Towards High-Resolution Multi-Sensor Gridded ACSPO L3S SST Product

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NOAA STAR; CCNY; GST, Inc.

Supported by JPSS Program

Current ACSPO SST Products from VIIRS, MODIS, AVHRR FRAC/GAC, ABI, AHI

L2P (Swath Projection)

- Assimilated into NOAA Geo-Polar Blended and CMC L4 products
- EUMETCast initially pulled L2P data but requested reduced volume data
- BoM, Met Office, JMA also requested reduced volume VIIRS files
- All polar products (VIIRS, MODIS, AVHRR) organized in 10-min granules, 144/day
- Geostationary products are full-disk (FD) hourly granules

L3U: Gridded Equiangular (0.02°) Un-collated produced from all sensors

- Polar: 10-min granules; Geo: 1FD/hr (consistently with L2P)
- Uniform L3U algorithm is used across all sensors (with sensor-specific parameters, adjusted to noise and original L2P resolution in individual sensor data)
- All L3Us routinely validated against iQuam buoys and monitored in SQUAM/ARMS. L3U global coverage, performance statistics, image quality are comparable to L2P.
- L3U data are much smaller in size than L2P data, and preferred by many users

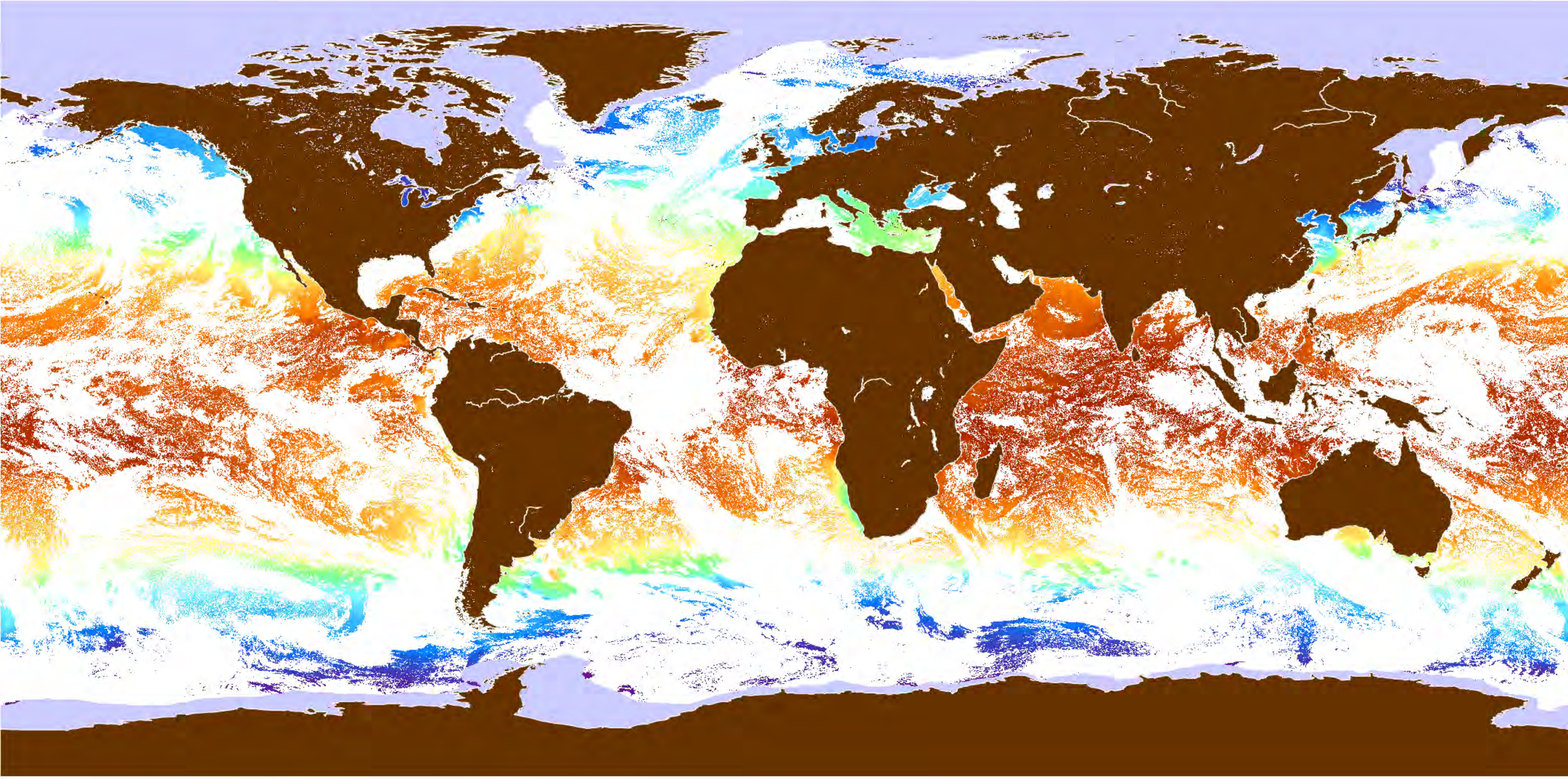
Collated/Super-Collated Gridded SST Products (L3C/S)

- Having multiple overpasses from the same sensor (in particular, in the high latitudes) naturally leads to “collating” the uncollated gridded L3Us and creating L3C.

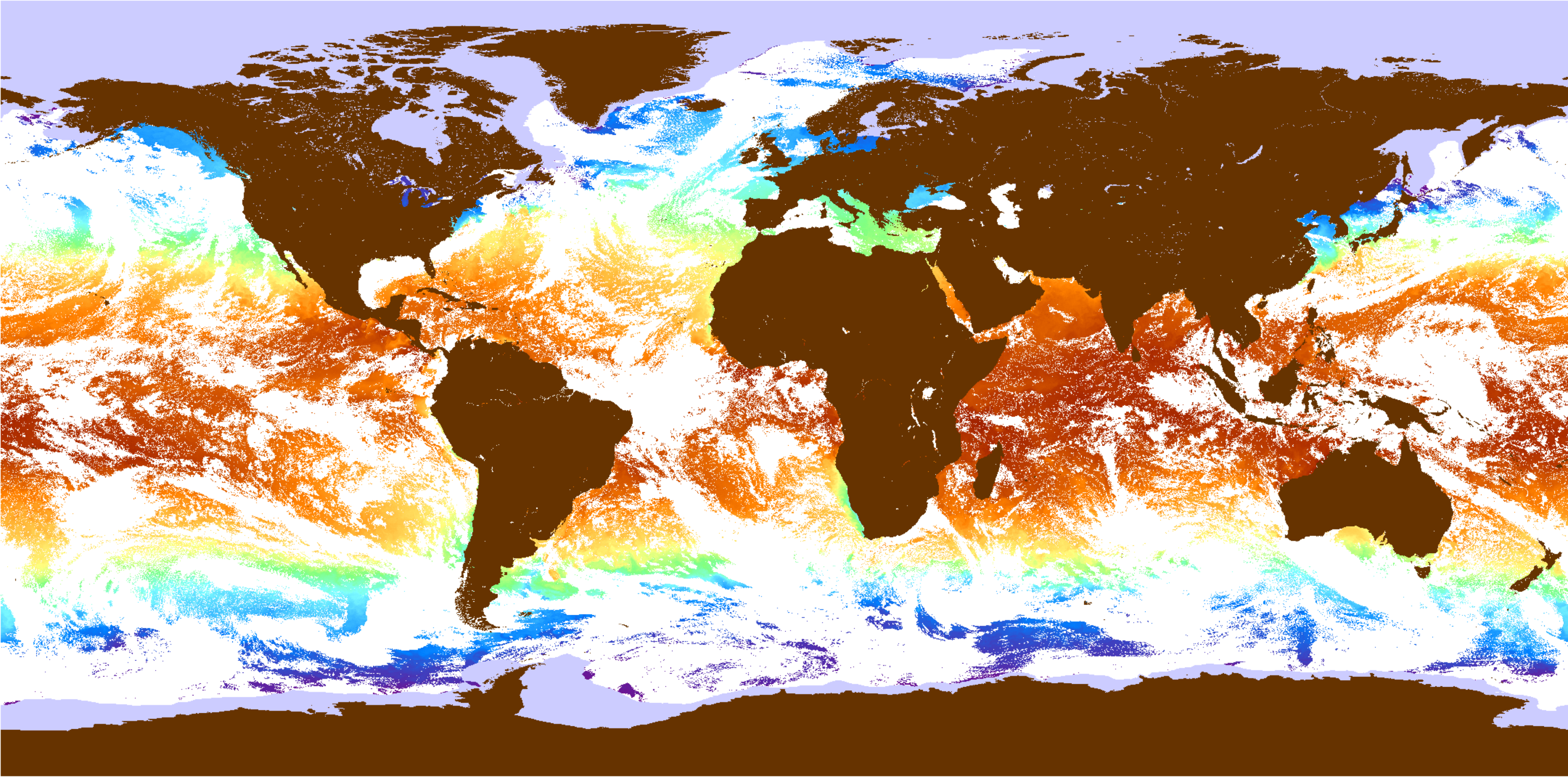
- Data of multiple sensors can be further super-collated into L3S

- (Super) collating data of multiple passes/sensors:
  - Reduces the data volumes & number of files
  - Improves data coverage & quality
  - Preserves spatial resolution of original L2P/3U observations
  - Reconciles multiple data sets, by minimizing residual biases (angular, overpass-to-overpass, satellite-to-satellite)
  - Spares users from dealing with multiple inconsistent datasets
  - Delivers one good, sensor-agnostic SST product, with improved accuracy, coverage, and resolution

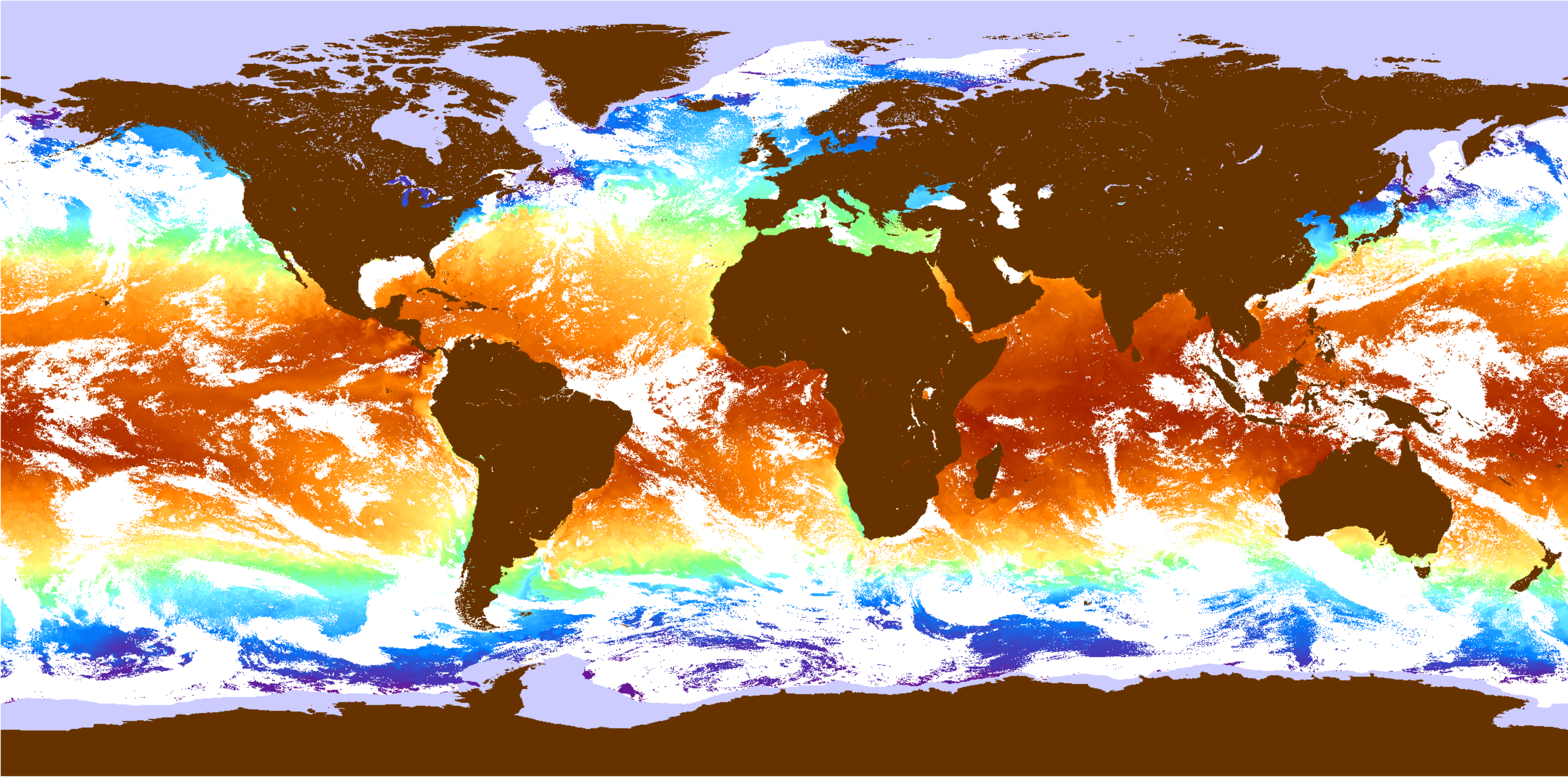
NPP VIIRS April 1, 2019
All Night Overpasses



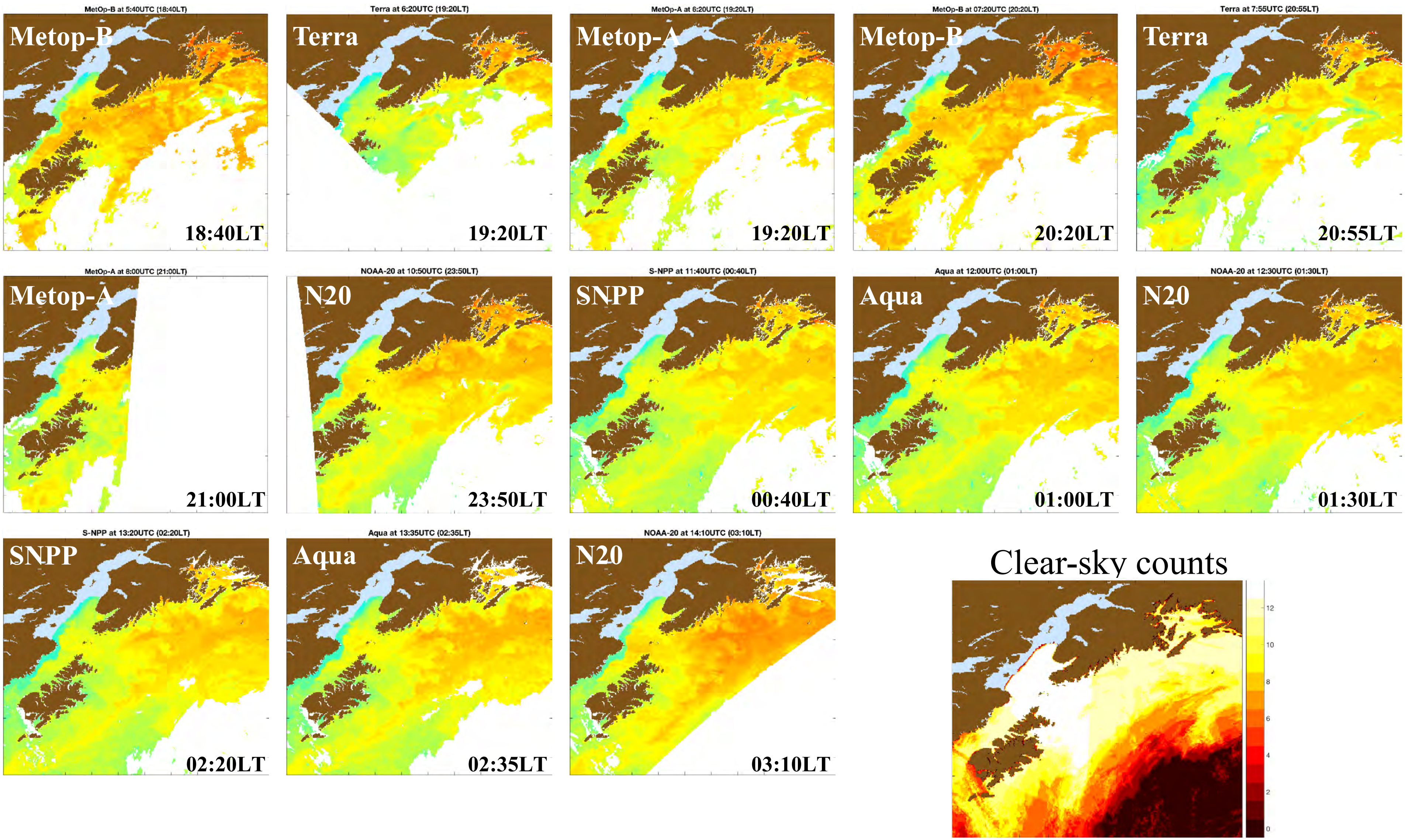
2 VIIRSs (NPP + N20)
All Night Overpasses



VIIRS(NPP& N20) + AVHRR(MetOp-A/B/C)
All Night Overpasses



VIIRS, MODIS, AVHRR Overpasses
14 Apr 2018 NIGHTTIME



High-resolution, Satellite-based, Gap-free

User's wish list:

- **high resolution**
- **satellite based**
- **gap free**

High-resolution, Satellite-based, Gap-free myth

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- **high resolution**
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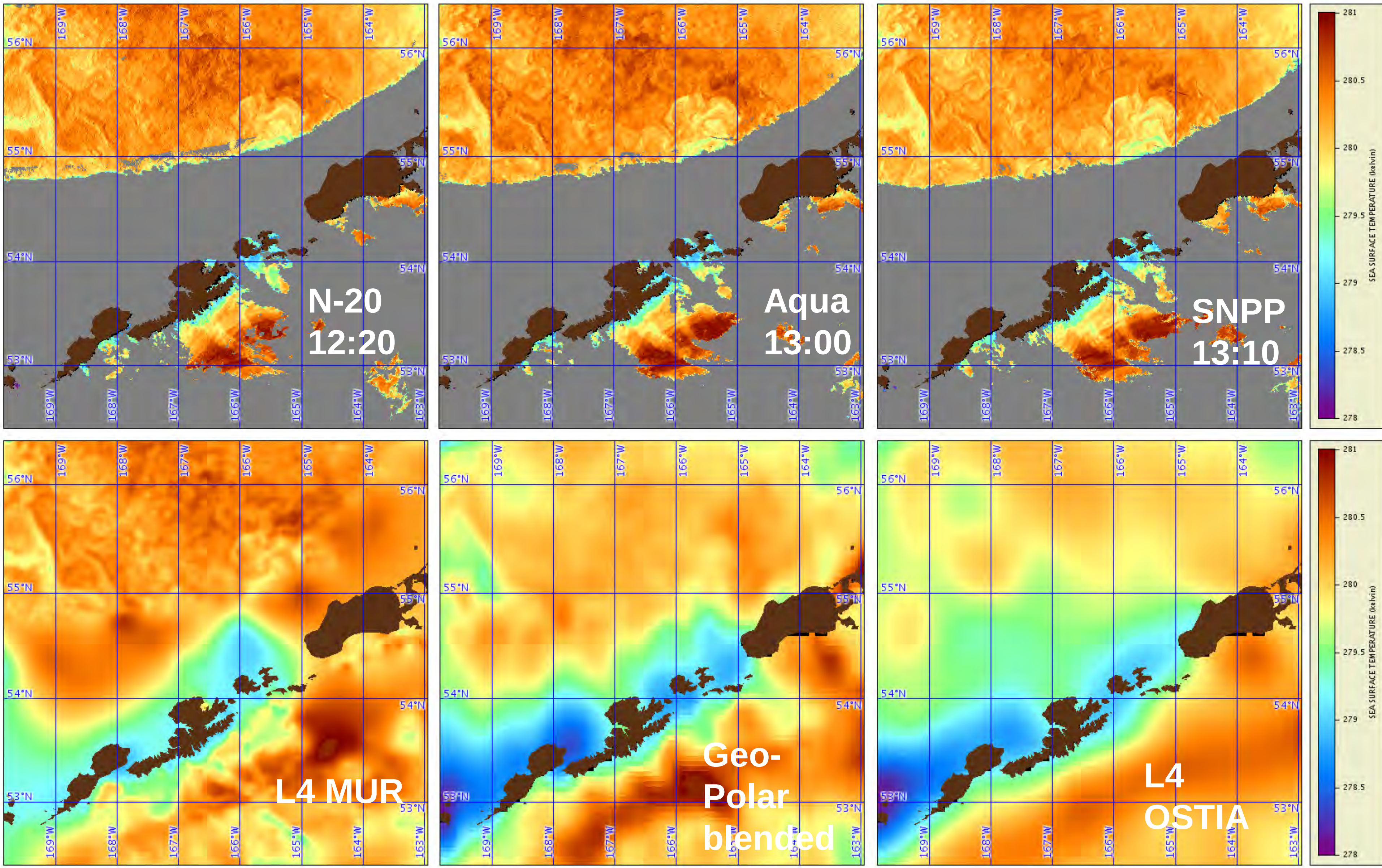
- **gap free**

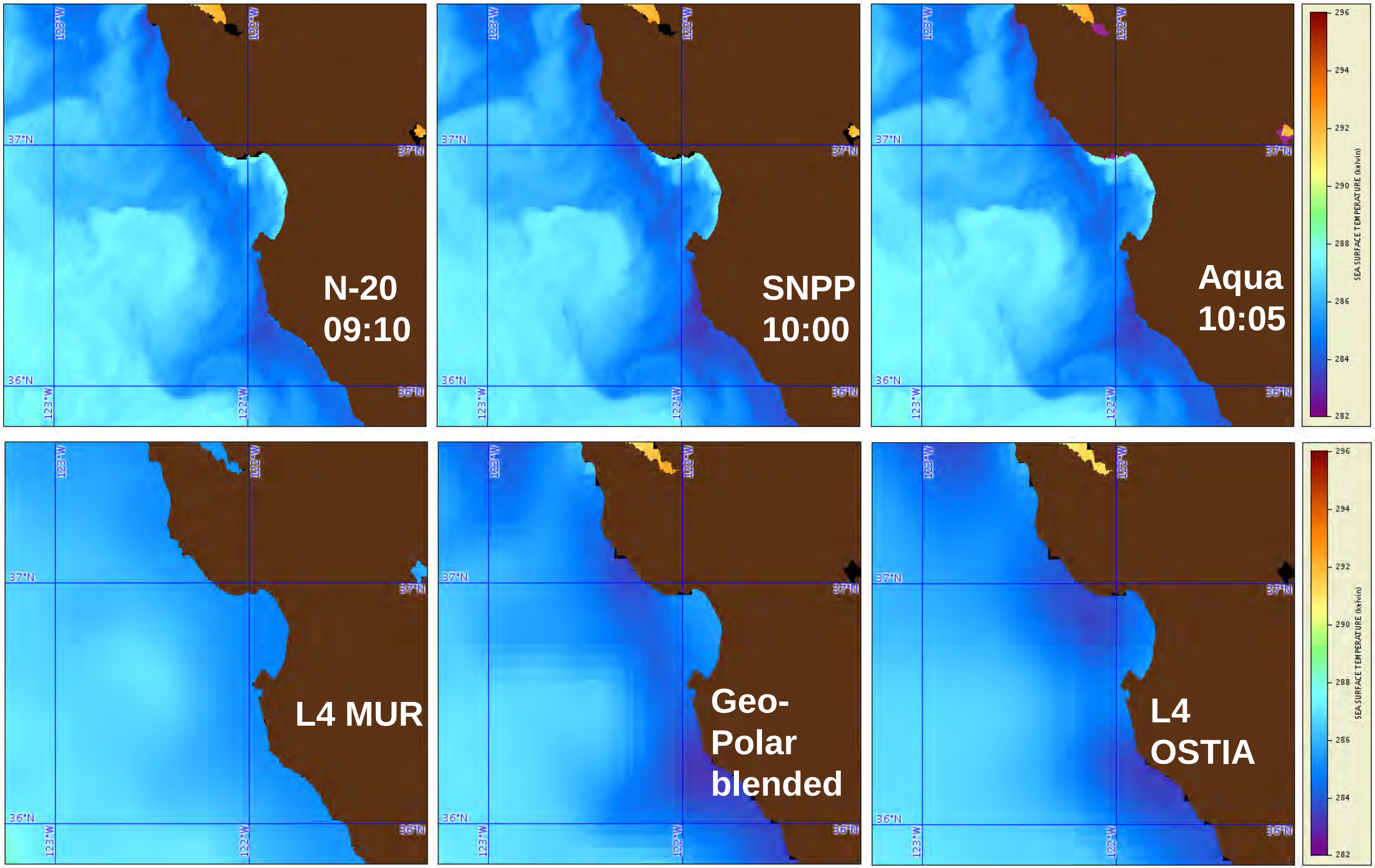
Can it be done? Sure: pick 2

- High res, satellite based (not gap free) **L3C/S**
- Satellite based, (nearly) gap free (not high res) **L3S weekly or monthly** at a lower than sensor spatial resolution
- High res, gap free (not guaranteed to be satellite based) **L4**

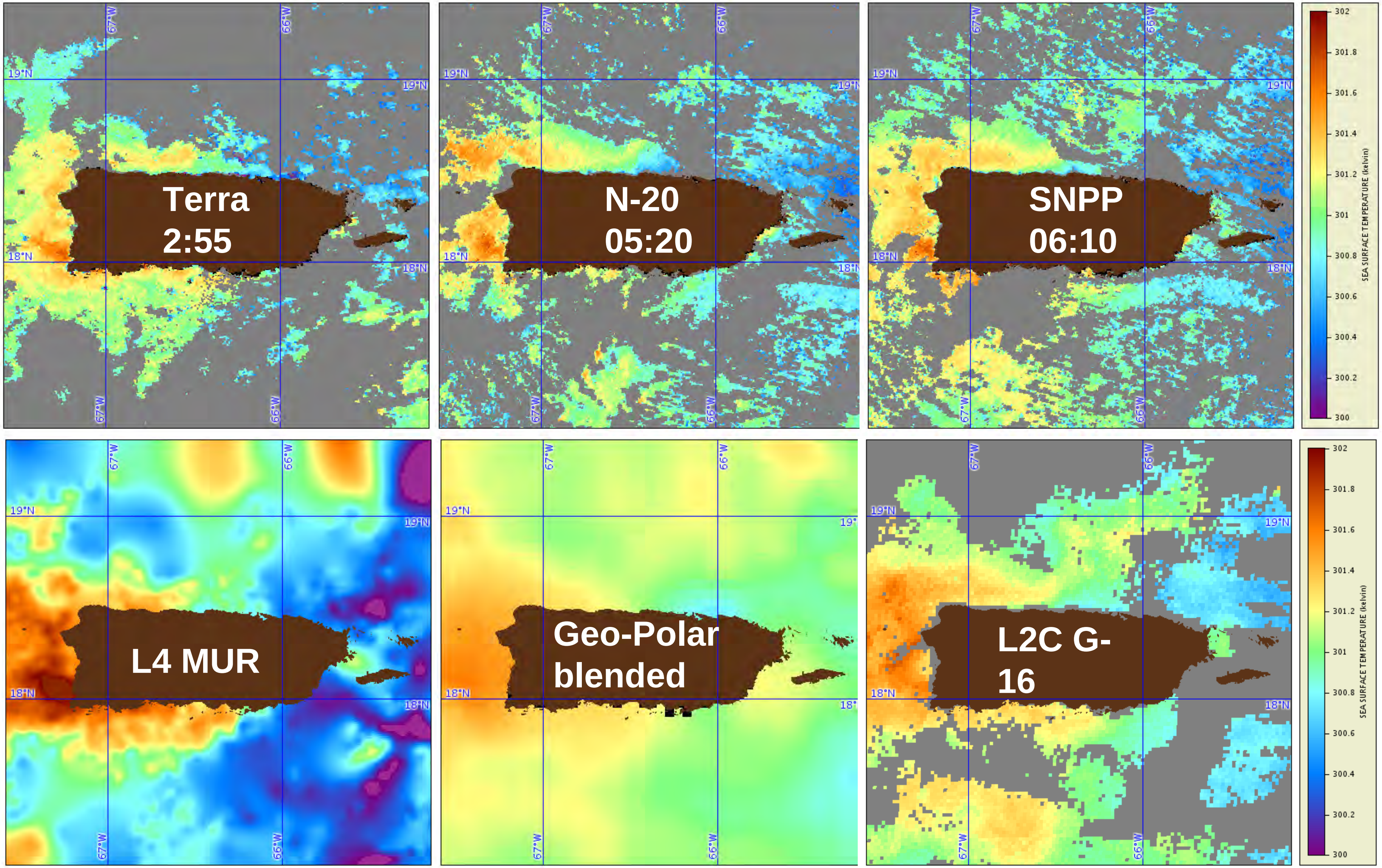
Is gap free reliable in cloud-obscured regions?
Example: Aleutian Island, June 7, 2018



Is high resolution claim in L4 products valid?
Example: Monterey Bay, June 12, 2018



Is high resolution claim in L4 products valid?
Example: Puerto Rico, June 24, 2018



L4 as a way to blend: Limitations

Customarily, L4 (analyses) products are employed to blend together data from different sensors, and create one sensor agnostic, reconciled SST.

The L4s are fundamentally different from L2/L3, in at least two respects:

- They degrade (smooth) the native sensor resolution (even where satellite SSTs are present);
- They create (model) new SSTs in L2/3 data voids, and often do not provide identification which pixels have been modeled.

Currently users face a dilemma to either

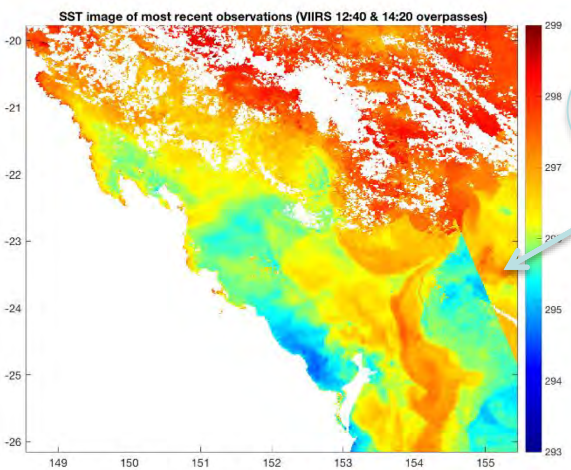
1. learn how to deal with huge, and ever growing, volumes of L2/3 data (how to obtain, read, process, reconcile and fuse those, often without full understanding of the error characteristics in the L2/3 data), or
2. use an L4 product, perhaps without realizing what data come from real observations (~30%, globally) and how much they were smoothed, and what data have been estimated/interpolated/filled from a climatology (~70%), and what is the quality of L4 SST and its feature resolution.

Possible Approaches to Collation

1. Mosaicking (keeping the most recent value)
2. Simple averaging
3. Weighted averaging (e.g. in inverse proportion to noise in SST)

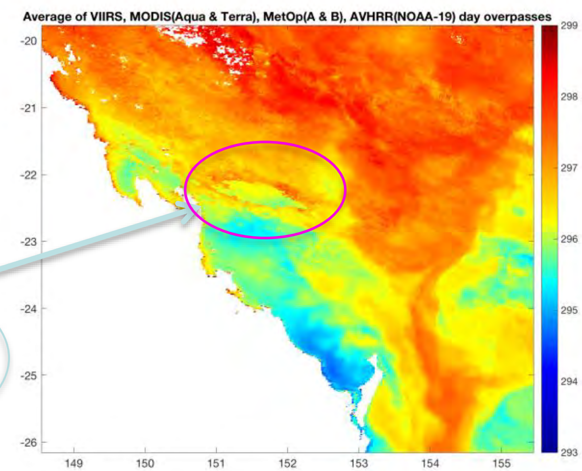
Potential problems with above approaches:

- Cross-sensor & overpass-to-overpass biases, which may be regional, view angle dependent, and variable in time;
- Residual cloud leakages in L2P/3U data

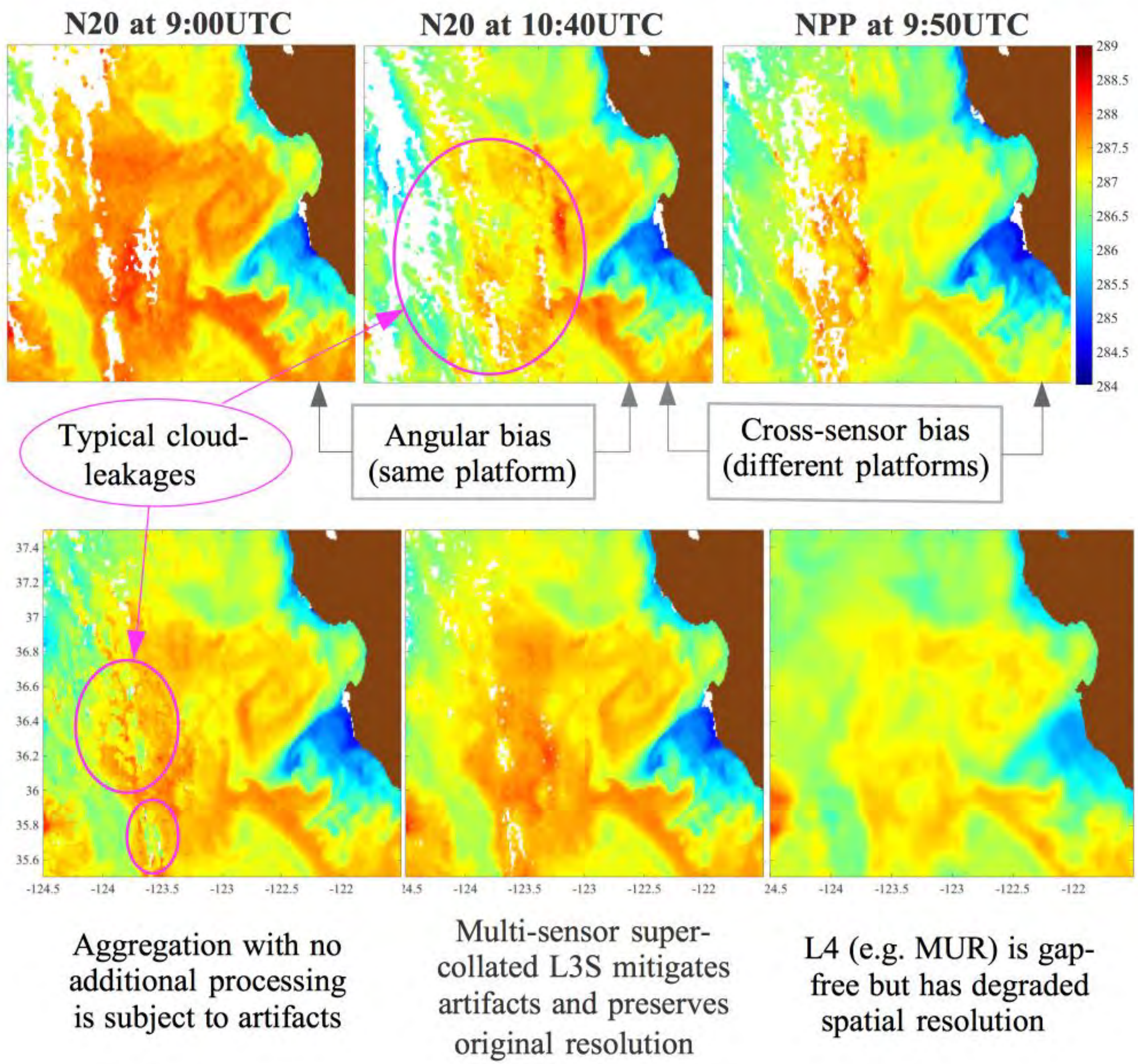


Artifact in "keeping the most recent" due to cross-sensor bias

Artifact in "averaging" due to cloud leakages



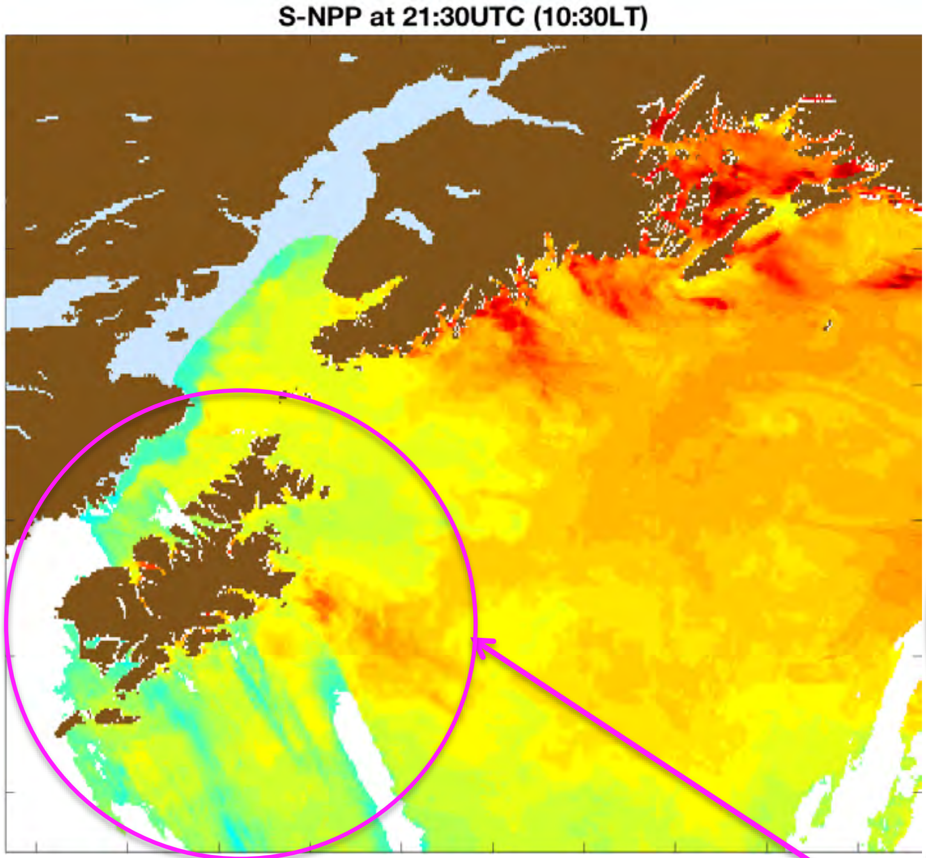
Aggregation without additional processing leads to artifacts in L3S



Current (Super) Collation Challenges

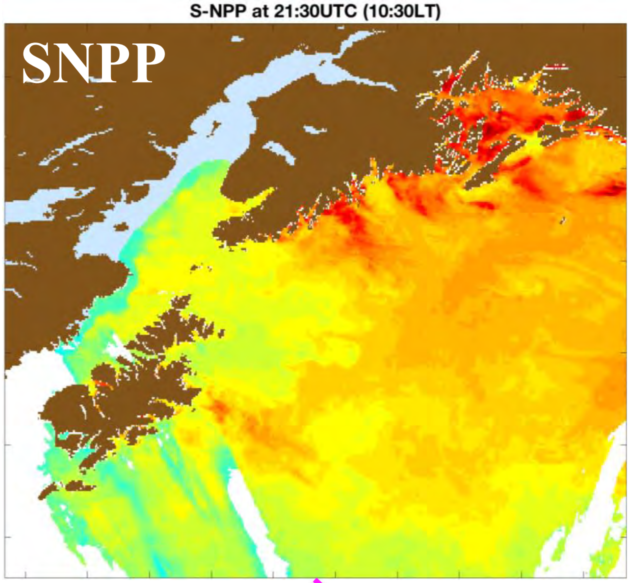
1. **Residual errors in the current L2P algorithms**
   - Cloud leakages
   - Angular dependencies
   - Cross-sensor biases
2. **Ice mask maybe suboptimal**
   - Currently, external ice mask is used in ACSPO (from CMC L4)
3. **L3Us to be collated, come from data of different sensors**
   - Different spatial resolution of original L2P (VIIRS/AVHRR/MODIS)
   - Different noise in L2P, which may be differently transformed into L3U
4. **Different acquisition time**
   - SST features move
   - SST may change due to diurnal cycle

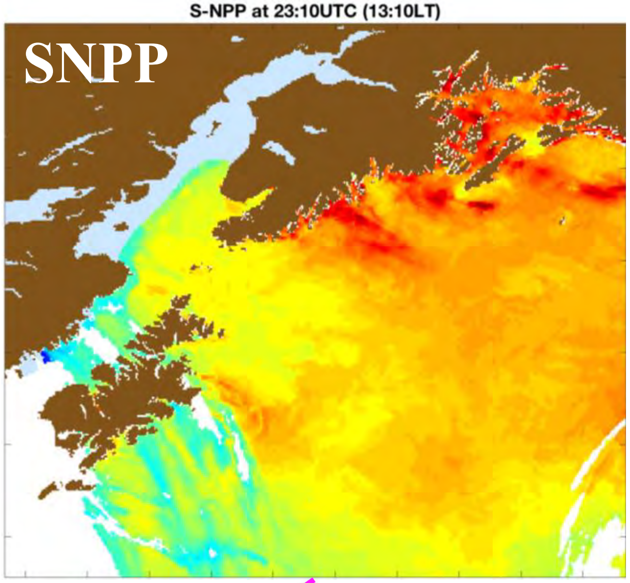
Residual Clouds in L2P: Some types are too difficult to detect

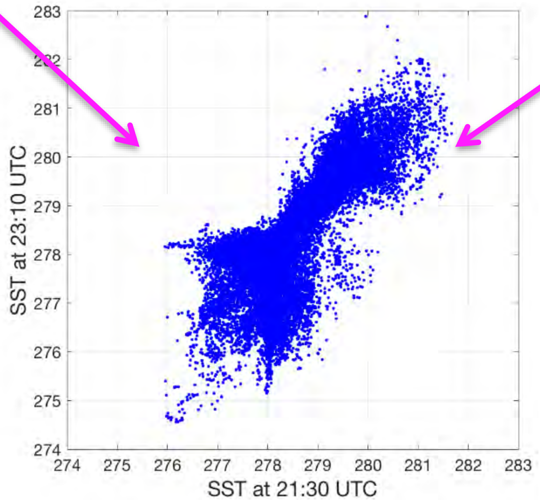


Some types of clouds (e.g. low cirrus) are very difficult to detect from individual L2P granules alone. They often remain undetected and affect SST retrievals

Additional Cloud Screening Using Multiple Passes:



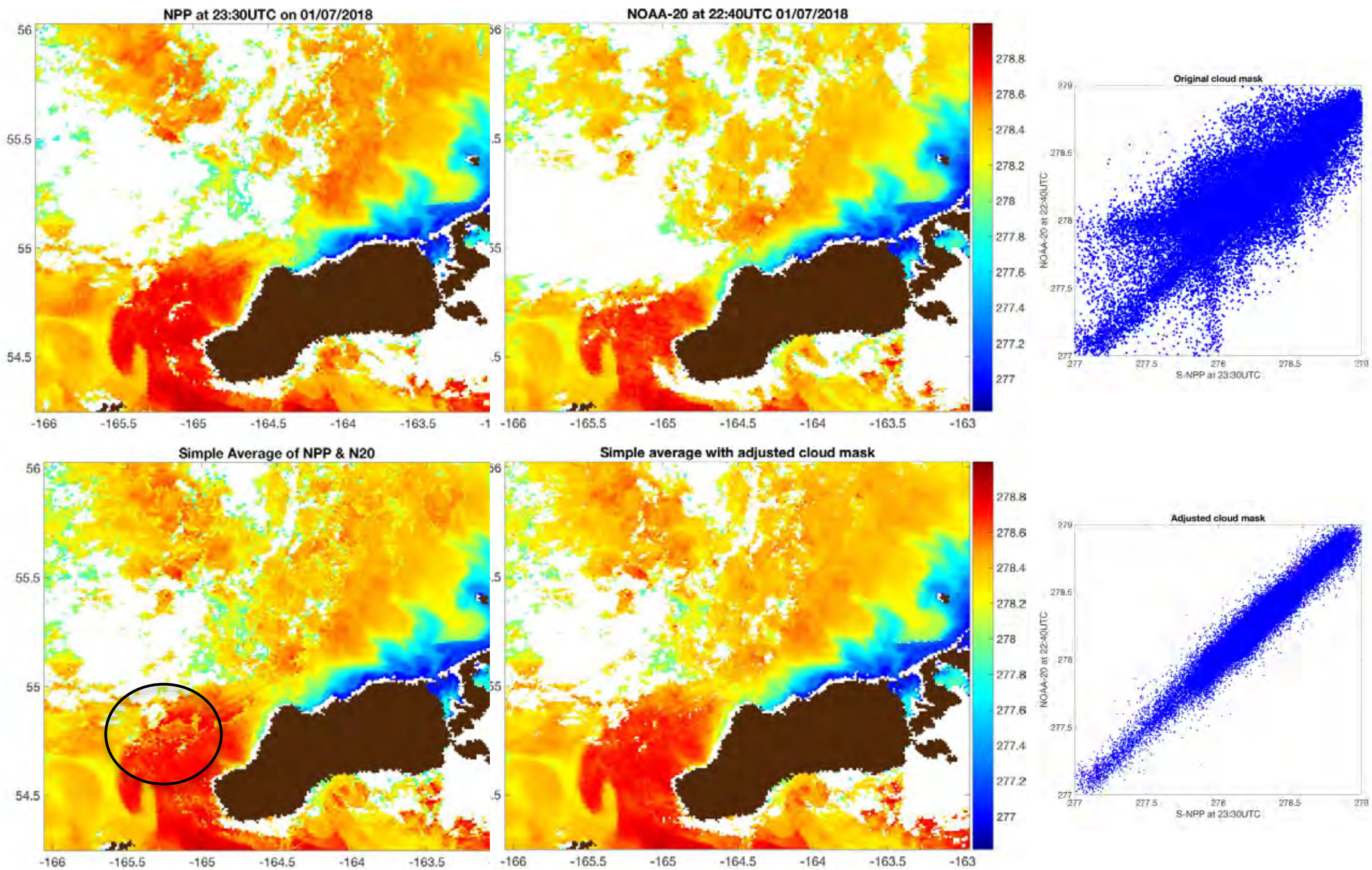




- Significant differences between the two overpasses likely come from residual cloud

- This consistency check is helpful when the pixel was identified by ACSPO mask as clear from (at least) two passes <u>and</u> at least one look was "truly clear"

Need for Additional Cloud Screening



Top row: Two daytime VIIRS overpasses (NPP @23:30UTC and N20 @22:40UTC), along with scatter plot of clear-sky SST values. Bottom row: Average of the two overpasses, using (left) original L2P cloud mask and (right) adjusted mask, obtained using temporal information (as explained below).

Towards Collated/Super-Collated: Initial Focus on residual cloud leakages

The focus of this presentation is on two aspects of the night-time collation:

1. hi-res compositing of L3U SST imagery (which come from L2P with various sensor-specific spatial resolutions);

2. minimization of cloud leakages.

The other issues affecting composite imagery, e.g. SST biases (which may be angular, regional, sensor- and overpass-specific, and may also vary in time), different overpass times, suboptimal ice mask, etc., are not analyzed here, and will be considered elsewhere.

Compositing Algorithm (Focus on Additional Cloud Screening)

Step 1: Compute average of the stack of SST images over clear sky domain, (initially, using ACSPO mask);

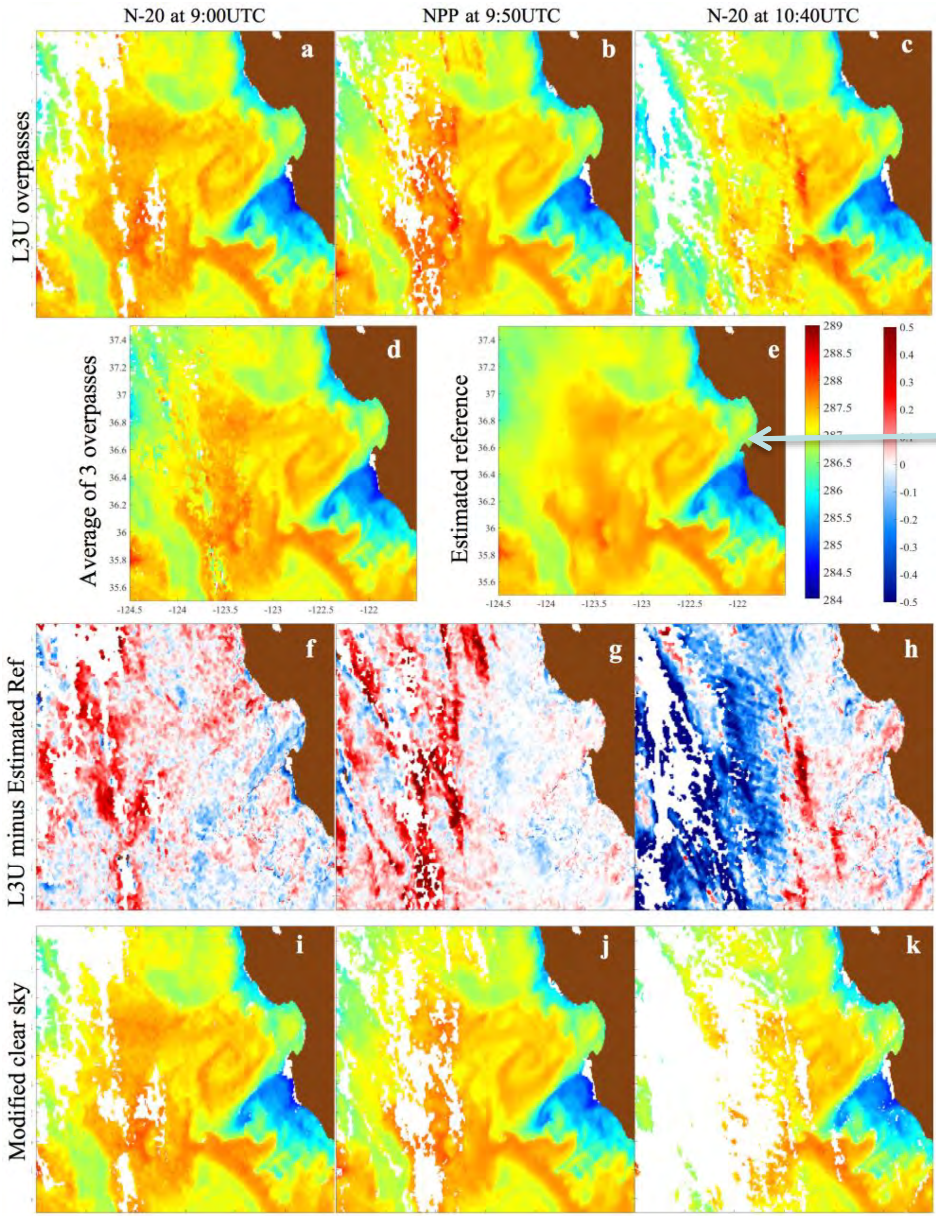
Step 2: Iteratively compute image pyramid, for a sequence of progressively spatially smoother (more blurred) $B_1, B_2, \ldots, B_k$ and corresponding hi-res features ("details") $D_1, D_2, \ldots, D_k$, using windowed averages with increasing spatial window size, w_k;

Step 3: Reconstruct the pyramid approximation as $F_k = B_k + D_1 + D_2 + \ldots + D_k$;

Step 4: Perform additional cloud screening per overpass, comparing last fused result F_k from step 3, with SST images T_t for each individual overpass. **This step removes residual cloud leakages, based on multi-sensor information, which was not present at the stage of L2P processing**;

Step 5: Repeat Steps 1-3 using modified clear-sky domain obtained in Step 4, for all available overpasses.

Compositing Algorithm: Cloud Mask modification



With ACSPO Mask

Multi-sensor reference (estimated by pyramid)

Individual SSTs compared to multi-sensor reference

Modified Mask

Obtaining multi-sensor reference via Image Pyramid

- To preserve the hi-res details of individual overpasses, we use a well-established technique of image processing, modified to address the cloud contamination problem present in satellite imagery.
- Hierarchical representation of the image such as Laplacian or wavelet image pyramid has been successfully used for decades for image morphing, blending and stitching into a seamless image mosaic.
- Image pyramids can be used to extract image features at multiple scales, and then create a high fidelity composite image from a set of images, parts of which can have different scales.

Image Pyramid (background)

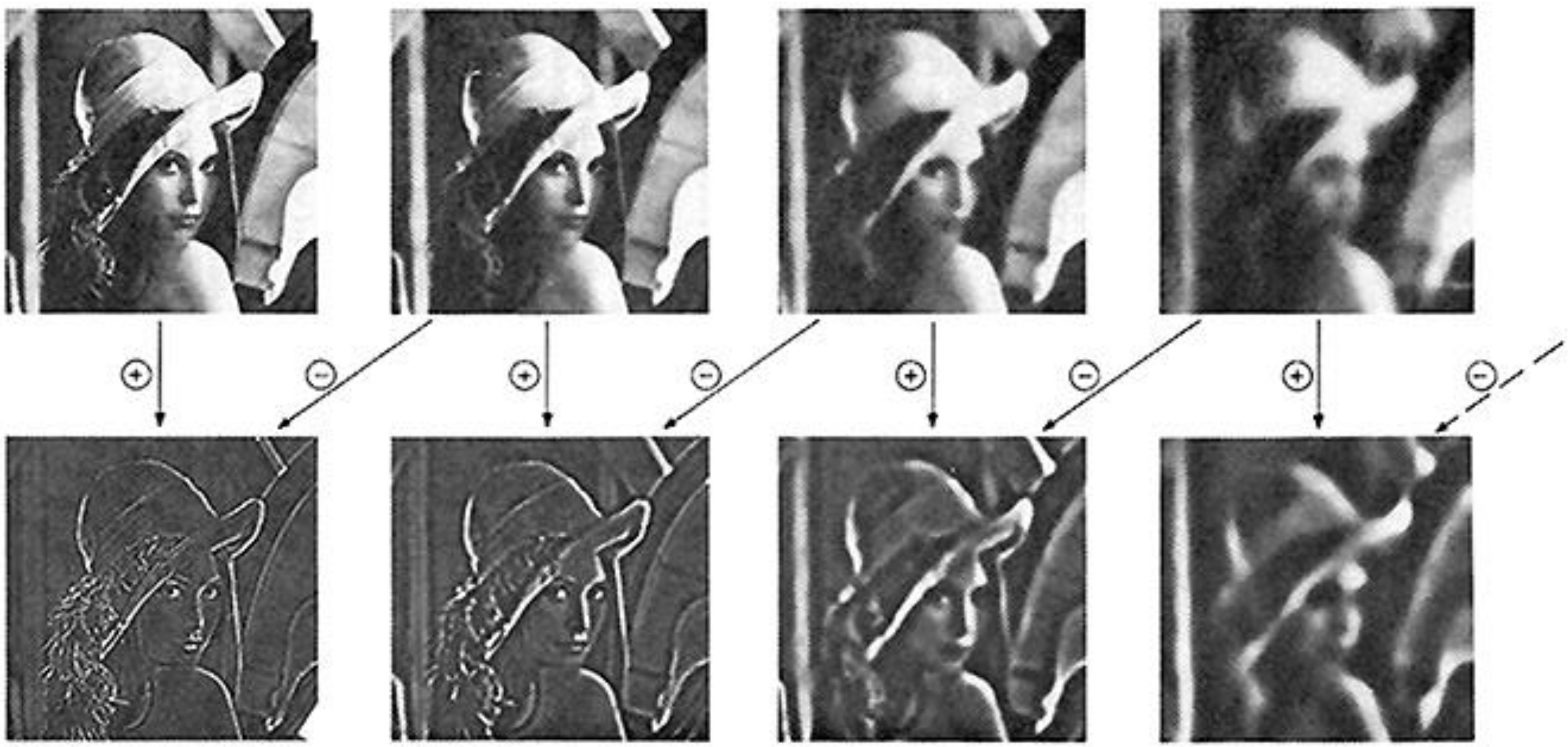


Fig 5. First four levels of the Gaussian and Laplacian pyramid. Gaussian images, upper row, were obtainedby expanding pyramid arrays (Fig. 4) through Gaussian interpolation. Each level of the Laplacian pyramid is the difference between the corresponding and next higher levels of the Gaussian pyramid.

Reprinted from: Burt, P., and Adelson, T, The Laplacian Pyramid as a Compact Image Code, *IEEE Trans. Comm.* **9** (*4*): 532–540 (1983).

IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. COM-31, NO. 4, APRIL 1983

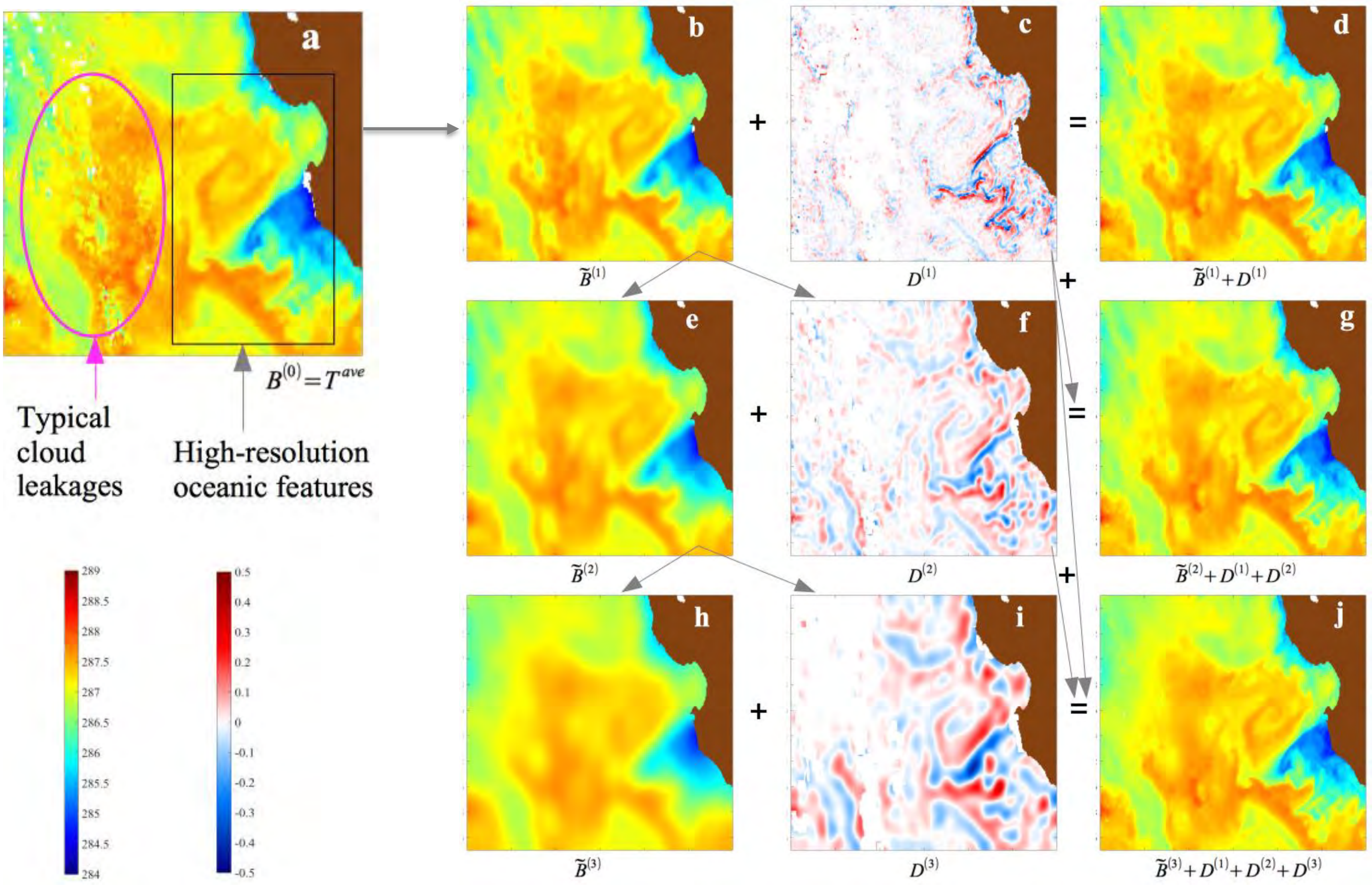
Compositing Algorithm: Modified Image Pyramid

The process of decomposing the image into low-res (blurred) image $B^{(k)}$ and hi-res feature image $D^{(k)}$ is a more involved, than just blurring and subtracting of the conventional image pyramid construction.

The hi-res features that correspond to artifacts due to cloud leakages or retrieval biases need to be identified and removed so that the resultant image $D^{(k)}$ has only oceanic features, present at least in one of available overpasses.

The decision of accepting or rejecting the value $B^{(0)}$-$B^{(1)}$ at each pixel, can be done via some (local) image similarity index.

Compositing Algorithm: Modified Image Pyramid (Illustration)



Compositing Details
Using Structural Similarity Index

The SSIM index has been successfully used in image processing for quality assessment.

It combines 3 important factors:

- similarity of local intensities (represented by mean in the window);
- contrast (expressed by standard deviation); and
- structure (represented by cross-covariance).

$$\mathrm{SSIM}(\delta_t, \delta_c) = \frac{(2\mu_t\mu_c + C_0)(2\sigma_{t,c} + C_1)}{(\mu_t^2 + \mu_c^2 + C_0)(\sigma_t^2 + \sigma_c^2 + C_1)}$$

Journals & Magazines > IEEE Transactions on Image Pr... > Volume: 13 Issue: 4

Image quality assessment: from error visibility to structural similarity

4 Author(s) Zhou Wang ; A.C. Bovik ; H.R. Sheikh ; E.P. Simoncelli **View All Authors**

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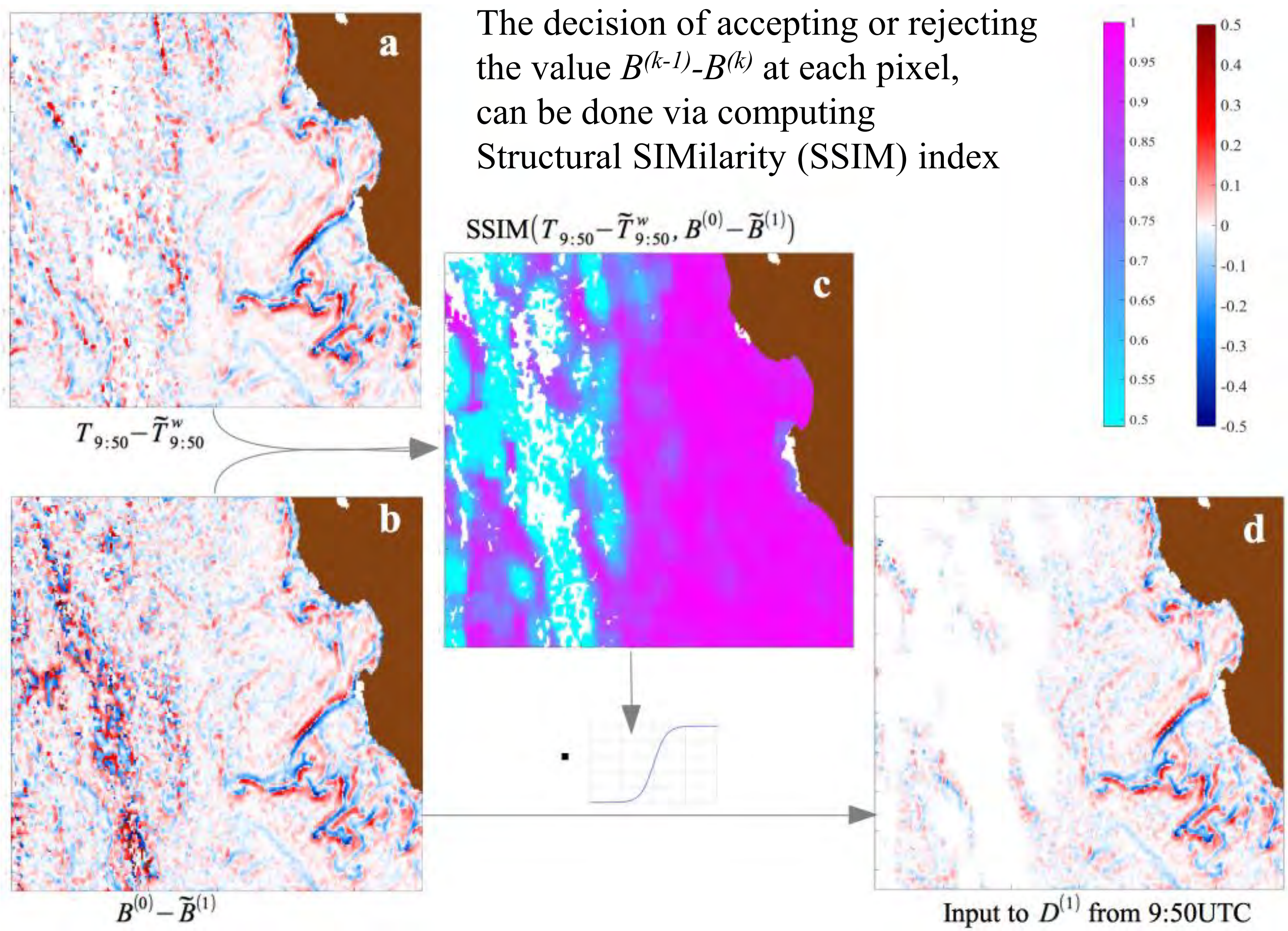
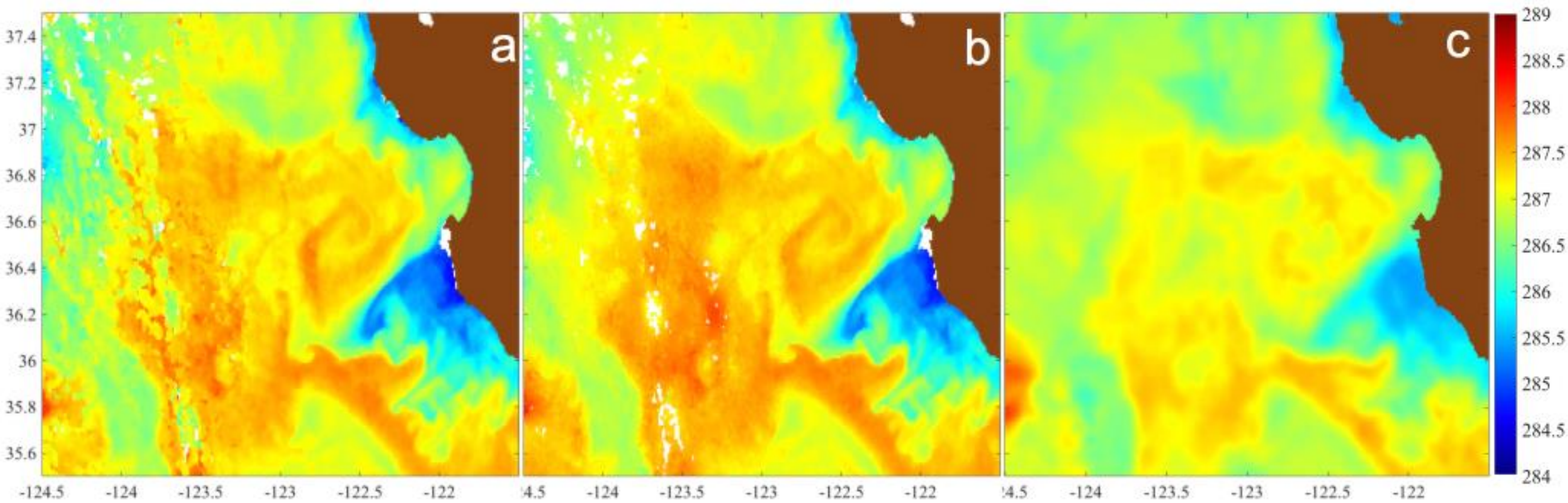
Overview of the Compositing Algorithm: Compositing Details

The decision of accepting or rejecting the value $B^{(k-1)}$-$B^{(k)}$ at each pixel, can be done via computing Structural SIMilarity (SSIM) index



Final Step: L3S



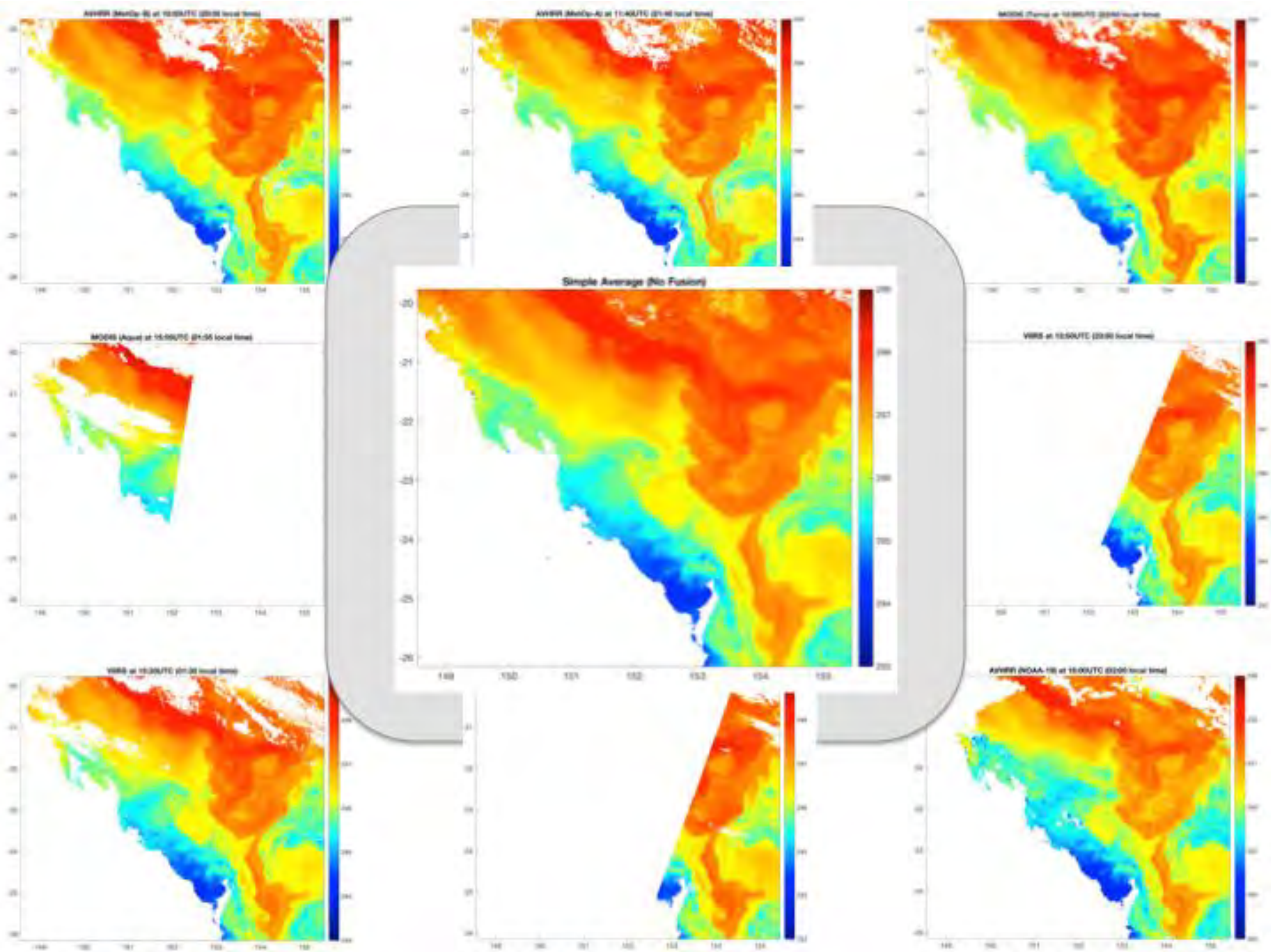
SST data in Monterey Bay on 1 January 2019.

a) Simple average using modified mask;

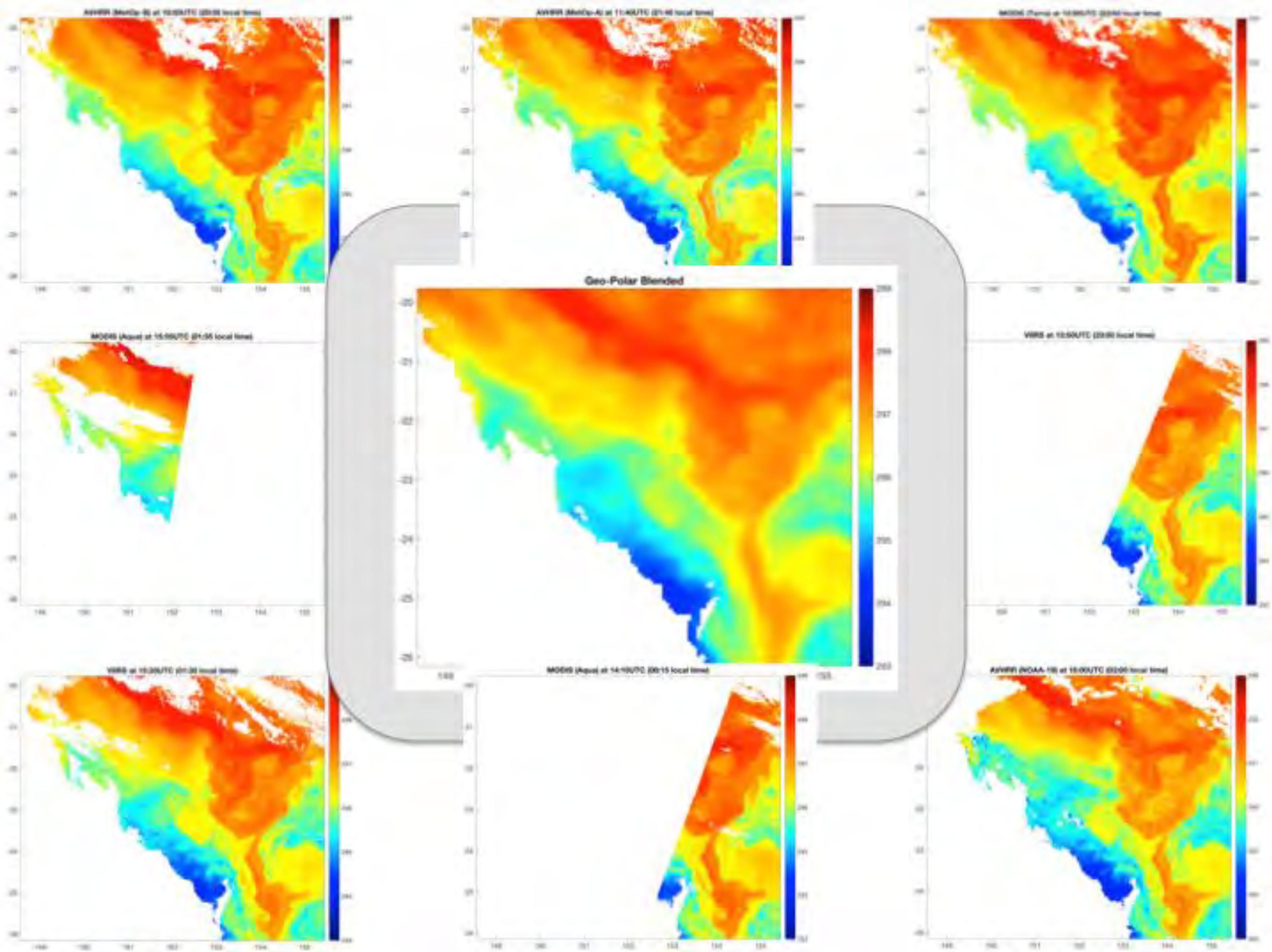
b) ACSPO 0.02° super-collated L3S;

c) JPL L4 MUR SST product (shown for comparison).

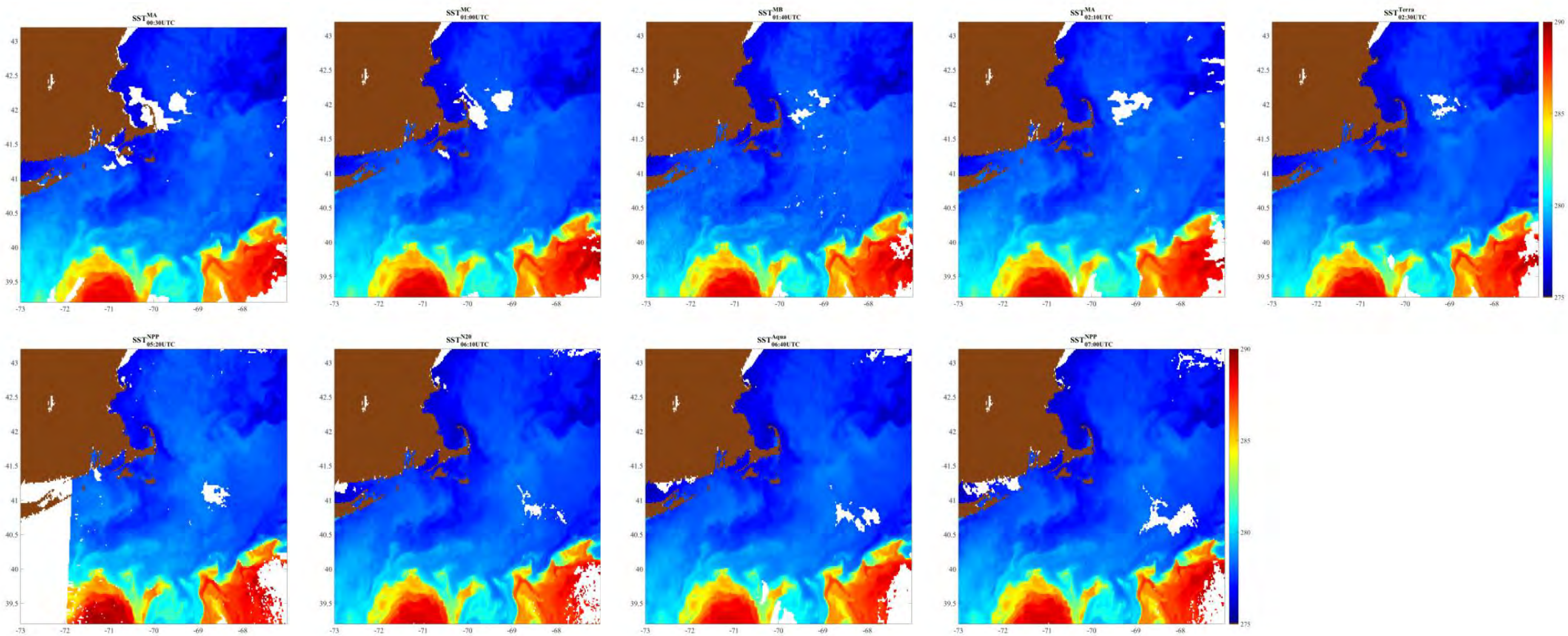
Great Barrier Reef 09/07/2017



Comparison with L4 (geo-polar blended)



A Rare Case of Multiple Clear-Sky Looks

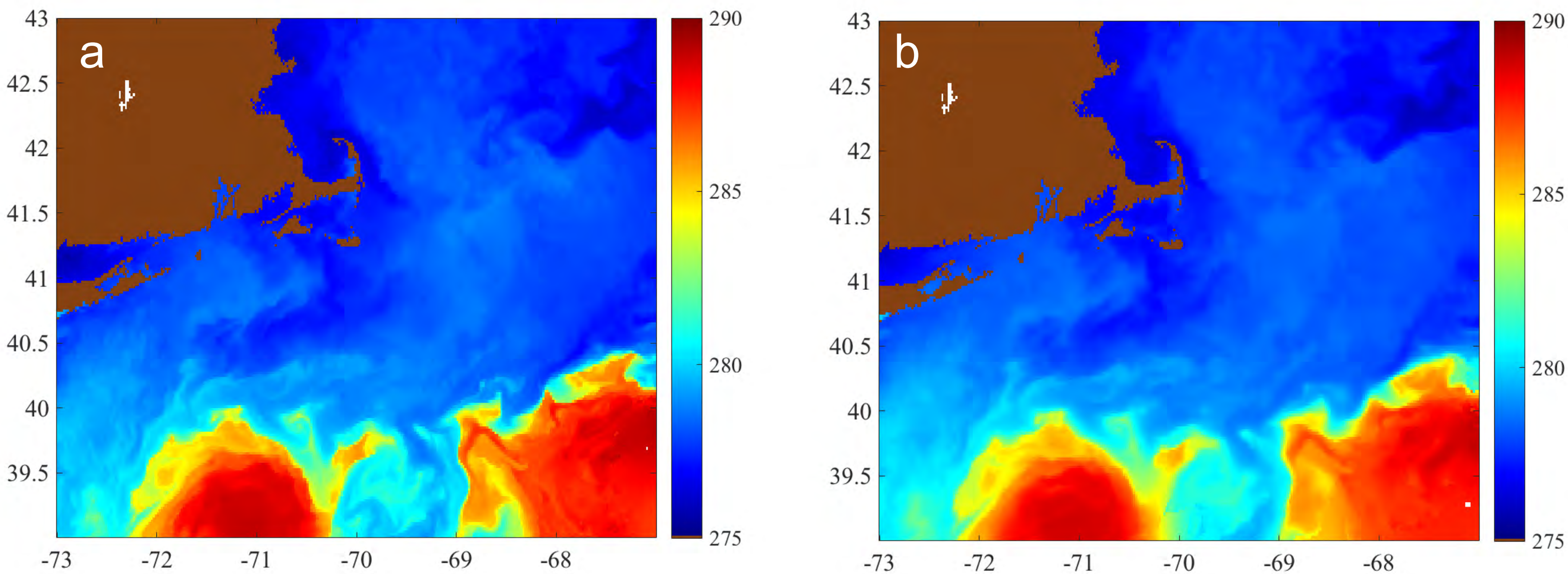


Nighttime SST over the Georges Bank/Nantucket Shoals on 20 March 2019 (Local time=UTC–5 hours):

Evening Looks: MetOp-A/AVHRR @00:30UTC, MetOp-C/AVHRR @01:00UTC, Metop-B/AVHRR @01:40UTC, MetOp-A/AVHRR @02:10UTC, Terra/MODIS @02:30UTC

Midnight-to-2am Looks: NPP/VIIRS @05:20UTC, N20/VIIRS @06:10UTC, Aqua/MODIS @06:40UTC, NPP/VIIRS @07:00UTC

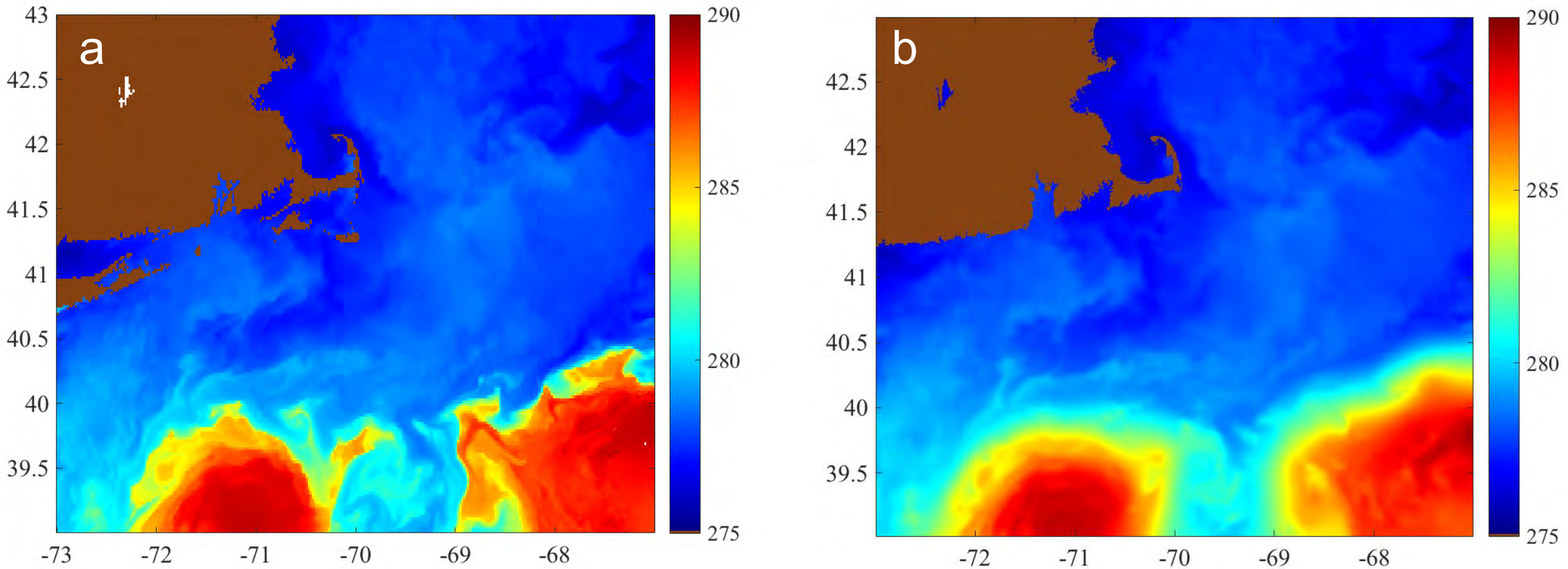
A Rare Case of Multiple Clear-Sky Looks



a) ACSPO 0.02° L3S based on ACSPO L3Us from 4 midnight-2am overpasses (NPP/VIIRS @05:20UTC, N20/VIIRS @06:10UTC, Aqua/MODIS @06:40UTC, NPP/VIIRS @07:00UTC)

b) ACSPO 0.02° L3S based on ACSPO L3Us from 5 evening overpasses (MetOp-A/AVHRR @00:30UTC, MetOp-C/AVHRR @01:00UTC, Metop-B/AVHRR @01:40UTC, MetOp-A/AVHRR @02:10UTC, Terra/MODIS @02:30UTC)

L3S versus L4: Example of Missing Features in L4 due to Conservative Mask in L2P MUR inputs



a) ACSPO 0.02° L3S based on ACSPO L3Us from 4 midnight-2am overpasses;

b) Corresponding 1km JPL MUR L4 SST. (Note that the ACSPO and MUR SST products are shown with their own land-sea masks).

Over-screening clear-sky domain in dynamic areas is typical in L2P/3U products (which was likely the case with the JPL MODIS & NAVO AVHRR L2Ps, used in MUR). This may lead to degraded feature resolution in L4, especially in dynamic areas, exactly where its hi-res potential is needed most for users.

Conclusion

We have introduced an approach to hi-res collation of the SST imagery.

The algorithm is based on a modified image pyramid algorithm, employed to aggregate SST imagery with various sensor-specific spatial resolutions, while additionally checking for residual cloud contamination.

The focus at this stage is minimization of cloud leakages.

The remaining challenges of the multi-sensor data fusion include:

- minimizing sensor-specific residual biases (angular, regional, seasonal, and cross-sensor);
- proper handling of the effect of different spatial resolutions and noise levels in the original L2P data gridded into un-collated L3Us;
- and mitigating the varying acquisition time for different satellite images (leading to feature displacement, and SST differences due to the diurnal cycle).

Acknowledgement

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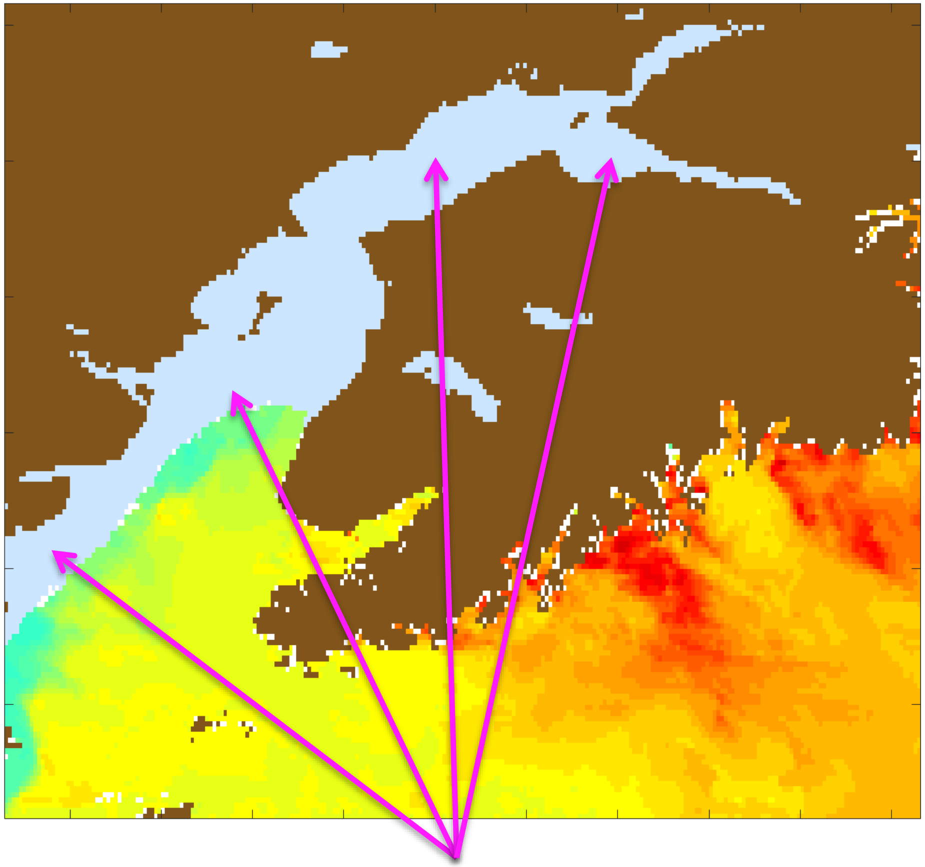
- NOAA Ocean Remote Sensing (ORS; Paul DiGiacomo and Marilyn Yuen-Murphy, Program Managers).

Thanks go to our SST Colleagues (Boris Petrenko, John Sapper, NOAA, USA; Helen Beggs and Chris Griffin, BoM, Australia) for helpful discussions and feedback.

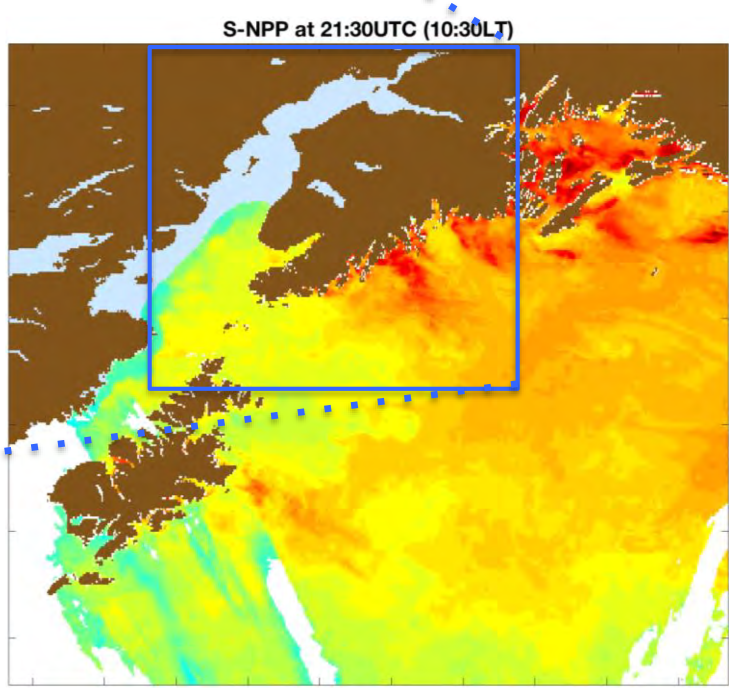
Backup slides

ACSPO Uses External Ice Mask (CMC daily 0.1º): Example SNPP Daytime



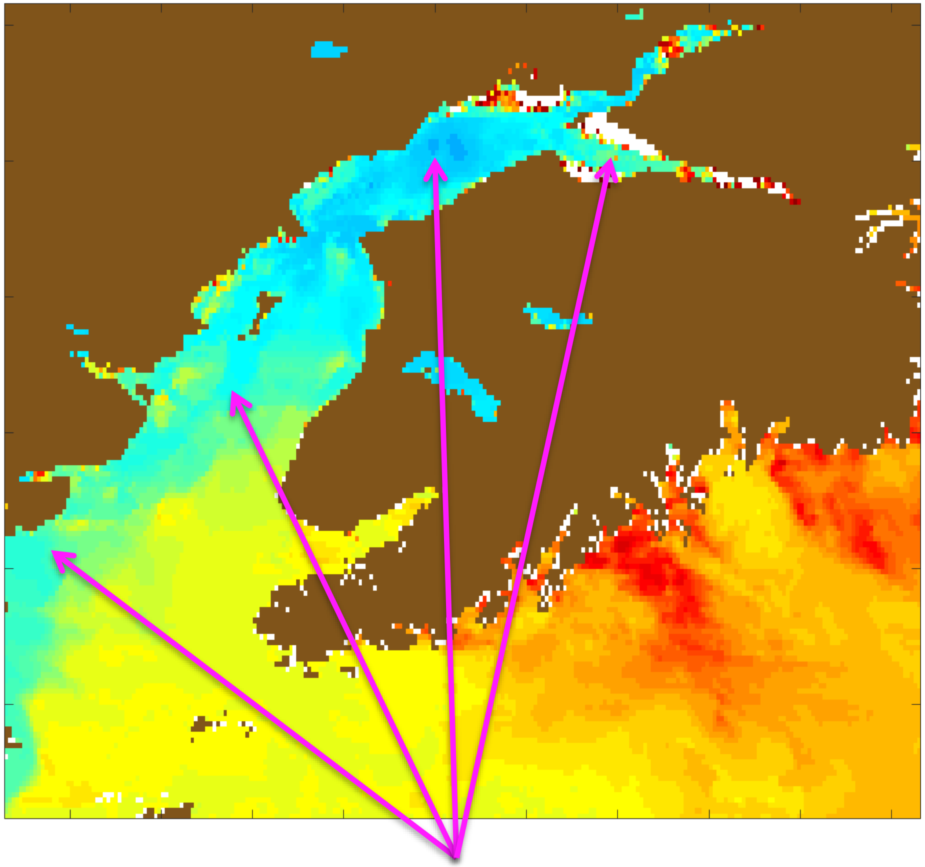
Cook Inlet activities include:

- Commercial fishing
- Oil and gas development
- Shipping traffic
- Tourism



- Currently ACSPO uses Canadian Met Centre (CMC) ice extent mask
- It has lower spatial resolution and tends to be on a conservative side

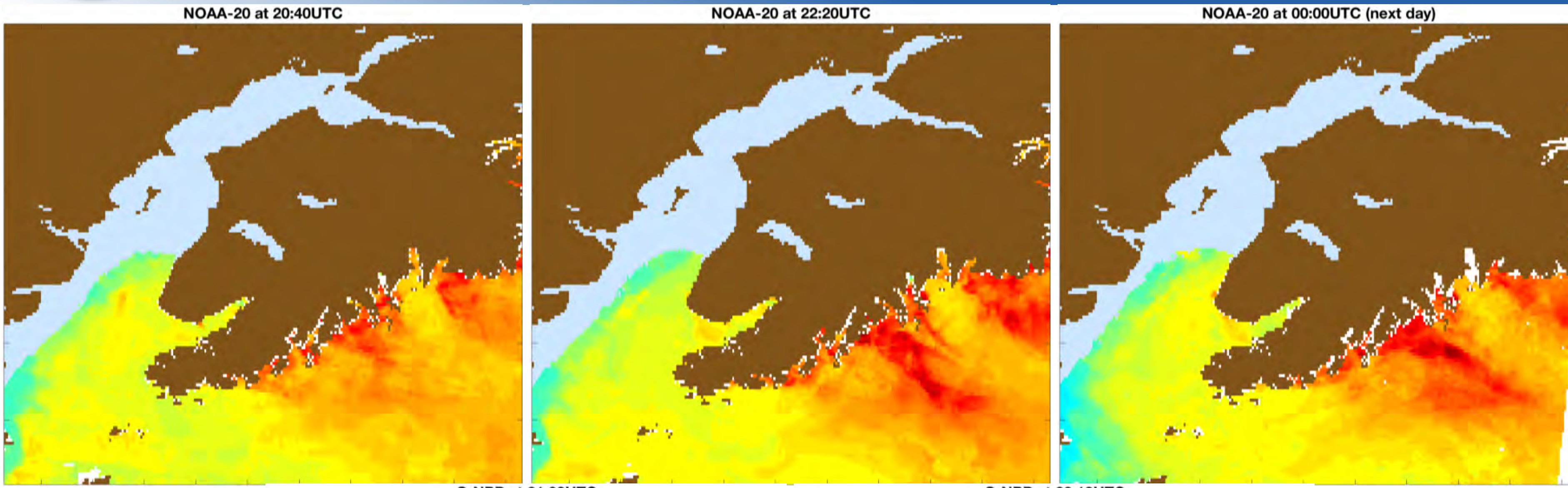
SST Field without CMC Ice Mask Overlaid: Example SNPP Daytime



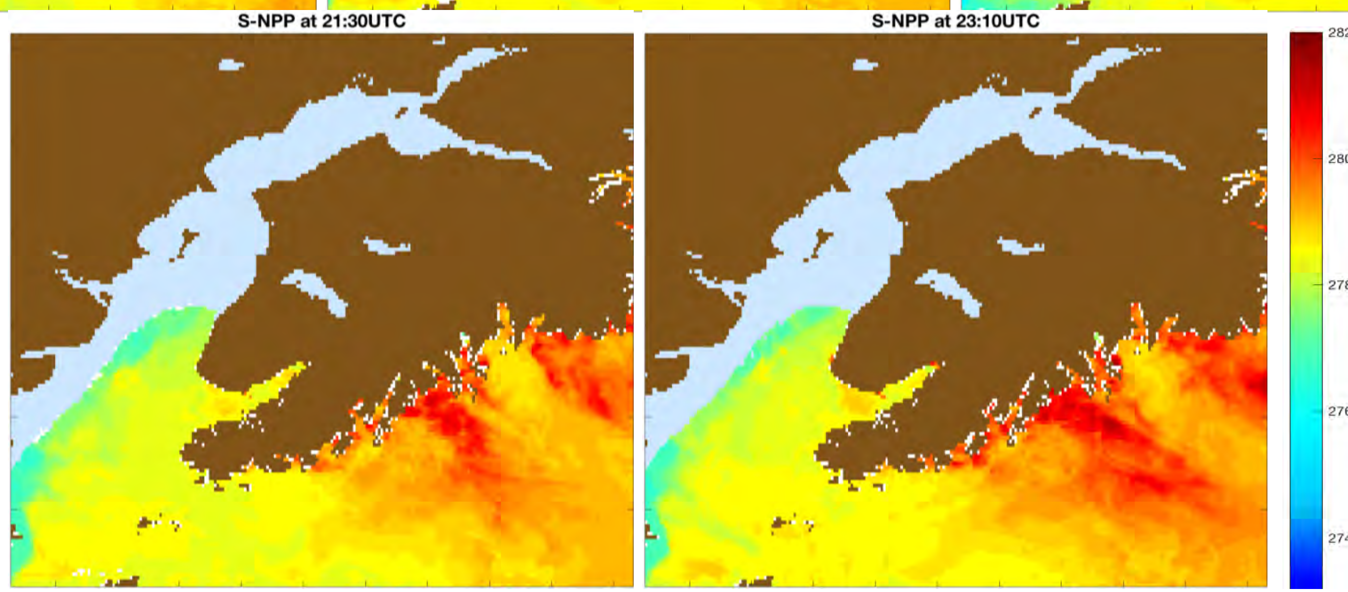
- We will not develop "ACSPO ice mask"
- However, we may consider an "ice mask correction" and restoral to SST
- We may also explore other ice masks

In fact, the Cook Inlet was ice-free on 14 April 2018

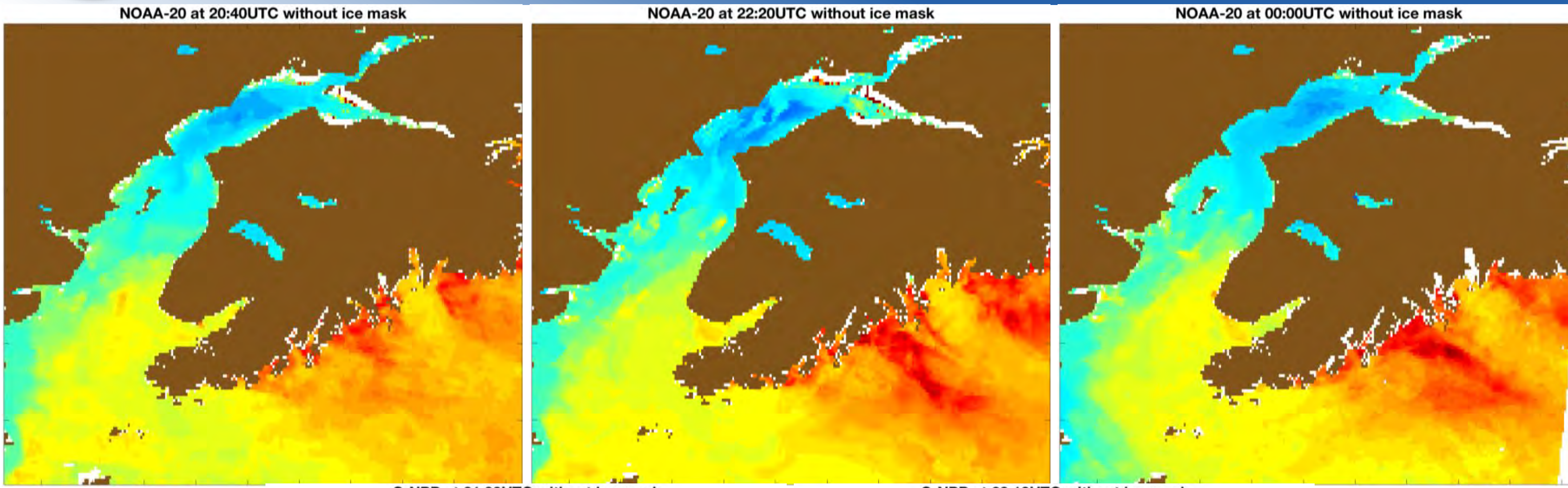
Daytime VIIRS SST w/CMC Ice Mask overlaid



Cook Inlet on 14 Apr 2018 with CMC Ice Mask overlaid



Daytime VIIRS SST Without CMC Ice Mask overlaid



In fact, Cook Inlet on 14 Apr 2018 was Ice-Free