

Ocean Systems

The Magazine for Ocean Professionals



**OCEANOGRAPHIC INSTRUMENTATION;
ENVIRONMENTAL MONITORING**

Measuring air temperature at the surface of the sea with a CAT4 sensor

Innovative CAT4 sensor developed for integration into directional Waverider buoys proven in multiple real world applications

Accurate real-time air temperature is extremely useful for scientific and operational reasons. Knowledge of the air temperature just above the air-sea interface in combination with the water temperature at the surface is needed to determine air-sea interactions when it comes to, for instance, wave growth attributed to wind. Furthermore, air temperature has become a critical parameter of interest since climate change has become such an important topic over the last decade.

From an operational point of view, knowledge of the air temperature is extremely valuable. For instance, when the duration of a measurement campaign is limited by freezing seas, real-time availability of the air temperature data can contribute to the decision to extend a measurement campaign to the limit, without risking the equipment getting lost in drifting ice. Another operational benefit of the availability of the air temperature is found in the detection of a sudden drop in air temperature due to the passing of a weather front. This is a harbinger of bad or changeable weather, endangering offshore operational activities.

THE DATAWELL SOLUTION

An accurate and reliable air temperature measurement at sea is quite a challenge. On the one hand, compared to a land-



Figure 1. The Datawell Waverider is a buoy specifically designed for measuring waves, ensuring accurate, real-time and reliable wave data

based sensor, spray and reflection of the solar radiation on the water surface pose extra requirements on the shielding of the temperature sensor, while on the other hand the marine environment is notoriously hard for mechanical

constructions. Therefore, the shielding of a temperature sensor on a small buoy becomes a trade-off between functionality and vulnerability.

An innovative design developed by Datawell, the Netherlands, for integration

Temperature at the with Datawell buoys

into its well-known directional Waverider buoys, senses the impact of radiation and evaporation instead of shielding the temperature sensor. This highly effective design avoids the trade-off altogether.

To date, this novel design has been proven in multiple "real world" applications, one of them being a study of the spatial resolution of the air temperature just above sea level between two islands in the Wadden Sea in the Netherlands.

THE CHALLENGES TO MEET

The reading of a bare, unshielded thermometer can significantly deviate from the local air temperature. Exposed to solar radiation, the temperature of the sensor can rise by several degrees Celsius. Likewise, thermal radiation by infrared emission in clear sky conditions can lower the temperature of the sensor significantly. The conventional method to greatly reduce these effects is to place a protective shield around the sensor, while still allowing wind to blow through. However, in low wind conditions, the sensor can still warm up by some degrees due to solar radiation. Adding a ventilator to the design overcomes this problem, however it makes the instrument more complicated, vulnerable, and susceptible to interference.

Another, sometimes severer, effect is the evaporation of water. A wet sensor due to rain or fog can cool down several degrees in unsaturated air, effectively becoming a wet-bulb sensor instead of a temperature sensor. A shielded sensor designed for land use will hold off moisture in most conditions, although in the case of fog, or when rain and snow combine with wind, the sensor will become wet.

Measuring the air temperature at sea poses even greater challenges. The sun heats a buoy or ship hull, thereby generating a different microclimate; a well-known pitfall on large buoys in low wind conditions. Spray generated by the buoy splashing in the waves is another way air temperature measurements can be hindered at sea. In contrast, small buoys such as the Waverider buoy create less of a microclimate above the hull, but have a unique challenge of their own: the required shielding of the air temperature sensor, which has to be placed well above the water surface, has a large impact on the stability of these small buoys in stormy conditions. All in all, there are quite some challenges to meet for accurate and reliable air temperature measurements at sea.

A FIT FOR PURPOSE AIR TEMPERATURE SENSOR

The Datawell Waverider is specifically designed for measuring waves, ensuring accurate, real-time and reliable wave data. In order to measure high frequency waves, a relatively small hull (0.7m/0.9m diameter) is required. With respect to air temperature measurements this small hull is favourable as well, since it avoids the microclimate issue. Furthermore, to minimise the impact of the mooring on the wave-following properties of the buoy, a rubber cord is incorporated in the mooring line layout. This extremely flexible mooring, in combination with the small hull, significantly reduces the amount of spray generated by the hull hitting into the waves.

The typical Waverider is equipped with an HF antenna, an ideal location to integrate the air temperature sensor. The

straightforward approach to incorporate a shielded sensor in the antenna proved to be inadequate, introducing excessive fatigue of the materials, acting as a sail and making the antenna oscillate severely at the slightest breeze. Reinforcing the antenna could overcome these problems, however this makes the elegant slender buoy design less stable. Restoring the stability makes the buoy more bulky, decreasing the wave measuring capabilities and ease of handling.

A different approach has been taken to measure the air temperature on the Waverider, thus avoiding these challenges and compromises. It is an approach that increases the accuracy and the reliability of the air temperature measurement on the one hand, while maintaining the Waverider's slender design on the other. The basic idea is not to shield an air temperature sensor, but to quantify the impact of the different environmental phenomena on the air temperature measurement and to either compensate for the impact, or to register the impact and



Figure 2. The Waverider buoy's HF antenna is an ideal location to integrate the air temperature sensor

flag the measurement. Four temperature sensors are integrated into the antenna, each covered with a different material. One temperature sensor is covered with a white plastic, while a second is covered with a black plastic. The impact of solar radiation on these two sensors is different and proportional to the absorption coefficient of the two materials, giving the ability to compensate for the solar radiation. Likewise, the impact of infrared emission is compensated by adding a metal cover on a third temperature sensor since the infrared emissivity of metal differs significantly from the infrared emissivity of plastics. Based on these three temperature measurements, the corrected air temperature can be calculated.

A bonus of this approach is that extreme conditions can be detected as well. In case the antenna is exposed to strong solar radiation combined with virtual windless conditions, excessive temperature differences between the black and white covered temperature sensors will show up. In this situation a first order correction of the impact of solar radiation might not suffice to guarantee the desired accuracy of the air temperature measurement. These “solar induced uncertainty” (SIU) occasions are easily flagged, adding to the reliability of the instrument.

The next question, how to deal with the impact of evaporation? This is not practical to correct for, since it is a combination of many parameters, such as the relative humidity of the passing air, the wind speed and the size and distribution of droplets on the surface that determine the evaporation. Evaporation cools down the temperature sensors. Since compensation for this cooling is not practical, detection of the interference is the second best option. This is achieved by adding a fourth temperature sensor in the antenna covered with a material with a surface structure designed to hold more water than the other covers. When water on the antenna evaporates, this sensor cools down more and for longer than the other temperature sensors. Therefore, when this sensor is warmer than the others, one can be sure

the complete antenna, with the other temperature sensors inside, is not cooled down due to evaporation.

The combination of these four temperature sensors, integrated along with a flashlight in the HF antenna, provide an accurate, reliable and low cost air temperature sensor called the Compact Air Temperature sensor, or CAT4 for short. By selecting the right materials, those that are long lasting and UV-stable, and in the case of metal, a certain type of stainless steel that does not suffer from so called tea-staining in marine environment, the air temperature can be measured continuously for three years, a similar time period to how long a Datawell Waverider can be deployed without any maintenance.

VALIDATION OF THE CAT4 CONCEPT

In order to validate this novel concept for air temperature measurements an aspirated reference weather station (Davis Vantage Pro 2) and a CAT4 antenna have been placed 10 metres high and two metres apart at the Datawell production facility in Heerhugowaard, the Netherlands.

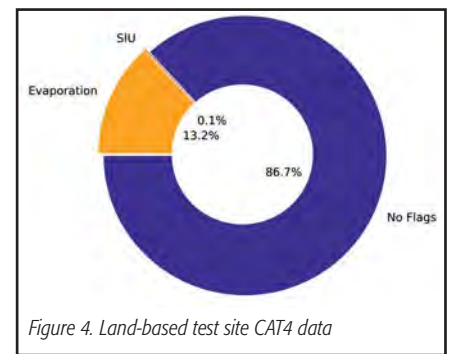


Figure 4. Land-based test site CAT4 data

This setup ensures that any temperature difference between the two measurements has to be attributed to instrumental error. A two-day record taken in the summer, showing all facets of the CAT4 concept, is shown in Figure 3.

Between sunrise and sunset the background of the figure is white while the grey background marks the night period. The first day of this record was a sunny day, resulting in heating of the white sensor by some 2°C. This heating is adequately compensated by the correction mechanism of the CAT4 sensor, even when the SIU flag is raised.

In the morning of the second day there was a period of drizzle or very light rainfall. The evaporation flag is raised until the

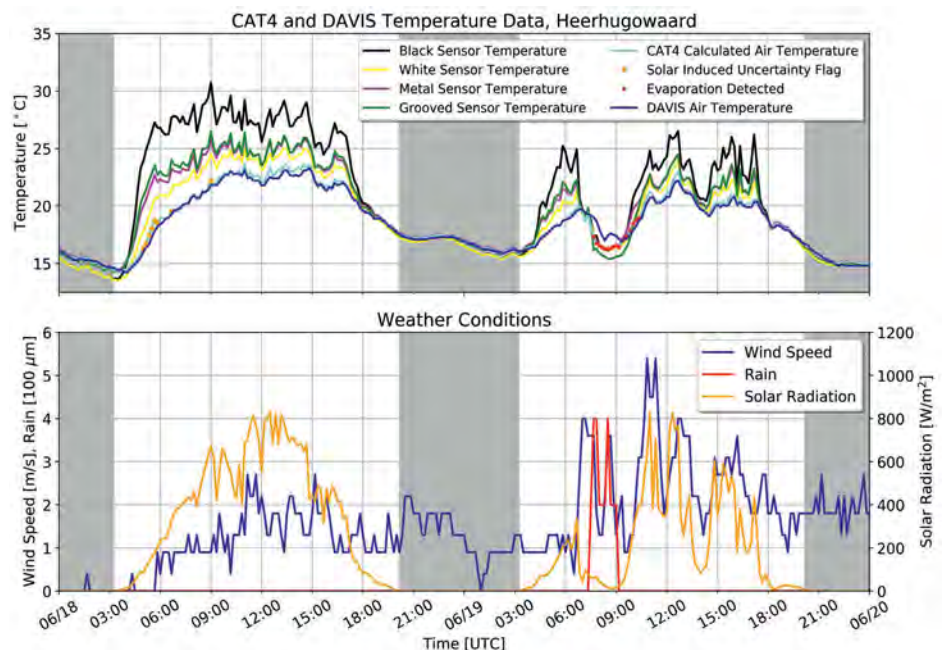


Figure 3. CAT4 and DAVIS temperature data, complemented with DAVIS solar radiation, wind speed and rain data. When the difference between the black and white temperature sensors is larger than 6°C, a SIU flag is set. This flag is present in wind still and sunny conditions, as can be seen on June 18 (first day). When the sensor becomes wet, evaporative cooling can be present adversely affecting the air temperature measurement. Evaporation can be detected when the grooved sensor is cooler than the metal sensor. When the difference is larger than 0.3°C an evaporation flag is set. Such a situation is shown on June 19, when some rain is present. During the period of rain and sometime after that the grooved sensor is clearly cooler than the other sensor, indicating the effect of evaporative cooling on the air temperature measurement

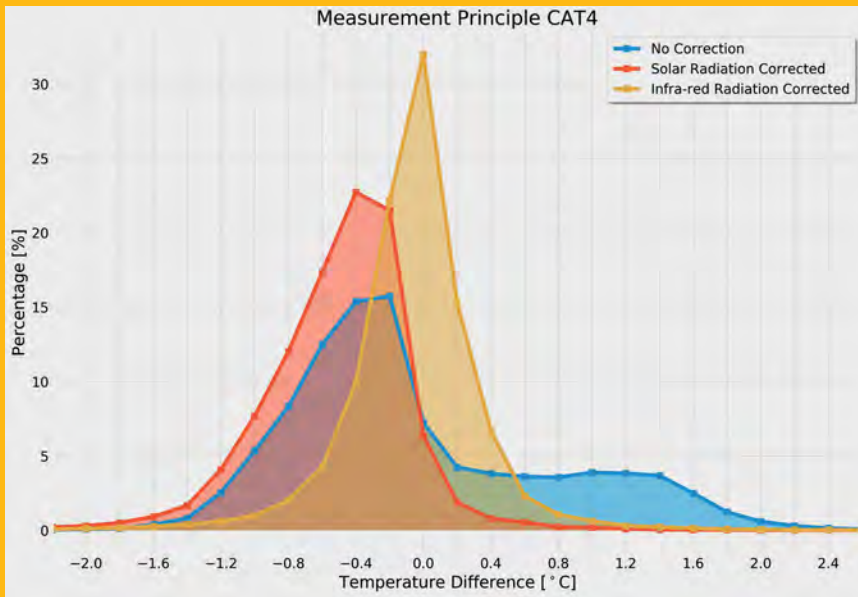


Figure 5. Temperature difference between the reference station and the CAT4 antenna over the course of one year

sensors are dry again. This evaporation flag turns out to be predominant, the SIU flag is hardly set at this location. Over the course of a year, on average a little over 13% of the measurements are flagged. The

statistics of the temperature difference between the reference station and the CAT4 antenna over the course of one year are shown in Figure 5. When all flagged measurements are removed, the sensor

covered in white is regarded as the uncorrected measurement. In that case, the error window ranges from approximately -1°C to $+2^{\circ}\text{C}$. By correction for solar radiation, the heating of the sensor can be corrected, resulting in a significant decrease of the error window on the positive side. A positive error means that the CAT4 air temperature is warmer than the air temperature of the Davis weather station. Furthermore, applying the correction for infrared emission, the error window reduces again. This time it reduces on the negative side, resulting in an overall error window equal to approximately -0.5°C to $+0.5^{\circ}\text{C}$.

Although this land-based test site obviously does not replicate the conditions at sea perfectly, the validation of the CAT4 compensation concept is convincing.

OPERATIONAL EXPERIENCE

Several years of long-term testing of the CAT4 at sea have been conducted in

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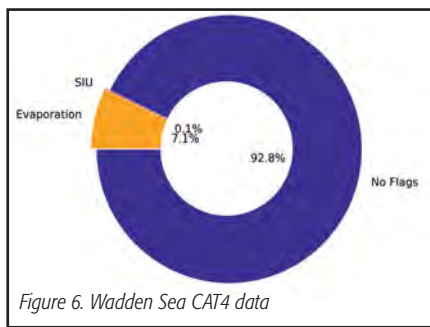
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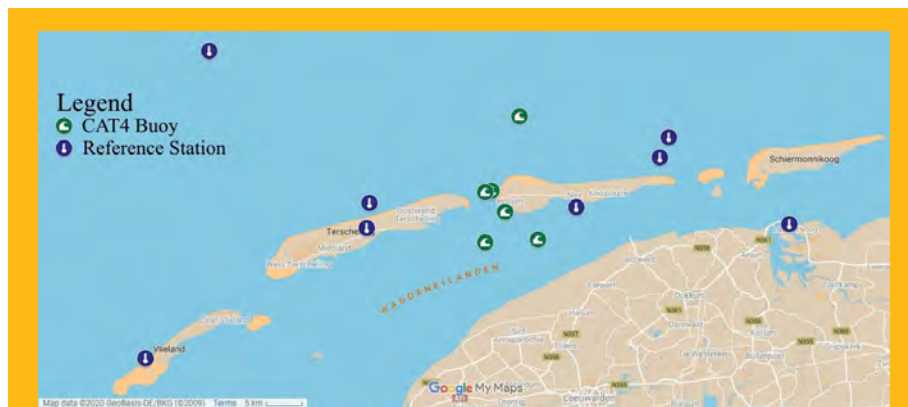


cooperation with national institutes. This validation trajectory of the CAT4 instrument delivered much experience and many insights, both in respect to the quality of the instrument and with its perception within the oceanographic community. Overall, when the evaporation and solar induced error flags are taken into account, the CAT4 concept turns out to be very reliable and the air temperature measurements have shown to be very accurate.

A pleasant surprise arising from the solution is the minimal amount of spray on the instrument. Even when the instrument is deployed in relatively shallow water, the small and flexibly moored buoy rarely generates spray to such a degree that the antenna becomes wet and cooled by evaporation. This is also reflected in the flag statistics. The evaporation flag is set in only 7% of the measurements. This percentage is even lower than the land-based validation site.

An unexpected challenge was to dispel the misconception that the CAT4 design is hindered by the antenna being wet due to rain. By noting that in the case of rain the air is typically saturated with water and therefore no evaporation and associated cooling can take place, this misconception can be swiftly settled.

A possible drawback of the CAT4 concept could be the growth of algae on the antenna. The material designed to hold extra water is potentially vulnerable to turning green, much like tree trunks and branches do. However, it is well known that algae do not grow on the sun-exposed side of a tree. How does this affect the CAT4 antenna? Fortunately, the mobility of a buoy in operation exposes all sides of the antenna sufficiently to the sun to prevent algae growth altogether.



AIR TEMPERATURE SPATIAL RESOLUTION AT SEA

As part of a major project, the air temperature sensors have been deployed on an extensive network of Waverider buoys in the Dutch Wadden Sea. Relatively closely spaced between two islands, an array of the buoys have been installed to study the behaviour of North Sea waves penetrating into the Wadden Sea. Some of these buoys, equipped with CAT4 antennas, are deployed close to existing conventional meteorological measurement sites, both on land and on sea. In this way a study to assess spatial resolution of the air temperature just above sea level under various wind conditions both on sea and

nearshore has been conducted. An overview of the locations of the CAT4 equipped Waveriders and nearby reference stations is presented in Figure 7.

Over the course of approximately one year, the air temperature at the various buoys and stations was collected and analysed. It is to be expected that the temperature readings of two stations in close proximity to each other would be fairly similar, whereas stations with larger spacing in-between or in other microclimates would differ substantially more. As a defining quantity for the uniformity of the measured air temperature between two stations, the standard deviation of the difference between both

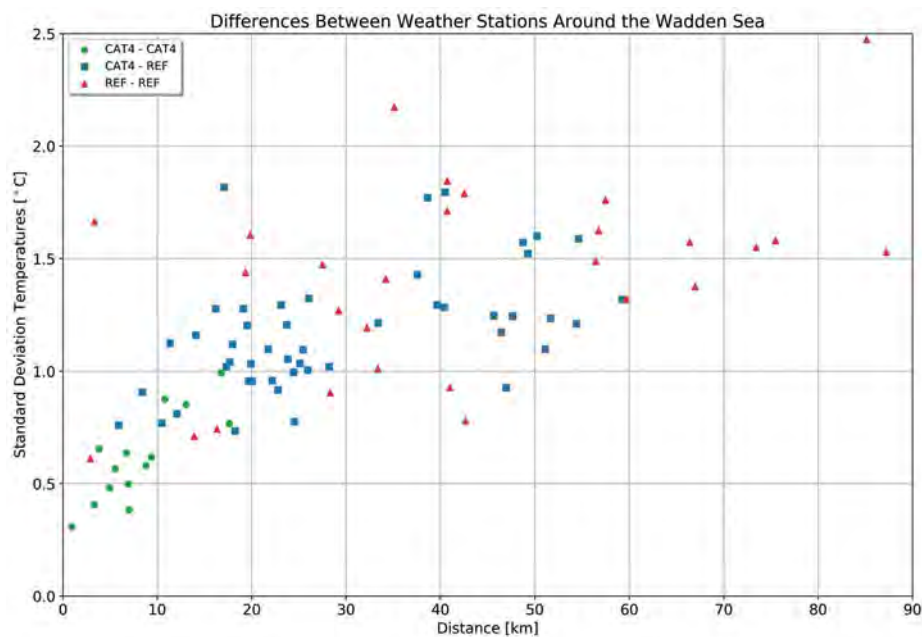


Figure 8. Standard deviation between air temperatures from reference stations and Waveriders equipped with a CAT4 air temperature sensor plotted against distance between the stations. Overall standard deviations increase with distance. Some exceptions are seen. These can be explained by the difference in local conditions. For instance, the red triangle with standard deviation of 1.70°C and 2km apart – these are two reference station in close proximity, however one is situated in the North Sea, while the other is situated in the middle of an island

air temperature sensors is taken, after the flagged measurements have been removed from the record. In Figure 8 this quantity is plotted against the distance between the stations. By shape and colour three groups are defined – standard deviation of the air temperature difference between:

- Two buoys equipped with the CAT4 sensor (green dots)
- Buoys and reference stations in the vicinity of the buoys (blue squares)
- Two reference stations which are typically further apart (red triangles)

The trend of the standard deviation of the air temperature difference is obvious: the closer the buoys are spaced, the smaller this quantity becomes. A typical value is 0.5°C for distances smaller than 10 kilometres when placed in a similar climate condition, or below 1.5°C when keeping the distance smaller than 30 kilometres. A few exceptions are related to the difference between the local climate conditions at the open North Sea and the (islands) of the Wadden Sea, resulting in a larger standard deviation of the air temperature difference than expected.

SOLAR INDUCED UNCERTAINTY

For practical reasons, testing and validation of the CAT4 concept concentrated on test sites in the North Sea. In order to evaluate the instrument in different climate and weather conditions and to gain valuable user experience, the product was sent to multiple Waverider owners around the world. For more sun-exposed sites, CAT4 antennas were sent to Australia and California, USA. Some of these locations are close to existing conventional meteorological measurement sites. At one such site in California, based at the Scripps

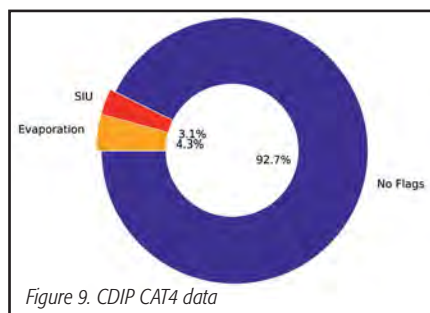


Figure 9. CDIP CAT4 data

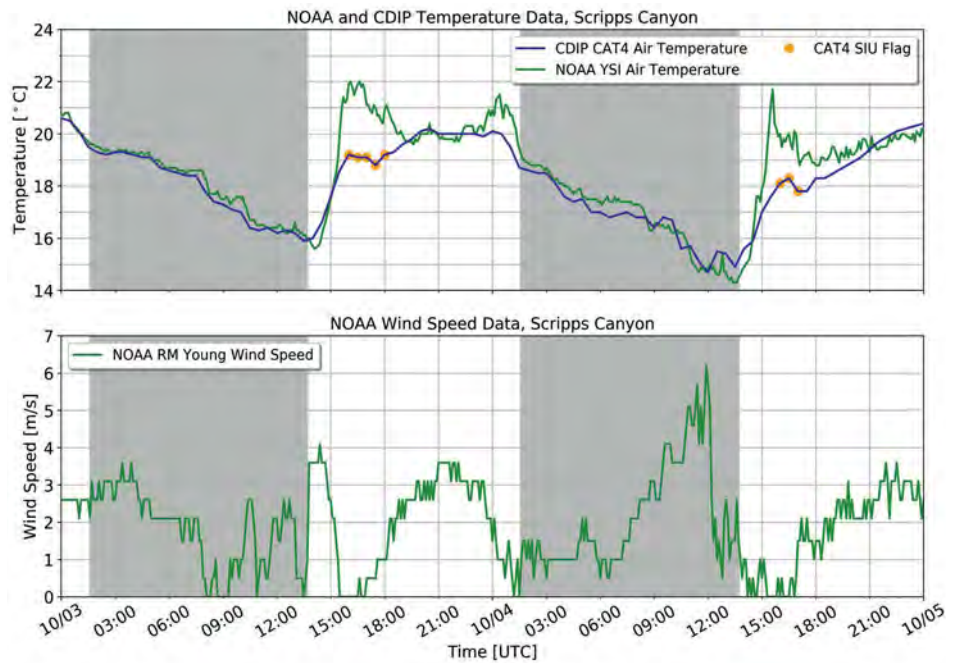


Figure 10. NOAA YSI air temperature at the Scripps Pier and CDIP CAT4 air temperature from a Directional Waverider at 800m from the pier, complemented with wind speed data. This data is accessible for the public via a variety of official platforms, including ones operated by the Coastal Data Information Program and the National Data Buoy Center. Generally, the air temperature measurements correlate very well, except in sunny windless conditions. These conditions are often flagged by the CAT4 air temperature sensor – at these times the air temperature of YSI air temperature sensor can be significantly greater than the CAT4 air temperature sensor due to the microclimate that can form under the shields of the air temperature sensor

Institution of Oceanography and called Scripps Nearshore, a Waverider is deployed as part of the Coastal Data Information Program (CDIP). The site is situated at roughly 800 metres from the Scripps Pier. The pier is equipped with a YSI air temperature sensor, making the site ideal for making a one-on-one comparison with the CAT4 antenna mounted on a directional Waverider. A typical result is presented in Figure 10.

The CAT4 antenna at Scripps Nearshore has been in use for roughly one year, continuously gathering temperature data. The SIU flag is set at approximately 3% of the measurements. During the year of operation the standard deviation of the temperature difference is 0.6°C, in agreement with the results of the project in the Wadden Sea. Two noteworthy results of this comparison show up. Firstly, the SIU flag indicating a temperature difference larger than 6°C between the black and the white covered temperature sensor, is not set at noon when solar radiation is at its maximum, but in the morning and evening when the sun’s rays are more horizontal. At this time, the sun’s

rays give full exposure to the vertical antenna and reflections off the water surface can be more prominent. Secondly, in the case of bright sunshine and windless conditions there is a significant difference in measured temperatures. The CAT4 reports the lowest temperature, as is to be expected, when a shielded air temperature sensor is not forcefully ventilated.

CONCLUSION

Though the conditions for measuring the air temperature just above the seawater on a small buoy are notoriously challenging, the concept of compensating for radiation effects and detection of cooling down by evaporation has shown to give accurate and reliable measurements. Land-based validation has shown that the accuracy is better than 0.5°C. The fraction of the time this accuracy of the measurements cannot be guaranteed due to unfavourable conditions at sea is less than 10%. All in all, the CAT4 air temperature sensor has proven to be an effective and valuable instrument to be used in the harsh marine environment and is much appreciated by the Waverider users.