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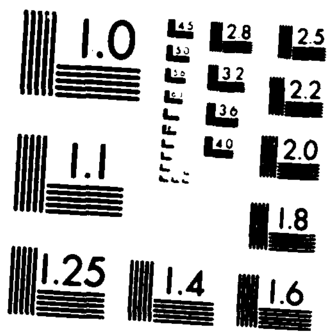

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NSTL, Mississippi 39529

Multichannel Sea Surface Temperature Retrievals for Navy Utilization

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March 1985

ABSTACT

This publication includes minutes of a meeting that addressed aspects of multichannel sea surface temperatures and their implementation at the Fleet Numerical Oceanography Center. The meeting was held at the Naval Ocean Research and Development Activity, NSTL, Mississippi, and focused on present capabilities, as well as problems.

ACKNOWLEDGMENTS

The author wishes to thank all of the MCSST meeting participants for contributing to the detailed discussions outlined in this technical note. Their past experience and knowledge gained is an extremely valuable asset that must continue to be utilized if the Navy is to produce high quality MCSST data at FNOC. Special thanks are due to Paul McClain and Bill Pichel who have spent many hours over the last several years bringing the author up to date on MCSST development and implementation. This report was supported by the Satellite Oceanography Tactical Application (SOTA) program, sponsored by CAPT David Honhart of OP-952 and managed by Al Pressman of NORDA's Remote Sensing Branch under program element 63704N.

MULTICHANNEL SEA SURFACE TEMPERATURE (MCSST) RETRIEVALS FOR NAVY UTILIZATION

INTRODUCTION

A meeting was held at the Naval Ocean Research and Development Activity (NORDA) on December 12-14, 1984, to address several aspects of multichannel sea surface temperatures (MCSSTs) and their implementation at the Fleet Numerical Oceanography Center (FNOC). The specific goals of the meeting were (1) to provide a forum for questions and answers between researchers and operational MCSST personnel (see Table 1), (2) to investigate ways to increase the accuracy and efficiency of MCSST software, and (3) to provide recommendations to the NASA Earth Resources Laboratory (ERL) and to FNOC on MCSST techniques for Navy utilization. This technical note includes the minutes to the meeting and covers the discussion on a list of 10 agenda items that focused on the present capabilities, as well as on problems that still remain to be solved with operational use of MCSST data. The topics were

1) cloud detection,
2) water vapor correction,
3) aerosol correction,
4) noise contamination,
5) seasonal problems,
6) instrument calibration,
7) accuracy,
8) resolution,
9) contouring of data, and
10) channels for future satellites.

As explained in the notices for the meeting, all subjects were not scheduled to be dealt with to the same degree. Thus, the length of time spent on any given area was directly proportional to the interest and number of questions. Items 5, 8, and 10 were covered only briefly, while considerable attention was given to items 1, 2, 3, 6, and 7. The following commentary summarizes the more important points raised during the discussions.

TOPIC:

(1) Cloud tests

a. The visible cloud detection tests have evolved over the years to the point where they take into account various aspects of the sensor and sun angles existing for a given retrieval. This increased sophistication has resulted in the ability to extract numerous MCSSTs from partly cloudy regions, as well as better accuracy due to less cloud contamination in targets selected for final processing. The visible cloud threshold table that defines the acceptable values is still being fine-tuned. In this regard, image processing capabilities will greatly enhance any efforts to update this type of cloud test. The ability to actually see the areas that meet or exceed the test criteria overlayed on the image will accelerate the updating process.

The National Environmental Satellite Data and Information Service (NESDIS) has now implemented their MCSST cloud tests on an image processor so that they can carry out more extensive tests as mentioned above. It is recommended that NORDA provide any assistance possible to NESDIS in this effort to utilize the capabilities of such

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a system, since one has been in place at NORDA for 7 years. If it is possible to divide some of the tasks required to update these tests, then NORDA and NESDIS could work in tandem.

Recommendation: Establish close link between cloud testing procedures between the image processing facilities at NORDA and NESDIS.

b. The advantage of having channel 3 on the Advanced Very High Resolution Radiometer (AVHRR) has routinely been negated by the high noise levels experienced shortly after liftoff on all satellites to date. The ability to discern clouds at night has sometimes degraded to the point where no retrievals can be made. The majority of the MCSSTs thus come during the day when channel 2 (visible) is the main cloud detector. The reason for the 80,000 MCSSTs, in view of this development, lies in the fact that several high-density retrieval areas significantly increase the total number of available reports. A clean channel 3 would alleviate some of the burden now experienced by daytime algorithms. Software changes could then be made to calculate multiple MCSSTs per target array at night.

c. Areas of high sunglitter could be calculated and processed correctly if the appropriate data were available. This will be the case for the Navy Remote Ocean Sensing System (NROSS) when a scatterometer, altimeter, and low-frequency microwave radiometer will provide surface winds, significant wave height, and SST independent of the AVHRR. The sunglitter potential could then be calculated and used to help distinguish between glitter and sun contaminated AVHRR data.

d. The tests that use one channel to predict the temperature in another are not very effective in terms of the additional targets that are rejected and are serious candidates to be dropped from the FNOC MCSST software. The intercomparison tests that follow the prediction tests will likely catch these cloud-contaminated targets.

(2) Water vapor correction

a. The multichannel algorithms correct for the intervening attenuation due to water vapor by utilizing the differential absorption that occurs between channels 3, 4, and 5. The coefficients used to combine these channels originated in November 1981 and were updated significantly in September 1982 when new temperature dependent bias corrections were implemented. This change was possible when a sufficient surface truth data base was available to determine if the coefficients were suitable for a diverse range of SSTs.

The present accuracy of 0.5-0.7°C indicates that the water vapor correction is doing a very good job over the global range of temperatures. However, a number of surface truth studies in regional areas suggest that MCSST values can be on the low or high side, depending on the particular circumstances that occur at the time. In other words, MCSSTs in the Great Lakes during the spring have problems, while corresponding ones in the Gulf of Mexico during winter are probably as accurate as expendable bathythermographs (XBTs). This topic quickly gets beyond just water vapor correction and into skin vs. bulk temperature arguments, as well as low-level atmospheric inversions. More will be said about this later.

b. As noted in the discussions, there must be some gradient in either channel 4 or 5 for the split window equation MCSST data to sense a front (i.e., if the thermal field for channels 4 and 5 is flat due to very large water vapor attenuation, then no set of coefficients can bring out the true SST field. Thus, in some tropical environments, infrared SSTs cannot see the actual SST gradients.

More work is needed in the area of water vapor corrections, especially with extended surface truth and high-quality radiosonde data. Unfortunately, this is not easy to come by, but there is an opportunity during some upcoming field programs. The Tropical Ocean Global Atmosphere (TOGA) effort in the tropical Pacific will have a considerable number of SSTs and upper air data that may be beneficial to water vapor modeling efforts.

Recommendation: It is imperative that a clean channel 3 be operational to provide accurate global MCSSTs. Without this infrared (IR) window's ability to see through moisture, tropical applications of MCSSTs will not reach their full potential.

c. A number of microwave sensors will be launched in the future that may help provide additional data to determine the appropriate water vapor correction. The Special Sensor Microwave/Imager (SSM-I) will be available in 1986 and will provide multichannel microwave data at 12-25 km resolution that may help IR data more adequately define the correct amount of water vapor. The poorer resolution of this instrument and the collocation of the two sensors is a problem, but research efforts can afford this type of luxury.

(3) Aerosol correction

a. Confidence in the capability of MCSSTs erroded significantly when the volcanic aerosols from the El Chichon eruption degraded the retrievals. The sulphuric acid particle cloud circled the globe and eventually spanned both hemispheres while adversely affecting MCSSTs by totally disrupting all cloud screening tests. The aerosols elevated the brightness temperatures to the degree that the cloud tests threw out virtually all targets whether or not they were cloud contaminated. The noise in channel 3 only made matters worse and resulted in few, if any, retrievals in the area of the volcanic cloud. This problem has dissipated along with the cloud, but needs to be addressed for future incidents.

NESDIS has done research on this problem and now has available a new algorithm that utilizes channels 3, 4, and 5, which theoretically will produce MCSST data to within 1°C accuracy. However, there is no noise-free channel 3, 4, and 5 data available during the volcano time period to test the new equations on. We will have to wait and see what the next occurrence brings.

Work has also been done by Dr. Griggs of Science Applications International Corporation (SAIC) while under contract to both NESDIS and the Naval Environmental Prediction Research Facility (NEPRF) concerning the use of the AVHRR to calculate the aerosol optical depth. This parameter could then be used to adjust the MCSSTs and derive a more accurate retrieval. Further work needs to be done on both these techniques with actual data.

Recommendation: Bring this effort to the forefront, since it appears capable of improving MCSSTs now, as well as being able to deal with volcanic and dust storm extremes.

b. The simple fact that a volcanic cloud of aerosols caused tremendous headaches with MCSST data points out that MCSSTs are not fault-proof. The present good accuracy of these values has directly resulted form the continued diligent efforts by NESDIS personnel. The volcano was just another in a series of problems that pop up from time to time. Thus, the MCSST software cannot be installed at FNOC and then left unattended for the foreseeable future. Manpower must be made available to monitor the ever-changing conditions under which the infrared sensors work. NORDA, the Satellite Oceanography Tactical Application (SOTA) program, and FNOC will have to allocate the resources necessary to come up with the updates needed to keep the MCSST algorithms in tune with our changing understanding of the intervening atmosphere, as well as the quirks of nature and the sensor itself.

Recommendation: The NESDIS MCSST software contains a large amount of flexibility that allows offline testing with little or no impact on the operational production. This must be carried over to the FNOC system or it will quickly become obsolete.

(4) Noise contamination

a. As mentioned previously, the noise in channel 3 has been a problem for all AVHRR sensors. Sometimes the noise is acceptable for up to a year after launch, other times it comes more quickly. Engineers believed they had fixed the problem on NOAA-9, but they thought it was solved on NOAA-8 also. Early readings from NOAA-9 indicate the noise issue is still with us, possibly more so than ever.

b. The ever-changing noise contamination directly affects not only the cloud tests but the final MCSST values if that channel is used to produce an atmospheric correction. The triple window equations are used at night and this combination of channels has proven in the past to be the most accurate and thus indicates that MCSST retrievals will not achieve their full potential until the noise problem is successfully dealt with.

Recommendation: The Navy should indicate to NOAA that they are genuinely interested in the problem of noise in channel 3 for the production of MCSST data at FNOC and request to be kept up to date on the efforts to remedy it.

c. The noise in each channel must then be routinely monitored to assure that the MCSST values will not be degraded. If a critical level is reached, then decisions must be reached and action taken to modify the algorithm used. This requires a certain level of manpower and resources not presently set aside for the production of MCSST data at FNOC.

Recommendation: FNOC and NORDA must have corresponding billets devoted to the constant monitoring and application of changes as they occur. This must be in turn backed up by the necessary exploratory research and widespread cooperation with others in the community to be successful. The general notion that IR SSTs need little or no attention since they have reached a high level of confidence is incorrect. Only continued work will maintain the high-quality SST values needed daily for numerous Navy applications.

(5) Seasonal problems

a. NESDIS has experienced a number of confusing instances where MCSST data started to go bad in a certain area for no apparent reason. They then immediately committed several people full time for 3-4 weeks to analyze the cloud tests and find out why cloud-contaminated data was being let through to the MCSST equations. In one case, they proved that the culprit was very low sun angles in the northern Pacific as we went from fall to winter, and the distinction between the use of day and night algorithms crossed a fine line. The low sunlight caused the cloud top values to change just enough to sneak by the cloud test.

b. We already mentioned the problem in the Great Lakes during the spring when the air-sea temperature differences are quite large with the air much warmer than the SST. NESDIS is looking into how to correct for this, but they need an adequate data base of SST and radiosonde data to attack the question.

c. NESDIS also had some problems with MCSST values in the SW Pacific near Indonesia when numbers were consistently too high, but were still within the climatological threshold. They found that the original data set used to derive the MCSST equations did not contain the extremely moist atmospheres common to this area during the summer. A subsequent effort obtained data for this condition and the equations were recalculated, which resulted in significantly improved accuracy.

Recommendation: These types of problems come up every once in a while and require immediate attention by a group of people capable of devoting full time to the problem who are familiar with the operational scheme. A multiagency SST Research Panel made up of NESDIS, NORDA, and FNOC experts should meet periodically in person or via teleconferences to coordinate and research algorithm problems and changes.

(6) Instrument calibration

a. Calibration of the AVHRR data has taken on increased significance because of several developments. First, the thermal sensitivity of the sensor is now 0.12°K. Second, the accuracy of MCSST data on a global basis has been demonstrated to be between 0.5 and 0.7°C. Third, the MCSST equations are extremely sensitive to calibration errors, since the whole concept of atmospheric correction is based on the differential absorption between two or more channels. Therefore, if one channel is miscalibrated or the calibration changes from one line to the next, an artificial jump in the MCSST value will result.

This can be seen in the following example where the split window equation is used on some actual data for the Gulf of Mexico. Equation (1) below is the operational split window formula for NOAA-7. One can clearly see that the channel 4 values are multiplied by 3.6139, while the channel 5 temperatures are multiplied by -2.5789. A 0.1°C increase in the channel 4 value will then result in a MCSST increase of 0.361, while a corresponding increase in channel 5 will give a decrease of 0.258°C. These numbers are large when compared to the reported accuracies of 0.5-0.7°C. Thus, one must be very careful as to how the data is calibrated.

$$MCSST = 3.6139 \times T11 - 2.5789 \times T12 - 283.18, \quad (1)$$

where T11 = channel 4 temperature in K,
T12 = channel 5 temperature in K.

The topic of AVHRR calibration is not helped when one considers that the principal document used by all parties is National Environmental Satellite Service (NESS) Technical Report #107. This review of the calibration procedures is worded in a confusing manner in several critical sections. For example, a number of independent researchers have questioned the section dealing with the application of a nonlinearity correction. It appears now that NESS has confirmed that such an adjustment is not done to the operational MCSST data. This aspect shoud be included in future validation efforts to determine the effect it would have if implemented at FNOC.

c. The calibration technique has at least two major forks in the road. One can approximate the spectral characteristics of each AVHRR channel by using a central wavenumber or actually grind out the integral value that spans between, say, 10.3-11.3 μm. Most folks take the easy way out and use the central wavenumber approach. I know that work has been done in the past on the difference of the two methods and would like one of the meeting participants to jog my memory with some numbers. Please send me some information if you have it available.

d. After the above questions have been conquered, one must then decide how many scan lines to use in calibrating the data. The NESDIS computer compatible tapes (CCTs) can produce a new set of slope and intercept values every 5 scan lines, depending on the fluctuations of the reference black bodies onboard the satellite. However, the recalculation of the calibration coefficients every 5 lines will produce slight changes which, when combined with the MCSST coefficients, will give ever changing SST retrievals. It is best, then, to average a number of scan lines together to smooth out this jump, which can easily be seen in imagery format. Several MCSST producers select a large number of lines to average (100-700), while others simply average the slope-intercept data over the whole data set being processed and then go back and calibrate it with one set of coefficients. Still others use varying running averages that allow new values to affect the current number to different degrees. The method selected is up to the end user and the specific application the data is intended for.

Recommendation: FNOC should average as large a segment as possible to bring about consistency unless NORDA or NESDIS find that more frequent updates are required.

(7) Accuracy

a. Satellite-derived SSTs have come a long way since their first use back in 1970 with the ITOS system. The root mean square (RMS) error when compared to ships was about 2.5°C. By 1980 this value had dropped to 1.5°C because the sounder onboard the TIROS spacecraft provided a meaningful atmospheric correction for the IR data. The next large stride forward occurred with the operational implementation of the mulitchannel technique when pixel-by-pixel corrections for water vapor were possible. This procedure allowed a break through the 1°C RMS barrier while approaching the threshold of 0.50°C. This appears to be about the best we can do with GAC data since accuracy degrades with increasing channel 3 noise.

b. The advances in the state of the art for satellite IR SSTs has now brought up another issue. What constitutes the best "surface truth" for comparison purposes?

1. Ships have been used since the beginning because they represented the only data set in which you could collect large numbers of reports over short time intervals and because they cover a relatively large range of SSTs. However, closer scrutiny indicates that ship "intake temperatures" have considerable problems of their own. Accuracy from ship to ship can vary dramatically and the "intake" temperature can be biased on the high side due to the heat of the vessel and the depth at which it is taken (3-10 m is quite different from the upper centimeters sensed by the satellite). Thus, the RMS value of MCSSTs when compared to ships can be large and very misleading.

Ship data must be very carefully screened to be used for this type of application. Several procedures were applied to the Jet Propulsion Lab (JPL) Workshop ship data base to throw out dubious ship SSTs. The result was that a considerable number of ship observations were removed from the total data set, and the matchups with MCSSTS were then on the order of 0.5-0.6°C.

Recommendation: The screening procedures for ship data at FNOC should be checked and compared with the efforts by JPL and changes made if it is determined that poor ship reports are being allowed into the thermal structure analysis or as comparisons for MCSST data. A well-coordinated anchor network of well-calibrated ships would be useful for MCSST accuracy monitoring.

2. Buoys have increased in number over the last 5-10 years such that they now represent a respectable data set by themselves. The potential for very accurate temperature readings at depths of about 1 m make them a promising addition to any surface truth effort. However, most of the large fixed buoys are deployed in coastal waters where the SST gradient is quite strong. Thus, a matchup of an MCSST value that is located 20 km from a fixed buoy can be totally erroneous because the two sensors are measuring different water samples. Care must then be taken to collocate the two measurements as close as possible to eliminate this problem. The obvious limitation of this restriction is the fact that fewer matchups will result and the sample may have little statistical significance.

Drifting buoys have literally dropped into the picture as surface truth candidates within the last couple of years as more oceanographic field programs utilize them, partly because of declining costs. These air-deployable buoys are now scattered over the world's oceans and thus report back a spectrum of SSTs under a wide range of water vapor conditions. Their calibration is relatively good and they usually exist in deep-ocean regions where the SST gradient is much smaller than the fixed buoys. Therefore, the capture radius used for colocating MCSST data can be larger.

Recommendation: The Navy should take every opportunity to encourage the drifting buoy program through not only its Office of Naval Research (ONR) sponsored research but also for operational SST analysis at FNOC. The inclusion of a 200-300 m chain with temperature sensors that reports to FNOC every 6 hours via satellite would be invaluable for the Expanded Ocean Thermal Structure (EOTS) analyses or the Optimum Thermal Interpolation System (OTIS).

Recommendation: The MCSST software at FNOC must have the capability to utilize all SST reports received by FNOC for possible inclusion in an MCSST surface truth data base to determine if, when, and where a problem may come up. Monthly means of drifting buoy reports could be used for climatological SST accuracy determination.

3. FNOC collects about 200 XBTs per day from around the world and a significant percentage is tossed to the side by various screening tests. The remaining ones are treated with high regard and are weighted accordingly when combined with MCSST and ship data. The manufacturer reported SST accuracy is very good, but actual field tests indicate that they have their own share of problems. The probe has probably reached a depth of 3-5 m before thermal equilibrium is reached, thus negating a true sea surface temperature, especially if any vertical gradient exists due to daytime insolation or nighttime cooling. It is also difficult at times to pick off an SST value form an XBT trace. When all these items are added together, the true accuracy of the XBT can quickly degrade to 0.3-0.5°C and more in severe cases. The question remains, then, "What do you use as surface truth if MCSST values are approaching the 0.5°C mark?"

Recommendation: In light of the above comments MCSST data should obviously be weighted more than ship data and possibly a little less than XBTs. The present method at FNOC puts much more emphasis on XBTs and should be reevaluated in view of the research done by a number of independent efforts.

(8) Resolution

a. The NESDIS MCSST operational software uses Global Area Coverage (GAC) 4-km data. It forms a 2x2 array of GAC cells to form a unit array after these neighboring values pass the series of cloud tests outlined above. The MCSST retrieval is thus derived from an 8 km by 8 km IR pixel which has already been averaged in the cross scan direction onboard from the full resolution (1.1 km) data. This averaging of pixels increases the chance for cloud contamination in partly cloudy conditions.

b. The question then arises, "What resolution SST data does FNOC require to meet the Fleet's needs?" This is a contradictory question because FNOC has a global responsibility, as well as the need to define fronts and eddies, which necessitates high spatial resolution. Is GAC data good enough?

GAC does not have the ability to penetrate partly cloudy to cloudy areas in the same manner as Local Area Coverage (LAC - 1.1 km) data and thus does not retrieve as many SSTs. The averaging process also decreases its accuracy relative to LAC, since clouds can sneak in and pass the screening tests more easily. However, there is no global availability of LAC data. Therefore, it seems reasonable to suggest that FNOC use all the LAC data it can efficiently process in those regional areas of extremely high interest where infrared remote sensing can be successfully undertaken. This would limit the amount of additional processing and achieve maximum effect on the regional SST analyses.

Recommendation: It is suggested that the FNOC MCSST software be looked at with respect to the problems associated with processing GAC and a limited amount of LAC data. This would directly benefit the thermal structure analyses that are an integral part of FNOC's mission.

(9) Contouring SST data

a. The method used to analyze and contour the SST data at FNOC is very important with regard to the final product. The assimilation of the MCSST data with in situ measurements from ships, XBTs, and buoys is critical when dealing with SST analyses that are obtaining better spatial resolution. Otherwise, these high-density observations will be smoothed out, and the resulting isotherm patterns will make it difficult to locate the fronts and eddies of tactical interest.

FNOC presently uses the Fields by Information Blending (FIB) technique, which weights XBTs highest, MCSSTs next, and ship observations last in accuracy. This method is in the process of being replaced by an optimal interpolation routine sponsored by NORDA. Optimum interpolation (OI) can take into account the differing accuracies of the SST reports from the separate platforms, as well as the time and space correlations of the thermal structure in the ocean. This method allows a much more realistic weighting of new ocean temperature values based on our understanding (albeit imperfect) of ocean processes.

For example, XBT values below the thermocline are allowed to reside in the data base longer than SST values. Their perishability is longer due to the fact changes at this depth occur over a much greater time span than those in the upper layer. The Ocean Sensing and Prediction Division at NORDA will implement OI at FNOC in the near future and carry out an operational evaluation. An increase in horizontal resolution of these regional analyses, when combined with the new OI technique, should create significant improvement in the thermal structure provided to the Thermodynamic Ocean Prediction System (TOPS).

(10) Channels for future satellites

a. It should be mentioned from the outset that before you can move forward you must first have a firm base from which to work. This comment is in reference to the on-again/off-again Congressional support of the two-polar orbiter concept. NOAA presently is slated to keep two polar orbiters active, but there have been repeated attempts to cut this back to one as a cost-saving measure. What happens in the future remains to be seen.

It should also be noted that a failure of the AVHRR is not considered serious enough to launch a new bird. The HIRS is the key sensor as far as NOAA is concerned because of its use in atmospheric analyses for National Meteorological Center (NMC) forecasts. Thus, under the one-satellite proposal, it is a distinct possibility that no MCSSTs will be available because of a bad AVHRR, and NOAA will not do anything about it. This would have a large negative impact on the SST products at FNOC.

Recommendation: It is strongly suggested that the Navy urge NOAA to continue the two-polar orbiter system, at least until the Navy has a suitable sensor of its own flying.

b. A number of suggestions concern modifications to the present AVHRR, as well as new sensors, to accomplish the task of global SSTs. These have included but are not limited to:

A split window channel in the 3.55-3.93 μm window.

Different digitization schemes for channels 1, 2, and 3.

GAC data that uses subsampled data instead of averaged data in the cross scan direction.

Change slightly the spectral response of some of the channels.

Increase the resolution and enhance the capabilities to see through holes in clouds.

Use VAS data in areas where geostationary coverage is adequate.

c. The Navy is presently considering the sensor suite for the next version of the Defense Meteorological Satellite Program (DMSP-NEXT). One of the sensors mentioned as a likely candidate is an AVHRR-like instrument to replace the Optical Line Scanner (OLS). This option would greatly enhance the Navy's position in providing uninterrupted global MCSSTs at high resolution for many applications.

Recommendation: NORDA should begin an effort to describe and justify sensors on DMSP-NEXT with FNOC that will provide the data to satisfy specific demands now required by the analyses and models that NORDA is responsible for.

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This publication includes minutes of a meeting that addressed aspects of multichannel sea surface temperatures and their implementation at the Fleet Numerical Oceanography Center. The meeting was held at the Naval Ocean Research and Development Activity, NSTL, Mississippi, and focused on present capabilities, as well as problems.

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