Assessment of Suomi-NPP VIIRS Sea Surface Temperature retrievals.

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February 24, 2013

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Abstract

The results of analyses of the first several months of on-orbit measurements of the VIIRS on the Suomi-NPP satellite used to derive skin Sea-Surface Temperature (SST) are presented. The analyses are largely based on our experience with AVHRR and MODIS SST retrievals and include assessments of the spatial and temporal characteristics of the uncertainties in the SSTs that are derived using the operational Integrated Data Processing Segment (IDPS) algorithms. We have also developed alternative algorithmic approaches to overcome some of the shortcomings of the operational processing. We conclude that the VIIRS measurements are capable of matching and improving upon the accuracies of SSTs from the MODIS's on *Terra* and *Aqua*, and that the VIIRS SSTs have the potential to contribute to the extension of the satellite-derived Climate Data Records of SST into the future.

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I. EXECUTIVE SUMMARY

We report on our initial analysis of the integrity of the VIIRS measurements, on the accuracies of the derived skin Sea-Surface Temperatures (SST), and their potential to contribute to the Climate Data Record of SST. These analyses are based on less than one-year of on-orbit data. Our approach has been to assess the characteristics of the operational Integrated Data Processing Segment (IDPS) algorithms and when inadequacies were identified, to derive alternative processing algorithms. Thus, we have addressed the initial program directives to assess the suitability of the IDPS products as the basis for Climate Data Records (CDRs) though interactions with the wider VIIRS SST community which includes teams at NOAA, led by A. Ignatov, the Navy, led by D. May, and our group at RSMAS. Together this wider team has explored the official IDPS product suite, together with a group of alternative SST algorithms, including cloud identification, and quality determination approaches. Our conclusions are summarized here and discussed in greater detail in the following sections.

Our approach has been to assess the performance of VIIRS in producing accurate SSTs has used a series of analyses:

a) Assessing the accuracies of the top-of atmosphere brightness temperatures measured by VIIRS, and for this we use atmospheric radiative transfer simulations
b) Assessing the spatial characteristics of the VIIRS SST fields by comparison with global SSTs derived from other sensors and represented in analysis fields
c) Assessing the accuracies of the VIIRS skin SST retrievals in conditions that have passed a series of cloud screening tests and other quality tests, and this is done by comparing the VIIRS SSTs at the level of individual pixels, of small arrays of adjacent pixels with the subsurface measurements from drifting or moored buoys
d) Assessing the accuracies of the VIIRS skin SST retrievals, as in c) but using ship based infrared radiometers which measure the infrared emission from the ocean and atmosphere leading to a measurement of the skin SST. These instruments have NIST-traceable calibration and are therefore the basis of the generation of CDRs of SST

Our main findings are summarized as:

- Infrared bands of VIIRS are very “clean” and are lacking many of the instrumental artifacts that were present in the initial MODIS measurements
- Spatial and temporal distributions of TOA brightness temperature and uncertainties in derived SSTs tally well with those derived from atmospheric radiative transfer equation simulations
- Validation using other satellite-derived SSTs, analysis fields, ship-board radiometers and buoys indicate the VIIRS SSTs are of good accuracy and have the potential to make significant contribution to SST CDRs

- Using standard VIIRS Cloud Mask (VCM) does not give best results; a Decision Tree approach based on experience with MODIS, with thresholds derived for VIIRS Channels, gives better results
- 11 – 12 µm (day and night) SST retrievals show accuracies comparable to those of MODIS
- 3.75 – 11 – 12 µm (night) SST retrievals show improved accuracies
- 3.75 – 4.05 µm (night) SST retrievals are more accurate and appear to be better able to account for dust aerosols; there is scope for further improvement (new developmental algorithm)

The main findings are tabulated below in headings relative to the mission elements.

1. High-Performance Sensor	• VIIRS Characterization appears to be good • On-orbit calibration appears to be good • Instrumental artifacts much smaller than for MODIS
2. Computational and Data Infrastructure	• Reprocessing not currently supported, but will be necessary • Access to data through CLASS unwieldy • Default granule size too small and unwieldy, Miami uses 4X granules from CLASS
3. Algorithms	• Algorithms are based on heritage formulations, but coefficient determination can be improved • VCM is sub-optimal; Miami Decision Tree cloud screening gives improvements
4. Calibration	• No major issues identified in the procedure
5. Maneuvers	• Pitch maneuver - done in February 2012, repeat if necessary?
6. Reprocessing	• Reprocessing currently not planned, but vital for CDR generation, needed for correction of current SDR artifacts
7. Validation	• Based on: radiative transfer simulations, satellite skin SSTs, skin SSTs from ship radiometers, subsurface SSTs from buoys.
8. *In situ* Data	• Continuing: ship radiometers & buoys
9. User Tools	• Anticipated take advantage of GHRSST (RDACs and GDAC)

In the following sections we present some of the results of the analyses on which these conclusions are based. Many of the analyses are based on our experience with AVHRR and MODIS SSTs.

The assessment of SST performance will improve as data are accumulated in the coming years..

II. INTRODUCTION

A. Background

Sea-Surface Temperature (SST) is a critically important parameter in the climate system, and has been declared by the Committee on Earth Observation Satellites (CEOS) and the World Climate Research Program (WCRP) to be an Essential Climate Variable (ECV). SST has an advantage over other ECVs in that temperature is one of seven SI base quantities, and as such can be traced to reference standards. This is great a advantage in generating Climate Data Records (CDRs), the concept of which was formally introduced in a report of the National Academy of Sciences (NRC, 2004) as being "*a data set designed to enable study and assessment of long-term climate change, with 'long-term' meaning year-to-year and decade-to-decade change. Climate research often involves the detection of small changes against a background of intense, short-term variations…. The production of CDRs requires repeated analysis and refinement of long-term data sets, usually from multiple data sources*." The report emphasized the need for "Data Stability," reasoning that "*because natural signals are often small, it is difficult to ascribe particular events or processes to climate change…..* [so that] *long-term, high-quality measurements are needed to discern subtle shifts in Earth's climate. Such measurements require an observing strategy emphasizing a strong commitment to maintaining data quality and minimizing gaps in coverage*." Because of the global coverage provided by polar-orbiting earth-observation satellites, satellite-derived SSTs are seen as the basis of CDRs. This requires the convincing determination of the uncertainty characteristics of satellite SST retrievals from a long time series of measurements taken by a sequence of satellite radiometers, the most recent of which is VIIRS.

The heritage sensor for VIIRS is MODIS, with VIIRS having a sub-set of MODIS bands, including having four of the five MODIS bands that are used for the derivation of skin SST. Because of the influence of reflected and scattered solar radiation, measurements of satellite radiometers taken in the mid-infrared atmospheric transmission window cannot be used in the daytime part of each orbit. The standard atmospheric correction algorithm used in both day and night conditions is therefore based on the measurements in the 10-13μm atmospheric transmission window, and the form of the algorithm is derived from that used for MODIS and AVHRR and is referred to the as the Non-Linear SST (NLSST; Walton et al., 1998):

$$SST = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{12}) T_{sfc} + a_3 (T_{11} - T_{12})(\sec(\theta) - 1) \quad (1)$$

where a_0, a_1, a_2, a_3 are coefficients, T_{11} is the brightness temperature measured in the band centered near $\lambda = 11$ μm, T_{12} is the brightness temperature measured in the band centered near $\lambda = 12$ μm. T_{sfc} is a first guess or climatological SST that scales the coefficient multiplying the T_{11}-T_{12} brightness temperature difference to account for the differing distribution of atmospheric water vapor that is correlated with the SST. θ is the sensor zenith angle and this term compensates for the increasing path length when the scan is away from nadir.

The MODIS night-time algorithm, based on measurements close to λ = 4μm, is

$$SST_4 = a_0 + a_1 T_{3.9} + a_2 (T_{3.9} - T_{4.0}) + a_3 (\sec(\theta) - 1) \quad (2)$$

However, the MODIS band at λ=3.95μm is missing from VIIRS and so a similar algorithm using the VIIRS band at λ=3.7μm is being developed.

The coefficients are different for each algorithm and for each instrument as the relative spectral response functions are different for each sensor (Figure 1).

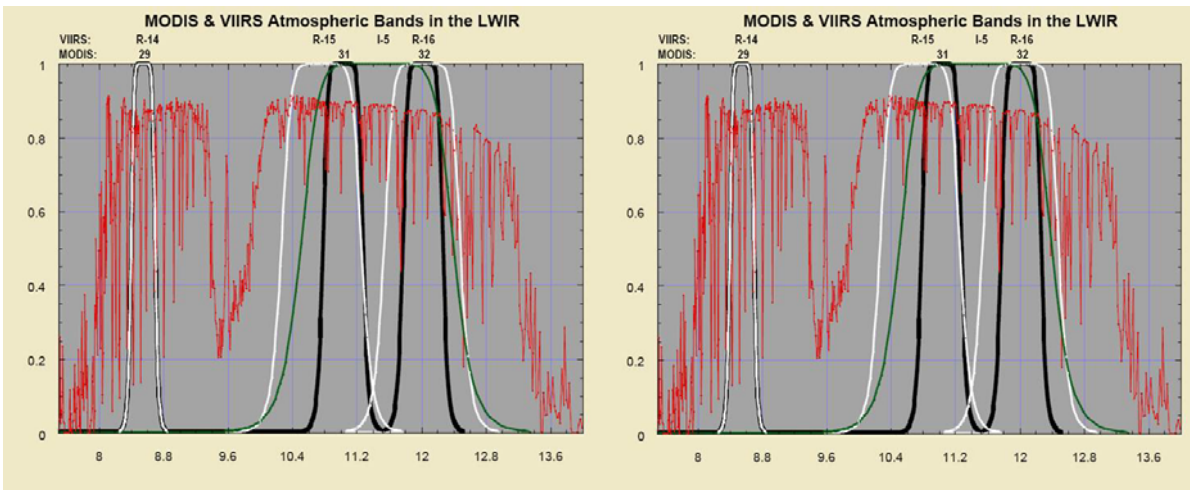


Figure 1. Relative spectral response (RSR) functions for the infrared bands used for SST retrieval for MODIS (black) and VIIRS (white). The green lines are the broad-band RSR functions of the VIIRS imaging bands, and the red is the atmospheric transmission spectrum for vertical propagation through a cloud-free standard atmosphere. The x-axis is wavelength in μm.

B. Science Team Effort

Our approach has been to assess the performance of VIIRS in producing accurate SSTs has used a series of analyses:

a) Assessing the accuracies of the top-of atmosphere brightness temperatures measured by VIIRS, and for this we use atmospheric radiative transfer simulations

b) Assessing the spatial characteristics of the VIIRS SST fields by comparison with global SSTs derived from other sensors and represented in analysis fields

c) Assessing the accuracies of the VIIRS skin SST retrievals in conditions that have passed a series of cloud screening tests and other quality tests, and this is done by comparing the VIIRS SSTs at the level of individual pixels, of small arrays of adjacent pixels with the subsurface measurements for from drifting or moored buoys

d) Assessing the accuracies of the VIIRS skin SST retrievals, as in c) but using ship based infrared radiometers which measure the infrared emission from the ocean and atmosphere leading to a measurement of the skin SST. These instruments have NIST-traceable

calibration and are therefore the basis of the generation of CDRs of SST (Minnett and Corlett, 2012).

Our efforts are coordinated with those being led by Dr. Alexander Ignatov of NOAA/NESDIS/ STAR, and with Dr Doug May of the Naval Oceanographic Office. While their priorities have been focused on the utility of operational products, ours have been more directed towards assessing the potential of the operational (IDPS) algorithms to provide SSTs suitable to extend the NASA CDR into the future; when shortcomings in the operational approach are identified, to determine and recommend improvements that will lead to CDR quality retrievals.

The standard IDPS atmospheric correction algorithms are

$$SST = a_0 + a_1 T_{11} + a_2 (T_{11} - T_{12}) RSST + a_3 (T_{11} - T_{12})(\sec(\theta) - 1) \quad (3)$$

where a_0, a_1, a_2, a_3 are coefficients derived by regression analysis, T_{11} is the measured brightness temperature at 11 µm (VIIRS band M15), T_{12} is the measured brightness temperature at 12 µm (VIIRS band M16), *RSST* is a modeled, first guess SST, and θ is the sensor zenith angle.

The night-time IDPS algorithm is based on three infrared bands:

$$SST = a_0 + a_1 T_{11} + a_2 (T_{3.7} - T_{12}) RSST + a_3 (\sec(\theta) - 1) \quad (4)$$

where a_0, a_1, a_2, a_3 are coefficients derived by regression analysis (different from daytime algorithm), $T_{3.7}$ is the measured brightness temperature at 3.7 µm (VIIRS band M12) – other symbols are as in Eq. 3.

C. Ocean PEATE Capabilities

The VIIRS data used here have come primarily from the NOAA CLASS. It is anticipated that the Ocean PEATE, or the Ocean Biology Processing Group at NASA GSFC, will be involved in the reprocessing of the SST data necessary to attain quality appropriate of a CDR. To this end, the Ocean PEATE will need to process nighttime SDR files as input to the SST processing chain.

D. Instrument On-Orbit Performance

The results presented here have an inherent limitation in that they are based on less than one year of data. However these results represent a sound assessment of the VIIRS insofar as is currently possible.

1. Instrumental performance and artifacts

VIIRS lacks many of the instrumental artifacts that were present in MODIS, such as the "response *vs* scan angle" (RVS) resulting from the wavelength dependent reflectivity of the scene mirror on the angle of incidence of the radiation at the mirror surface, also the magnitude of detector banding coupled to which side of the scan mirror is being used compared to MODIS. With the rotating telescope of the VIIRS fore-optics, it was expected that if these effects were to

be found they would have been caused by the double-sided half-angle-mirror. While there is evidence of these effects, they are not a major source of qualitative or quantitative shortcomings of the infrared channels of the S-NPP VIIRS.

We anticipate there to be some effects from changes of pixel aggregation across the swath, but these are not pronounced and have not yet been quantified although they likely contribute to the growth in SST standard deviation as a function of increased scan angle.

Occasional anomalous values have been found in some of the infrared bands which have dual gain. This phenomenon was also identified by the VIIRS Characterization Support Team (VCST), which was able to identify the source of the problem to anomalies in the dual gain calibration sequence. The anomalies can be corrected in a future SDR reprocessing, but there is currently no support for reprocessing in the IDPS.

E. Calibration Assessment

The analyses done at RSMAS have not revealed any fundamental problems with the on-board calibration of the infrared channels, but such effects, if any, in derived products can be quite subtle, and may be revealed in analyses of more than a single year of data.

F. Processing Assessment

We have not undertaken a thorough assessment of the IDPS processing, finding it more efficient to download the Level 1 data from the NOAA CLASS and process the data using local facilities using the IDPS algorithms and others developed in-house; the assessment of IDPS processing that has been undertaken has been in the context of collaboration with the larger VIIRS SST community.

2. Algorithm Assessment

There are two distinct algorithms needed for the retrieval of SST from the top-of-atmosphere brightness temperature measurements: identifying with confidence those pixels that are free of contamination from clouds, and correction for the effects of the intervening cloud-free atmosphere.

The standard IDPS operational processing scheme uses the VIIRS Cloud Mask (VCM) to identify cloud-free pixels. Our experience with MODIS is that the Standard MODIS Cloud Mask was not optimal for the identification of cloud-free pixels over the open ocean, and this was found to be the case for VIIRS[1]. As with MODIS, we developed a “decision-tree” cloud identification algorithm, based on the approach developed for the AVHRR Pathfinder program (Kilpatrick et al., 2001).

The assessment of the atmospheric correction algorithm was based on the IDPS formulation with the operational coefficients, using the sequence of analyses given above, and in parallel an

[1] This conclusion was also reached independently by the NOAA/NESDIS/STAR team.

alternative approach was followed, based on our MODIS experience, in which the coefficients were determined for each month, in two sets determined by the $T_{11} - T_{12}$ brightness temperature differences:

- $T_{11} - T_{12} \leq 0.8$K (temperate to polar)
- $T_{11} - T_{12} > 0.8$K (equatorial to temperate)

3. Reprocessing

Based on previous experience with retrieving global fields of SST from satellite radiometers, it is clear that systematic instrumental and algorithmic uncertainties in the derived fields become apparent in longer time series of the data. Some are regional and others seasonal, and require time before patterns of the errors become evident and corrections can be derived and tested. Thus it is self-evident that reprocessing of the entire data set will be necessary if the full potential of VIIRS is to be realized in providing accurate measurements of SST, and if VIIRS is to contribute to the SST Climate Data Record. One improved algorithm that has been incorporated into the VIIRS algorithm suite is the latitude dependent "LATBAND" formulation that has been implemented for MODIS AQUA and TERRA. In this the coefficients are derived in zonal bands around the globe. The VIIRS results to date indicate that the VIIRS LATBAND implementation reduces seasonal anomalies relative to either *in situ* or SST reference fields similar to what we see with the MODIS LATBAND implementation. Reprocessing will permit introduction of the LATBAND algorithm and realize the benefits of other enhancements, such as in the SDR generation and cloud screening. .

G. Product Structure

4. Granule Size

The native granules, which contain measurements from time intervals of order 86 seconds are too small, making the accumulation of an orbit or a day's worth of data very ungainly. The 4x granules produced by the NOAA CLASS are better and more efficient to handle.

III. SCIENCE QUALITY ASSESSMENT

As stated above (Section B), our approach to assess the scientific quality of the VIIRS SSTs is based on comparisons with brightness temperatures and SSTs derived from other sources. Comparisons with other global SST fields are used here in a qualitative sense, as the comparison fields have their own uncertainties which are generally not well known. For quantitative comparisons we use independent measurements from drifters and ship-based radiometers.

H. Data Collection

5. Drifters

Quality-controlled subsurface SSTs from drifters are used in generating matchups with the satellite data. The quality assurance is done through the NOAA iQUAM – *in situ* Quality Monitor[2], which is interrogated on a daily basis. The distribution of the of VIIRS-buoy matchups are shown in Figure 2

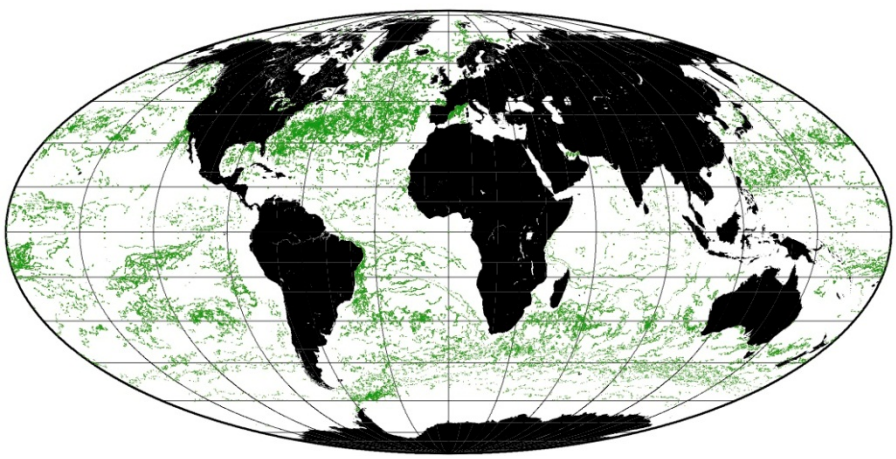


Figure 2. Distribution of VIIRS-buoy matchups.

It has recently become apparent that the accuracies of the thermometers in the drifting buoys are not as good as the ~0.1K that was believed, but probably closer to ~0.25K (O'Carroll et al., 2008), which means that the uncertainties in the buoy measurements makes a significant contribution to the discrepancies between the satellite and *in situ* measurements. In response to requests from the Group for High Resolution SST (GHRSST[3]; Donlon et al., 2007), new generations of drifters are being developed and deployed, with the ultimate goal of having accuracies of 0.01K. The first step was to add a second decimal place in the temperature values transmitted in real-time by satellite. The distribution of the VIIRS matchups with these buoys is shown in **Error! Reference source not found.**.

[2] See http://www.star.nesdis.noaa.gov/sod/sst/iquam/
[3] See https://www.ghrsst.org/

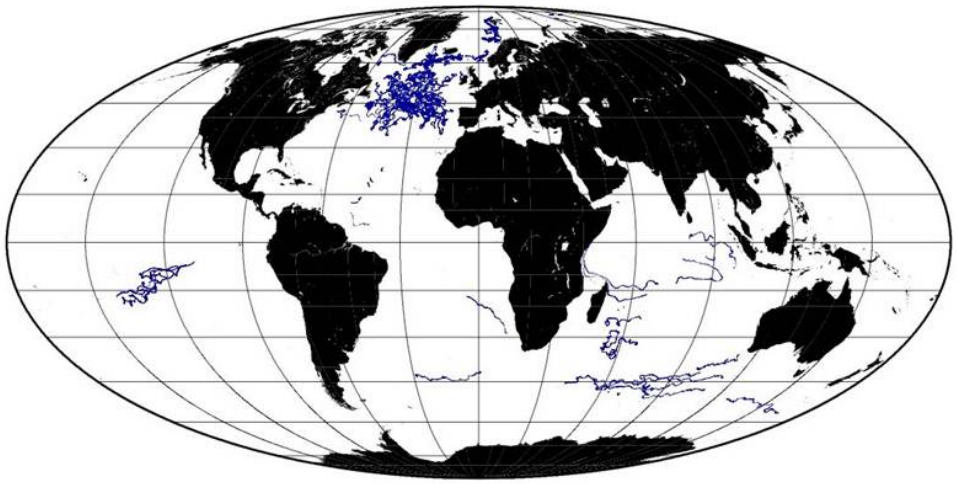


Figure 3. Distribution of of GHRSST drifting buoys.

6. Ship radiometers – M-AERI

The skin SST measurements for VIIRS validation have been taken by the Marine-Atmospheric Emitted Radiance Interferometers (M-AERI; Minnett et al., 2001), which are Fourier Transform spectroradiometers taking measurements of the infrared emission from the sea surface and atmosphere in the wavelength range of 3 to 18 μm. They have two internal black bodies to provide accurate at-sea calibration, and laboratory calibration before and after each field deployment provides traceability to SI standards (Rice et al., 2004; Minnett and Corlett, 2012). Figure 4 shows skin SST measurements taken in the North Atlantic Ocean.

With separate funding from NASA, a second-generation M-AERI is being developed and one of the new design instruments is currently mounted together with an original M-AERI on a two month deployment on the R/V *Knorr*. The data are stored on-board and following post-cruise calibration, the skin SSTs are included in the generation of the VIIRS SST Match-Up Data Base.

7. Ship radiometers – ISAR

A second type of ship-board instrument, the Infrared Sea surface temperature Autonomous Radiometer (ISAR; Donlon et al., 2008) also provides skin SST for VIIRS validation. ISARs are autonomous filter radiometers with two internal blackbody calibration targets and, as with the M-AERIs, pre- and post-deployment laboratory calibration against NIST-traceable calibrators provides SI traceability. Data relayed in real-time by Iridium. We have two ISARs which have been deployed on commercial vessels since the VIIRS SST infrared data stream began. One is on the M/V *Andromeda Leader* which plies between Japan and the USA, with the round-trip taking about two months (Figure 5).

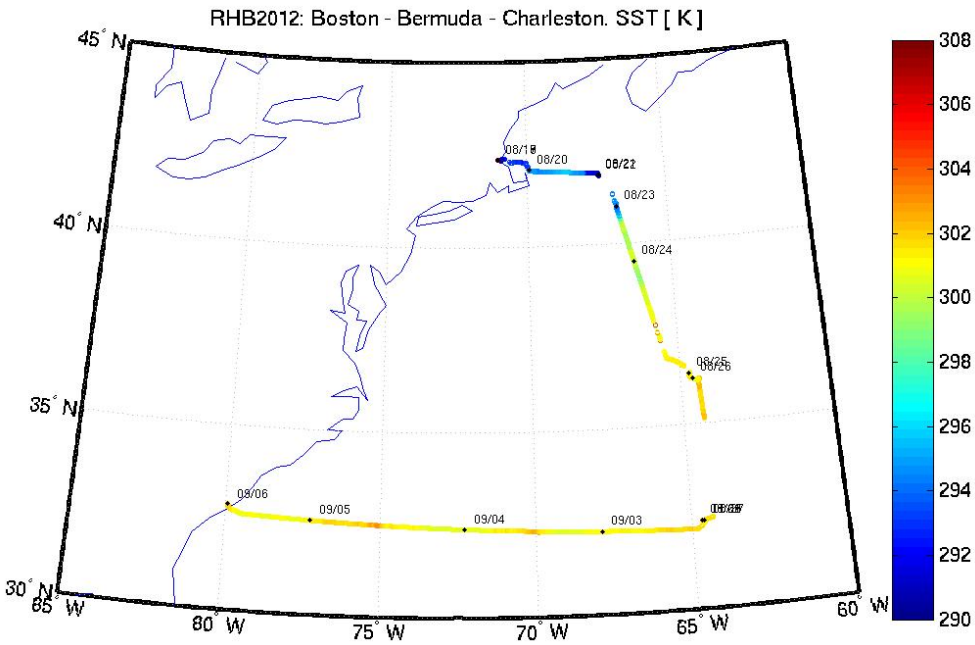


Figure 4. Measurements of the Skin SST from NOAA Ship *Ronald H Brown*, 18 August – 6 September, 2012. The color scale, on the right, is skin SST in K.

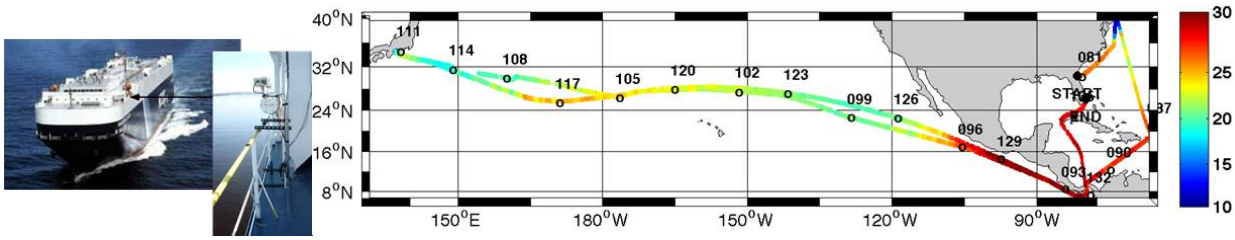


Figure 5. The skin SST measured by an ISAR on the M/V *Andromeda Leader* from 20 March to 14 April, 2012. The numbers of on the ship track are days of the year, and the colors indicate temperature as indicated at right in °C. Photographs of the ship and the ISAR are also shown.

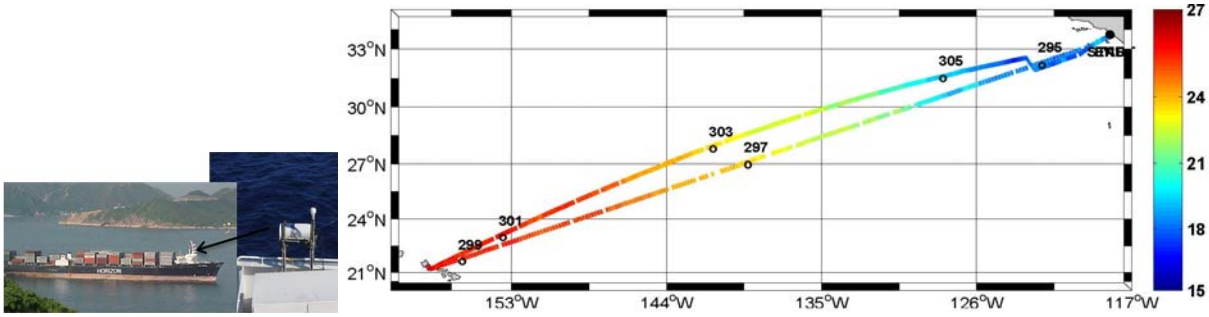


Figure 6. The skin SST measured by an ISAR on the M/V *Horizon Spirit* from 20 October to 1 November, 2012. The numbers on the ship track are days of the year, and the colors indicate temperature as indicated at right in °C. Photographs of the ship and the ISAR are also shown.

The second ISAR was mounted on the M/V *Horizon Spirit* as part of the DoE MAGIC field campaign[4]. Starting in October, 2012, the ship sailed between Los Angeles, California, and Honolulu, Hawaii, taking two weeks for a round trip (Figure 6). A mechanical failure of the ship curtailed the measurement campaign in December, 2012; an alternative ship is being sought while the *Horizon Spirit* is in dry dock undergoing repairs.

I. Evaluation

8. Spatial Distribution of Differences with Heritage Data

The evaluation of the integrity of the spatial distribution of the VIIRRS SSTs has been conducted by comparisons with independent fields. The first used is the daily, global SSTs derived from AVHRR data using Optimum Interpolation (OI) to produce a regular, gap-free fields. These are frequently referred to as the Reynolds SST (Reynolds and Smith, 1994). An example of the difference field, VIIRS – Reynolds is shown in Figure 7. The VIIRS SSTs are derived using the 3-band night-time algorithm but with the Miami Decision-Tree cloud mask. The data are from data day 2012-225 (August 12, 2012) and are limited to those with the best quality flag and are limited to satellite zenith angles <55°. The blue areas are where the VIIRS SSTs are likely to be influenced by the presence of atmospheric aerosols, and are therefore cooler than the correct SSTs. The Reynolds OI field is tied to *in situ* measurements and is therefore less influenced by the atmospheric conditions. The areas where VIIRS appears to be warmer than the Reynolds OI fields are more difficult to understand, and it is not clear whether the VIIRS SSTs are showing a warm bias, or whether the Reynolds SSTs have a cold bias.

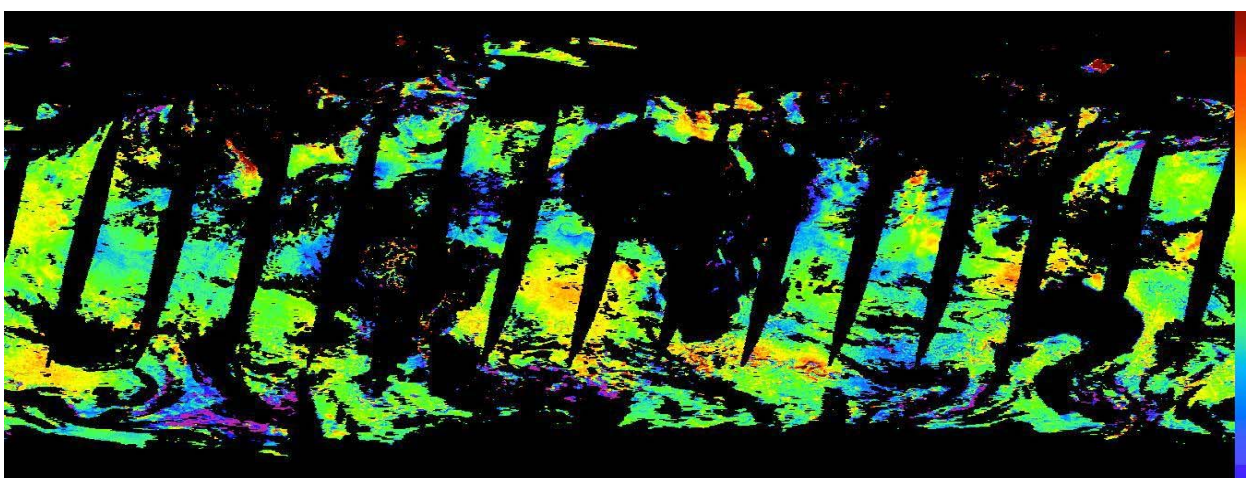


Figure 7. An example of the difference SST field, VIIRS – Reynolds OI. The color scale is ±5K. with red indicating VIIRS warmer than Reynolds OI, and blue cooler. Black indicates land, clouds, and gaps between adjacent swaths.

[4] See http://www.arm.gov/sites/amf/mag/

Figure 8 shows the comparison of VIIRS SSTs (as in Figure 7) with SSTs derived from the microwave radiometer WindSat on the US Navy Coreolis satellite. Because the sources of uncertainties in the microwave SSTs are different to those in the infrared SSTs, the uncertainties in the SSTs used to derive the differences shown in Figure 8 are uncorrelated. A major source of error in microwave SSTs is the contamination of the measurements by land emission entering the radiometer through the antenna side lobes. Another concern about this comparison is that the geometry of the WindSat swaths requires the compiling of five-days of measurements to generate complete global fields. The terminator orbit of Coreolis means the overpass times are not close to S-NPP. But these concerns aside, the SSTs from WindSat are of good quality. The differences between VIIRS and WindSat SSTs (Figure 8) show the same cold bias in regions where we expect aerosol contamination of the VIIRS retrievals, but lack the areas that show a warm bias when compared to the Reynolds OI fields (Figure 7). Although not definitive, this is indicative of regional cold biases in the Reynolds OI fields, not warm biases in the VIIRS SST retrievals.

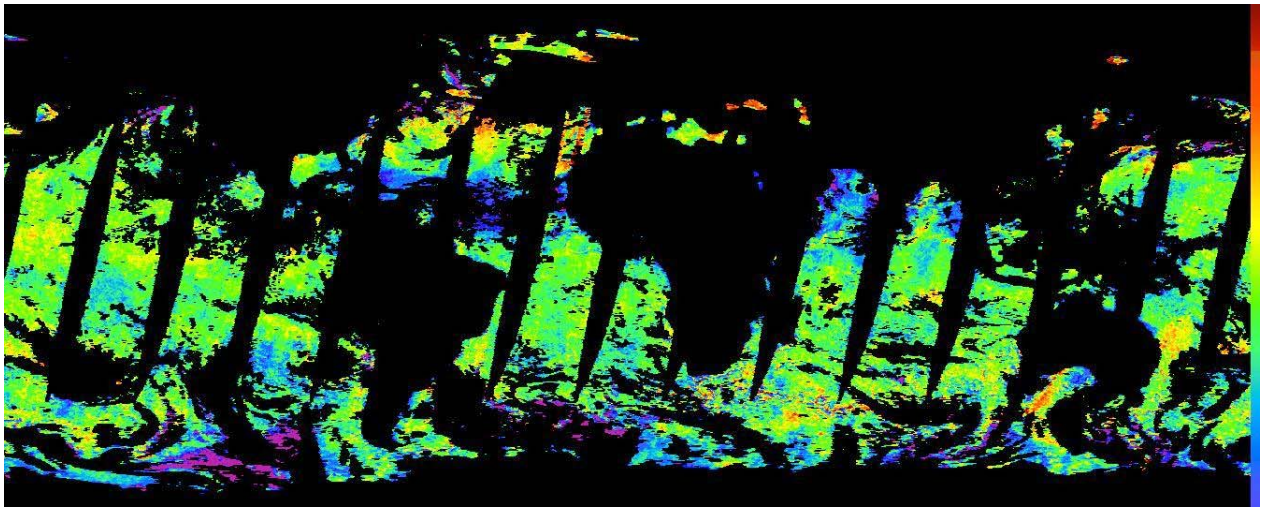


Figure 8. As Figure 7, but VIIRS infrared SST - WindSat microwave SST.

9. Comparison to *In Situ* Measurements

As an example of the results of comparisons with *in situ* measurements, Figure 9 shows the comparison of the VIIRS skin SSTs with skin SSTs measured by the ISAR in the Pacific Ocean from early February to late October, 2012. The comparison is shown as a time series of the temperature differences. The VIIRS SSTs are derived at night using the 3-band algorithm (Equation 4) using the Miami Cloud Mask, and retrieval coefficients also derived at Miami. The mean of these 267 matchups is 0.029K, with a standard deviation of 0.416K. These are very encouraging numbers. The causes of the outliers are being investigated. In section 12 below, we present a comparative analysis of the IDPS and Miami algorithm performances, and the limitations of the IDPS algorithm are examined.

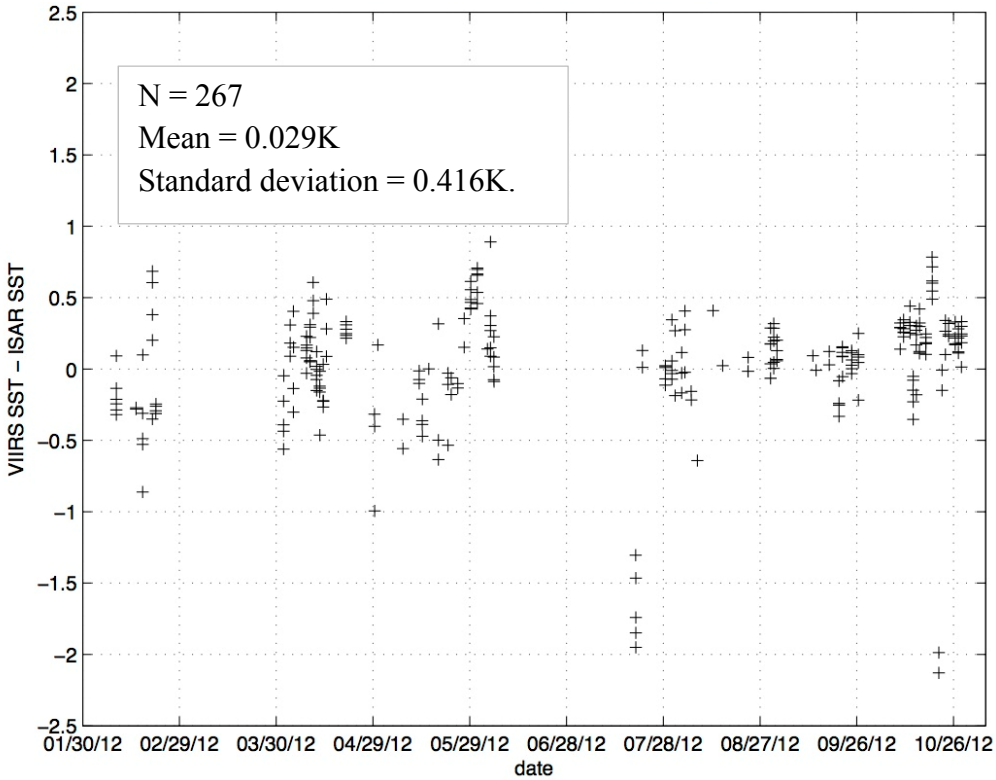


Figure 9. Time series of VIIRS night-time 3-band SST retrievals referenced to skin SST measured by the ISAR in K.

10. Level-2 and EDR Comparison

The time series of the median and standard deviations of the daily differences between the VIIRS skin SSTs derived with the IDPS algorithms using the 3-band night-time measurements and subsurface temperatures measured from drifting buoys are shown in Figure 10. The Miami Decision-Tree cloud mask has been used here. As a result of the ocean thermal skin effect, a cool bias in the median values of about -0.17K is expected and this is shown as the dotted line in the left-hand panel. The red line indicates the time when there was a change in brightness temperature computation resulting from a correction to the LUTs used in the calibration software. The medians reveal a seasonal characteristic to the differences, which can be ascribed to a shortcoming in the IDPS atmospheric correction algorithm. However, provided the causes of this, and other systematic sources of uncertainty, can be identified and corrected, the size of the random error (right hand panel) is very encouraging for the potential accuracies of VIIRS skin SST retrievals.

The systematic seasonal characteristic of the IDPS SST retrievals is not limited to the 3-band algorithm (Equation 4) but is also present, and more pronounced, in the 2-band algorithm (Equation 3), as shown in Figure 11. In the lower panel of Figure 11 the time series of the

median errors have been calculated for latitude zones around the globe. These zones cover 20° of latitude, with the exception of polewards of 40°, and the time series within each panel (colored lines) indicate that there is a regional character to the uncertainties.

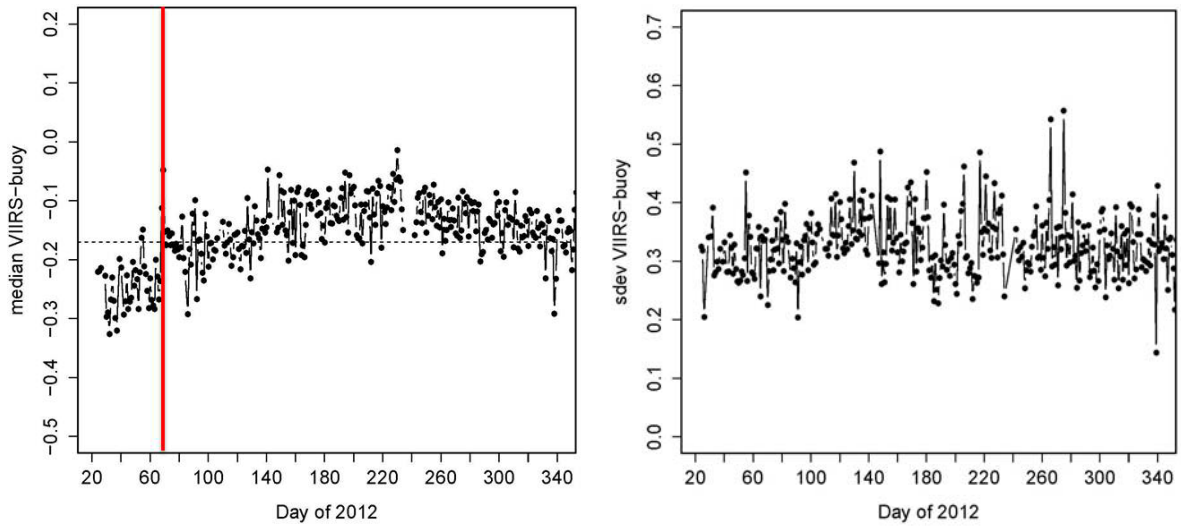


Figure 10. The medians (left) and standard deviations (right) of the differences between the IDPS 3-band night-time VIIRS skin SSTs and the subsurface temperatures measured from drifting buoys, in K. We expect a cool bias in the median values of about -0.17K, resulting from the thermal skin effect and this is shown as the dotted line in the left-hand panel. The red line indicates the time when there was a change in the SDR brightness temperature computation. Day 20 is January 20, and 340 is December 5, 2012.

Most of these undesirable seasonal and regional characteristics in the VIIRS IDPS SSTs can be removed by using a Level 2 processing scheme based on our experience with the MODIS and AVHRR retrievals. This involves generating the coefficients for the NLSST algorithm (Equation 1) using matchups in zonal bands in monthly intervals, with smoothing across the domain boundaries (Figure 12).

11. New Algorithms

As mentioned above, it was realized early in the assessment that the standard VIIRS Cloud Mask was not optimized for identifying clear-sky pixels over the ocean. Again, building on our experience with MODIS and AVHRR, an alternative and computationally efficient series of tests were developed for VIIRS. This Decision-Tree Approach (Figure 13) was found to improve the number of clear-sky pixels and the SST uncertainty statistics.

12. Continuation of the Heritage SST algorithms

The Decision-Tree cloud identification algorithm is based on the MODIS and AVHRR cloud detection approach, and therefore VIIRS SSTs derived using this are consistent, in terms of cloud screening, with the SSTs derived from the heritage instruments and provide continuity

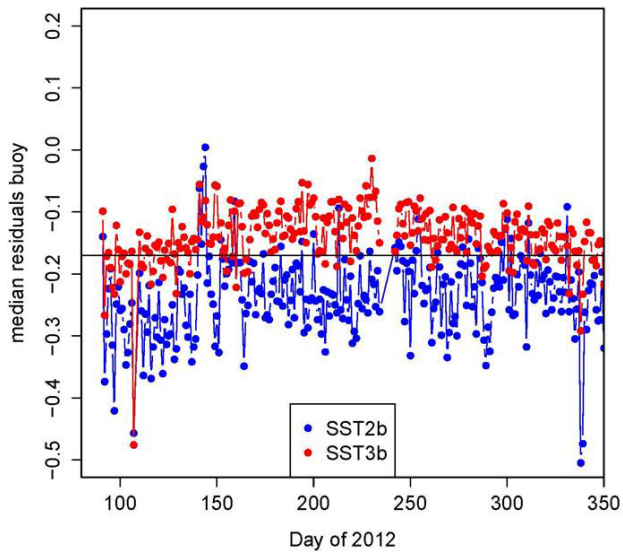
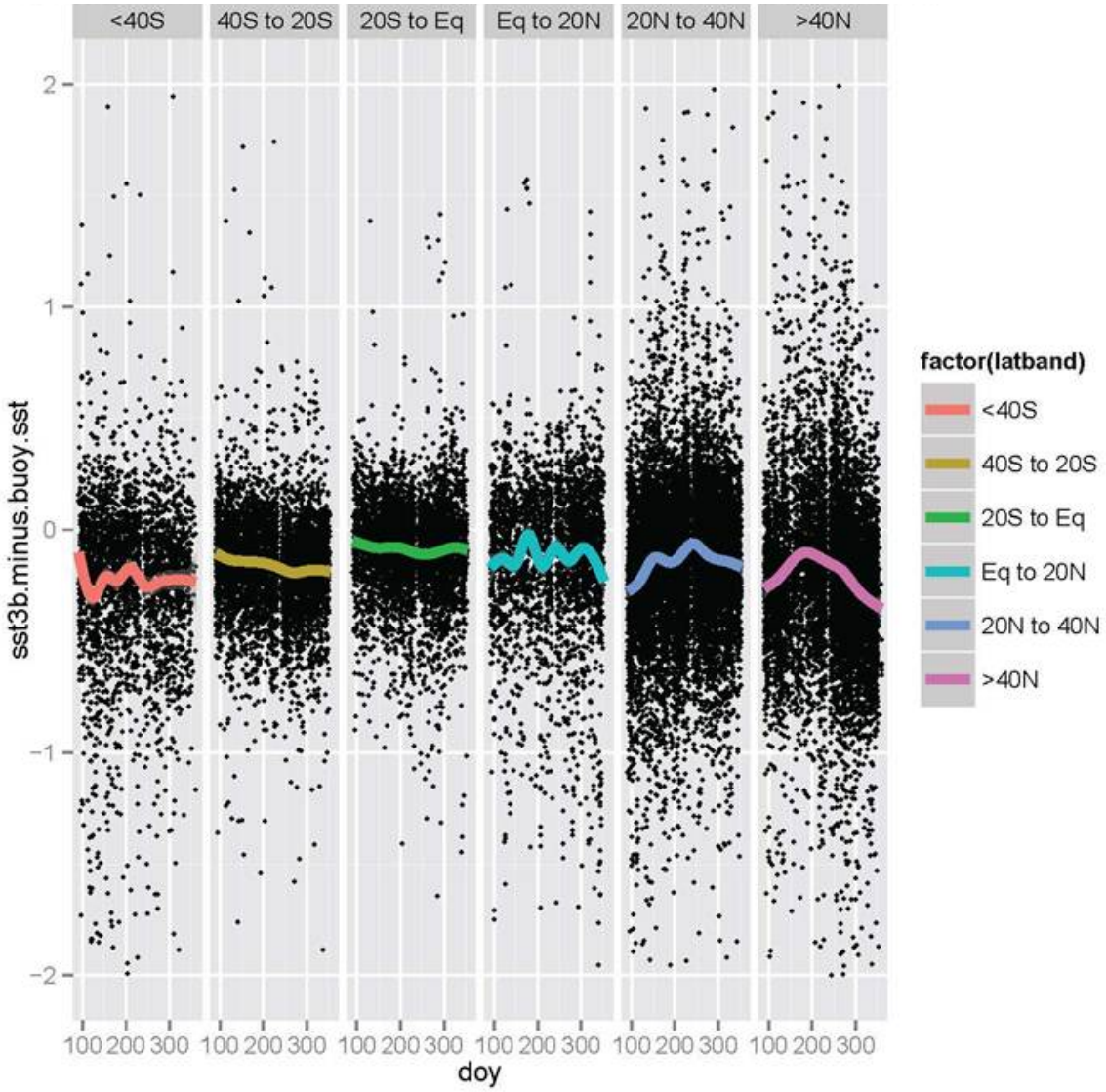


Figure 11. The medians (left) of the differences between the IDPS 3-band (red) and 2-band (blue) night-time VIIRS skin SSTs and the subsurface temperatures measured from drifting buoys, in K. The panel below shows the time series of the median errors in latitudinal bands (colors) and the individual points (black). Day 100 is April 9, and 350 is December 15, 2012. Data from the period before the red line in Figure 10 are removed from this plot.



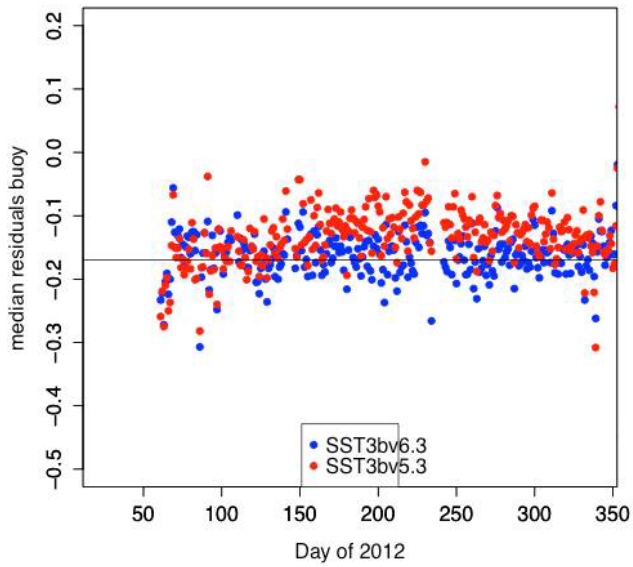
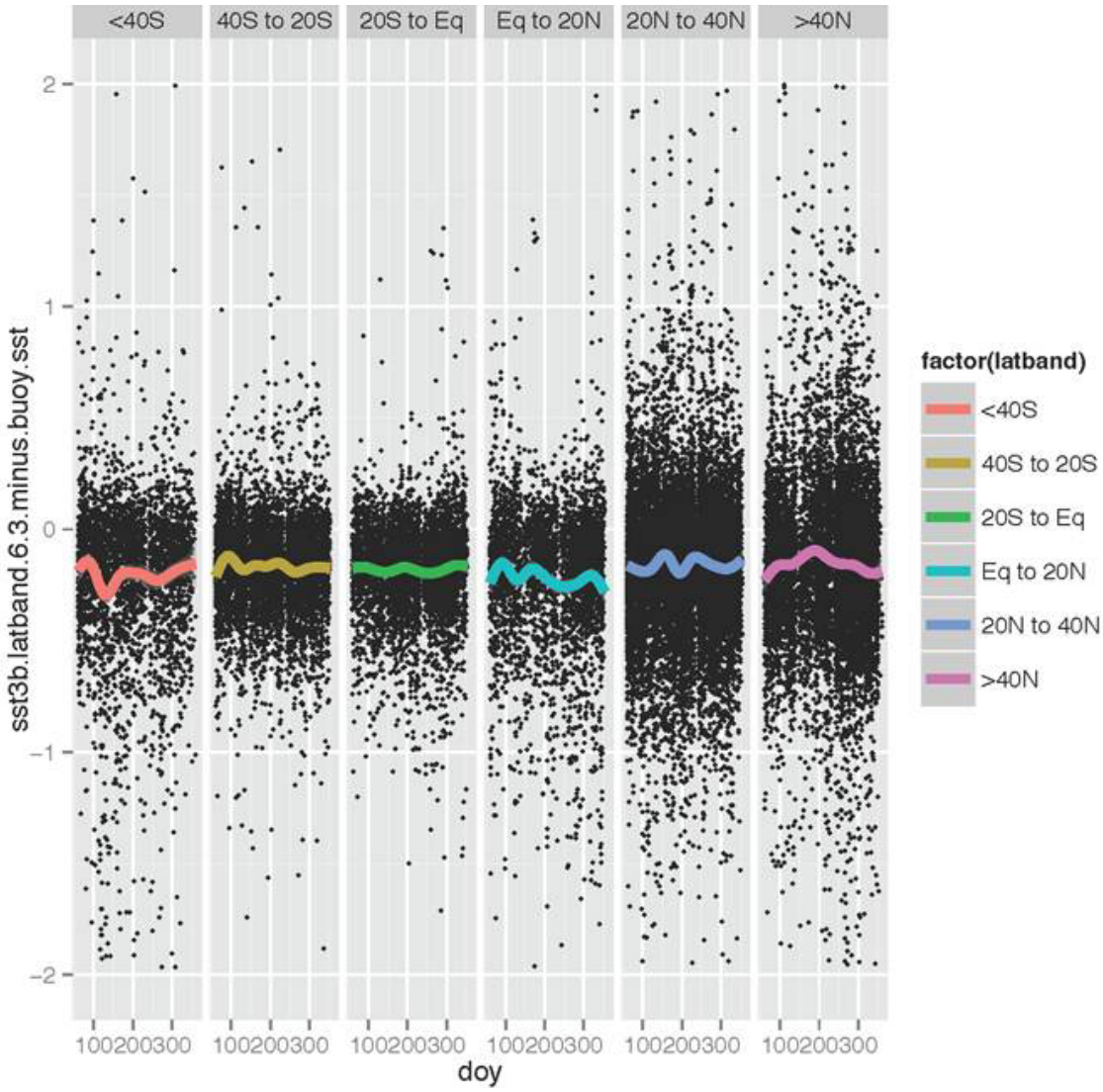


Figure 12. As Figure 11, but with the VIIRS atmospheric correction algorithm based on monthly coefficients derived in the latitudinal zones.



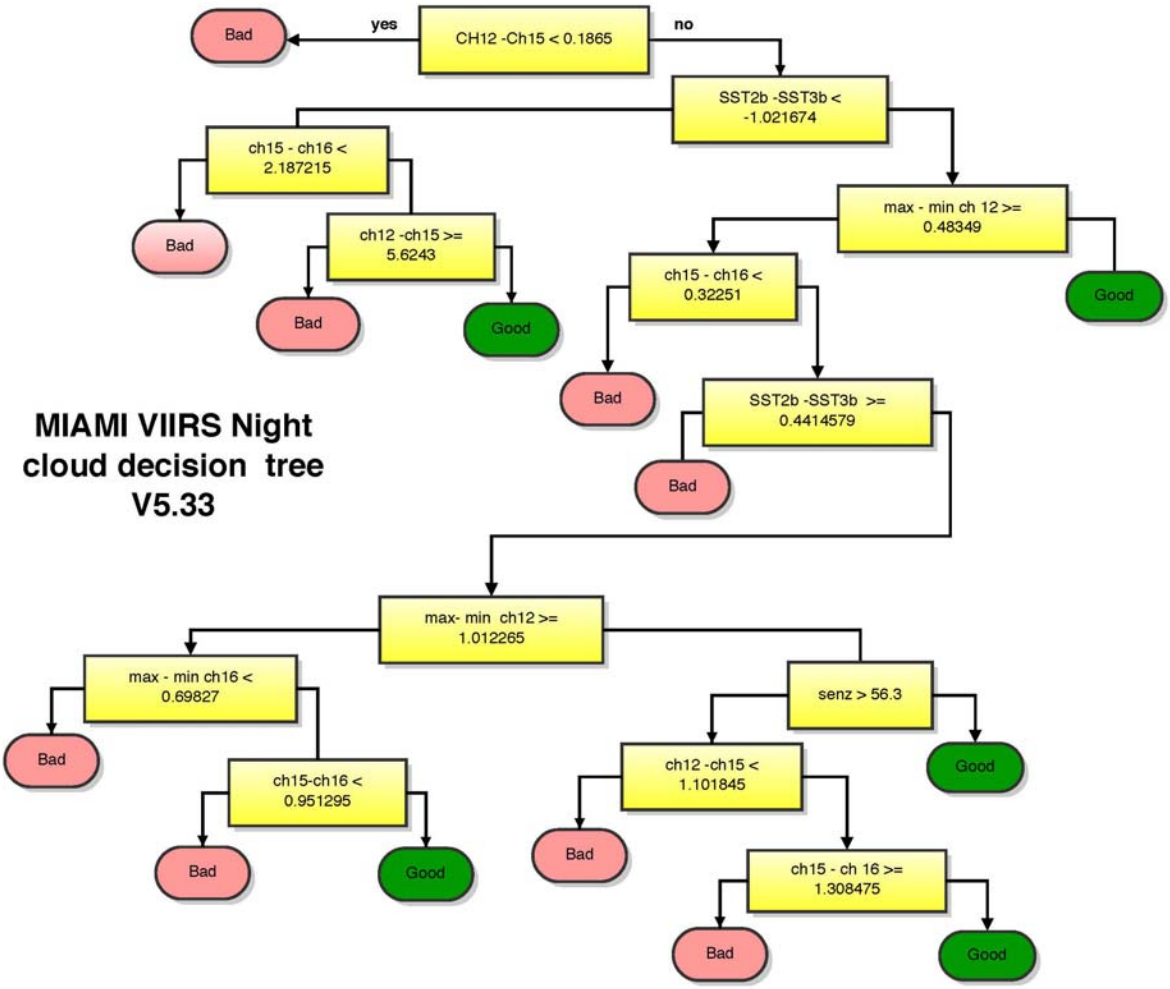


Figure 13. Miami Decision-Tree approach to the identification of cloud-free pixels. Each test is derived from physical expectations based on the radiometric measurements in different VIIRS bands, and on the measurement geometry. Only pixels that are designated "Good" provide high quality SSTs. This example is for night-time measurements.

The use of the NLSST as the basis of the clear-sky day-night, two band atmospheric correction provides continuity with heritage satellite radiometers.

The most appropriate method, however, of ensuring continuity with SSTs derived from heritage instruments and thereby underpinning the derivation of SST Climate Data Records is the characterization of uncertainties in the satellite-derived SSTs though comparisons with SI-traceable measurements of the skin SST using ship-board radiometers.

IV. DISCUSSION AND SYNTHESIS

The initial perception based on early on-orbit data that the infrared bands on VIIRS are "clean" and lack many of the instrumental artifacts present in the MODIS data has been supported by subsequent detailed analyses.

Using qualitative and quantitative metrics, several shortcomings with the operational IDPS SSTs were identified, which include systematic seasonal and regional bias errors in the retrieved SSTs when compared to the measurements of drifting buoys. In addition, the use of the standard VIIRS cloud mask is sub-optimal for the requirements of identifying cloud-free pixels for SST retrievals. Based on our experience with MODIS, alternative algorithms were developed that overcame these problems, to a very large degree, resulting in derived SST fields with much reduced seasonal and regional components to the bias errors. Comparisons of skin SSTs derived from these alternative algorithms with skin SST measurements taken from ship-board radiometers in the Pacific Ocean show a bias error of close to zero (0.029K) for measurements taken over a ten-month period (Figure 9). The scatter in the comparisons with drifters and with radiometers indicates that the VIIRS SSTs are comparable in accuracy with those of the heritage instrument, MODIS, and have a good potential to extend reliable and accurate SSTs into the future.

Comparisons of global fields of SSTs derived from VIIRS and from the microwave radiometer WindSat on the US Navy satellite Coreolis show cold biases in the VIIRS infrared SSTs in regions where heavy loading of atmospheric aerosols are expected (Figure 7). Similar cold biases have previously been identified in the SSTs derived from other infrared radiometers. Comparisons with Reynolds Optimally Interpolated fields showed these cold biases in the VIIRS retrievals, but also warm biases, particularly in the southern hemisphere (Figure 7). The absence of these areas of warm bias in the comparison with microwave-derived SSTs is strongly suggestive of cold biases in the Optimally Interpolated fields.

Both the IDPS and Miami algorithms require well-calibrated top-of-atmosphere brightness temperatures. The Miami approach of deriving seasonally and zonally varying coefficients is more robust to local anomalies in the atmosphere and artifacts from the instrument. An instrumental artifact that was presented at the VIIRS Calibration Workshop on January 22, 2013, is an orbital signal in the temperature of the internal calibration target measured by two of the six thermometers embedded in the target (Figure 14). This indicates temporally varying temperature gradients in the blackbody. These have the potential to introduce regionally and, depending on the source of the gradients, temporally varying SST retrieval errors. This signature is currently being investigated by the VIIRS Characterization Support Team, and it is anticipated that an algorithm to correct any unwanted consequences will be found. This underlines the need for reprocessing the VIIRS data to remove, or reduce, such artifacts, and ultimately improve the accuracy of the derived SSTs.

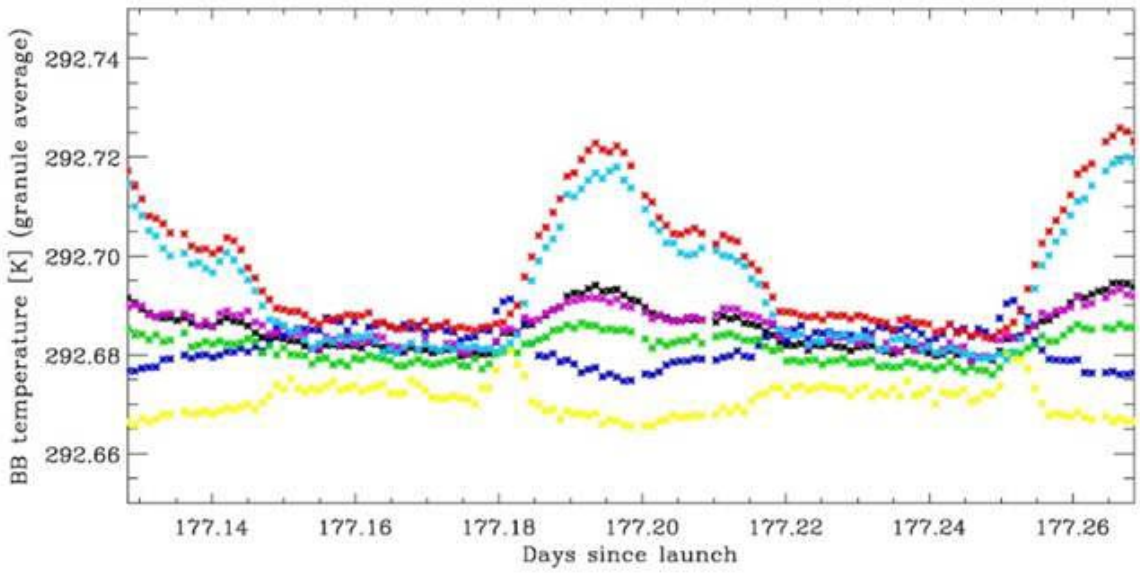


Figure 14. Time series of the output of thermometers on the VIIRS blackbody over two orbits. Two of the thermometers show a significant orbital signal. The plot is from the presentation given by J. McIntire of the VIIRS Characterization Support Team (VCST) during the SNPP VIIRS Calibration Workshop on January 22, 2013.

Even without corrections to these artifacts, the quality and the accuracy of the VIIRS SSTs are comparable to those of MODIS, and therefore are at a stage where they can be released to the wider community for use and further evaluation through a range of non-CDR applications. The mechanism for the distribution of high-quality VIIRS SSTs to the community could take advantage of the model developed for the processing and distribution of MODIS SSTs, involving the groups at Miami, the Goddard Ocean Biology Processing Group, and the JPL PO.DAAC GHRSST Global Data Assembly Center (GDAC).

The results presented here are a selection from a much larger body of work undertaken to assess the accuracies of the VIIRS SSTs, but additional unreported results support the conclusions presented here.

V. CONCLUSIONS

Our conclusions can be summarized by:

- VIIRS infrared bands used to derive SST produce "clean" top-of-atmosphere brightness temperature measurements.
- The use of the VIIRS Cloud Mask (VCM) for clear-sky identification for SST retrieval is sub-optimal. Miami decision-tree cloud screening improves statistics and coverage.
- A change in the algorithm used to produce calibrated brightness temperatures, resulting from a revision of SDR processing algorithm, will require reprocessing for CDR generation. Reprocessing will also be necessary to reduce the effects of orbital-dependent temperature gradients in the onboard blackbody calibration target, and to take advantage of enhancements in the atmospheric correction algorithm and the cloud screening procedures.
- The IDPS atmospheric correction algorithm exhibits mean errors with seasonal and regional characteristics, which are much reduced using atmospheric correction algorithms derived from a large database of matchups between VIIRS brightness temperatures and *in situ* measurements generated at the University of Miami.
- The standard deviation of the SSTs derived using IDPS atmospheric correction algorithm indicate VIIRS capable of producing climate-quality SSTs once the systematic errors are removed, such as by using the Miami cloud-screening and atmospheric algorithms.
- At present, the use of the Miami SST algorithms leads to VIIRS retrievals that are as accurate as those derived from MODIS measurements. It is anticipated that the results of continuing research and analysis will lead to further improvements in accuracies.

VI. RECOMMENDATIONS

Our main recommendations are to:

1. Continue development of "Match-up Data Bases" with ship radiometer and buoy data.
2. Continue to use ship radiometers to provide skin SST retrieval validation.
3. Use Matchup-data Bases to determine validation statistics and assess temporal degradation of the SST retrievals, if any.
4. Continue to refine the way ship radiometers to provide pathway to generation of SST CDRs.
5. Exploit AMSR-2 data (once data are released and validated) as a possible source of microwave SSTs that are less sensitive to the sources of uncertainties in the VIIRS infrared SST retrievals.
6. Use "GHRSST" drifting buoys, with higher thermometric accuracies, to provide matchups capable of a more robust estimate of VIIRS SST uncertainties.
7. Use Matchup-data Bases and radiative transfer simulations to refine algorithms, with a special focus on regional and seasonal errors including upwelling zones, and those caused by aerosols.
8. Explore the use of the panchromatic Day-Night Band data for improved night-time cloud screening (Figure 15).
9. Prepare for the need to reprocess the data for consistency and eventual generation of Climate Data Records.

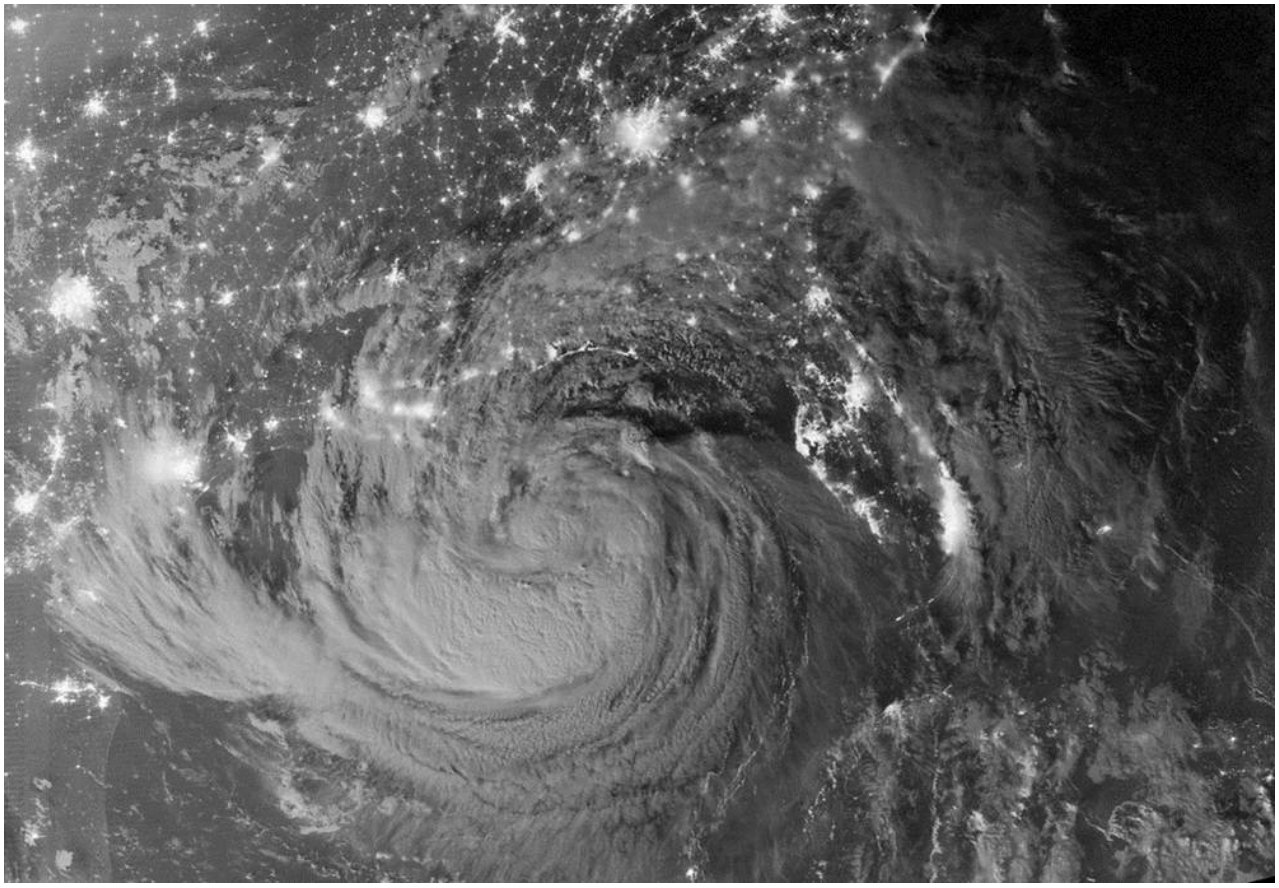


Figure 15. An example of the VIIRS panchromatic Day-Night band image of clouds illuminated by moonlight at night. Here Hurricane Isaac practically fills the Gulf of Mexico on the night of 27-28 August 2012. The phase of the moon was waxing gibbous, with 89% of the visible moon's surface illuminated.

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