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Advances in Search and Rescue at Sea

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Abstract:

A topical collection on “Advances in Search and Rescue at Sea” has appeared in recent issues of Ocean Dynamics following the latest in a series of workshops on “Technologies for Search and Rescue and other Emergency Marine Operations” (2004, 2006, 2008 and 2011), hosted by IFREMER in Brest, France.

Here we give a brief overview of the history of search and rescue at sea before we summarize the main results of the papers that have appeared in the topical collection.

Keywords: Search and rescue (SAR) ; Trajectory modelling ; Stochastic Lagrangian ocean models ; Lagrangian measurement methods ; ocean surface currents.

1. A brief history of SAR planning

Measuring and predicting the drift of search and rescue (SAR) objects has come a long way since Pingree (1944) made the first drift or “leeway” study of life rafts and presented it as “Forethoughts on Rubber Rafts”. The data were unfortunately of limited value, but the general method differed little from that of the earliest successful leeway study by Chapline (1960) who estimated “The drift of distressed small craft” using visual observations of drift nets to establish the current while simultaneously estimating the angle and speed with which the object drifted relative to the wind. This method of conducting leeway studies is known as the indirect method as it indirectly measures the motion of the object relative to the ambient current (the leeway). The method reigned supreme (eg, Hufford and Broida 1976) until the 1990s with the possible exception of Suzuki and Sato (1977) who attempted to log the motion relative to the ambient current using a bamboo pole partly submerged and attached to the side of the ship by string. It should be obvious that the precision of these early experiments was not impressive, but the results were still of remarkable importance in the everyday work of rescue centres around the world.

In 1944 The United States Navy Hydrographic Office issued a manual on "Methods for locating survivors adrift at sea on rubber rafts" (US Navy Hydrographic Office, 1944) which summarized much of the current knowledge at the time of how objects on the sea surface would drift and how to conduct the search. The mathematical field of search theory and the wider topic of operations research (OR) grew out of a need to respond to the German submarine threat during the second world war. The early work was pioneered by Koopman, who after having provided a working manual (Koopman, 1946) of search and screening outlined the fundamentals of search theory in a seminal series of papers (Koopman, 1956a,b, 1957). Without a theory of search the field of search and rescue would not exist and without a theory of how the object moves, there is no way to define the search area for a moving target (Washburn, 1980), so the two fields of object drift and search theory grew up together in the post-war years. We refer to the combined effort of modelling the object drift and optimally allocating the search effort as SAR planning. In the 1950s the United States Coast Guard (USCG) first applied the principles of search theory to SAR planning when it published its search planning doctrine in a SAR manual. Since computers were not widely available, the methods were simplified and adapted for manual calculation. Around 1970 the USCG implemented the first computer-based search and rescue planning system (SARP) which was a computer implementation of the manual methods in the SAR manual. In 1974 the USCG implemented the first Bayesian SAR planning system, the Computer Assisted Search Planning (CASP), see Richardson and Discenza (1980). CASP was among the first applications of computer-assisted Bayesian methods (See McGrayne 2011 for a popular account of the post-war applications of Bayesian methods in search theory and Koopman 1980 for a comprehensive account of its early history). For more details on search theory, see Stone (1989); Frost and Stone (2001) and the upcoming encyclopedic entry by Stone (2013).

CASP produced probability distributions by Monte Carlo methods, generating an ensemble of particle trajectories to estimate the location of the search object as a function of time. The trajectories accounted for the uncertainty of the initial position of the search object and moved the particles in accordance with a primitive drift model. This model relied on historical ship recordings of surface currents on a $1^\circ \times 1^\circ$ monthly climatology grid and wind fields from the US Navy Fleet Numerical Oceanography Center (FNOC) on a $5^\circ \times 5^\circ$ grid at 12 hour intervals forecast to 36 hours into the future. After an unsuccessful search, CASP computed the Bayesian posterior distribution for the location of the search object at the time of the next search by accounting for unsuccessful search and motion due to drift. A less coarse $3^\circ \times 3^\circ$ resolution ocean model without tides was added in 1985. There were several evaluations of SARP and CASP drift estimates using satellite tracked buoys during the early 1980s (Murphy and Allen, 1985). Both SARP and CASP had mixed records at predicting the drift of search objects and very limited capabilities on or inside the continental shelf due to the coarse forcing fields.

Near-real time surface current measurements near the last known position (LKP) are essential to SAR operations. The USCG devised the self-locating datum marker buoy (SLDMBs) based on the Code-Davis drifters developed in the 1980s (Davis, 1985). As Argos transmitters became smaller and global positioning system (GPS) receivers more reliable and affordable this eventually led to operational use of SLDMBs in SAR operations (Allen, 1996). When air deployment of SLDMBs was approved in January 2002 their use became standard routine with most

SAR cases, representing a major advancement in the real-time acquisition of surface currents. They remain an essential tool for rapidly establishing the currents near the presumed point of the incident. A new generation of commercially available light-weight GPS-based SLDMBs that can be deployed from aircraft (adhering to the NATO A-size sonobuoy standard dimensions) is now appearing. These new drifters have a much higher report frequency as they rely on the Iridium satellite network rather than ARGOS. The new generation SLDMBs will also open up new possibilities for physical oceanographers as the cost has come down while precision and reliability have improved greatly compared with earlier models.

With the advent of high-resolution operational ocean models and the continued improvement of numerical weather prediction models (NWP), the potential for making more detailed predictions of the fate of drifting objects grew in the 1990s, and although the improved weather forecasts led to better forcing, drift models remained somewhat impervious to the advances in ocean modelling and numerical weather forecasting. This can perhaps best be understood in light of the great uncertainties in the drift properties of SAR objects. Without a proper estimate of the basic drift properties and their associated uncertainties, forecasting the drift and expansion of a search area remains difficult. An important change came when the *direct method* for measuring the leeway of a drifting object became common practice (Allen and Plourde, 1999; Allen, 2005; Breivik et al., 2011; Hodgins and Hodgins, 1998). The direct method measures the object's motion relative to the ambient water using a current meter. Current meters small enough and flexible enough to be towed or attached directly to a SAR object started to become available in the 1980s, and since then almost all field experiments on SAR objects have employed a direct measurement technique (Allen and Plourde, 1999; Breivik et al., 2011; Maisondieu et al., 2010). The direct method, together with a rigorous definition of *leeway* as

> Leeway is the motion of the object induced by wind (10 m reference height) and waves relative to the ambient current (between 0.3 and 1.0 m depth)

and finally the decomposition of leeway coefficients in *downwind* and *crosswind* components makes it possible to follow a rigorous procedure for conducting leeway field experiments. See Allen and Plourde (1999); Breivik and Allen (2008); Breivik et al. (2011) for further details.

It was not until the 2000s that all the necessary components required for fully stochastic modelling using high-quality drift coefficients and detailed current and wind forecasts were in place. The first operational leeway model to employ the USCG table of drift coefficients (Allen and Plourde, 1999) with high-resolution ocean model current fields and near-surface wind fields went operational in 2001 (see Hackett et al. 2006; Breivik and Allen 2008; Davidson et al. 2009).

The modern era of *SAR planning* involving the Bayesian posterior updates after the search began in 2007 when USCG launched the Search And Rescue Optimal Planning System (SAROPS), see Kratzke et al. (2010). SAROPS employs an environmental data server that obtains wind and current predictions from a number of sources. It recommends search paths for multiple search units that maximize the increase in probability of detection from an increment of search. As with CASP, it computes Bayesian posterior distributions on object location accounting for unsuccessful search and object motion.

By the late 2000s it was clear that although the level of sophistication and detail had grown dramatically since the early days of drift nets and CASP the uncertainties in SAR predictions remained stubbornly high. The fundamental challenge of estimating and forecasting search areas in the presence of large uncertainties remains essentially the same, even though certain error sources have been diminished. The slow progress that has been made over the past decades in reducing the rate of expansion of search areas (perhaps the single best estimate of improvement) is an unavoidable consequence of SAR planning being at "the top of the food chain" in the sense that errors creep in from the current fields, the wind fields, missing processes (e.g., wave effects, see Breivik and Allen 2008; Röhrs et al. 2012), the last known position and not least from poor estimates of the real drift properties of the object. Indeed, sometimes the type of object may not even be known, effectively making the modelling exercise into an ensemble integration spanning a range of object categories. All these error sources accumulate and make SAR planning as much art as science, where rescuers still often rely as much on their "hunches" as on the output of sophisticated prediction tools. The fact that the majority of SAR cases occur near the shoreline and in partially sheltered waters (Breivik and Allen, 2008) compounds the difficulties as the resolution of operational ocean models in many places of the world is still insufficient to resolve nearshore features.

2 The state of the art of drift prediction

Throughout the last decade these advances and obstacles to further progress have been presented mainly through a series of workshops organized on "Technologies for Search and Rescue and other Emergency Marine Operations" (2004, 2006, 2008 and 2011, see Breivik and Olagnon 2005) organized by the French marine research institute (IFREMER) with support from the Norwegian Meteorological Institute, USCG, the French-Norwegian Foundation and the Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). As the last of these workshops drew near we decided that it was time to put some of the advances on a more academic footing by publishing a special issue, and *Ocean Dynamics* agreed to arrange a topical collection on "Advances in search and rescue at sea". This topical collection focusses on recent advances in the understanding of the various processes and uncertainties that have a bearing on the evolution of trajectories at the sea surface, from the drift properties of the objects themselves to the quality of the forcing fields.

The diffusivity of the ocean is an important factor when reconstructing the dispersion of particles either based on observed or modelled vector fields. In either case the dispersion is to the lowest order governed by the advection-diffusion equation (Taylor, 1921) by assuming an "eddy-diffusivity" coefficient. In many cases this simple stochastic model is sufficient for estimating the dispersion of SAR objects over relatively short time periods. De Dominicis et al. (2012) report carefully evaluated estimates of the eddy diffusivity from a large data set of drifter trajectories in the Mediterranean Sea. Such regional (and possibly seasonal) estimates of diffusivity and the integral time scale should be carefully considered as their impact on the dispersion of SAR objects may be substantial.

Stochastic ensemble trajectory models of drifting objects normally employ deterministic (single-model) current and wind vector fields and perturb the trajectories either with a random walk diffusivity (Breivik and Allen, 2008; De Dominicis et al., 2012) or with a more sophisticated second-order random flight model (Spaulding et al., 2006; Griffa, 1996; Berloff and McWilliams, 2002). However, the advent of true ocean model ensembles (Bertino and Lisæter, 2008) have now opened up the possibility of exploiting a full vector field ensemble for estimating drift and dispersion in the ocean. Melsom et al. (2012) compared the dispersion of passive tracers in a 100-member ensemble of the TOPAZ ocean prediction system to the dispersion found adding random flight perturbations to the ensemble mean vector field and a deterministic vector field. The results are not conclusive in favour of the full ensemble, which is important to keep in mind when considering the cost-benefit of such computationally expensive operational ocean forecast systems. An alternative to a full model ensemble is to employ multi-model ensembles (see Rixen and Ferreira-Coelho 2007; Rixen et al. 2008; Vandenbulcke et al. 2009), which is what Scott et al. (2012) did when they assembled five model reanalyses and compared the weighted average with observed trajectories in the equatorial Atlantic.

Several workers (Barrick et al., 2012; Kohut et al., 2012; Frolov et al., 2012; Kuang et al., 2012; Abascal et al., 2012) investigated the potential for high-frequency (HF) radar monitoring systems to supply near real-time current fields to reconstruct the trajectories and the dispersion of drifting objects in the coastal zone. Kohut et al. (2012) explored the impact on search areas from switching to an optimal interpolation (OI) scheme for calculating total vectors from radial vector fields. Such techniques for extending the range of HF radars (see also Barrick et al. 2012 discussed below) can make a significant difference when investigating nearshore SAR cases.

HF radar fields and drifter studies can be used to evaluate the quality of ocean model current fields. Since the rate of expansion of search areas depends intimately on the quality of the forcing, it remains very important to establish good error estimates for each ocean model being used for SAR prediction. Kuang et al. (2012) assessed the New York Harbor Observing and Prediction System (NYHOPS) using boths SLDMBs and HF currents. They found good agreement between model, HF radar and three drifter trajectories in the Middle Atlantic Bight and were able to quantify the root-mean-square differences between the modelled NYHOPS and the observed HF fields.

HF short-term prediction of surface current vectors out to typically 12-24 hours is a technique with great potential for near-shore SAR operations. Barrick et al. (2012) employed open modal analysis (OMA, see Lekien et al. 2004) to decompose the vector field into divergent and rotational modes within the HF domain along the complex coastline of northern Norway (see Whelan et al. 2010 for a description of the radar deployment). They then predicted the short-term variation of the amplitudes of the most energetic modes based on a relatively short history of archived vector fields, giving short-term forecasts out to 24 hours. Frolov et al. (2012) chose empirical orthogonal functions (EOFs) instead of normal modes and then employed an autoregressive method to make short-term predictions out to 48 hours for an HF network in Monterey Bay.

Although the direct leeway field method was established as the superior technique for establishing the leeway of drifting objects already in the late 1980s, the technique was only recently presented in the open literature by Breivik et al. (2011). Breivik et al. (2012a) explored how the technique can be applied to relatively large objects such as shipping containers and combined the field results with estimates from earlier work on shipping containers by Daniel et al. (2002) to estimate how the drift varies with immersion.

Most trajectory models for small surface objects ignore the direct wave excitation and damping since only waves whose wave length is comparable to the dimensions of the object will excert a significant force on the object (Breivik and Allen, 2008; Mei, 1989). Since SAR objects are typically smaller than 30 m their resonant ocean waves will have only negligible energy. However, waves will also affect an object through the Stokes drift (Phillips, 1977; Holthuijsen, 2007), which is a Lagrangian effect not visible in an Eulerian frame of reference. Röhrs et al. (2012) explored how the Stokes drift affects surface drifters with and without leeway directly and through the addition of the Coriolis-Stokes effect to the momentum equation. The term adds an additional deflection to upper-ocean currents caused by the Coriolis effect acting on the Stokes drift. This has clear relevance for the operational forecasting of SAR objects as well as for the interpretation of SLDMB trajectories, although it is not clear yet how large the effect is for real-world search objects that also move under the direct influence of the wind.

Finally, the importance of being able to estimate the point of an accident based on a debris field was made poignantly clear after the AF447 aircraft accident on 1 June 2009 in the equatorial Atlantic (see Stone et al. 2011 for an account of the search effort following the accident). Using SAR trajectory models for backtracking is not trivial since it effectively means reversing the (usually weakly nonlinear) processes that propel the object. In principle it is better to run a model forward and iterate, as Breivik et al. (2012b) has demonstrated, but nevertheless direct backtracking can be employed if the model integration times are modest. Drevillon et al. (2012) describes the amount of preparation that went into the so-called "Phase III" of the search. Detailed regional atmospheric reanalyses and ocean model hindcasts were performed to prepare a multi-model high-resolution ensemble of wind and current fields that were then used to perform a range of backtracking trajectory integrations. Similarly, Chen et al. (2012) included a wind drag factor and were able to estimate the point of impact for the AF447 accident based on backtracking the observed debris field. The method of using a wind drag coefficient to fine-tune the drift properties was also employed by Abascal et al. (2012) to investigate the optimum balance of HF current fields and wind fields required to backtrack drogued and undrogued drifters.

The 12 articles in this topical collection provide a snapshot more than a complete overview of the state of object drift modelling and SAR prediction at sea as it stands today. We hope that by putting together this special issue we provide a starting point for new workers in the field as well as a body of references of what has been published earlier. This is particularly important in an operational field such as SAR planning where a majority of the work to date is "grey literature" in the form of technical reports that may not be readily accessible or properly vetted through peer review. SAR planning and object drift modelling demand both mathematical rigour and experimental finesse to advance further. Peer-reviewed communication is the most efficient way to achieve this. It is our hope that this special issue will contribute to a more academic approach to this exciting field.

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http://www.ifremer.fr/web-com/sar2011

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References

Abascal, A., Castanedo, S., Fernández, V., Medina, R., 2012. Backtracking drifting objects using surface currents from high-frequency (HF) radar technology. Ocean Dynam 62 (7), 1073–1089, doi:10.1007/s10236–012–0546–4.

Allen, A., 1996. Performance of GPS/Argos self-locating datum marker buoys (SLDMBs). In: OCEANS'96. MTS/IEEE, Prospects for the 21st Century. Conference Proceedings. Vol. 2. IEEE, pp. 857–861, doi:10.1109/OCEANS.1996.568341.

Allen, A., 2005. Leeway Divergence Report. Tech. Rep. CG-D-05-05, US Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, USA.

Allen, A., Plourde, J. V., 1999. Review of Leeway: Field Experiments and Implementation. Tech. Rep. CG-D-08-99, US Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, USA, available through http://www.ntis.gov.

Barrick, D., Fernandez, V., Ferrer, M. I., Whelan, C., Breivik, Ø., 2012. A short-term predictive system for surface currents from a rapidly deployed coastal HF radar network. Ocean Dynam 62, 725–740, doi:10.1007/s10236–012–0521–0.

Berloff, P. S., McWilliams, J. C., 2002. Material Transport in Oceanic Gyres. Part II: Hierarchy of Stochastic Models. J Phys Oceanogr 32 (March), 797–830.

Bertino, L., Lisæter, K., 2008. The TOPAZ monitoring and prediction system for the Atlantic and Arctic Oceans. Journal of Operational Oceanography 1 (2), 15–18.

Breivik, Ø., Allen, A., Maisondieu, C., Roth, J.-C., Forest, B., 2012a. The Leeway of Shipping Containers at Different Immersion Levels. Ocean Dynam 62, 741–752, doi:10.1007/s10236–012–0522–z, arXiv:1201.0603.

Breivik, Ø., Allen, A. A., 2008. An operational search and rescue model for the Norwegian Sea and the North Sea. J Marine Syst 69 (1–2), 99–113, doi:10.1016/j.jmarsys.2007.02.010, arXiv:1111.1102.

Breivik, Ø., Allen, A. A., Maisondieu, C., Roth, J. C., 2011. Wind-induced drift of objects at sea: The leeway field method. Appl Ocean Res 33, 10 pp, doi:10.1016/j.apor.2011.01.005, arXiv:1111.0750.

Breivik, Ø., Bekkvik, T. C., Ommundsen, A., Wettre, C., 2012b. BAKTRAK: Backtracking drifting objects using an iterative algorithm with a forward trajectory model. Ocean Dynam 62, 239–252, doi:10.1007/s10236–011–0496–2, arXiv:1111.0756.

Breivik, Ø., Olagnon, M. (Eds.), 2005. Proceedings of Technologies for Search, Assistance and Rescue workshop, Brest, France, 18-20 Oct. 2004, Available on request from IFREMER.

Chapline, W., 1960. Estimating the drift of distressed small craft. Tech. Rep. 2, US Coast Guard Academy.

Chen, C., Limeburner, R., Gao, G., Xu, Q., Qi, J., Xue, P., Lai, Z., Lin, H., Beardsley, R., Owens, B., Carlson, B., 2012. FVCOM model estimate of the location of Air France 447. Ocean Dynam 62, 943–952, doi:10.1007/s10236–012–0537–5.

Daniel, P., Jan, G., Cabioch, F., Landau, Y., Loiseau, E., 2002. Drift Modeling of Cargo Containers. Spill Science and Technology Bulletin 7 (5-6), 279–288.

Davidson, F. J. M., Allen, A., Brassington, G. B., Breivik, Ø., Daniel, P., Kamachi, M., Sato, S., King, B., Lefevre, F., Sutton, M., Kaneko, H., 2009. Applications of GODAE ocean current forecasts to search and rescue and ship routing. Oceanography 22 (3), 176–181, doi:10.5670/oceanog.2009.76.

Davis, R. E., 1985. Drifter observations of coastal surface currents during CODE: The method and descriptive view. J Geophys Res 90 (C3), 4741–4755.

De Dominicis, M., Leuzzi, G., Monti, P., Pinardi, N., Poulain, P.-M., 2012. Eddy diffusivity derived from drifter data for dispersion model applications. Ocean Dynam, 18, doi:10.1007/s10236–012–0564–2.

Drevillon, M., Greiner, E., Paradis, D., Payan, C., Lellouche, J.-M., Reffray, G., Durand, E., Chune, S. L., Cailleau, S., 2012. A strategy for producing refined currents in the Equatorial Atlantic in the context of the search of the AF447 wreckage. To appear in Ocean Dynam, doi:10.1007/s10236–012–0580–2.

Frolov, S., Paduan, J., Cook, M., Bellingham, J., 2012. Improved statistical prediction of surface currents based on historic HF-radar observations. Ocean Dynamics 62 (7), 1111–1122, doi:10.1007/s10236–012–0553–5.

Frost, J., Stone, L., 2001. Review of search theory: Advances and applications to search and rescue decision support. Tech. Rep. CG-D-15-01, US Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, USA.

Griffa, A., 1996. Applications of stochastic particle models to oceanographic problems. In: Adler, R., Muller, P., Rozovskii, B. (Eds.), Stochastic Modelling in Physical Oceanography. Birkhauser, Boston, pp. 113–128.

Hackett, B., Breivik, Ø., Wettre, C., 2006. Forecasting the drift of objects and substances in the oceans. In: Chassignet, E. P., Verron, J. (Eds.), Ocean Weather Forecasting: An Integrated View of Oceanography. Springer, pp. 507–524.

Hodgins, D. O., Hodgins, S. L. M., 1998. Phase II Leeway Dynamics Program: Development and Verification of a Mathematical Drift Model for Liferafts and Small Boats. Tech. rep., Canadian Coast Guard, Nova Scotia, Canada.

Holthuijsen, L., 2007. Waves in Oceanic and Coastal Waters. Cambridge University Press.

Hufford, G., Broida, S., 1976. Estimation of the leeway drift of small craft. Ocean Engng 3 (3), 123–132, doi:10.1016/0029–8018(76)90028–7.

Kohut, J., Roarty, H., Randall-Goodwin, E., Glenn, S., Lichtenwalner, C., 2012. Evaluation of two algorithms for a network of coastal HF radars in the Mid-Atlantic Bight. Ocean Dynamics 62, 953–968, doi:10.1007/s10236–012–0533–9.

Koopman, B., 1946. Search and Screening. Tech. Rep. 56, Office of the Chief of Naval Operations.

Koopman, B., 1956a. The Theory of Search, Part I: Kinematic Bases. Operations Research 4, 324–346.

Koopman, B., 1956b. The Theory of Search, Part II: Target Detection. Operations Research 4, 503–531.

Koopman, B., 1957. The Theory of Search, Part III: The Optimum Distribution of Searching Effort. Operations Research 5, 613–626.

Koopman, B., 1980. Search and screening: general principles with historical applications. Pergamon Press New York.

Kratzke, T. M., Stone, L. D., Frost, J. R., 2010. Search and Rescue Optimal Planning System. In: Proceedings of the 13 International Conference on Information Fusion. IEEE, p. 8 pp.

Kuang, L., Blumberg, A. F., Georgas, N., 2012. Assessing the Fidelity of Surface Currents from a Coastal Ocean Model and HF Radar using Drifting Buoys in the Middle Atlantic Bight. Ocean Dynam.

Lekien, F., Coulliette, C., Bank, R., Marsden, J., 2004. Open-boundary modal analysis: Interpolation, extrapolation, and filtering. Journal of Geophysical Research C 109 (C12), 13, doi:10.1029/2004JC002323.

Maisondieu, C., Breivik, Ø., Roth, J., Allen, A., Forest, B., Pavec, M., 2010. Methods for Improvement of Drift Forecast Models. In: 29th International Conference on Ocean, Offshore and Arctic Engineering: Volume 4. ASME, pp. 127–133, doi:10.1115/OMAE2010–20219.

McGrayne, S., 2011. The Theory that Would Not Die: How Bayes' Rule Cracked the Enigma Code, Hunted Down Russian Submarines, and Emerged Triumphant from Two Centuries of Controversy. Yale University Press.

Mei, C. C., 1989. The applied dynamics of ocean surface waves, 2nd Edition. World Scientific, Singapore.

Melsom, A., Counillon, F., LaCasce, J., Bertino, L., 2012. Forecasting search areas using ensemble ocean circulation modeling. Ocean Dynam, 13, doi:10.1007/s10236–012–0561–5.

Murphy, D., Allen, A., 1985. An Evaluation of CASP Drift Predictions near the New England Shelf/Slope Front. Tech. Rep. CG-D-16-85, US Coast Guard Research and Development Center, 1082 Shennecossett Road, Groton, CT, USA, available through http://www.ntis.gov.

Phillips, O. M., 1977. The Dynamics of the Upper Ocean, 2nd Edition. Cambridge University Press, Cambridge.

Pingree, F., 1944. Forethoughts on Rubber Rafts. Technical Report, Woods Hole Oceanographic Institution.

Richardson, H. R., Discenza, J. H., 1980. The United States Coast Guard Computer-Assisted Search Planning System (CASP). Nav Res Logist 27, 659–680, doi:10.1002/nav.3800270413.

Rixen, M., Ferreira-Coelho, E., 2007. Operational surface drift prediction using linear and non-linear hyper-ensemble statistics on atmospheric and ocean models. J Marine Syst 65 (1-4), 105–121, doi:10.1016/j.jmarsys.2004.12.005, marine Environmental Monitoring and Prediction - Selected papers from the 36th International Liège Colloquium on Ocean Dynamics, 36th International Liège Colloquium on Ocean Dynamics.

Rixen, M., Ferreira-Coelho, E., Signell, R., 2008. Surface drift prediction in the adriatic sea using hyper-ensemble statistics on atmospheric, ocean and wave models: Uncertainties and probability distribution areas. J Marine Syst 69 (1–2), 86–98, doi:10.1016/j.jmarsys.2007.02.015, maritime Rapid Environmental Assessment - New Trends in Operational Oceanography.

Röhrs, J., Christensen, K., Hole, L., Broström, G., Drivdal, M., Sundby, S., 2012. Observation based evaluation of surface wave effects on currents and trajectory forecasts. To appear in Ocean Dynam, 14 pp, doi:10.1007/s10236–012–0576–y.

Scott, R., Ferry, N., Drévillon, M., Barron, C., Jourdain, N., Lellouche, J.-M., Metzger, E., Rio, M.-H., Smedstad, O., 2012. Estimates of surface drifter trajectories in the equatorial Atlantic: a multi-model ensemble approach. Ocean Dynamics 62 (7), 1091–1109, doi:10.1007/s10236–012–0548–2.

Spaulding, M., Isaji, T., Hall, P., Allen, A., 2006. A hierarchy of stochastic particle models for search and rescue (SAR): Application to predict surface drifter trajectories using HF radar current forcing. Journal of Marine Environmental Engineering 8 (3), 181.

Stone, L., 1989. Theory of Optimal Search, second edition. INFORMS.

Stone, L., Keller, C., Kratzke, T., Strumpfer, J., 2011. Search analysis for the underwater wreckage of Air France Flight 447. In: Information Fusion (FUSION), 2011 Proceedings of the 14th International Conference on. IEEE, p. 8 pp.

Stone, L. D., 2013. Search Theory. In: Gass, S., Fu, M. (Eds.), Encyclopedia of Operations Research and Management Science. Springer.

Suzuki, T., Sato, H., 1977. Measurement of the drifting of a fishing boat or research vessel due to wind and wave. Journal of Japan Institute of Navigation 65 (4), 1225–1245, doi:10.1175/2007JAS2427.1.

Taylor, G. I., 1921. Diffusion by continuous movements. Proc Lond Math Soc 20, 196–211.

US Navy Hydrographic Office, 1944. Methods for locating survivors adrift at sea on rubber rafts. Technical Report 235, United States Navy Hydrographic Office.

Vandenbulcke, L., Beckers, J.-M., Lenartz, F., Barth, A., Poulain, P.-M., Aidonidis, M., Meyrat, J., Ardhuin, F., Tonani, M., Fratianni, C., Torrisi, L., Pallela, D., Chiggiato, J., Tudor, M., Book, J., Martin, P., Peggion, G., Rixen, M., 2009. Super-ensemble techniques: Application to surface drift prediction. Progress In Oceanography 82 (3), 149 – 167, doi:10.1016/j.pocean.2009.06.002.

Washburn, A. R., 1980. On search for a moving target. Nav Res Logist Q 27, 315–322.

Whelan, C., Barrick, D., Lilleboe, P., Breivik, Ø., Kjelaas, A., Fernandez, V., Alonso-Martirena, A., 2010. Rapid deployable HF RADAR for Norwegian emergency spill operations. In: OCEANS 2010 IEEE-Sydney. IEEE, pp. 1–3, doi:10.1109/OCEANSSYD.2010.5603848.