A Rapidly Relocatable Prediction System: Operational Implementation and Validation

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A*bstract*–MODAS-NRLPOM is a scalable, portable, and rapidly relocatable system for nowcasting and short-term (2-day) forecasting in support of real-time naval operations. The analyses and forecasts can be available within an hour or two of a request, making the system useful in emergency situations.

The Modular Ocean Data Assimilation System (MODAS) combines remote sensed data (altimetry and sea surface temperature) with in situ measurements to produce an analysis of the ocean that can be considerably more accurate than conventional climatology. Geostrophic velocities are derived from the T and S distributions, and the barotropic transport is computed from the computed dynamic height.

The MODAS nowcast field provides initial and boundary condition for NRLPOM, a version of the Princeton Ocean Model (POM) that has been implemented at the Naval Research Laboratory (NRL) for real-time naval applications.

We will present the results from real-time exercises in coastal domains. The goals are 1) to determine the network of observations necessary for accurate dynamical and acoustic prediction in coastal waters, 2) to verify the accuracy of the operational datasets available for the MODAS nowcast, and 3) to evaluate the nowcast and forecast capabilities using model-data comparisons.

I. INTRODUCTION

The Modular Ocean Data Assimilation System (MODAS) is one of the Navy's tools for producing rapid estimates of 3D temperature and salinity fields (Harding et al. [1]). MODAS includes a static climatology from historical profiles and a dynamical climatology, which is a means of assimilating near real-time remote-sensed data and in situ observations (Carnes et al. [2]). MODAS estimates of Sea Surface Height (SSH), Sea Surface Temperature (SST), and temperature and salinity fields are routinely assimilated into operational global models (Rhodes et al. [3]).

MODAS has been extensively applied and validated. The static climatology is at least as high quality as comparable fields from Levitus [4] dataset, but with increased horizontal resolution. The dynamical climatology provides increasingly accurate estimates of the ocean temperature and salinity, depending on the accuracy and availability of the observations (Fox et al. [5]).

MODAS has proven to be a valuable tool in deep and open areas where 1) satellite images provide location and scale of mesoscale features, 2) a high correlation exists between surface and subsurface structures, and 3) the timescale of the dominant features is larger than the operational timescale. In coastal areas and semi-enclosed seas, MODAS fields may lack the accuracy required for an accurate acoustic prediction and detection (Peggion et al. [6]). The primary causes are:

- Altimetry data may not be reliable over shallow (<200 m) and coastal waters.
- The correlation between surface and sub-surface structures is weak.
- In the current default configuration, MODAS ingests global satellite imagery that is processed at approximately 1/8^{o} degree resolution. This grid spacing may be too coarse for the variability of the littoral and coastal areas (i.e., an increased spatial resolution in MODAS field may merely be the result of interpolation, unless a high-concentration of in situ data is available).
- SST satellite images may be available at a time interval greater than the timescale of the dominant features.
- The variability of coastal areas may be characterized by highly energetic, yet short timescale, features which make it difficult to assimilate into the MODAS nowcast knowledge of the ocean's past state. Therefore, for persistent cloud coverage, MODAS fields may tend to relax toward climatology (Fig. 1).

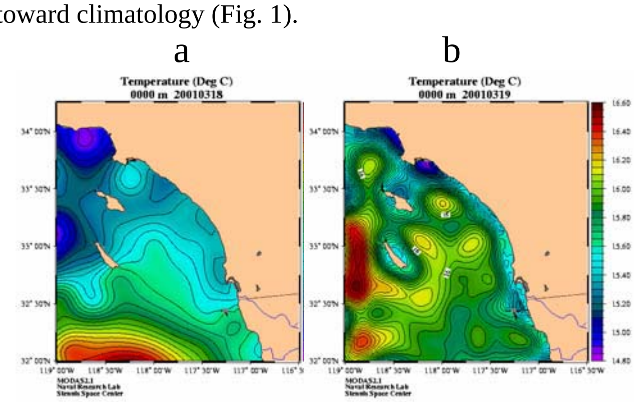

Fig. 1. MODAS nowcast field from two consecutive days: a) persistent cloud coverage, b) clear day. Due to the closeness of the coast, no altimetry data are assimilated.

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A simple, cost-effective way to verify the MODAS limits and skills in littoral areas is the use of a dynamical model. The working hypothesis is that MODAS fields are accurate enough to allow a dynamical model to spin up the correct physics. MODAS itself includes a module, NRLPOM (an improved, portable, rapidly relocatable, user-friendly version of the Princeton Ocean Model (POM) (Blumberg and Mellor [7])), that is implemented to supply short-term (2-day) forecasts. The 48-hour interval is chosen since it is the typical period in which meteorological mesoscale forecasts are available and reliable. Main features of NRLPOM include:

- Option for tidal flow. The tidal forcing, from the Grenoble Tidal Model (GTM) can be specified as geopotential and/or boundary conditions.
- Initialization from MODAS or previous runs (such as yesterday's nowcast).
- Diagnostic/cold/warm/(and combination) start.
- Statistics of the model stability and energy budget.
- Option for one-way nesting between domains of different spatial resolution.
- Option for coupling with large-scale ocean models

This paper is organized as follows. Section II illustrates the default configuration of the system and discusses problems associated with real-time operational applications. Section III discusses evaluation criteria and validates the system through a model-data comparison, and Section IV summarizes and discusses this study.

II. SYSTEM CONFIGURATION

MODAS-NRLPOM is designed to provide the nowcast analysis and forecast within a few hours of a request, which makes the system useful in emergency situations. The goal is to provide a reliable representation anywhere with the available data (i.e., in spite of the lack of observations) (Fox et al. [8]). The code is a modular collection of over 200 programs that can be combined to perform desired tasks. Namelist files and use of allocated memory allow the same executable (on a given platform) to be used for all simulations. Switches and flags control the numerical and physical parameters. The major challenge is to provide a default set of parameters that can provide accurate solutions for any given configuration. Table 1 illustrates the input observations and Table 2 the output products.

The system relies on default datasets, such as the remote sensed observations processed at the Naval Oceanographic Office (NAVOCEANO), the DBDBV2 global bathymetry, and the NOGAPS winds (Hogan and Rosmund [9]). However, switches and flags allow the use of more accurate, high-resolution datasets, when available. The configuration depends heavily on the availability of accurate bathymetry databases. Difficulties associated with the treatment of topographic features on a scale ranging from 2 to 0.5 grid resolution are well known, and the solution cannot be easily generalized to a wide range of applications (Hurlburt and Townsend [10], Metzger and Hurlburt, [11]). Potential problems may be partially alleviated by the development of graphic tools to quickly access, merge, and manually edit bathymetry files.

TABLE I

INPUT DATA PROCESSED BY MODAS

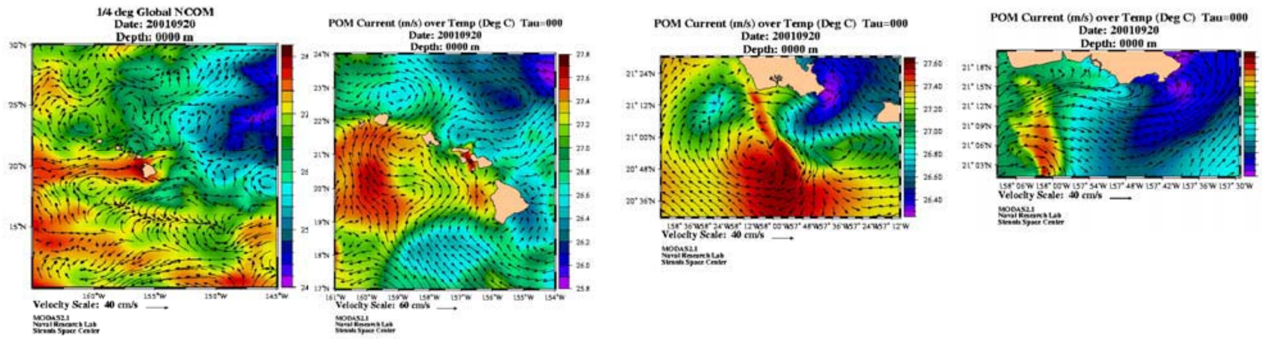
Observations	
	Profiles (BT, CTD, SeaSoar)
	Buoys (fixed, drifting)
	Ship sea surf temps
	MCSST
	Sea surface height
Dynamic Grids	
	Sea surf temperature and heights
	Surface wind or wind stresses
Static Grids	
	Bathymetry (DBDBV, other)
	Altimeter correction grid
	(U,V) current climatology
MODAS climatology, regression database	

TABLE II

OUTPUT GRIDS MODAS NOWCASTS AND POM FORECASTS:

3D volumes of	
	Temperature
	Salinity
	Currents
	Sound speed
2D derived quantities:	
	Slices of T, S, sound speed, currents at arbitrary depths
	Mixed layer depth
	Sonic layer depth
	Deep/shallow sound channel axes
	Depth excess

MODAS-NRLPOM is routinely coupled with large-scale models. While MODAS estimates the baroclinic component under the geostrophic assumption, the barotropic velocities are often inadequate, primarily where it is not possible to apply the dynamic height algorithm to evaluate the transport and/or make use of altimetry data. To partially remove the problem, NRLPOM is capable of substituting the MODAS barotropic field with the barotropic, non-tidal flow from other existing circulation models. Fig. 2 illustrates a coupling-nesting procedure.



NCOM ¼° → **NRLPOM** → **NRLPOM** → **NRLPOM+tide**

¼° - NOGAPS | **7 km - DAMPS_27** | **1.5 km - DAMPS_9** | **0.5 km – DAMPS_9**

Fig. 2. A coupling/nesting procedure. See text for definition of terms.

The simulations were in support of the recovery operations of the Ehime Maru off Pearl Harbor (August 2001). The global 1/4^o Navy Coastal Ocean Model (NCOM, Martin, [12]) forced by the NOGAPS winds (a prototype of the 1/8^o global model that will be operational at the end of 2002) provides boundary conditions to a regional NRLPOM domain (approximately 7 km horizontal resolution) forced by the 27 km resolution DAMPS winds (Hodur, [13]). Nested within the regional model is a high-resolution (1.5 km) grid of the area south of the Oahu Island. Finally, the coupled system includes a 0.5 km resolution in the littoral areas with tides. Both of the latter domains are forced by the 9 km DAMPS operational winds.

The coupling procedures have proven to be computationally robust and suitable for operational applications. Since only the barotropic field is required, the method is independent of the vertical formulation (i.e., layers; z, σ, and hybrid levels) of the parent model.

In the standard applications, the schematic of the forecasting evolves as follows:

- MODAS nowcast field (temperature, T, salinity, S, horizontal velocities, u and v, and sea surface height, η at time Hr(00) provides initial and boundary conditions for NRLPOM.
- NRLPOM is started at Hr(-24) and forced by the available operational winds. During the nowcast, T and S are nudged to MODAS fields, with timescales of 48 and 96 hours for surface and sub-surface levels, respectively.
- After Hr(00), the solutions are updated with the full prognostic mode and forced by the forecasted winds.
- No data are assimilated or nudged into the prediction system after the nowcast.

III. VALIDATION

One of the major problems in evaluating a real-time forecasting system is the lack of data for validating the results. Most of the applications already lack in situ data to be ingested into MODAS, so that the model-data comparison is virtually impossible. Exercises such as the Littoral Environmental Observatory at 15 m (LEO 15) are unique opportunities (Glenn et al. [17], [18]). MODAS-NRLPOM participated in the summer 2000 program (July 12-August 5, 2000). Two datasets, one to generate MODAS nowcasts and one to conduct the model-data comparison were extracted from the LEO-15 databases. Since the observations were posted to the web page in real time, the model-data comparison and the model parameters were calibrated before the next forecast cycle was submitted (Peggion et al. [6]). Fig. 3 depicts a 48-hour forecast and the corresponding satellite image and indicates that the model was able to predict an upwelling event at the correct location.

A posteriori analysis and hindcast simulations are necessary for an overall evaluation of the model performance, but they cannot provide the information necessary during naval operations. In this regard, the goal is to evaluate the solution and make the necessary changes in the model calibration to improve the quality of the following simulations. Therefore, a timely, useful validation requires real-time, easily accessible data, such as those available from the web.

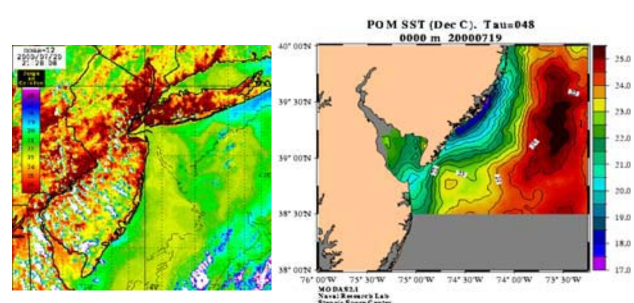


Fig. 3: Comparison between the SST from remote sensing and the 48-hour forecast from MODAS-NRLPOM.

An example of a "real-time" model-data comparison is illustrated in Fig. 4. The model forecasted tidal amplitude is evaluated verses real-time data from the gauge #1612340 (Honolulu station) maintained by the NOAA Center for Operational Oceanographic Products and Services (www.coops.nos.noaa.gov/). The solution is relative to the simulations in support of the Ehime Maru recovery as previously described.

Moreover, a stringent model evaluation also requires independent (i.e., not assimilated nor used in the initialization) datasets. As part of the evaluation, MODAS nowcast and NRLPOM forecasted SST were compared with real-time observations from the National Data Buoy Center (NDBC) network (www.ndbc.noaa.gov). The process highlighted significant differences between the MCSST observations and the buoy values and emphasized that one aspect, often neglected or underestimated, is the comparison between the ingested and validating data. The problem is illustrated in Fig. 5 and 6 by comparison of buoy measurements with MCCST observations from different sources, and the SST at the buoy location from the global (approximately 9 km resolution) MODAS-2D field. The latter product is routinely assimilated into operational global forecast systems, such as the 1/16^{o} NLOM (www.ocean.nrlssc.navy.mil/global_nlom) and the 1/8^{o} NCOM (www.ocean.nrlssc.navy.mil/global_ncom).

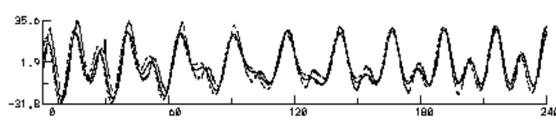


Fig. 4. Comparison between the forecasted tidal amplitude and gauge data at the Honolulu station. Model (solid line), GMT (fine dashed line), observations (coarse dashed line). Tidal amplitude is in cm, time in hours.

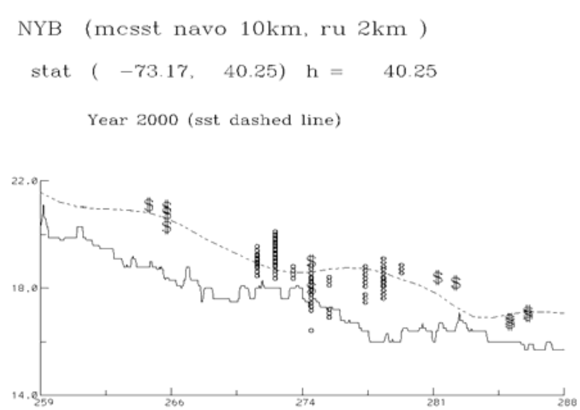


Fig. 5: Comparison of the SST from NOAA buoy #44025 In the NY Bight (solid line) with the MCSST from two independent datasets: the NAVOCEANO operational unclassified product (**$**) and 1-week high-resolution (1 km) product processed at Rutgers University (**o**). The dashed line is the SST from MODAS-2D at the buoy location. (September 16-October 15,2000).

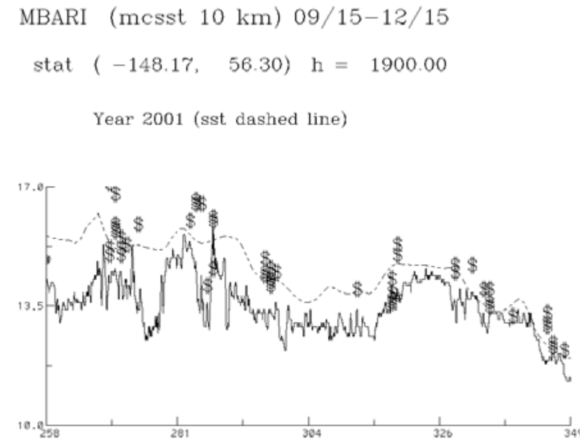


Fig. 6. Comparison between the Buoy #46042 and the MCSST data. Same as Fig. 5**.** (September 15 – Dec 15, 2001).

It is implicitly assumed that the infrared measurements are representative of the temperature beneath the surface layer (about 0.02 mm thick) in which the upwelling radiation originates. Therefore, the apparent infrared temperature, henceforth referred to as the skin temperature, may not be representative of the temperature at a slightly greater depth, henceforth referred to as the SST. Several phenomena that warm or cool the surface of the ocean may contribute to the mismatch (Stewart [14]). The error may be estimated using one of the correction schemes proposed by several authors, such as Saunders [15] and Simpson and Paulson [16]. Typically, the difference between the skin temperature and the SST is less than 1° in the open ocean.

In coastal and shallow water, the problem has not been extensively investigated. However, preliminary studies indicate that the mismatch is more severe in shallow and coastal areas, especially during the cooling season. The discrepancies appear to be independent of the source and resolution of the dataset. No systematic differences have been found between NOAA-16 and NOAA-14 observations, nor has a significant day/night bias been noticed (L'Heureux, personal communication).

The ambiguity between the interpretation of skin temperature and SST has a clear impact in the model evaluation and model-data comparison. Tables 3 and 4 summarize the statistics among buoy observations (i.e., the independent dataset), the SST from MODAS-2D, and the solution from the NCOM 1/4^{o} global model. Values are relative to the data depicted in Fig. 5.

Clearly, the skin temperature is not representative of the SST, and it is necessary to evaluate possible solutions. One of the major problems is how to calibrate the MCCST on a global scale and yet provide a more accurate representation locally. At this stage, we have not yet fully estimated the impact on MODAS temperature 3D field. We anticipate, that the assimilation of in situ measurements, such as XBT or CTD, would create a bulls-eye effect with spurious small-scale eddies. It appears evident that NCOM solution is affected by the bias introduced in the MODAS-2D analysis. However, we consider the model performance successful, because the error is within the range of the bias between the ingested and validating dataset set.

TABLE III
BASIC STATISTICAL FUNCTIONS OF OBSERVATIONS AND MODEL OUTPUTS. SEE TEXT FOR DEFINITIONS OF TERMS.

	Buoy	**MODAS-2d**	**NCOM**
Mean	18.59	19.31	19.60
Minimum	16.50	17.23	17.30
Maximum	21.20	21.72	21.77
St. Dev.	1.74	1.77	1.68

TABLE IV
BASIC STATISTICAL CROSS-FUNCTIONS BETWEEN OBSERVATIONS AND MODEL OUTPUTS. ERROR IS DEFINED AS THE DIFFERENCE BETWEEN FIRST AND SECOND ARGUEMENT OF EACH COLUMN. SEE TEXT FOR DEFINITIONS OF TERMS.

	Buoy/ MODAS2D	**Buoy/ NCOM**	**MODAS2/ NCOM**
Mean error	-0.72	-1.01	-0.29
Max. error	-1.52	-2.18	-1.29
Correlation	0.98	0.97	0.98
St. Dev.	0.36	0.44	0.36

IV. SUMMARY AND FUTURE DIRECTIONS

An ocean nowcast and forecast system for the 3D analysis of currents and thermohaline structure in both deep and shallow water has been presented. The system is portable, user-friendly, and rapidly relocatable. The approach is not to design a forecasting system for a given area or region such as the Northern Gulf Littoral Initiative (NGLI), (http://128.160.23.41/) or the Mediterranean Forecasting System (http://www.cineca.it/~mfspp000/), which are supported by a network of long-term observations and are continuously evaluated and calibrated. On the contrary, MODAS-NRLPOM analysis and forecast can be available anywhere within few hours of a request, making the system useful in emergency situations.

The system relies on default datasets and parameter calibrations, which provide *good* representations *anywhere* with the available data. The prediction system has been designed and implemented so that no data are ingested and assimilated during the forecasting simulations. Issues associated with the model configuration and assessment have been discussed. One of the biggest limitations is access to accurate bathymetry databases and an interactive editing of the topographic features on a scale comparable to the model grid resolution.

The 3D MODAS nowcast field depends on the 2D grids of height anomalies and temperatures (Jacobs et al., [19]) derived from the global products processed at NAVOCEANO. It has been found that the mismatch between the skin temperature of the MCSST data and the SST, the temperature beneath, may affect the validation criteria and the model-data comparison. The bias is carried consistently in the MODAS 2D and 3D and the forecasting models. The error is more severe in shallow and coastal waters where it is not possible to make use of the altimetry data. Therefore, suitable nowcast and forecast would depend on the availability of in situ measurements.

A wide range of applications confirm that 1) the MODAS analysis is more accurate than climatological fields, and 2) the MODAS field is able to allow a dynamical model to spin up the correct physics (with the correct externally supplied forces). Generally, the NRLPOM hindcast is more accurate than MODAS nowcast. The accuracy of the forecasted fields depends upon the forecasted forcing. Operational meteorological fields are usually available on a spatial resolution that is too coarse for a correct prediction of the variability of the littoral regions.

The capability of efficient real-time nowcasting and forecasting has important implications for ocean sciences, technology, and ecosystem monitoring. It makes knowledge of the present and future state of the ocean possible with minimal observational resources. Unfortunately, realistic operational applications may lack the necessary network of observations for both an accurate description and evaluation of the model performances.

The 1/4 degree resolution global NCOM model used in this study has recently been upgraded to 1/8 degree resolution and is presently in the process of being transitioned to operational use at the Naval Oceanographic Office. In addition, the relocatable NRLPOM version of POM is being replaced with a similarly configured relocatable version of NCOM. The improved resolution and bathymetry in the 1/8 degree global NCOM model and the greater compatibility provided by NCOM-to-NCOM nesting over NCOM-to-POM nesting should increase the forecast skill of the overall system.

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