MASDA – MODAS Adaptive Sampling Decision Aid

Mona J. Collins, NRL 7183
Stennis Space Center, MS, 39529, USA
mona.collins@nrlssc.navy.mil

Donald R. DelBalzo, NRL 7183
Stennis Space Center, MS, 39529, USA
delbalzo@nrlssc.navy.mil

Charlie N. Barron, NRL 7323
Stennis Space Center, MS, 39529, USA
barron@nrlssc.navy.mil

Abstract – **The Modular Ocean Data Assimilation System (MODAS) produces oceanographic nowcasts based on a) climatology, b) remotely-sensed sea surface temperature and height, and c) in-situ measurements. Recent analyses have shown that the locations of in-situ measurements can have a profound influence on the accuracy of the MODAS synthetic profiles. Small-scale variability combined with sparse sampling and inappropriate covariance scales can lead to a spreading of unrepresentative anomalies. The MODAS Adaptive Sampling Decision Aid (MASDA) is being developed to guide the selection of Airborne Expendable Bathy Thermograph (AXBT) measurement locations to improve the accuracy of MODAS analyses while minimizing the number of required measurements. MASDA uses the computed MODAS temperature uncertainty to predict the optimum sampling locations. The iterative in-flight MASDA approach is to recommend sequential measurement locations based on sequentially computed temperature uncertainty. The pre-flight combinatorial MASDA approach is to recommend the best combination of N measurement locations based on the computed temperature uncertainty. These environmentally driven sampling strategies are expected to increase accuracy of MODAS analyses relative to MODAS analyses based on alternate sampling strategies with the same number of observations. AXBT measurements from several ocean areas are being used to develop and test MASDA algorithms. Preliminary results showing improvement in MODAS accuracy using the MASDA method for selecting observations compared to more subjective selection methods are presented.**

I. INTRODUCTION

The Modular Ocean Data Assimilation System (MODAS) produces oceanographic nowcasts based on a) climatology, b) remotely-sensed sea surface temperature and height, and c) in-situ measurements [1-5]. Recent analyses have shown that the locations of in-situ measurements can have a profound influence on the accuracy of the MODAS synthetic profiles. Small-scale variability combined with sparse sampling and inappropriate covariance scales can lead to a spreading of unrepresentative anomalies.

The MODAS Adaptive Sampling Decision Aid (MASDA) is being developed to guide the selection of Airborne Expendable Bathy Thermograph (AXBT) measurement locations to improve the accuracy of MODAS analyses while minimizing the number of required measurements, *i.e.*, to reduce cost and time. MASDA uses the computed MODAS temperature uncertainty to predict the optimum sampling locations. The iterative in-flight MASDA approach is to recommend sequential measurement locations based on sequentially computed temperature uncertainty, *i.e.*, choose the best location, assess the impact, choose the next, etc. The pre-flight combinatorial MASDA approach is to determine the best combination of N measurement locations based on the computed temperature uncertainty, *i.e.*, choose many sets of N locations, then assess the combined impact of all N locations for each of them, and then select the best set. By focusing on reducing uncertainty, these environmentally driven sampling strategies are expected to maximize accuracy of MODAS analyses relative to MODAS analyses based on alternate sampling strategies with the same number of observations.

AXBT measurements from several ocean areas are being used to develop and test MASDA algorithms. In the development phase, MASDA is constrained to select preferred observation points from among the set of AXBT measurement locations. After the MODAS assimilation of the MASDA-selected measurements, the MODAS temperatures over the entire set of measurement locations are compared to the AXBT measurements to determine how accurate the resulting MODAS temperatures are. Preliminary results show improvement in MODAS accuracy using the MASDA method for selecting observations compared to more subjective selection methods.

II. MASDA

MODAS produces oceanographic nowcasts and corresponding oceanographic uncertainty nowcasts. Initially the MODAS uncertainty field is based on the climatological standard deviations and the uncertainties in the sea surface temperature and height projected to the derived synthetic profiles. When in-situ measurements are ingested by MODAS, the uncertainty at and around the measurement locations is reduced in the MODAS nowcasts. It is this ability to provide temperature uncertainty that makes MASDA possible. MASDA uses the computed MODAS temperature uncertainty to predict the optimum sampling locations that will minimize the uncertainty over the AXBT operational region. Since we can *a priori* estimate the uncertainty (but not the actual error), MASDA assumes that observations that minimize uncertainty also tend to maximize accuracy of the MODAS analyses. MASDA incorporates two approaches to predicting the optimum sampling locations. They are a) the iterative in-flight approach and b) the pre-flight combinatorial approach.

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A. Iterative In-flight Approach

The iterative in-flight approach starts with the most recent MODAS uncertainty field. The sequence of in-flight steps follows. 1) Evaluate the MODAS uncertainty field to determine the location of highest temperature uncertainty. 2) Make an AXBT measurement at that location. 3) Assimilate the AXBT measurement into MODAS to produce a new MODAS field and associated uncertainty. 4) Evaluate this new uncertainty field to determine the location of highest temperature uncertainty. 5) Repeat steps 2 through 4. This iterative process continues until the available AXBT devices are expended or the uncertainty reaches an acceptable level. In this way, MASDA uses information from previous measurements to avoid over-sampling the environment and to improve the accuracy of MODAS analyses by sampling the environment more objectively and efficiently.

As MASDA development progressed, it became apparent that using the magnitude of MODAS uncertainty as the sole deciding criterion was insufficient or inadequate. Sometimes, the MASDA-preferred location was in very shallow water. Although the uncertainty was highest there, little temperature vs. depth information would be obtained by a measurement at that location, limiting the relevance of that observation to estimates over the upper 300-m. Often a nearby location with slightly less uncertainty but in deeper water would provide more temperature vs. depth information and result in a more accurate MODAS temperature nowcast. In addition, the defined region of interest may cause some observations to be more or less useful. A measurement has impact on the analysis within a radius of its location as defined by the MODAS covariance model, which for this study is based on the Rossby radius of deformation. Sometimes, the MASDA preferred location, based on maximum uncertainty, was near the coastline or the edge of the operational area. Such a location might have most of its influence outside the area of interest. Nearby locations away from the boundary provide information relevant to larger (useful) regions. Such locations with only slightly lower uncertainty can be expected to more efficiently increase overall MODAS nowcast accuracy.

In order to address these two issues of water depth and area of impact, water volume is now used to weight the uncertainty prior to selection of the preferred measurement location. The volume is a function of the water depth and the Rossby radius. The maximum water depth is set to 300 m since this is the useful depth limit for AXBT measurements. The volume does not include land or extend outside the AXBT operational area. By weighting the uncertainty by volume, MASDA can select locations with lower absolute uncertainty but higher volumetric impact.

B. Pre-flight Combinatorial Approach

The second MASDA approach is the pre-flight combinatorial approach. While the in-flight method targets locations of maximum non-weighted or volume-weighted uncertainty, the pre-flight method calculates the impact of the observation(s) on the uncertainty of the MODAS product. Like the iterative in-flight approach, the most recent MODAS uncertainty field is used. Unlike the iterative in-flight approach, the pre-flight combinatorial version of MASDA is run before the AXBT flight leaves the ground. The user must specify the number of AXBT devices to be dropped and potential measurement locations. MASDA determines every possible combination of the potential measurement locations with the specified number of drops and the total volume-weighted uncertainty for each combination. Overlapping volumes for locations within a combination are divided equally among those locations. MASDA then selects the 50 combinations with highest total volume-weighted uncertainty. For each of those combinations, MODAS is run, ingesting simulated measurements placed at the measurement locations within the combination, to determine which combination results in the minimum average uncertainty over the AXBT operational region. That best combination of AXBT measurement locations is then recommended.

Although the pre-flight combinatorial approach is not designed to be an iterative approach, it can be by specifying one AXBT drop and running MASDA sequentially. The result using the pre-flight combinatorial approach in this way is not necessarily the same as the iterative in-flight approach. The two can be different because the procedure behind each is different. For the next measurement location, the in-flight approach picks the location of maximum volume-weighted uncertainty from the most recent MODAS uncertainty field. For the next measurement location, the iterative pre-flight approach picks the location where a simulated measurement ingested into MODAS results in the minimum average uncertainty over the AXBT operational region. Those measurement locations may not be same.

III. MASDA RESULTS

In order to demonstrate MASDA, 44 AXBT measurements taken in the summer from one ocean area are used. The measurements were distributed in a nearly uniform pattern throughout the area of interest (outlined in white). Fig. 1 shows the bathymetry for this region with shallow water depths in the West and deeper water depths in the East. The depth is indicated by color with the dark blue color representing depths of 1800 m and greater.

The MODAS temperature uncertainty based on climatology and sea surface temperature (SST) is shown in Fig. 2. The darkest blue color indicates uncertainties less than 1.50°C and the darkest red color indicates uncertainties of 1.74°C and greater. In its development phase, MASDA is constrained to select preferred measurement locations from the set of AXBT measurement locations. The star indicates the AXBT location that is chosen as the first measurement location when maximum, unweighted uncertainty is the deciding criterion for MASDA. Notice that this location is a near-shore, shallow water location. It does have the highest uncertainty but a measurement at this location will provide limited temperature-depth information and have limited regional impact.

The water volume is shown is Fig. 3. The volume is a function of the Rossby radius (as used in MODAS covariance

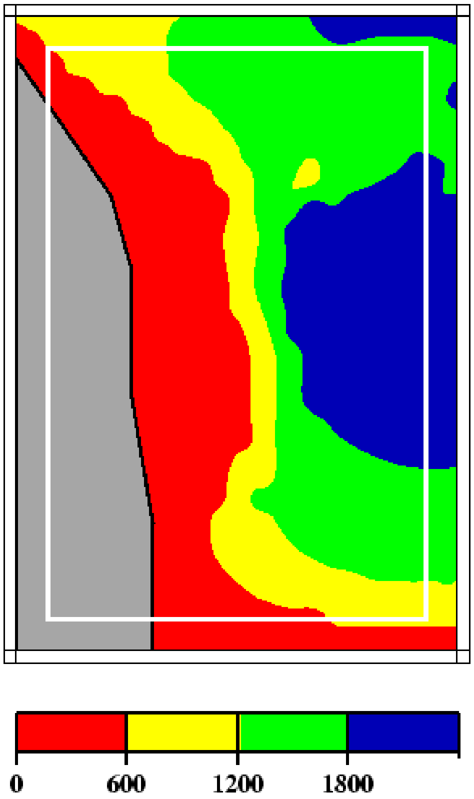

Fig. 1. Bathymetry (m) in the study area.

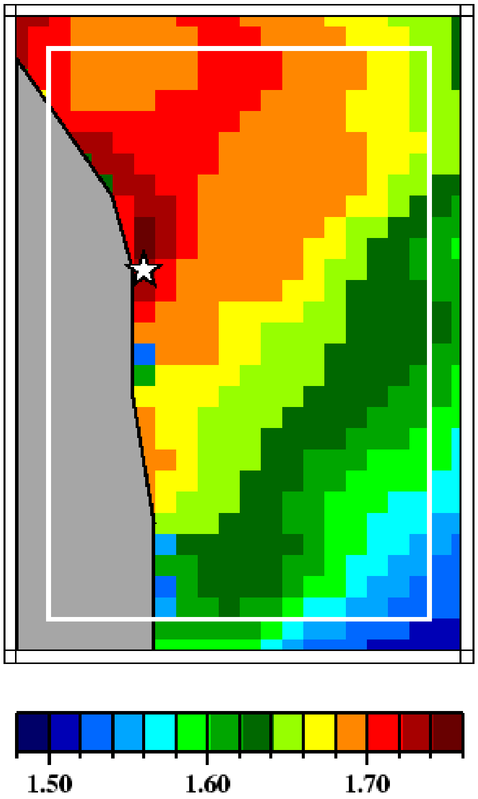

Fig. 2. MODAS uncertainty (°C) in the study area. The star indicates the AXBT location with the maximum uncertainty.

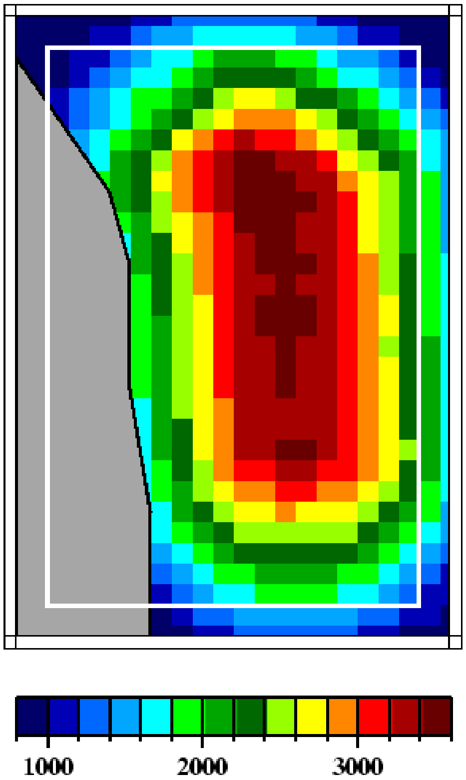

Fig. 3. Water volume (km^3) in the study area.

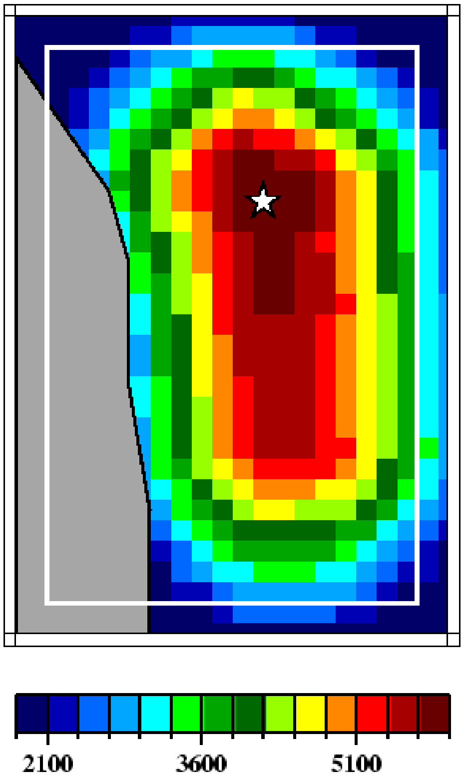

Fig. 4. Volume-weighted uncertainty (km^3 * °C) in the study area. The star indicates the AXBT location with the maximum volume-weighted uncertainty.

model) and the water depth. The maximum water depth used in computing the volume is 300 m. The darkest blue color indicates volumes of less than 1000 km^3 and the darkest red color indicates volumes of 3400 km^3 and greater. The volume is greatest in the deeper water away from the operational boundaries. It is least in very shallow water and near the corners of the operational area.

The volume-weighted uncertainty is plotted in Fig. 4. The darkest blue color indicates volume-weighted uncertainty is less than 2100 (km^3 * °C) and the darkest red color indicates volume-weighted uncertainty is greater than 5500 (km^3 * °C). The star indicates the AXBT location chosen for the first measurement when volume-weighting is applied. The uncertainty at this location is lower than that of the location selected by the unweighted method (1.69°C vs. 1.74°C), but the greater volume more than compensates.

Current methods for selecting AXBT locations are highly subjective, but they provide the only benchmarks available. To assess MASDA, 20 or more combinations of N measurement locations were hand-selected. The two main criteria for the hand selection were to 1) use each measurement location in at least one combination and, more importantly, 2) spread the observations to sample the entire environment. These selections were somewhat biased because all the data, including the AXBT measurements and previous MODAS and MASDA results, were known by the selector. For one observation, each AXBT measurement location was selected, so there are 44 combinations with one observation. There are 30 combinations with two observations, 30 with three, 20 with four, and 30 with five.

The average uncertainty as a function of the number of observations is shown in Fig. 5. The uncertainty is averaged over the first 100-m of depth and then all 44 AXBT measurement locations. The average uncertainty for zero observations is the average of the climatology and SST uncertainties at the AXBT locations. The purple dots (labeled “Select”) indicate the uncertainties for the hand-selected combinations. When uncertainty alone is the deciding criterion by which the iterative in-flight MASDA selects preferred locations, the blue line (labeled “Uncert”) shows the result. With each added observation, the average uncertainty decreases but hand-selecting the measurement locations is normally better.

When volume-weighted uncertainty is the deciding criterion by which the iterative in-flight MASDA selects preferred locations, the green line (labeled “Volume”) in Fig. 5 results. Again, the average uncertainty decreases as the number of observations increase. For the first five observations, the average uncertainty is less with volume-weighting than without. For one and two observations, the volume-weighted MASDA approach results in uncertainties equal to or less than the minimum uncertainty of the hand-selected combinations (“Select”). For three or more observations, there are hand-selected combinations with lower average uncertainty. For the iterative approach, each single selection is optimal for reducing uncertainty from the step immediately prior, but an alternate deployment (one which produces sub-optimal intermediate reductions in uncertainty) may ultimately lead to greater uncertainty reduction.

The red stars (labeled “Combo”) are the pre-flight combinatorial MASDA results. Since there are only 44 AXBT locations, there are only 44 combinations with one observation. For multiple observations, there are 50 combinations each. Data from MASDA-selected locations are ingested into MODAS to determine which combination results in the minimum average uncertainty, as shown in Fig. 5. In cases with more than one observation, the pre-flight combinatorial MASDA produced sets of observations which reduced uncertainty more than the other methods (“Select”, “Uncert”, and “Volume”).

The pre-flight combinatorial MASDA approach can be run in an iterative fashion by specifying one location at a time and running MASDA sequentially. The result is shown in Fig. 5 as a black line (labeled “Iterate”). When MASDA is used in this fashion, the minimum uncertainty is not reduced for three and more observations as much as the combinatorial planning method. However, the minimum uncertainty is the same or less than that for both the unweighted uncertainty (“Uncert”) and volume-weighted uncertainty (“Volume”) iterative in-flight MASDA. Table I lists the average uncertainty for all these cases. The hand-selected uncertainty listed in the table is the minimum of the average hand-selected uncertainties. The minimum, rather than the average, of the average hand-selected uncertainties was chosen for consistency.

TABLE I

AVERAGE UNCERTAINTY VS. NUMBER OF OBSERVATIONS

Number of Observations	Select	In-flight MASDA		Pre-flight MASDA	
		Uncert	Volume	Combo	Iterate
0	1.675				
1	1.467	1.522	1.467	1.467	1.467
2	1.326	1.425	1.321	1.318	1.318
3	1.238	1.331	1.256	1.203	1.232
4	1.153	1.286	1.218	1.132	1.160
5	1.087	1.197	1.165	1.072	1.094

Building confidence in MODAS by optimally reducing uncertainty is one goal of this work. Another goal is to reduce absolute temperature differences between the MODAS and AXBT temperatures. The average RMS error as a function of the number of observations is shown in Fig. 6. The RMS error is averaged over the first 300-m of depth and then all 44 AXBT locations. The AXBT measurements are compared to the MODAS first guess temperatures (climatology with SST assimilation) to determine the average RMS error for zero observations. The format of this figure is similar to the previous figure. The errors for the hand-selected combinations with the minimum average uncertainty are outlined in black. The minimum average uncertainty was chosen for consistency. For the first two observations, they are over-plotted by the pre-flight combinatorial MASDA errors.

Table II summarizes these results. For the in-flight MASDA (“Uncert” and “Volume”), there is no consistent improvement in error reduction when the volume-weighting

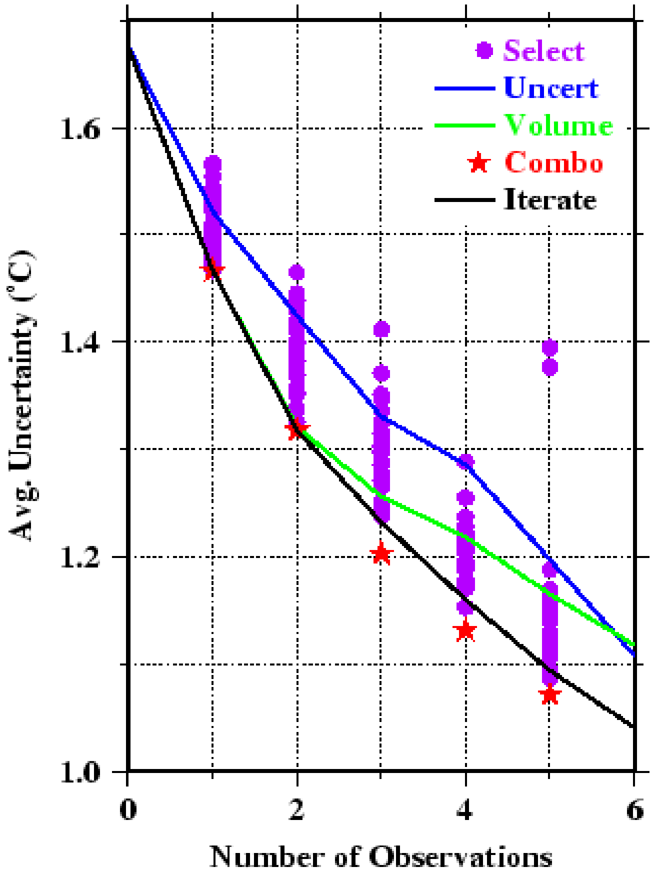

Fig. 5. Average uncertainty (°C) vs. number of observations.

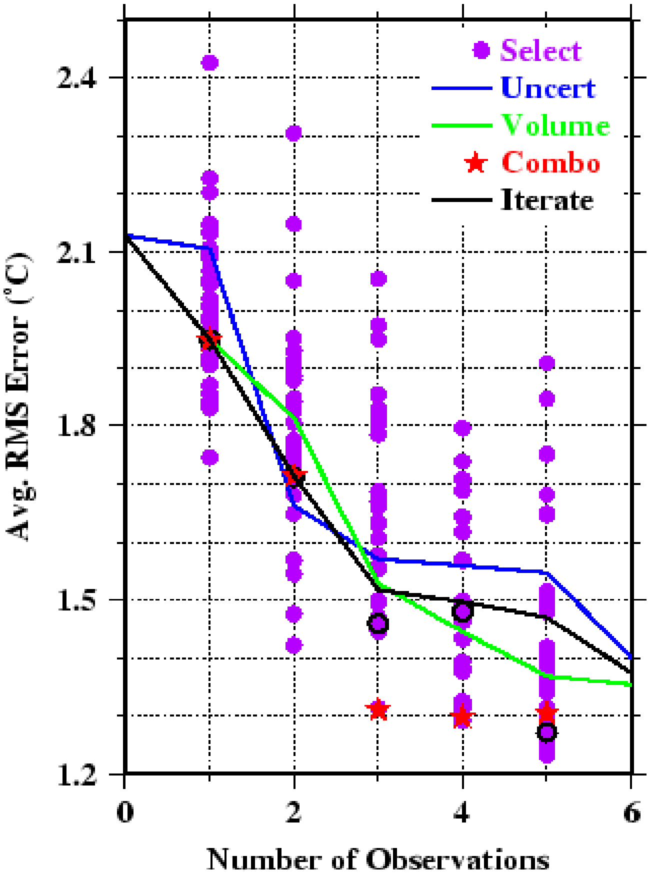

Fig. 6. Average RMS error (°C) vs. number of observations.

is applied prior to selection of preferred locations. The pre-flight iterative errors (“Iterate”) are similar to the in-flight errors (“Uncert” and “Volume”). The non-iterative, pre-flight combinatorial MASDA approach (“Combo”) is the best overall MASDA technique to date for reducing error, especially for 3 or more observations.

TABLE II

AVERAGE RMS ERROR VS. NUMBER OF OBSERVATIONS

Number of Observations	Select	In-flight MASDA		Pre-flight MASDA	
		Uncert	Volume	Combo	Iterate
0	2.129				
1	1.949	2.106	1.949	1.949	1.949
2	1.711	1.663	1.813	1.713	1.713
3	1.459	1.570	1.528	1.311	1.517
4	1.479	1.560	1.445	1.299	1.497
5	1.271	1.547	1.369	1.305	1.470

Minimum average uncertainty does not necessarily equate to minimum average RMS error. If the true error field were known beforehand, implying that the true temperature field is known, there would be no question of where the measurements (if any) should be made and MASDA would not be needed. The MODAS uncertainty is the best guide available at this time to help select measurement locations to improve MODAS nowcasts. As MASDA development progress, MASDA will continue to be tested in the various ocean areas. The MASDA pre-flight combinatorial approach still needs further software development and evaluation. As the number of measurements to be made increases, the task of computing all the combinations becomes unreasonable. If further testing confirms that the uncertainty reduction using the pre-flight combinatorial MASDA approach in an iterative fashion is comparable to the uncertainty reduction using the pre-flight combinatorial MASDA approach in its original non-iterative fashion, it may be the best solution.

IV. SUMMARY

Data from several ocean areas were used to develop an approach for optimal AXBT sampling in support of MODAS nowcasts. The MASDA algorithms for selection of optimum sampling locations were examined in the study area and evaluated in terms of reduced temperature uncertainty and increased MODAS accuracy. The in-flight MASDA approach recommends sequential measurement locations based on sequentially computed MODAS temperature uncertainty. The pre-flight, planning MASDA approach recommends the best combination of N measurement locations, also based on MODAS temperature uncertainty. Volume weights on the uncertainty estimates improve MASDA AXBT location selections based on reduced average uncertainty. Associated error reduction is greatest when the pre-flight combinatorial method is used. These preliminary results are encouraging and are leading to better algorithms for choosing sampling locations to maximize MODAS accuracy and minimize the number of required samples.

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