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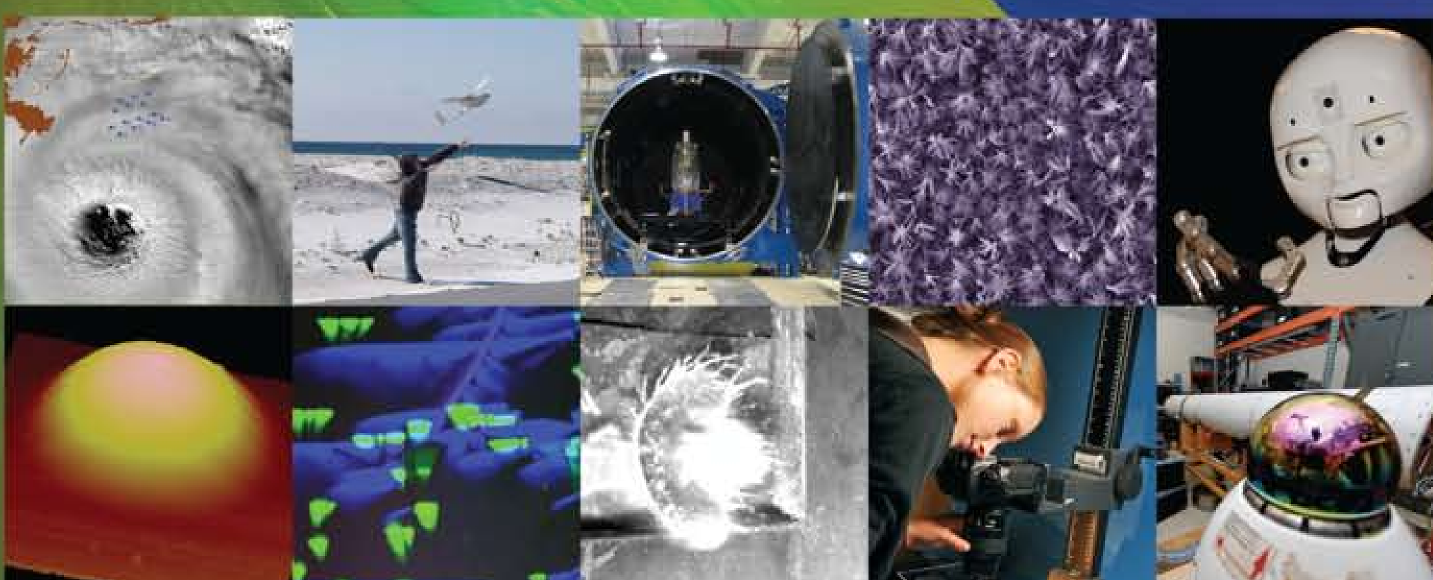

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become available for use in predicting, understanding, and adapting to changing Arctic ice conditions.

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[Sponsored by ONR]

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Predicting "Ocean Weather" Using the HYbrid Coordinate Ocean Model (HYCOM)

E.J. Metzger,[1] H.E. Hurlburt,[1] A.J. Wallcraft,[1] O.M. Smedstad,[2] J.A. Cummings,[1] and E.P. Chassignet[3]
[1]*Oceanography Division*
[2]*QinetIQ North America/Planning Systems, Inc.*
[3]*Florida State University*

Introduction: Development of an advanced global ocean prediction system has been a long-term Navy interest. Such a system must provide the capability to depict (nowcast) and predict (forecast) the oceanic "weather," some components of which include the 3D temperature, salinity, and current structure, the surface mixed layer, and the location of mesoscale features such as eddies, meandering currents, and fronts. The space scale of these eddies and meandering currents are typically ~100 km and current speeds can easily exceed 1 ms^{-1} in the Gulf Stream (Atlantic) and Kuroshio (Pacific). Numerical ocean models with sufficiently high horizontal and vertical resolution are needed to depict the 3D structure with accuracy superior to climatology and/or persistence (i.e., a forecast of no change). The existing two-model operational system, run daily at the Naval Oceanographic Office (NAVOCEANO), is based on the 1/32° Navy Layered Ocean Model (NLOM) and the 1/8° Navy Coastal Ocean Model (NCOM). Unlike NLOM, NCOM has high vertical resolution, but it has medium range horizontal resolution (15 km at mid-latitudes near 40°N) that is eddy-permitting. The next-generation system is based on a single model, the HYbrid Coordinate Ocean Model (HYCOM), that was developed as part of a multi-institutional consortium between academia, government, and private industry. At 2.2 times the horizontal resolution of NCOM, the HYCOM system is eddy-resolving, a distinction associated with important dynamical implications for both ocean model dynamical interpolation skill in the assimilation of ocean data and for ocean model forecast skill.[1] It represents the world's first eddy-resolving global ocean prediction system with both high horizontal and high vertical resolution and has been running daily in the operational queues at NAVOCEANO since 22 December 2006. The HYCOM system has been validated against observational data[2] and is scheduled for operational testing in 2009.

Prediction System Description: The ocean component of the nowcast/forecast system is 1/12° global HYCOM (mid-latitude resolution of ~7 km) with 32 hybrid vertical coordinate surfaces. The truly generalized vertical coordinate can be isopycnal (density tracking — often best in the deep stratified ocean), levels of equal pressure (nearly fixed depths — best used in the mixed layer and unstratified ocean), or sigma-levels (terrain-following — often the best choice in shallow water). HYCOM combines all three approaches by choosing the optimal distribution at every grid point and time step. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics.

HYCOM employs the Navy Coupled Ocean Data Assimilation (NCODA), which is a fully 3D multivariate optimum interpolation scheme, to assimilate observational data. The data include surface observations from satellites, such as altimeter sea surface height (SSH) anomalies, sea surface temperature (SST), and sea ice concentration, plus in situ SST observations from ships and buoys and temperature and salinity profile data from XBTs, CTDs, and Argo floats. The 3D ocean environment can be more accurately nowcast and forecast by combining these diverse observational data types via data assimilation and using the dynamical interpolation skill of the model.

Real-time Results: Where possible, the real-time system is evaluated using independent observations; some examples follow. Figure 3 shows simulated SSH

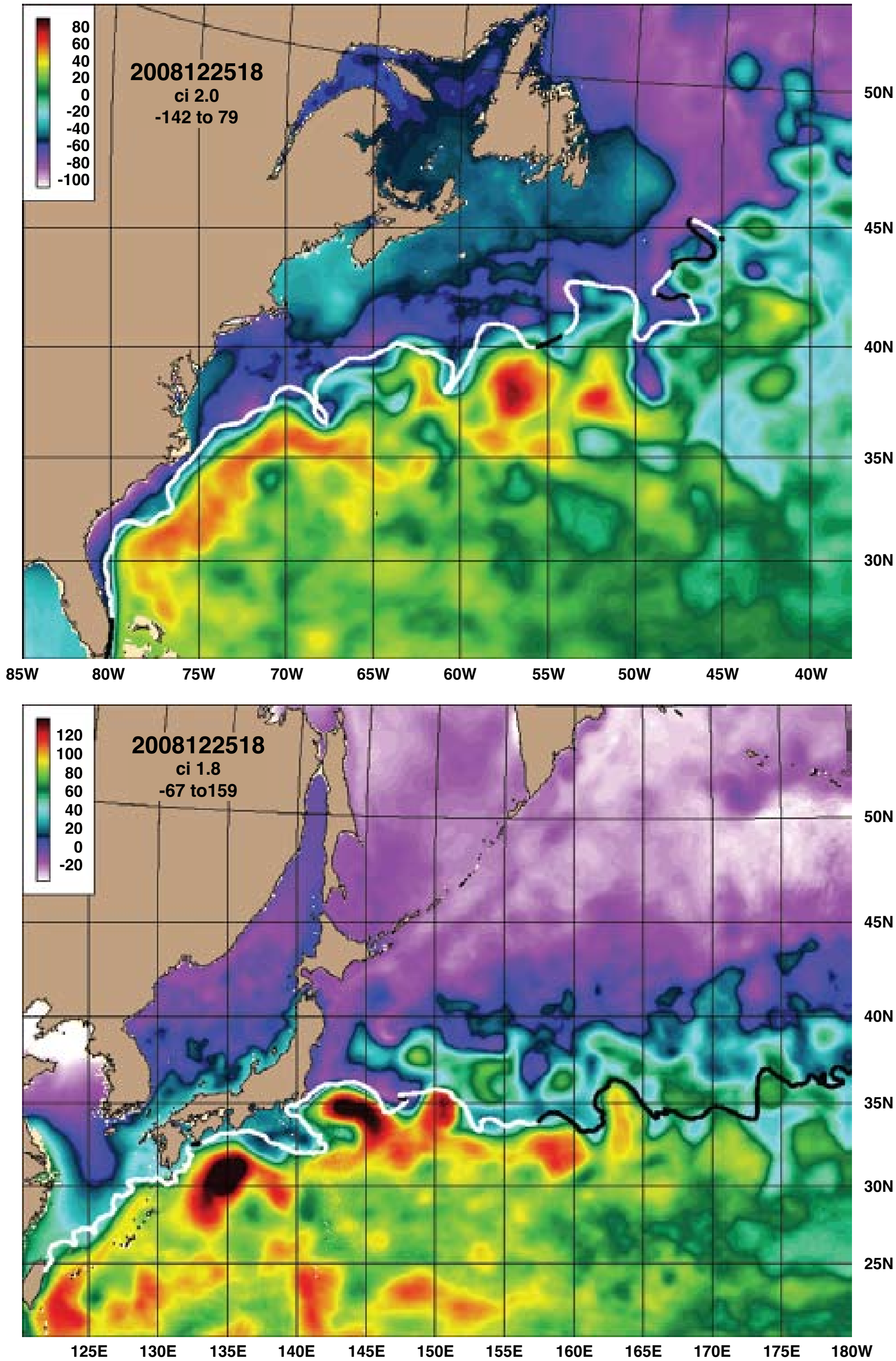

FIGURE 3
Sea surface height (cm) from the 1/12° global HYCOM/NCODA forecast system for the Gulf Stream in the Atlantic Ocean (top) and the Kuroshio in the Pacific Ocean (bottom) on 22 December 2008. The ribbon of high gradient color shows the location of these western boundary currents; embedded within the meandering flow are warm and cold core eddies. The currents generally flow parallel to the isolines of height and are strongest where the gradients are the tightest. An independent infrared (IR) analysis of the north edge of both current systems performed by the Naval Oceanographic Office is overlain on each image. A white (black) line means the IR analysis is based on data less (more) than four days old.

for the Gulf Stream and the Kuroshio current systems. The assimilation of satellite altimeter SSH anomalies is essential to accurately map the circulation in these highly chaotic regions dominated by flow instabilities. Infrared-based frontal analyses showing the northernmost edge of the currents are overlain on the images. They provide an independent analysis of the current positions and clearly indicate the ocean nowcast/forecast system is accurately mapping these western boundary currents.

Figure 4 shows an example that uses drifting buoy trajectories to validate the flow field in the Kuroshio. Drifting buoy temperature (but not velocity) is assimilated into the system, allowing the trajectory to be an independent validation source. The white box focuses on a warm core eddy about to detach from the Kuroshio, and a pair of drifting buoys is noted on the western and eastern sides. These two drifters pass within a half degree of each other while traveling in opposite directions. Close examination indicates the two buoys are on opposite sides of a saddle point that still connects the main current with the detaching eddy. Thus, the system is able to accurately assimilate the altimeter data and act as a dynamical interpolator.

SST forecast skill of the system is examined in Table 2. Shown are the mean error (bias), root-mean-square-error (RMSE), skill score (a non-dimensional quantity with perfect skill having a value of 1), and correlation as a function of forecast length. The bias and RMSE gradually grow with forecast length. The spatial distribution of the mean error is shown in Fig. 5 for the analysis time and for a 3-day forecast. The

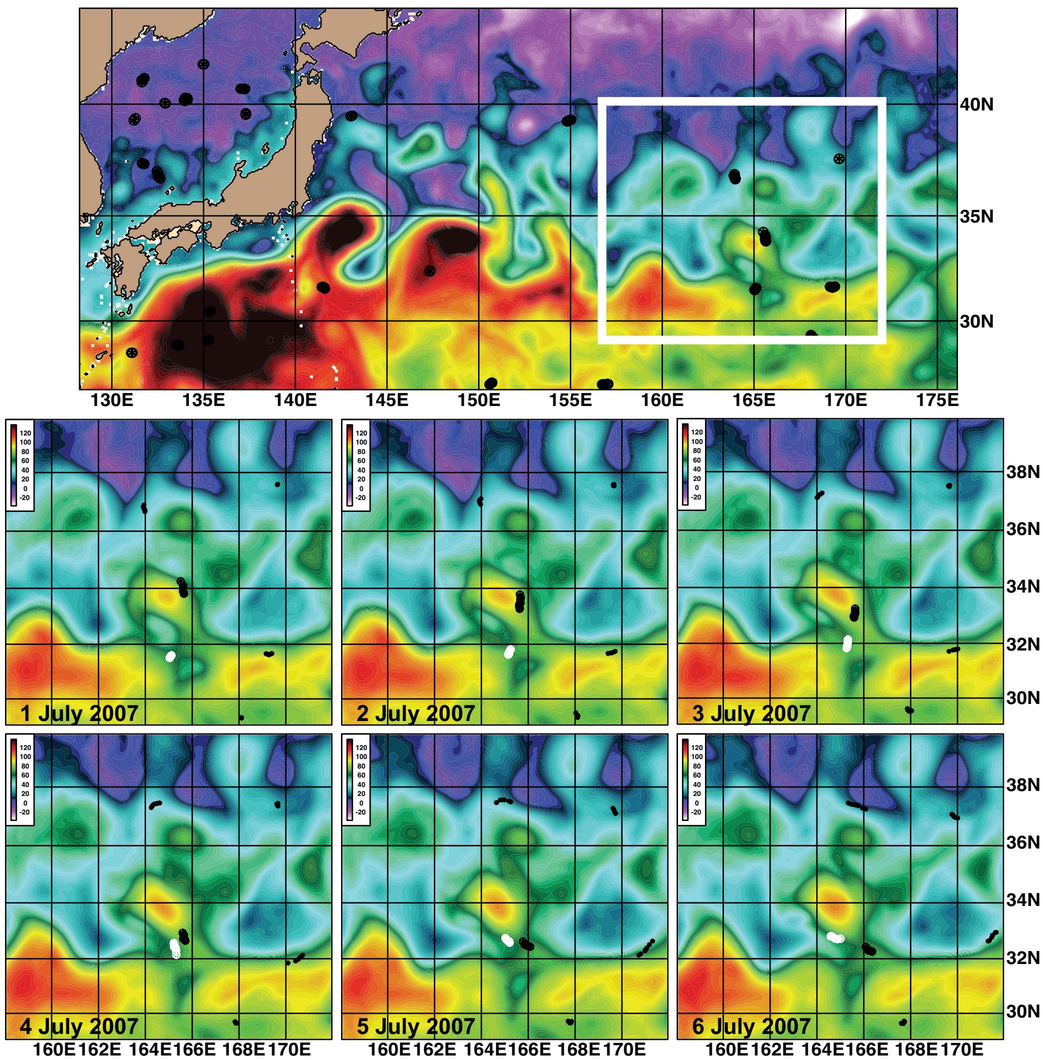

FIGURE 4
Sea surface height (cm) from the 1/12° global HYCOM/NCODA forecast system for the Kuroshio on 1 July 2007 (top). Drifting buoy tracks over a 1-day time period are overlain on each panel. The white box defines the focused area of the bottom six panels that span the time frame 1–6 July 2007. A warm core eddy is about to detach from the Kuroshio, and two drifting buoys (highlighted in white and black) are traversing its western and eastern sides.

TABLE 2 — SST Error Statistics vs ~33,000,000 MCSST Observations; Analysis Between 45°S and 45°N

	Mean Error	RMSE	Skill Score	Correlation
Analysis	-.02	.36	.99	1.0
1-day forecast	-.09	.44	.99	1.0
2-day forecast	-.14	.52	.99	.99
3-day forecast	-.18	.60	.98	.99
4-day forecast	-.22	.67	.98	.99
5-day forecast	-.26	.72	.98	.99

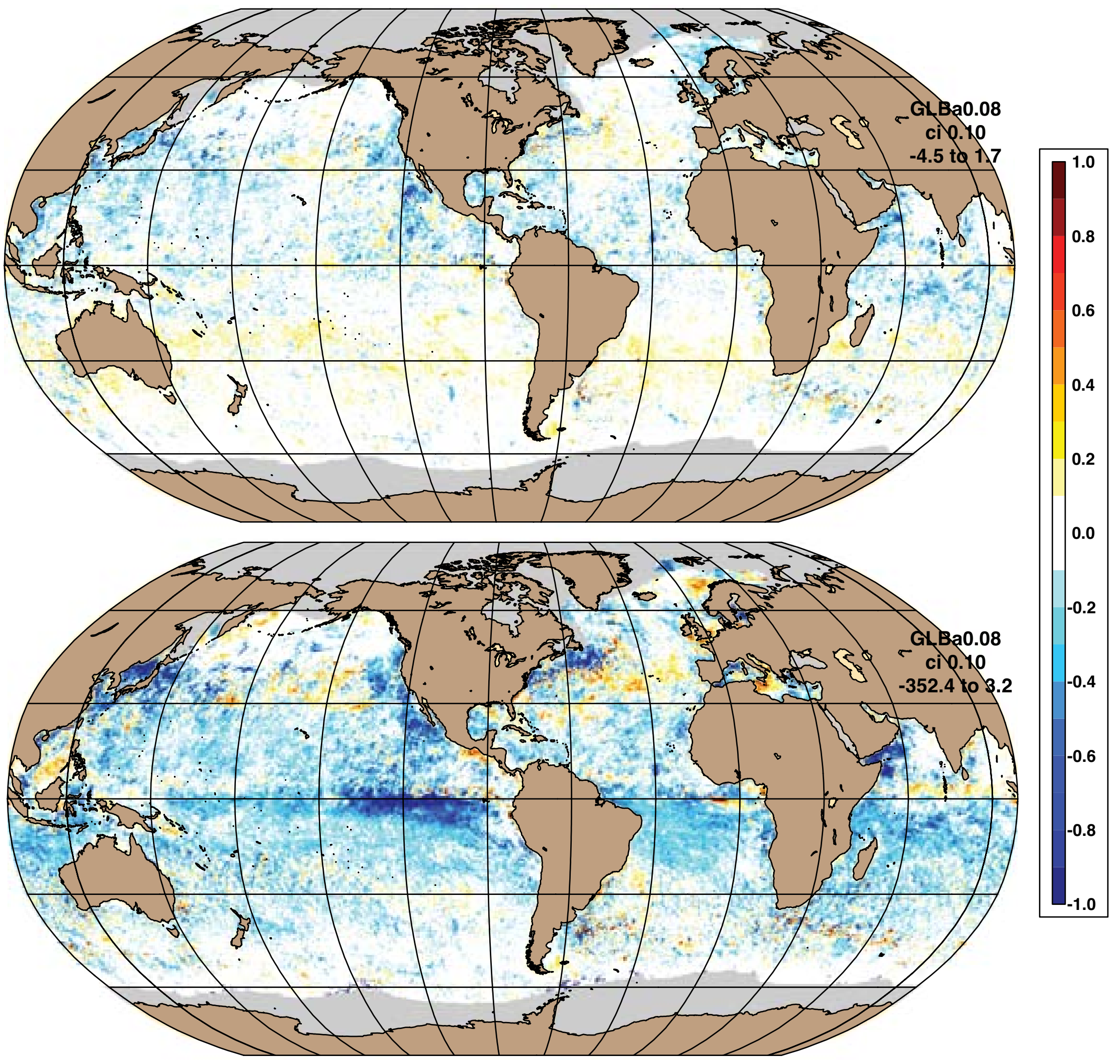

FIGURE 5
Sea surface temperature (SST) mean error (bias) relative to ~33,000,000 multi-channel SST (MCSST) observations at the analysis time (top) and for a 3-day forecast (bottom). Red (blue) colors indicate simulated SST is warmer (cooler) than observed. Values between ±0.1 °C are white. The gray area near the poles is an annual average ice coverage mask.

system has demonstrated forecast skill lasting up to about a month for the meandering currents and eddies in some regions.

Impact: A next-generation 1/12° global ocean nowcast/forecast system is running in real time at NAVOCEANO. It is designed to replace an existing nowcast/forecast system and have more than twice as fine grid resolution. It can more accurately depict such features as western boundary currents and sharp ocean fronts, thus providing improved environmental awareness to the Fleet.

[Sponsored by ONR, NOPP, and HPCMO]

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Littoral Battlespace Characterization Using Small Unmanned Aerial Systems

K.T. Holland,[1] D. Lalejini,[1] and K. Plavnick[2]
[1] *Marine Geosciences Division*
[2] *Naval Oceanography Special Warfare Command*

Motivation: Few environmental regions are as dynamic as the littoral, where dramatic changes in winds, waves, and bathymetry can occur over time scales as short as a few hours. A long-term goal for the Littoral Dynamics Team within the Naval Research Laboratory (NRL) is to extract littoral meteorological and oceanographic (METOC) conditions from intelligence, surveillance, and reconnaissance (ISR) imagery collected by either space or airborne platforms in near real time. Our most recent efforts have focused on developing capability to provide actionable battlespace awareness for amphibious operations through the analysis of motion imagery from Small Unmanned Aerial Systems (SUAS). These systems are relatively inexpensive and are widely used within the Department of Defense.

Technical Approach: Although we have investigated a number of suitable platforms, our military customers commonly use the Raven B SUAS manufactured by Aerovironment, Inc. This platform, with a wingspan of 1.4 m and a weight of 1.9 kg, is ideally suited for low-altitude ISR. The system can carry either dual color video cameras with digital pan/tilt/zoom or a single infrared (IR) camera, downlinked live to a ground control station (GCS). Within the GCS, the video is timestamped and aligned with position and attitude metadata. Although direct orthorectification of imagery frames is possible using an external laptop computer, time latencies and sensor misalignments can result in geo-referenced mosaics with substantial errors. Instead, NRL has developed an image matching approach based on scale-invariant tie-points to automatically create mosaics suitable for littoral characterization that can be geo-registered using optimized metadata with only limited manual intervention.

Exercise Demonstration: This approach was demonstrated during 21–28 July 2008 in support of Exercise Trident Warrior 2008 and Exercise Rim of the Pacific (RIMPAC) 2008 while working from Bellows Beach, Hawaii. Our joint civilian and military team managed and flew the Raven B for purposes of collecting surf zone imagery in support of U.S. Navy and Marine Corps amphibious operations (Fig. 6). Military support, including transmission of our products to the fleet, was coordinated through the Naval Oceanographic Operations Command, ISR Oceanography Directorate. This was the first time Raven B had been used for this purpose during a major exercise.

Five flights (averaging 55 minutes duration) over 4 days resulted in nearly 600 images and video clips. These clips were analyzed immediately after collection to create a number of timely environmental products (Figs. 7 and 8). These products were used by METOC personnel aboard the USS *Bonhomme Richard* (LHD 6) who indicated that these products were useful in planning RIMPAC landings at Bellows Beach.

A related part of the demonstration purpose was to develop, refine, and assess the concepts of operations (CONOPs) and tactics, techniques, and procedures (TTPs) associated with collecting Raven B overhead imagery for littoral characterization, planning, and tactical decision-making. By flying at various altitudes and flight paths (dwells, orbits, and strip maps), we were able to develop an optimal collection strategy and demonstrate that this system could provide quality, timely, and actionable intelligence that impacted operations through improved battlespace METOC characterization. For example, cloudy weather conditions on some mornings would have precluded the use of higher altitude surveillance platforms. The overall demonstration proved that effective METOC characterization of the littoral battlespace was possible by exploiting tactical, non-traditional METOC sensors, specifically imagery from a locally controlled SUAS.