Ocean Prediction with Improved Synthetic Ocean Profiles (ISOP)

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Knowledge of the present ocean environment and its evolution in time informs effective planning and conduct of Navy activities. The three-dimensional (3D) temperature, salinity, and current structure, from the surface mixed layer to the deep ocean interior, reflects interactions of meandering currents, eddies, and fronts. These ocean characteristics are important not only for understanding underwater acoustic transmission properties and their effects on detection systems, but also for maintaining safe operations at sea, strategic planning, and tactical fleet operations on and below the ocean surface. Search and rescue operations, hazard mitigation, and disaster response in the ocean also benefit from knowledge of the operating environment.

PREDICTING THE OCEAN ENVIRONMENT

Three key components are required for accurately representing present ocean conditions and predicting future conditions: observations, a forecast model, and data assimilation. Observations are required because a single ocean measurement from an instrument with a high level of accuracy provides the best estimate of the measured quantity (i.e., temperature, salinity, pressure, current speed), but only at the time and location of the measurement. It is essential to have precise observations in sufficient quantity and spatial distribution to represent mesoscale features (e.g., the "weather" of the ocean). A numerical ocean model capable of accurately representing dynamical ocean processes on relevant space and time scales is also required because such models — driven by appropriate surface and lateral boundary forcing — produce realistic simulations of observed ocean features. However, correct model physics and forcing by themselves do not ensure accurate depiction of the actual ocean environment at a given time. Hence the need for ocean observations and, consequently, a method for assimilating them into the dynamical model. Combining observations with a realistic ocean model via data assimilation results in a better depiction of the 3D ocean environment than a purely statistical analysis of the observations. Within the data assimilation system, the observations guide the model, while the model fills the gaps between the observations using numerical methods that efficiently represent the physics of the ocean. Such an accurate depiction of the present ocean environment is essential for producing a valid ocean forecast. These three key components are combined in a daily sequence that blends the observations with the previous day's forecast (or other background field) using data assimilation to initialize the next forecast in the cycle (Fig. 1). Thus, because it is part of a cycling system, the dynamical model, in addition to extending the influence of new observations in space, also extends in time the influence of past observations on both the analysis and the forecast.

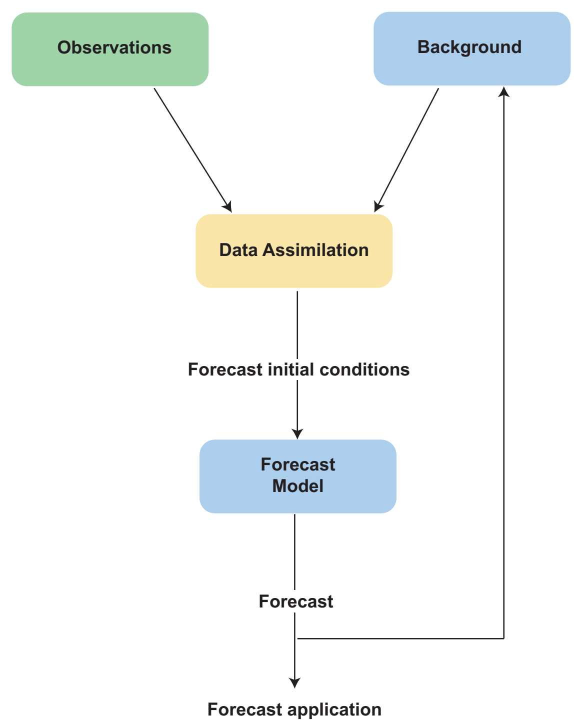

FIGURE 1
An analysis/forecast cycle showing the role of the three key components: observations (green), a data assimilation system (yellow), and a forecast model (blue).

There are not enough daily in-water ocean measurements to permit accurate representation of the 3D ocean mesoscale by a data assimilation system. Even with the increasing number of globally distributed, in situ observations (e.g., from free-drifting arrays such as Argo floats), coverage is too sparse in almost all regions to delineate the ocean on scales that would influence Navy planning. Daily satellite-measured sea surface height (SSH) and sea surface temperature (SST) observations, on the other hand, are abundant enough by comparison (Fig. 2) to detect mesoscale features at the ocean surface globally. Historical relationships between SSH and SST observations and coincident observations of the ocean interior make it possible to infer ocean subsurface conditions. By projecting the ubiquitous space-based SSH and SST observations downward in areas where subsurface in situ data are not available, a sufficient number of synthetic vertical temperature and salinity profiles are generated such that the data assimilative ocean prediction system can produce accurate analyses and forecasts of the environment at time and space scales of importance to Navy and public ocean-based activities. Thus, satellite-based global observations of SSH and SST are and will continue to be the most important observations for assimilative ocean models in most regions of the world, making their availability in real time on a daily basis critical for successful analysis and forecasting of the 3D ocean environment.

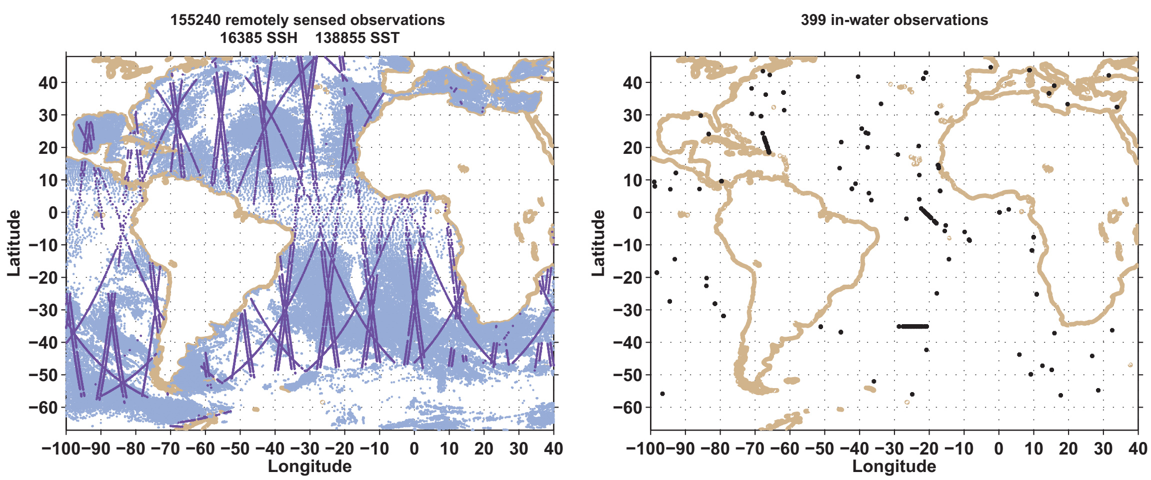

FIGURE 2
An example of the relative contribution of space-based ocean and in-water observations in a data assimilation system over the same approximately 36-hour time period. The left panel shows satellite-measured surface observations and the right panel shows in situ subsurface observations. There are nearly 400 times more satellite-measured observations than in-water observations.

IMPROVED SYNTHETIC OCEAN PROFILES (ISOP)

One past approach used to infer ocean subsurface information in the absence of in situ ocean profile data is multivariate linear regression between surface and subsurface variables. Multivariate regression between historical observations of SSH and SST and temperature and salinity at defined depths is the method used in the Navy's Modular Ocean Data Assimilation System (MODAS).[1] The one-dimensional (1D) variational Improved Synthetic Ocean Profile (ISOP)[2] method provides a new capability for inferring the ocean subsurface structure. MODAS and ISOP each extend surface ocean data downward by creating a profile anywhere in the global ocean given a measurement of SSH and SST, with ISOP also using an initial estimate or prior forecast of the temperature and salinity profile and the mixed-layer depth (MLD). ISOP also computes both temperature and salinity at depth using surface observations, while MODAS computes temperature only and then estimates salinity from historical temperature–salinity regressions. Both systems can also be used to estimate salinity for pairing with data from a temperature-only observing system (e.g., to estimate sound speed using temperature from an expendable bathythermograph).

ISOP represents the water column in three layers, as shown in Fig. 3. The upper layer (pink) extends from the surface to the input MLD value. This layer is either constructed using a historical observation-based model or it is prescribed using the vertical structure of the portion of the input profile above the MLD. Below the surface layer is a dynamic interior layer (green) constructed using covariances of SST and SSH with coupled empirical orthogonal functions (EOFs) of temperature (T) and salinity (S), as well as coupled EOFs of vertical gradients of T and S in the upper 1000 m. This layer is merged below 1000 m to climatology or a model forecast to form the deep layer (purple). The additional constraint

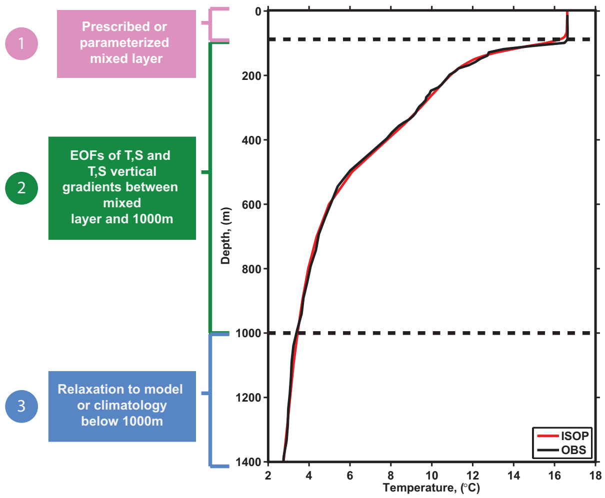

FIGURE 3

The three layers constructed by ISOP shown relative to a typical ocean temperature profile versus depth. The ISOP profile is shown in red, and the observation (OBS) is shown in black.

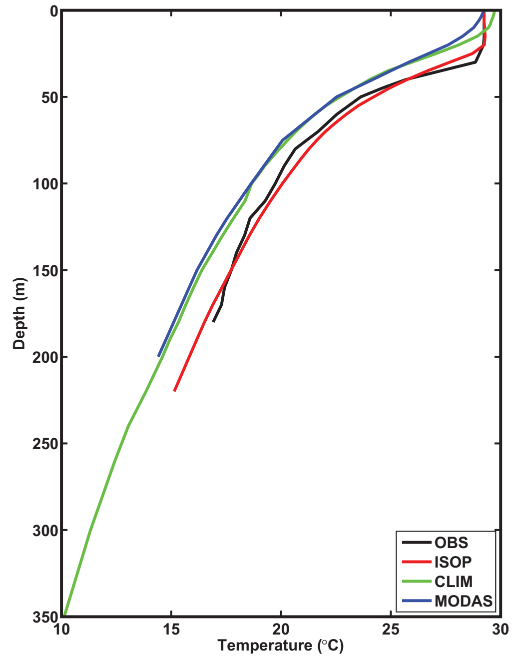

FIGURE 4

Comparison of ISOP and MODAS synthetics to an actual ocean temperature profile. The observation (OBS) in black deviates from the average conditions in the ocean given by climatology (CLIM) in green. The legacy MODAS system is in blue and ISOP is in red.

on the T and S vertical gradients in the dynamic layer constitutes a significant advancement of ISOP over MODAS that ultimately improves predictions of acoustic propagation. Because it depicts real ocean profiles more accurately than MODAS (Fig. 4), ISOP recently replaced MODAS for synthetic observations in the Navy Coupled Ocean Data Assimilation (NCODA) system,[3] the data assimilation component of the Navy's global and regional ocean prediction systems. ISOP used within NCODA as part of cycling assimilation/forecast systems uses SST and SSH observations and their uncertainties along with model MLD, T, and S forecasts and forecast errors to produce synthetic T and S profile observations for assimilation.

IMPACT OF ISOP ON OCEAN PREDICTION

Global and regional ocean analyses and forecasts using ISOP have been validated as part of the process of transitioning capabilities developed by the U.S. Naval Research Laboratory (NRL) to the operational Navy forecast centers.[4,5] A comparison of two Navy Coastal Ocean Model (NCOM)[6]-based RELOcatable (RELO)[7] ocean prediction system Gulf of Mexico test cases is presented to show the impact of synthetic ocean profile observations from ISOP on ocean prediction. Slightly more than four months (late May through September 2010) of temperature and salinity forecasts from each experiment are compared to nearly 3700 unassimilated in situ observations. Use of ISOP instead of MODAS synthetic profiles reduces the mean error (ME) (bias) and root mean square error (RMSE) of the 48-hour forecast temperatures at nearly all depths. The salinity forecast errors are also reduced at all depths, but most significantly in the upper ~75 m (Fig. 5). The ME absolute values and RMSEs of the 24- and 48-hour temperature forecasts averaged from the upper 500 m are reduced with ISOP by at least 40% and 20%, respectively, and by more than 60% and 50%, respectively, for salinity (Fig. 6).

The impact of the vertical gradient constraint in ISOP is assessed via comparison of model forecasts of ocean properties that affect acoustic transmission loss predictions: sonic layer depth (SLD) and below layer gradient (BLG) (Fig. 7). The SLD identifies the near-surface sound speed maximum, thereby defining the depth of the surface acoustic duct. The BLG is a measure related to the strength of the surface acoustic duct. The 48-hour SLD forecasts at 56% of the nearly 3700 in situ profile locations are more accurate with ISOP than with MODAS synthetics, while 29% are more accurate in the MODAS case and nearly 15% are equivalent between the two cases (Fig. 8a). For the BLG 48-hour forecast, the accuracy ratio is 62% better with ISOP to 37% better with MODAS (Fig. 8b). In summary, ISOP improves sound speed predictions over MODAS. The SLD and BLG biases are nearly 20% and 33% lower, respectively, while the RMSEs are reduced by about one-third and by about 15% to 17%, respectively (Fig. 9). Based on the demonstrated superior performance of ISOP relative to MODAS, NRL is transitioning the ISOP capability to the Navy's NCODA-based assimilative ocean prediction systems.

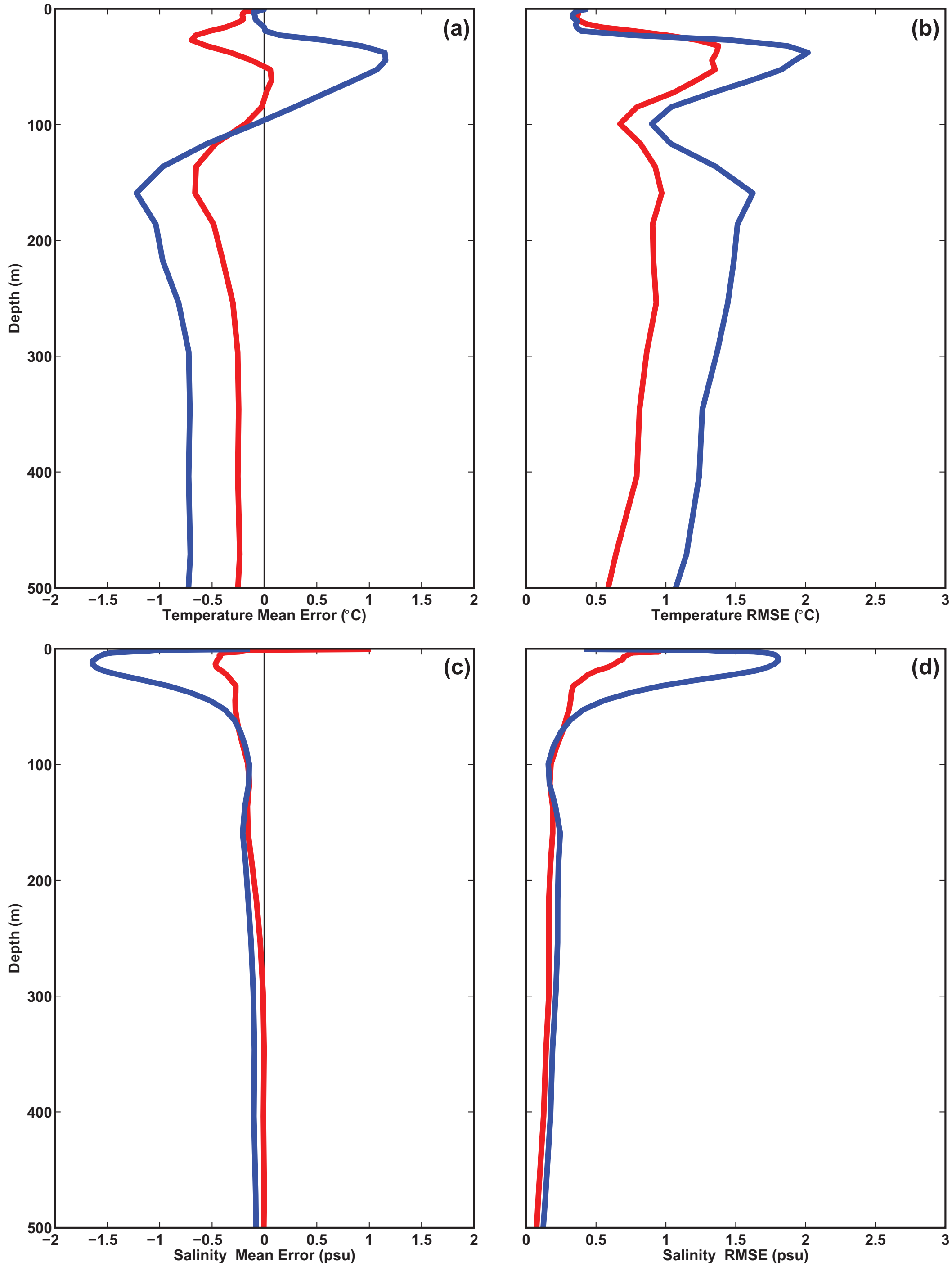

FIGURE 5

Gulf of Mexico RELO 2010 ISOP (red) and MODAS (blue) 48-hour forecast temperature (a and b) and salinity (c and d) mean (a and c) and root mean square error (b and d) versus depth.

Statistic	Forecast	ISOP	MODAS
Vert-avg Temp., °C |bias|	Nowcast	0.26	0.48
	24 hr	0.28	0.48
	48 hr	0.29	0.48
Vert-avg Temp., °C RMS err	Nowcast	0.76	0.99
	24 hr	0.77	0.98
	48 hr	0.76	0.98
Summary Score		6	0

Statistic	Forecast	ISOP	MODAS
Vert-avg Salinity, psu |bias|	Nowcast	0.27	0.77
	24 hr	0.27	0.76
	48 hr	0.27	0.76
Vert-avg Salinity psu RMS err	Nowcast	0.43	0.88
	24 hr	0.43	0.88
	48 hr	0.43	0.87
Summary Score		6	0

FIGURE 6
Temperature (upper panel) and salinity (lower panel) mean bias and root mean square (RMS) nowcast and forecast errors averaged over the upper 500 m using ISOP and MODAS synthetics in the Gulf of Mexico RELO ocean prediction system during summer 2010.

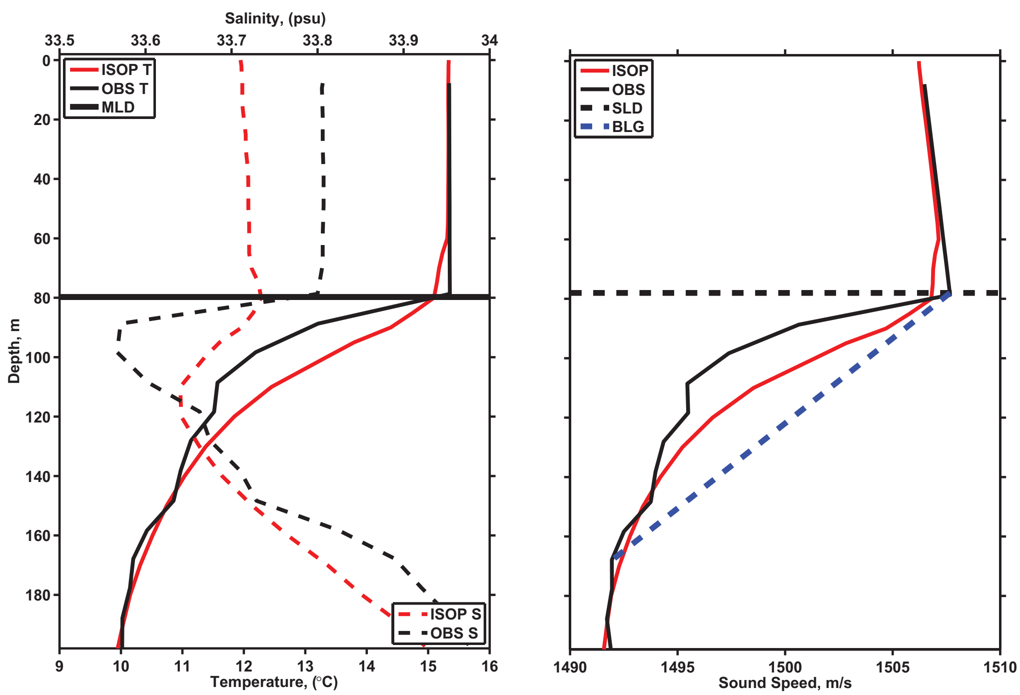

FIGURE 7
Ocean properties that affect predictions of acoustic transmission loss: mixed layer depth (MLD), sonic layer depth (SLD), and below layer gradient (BLG) are shown relative to ocean temperature and salinity (left panel) and sound speed (right panel) profiles. Horizontal lines show the depth of the MLD and SLD in the left and right panels, respectively. The blue dashed line in the right panel shows the gradient estimated as BLG.

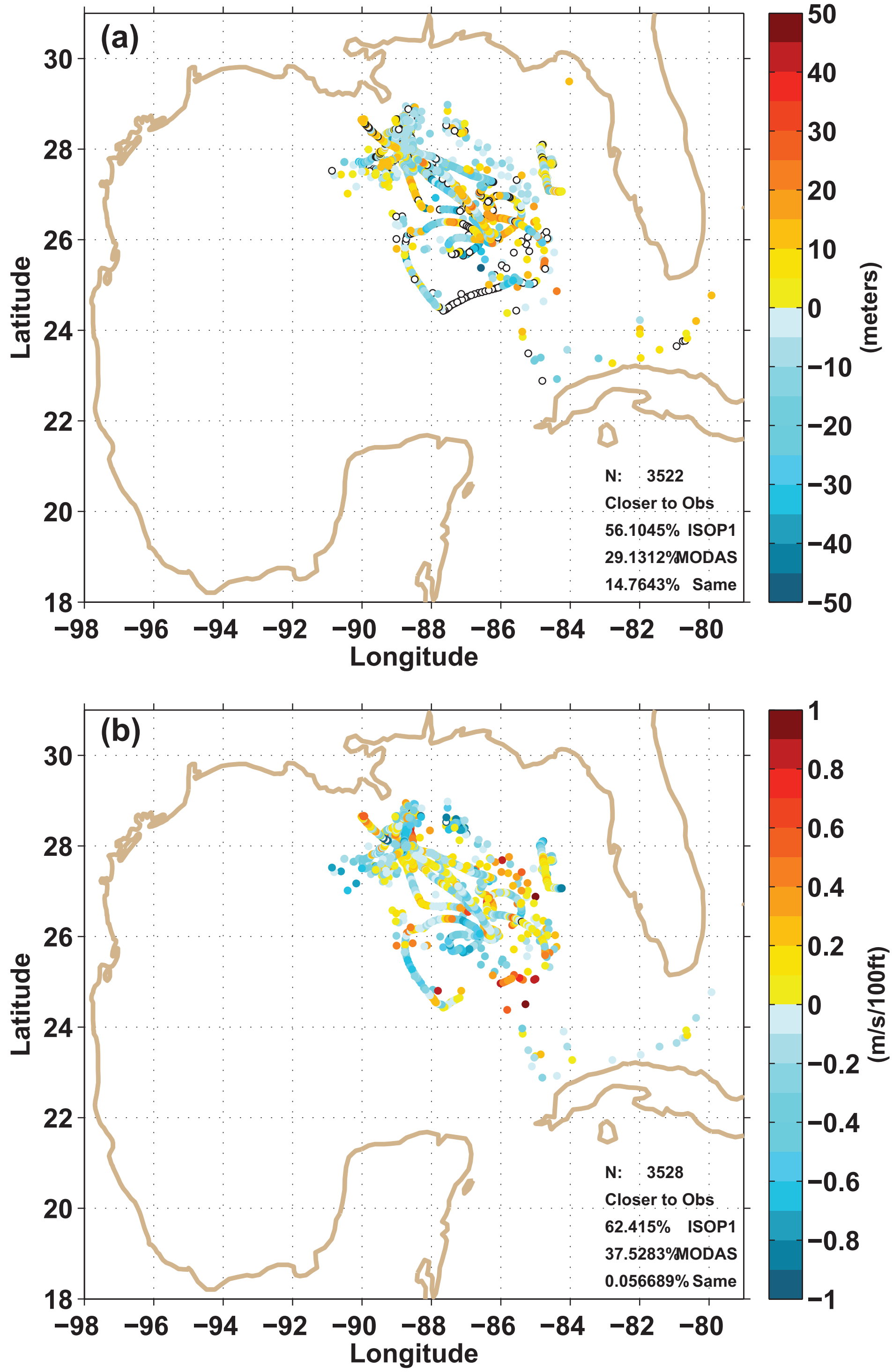

FIGURE 8

Relationship between the 48-hour SLD (a) and BLG (b) forecast errors by location between ISOP and MODAS in the Gulf of Mexico RELO ocean prediction system during summer 2010. Locations with ISOP closer to observed are blue. Locations with MODAS closer to observed are red. Open black circles indicate where the ISOP and MODAS absolute errors are nearly equal.

		ISOP		MODAS	
Statistic	Forecast	Bias	RMS Err	Bias	RMS Err
SLD (m)	Nowcast	-3.99	12.04	8.69	14.55
	24 hr	-2.04	9.80	8.93	14.50
	48 hr	-1.95	9.63	8.75	14.39
BLG m/s per 100 ft	Nowcast	-0.270	0.510	-0.415	0.596
	24 hr	-0.266	0.498	-0.417	0.596
	48 hr	-0.271	0.503	-0.430	0.606
Summary Score		12		0	

FIGURE 9
Nowcast and forecast SLD and BLG mean bias and root mean square (RMS) errors using ISOP and MODAS synthetics in the Gulf of Mexico RELO ocean prediction system during summer 2010.

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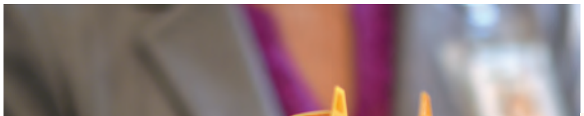
Fathoming the fathoms: Creating accurate ocean forecasts for naval operations

In order to effectively plan and conduct activities on and below the ocean surface, Navy operational planners need to understand and predict the ocean subsurface, including temperature and salinity values from the surface to the ocean depths. Our researchers at the U.S. Naval Research Laboratory have developed a new model for predicting these characteristics – the Improved Synthetic Ocean Profile (ISOP) system. Representing the water column in layers, ISOP merges real time observational data (sea surface height and sea surface temperature acquired daily via satellite) with the previous day's forecast to depict the present ocean state from which the next forecast is generated. ISOP is able to create more accurate vertical profiles of temperature and salinity than legacy systems. Reliable forecasts of ocean temperature and salinity are not only important for Navy operations and mission planning in general, but also for accurate predictions of underwater sound speed propagation properties which, in turn, optimize the Navy's submarine detection capabilities.

NRL REVIEW



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