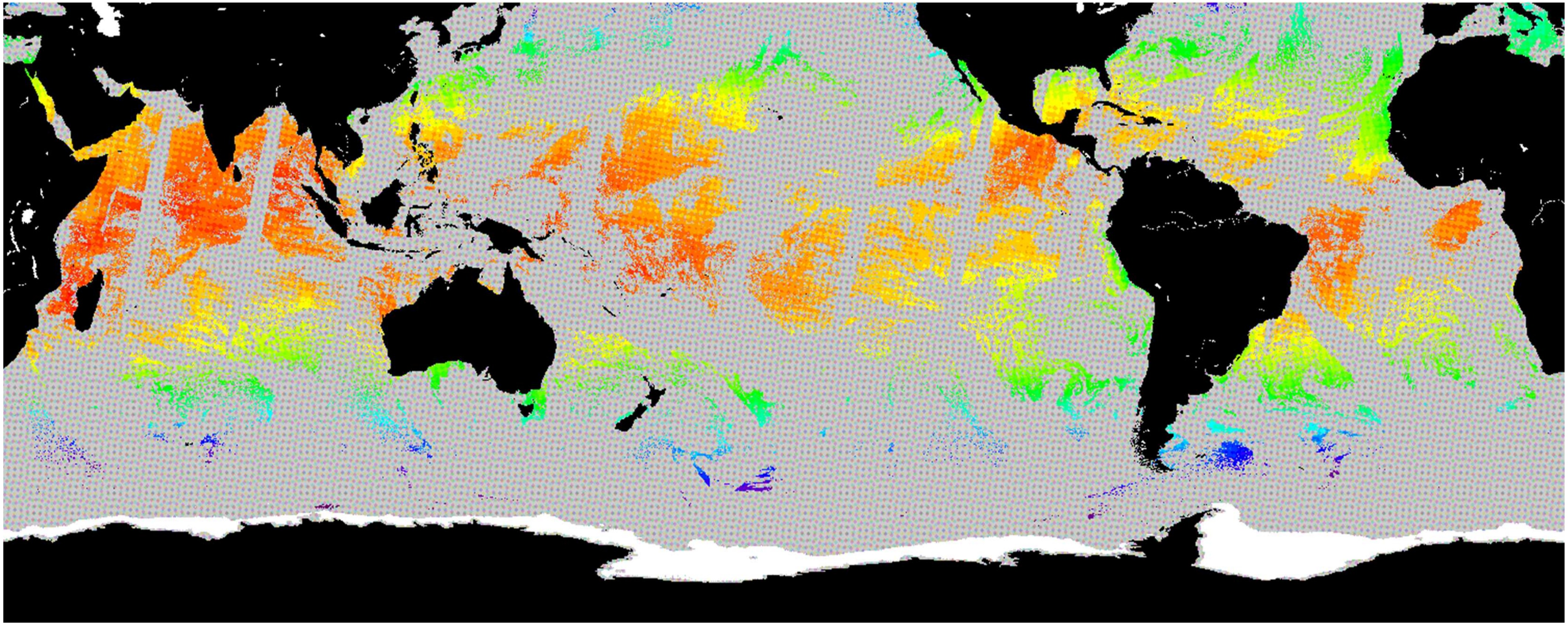
Level 2

Derived geophysical variables at the same resolution and location as Level 1 source data.

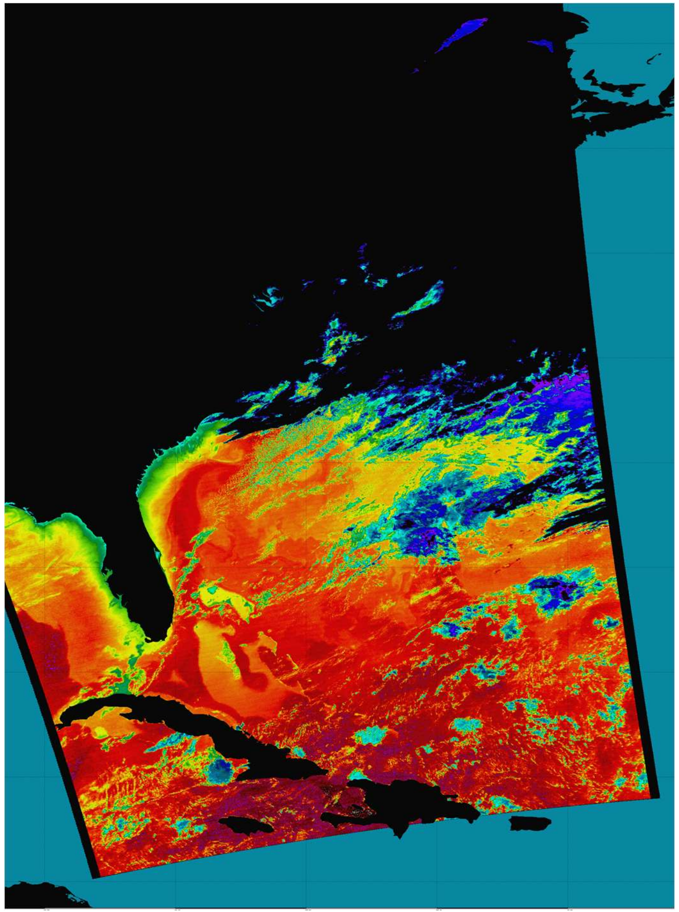


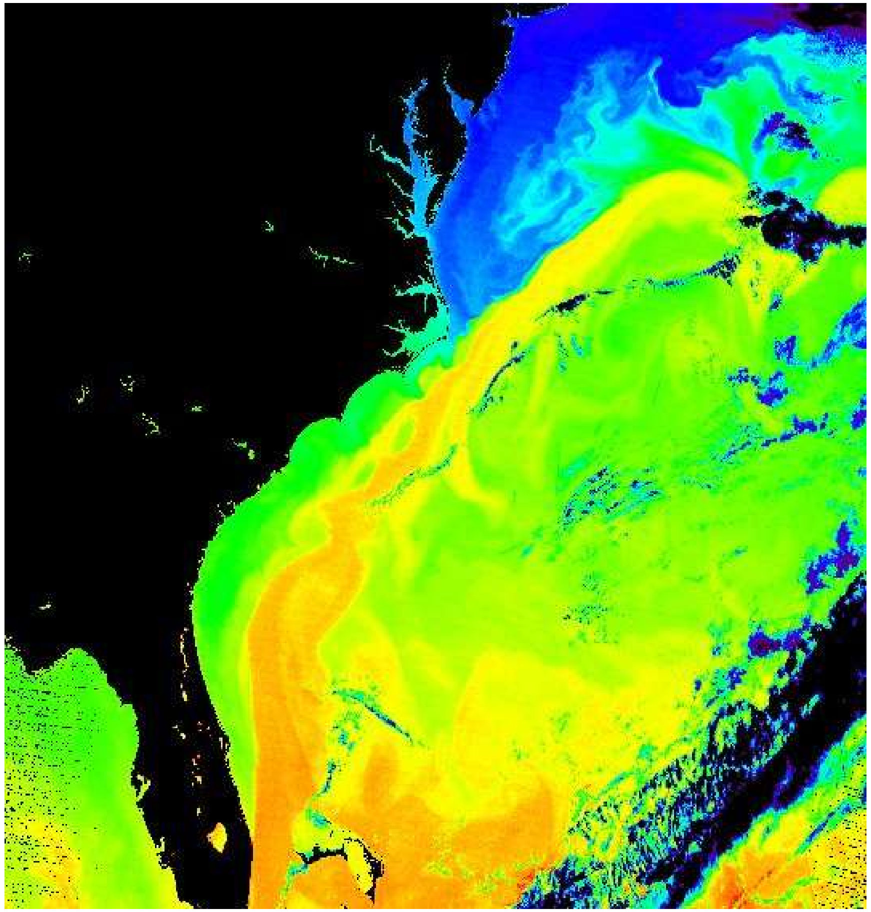
Level 3

Variables mapped on uniform space-time grid scales, usually with some completeness and consistency.

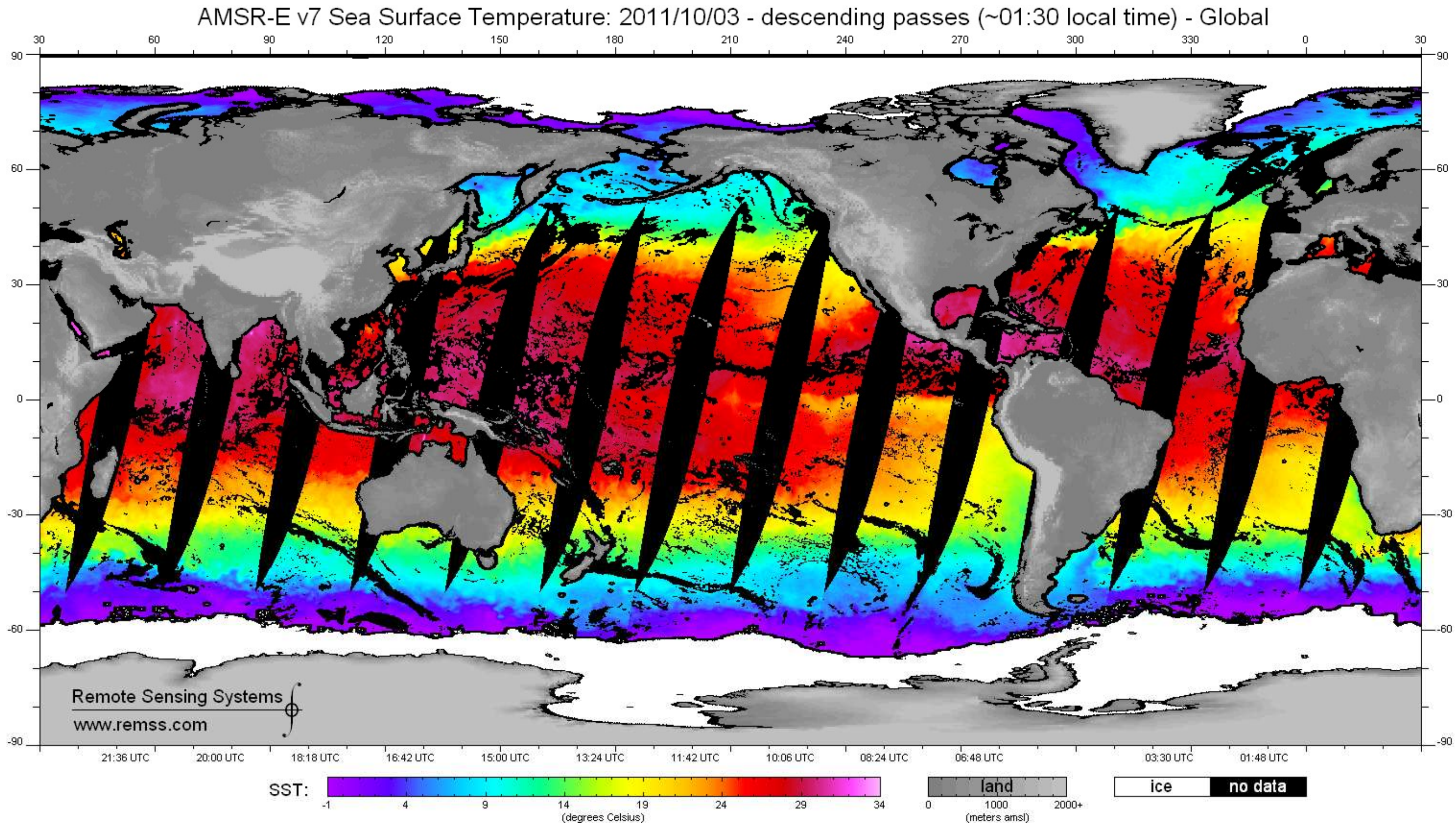


MODIS SST L3

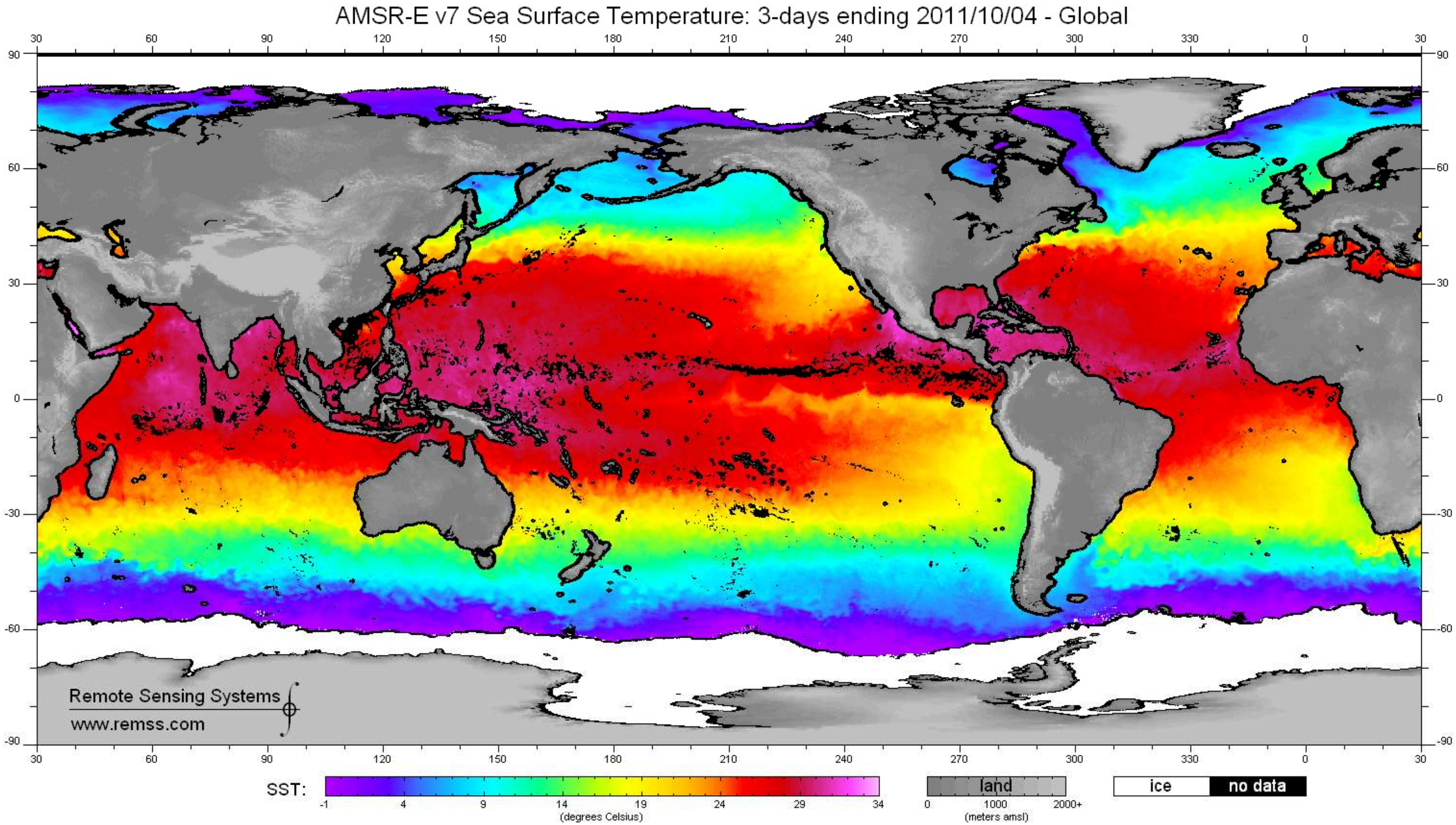




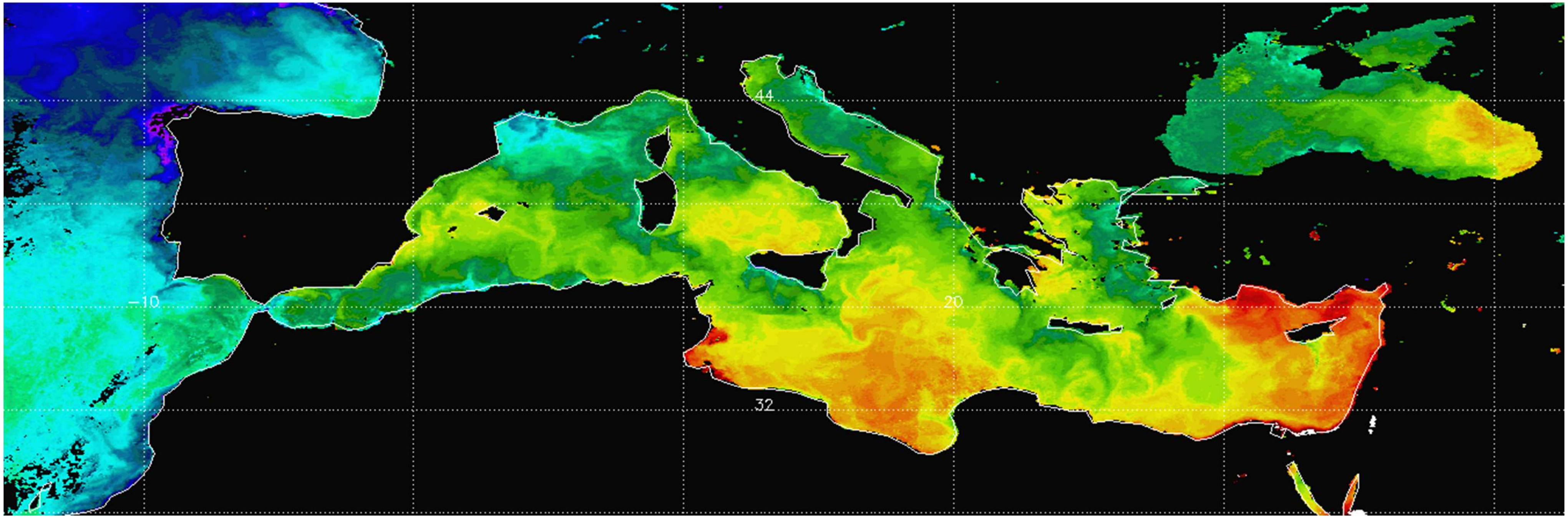
AMSR-E L3 SST – 1 day (descending)



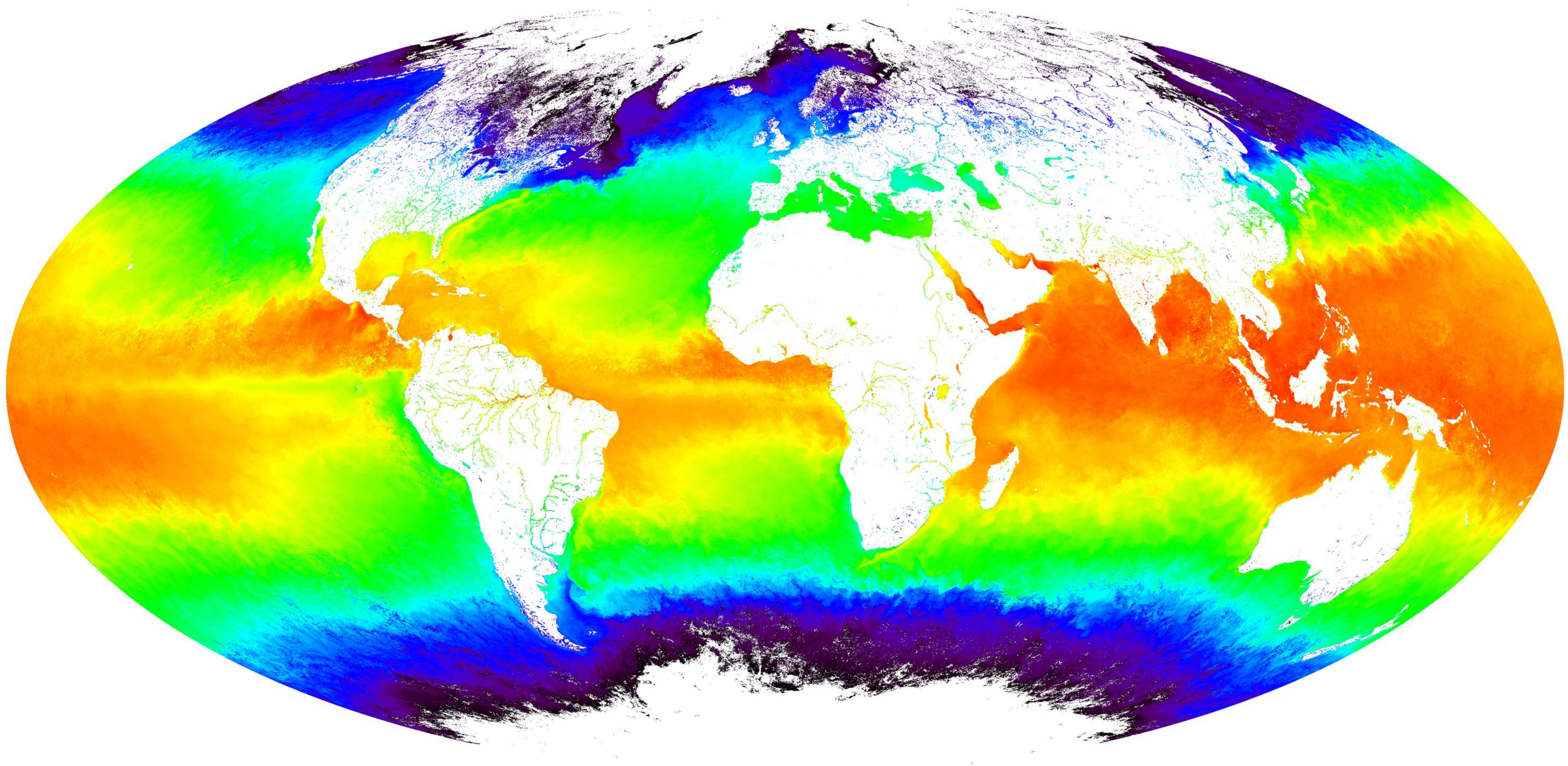
AMSR-E L3 SST – 3 days



MODIS L3 SST – 1 week



MODIS SST L3 – 1 Month



Additional GHRSST levels

GHRSST is the Group for High Resolution SST, and has introduced additional processing levels specific to satellite-derived SSTs.

- Level-2 Pre-processed (L2P)
- Level-3 Uncollated (L3U)
- Level-3 Collated (L3C)
- Level-3 Super-collated (L3S)

GHRSST L2P

L2P

- Sampled on the swath of the sensor, typically aligned with the satellite track, and represent the highest spatial resolution possible from the particular sensor.
- The L2P products contain the satellite SST retrievals with uncertainty information in the form of the Sensor Specific Error Statistics (SSES). SSES are derived from coincident satellite and reference measurements taken at the surface.
- Includes auxiliary fields for each pixel to help interpreting the SST data – sometimes refers to as Dynamic Flags.
- These data are ideal for data assimilation systems or as input to analysis systems.
- Distributed in self-describing netCDF format.

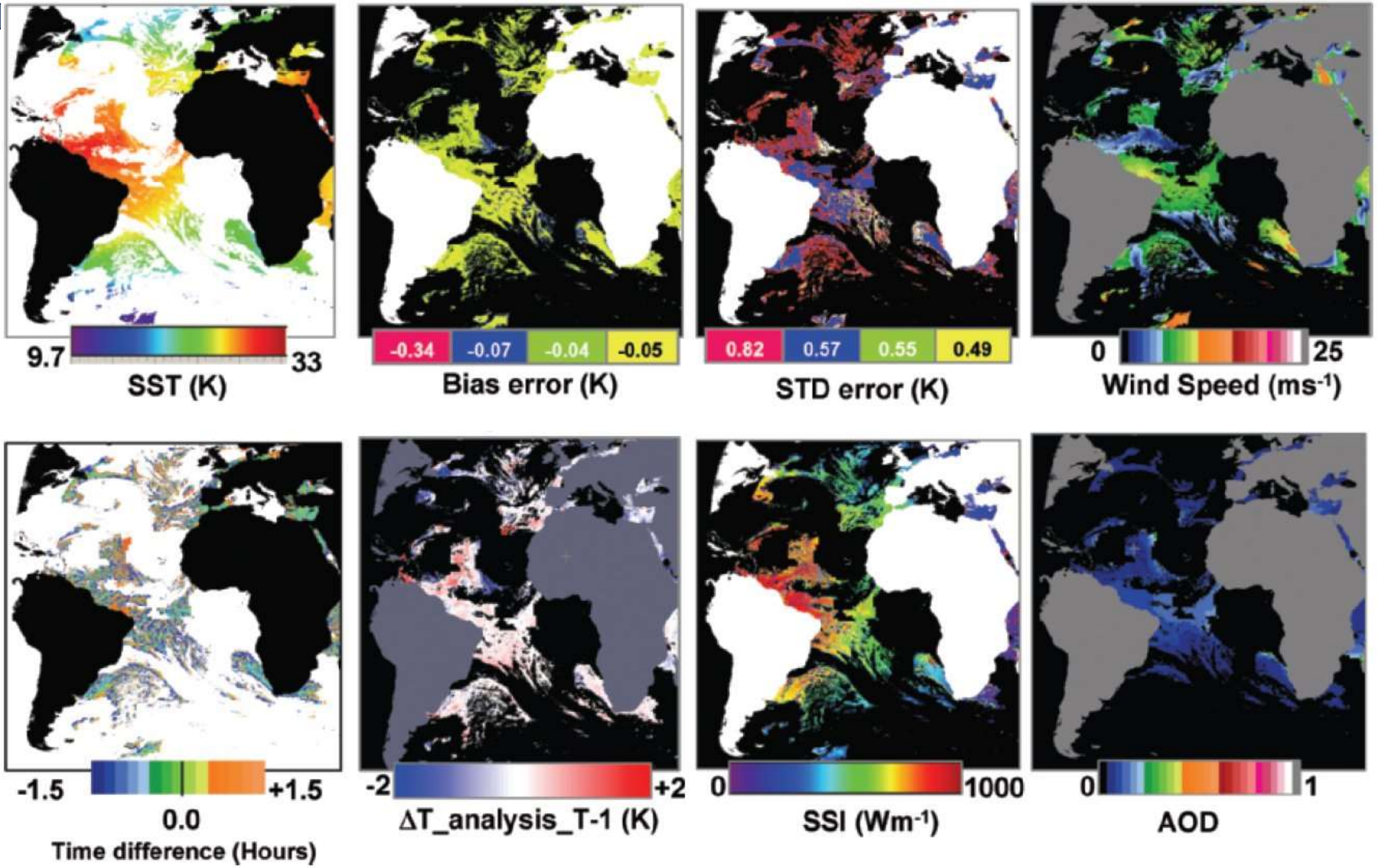
L2P – Auxiliary Data

- sst_dtime: offsets from the reference time of the SST data array in seconds for each SST pixel.
- sses_bias: best estimate of pixel bias error.
- sses_standard_deviation: best estimate of pixel standard deviation.
- dt_analysis: difference between SST measurement and a GHRSST L4 SST analysis within the previous 24 h.
- wind_speed: including dtime and source.
- sea_ice_fraction: including dtime and source.
- aerosol_dynamic_indicator: indicates the presence of atmospheric aerosols that may cause errors in the infrared atmospheric correction; including dtime and source.
- satellite_zenith_angle: (optional).
- solar_zenith_angle: (optional).
- surface_solar_irradiance: (optional) including dtime and source.
- Experimental variables, as desired.
- Quality levels and flags are also mandatory.

GHRSST Science Team (2010), The Recommended GHRSST Data Specification (GDS) 2.0, document revision 4, available from the GHRSST International Project Office, 2011, pp 123.

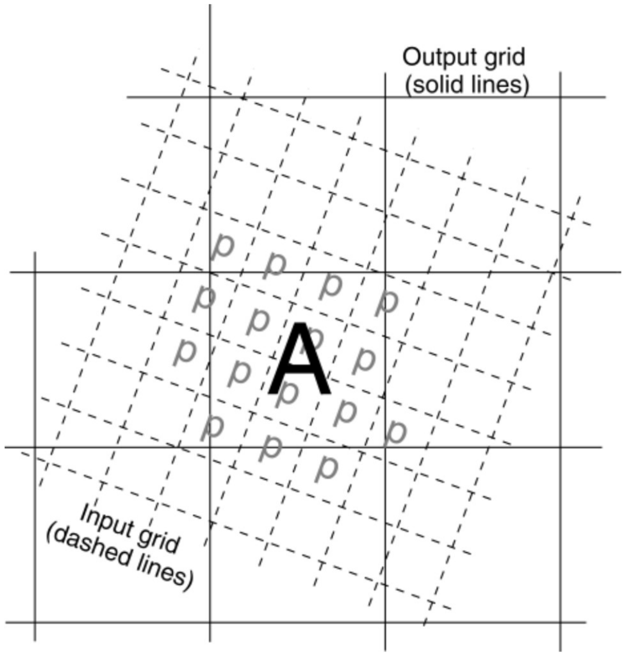
GHRSST L2P

SEVIRI SST retrievals with error estimates and diagnostic parameters.

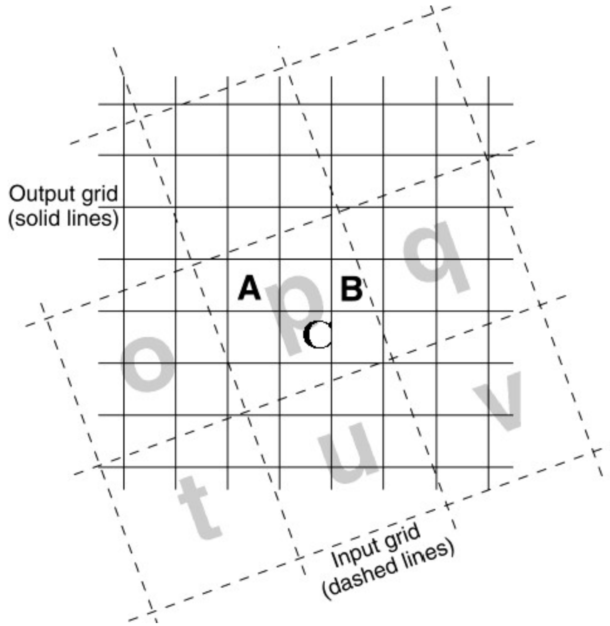


After Donlon et al. (2007) The Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project. Bulletin of the American Meteorological Society 88:1197-1213

Remapping to L3



L3 product output grid is **over-sampled** by the L2P input data. All pixels labelled *p* in the input data are possible contributors to the value for new cell *A.*

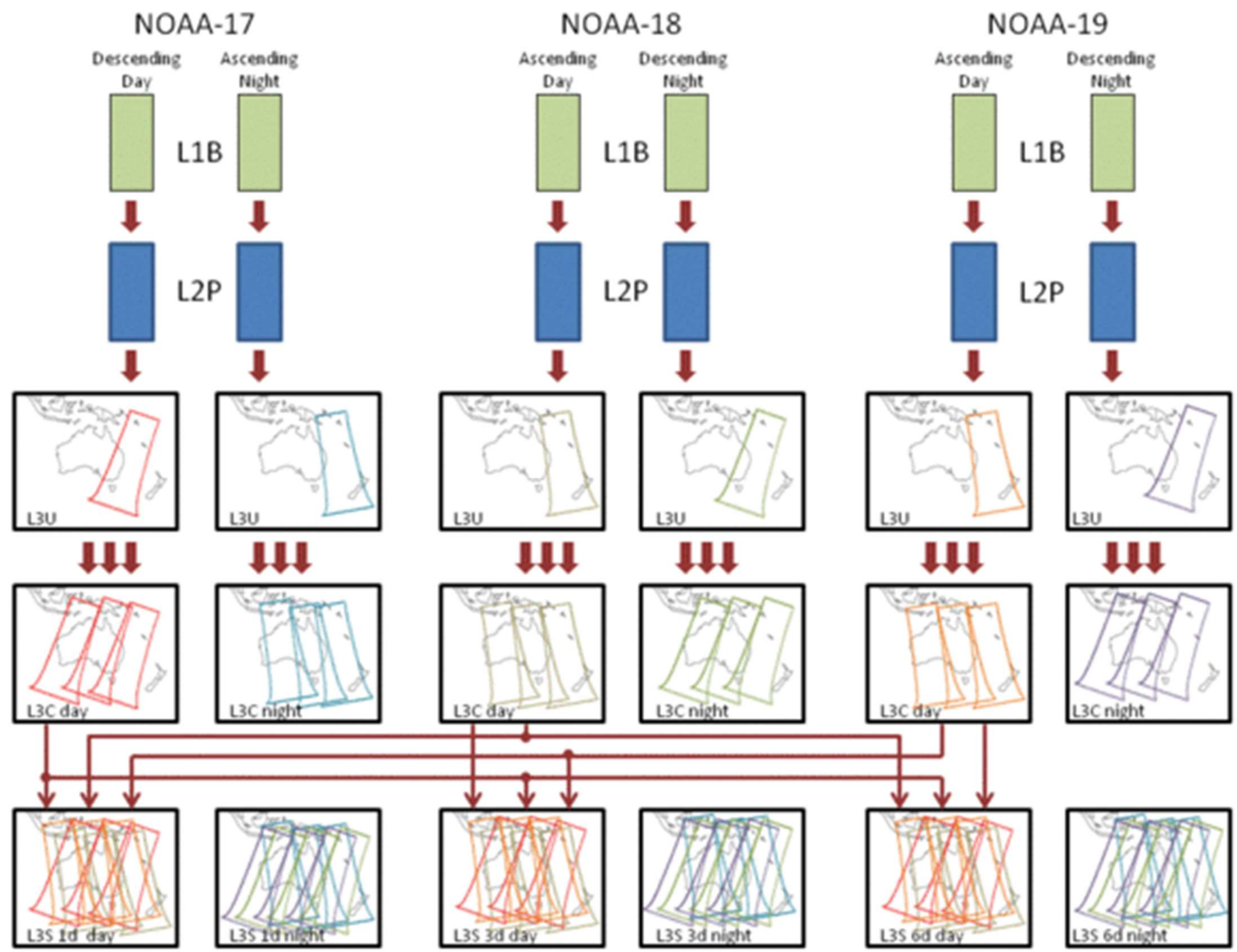


L3 output grid is **under-sampled** by the L2P data. Grid cells *A* and *C* are assigned the value of pixel *p*, Grid cell *B* is assigned the weighted average of *p* and *q* provided they both have quality flags with the same rating.

GHRSST L3

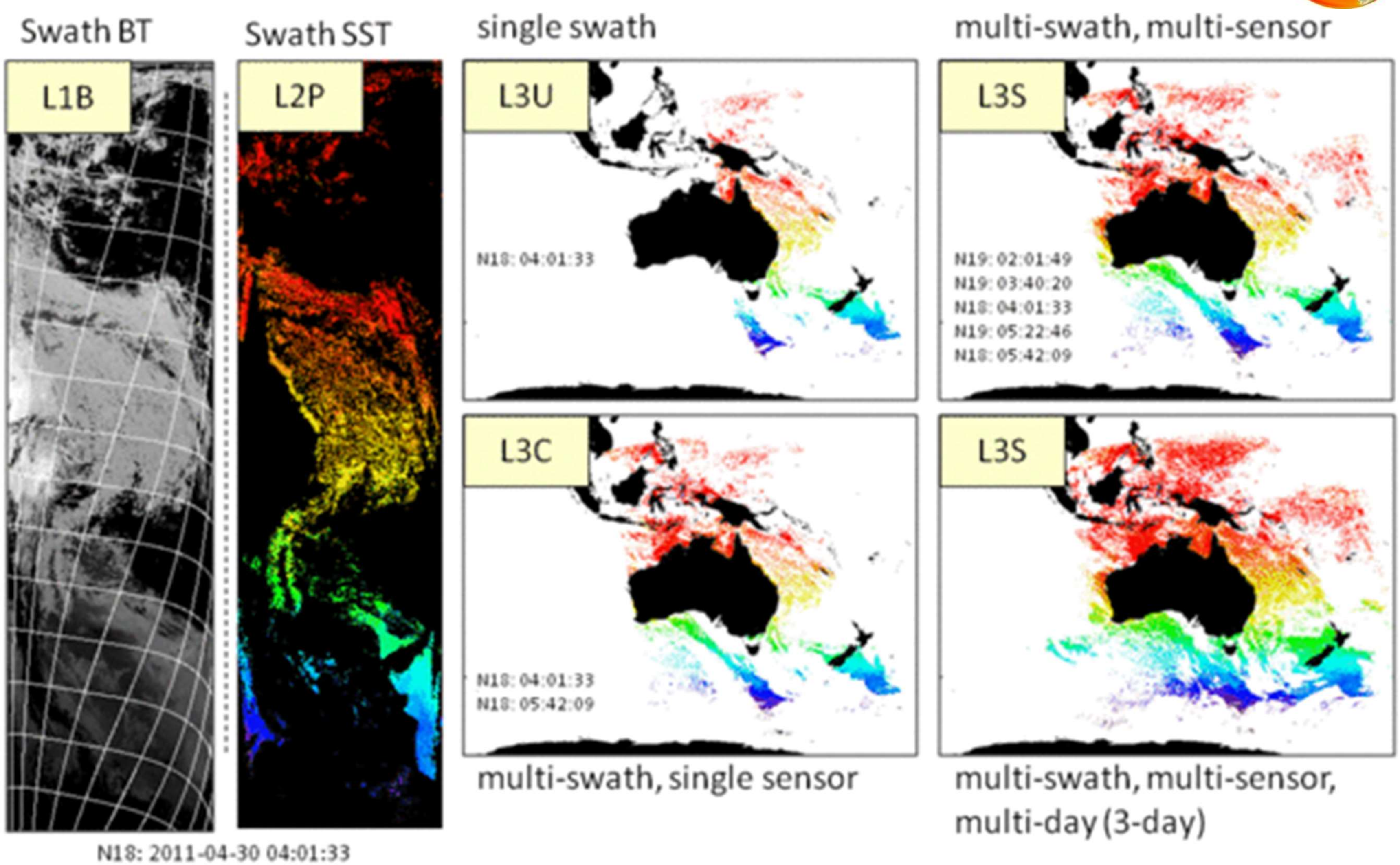
- Level-3 Uncollated (L3U): L2 data granules remapped to a space grid without combining any observations from overlapping orbits.
- Level-3 Collated (L3C): SST measurements combined from a single instrument into a space-time grid. Multiple passes/scenes of data can be combined. Adjustments may be made to input SST data.
- Level-3 Super-collated (L3S); SST measurements combined from multiple instruments into a space-time grid. Multiple passes/scenes of data are combined. Adjustments may be made to input SST data.

GHRSST L3 types



http://imos.org.au/sstproducts.html

NOAA AVHRR SSTs – IMOS at BoM

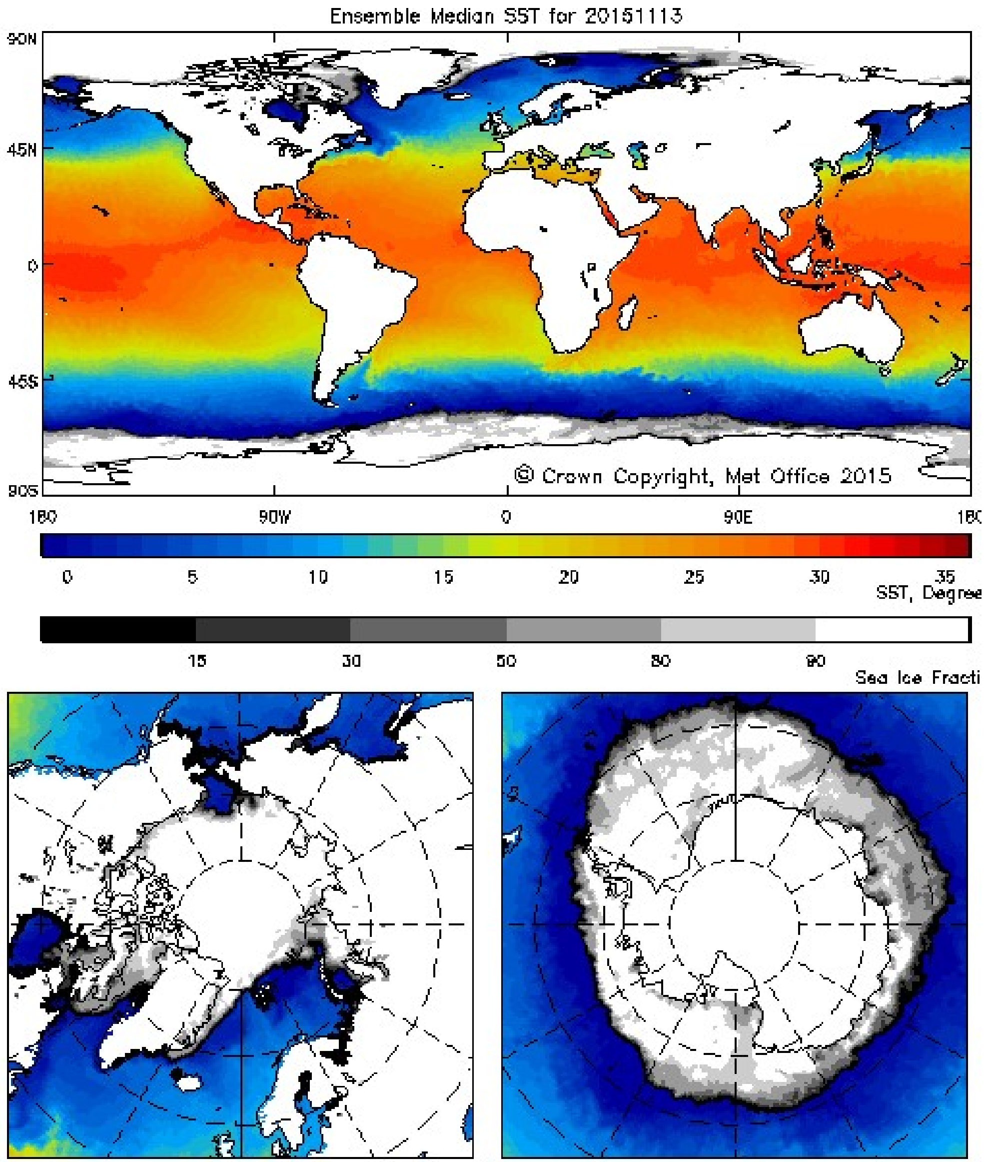


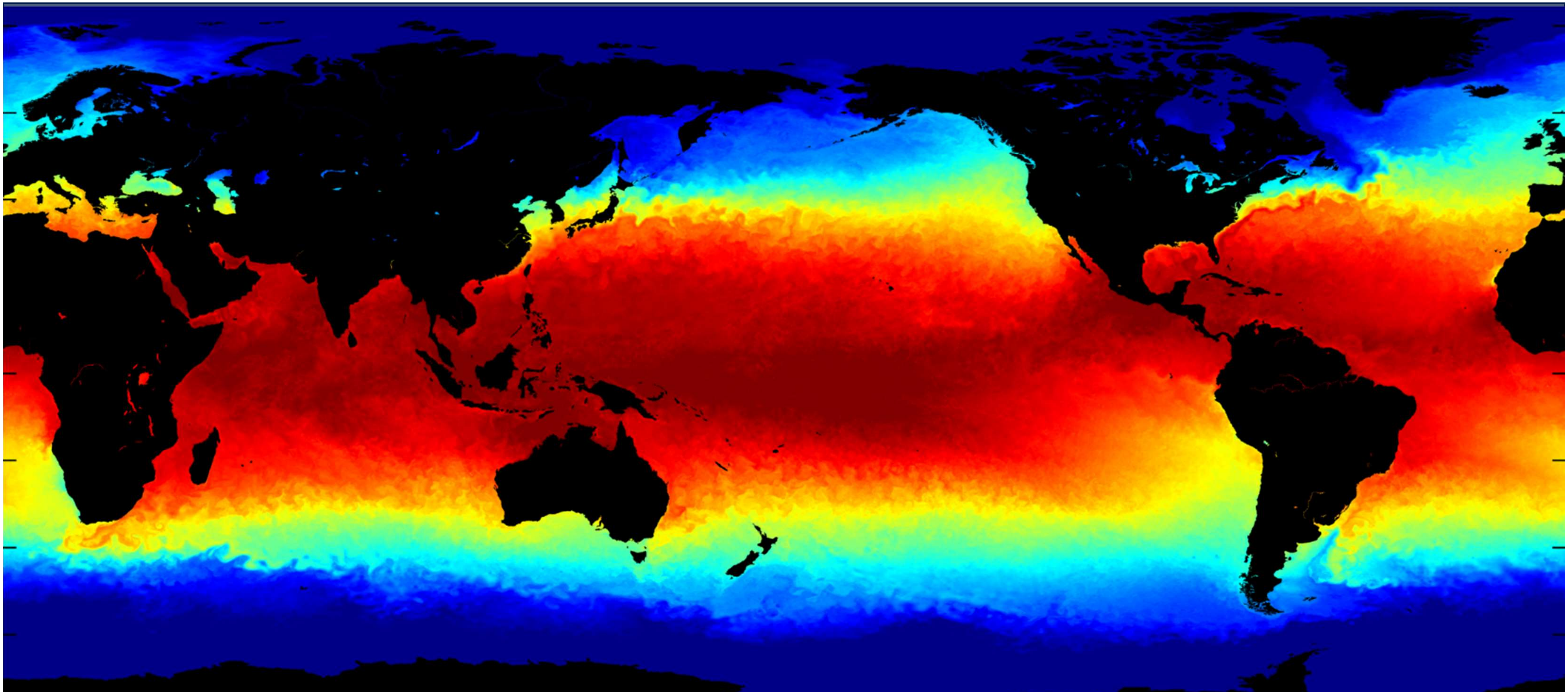
http://imos.org.au/sstproducts.html

Level 4

Model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

GHRSST Multi-product Ensemble (GMPE): the median of available daily SST analyses are displayed below. The analyses used are OSTIA, RTG, K10, MGDSST, RSS MW, RSS MW+IR, FNMOC, NOAA AVHRR OI, CMC, ODYSSEA and GAMSSA.

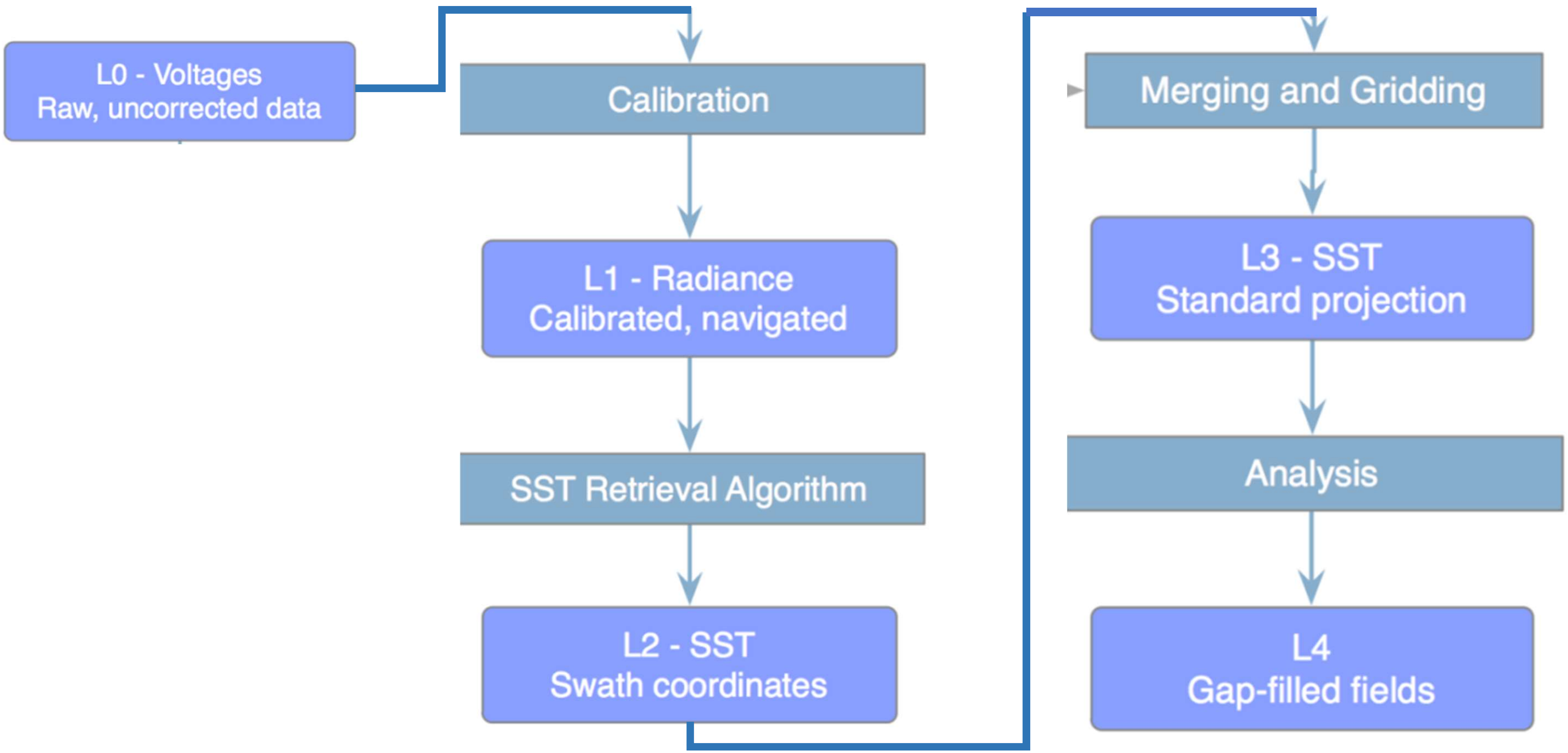




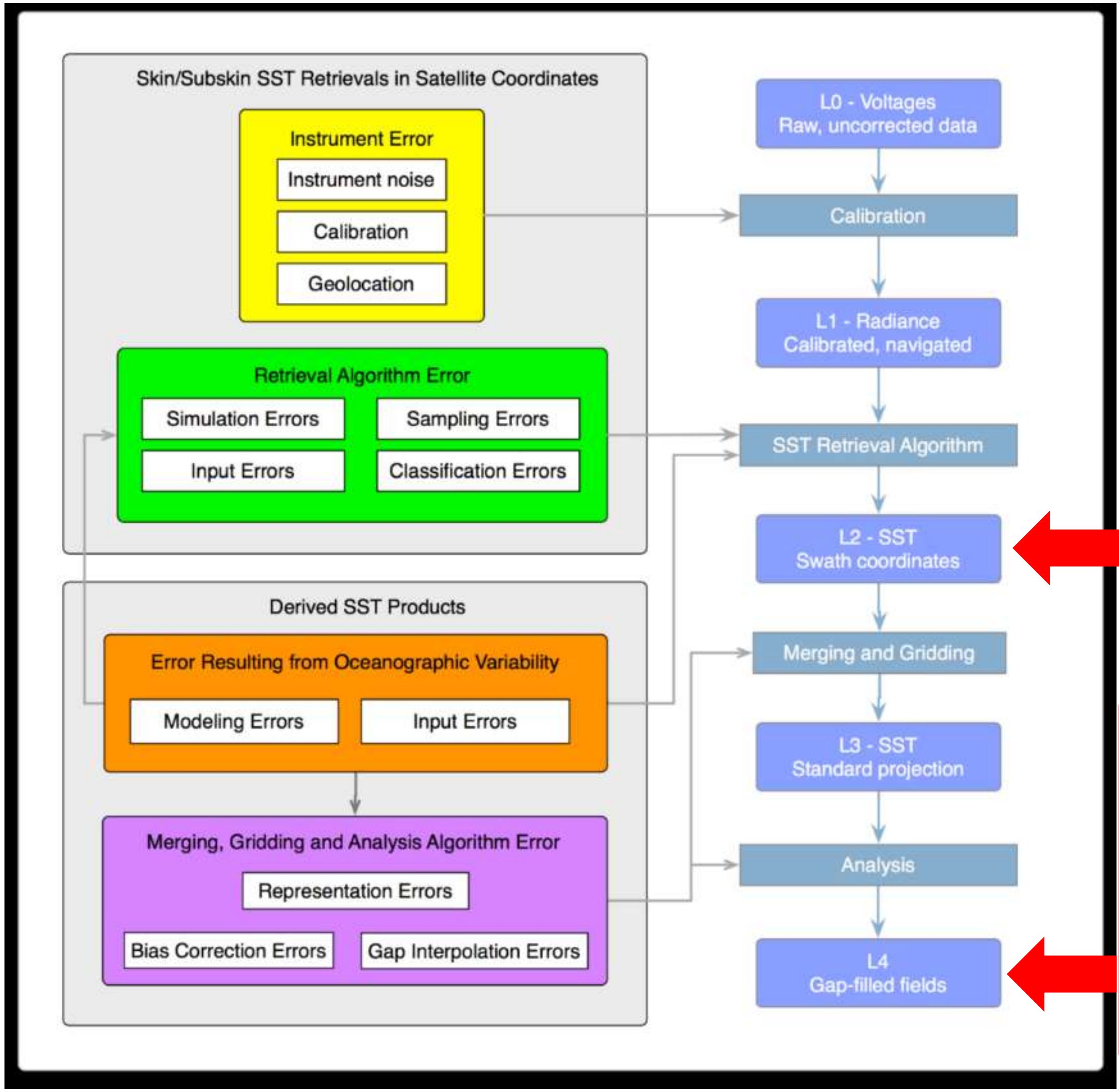
Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature (SST) Analysis – 13 November 2015

http://mur.jpl.nasa.gov/images_global.php

Data Levels - SST



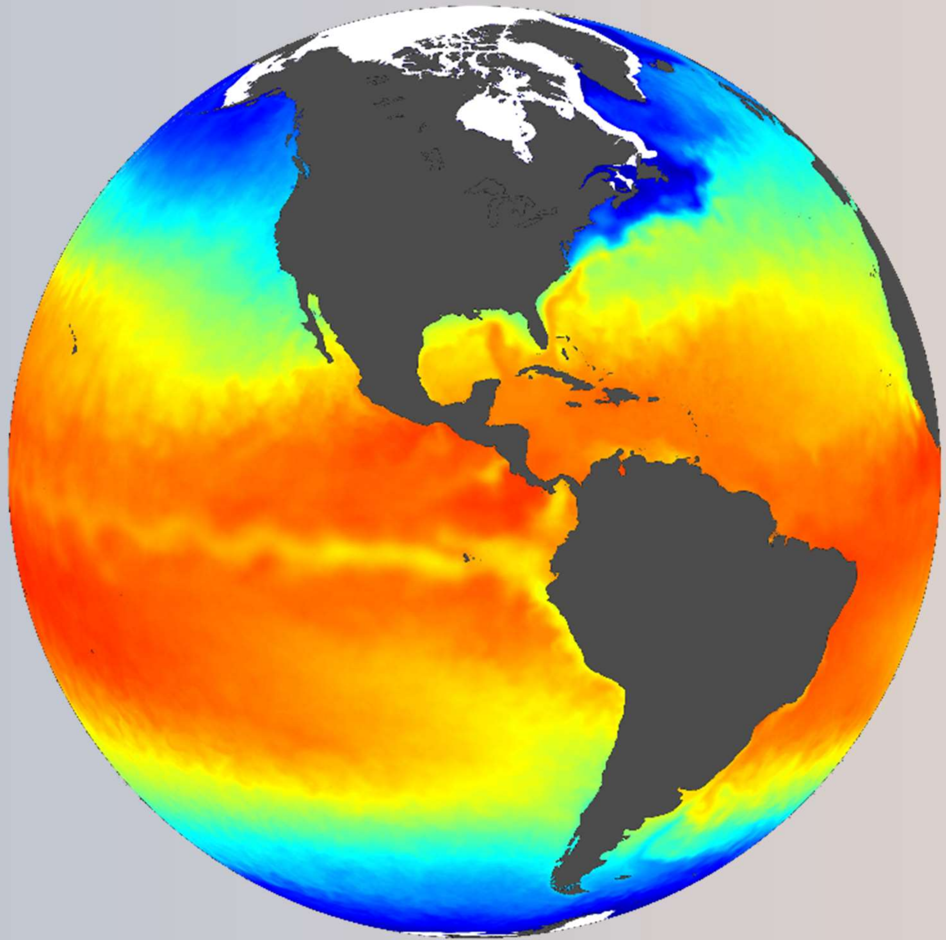
Error sources



From: Sea Surface Temperature Error Budget: ISSTST White Paper (2010).

L2 is where uncertainties in SST retrievals are derived by comparison with independent measurements in cloud-free conditions.

L4 fields are used to initialize climate models, and in other climate studies.



To provide operational users and the science community with the SST measured by the satellite constellation

Climate data records of sea surface temperature

Chris Merchant

GHRSST
Group for High Resolution Sea Surface Temperature

CEOS
Committee on Earth Observation Satellites
Sea Surface Temperature Virtual Constellation

Climate data records

- Physical climate can be defined as the statistical distributions of the elements of meteorological, oceanic and cryospheric state, over a period of time
- For the climatology of weather, 30 years is generally used as a climatological reference period, e.g., 1981 to 2010
- Climate is always changing (*variability*)
- We have concerns that human activities are perturbing climate (*forcing*), causing *climatic change* that cumulatively will be disruptive for human and ecological well-being
- Climate data records are time-series of measurements of a component of Earth's climate system that …
  - *cover sufficient duration in time,*
  - *are sufficiently stable and consistent in their measurement properties, and*
  - *have adequately low uncertainty relative to climate variability*
- … to enable quantitative undestanding of climatic change and variability

Time-series, climatology and anomaly

- Let time-series be T(t) --- this is the list of all the temperatures on some time interval, such as daily or monthly values
- Assume a “model” for this time-series of T(t) = C(t) + A(t) + noise
- The climatology term is periodic C(t+1 year) = C(t)
- The anomaly term, A(t), is non-periodic and represents departures from the climatology
- So “anomaly” just means “difference from the normal (mean) for the time of year”.
- (In English outside of climatology, anomaly means “something puzzling or unexpected”. In climatology, the “temperature anomaly” just refers to the de-seasonalized temperature, and does NOT imply the temperature is necessarily unusual.)

GCOS Requirements for CDRs

- An international working group of the “Global Climate Observing System” (GCOS) has identified a set of climate parameters that need to be measured to understand climate change
- These parameters are called “Essential Climate Variables”
- There is effort to ensure that every ECV is addressed with appropriate Climate Data Records that quantify how the climate parameter is changing over time
- Sea surface temperature is an essential climate variable
- Q: Why is SST essential for understanding climate?

GCOS CDR implementation plan

https://unfccc.int/files/science/workstreams/systematic_observation/application/pdf/gcos_ip_10oct2016.pdf

- The sampling requirements for the SST CDR can only be attained using satellite data
- The uncertainty and stability requirements are difficult to meet and demonstrate on the scales required

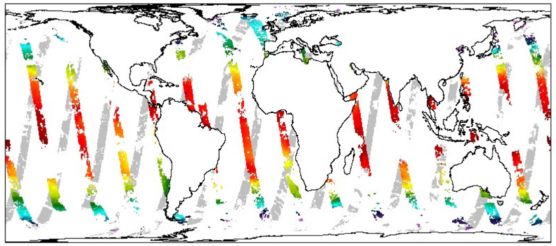
Ocean ECV Product Requirements					
ECV	Products	Frequency	Resolution	Required measurement uncertainty	Stability (per decade unless otherwise specified)
Sea Surface Temperature	Sea Surface Temperature	Hourly to weekly	1-100 km	0.1 K over 100 km scales	< 0.03 K over 100 km scales

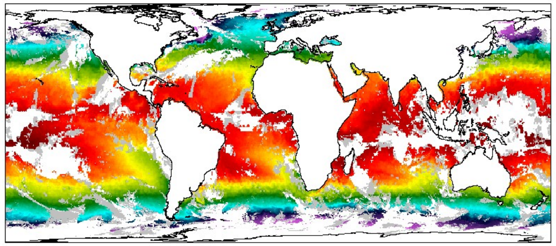
ESA SST CCI – an example CDR project

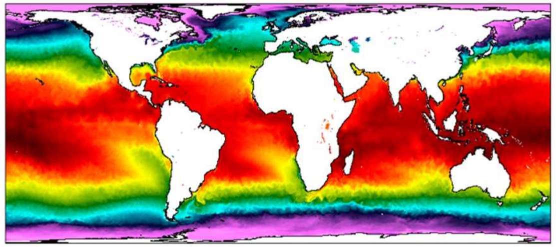
- Aim is to create a 35 year SST dataset
  - consistent L2, L3 and L4 (swath, gridded and analyzed)
  - multi-sensors – to get the length of timeseries
  - careful reconciliation of inter-sensor differences

- Using many of the techniques discussed in this course
  - Both coefficient-based retrieval and optimal estimation
  - Bayesian cloud detection
  - Modelling of skin to depth differences

Sea Surface Temperature CCI



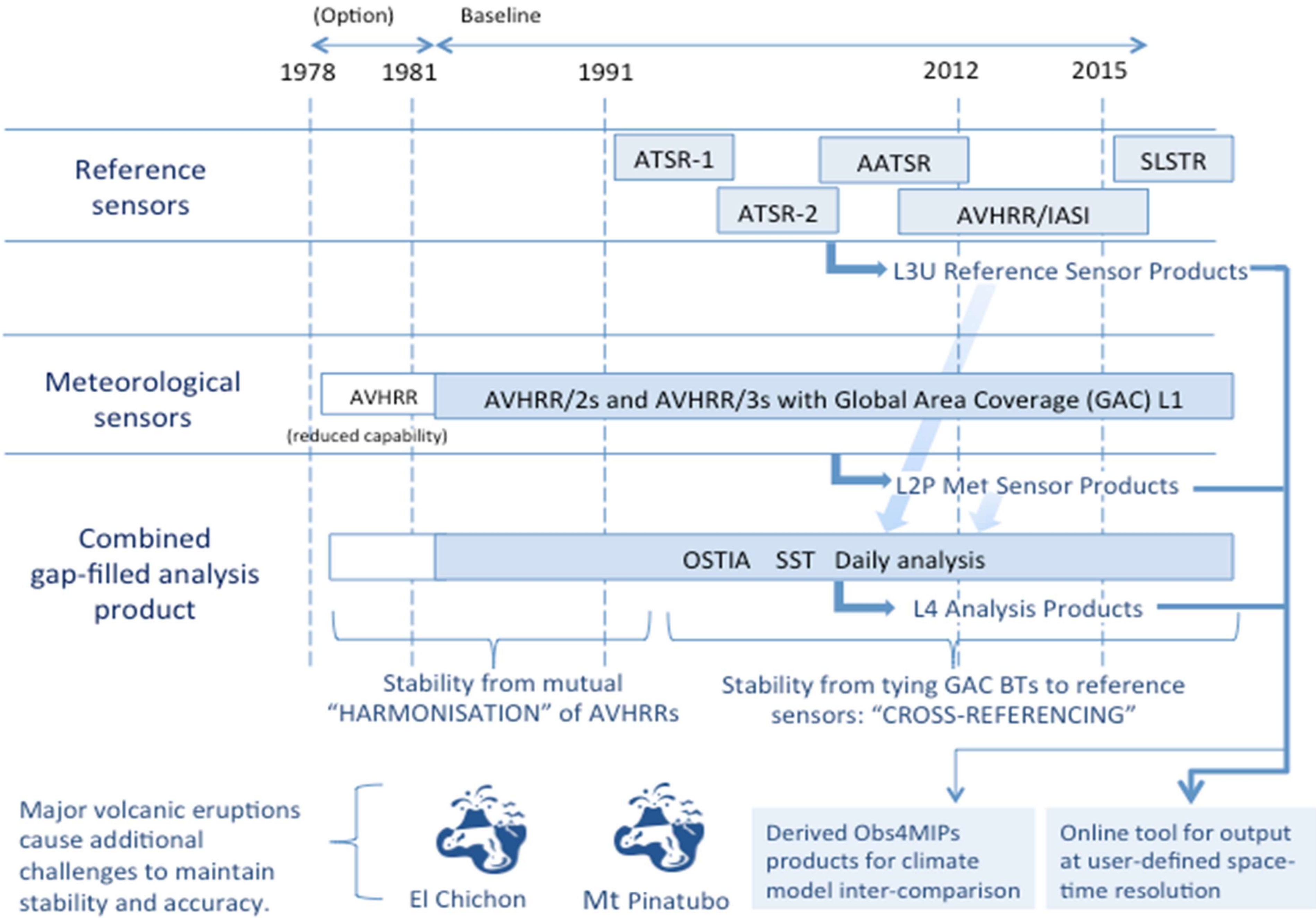




ATSRs: dual view, **stable** & **accurate**. Use as SST calibration reference.

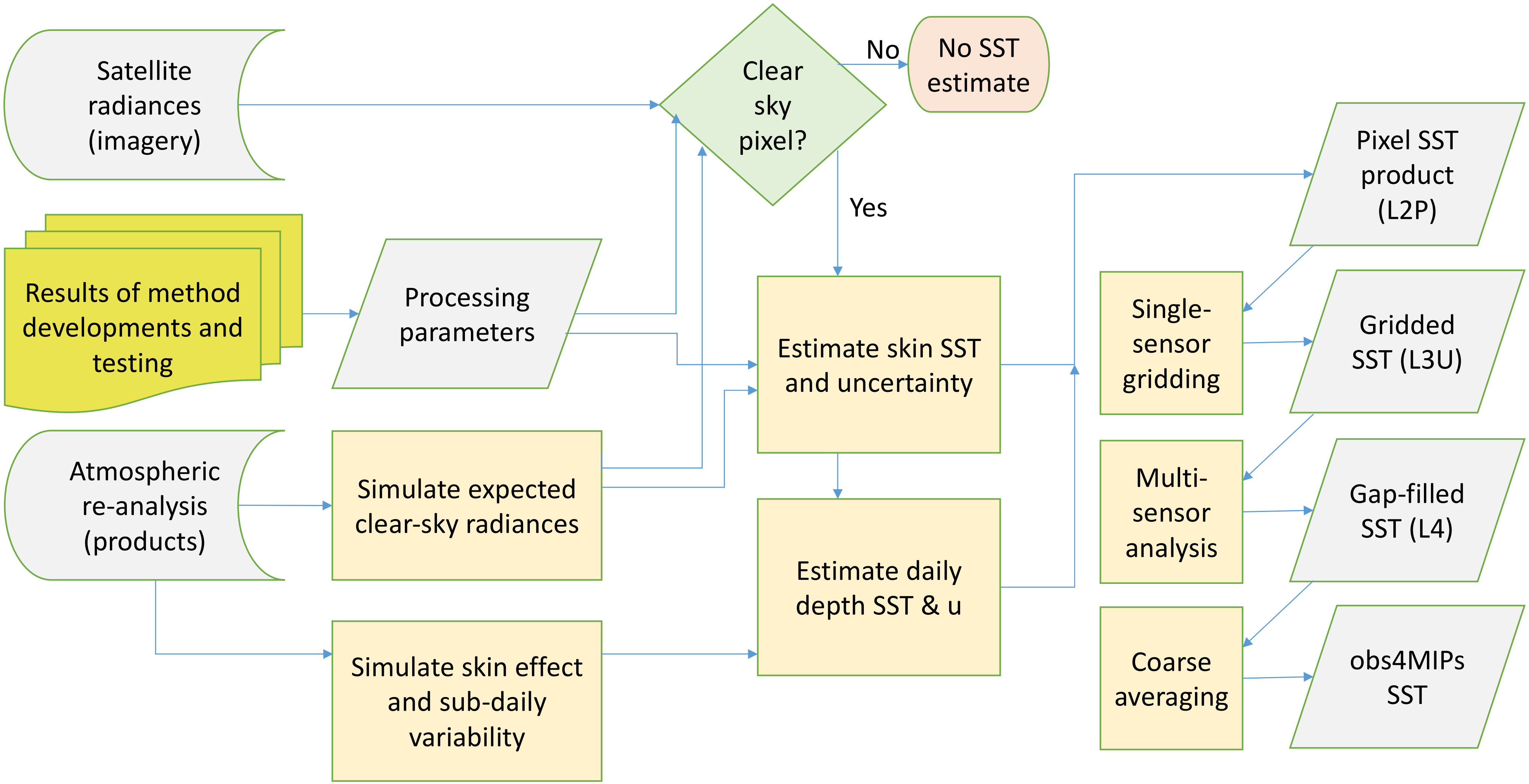
AVHRRs: single view, not designed for climate, **good coverage** and a **longer history**.

ATSRs & AVHRRs are blended. Using an improved version of Met Office "OSTIA".

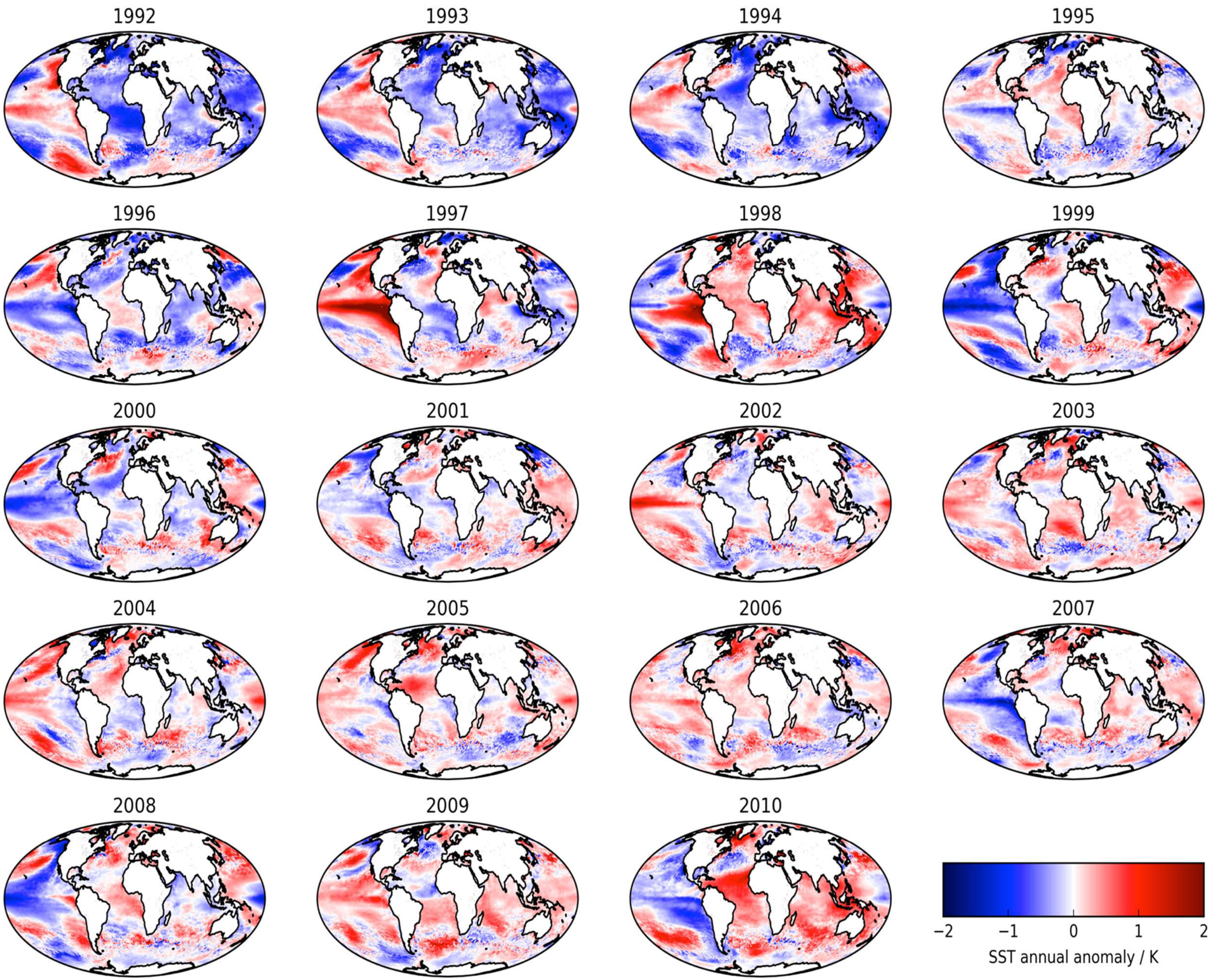


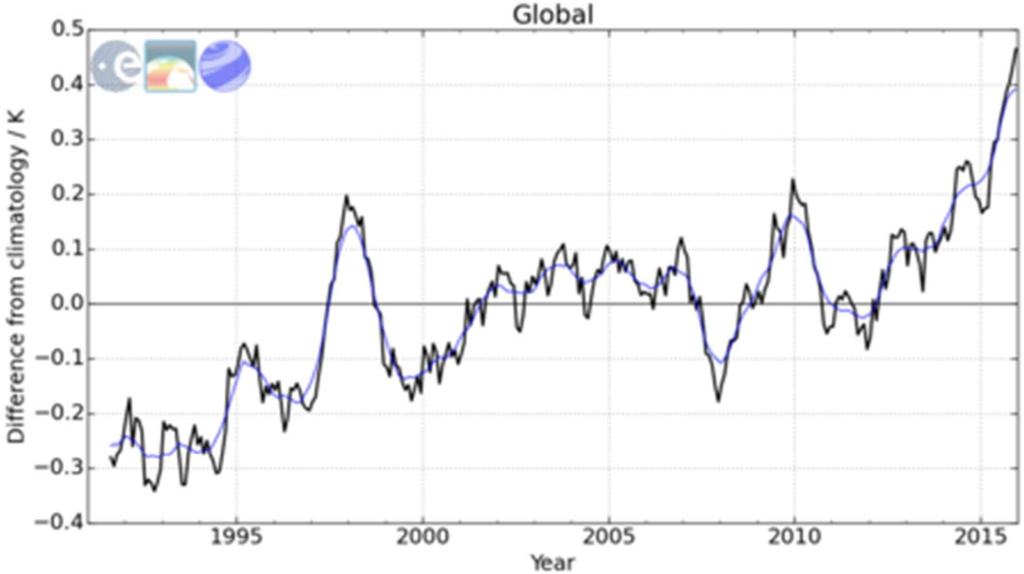
(Option)
Baseline
1978
1981
1991
2012
2015
Reference sensors
ATSR-1
AATSR
SLSTR
ATSR-2
AVHRR/IASI
L3U Reference Sensor Products
Meteorological sensors
AVHRR
(reduced capability)
AVHRR/2s and AVHRR/3s with Global Area Coverage (GAC) L1
L2P Met Sensor Products
Combined gap-filled analysis product
OSTIA SST Daily analysis
L4 Analysis Products
Stability from mutual "HARMONISATION" of AVHRRs
Stability from tying GAC BTs to reference sensors: "CROSS-REFERENCING"
Major volcanic eruptions cause additional challenges to maintain stability and accuracy.
El Chichon
Mt Pinatubo
Derived Obs4MIPs products for climate model inter-comparison
Online tool for output at user-defined space-time resolution

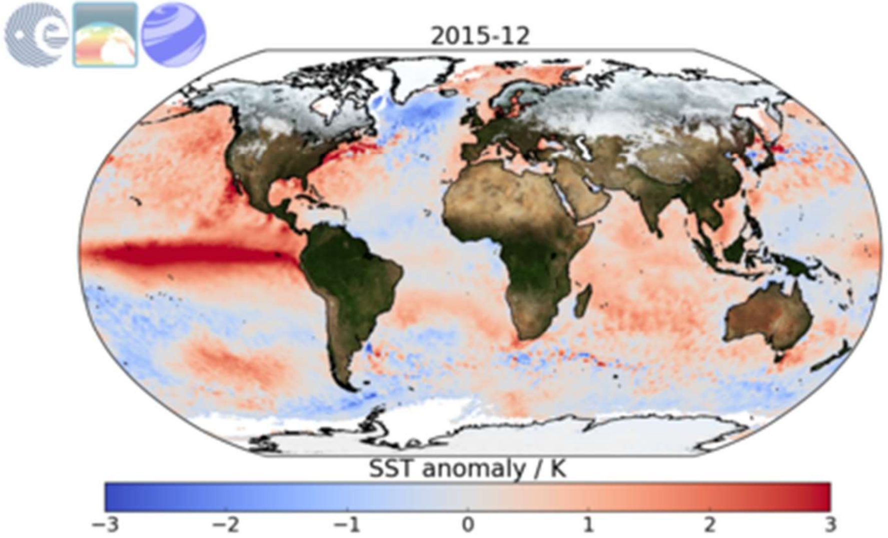
Overview of SST CCI processing

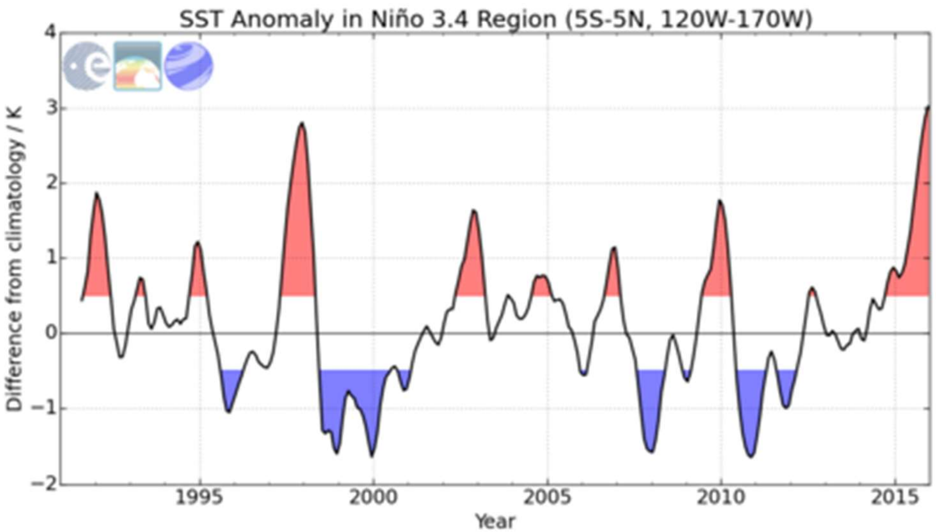


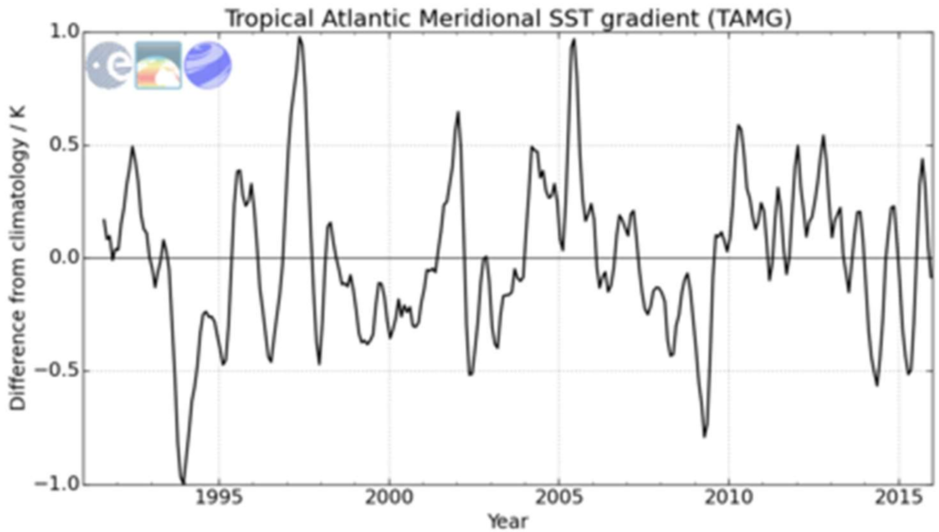
Annual anomalies in SST CCI data
www.esa-sst-cci.org

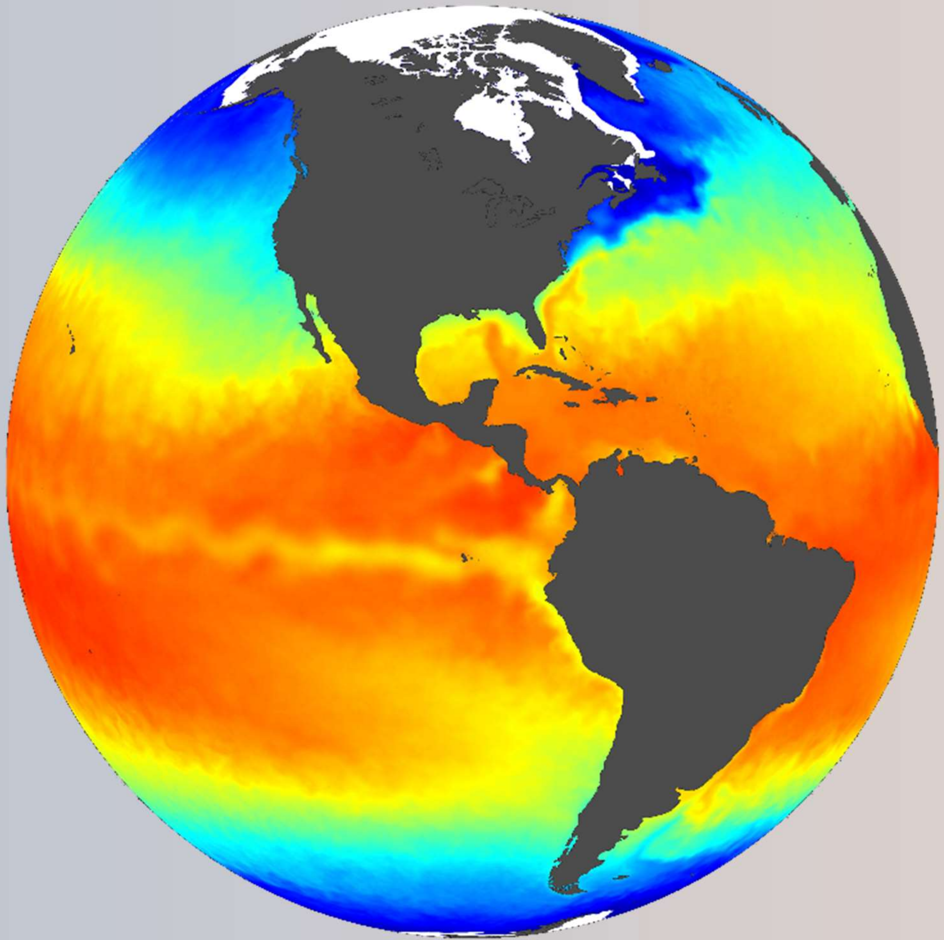



Global
Difference from climatology / K
Year


2015-12
SST anomaly / K


SST Anomaly in Niño 3.4 Region (5S-5N, 120W-170W)
Difference from climatology / K
Year


Tropical Atlantic Meridional SST gradient (TAMG)
Difference from climatology / K
Year



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Some applications

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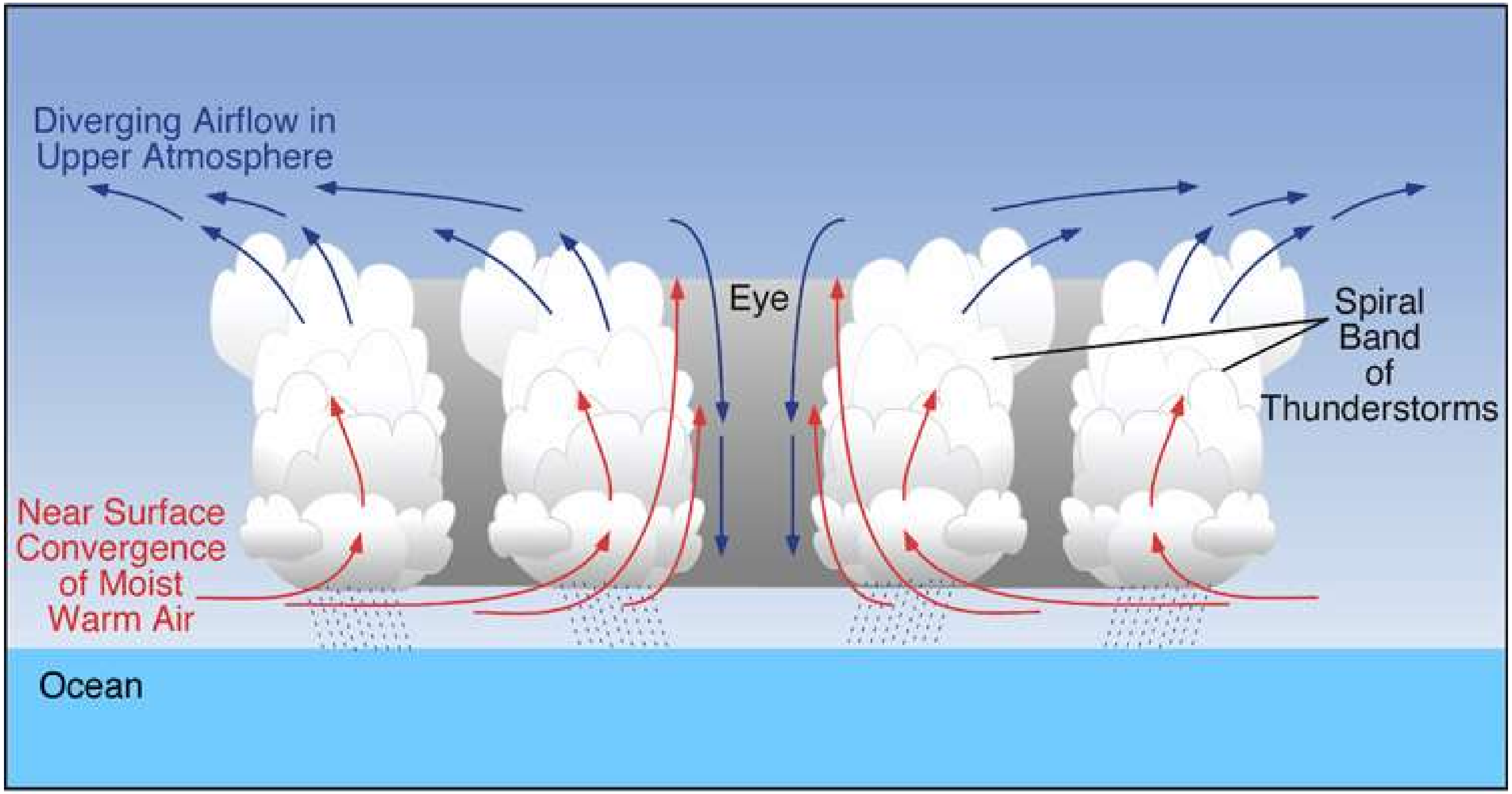
Vertical motion in typhoons & hurricanes

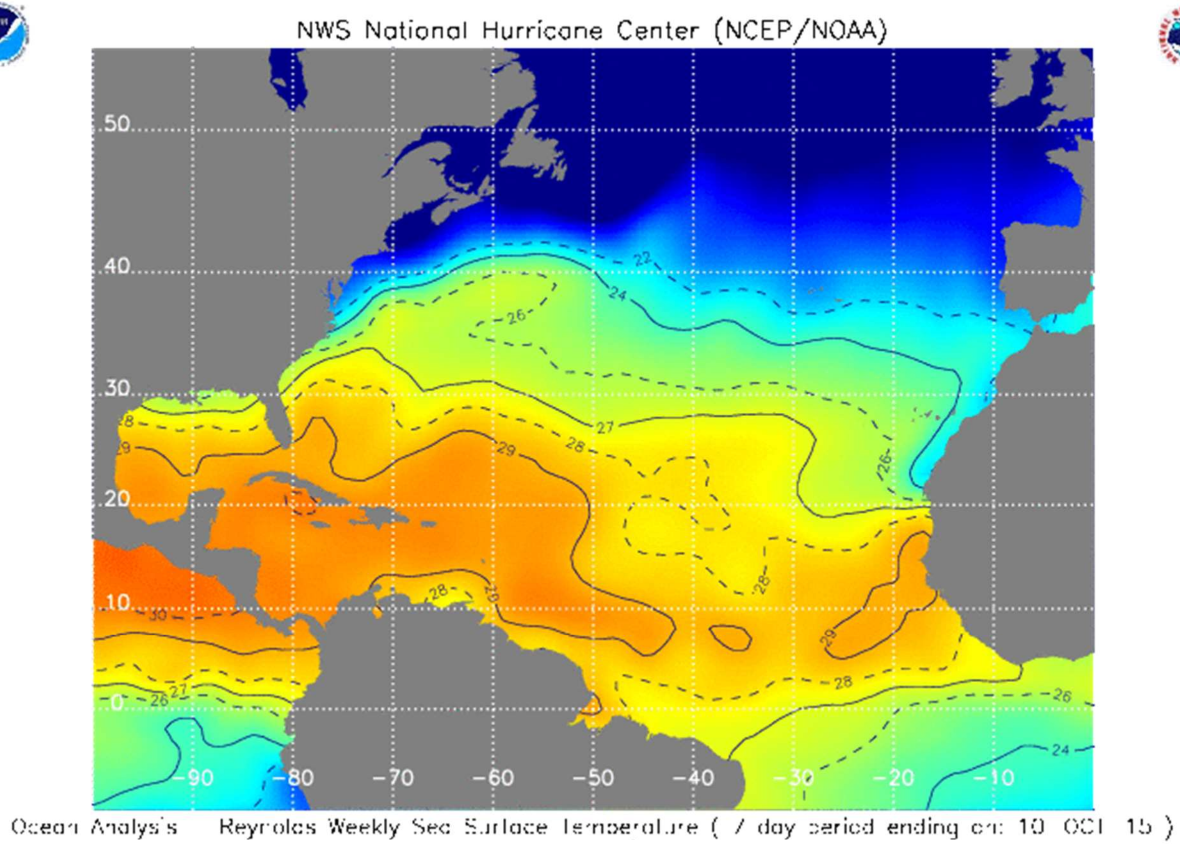


http://www.eoearth.org/view/article/156717/

Hurricane growth

Tropical cyclones, called hurricanes in the Atlantic Ocean, tend to grow when they are over water of SST > 26 – 28°C. Thus, knowledge of the areas of high SST are important to hurricane forecasting.

- SSTs are often based on AVHRR data, optimally interpolated to a regular complete grid ("Reynolds SSTs").
- But, microwave SSTs can also be used.



Ocean Analysis. Reynolds Weekly Sea Surface Temperature (7 day period ending 10 Oct 15)

15.0 17.5 20.0 22.5 25.0 27.5 30.0 32.5 35.0

From: http://www.nhc.noaa.gov/aboutsst.shtml

Upper Ocean Heat Content

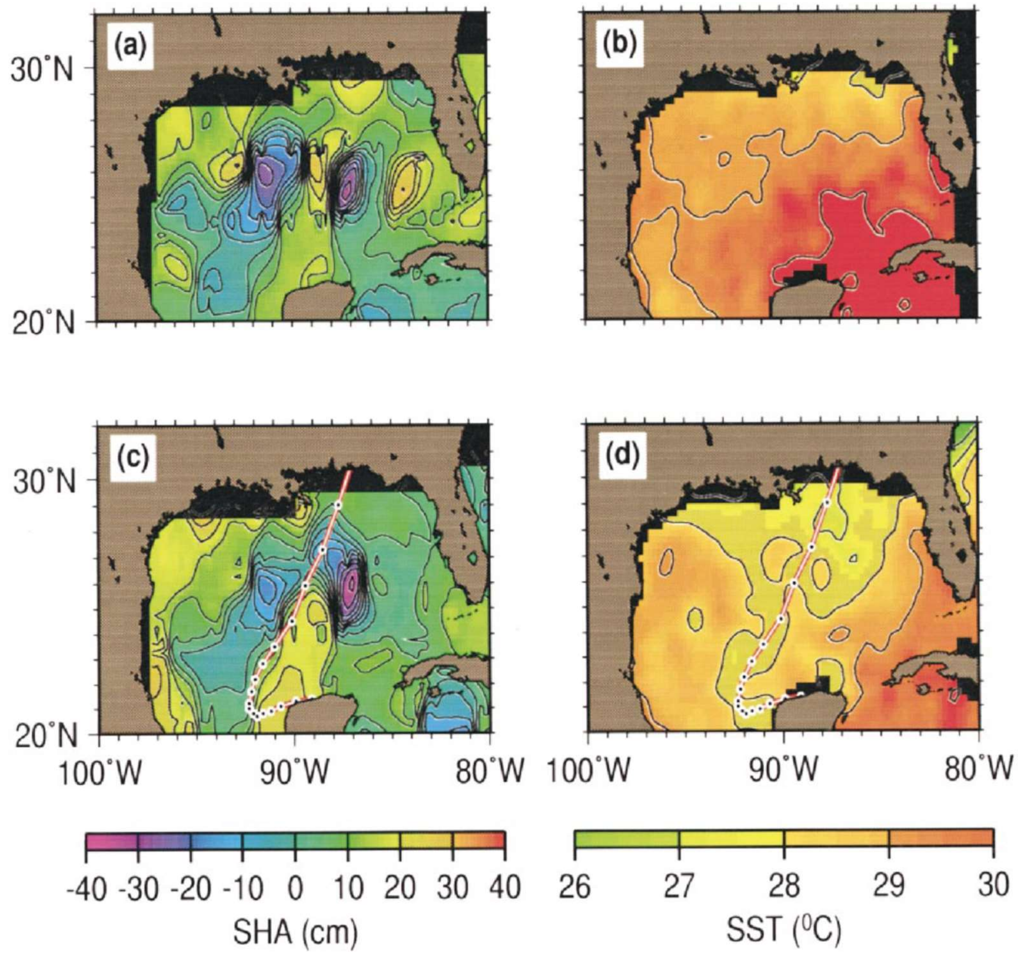
- Cyclone intensification depends not only on SST, but on the upper ocean heat content – i.e. the heat energy available to the storm.
- Conventionally calculated by integrating heat content from surface to the depth of the 26^{o}C isotherm.
- Requires knowledge of the temperature profile with depth.
- Derived from in situ measurements, ocean models, or satellite altimeter data with a simple model.

(a) Prestorm Opal altimeter-derived SHA (18–27 Sep 1995) showing positive height anomalies above 30-cm height corresponding to the WCR located on the right side of Opal's track.

(b) Prestorm objectively analyzed AVHRR SST composited from 27 to 28 Sep images.

(c) Post storm altimeter-derived SHA (28 Sep–8 Oct 1995) showing positive anomalies above 10-cm

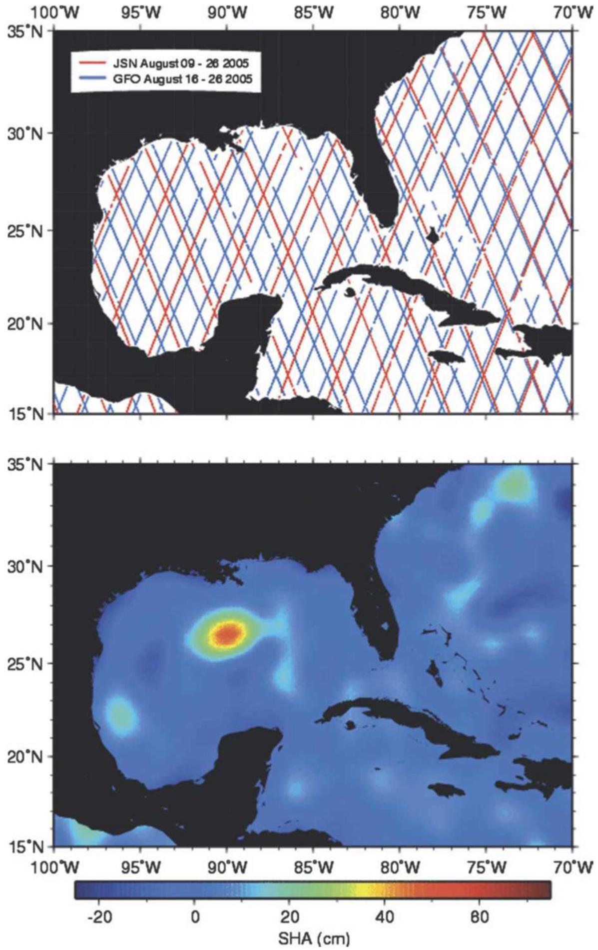
(d) Post storm objectively analyzed AVHRR SST composited from 4 to 5 Oct 1995 showing the ocean cooling induced by Opal's winds.

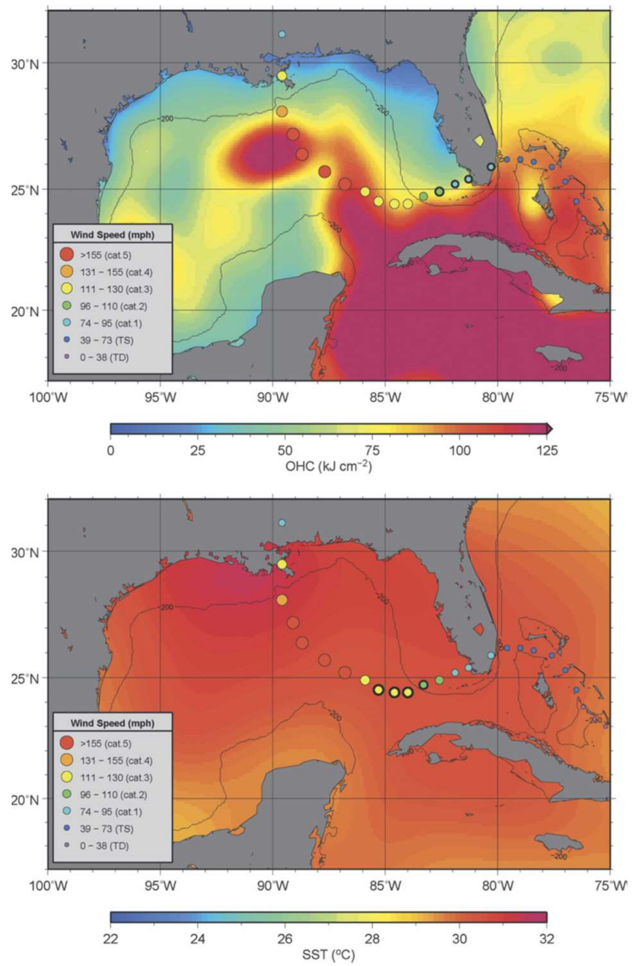


From: Shay, L.K., Goni, G.J., & Black, P.G. (2000). Effects of a Warm Oceanic Feature on Hurricane Opal. *Monthly Weather Review, 128*, 1366-1383.

Hurricane Katrina

Satellite Altimeter tracks from *Jason-1* and GFO and an objectively analyzed SHA for the prestorm analysis of Hurricane Katrina, 2005.



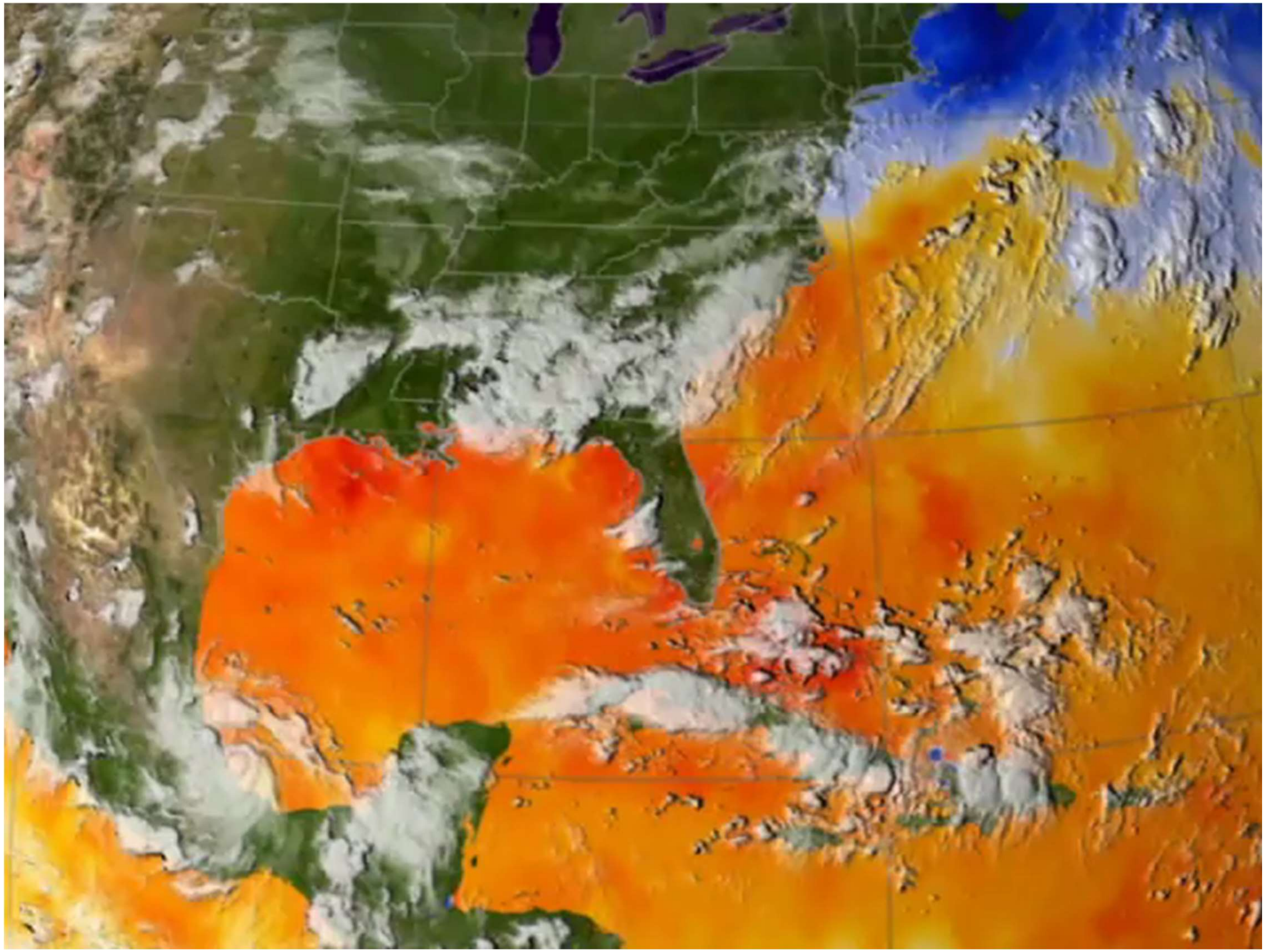


OHC and SST in the prestorm environment for Hurricane Katrina. The storm intensity and positions from the NHC are the circles.

Hurricane Katrina

SSTs are 3-day moving averages of AMSR-E data; cloud images are the GOES-12 Imager.

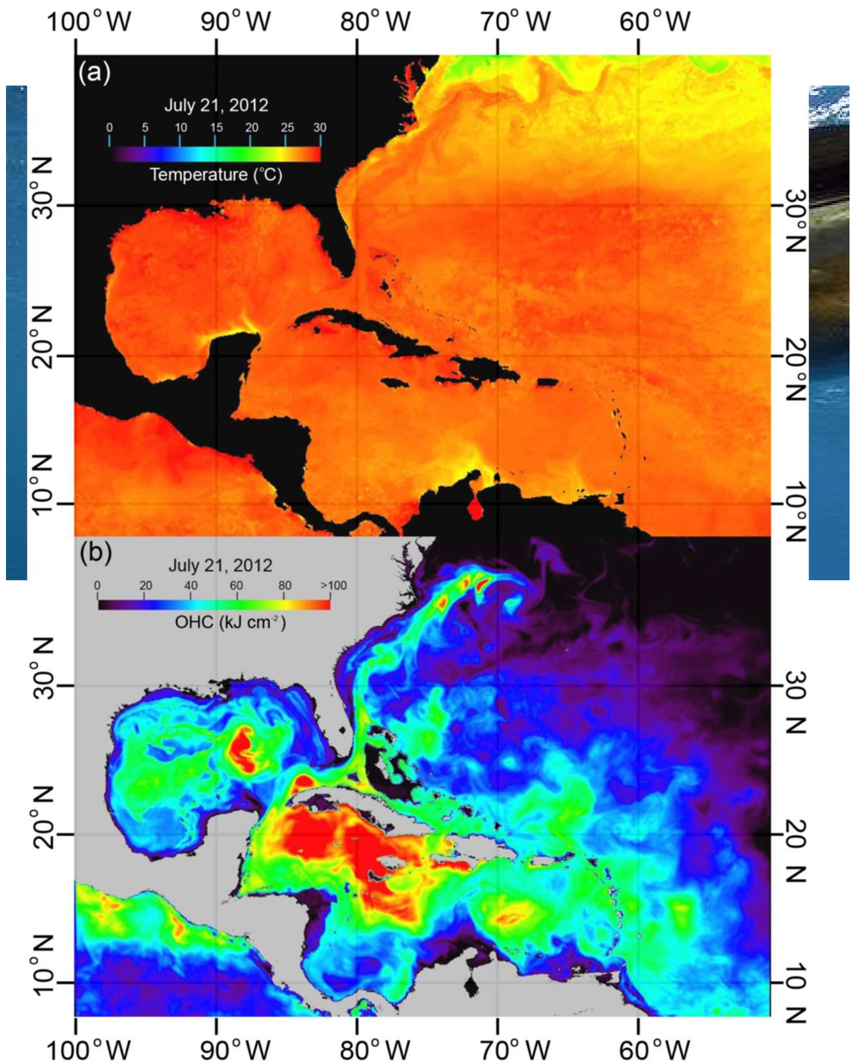
Red-orange SSTs are conducive to hurricane formation and intensification.



From: http://svs.gsfc.nasa.gov/vis/a000000/a003200/a003222/

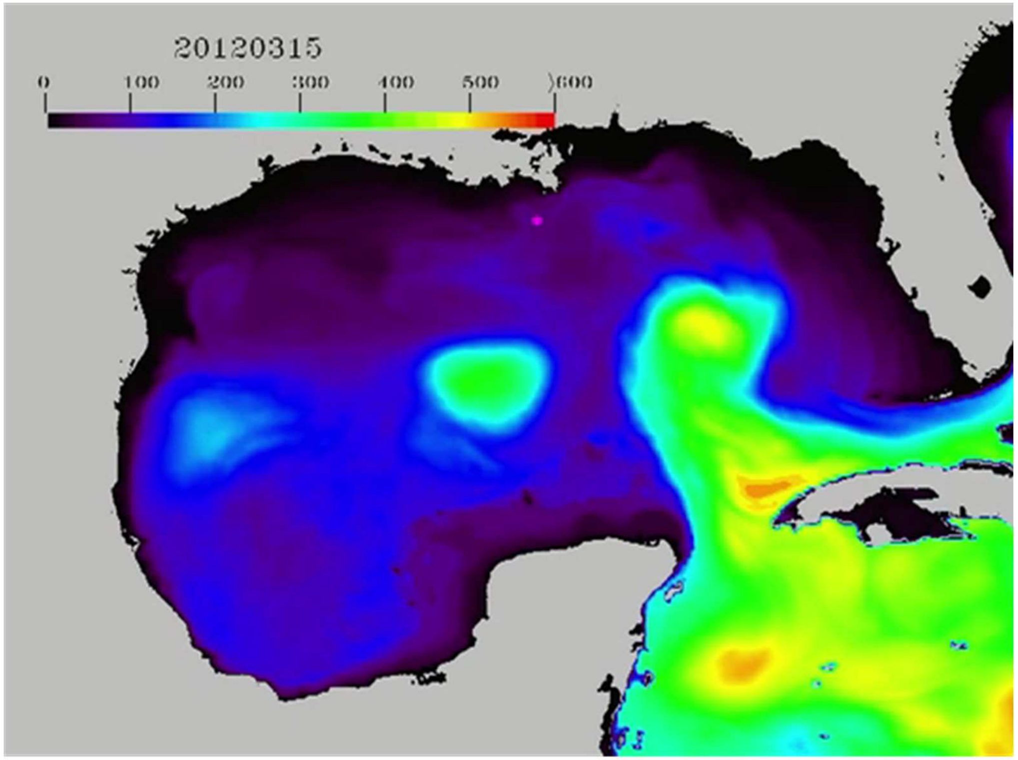
Application of OHC to fish behavior

- Migration and hunting tracks of large predator fish, such as sailfish and tuna, are known to be influenced by ocean parameters including temperature and temperature gradients.
- Fish can be tagged with devices that monitor T, P, and sunlight; dumping data via satellite when the device is released and reaches the surface.
- Recent results, using more sophisticated techniques to reconstruct the fish tracks, have revealed the influence of Ocean Heat Content.



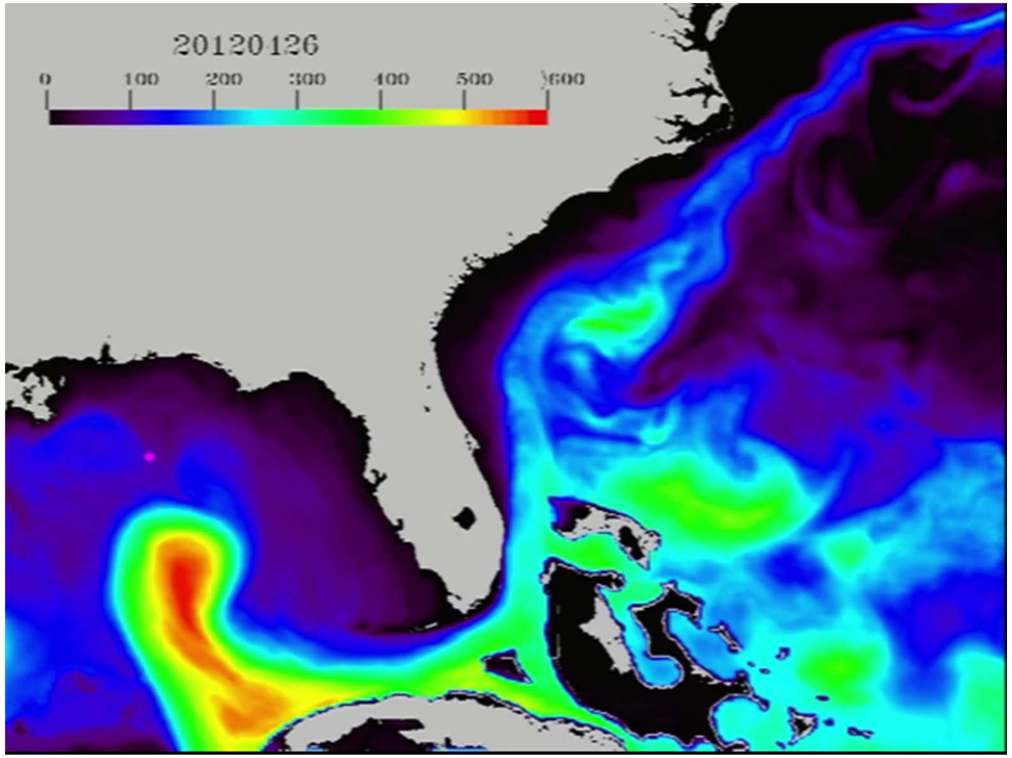
Luo, J., Ault, J.S., Shay, L.K., Hoolihan, J.P., Prince, E.D., Brown, C.A., & Rooker, J.R. (2015). Ocean Heat Content Reveals Secrets of Fish Migrations. *PLoS ONE, 10*, e0141101.

Tuna tracks



Yellowfin tuna in Gulf of Mexico

ftp.rsmas.miami.edu/users/jluo/OHC/track/YFT_OHC_track.mp4



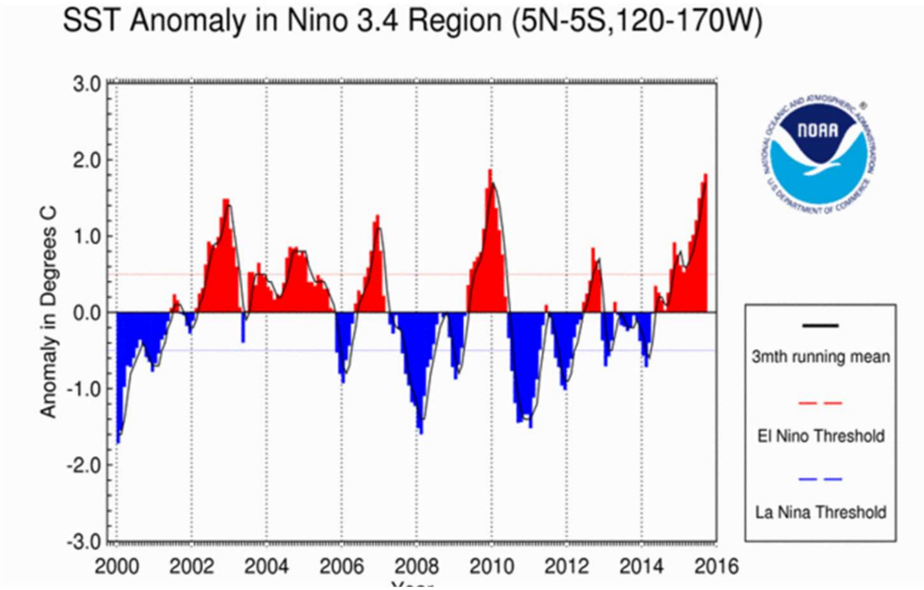
Bluefin tuna: Loop Current and Gulf Stream

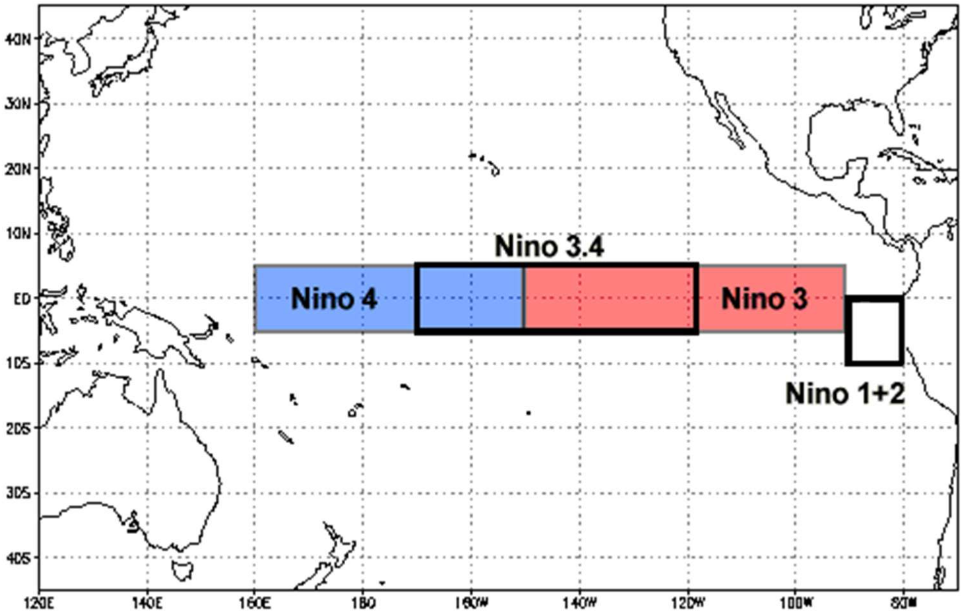
ftp.rsmas.miami.edu/users/jluo/OHC/track/BFT_OHC_track.mp4

Luo, J., Ault, J.S., Shay, L.K., Hoolihan, J.P., Prince, E.D., Brown, C.A., & Rooker, J.R. (2015). Ocean Heat Content Reveals Secrets of Fish Migrations. PLoS ONE, 10, e0141101.

El Niño – Southern Oscillation

El Niño (La Niña) is a phenomenon in the equatorial Pacific Ocean characterized by a five consecutive 3-month running mean of sea surface temperature (SST) anomalies in the Niño 3.4 region that is above (below) the threshold of ±0.5°C - the Oceanic Niño Index (ONI).

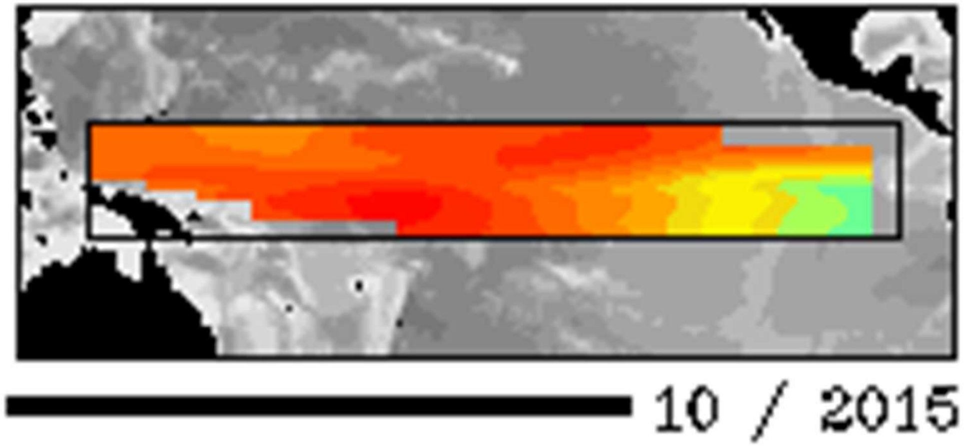




https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sst.php

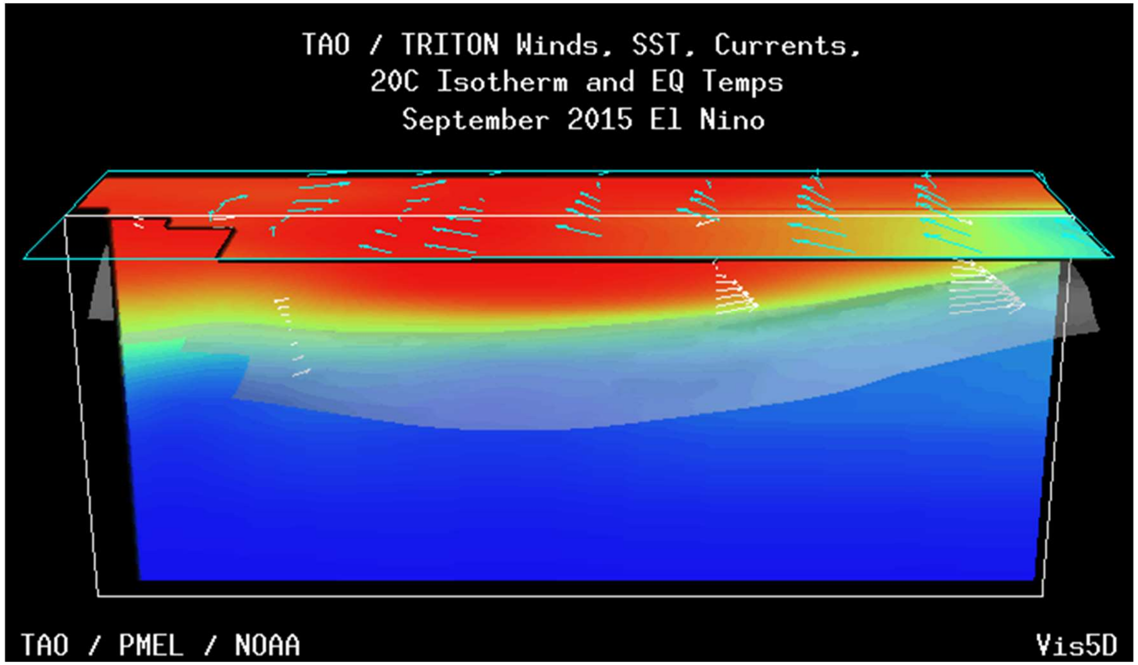
For animations see:
https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sea-temp-anom.php

El Niño – Southern Oscillation



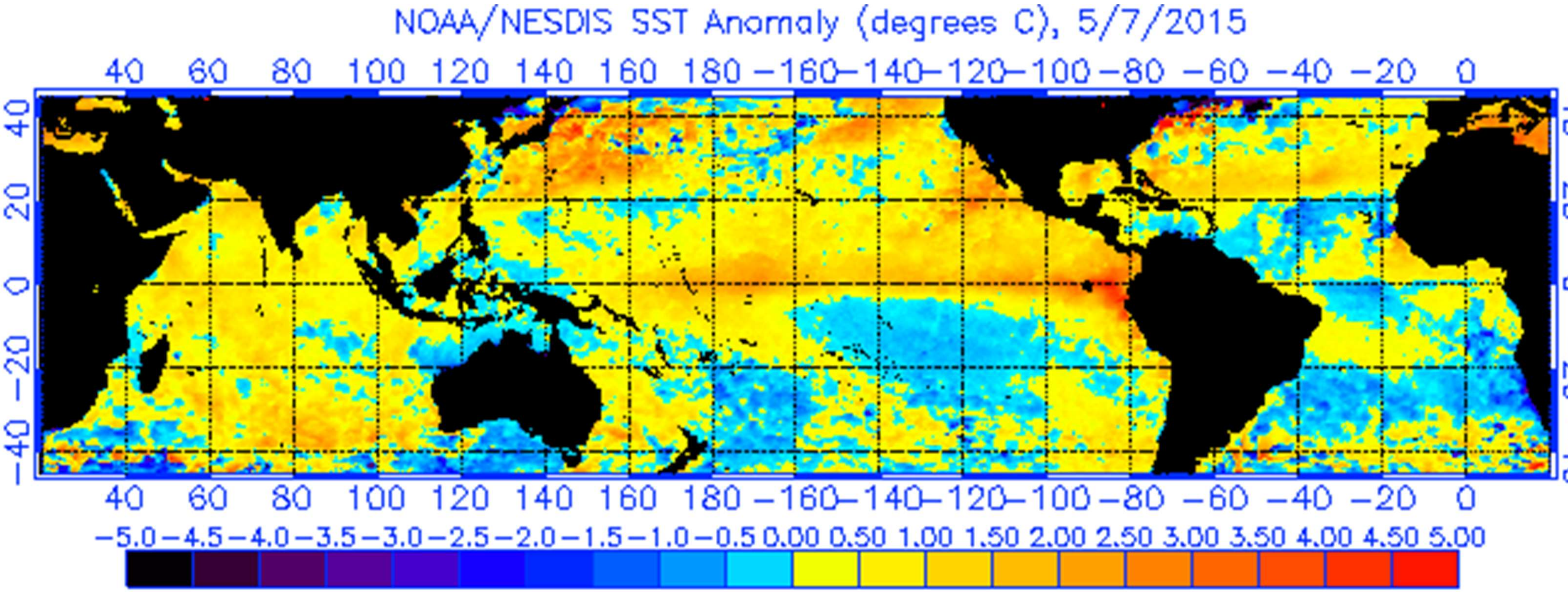
http://www.elnino.noaa.gov/ani.html

TOA mooring array data.

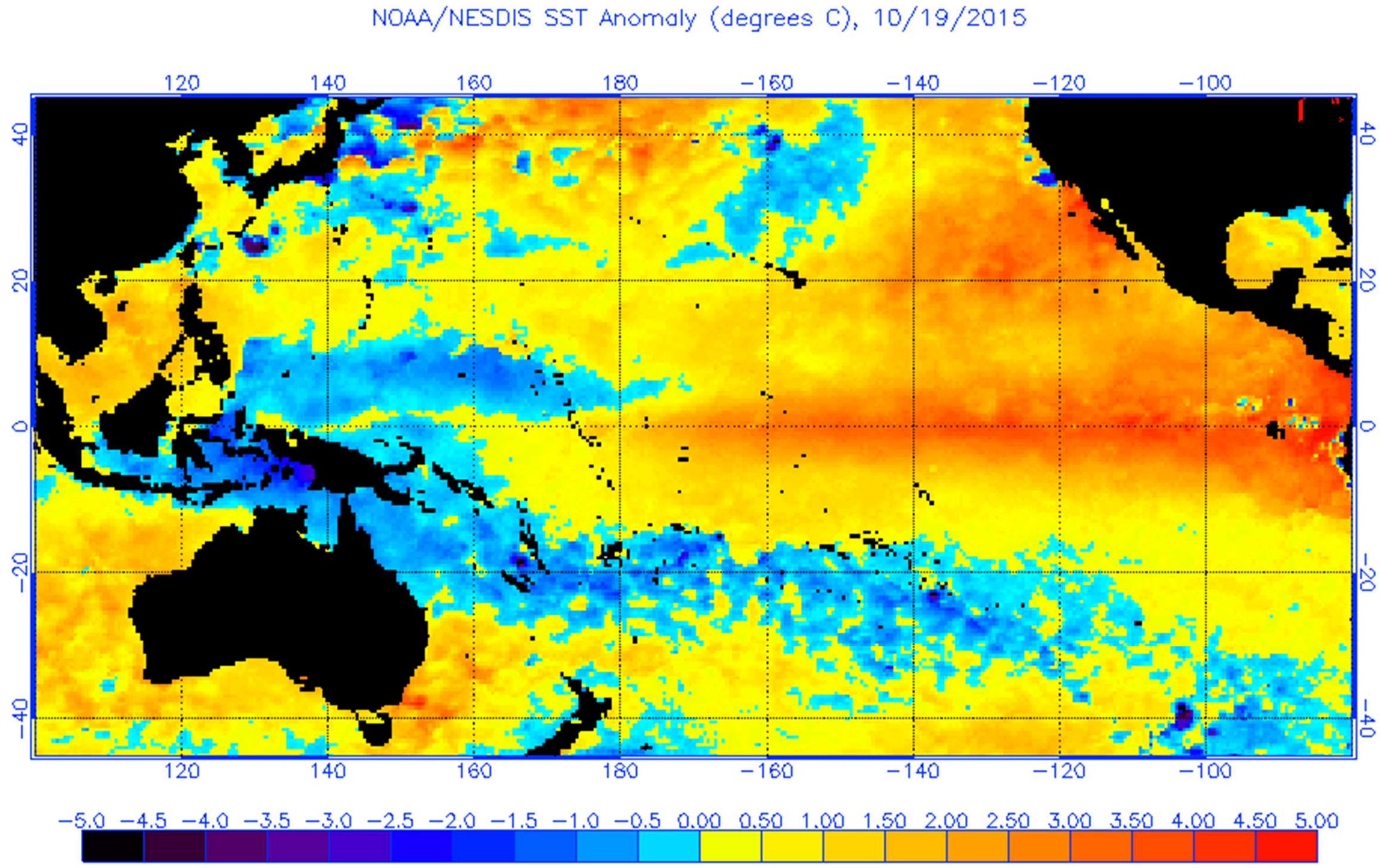


http://www.pmel.noaa.gov/tao/vis/tao-vis.htm

Tropical SST anomalies



Pacific Ocean SST anomaly



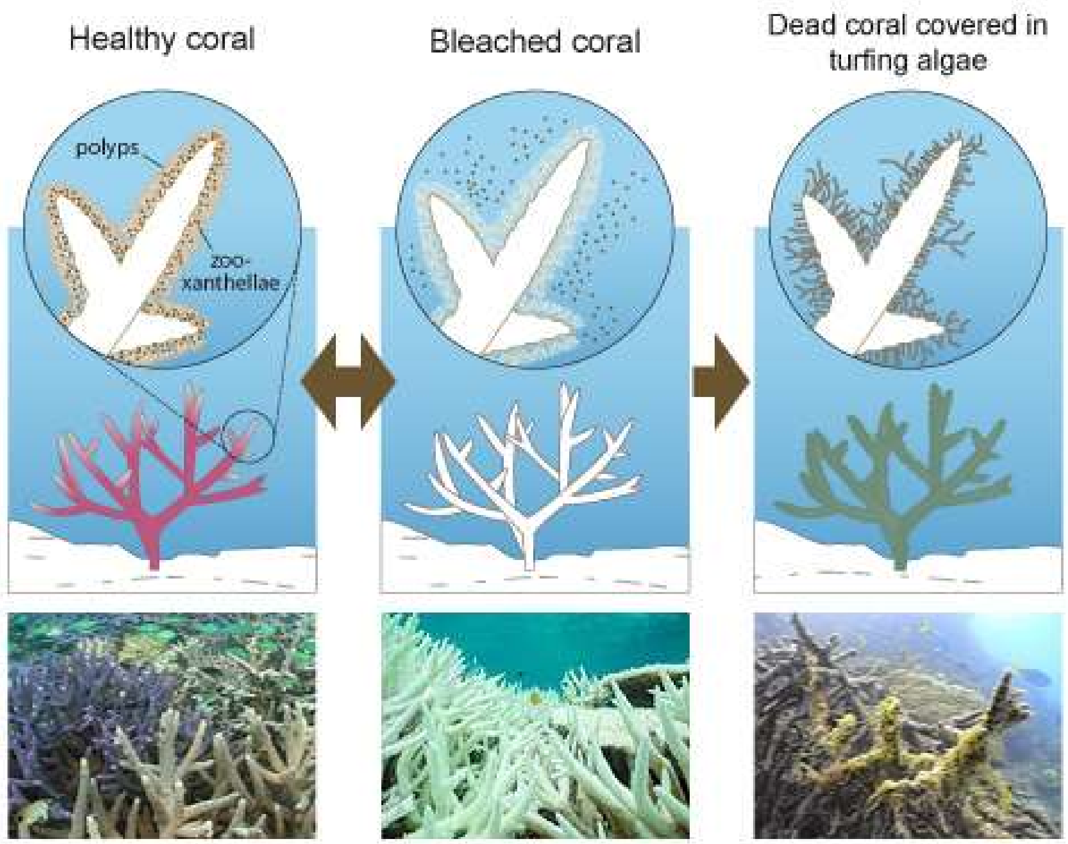
El Niño animations

http://www.esrl.noaa.gov/psd/map/clim/sst.anom.anim.year.html

https://www.ncdc.noaa.gov/teleconnections/enso/indicators/sea-temp-anom.php?begmonth=1&begday=1&begyear=2015&endmonth=8&endday=26&endyear=2015

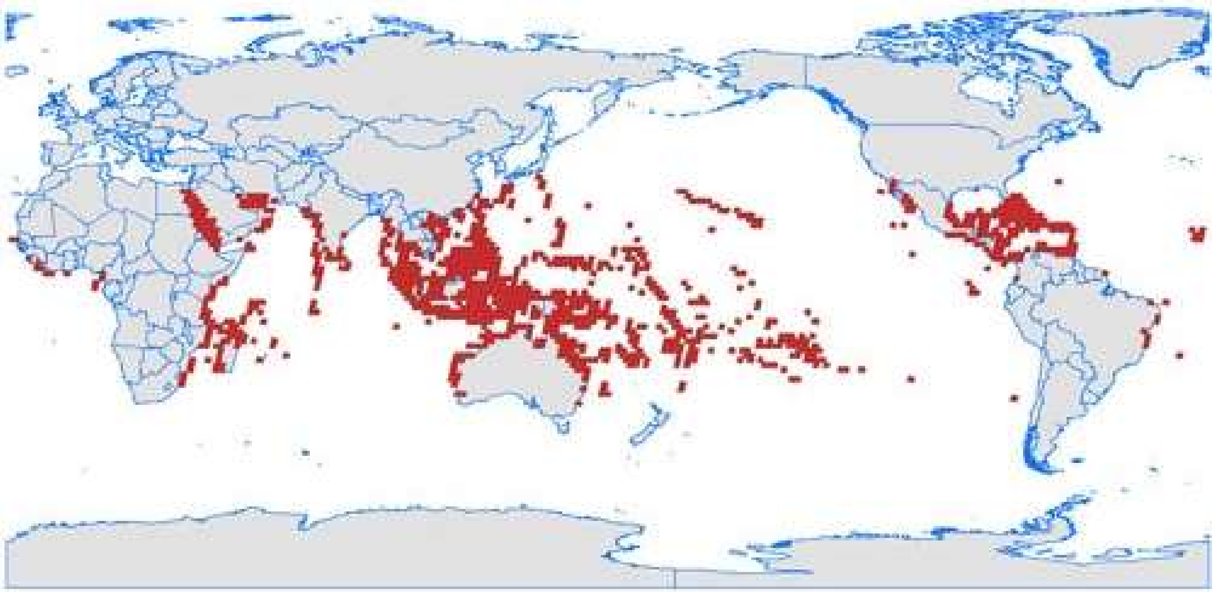
Coral bleaching

- Many types of coral have a special symbiotic relationship with a tiny marine algae (zooxanthellae) that live inside corals' tissue and are very efficient food producers that provide up to 90 per cent of the energy corals require to grow and reproduce.
- Coral bleaching occurs when the relationship between the coral host and zooxanthellae, which give coral much of their color, breaks down. Without the zooxanthellae, the tissue of the coral animal appears transparent and the coral's bright white skeleton is revealed.
- The main cause of coral bleaching is heat stress resulting from high sea temperatures. Temperature increases of only 1°C for only four weeks can trigger bleaching events.



http://www.gbrmpa.gov.au/managing-the-reef/threats-to-the-reef/climate-change/what-does-this-mean-for-species/corals/what-is-coral-bleaching

Coral reefs from space



Global view of coral reefs - 1700 images (red boxes) from the Landsat 7 spacecraft form the Millennium Coral Reef Mapping Project.

http://www.nasa.gov/vision/earth/lookingatearth/coral_assessment.html

Hawaii's Pearl and Hermes Atoll, shown here in a 20-mi x 20-mi Landsat 7 image, is part of the Northwestern Hawaiian Islands Marine National Monument.

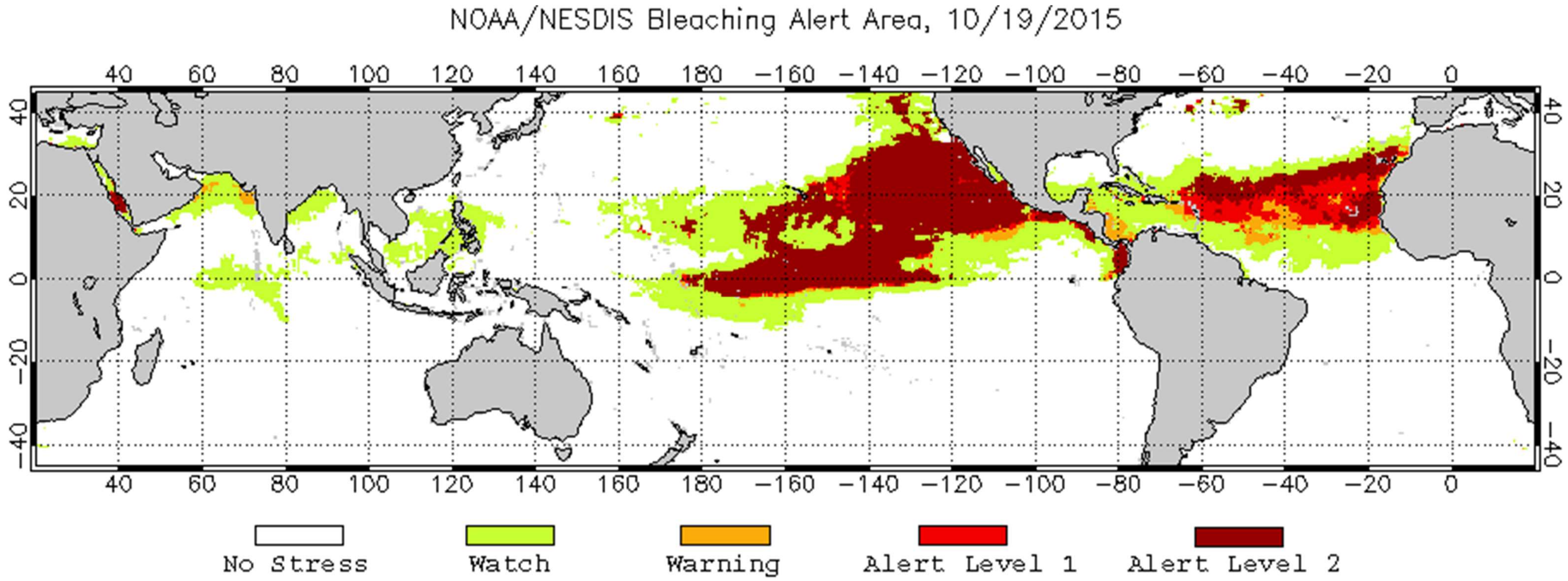
NOAA Coral Bleaching Services

Provides near-real-time information on thermal stress that induces coral bleaching for 24 selected reef sites around the globe. The information is extracted from near-real-time satellite remotely sensed global sea surface temperature (SST) measurements and derived indices of coral bleaching related thermal stress. Each reef site includes links to SST, SST Anomalies, Coral Bleaching HotSpots, Degree Heating Weeks, Time Series, SST Contour Charts, Ocean Surface Winds, and On-site Buoys as available for that reef.

See http://www.ospo.noaa.gov/Products/ocean/coral_bleaching.html

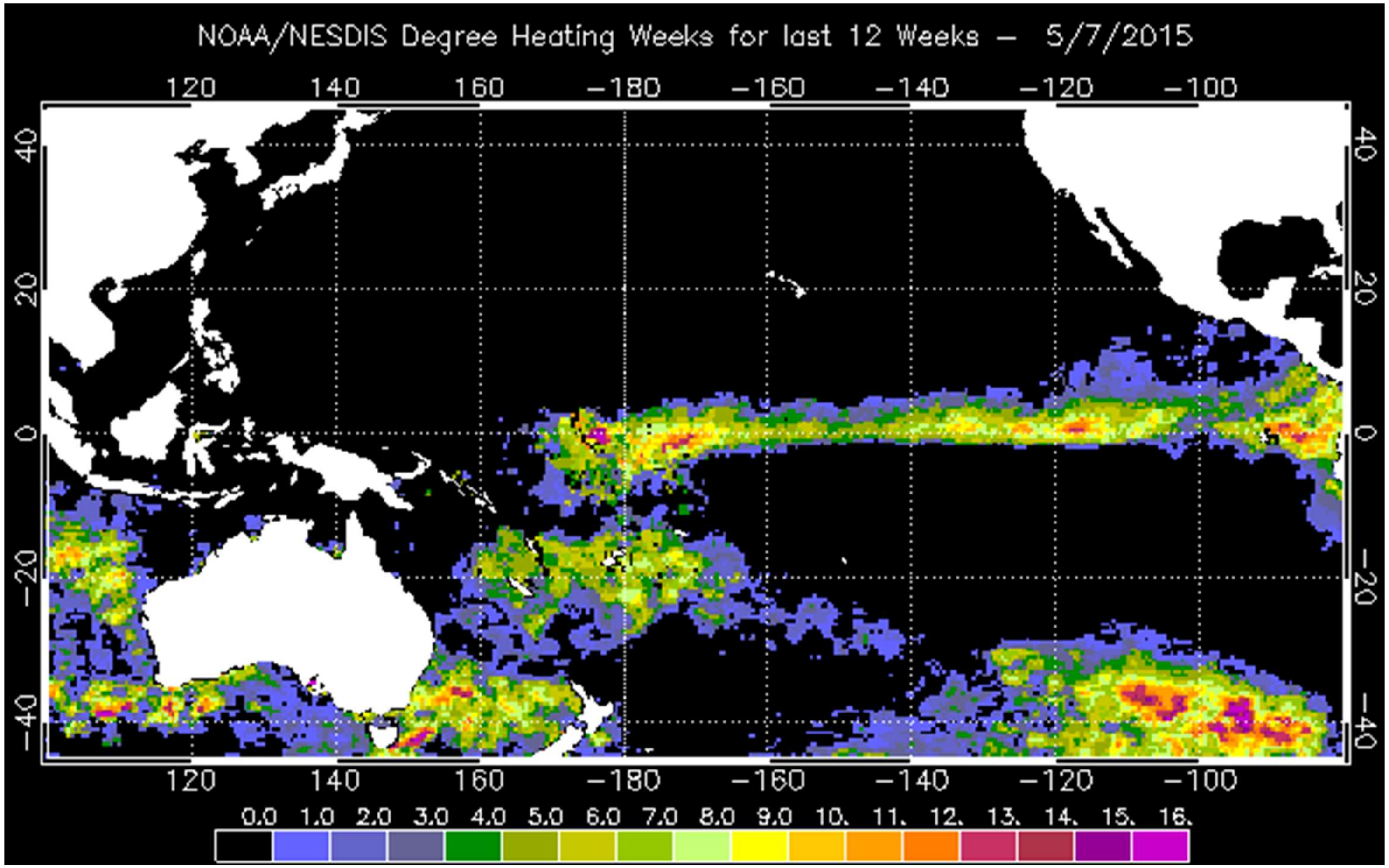
&
http://coralreefwatch.noaa.gov/satellite/methodology/methodology.php#baa

Coral Bleaching Alert



http://www.ospo.noaa.gov/Products/ocean/cb/baa/index.html

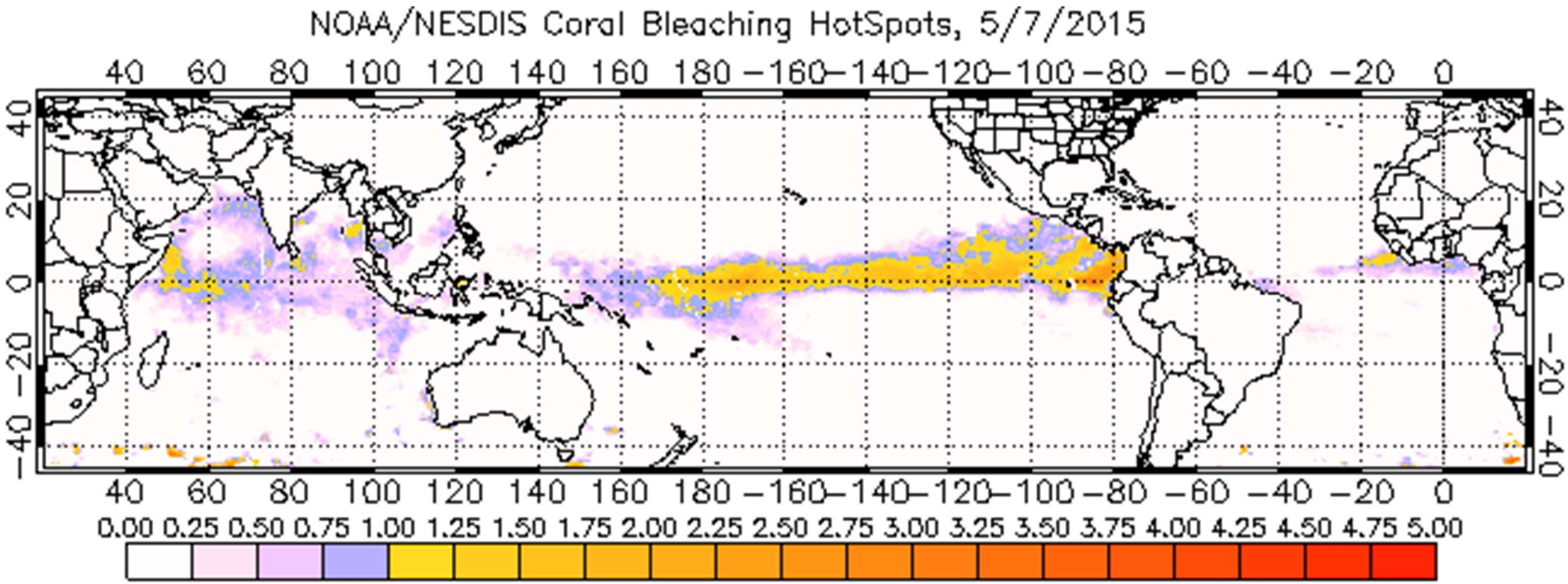
Degree Heating Weeks Pacific



Degree Heating Weeks (DHWs) indicate the accumulation of thermal stress that coral reefs have experienced over the past 12 weeks. One DHW is equivalent to one week of sea surface temperatures 1°C greater than the expected summertime maximum.

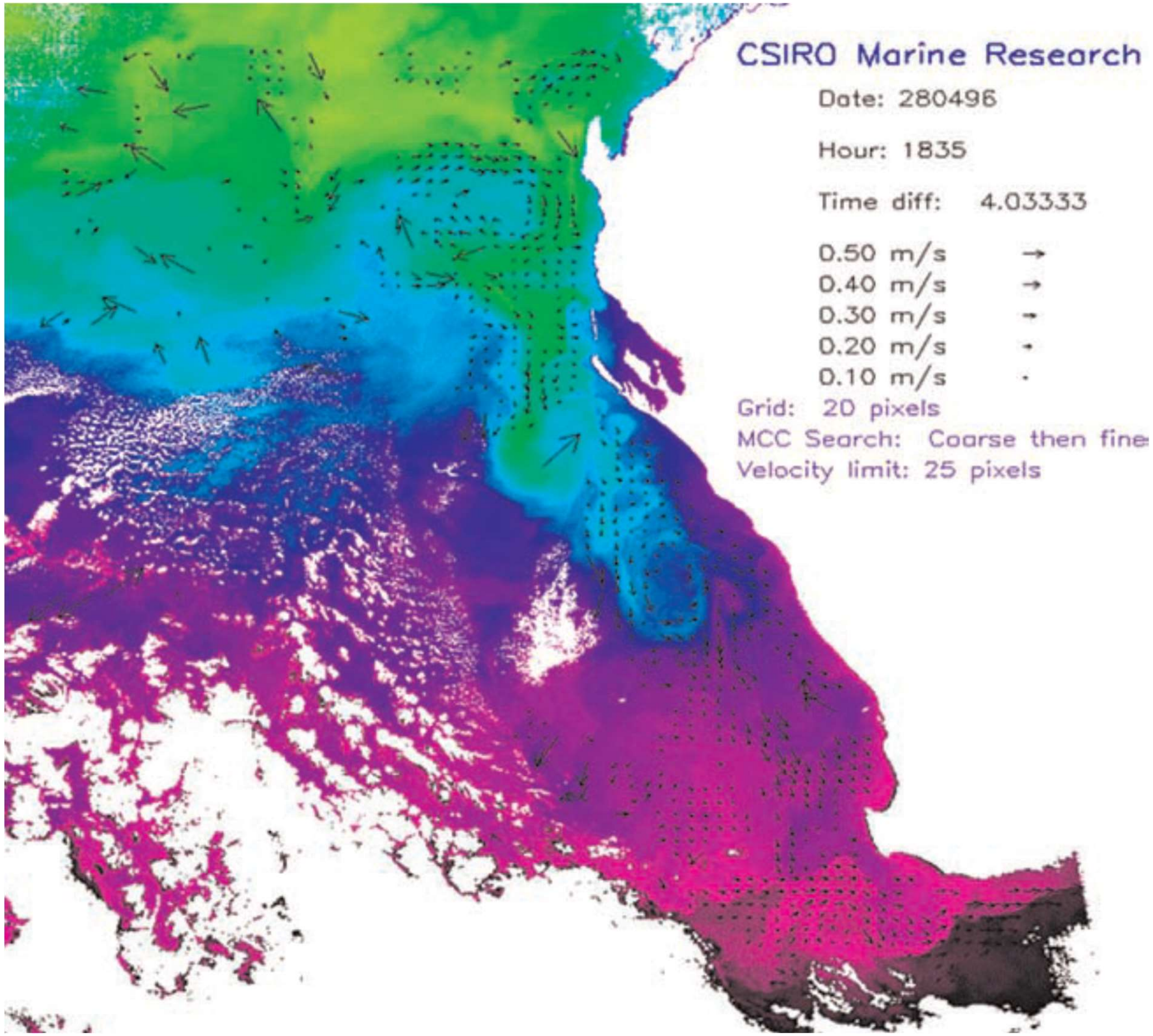
Hot spots

Coral Reef Watch's Coral Bleaching HotSpot product measures the occurrence and magnitude of thermal stress potentially conducive to coral bleaching. The HotSpot anomaly is based on the climatological mean SST of the hottest month (often referred to as the Maximum of the Monthly Mean (MMM) SST climatology).



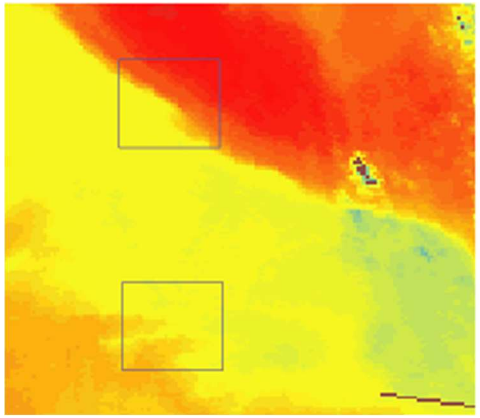
Surface currents

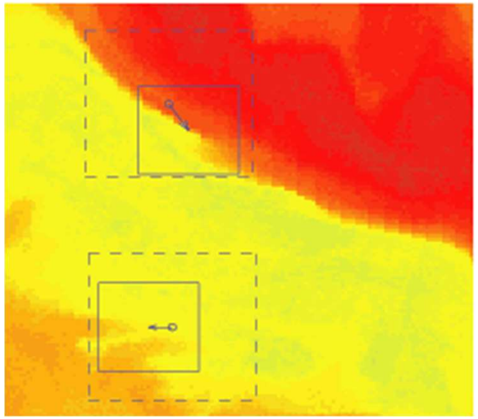
An example of the surface current field (arrows) derived from the Maximum Cross-Correlation method, between the NOAA-14 AVHRR channel 4 brightness temperatures shown in the image and those from the NOAA-12 AVHRR 4 h later. The images cover a large area of 1,6001,600 pixels including the Leeuwin Current off the west coast of Australia. The white area to the right (east) is Australia, and other white areas are clouds.



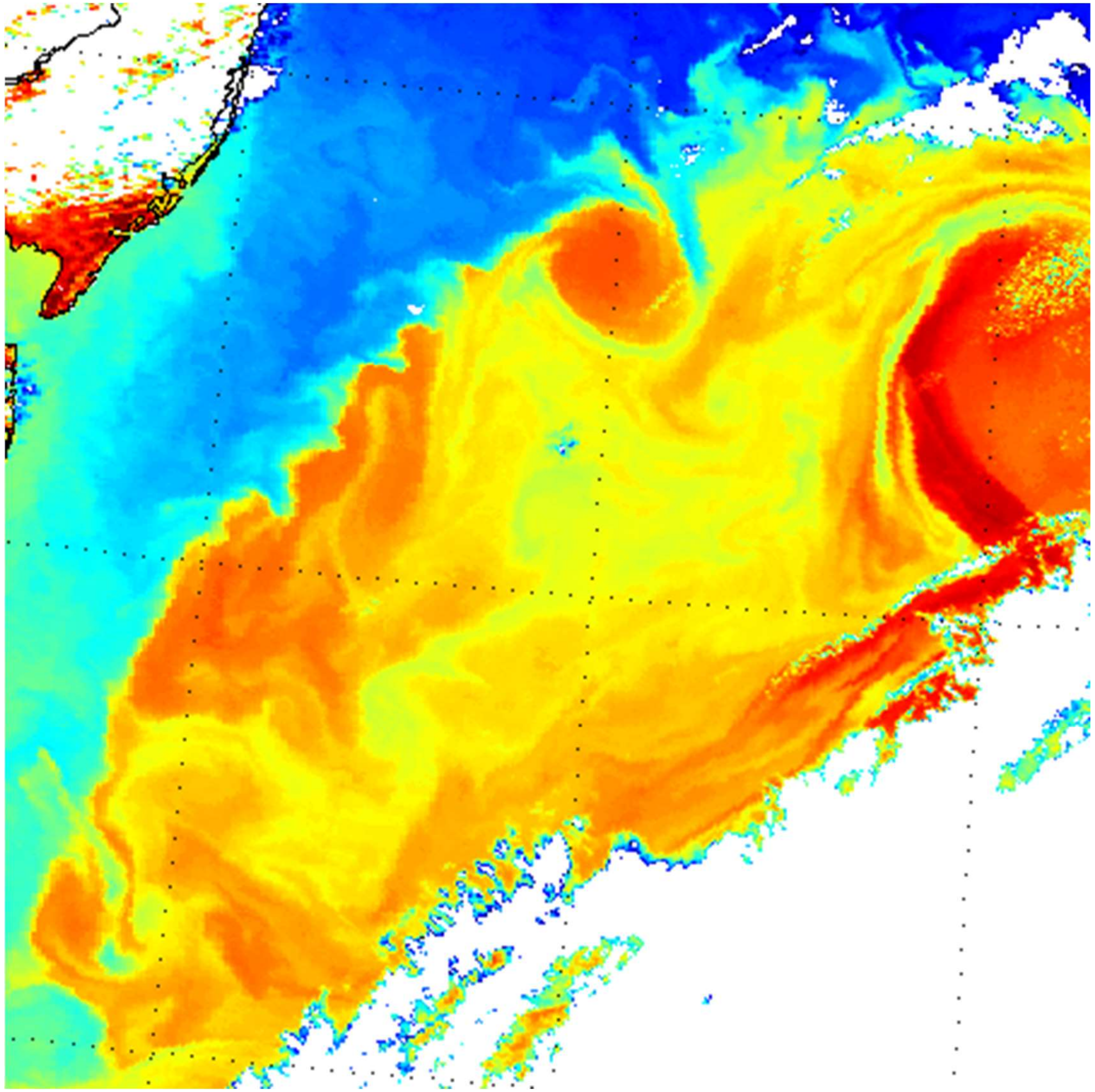
From Minnett, P.J., & Barton, I.J. (2010). Remote Sensing of the Earth's Surface Temperature. In Z.M. Zhang, B.K. Tsai, & G. Machin (Eds.), *Radiometric Temperature Measurements and Applications* (pp. 333-391): Academic Press/Elsevier.

Surface currents





The location of the subwindow in the second image that produces the highest cross-correlation with the subwindow in the first image indicates the most likely displacement of that feature. The velocity vector is then calculated by dividing the displacement vector by the time separation between the two images



Four sequential thermal images from the U.S. east coast, and the resulting MCC composite velocity field.

From http://ccar.colorado.edu/colors/mcc.html