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Evaluating SST Retrieval Masking under Volcanic Ash Conditions

JACKIE C. MAY

CHARLIE N. BARRON

Ocean Data Assimilation and Probabilistic Prediction Section
Ocean Sciences Division

JEAN-FRANÇOIS CAYULA

Peraton Inc.
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14. ABSTRACT
This report examines the capability of the Naval Research Laboratory (NRL) Sea Surface Temperature (SST) software suite to provide valid SST retrievals under conditions where recent volcanic activity introduces plumes of sulfur dioxide (SO_2) and other contaminants into the atmosphere. We evaluate SST retrievals under conditions of expected volcanic contamination and compare their characteristics relative to retrievals produced during periods of low volcanic influence, verifying that retrievals significantly affected by volcanic contamination are appropriately flagged while unaffected retrievals in clear or low contamination areas are retained. In particular, we examine conditions in a wide area, from 120°E to 0°E and between 30°N and 65°N, comparing retrievals in the month after the Raikoke volcano eruption on 22 June 2019 with retrievals from the same time period in 2014, when little volcanic activity extending into the stratosphere was observed. Reliability of the SST retrievals is evaluated with a previously developed method based on the orbital overlap that occurs with recent sunsynchronous satellites. The standard deviations of the NRL SST as determined by the orbital overlap method show a value of 0.52°K in 2014 without measurable volcanic activity in the area. This value only increases to 0.64°K for the same region a month after the Raikoke eruption when a significant concentration of SO_2 is present in the stratosphere. In the vicinity of the volcano, stronger contamination is readily detected and few SST retrievals are produced. We find that the present NRL SST software successfully excludes retrievals strongly affected volcanic plumes while allowing retrievals where he effects are found to be minor.

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Table of Contents

Table of Figures

1. Introduction

The Naval Research Laboratory (NRL) Sea Surface Temperature (SST) software suite produces near-real-time SST retrievals from satellite sensor data records (SDR). The current SST software (v2.7) processes data from 3 geostationary platforms and 5 polar-orbiting platforms: the Advanced Baseline Imager (ABI) onboard the Geostationary Operational Environmental Satellite (GOES) – 16 and 17 platforms; the Advanced Himawari Imager (AHI) onboard the Himawari-8 platform; the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi-National Polar-orbiting Partnership (S-NPP) and the Joint Polar Satellite System (JPSS-1) platforms; and the Advanced Very High Resolution Radiometer (AVHRR/3) onboard the Metop-A, B, and C platforms. We assume that the performance of systems in the present suite are a useful proxy for future NRL SST capabilities incorporating new satellite sources.

SST retrievals provided through the NRL SST software suite are based on combinations of brightness temperatures of infra-red radiation measured by satellite-mounted sensors. The coefficients for the retrieval algorithms are derived using matching in situ SST observations collected and paired with brightness temperatures observed under nominally clear sky conditions. As real time conditions deviate from this clear sky assumption, the reliability of the SST retrievals is degraded. To provide SST retrievals that are reliable and accurate, the SST software suite utilizes various tests, thresholds, and parameters to determine the applicability of the SST processing as well as to identify and mask out contamination evident in the SDR brightness temperature fields. Contamination can be from a variety of sources including: clouds, aerosols, dust, noise in the brightness temperature channels, sun angle, etc. Contaminated data are considered unreliable and are therefore masked out (or not used) within the SST retrievals. This method of identifying and removing contaminated data to produce reliable SST retrievals has been shown to work well, with the SST retrievals being in good agreement with nearby in situ data. The effectiveness of these tests and retrieval algorithms under conditions of cloud and dust contamination has been thoroughly evaluated. However, the SST retrievals until now had not been specifically evaluated in environments with high levels of volcanic ash and sulfur dioxide (SO_2). While large volcanic eruptions happen relatively infrequently, the impact of the volcanic ash and SO_2 can be wide spread and long lasting.

The Naval Oceanographic Office (NAVOCEANO) is the transition partner receiving the NRL SST software and evaluating new capabilities within the software before approving new versions for operational use. Recipients of the SST data streams produced by NAVOCEANO include the Fleet Numerical Meteorology and Oceanography Center (FNMOC), using SST retrievals for assimilation and validation purposes in their atmospheric and oceanic model systems; the Physical Oceanography Distributed Active Archive Center (PO.DAAC), retaining the data for archival and use by the participants in the international Group for High Resolution Sea Surface Temperature (GHRSST); as well as other users and applications. Given the importance of near-real-time SST retrievals for FNMOC forecasts and long-term climatological records, we need to understand and mitigate potential degradation of SST fidelity during periods of potential atmospheric contamination. In particular for this study, we focus on volcanic contamination.

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This report addresses requests by NAVOCEANO and FNMOC to assess the anticipated performance of NRL SST software in providing reliable SST retrievals under conditions impacted by stratospheric volcanic plumes.

This report provides validation of the NRL SST software suite v2.7 to mask out SST retrievals that are under conditions exposed to significant plumes of volcanic ash and SO_2.

2. SST retrievals

There are two categories of tests performed within the SST processing to identify and mask out contamination. The first category, which usually addresses the most obvious contamination, includes the brightness temperature bounds check, SST retrieval bounds check, and the SST retrieval versus background field check. The second category has more physical tests, including:

- Reflectance table test – checks if observed reflectance values are greater than values within the viable range defined within the reflectance table. If the reflectance values fall outside of the viable range, either low or high, then the SST retrievals are deemed unreliable. During daytime and under appropriate conditions, approximately 10% of the higher reflectance values that failed the initial test are later recovered as border line cases.
- Nighttime 4 µm test – compares the brightness temperature at 4 µm with an estimate of the 4 µm brightness temperature derived from the 10.x and 12.x µm brightness temperature channels. If the observed and estimated 4 µm brightness temperatures are similar, then the optical properties in these channels are consistent with clear sky conditions. If they differ significantly, then the SST retrievals are also likely to be unreliable due to atmospheric contamination.
- Brightness temperature difference test – checks the difference between the 10.x and 12.x µm brightness temperature channels as a function of the estimated SST. If they differ significantly, where the significant threshold is defined as a function of estimated SST, then the SST retrievals are also likely to be unreliable due to atmospheric contamination.
- Daytime correlation check test – checks whether brightness temperature and reflectance correlate to allow for differentiation between oceanic features and cloud induced features. This flags some cloud-related variations in SST retrievals that are missed by other tests while retaining SST fronts that are important for assimilation into the forecast models.
- Sand / dust check – this is applied to specific user-defined regions where sand / dust contamination is expected. It is restricted to areas more commonly exposed to sand / dust contamination to mitigate the risk of false positive flags where such contamination is unlikely.
- Proximity to cloud test – check to mask out retrievals at the edge of clouds. This test is based on geometry and logic criteria rather than quantified physical parameters (e.g. brightness temperature or reflectance). This test retains some SST retrievals that might be flagged due to spatial variability near ocean fronts while excluding retrievals that are more likely to indicate contamination by sparse clouds on the boundaries of more confidently identified cloud areas.

The SST retrievals are evaluated against a variety of sources, one of which is the Level 4 K10 (10km) gridded SST field produced by NAVOCEANO (Martin et al., 2012). The K10 field is produced by merging satellite-derived SST retrievals, weighing the various inputs based on age, distance, and quality in an effort to preserve fronts. If SST retrievals become older than 30 days, the K10 relaxes to the National Oceanic and Atmospheric Administration (NOAA) 1/4º daily Optimum Interpolation SST (OISST) – long term climate data record (CDR, Banzon et al., 2016). As the K10 is a composite updated by inserting recently available satellite SST retrievals, it does not represent conditions at a particular local lime of day or uniform time. One K10 is prepared each day for application in SST processing or evaluation. The platforms with NAVOCEANO processed SST retrievals that are included in the present K10 product are: AVHRR/Metop, VIIRS/S-NPP and JPSS1, and ABI/GOES. The satellite SST retrievals that are included in the K10 product but are not produced by NAVOCEANO include: Spinning Enhanced Visible and Infrared Imager (SEVIRI)/Meteosat Second Generation (MSG) and Advanced Microwave Scanning Radiometer 2 (AMSR2)/Japanese Space Exploration Agency Global Change Observation Mission 1st-Water (GCOM-W1).

3. Case Study: Raikoke Eruption 2019

Raikoke Volcano is on the Kuril Islands in the Sea of Okhotsk, north-east of Japan at 48.35°N, 153.23°E. An eruption from Raikoke occurred on 22 June 2019, producing a plume of volcanic ash and SO_2 that reached the stratosphere. Figure 1 shows the VIIRS composite image from 22 June 2019 over the Raikoke region. While the white areas of cloud coverage are quite extensive, a distinctly tan volcanic ash cloud can also be seen extending above the clouds diagonally south-east from Raikoke.

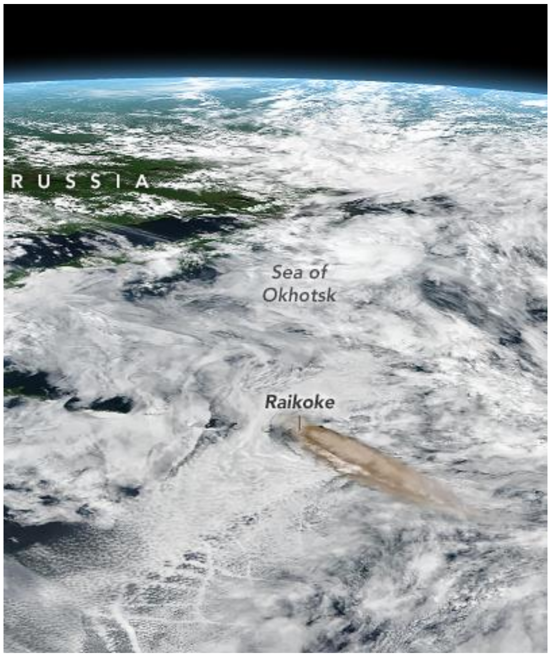

Figure 1: VIIRS composite image from 22 June 2019 over Raikoke. Clouds are seen in white and the volcanic ash cloud can be seen in tan extending from Raikoke.

The corresponding SO_2 plume from the Raikoke eruption can be seen from the TROPOsheric Monitoring Instrument (TROPOMI) sensor onboard the Sentinel-5P platform (Figure 2). On 24 June 2019, the SO_2 plume is seen to extend over the Bering Sea.

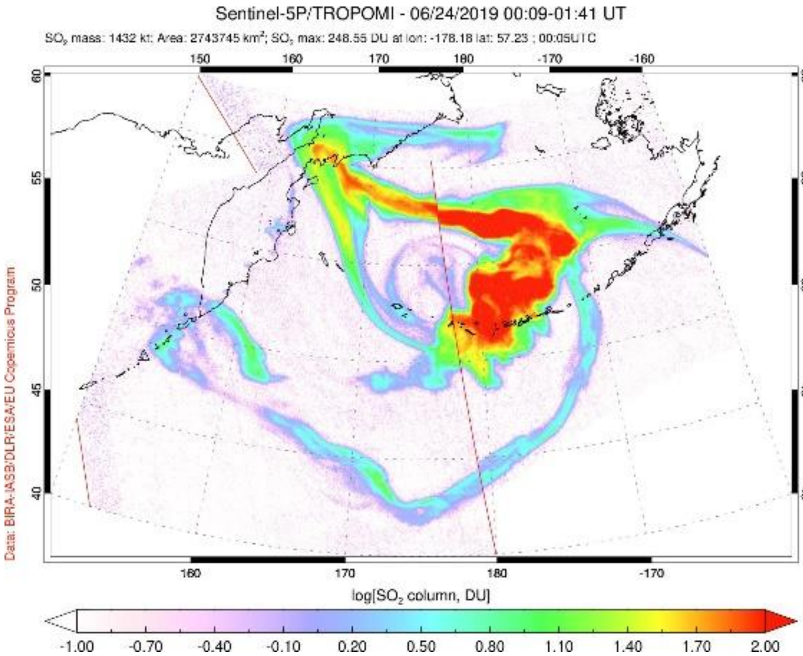

Figure 2: Sentinel-5P/TROPOMI measured SO_2 from 24 June 2019.

One month later, SO_2 can be found throughout the northern hemisphere, mostly at mid-to-high latitudes greater than 30°N, as shown in Figure 3. Strong sub-plumes identified with high effective SO_2 mass can also be seen, i.e. at 46.06°N, 167.3°E. This particular sub-plume could also be seen in the GOES-17/ABI 1.38 µm band (channel 4/cirrus), as shown in Figure 4. The 21 July 2019 time period will be used for the SST retrieval evaluation in this study.

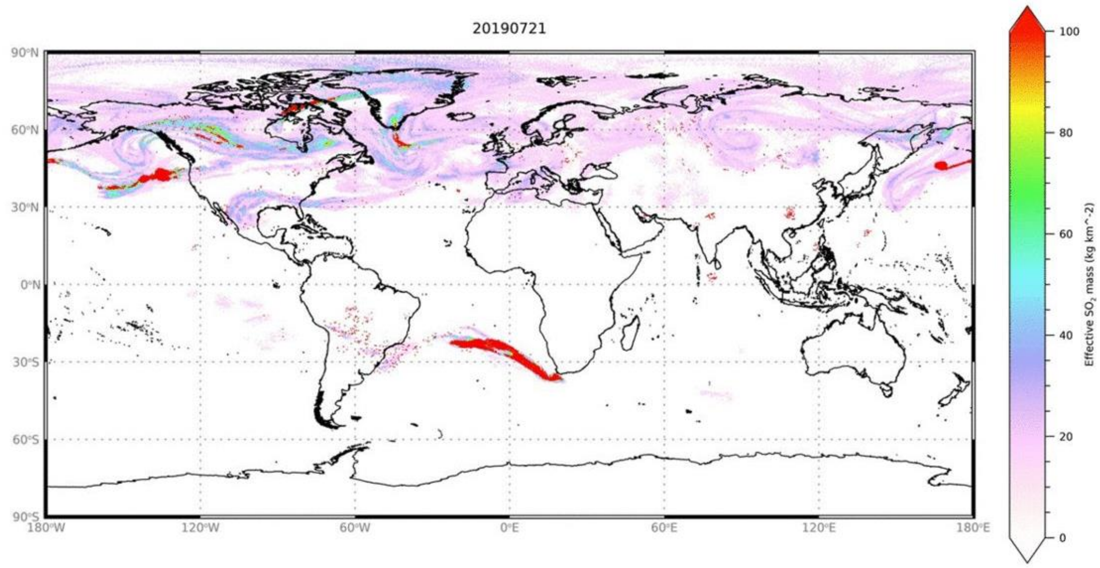

Figure 3: Effective SO2 mass as derived from the Infrared Atmospheric Sounding Interferometer (IASI) on-board Metop European satellites July 21, 2019, image provided by Dr. Michael Fromm (NRL-DC).

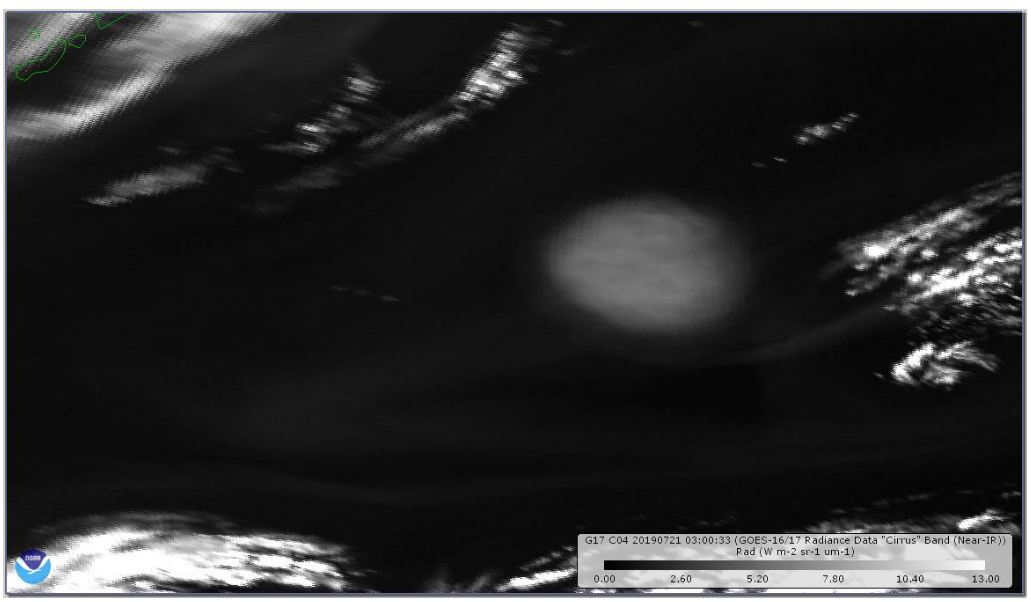

Figure 4: GOES-17/ABI Channel 4 imagery on July 21, 2019 at 3:00 UT. The SO_2 mass sub-plume can clearly be seen in the center of the image which corresponds to approximately to a 46.06°N, 167.3°E location, image provided by Dr. Michael Fromm (NRL-DC).

3.1. GOES-17 SST processing

Although the Himawari-8/AHI satellite data would be more appropriate for this region, the data were not readily available for this time period. Additionally, the typical GOES-17/ABI SST processing coverage does not extend to the Raikoke Volcano area as it is beyond the 65° threshold for satellite zenith angle. For completeness in this study, however, we removed the threshold test for the satellite zenith angle in the GOES-17/ABI SST processing. The resulting SST retrievals for GOES-17/ABI on 21 July 2019 at 0300 UTC are shown in Figure 5, with the intersection of the two black lines indicating the Raikoke Volcano. The SST processing appears to correctly flag and mask out contaminated data even without the satellite zenith angle threshold. It should be noted that some of the data may also be flagged and masked out because the produced SST retrieval becomes unreliable at high satellite zenith angles.

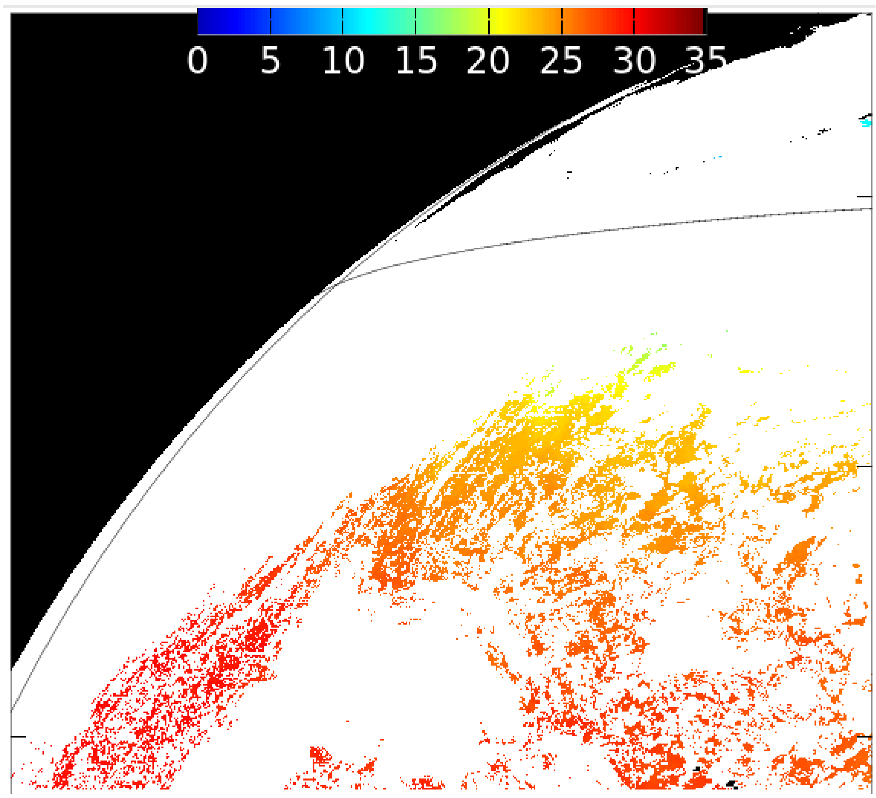

Figure 5: GOES-17/ABI SST retrievals without satellite zenith angle threshold on 21 July 2019 at 0300 UTC. The two black line indicate the latitude at 48.35°N and the longitude at 153.23°E with the intersection pointing to the Raikoke volcano.

3.2. S-NPP/VIIRS SST processing

The VIIRS and AVHRR sensors are both onboard polar-orbiting platforms. We have chosen to examine the performance of the VIIRS SST retrievals from the S-NPP platform in this study. The performance of the updated AVHRR retrievals is expected to be similar. Additionally, only the S-NPP/VIIRS SST daytime retrievals are presented here. The nighttime processing showed similar results, but are not included in this study.

S-NPP/VIIRS SST retrievals are examined in two separate regions, but for the same time period (21 July 2019). The first region is considered strong contamination and is associated with the strong sub-plume associated with the Raikoke eruption identified in Figure 4. The second region is considered weak contamination located between 30 and 60ºN and is away from the strong sub-plume. The concentration of contaminants is expected to be lower in this region.

3.2.1. Strong contamination

The S-NPP/VIIRS reflectance field from the 0.9 µm channel at approximately 0130 UTC on 21 July 2019 is shown in the left panel of Figure 6. Red colors indicate high reflectance (probably contaminated data) while blue colors indicate low reflectance (probably clear data). The semi-circular feature in the center of the image corresponds to the strong sub-plume identified in Figure 4 above. This strong sub-plume extends diagonally from the west side of the region at 45°N to the east side of the region at 52°N.

The corresponding S-NPP/VIIRS brightness temperature field from the 10.7 µm channel (M15) is shown in the right panel of Figure 6. The green area in the middle of the figure, along with the diagonal extension, corresponds to the strong sub-plume that was identified with high reflectance values seen in the left panel. Surprisingly though, the brightness temperatures in regions to the north and south of the sub-plume are only 5 to 6 K colder than expected and are associated with a smooth brightness temperature field. Cloud contaminated areas generally have much colder and more variable brightness temperatures. Those observations carry to the SST field when contamination is not flagged (figure not shown).

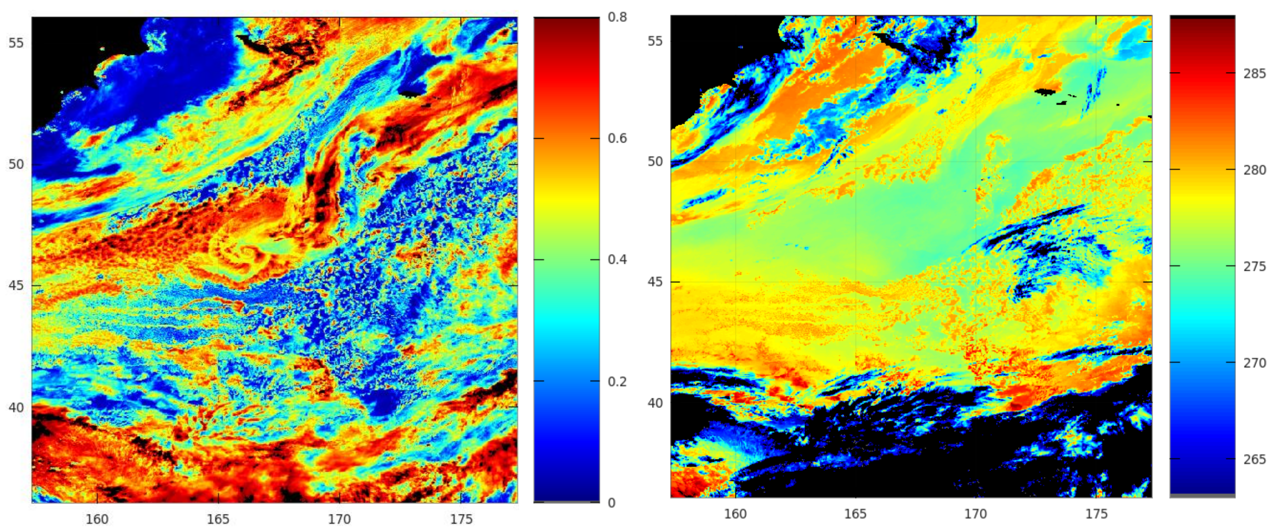

Figure 6: S-NPP/VIIRS reflectance field at 0.9µm (left) and brightness temperature field at 10.7µm (right) on 21 July 2019 at approximately 0130 UTC

The S-NPP/VIIRS resulting SST retrievals on 21 July 2019 at approximately 0130 UTC are shown in Figure 7. Black indicates an area flagged as contaminated or otherwise invalid by the NRL SST software; therefore, no SST retrieval is returned. Flagged areas are non-specific indicators of contamination, and the SST processing does not distinguish volcanic contamination from cloud contamination or other factors that preclude reliable estimation of SST.

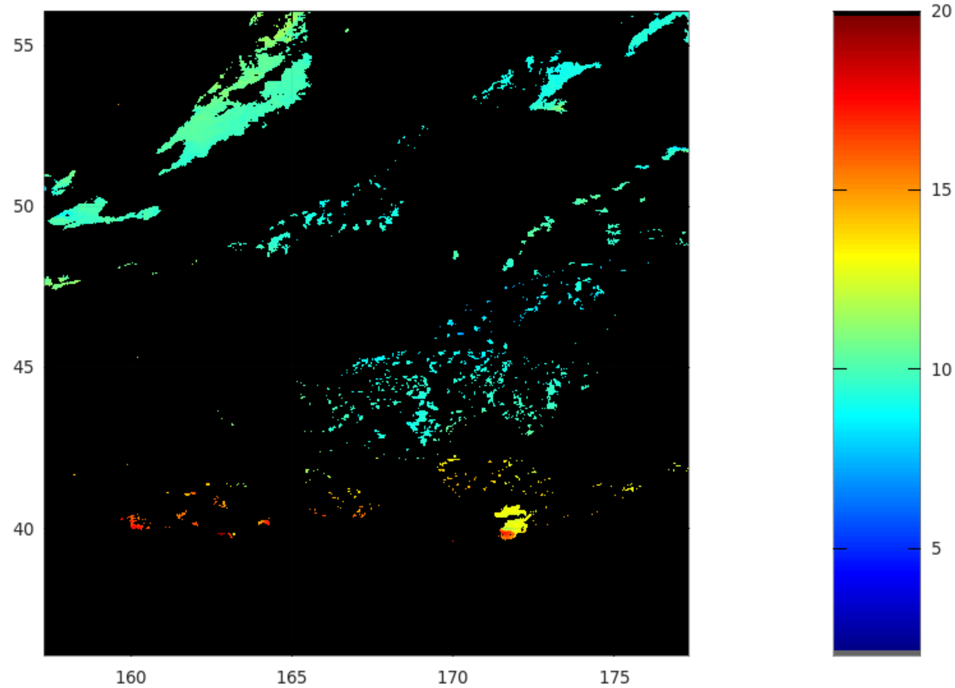

Figure 7: S-NPP/VIIRS SST retrievals on 21 July 2019 at approximately 0130 UTC. Areas that are identified as contaminated are blacked out, including the area corresponding to the Raikoke associated sub-plume.

3.2.2. Weak contamination

The S-NPP/VIIRS SST retrievals on 21 July 2019 from 30°N to 65°N and 120°E to 0°W are shown in the top panel of Figure 8. The SST retrievals produce expected results, with contaminated data being masked out. The K10 field is used as confirming evidence of the validity for the VIIRS SST retrievals. The bottom panel in Figure 8 shows the difference between the SST retrieval field and the K10 background field. Except for the warm spot off the east coast of the USA, which does not seem associated with the presence of contaminants, deviations of the SST field compared to the K10 field mostly fall within a normal range which shows up as a shade of grey.

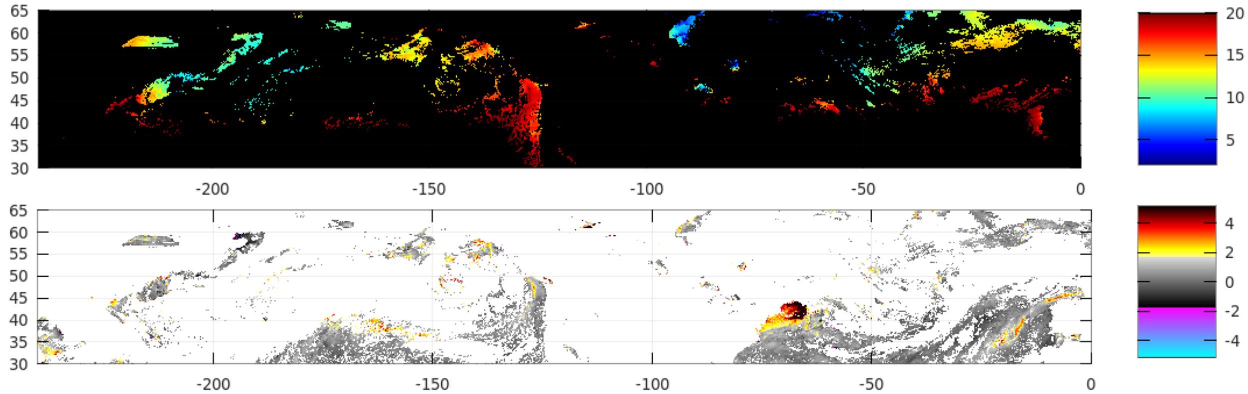

Figure 8: (Top) S-NPP/VIIRS SST retrievals on 21 July 2019 from 30°N to 65°N and 120°E to 0°W. Areas identified as contaminated are blacked out. (Bottom) Corresponding SST retrieval field minus K10 background field.

In an effort to further validate the S-NPP/VIIRS SST processing under weak contamination conditions, we have compared these SST retrievals to SST retrievals processed in this same region but a different year. S-NPP/VIIRS SST retrievals on 14 July 2014 from 30°N to 65°N and 120°E to 0°W are shown in the top panel of Figure 9, with the bottom panel showing the difference between the SST retrieval field and the K10 background field. As seen from 21 July 2019, the SST retrievals from 14 July 2014 also produce expected results, with contaminated data being masked out. Although not immediately obvious qualitatively, the number of SST retrievals in Figure 8 (21 July 2019) is approximately 14 million, while the number of SST retrievals in Figure 9 (14 July 2014) is approximately 16 million. The contamination from the Raikoke eruption is probably a primary reason for the difference in the number of retrievals.

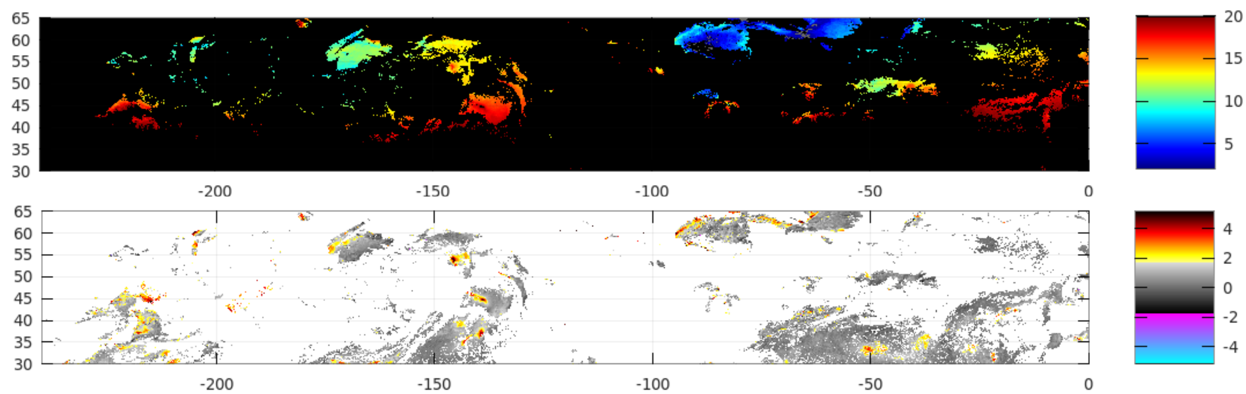

Figure 9: (Top) S-NPP/VIIRS SST retrievals on 14 July 2014 from 30°N to 65°N and 120°E to 0°W. Areas identified as contaminated are blacked out. (Bottom) Corresponding SST retrieval field minus K10 background field.

Another difference in the SST retrievals from 14 July 2014 and those from 21 July 2019, is the reliability of the SST retrievals. In this region, the reliability for the VIIRS SST retrievals is measured with the orbital overlap evaluation method (Cayula et al. 2015), which is briefly described here. Due to the nature of the orbital pattern with polar-orbiting satellites, there are regions of swath coverage overlap between consecutive orbits. These regions with swath coverage overlap increase with increasing latitude, resulting in locations at higher latitudes being more frequently visited than those at lower latitudes. At sufficiently high latitudes, this allows two or more views of the same area of ocean surface from different satellite view angles and optical paths. Over the approximately 100-minute time interval between consecutive orbits, the temperature difference between overlapping SST retrievals includes both true changes in the SST and changes in the SST estimate due to differences in the optical paths through the atmosphere.

SST retrievals within the overlap regions can be compared as a measure of the representativeness of the data. With this method, the SST retrievals from 21 July 2019 have an estimated standard deviation 0.64°K, while the SST retrievals from 14 July 2014 have an estimated standard deviation of 0.52°K. The comparatively slightly higher standard deviation from 21 July 2019 indicates that more data of marginally lower quality is accepted, which would be expected considering the widespread relatively light contamination displayed in Figure 3.

4. Conclusions

The NRL SST software suite v2.7 has been evaluated to determine the ability to flag and mask out contamination from a volcanic eruption using the SST processing tests and checks that are currently in place. In particular, the impact on the SST retrievals from the month following the 22 June 2019 Raikoke volcanic eruption are examined. The validation is performed using SST retrievals from 21 July 2019, which allows for areas with strong contamination and weak contamination to be evaluated separately. Without identifying its type, the SST processing was successfully able to flag contamination from volcanic ash and SO_2, especially when the contamination is strong and more likely to affect the SST retrieval value. When the contamination is weaker, there is a higher probability of the data to be accepted, which leads to lower overall reliability when the contamination is widespread. The S-NPP/VIIRS daytime results were presented here; however, the nighttime results were found to be similar. The AVHRR results are also expected to be similar. In summary, we find that the present NRL SST contamination tests successfully exclude retrievals where the impact of volcanic plumes exceeds acceptable levels while retaining retrievals where the volcanic impact is sufficiently small.

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