SATELLITE-DERIVED SEA SURFACE TEMPERATURES – A CASE STUDY OF ERROR VARIABILITY

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ABSTRACT

In situ measurements of skin and bulk sea surface temperatures have been obtained during a cruise of the RV Southern Surveyor during June 2006. Comparisons with satellite-derived estimates of SST show error variability that may lead to a better understanding of the role of the ocean surface and atmospheric conditions in contributing to the in situ/satellite differences. During the first half of the cruise the satellite estimates from AVHRR tended to be hotter than the in situ measurements while the reverse was the case for the latter half of the cruise. For AMSR-E on the AQUA satellite the estimates at night were in many cases warmer than the ship measurements while the daytime estimates were more accurate. AATSR gave measurements that were close to both the thermosalinograph and a ship-borne infrared radiometer. Measurements of total water vapour column from AMSR-E data and near-surface relative humidity suggest that the AVHRR anomalies are related to vertical water vapour structure in the lower atmosphere. This supports earlier theoretical work reported at the Salzburg ENVISAT Symposium in 2004 and demonstrates the possibility of reducing errors in the SST derivation from AVHRR and other nadir-viewing satellite instruments such as MODIS.

1. BACKGROUND

Two recent papers [1] [2] have suggested that errors in the sea surface temperature (SST) derived from some satellite-borne infrared radiometers are caused by anomalous vertical water vapour (WV) distributions in the lower atmosphere. Theoretical brightness temperatures at wavelengths of 11 and 12 µm were used to develop SST algorithms that were in turn used with the original 885 radiosonde profiles to derive an estimate of the surface temperature. The differences between the original and derived SSTs were shown to be dependent on the WV column above a height of 3.0 km. These results, shown in Fig. 1, clearly demonstrate that the differences (errors in deriving SST) are related to the WV structure in the atmosphere.

Reference [3] has shown that AATSR data over clear-sky oceans can be used to derive estimates of total water vapour (TWV) column using the six AATSR infrared measurements in the nadir and forward views. Further work [2] also demonstrated that it was theoretically possible to derive vertical water vapour structure using the same techniques. Original WV profiles could be re-constructed from model estimates of the six brightness temperatures as shown in Fig. 2. However, minor errors and inconsistencies in the radiative transfer model brightness temperatures currently limit the usefulness of this technique with real AATSR data. Future improvements in the accuracy of infrared radiative transfer modeling should eventually allow for an estimation of vertical WV distributions with accuracies that will allow their use in improving SST estimates from infrared radiometers.

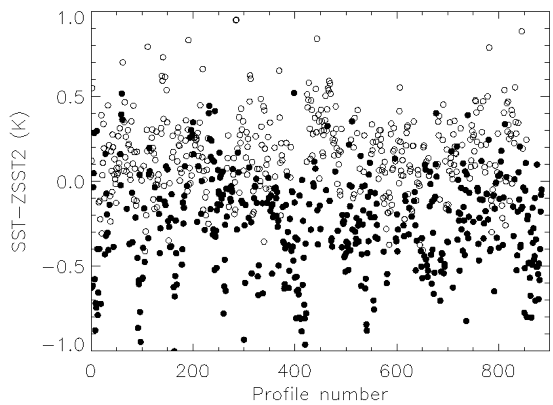

Figure 1. Differences between the original SST and that derived using a two-channel 11 and 12 µm algorithm for the radiosonde profile data set. The full circles are for water vapour amounts of more than 2.5 mm above 3 km and the open circles are for amounts less than 2.5 mm.

2. SHIP TRACK AND DATA COLLECTION

During June 2006 the RV Southern Surveyor operated off the north-west coast of Australia during a three-week period. The ship track is shown in Fig. 3. The DAR-011 infrared radiometer was deployed during the cruise and operated continuously except for a high-wind period (days 161-163) when there was a danger of sea-spray contamination of the exposed optical surfaces. A suite of meteorological instruments was also used to provide a full data set for the cruise.

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Measurements include surface pressure, wind speed and direction, air temperature and relative humidity and down-welling short-wave sky radiance. A thermosalinograph (TSG) also provided a full set of bulk SST and salinity at a depth close to 3 m. The ship data set is plotted in Fig. 4.

3. SATELLITE DATA COLLECTION AND ANALYSIS

During the cruise period data were collected from several satellites that provide estimates of SST at the ship location. These included the AVHRR instruments on the NOAA-17 and -18 satellites, the AATSR on ENVISAT, and the AMSR-E microwave instrument on the AQUA satellite. Full sets of geostationary data from the Japanese MTSAT-1R and the Chinese FY-2C were provided by the Australian Bureau of Meteorology.

Non-linear SST algorithms were used to provide SST estimates from the two AVHRR instruments, standard ESA-based algorithms were used for the AATSR data analysis, and the SST, WV and wind speed estimates from AMSR-E were provided by Remote Sensing Systems. The geostationary SST estimates were not used in the analysis presented in this paper. The orbiting satellite measurements of SST, along with the TSG and DAR estimates, are presented in Fig. 5.

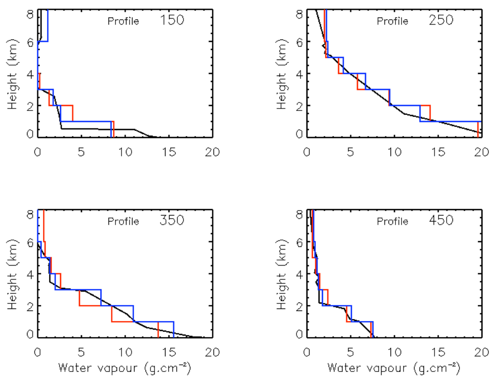


Figure 2. Reconstructed WV profiles using theoretically derived AATSR brightness temperatures for four randomly selected radiosonde profiles. The black lines are the original radiosonde WV profile, blue lines are the radiosonde WV amounts in 1-km layers up to a height of 6 km and the WV amount above 6 km. The red lines are the reconstructed WV amounts in the same layers.

4. SATELLITE-DERIVED SST ANOMALIES

The results shown in Fig. 5 show some interesting anomalies when comparing the ship and satellite measurements of SST. The AATSR shows excellent agreement with the TSG and DAR-011 results. However, it is interesting that the AATSR measurement taken around 1000 hrs local time on days 166 and 169 do not detect the early diurnal warming that is evident in the DAR ship-borne measurements. Whether this is due to this phenomenon being somewhat transient, or some other reason is not easy to assess. The AVHRR also fails to detect any instances of diurnal warming under light wind conditions.

The AMSR-E SST estimates taken during the daytime pass (at 1400 local time) again show excellent agreement with the ship measurements. However the night-time measurements all show that the AMSR-E estimates are too warm by approximately 1 ^{O}C. It is not clear whether this is related to the diurnal increase in wind speed around midnight or some other reason. This anomaly will be explored further with Remote Sensing Systems in the future.

The third anomaly with this data set is related to the AVHRR estimates. Prior to Day 162 there is either good agreement between the satellite and ship data or the AVHRR estimates are too hot by more that 1 ^{O}C. After day 162 the opposite is the case with the AVHRR estimates being either in good agreement with the ship data or are too cold by a similar amount.

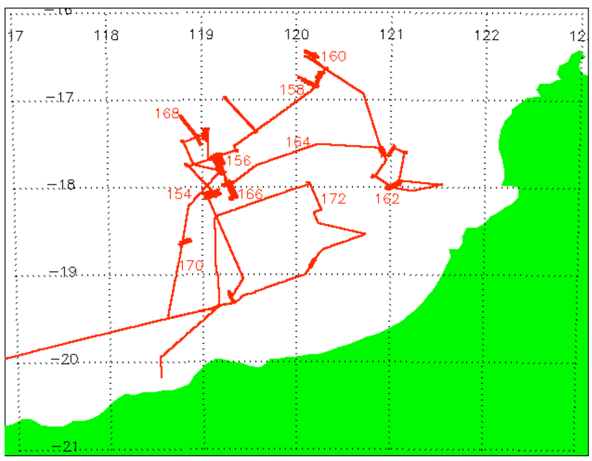
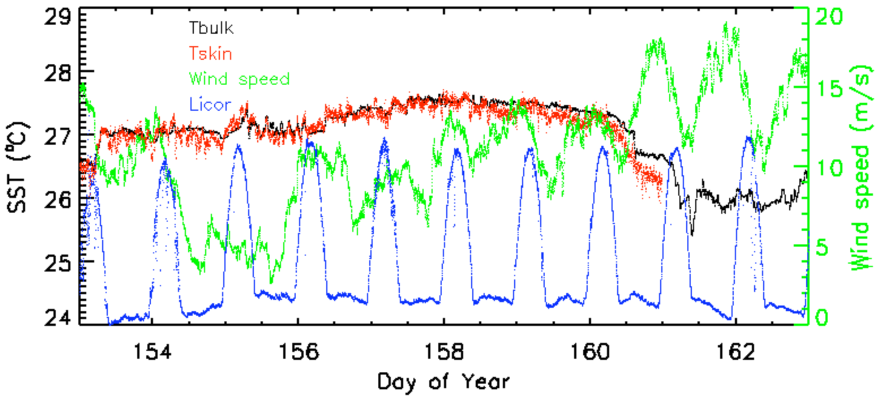


Figure 3. The track of the RV Southern Surveyor during June, 2006. The numbers alongside the track show the ship location at the start of each second day-of-the-year.



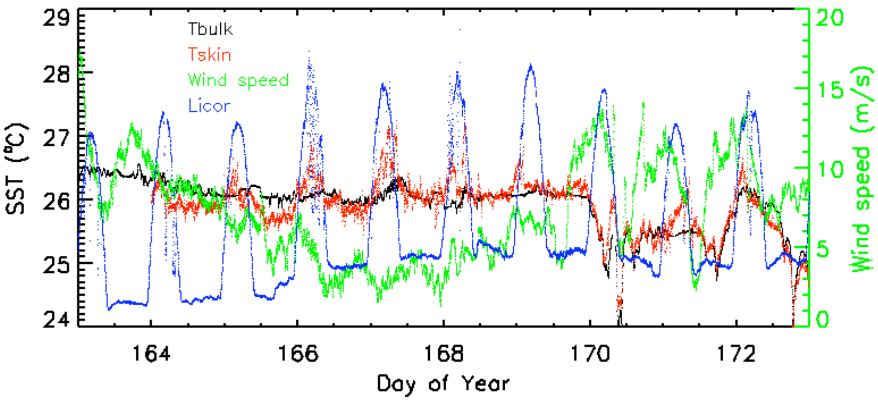


Figure 4. The ship-based data set for the entire cruise. T_{skin} is derived from the DAR-011 infrared radiometer, T_{bulk} from the thermosalinograph, and the Licor data are the down-welling short-wave radiances (with an obvious offset problem during the night).

5. AVHRR ANOMALY INVESTIGATION

The differences between the AVHRR and ship measurements of SST were initially plotted against the satellite zenith angle when viewed from the earth's surface (see Fig. 6). The results show that the larger errors are related to view angle and that the AVHRR usually performs well for view angles less that 35^{O}. The figure also confirms that the differences are negative before day 162 and positive afterwards. Further analyses were undertaken in an attempt to explain this anomaly.

The underlying basis for deriving surface temperatures from infrared satellite data is the differential absorption of the atmosphere at infrared wavelengths. Given that the main atmospheric absorber is WV, it is possible to assume that any brightness temperature difference in two channels is related to TWV content of the atmosphere [4]. To relate this brightness temperature difference to vertical WV amounts it is also necessary to "normalize" the differences for satellite zenith angle effects. The normalized temperature difference is plotted against the time of measurement in Fig. 7 and the figure suggests that there is less TWV in the atmosphere for the second half of the cruise. The figure also shows that the differences are independent of whether the data were from the instrument on NOAA 17 or NOAA-18, although there is a suggestion that NOAA-17 differences are lower in the last few days of the cruise. The normalized brightness temperature differences were also flagged for day and night time data and the results plotted in Fig. 8. Again the results show no dependence on whether the data are for day or night.

Finally, WV estimates are also available from two other sources – the TWV estimate from the AMSR-E microwave radiometer and the surface relative humidity (SRH) from the meteorological suite of instruments carried by the RV Southern Surveyor. The ship measurement was extracted for each pass of the AMSR-E satellite and the two WV estimates for the cruise are plotted in Fig. 9. The figure shows a TWV of more than 30 mm at the start of the cruise decreasing to near 10 mm for days 161-167, an increase to 25 mm for days 67-170, and then 10 mm for the remainder of the cruise. The ship measurements of SRH show a consistent value of 35 to 60% throughout the cruise. The figure also suggests that the profile has excess WV at upper levels before day 162 (higher TWVs and lower SRHs) and a lack of WV at the upper levels after day 162 (lower TWVs and higher SRHs). These vertical WV distributions support the thesis outlined above in which excess WV above heights of 3 km result in a satellite-derived SST that is hotter than the ship measurement, and is colder for those situations when there is a dearth of upper-level WV. This also suggests that any measurement of the vertical profile of WV in the lowest 6 or 8 km of the atmosphere can be used to tune satellite-derived SST algorithms resulting in an improved derivation of SST.

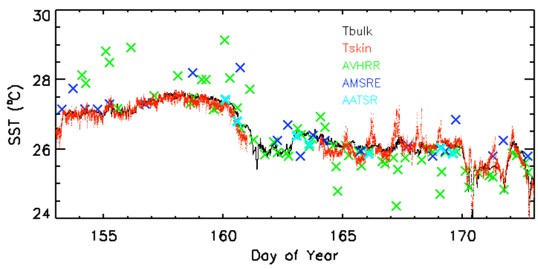


Figure 5. The ship and satellite measurements of SST for the full cruise.

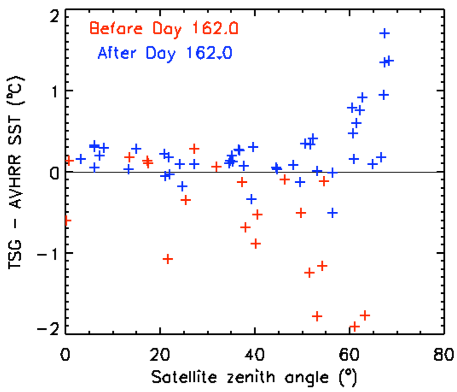


Figure 6. SST difference plotted against satellite zenith angle.

6. CONCLUSIONS

Derivation of simple algorithms to derive SST from infrared satellite data is often undertaken using a multiple regression analysis of surface and satellite data. The success of the algorithm is thus dependent on the assumption of a good "first guess" WV (or other absorbers) profile that is close to the ensemble average of the profiles of the atmosphere for the regression data set. If satellite data are collected with a WV profile that has a shape close to the ensemble average then the first guess is good and the derived SST will be accurate. However, if the WV profile is significantly different to the first guess then severe errors in the SST derivation can occur. Different situations are highlighted in four WV profiles that have been selected from the radiosonde data set mentioned above and are shown in Fig. 10. The top two profiles show cases when there is a good first guess as the shape of the WV profile is close to the average. There is a uniform linear decrease in temperature and also a steady decrease in WV amount with height. In these two cases the first guess is good and an accurate retrieval of SST will be made. In contrast, the bottom two cases are when the WV profile is anomalous. For the bottom right profile (# 20) there is an excess of WV above a height of 2 km, the first guess will be poor, and there will be errors in the derived SST similar to those present during the first half of the cruise. For the bottom left profile (# 19) there is no WV above 2.5 km, the first guess will again be poor, and the derived SST in error (but in an opposite sense to profile # 20.

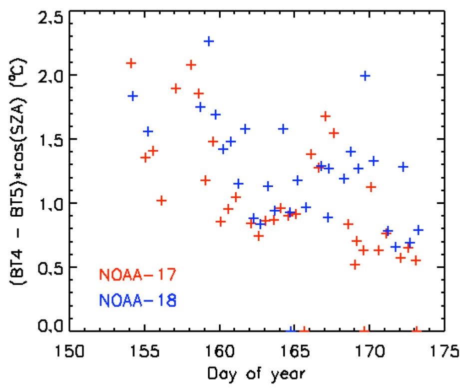


Figure 7. Normalised brightness temperature difference (a surrogate for TWV) plotted against measurement time, and flagged for NOAA-17 or -18 data.

Measurements of SST from several different satellites and ship-borne instruments have provided an insight into techniques that may improve the derivation of SST from satellite radiometers. Errors found in the analysed data set from the research vessel cruise off the north-west coast of Australia confirm an early hypothesis that many of the errors in satellite-derived SSTs can be attributed to anomalies in the vertical water vapour profile in the lower troposphere.

The data analysis undertaken here show that errors in SST derivation are strongly linked to anomalies in the water vapour structure in the atmosphere – and that any measure of this vertical water vapour structure will thus enable an improvement in the SST accuracy for AVHRR-type data analysis.

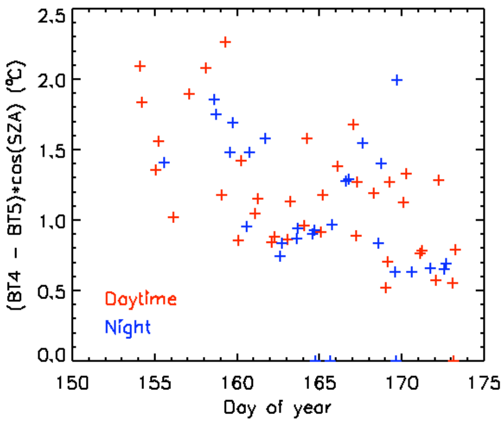


Figure 8. Normalised brightness temperature difference (a surrogate for TWV) plotted against measurement time, and flagged for day or night data.

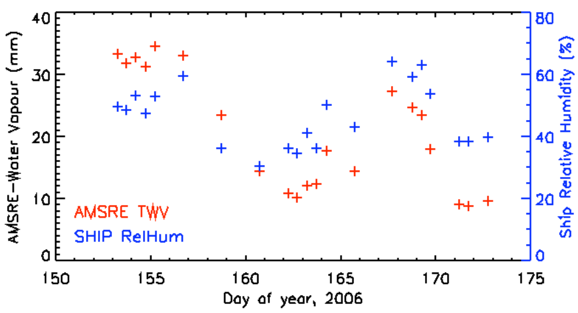


Figure 9. AMSR-E TWV and near-surface Relative Humidity plotted against measurement time.

Finally, useful measurements of vertical water vapour distribution near the surface (the lowest 8 km) over the global oceans are not easy. Possibilities may exist with any visible/infrared instrument that has sufficient spectral resolution to provide near-surface weighting functions that can be used to "sound" the low-level water vapour structure. This will then allow the development of SST algorithms based on the water vapour structure. One possibility is to use AATSR data as mentioned in [2]. Alternatively it may be possible to use the AIRS radiometer flying on the AQUA satellite or any similar instrument. The existing HIRS instrument on the NOAA meteorological satellite can provide good data throughout the depth of the atmosphere but may not have sufficient spectral discrimination to allow the derivation of water vapour structure near the surface [2].

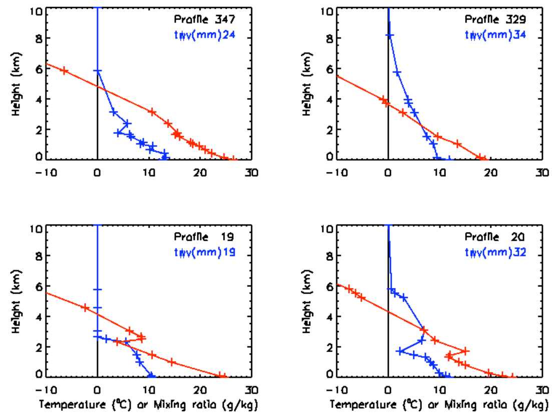


Figure 10. Four selected radiosonde profiles (air temperature, red; WV mixing ratio, blue) showing different water vapour profiles. In these cases there will be a good "first guess" for the top two cases and a poor "first guess" for the bottom two. See the text for further details.

7. ACKNOWLEDGEMENTS

The Australian Bureau of Meteorology has supplied a full set of geostationary data for this cruise while Remote Sensing Systems have supplied the AMSR-E data. Stephen Thomas operated the DAR-011 radiometer throughout the cruise. The captain and crew of the RV Southern Surveyor have also assisted with the data collection, and the CSIRO Data Centre has provided the TSG and meteorological data. This work has been carried out with support through the CSIRO Wealth from Oceans Flagship Program and the BLUElink Joint Project with the Royal Australian Navy and the Australian Bureau of Meteorology. Finally, ESA have kindly supplied the AATSR data.

8. REFERENCES

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