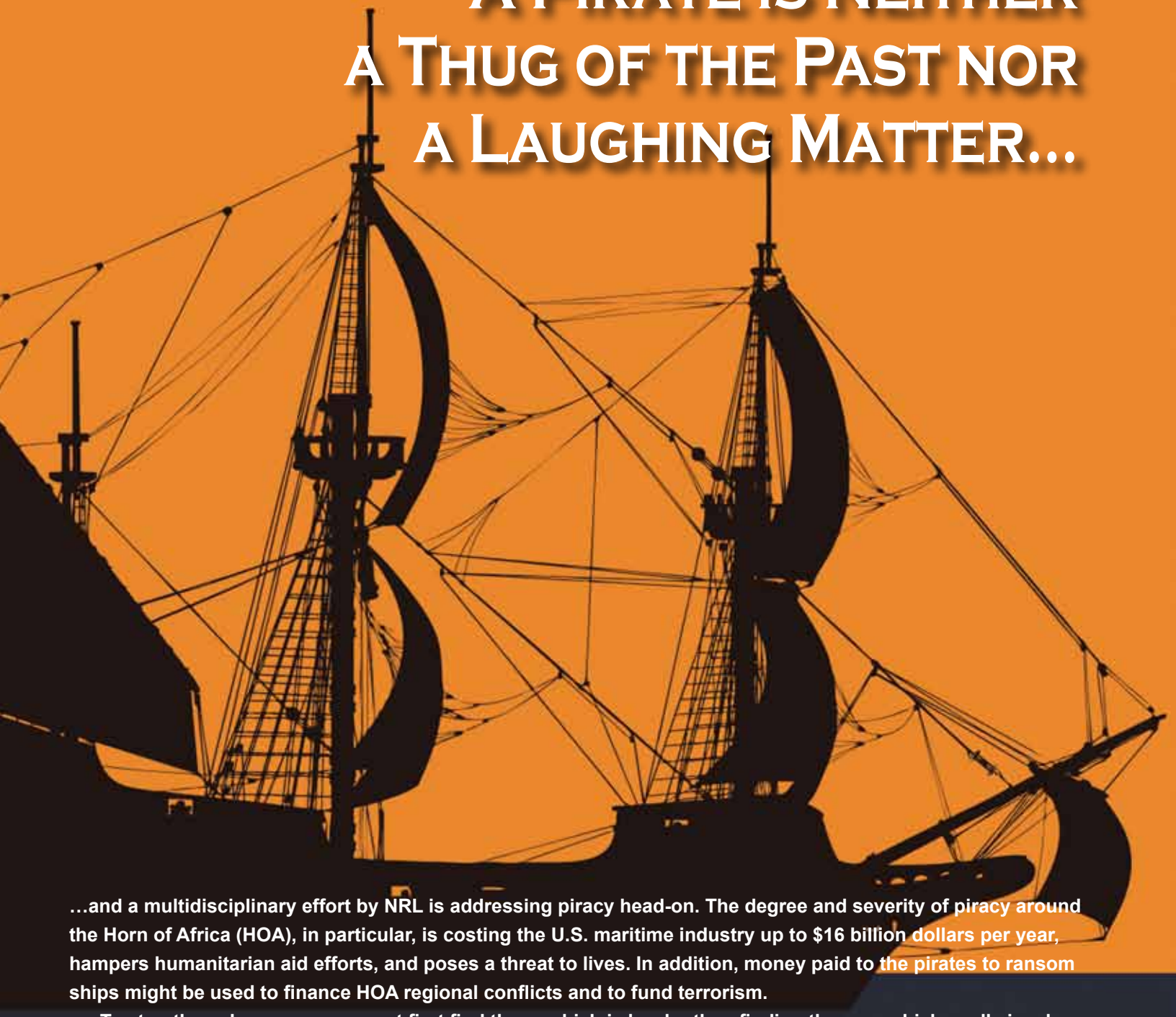
A Pirate is Neither a Thug of the Past nor a Laughing Matter...



…and a multidisciplinary effort by NRL is addressing piracy head-on. The degree and severity of piracy around the Horn of Africa (HOA), in particular, is costing the U.S. maritime industry up to $16 billion dollars per year, hampers humanitarian aid efforts, and poses a threat to lives. In addition, money paid to the pirates to ransom ships might be used to finance HOA regional conflicts and to fund terrorism.

To stop them, however, you must first find them, which is harder than finding the proverbial needle in a haystack. This is where NRL expertise steps in. Using a combination of real-time intelligence information and meteorological and information technology tools and techniques, NRL researchers are predicting where the pirates will be and when they are most likely to strike. Since pirates primarily use small, fast watercraft that are highly vulnerable to high winds and rough seas, predicting their movements and effectiveness relies on quickly and accurately predicting the weather. NRL is improving and making operational a NAVOCEANO product that dynamically couples intelligence and environmental information to predict when and where pirates are likely to strike, and then communicate that information to interdiction forces.

Hearkening back to the earliest missions of the U.S. Navy, when fighting piracy required that the U.S. Navy assert its domination of the high seas to stop the plundering of U.S. merchant vessels, today's Navy again seeks to enforce its domination of the seas, but now through information domination as much as through military might.

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Information Domination: Dynamically Coupling METOC and INTEL for Improved Guidance for Piracy Interdiction

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Global piracy activity is on the rise. The region around the Horn of Africa (HOA) experienced a tenfold increase in piracy in 2009 and 2010 relative to 2008 despite increased effort by European Union (EU), NATO, and U.S. Naval forces.[1] The U.S. Department of Transportation Maritime Administration outlines several economic impacts associated with enhanced piracy activity around the HOA.[2] These include the fuel and personnel costs associated with rerouting ships via the Cape of Good Hope, as well as the opportunity costs associated with increased transit times. For ships that choose to transit through high-risk areas, there are increased insurance costs for operating in an area with high piracy activity, costs of additional security, and costs of nonlethal deterrent equipment. In addition, there are national costs associated with increased naval activity to protect shipping in high-risk areas. It is estimated that piracy costs the U.S. maritime industry between $1 billion and $16 billion per year.[3] In addition to national and international economic impacts, piracy also threatens humanitarian aid efforts around the HOA. For example, the U.S.-flagged and crewed *MV Maersk Alabama* was en route to Somalia to deliver food aid when it was boarded by pirates. There is also concern that the money being paid in ransom for hijacked ships is being used to finance regional conflicts around the HOA and potentially to finance terrorist activities.

Because pirates tend to operate in small vessels, they are particularly vulnerable to adverse winds and seas. Several divisions at NRL are helping to operationalize and improve a product created and disseminated through the Naval Oceanographic Office (NAVOCEANO) in an effort to communicate the risk of pirate attack to commercial shipping taking into account environmental, intelligence, and behavioral information. Before describing the process of dynamically coupling environmental and intelligence information, the impact of the environment on pirate activity is quantified based on analysis of the historical record of pirate attacks. The novel approach of dynamic coupling of environmental and intelligence information is then described. Finally, a description of efforts associated with the use of autonomous intelligent agents for the elucidation of emergent pirate behavior is provided.

THE IMPACT OF METOC ON PIRATE ACTIVITY

Analysis by NRL of the meteorological and oceanographic (METOC) conditions associated with pirate attacks off the HOA indicates that meteorology and oceanography strongly modulate pirate activity. The NRL Oceanography Division constructed a reanalysis of the winds, waves, and currents in the region of the HOA during the period of January 2007 through July 2010. The reanalysis provides the best estimates possible of environmental conditions by blending information from observations and operational numerical models. Pirate events over the same period were collected and filtered to exclude events that occurred in ports.

In Fig. 1, the black curves plot the number of pirate events as a function of significant wave height (panel a), wind speed (panel b), and shipping density (panel c). The red solid curves plot the predicted number of pirate events under the assumption that the environment has no impact on pirate activity. The red dashed curves are the one standard deviation bounds. Insofar as the black curves are different from the red curves, the environment (and shipping density) impact pirate

behavior. Note that waves (panel a) have the largest impact on pirate activity, there is a small impact due to winds (b), and that pirates tend to attack in regions of relatively higher shipping density (c). These results tell us that it is important to account for the environment and shipping when building a product to provide guidance for piracy interdiction.

THE PIRACY PERFORMANCE SURFACE

NAVOCEANO currently disseminates a daily forecast product that fuses wave and ocean current information with historic and recent pirate activity. The resulting index communicates the suitability of pirate activity as a function of location and time and is used operationally by U.S., EU, and NATO interdiction forces. An example of the product, called the Piracy Performance Surface (PPS), is shown in Fig. 2. The PPS is constructed by modifying wave forecasts to account for the effects of currents, mapping from waves to an index bounded by 0 and 1, and performing a weighted sum between the environmental field and an index associated with historical pirate attacks (90% of weight is given to environmental conditions). Recent piracy attempts are included with higher weights that decay over time.

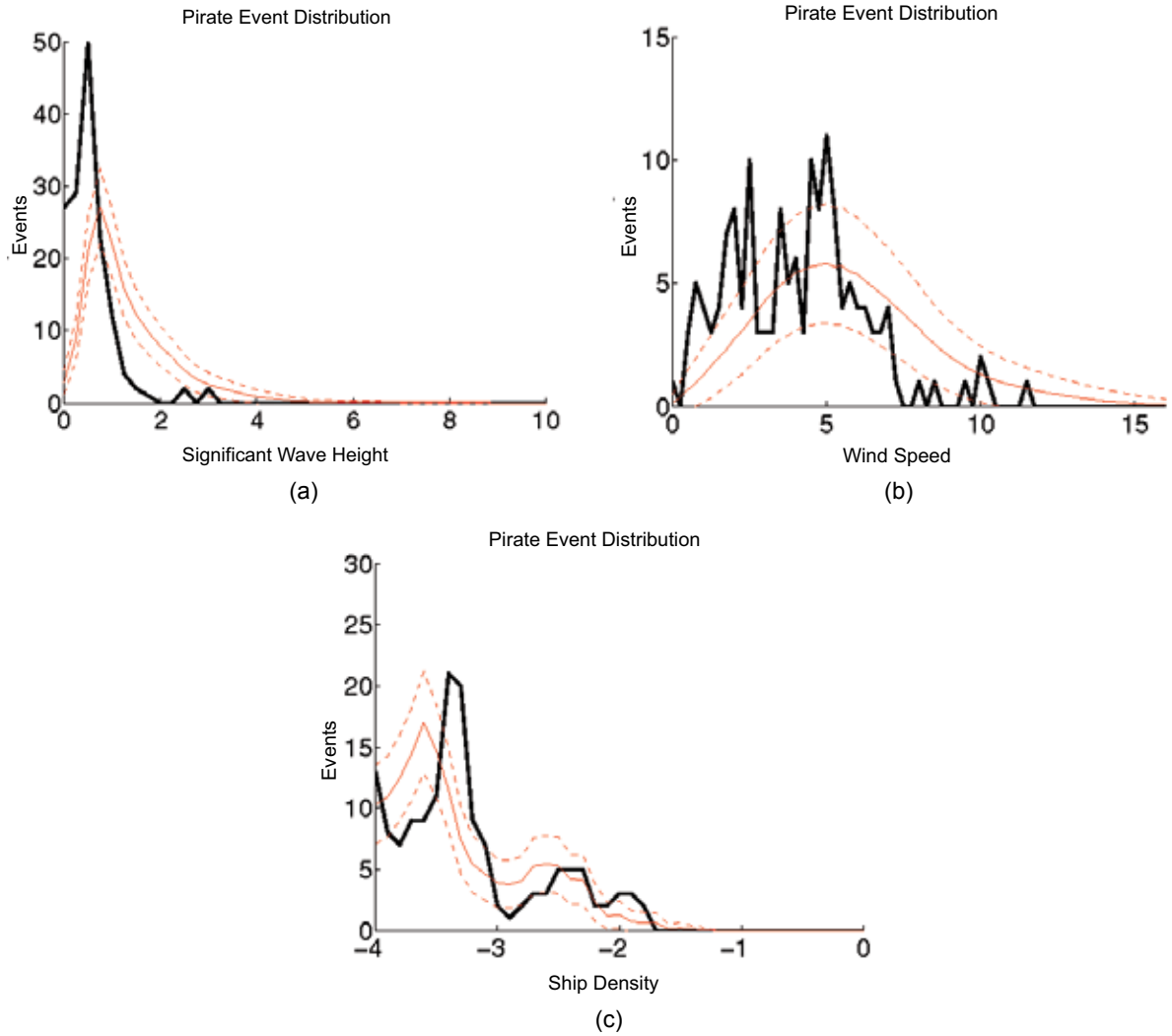


FIGURE 1
The black curves are the distribution of pirate events as a function of (a) significant wave height, (b) surface wind speed, and (c) commercial shipping density over the period January 2007 through July 2010. The red curves are the expected pirate event distributions under the assumption that the environment has no impact on pirate activity (dashed lines provide the one standard deviation bounds). Waves strongly impact pirate events; winds also impact pirate events, but to a much smaller degree. Pirates tend to operate in areas of relatively higher shipping density.

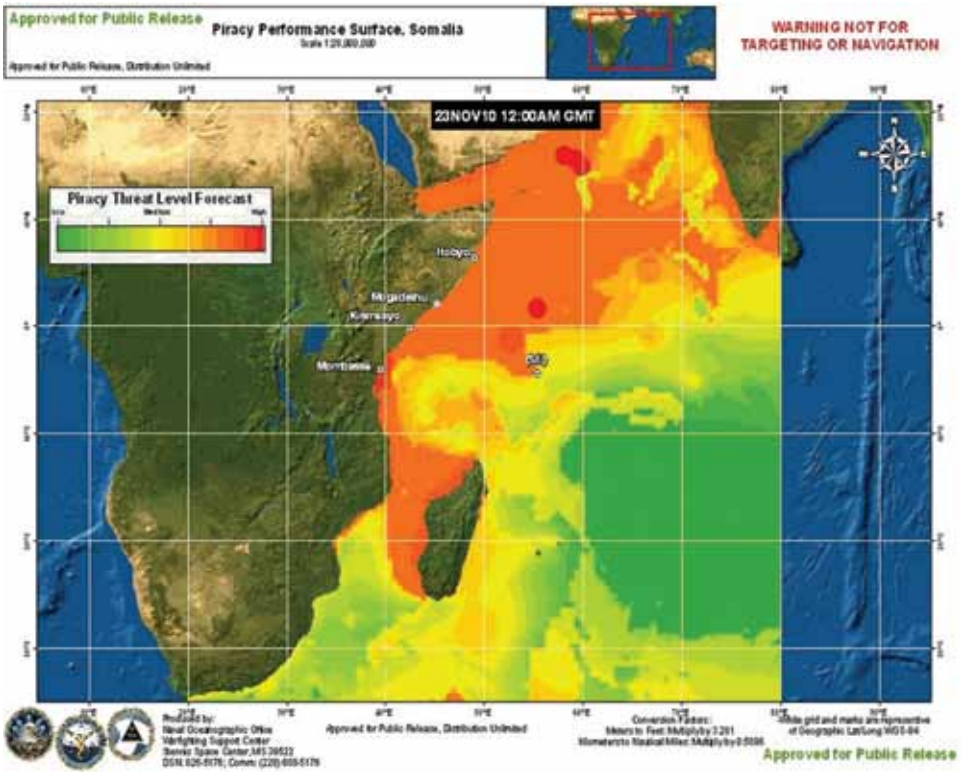


FIGURE 2
An example of the operational Piracy Performance Surface (PPS), which is created and disseminated once per day by NAVOCEANO for use by U.S., EU, and NATO pirate interdiction forces. The PPS thresholds wave height forecasts and merges with information about recent pirate activity.

EXPLICITLY PREDICTING PIRATE PROBABILITIES

A limitation of the PPS is that it uses only a small amount of intelligence information (historical attacks) and treats the environment separately from the intelligence information. Scientists at the NRL Marine Meteorology Division have developed a product that takes into account additional sources of intelligence information, such as pirate base locations and activity, details about pirate skiffs, and observations of likely pirate vessels. Instead of treating the environmental data and these additional sources of intelligence separately, this new product explicitly and dynamically couples the two.

The heart of the approach is the construction of a dynamic model of pirate tactics, techniques, and procedures that takes into account intelligence information (e.g., pirate CONOPS, equipment performance, base locations, numbers, and location of interdiction forces) and environmental information (e.g., forecasts of winds, waves, and currents). The pirate model predicts the track of a single pirate skiff as a function of time under the impact of the intelligence and environmental constraints (see Fig. 3(a)). The uncertainty associated with the intelligence and environmental information is accounted for by running the pirate behavior model not once, but tens of thousands of times, sampling from all available sources of uncertainty, whether they be subjective distributions (such as pirate base locations) or objective distributions (such as wave ensembles). This generates millions of possible pirate locations (see Fig. 3(b)), and these millions of points can be interpreted as draws from a pirate distribution function (see Fig. 3(c)). The distribution of pirate locations changes over a forecast period as the environment impacts skiff motion. The resulting pirate distribution function can be updated in real time when observations of pirate activity become available by transforming the distribution of pirate trajectories in a Bayesian manner.

Although this is useful, interdiction forces are less interested in where pirates are likely to be and more interested in where an attack is likely to occur. The ingredients necessary for an attack at a given location are (a) the presence of a pirate, (b) a vulnerable commercial ship within line of sight, and (c) environmental conditions that are conducive to an attack. The probability of condition (a) is provided by the pirate probability product described above. The probability of (b) is obtainable from various unclassified and classified sources, and the probability of (c) is obtainable from available environmental forecasts and the information

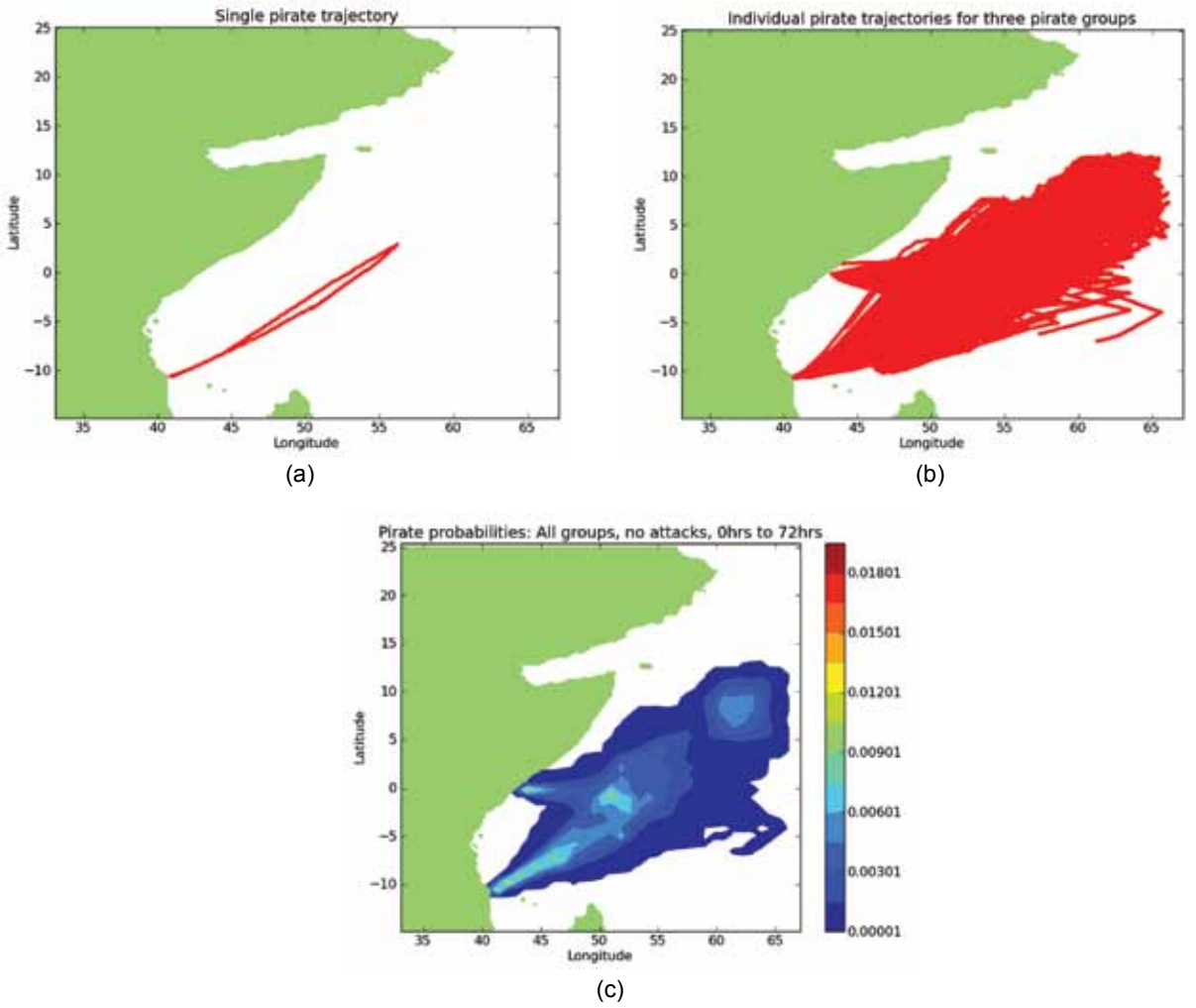
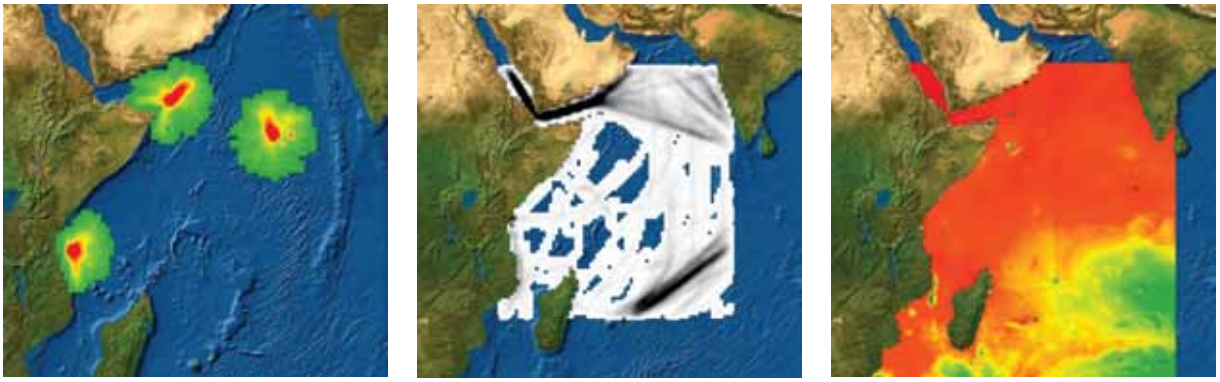


FIGURE 3
Example showing the construction of a pirate distribution. Panel (a) shows a single pirate trajectory. The pirate leaves base, transits at a set speed to a waypoint, hunts for commercial shipping, and then returns to base. Panel (b) shows the result of many thousands of pirate trajectories that sample from uncertainties in base location, skiff speed, environmental impact limits, hunting areas, hunting tactics, etc. Panel (c) plots the pirate distribution function for a 72-hr period. In this example, there are three active pirate groups: two operating from land bases and one from a sea-based mother ship.

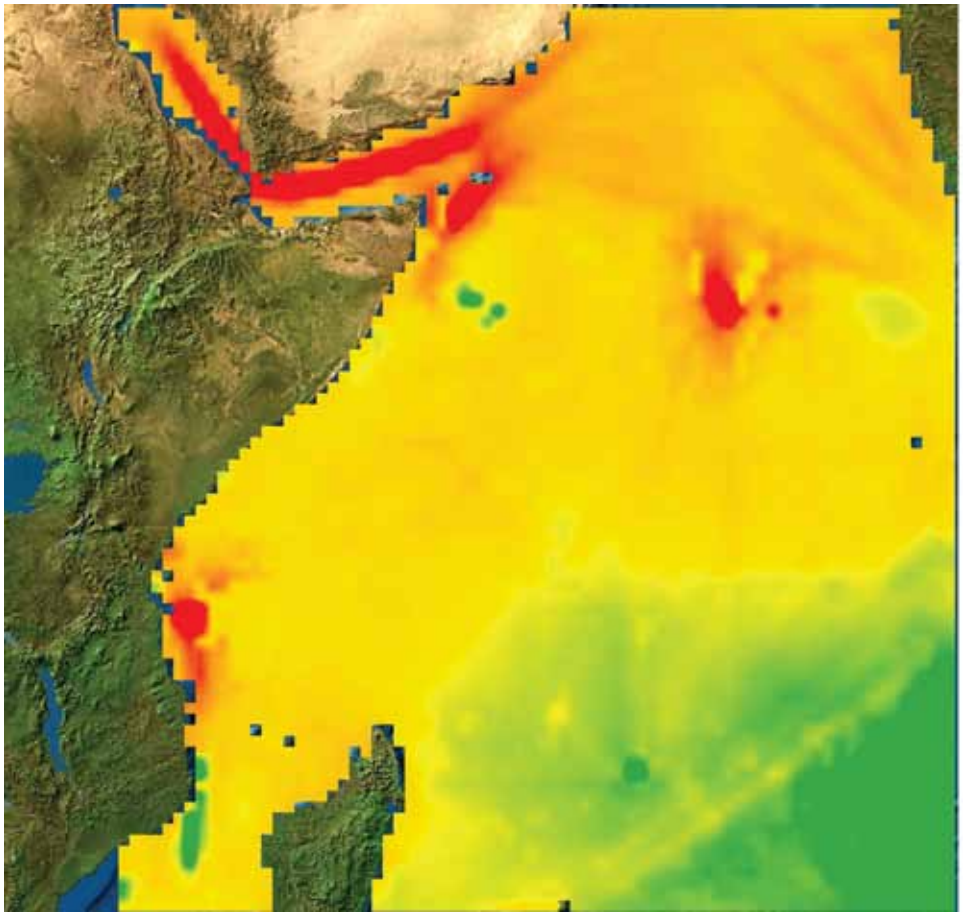
in Fig. 1. We define the probability of attack to be the joint probability of (a), (b), and (c), which is given by the convolution of those three distributions.

Note that the probability of attack as defined above is conditioned upon the intelligence information that went into the construction of the pirate probabilities. If the intelligence information is incorrect or incomplete (which it most likely is), then so too will be the attack probabilities. To account for inaccuracies in intelligence information, "intelligence inadequacy" terms are added to the pirate distribution (based on long-term historical attack information) and the shipping distribution (based on long-term historical shipping distributions). This introduces a loss of theoretical rigor, but enables the communication of useful information to the decision maker.

An example of the product (now denoted Pirate Attack Risk Surface, PARS) is shown in Fig. 4. Figure 4(a) plots the pirate distribution, Fig. 4(b) plots the shipping distribution, and Fig. 4(c) plots the probability of an environment conducive to an attack. Note that if one simply plotted the probability of attack as created by the product of the distributions in Figs. 4(a-c), there would be large areas in which there was zero probability of attack. The inclusion of the "intelligence inadequacy" term fills the space. Note also that the color scale in Fig. 4(d) is not linear in probability. The probabilities in locations far from areas where pirates are expected to be located based on intelligence are orders of magnitude smaller than those in areas where intelligence indicates pirate activity. A nonlinear transformation is applied to the probability field to communicate the risk of pirate attack.



(a) (b) (c)



(d)

FIGURE 4
An example of the PARS product. The pirate probabilities in panel (a) are convolved with the shipping distribution in panel (b) and the probability of encountering a favorable environment in panel (c). An additional "intelligence inadequacy" term in the form of the environmental probability of panel (c) is added to account for the situation in which pirates are operating in areas unknown to intelligence agencies. The resulting risk of attack in panel (d) nonlinearly maps the probability of pirate attack to risk space so that very low probability areas can still be highlighted.

The PARS product is being operationalized at NAVOCEANO with the help of NRL's Marine Meteorology and Marine Geosciences divisions. NAVOCEANO will disseminate the product to U.S., EU, and NATO forces off the HOA to aid in pirate interdiction efforts.

INTELLIGENT PIRATES

A significant limitation of the PARS is that the pirate entities used to construct the pirate probability field do not directly interact with commercial shipping.

An attack is assumed to take place if a pirate, a vulnerable ship, and favorable environmental conditions are all present at a particular location. It would be preferable if commercial shipping, naval ships, and perhaps neutral fishermen were included in the pirate simulation and allowed to interact. Such modeling is naturally carried out in the context of agent-based modeling, but a limitation of existing agent-based modeling frameworks is that none have been developed in which the movements and actions of the agents is influenced by spatio-temporally varying boundary conditions such as those provided by environmental forecasts. The NRL Information Technology Division is performing research to address this limitation and examine the environment's impact on piracy in the agent framework.

Agent-based modeling and simulation is a powerful paradigm to explore complex interactions of goal-driven entities in order to support decision-making. The model used for the pirate problem is based on a prey/predator game with a learned hunting model for a pirate group as predator. Unlike prey/predator games where the population oscillates based on evolutionary dynamics, the presence of pirates at sea fluctuates depending on intelligence information as well as current and past meteorological conditions.

Research in agent-based modeling and simulation of pirate attacks involves (1) learning pirate hunting skills from past history and PARS' predictive analysis, (2) modeling the dynamics of risk-taking behavior, (3) optimizing the allocation of naval forces in a given area to minimize piracy attacks, and (4) developing adversarial strategies for commercial ships. Figure 5 illustrates our approach.

We are exploring agent-based behavior in Repast,[4] a grid-based framework where asynchronous agents act concurrently in a decentralized manner. The basic sense-think-act pirate agent loop leverages existing piracy efforts by calling PARS at each time step to obtain next state probabilities based on environmental and intelligence characteristics (such as skiff speed and environmental thresholds).

CONCLUSION

The generation of pirate distributions by dynamically coupling environmental, intelligence, and behavioral information is a new paradigm for product generation by the Navy Meteorology and Oceanography community. Four NRL divisions are working together to provide this novel capability through official operational dissemination channels to decision makers associated with piracy interdiction. The intelligent agent effort is anticipated to reveal emergent pirate behavior that can be compared against previously observed pirate behavior to reveal changes in or inadequate

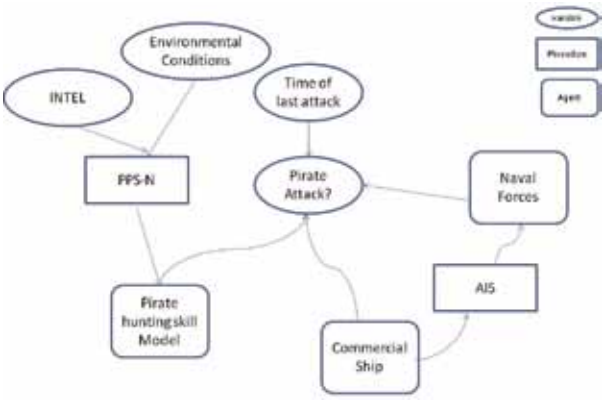


FIGURE 5
Conceptual framework for the agent-based modeling effort where pirates' risk-taking behavior is modulated by the time of last attack, and commercial ships alert Naval forces by broadcasting their location over AIS.[5]

representations of pirate behavior or its environmental dependencies. Such changes have been evident in the past as attack patterns have shifted in response to anti-piracy efforts, changing shipping patterns, and changes in pirate capabilities. Adapting the system to address these changes or deficiencies will ultimately improve the operational product. Similar approaches to product generation can be applied to any environmentally sensitive mission where the timescale of the event is similar to the timescale of impactful weather phenomena. We anticipate applying the approach to the drug interdiction problem where additional enhancements will be necessary to incorporate game theoretic aspects of the problem.

[Sponsored by ONR and SPAWAR PMW-120]

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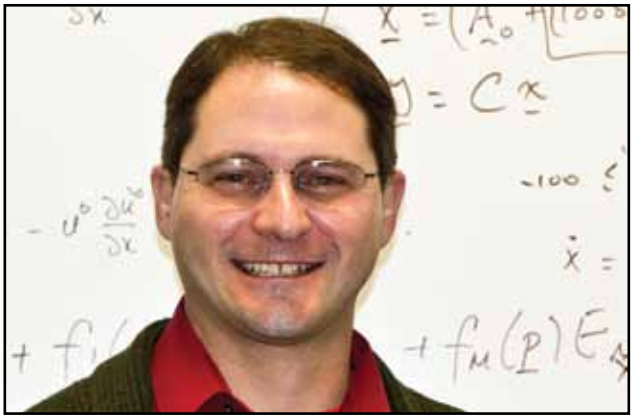

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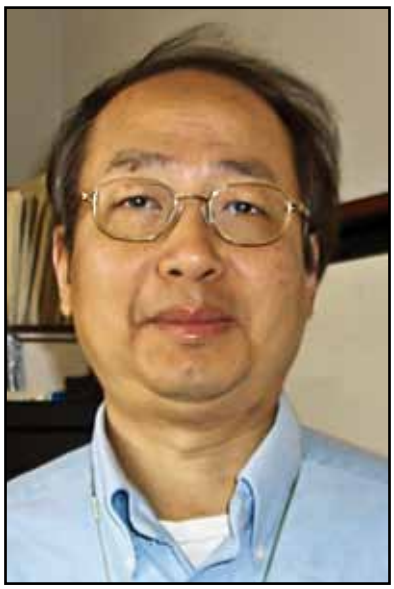

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