NATO Undersea Research Centre
Centre de Recherche Sous-Marine de l'OTAN

NURC Technical Report NURC-FR-2006-012

Surface drift prediction in the Adriatic Sea using hyper-ensemble statistics on atmospheric, ocean and wave models: uncertainties and probability distribution areas

Michel Rixen, Emanuel Ferreira-Coelho, Richard Signell

May 2006

NATO Undersea Research Centre (NURC)

NURC conducts world class maritime research in support of NATO's operational and transformational requirements. Reporting to the Supreme Allied Commander Transformation, the Centre maintains extensive partnering to expand its research output, promote maritime innovation and foster more rapid implementation of research products.

The Scientific Programme of Work (SPOW) is the core of the Centre's activities and is organized into four Research Thrust Areas:

- Expeditionary Mine Countermeasures (MCM) and Port Protection (EMP)
- Reconnaissance, Surveillance and Undersea Networks (RSN)
- Expeditionary Operations Support (EOS)
- Command and Operational Support (COS)

NURC also provides services to other sponsors through the Supplementary Work Program (SWP). These activities are undertaken to accelerate implementation of new military capabilities for NATO and the Nations, to provide assistance to the Nations, and to ensure that the Centre’s maritime capabilities are sustained in a fully productive and economic manner. Examples of supplementary work include ship chartering, military experimentation, collaborative work with or services to Nations and industry.

NURC’s plans and operations are extensively and regularly reviewed by outside bodies including peer review of the research, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification. The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to the Centre and the Supreme Allied Commander Transformation.

Surface drift prediction in the Adriatic Sea using hyper-ensemble statistics on atmospheric, ocean and wave models: uncertainties and probability distribution areas

Rixen, M., Ferreira-Coelho, E., Signell, R.

This document, which describes work performed under Project 1A5 (Shallow Water Acoustic Ensemble Prediction) of the NATO Undersea Research Centre Scientific Programme of Work, has been approved by the Director.

intentionally blank page

Surface drift prediction in the Adriatic Sea using hyper-ensemble statistics on atmospheric, ocean and wave models: uncertainties and probability distribution areas.

Rixen, M., Ferreira-Coelho, E., Signell, R.

Executive Summary: Nowadays, an increasing number of models are routinely providing weather forecasts and climate predictions, offering multiple options on resolutions, range, domains and derived fields.

NATO requirements include reliable tactical knowledge and forecasts of the sea surface components, where potential mine threats have to be mitigated or avoided and where search and rescue efforts have to be optimized. These issues become more challenging and relevant when considering support for Expeditionary Warfare (in remote areas with limited access) and countering naval asymmetric warfare (need for high accuracy and reliability).

The surface drift is the resultant of many different direct and indirect contributions of the atmosphere, the ocean and the sea surface itself. However, the prediction of the surface drift resultant still remains a challenge when the different components have competing contributions, like in coastal or near-shore areas.

One of the possible solutions to address these issues is to migrate from the traditional deterministic approaches towards probabilistic-stochastic methodologies, where instead of individual field estimates and products, the end-user is being offered optimal estimates and error bounds (or likelihood figures).

When multiple models and data become available, the envisaged probabilistic-stochastic alternative is the multi-model super-ensemble technique which uses an optimized combination of an ensemble of models. This technique has previously been demonstrated to improve forecast skills in the atmospheric and is applied here to the prediction of surface drift in the Adriatic. The technique combines optimally an atmospheric, an ocean and a wave model and is shown to outperform traditional forecast methods.

intentionally blank page

Surface drift prediction in the Adriatic Sea using hyper-ensemble statistics on atmospheric, ocean and wave models: uncertainties and probability distribution areas.

Rixen, M., Ferreira-Coelho, E., Signell, R.

Abstract: Despite numerous and regular improvements in underlying models, surface drift prediction in the ocean remains a challenging task because of our yet limited understanding of all processes involved. Hence, deterministic approaches to the problem are often limited by empirical assumptions on underlying physics. Multi-model hyper-ensemble forecasts, which exploit the power of an optimal local combination of available information including ocean, atmospheric and wave models, may show superior forecasting skills when compared to individual models because they allow for local correction and/or bias removal. In this work, we explore more in detail the potential and limitations of the hyper-ensemble method in the Adriatic Sea, using a comprehensive surface drifter data base. The performance of the hyper-ensembles and the individual models are discussed by analyzing associated uncertainties and probability distribution maps. Results suggest that the stochastic method may reduce the position errors significantly for 12 to 72 hours forecasts and hence compete with pure deterministic approaches.

Keywords: forecast – surface drift – ocean models – atmospheric models – wave models – multi-model super-ensembles – linear regression.

Contents

1 Introduction

Nowadays, a plethora of ocean, wave and atmospheric models are available on a routine basis, at the global, regional and local scale in many coastal areas. A fundamental question arises as to which model to be select or to rely on, what criteria to apply for this selection and what is the associated confidence level.

All such models have varying skills in space, in time, but also in frequency. A master model may introduce direct errors on a slave model in a one-way coupled implementation or even feedback errors on itself in two-way coupled implementations, generating a complex chain of errors known as the “uncertainty cascade”.

Much effort is spent on individual model improvements, limited at a point beyond which processes have to be simulated in a non-deterministic way. An original statistical approach was recently proposed to circumvent this limitation, aiming at combining optimally different models into a *super-ensemble* for weather and climate forecast (Krishnamurti *et al*, 2000a, 2000b; Kumar *et al*, 2003; Shin and Krishnamurti, 2003a, 2003b) using least squares optimization, dynamic linear models and probabilistic approaches.

These techniques have been also successfully applied in the ocean for sound velocity profile estimations (Rixen and Ferreira-Coelho 2005) and for surface drift problems (Rixen and Ferreira-Coelho, in press).

Surface drift prediction can be very challenging in certain areas because of the number, and the complex interplay of processes involved (e.g. Carniel et al 2002, Rixen and Ferreira-Coelho, in press), including Ekman transport, tides, Stokes drift, ocean currents, inertial oscillation, leeway effects, *etc*. A rule of thumb says that Ekman drift will set up a surface current of roughly ~3% of the wind speed, ~15° to the right of the downwind direction in the Northern hemisphere. But these values may vary according to the sea state and the stratification (*e.g.* Gill 1982). The other processes may have similar contributions to the flow. Indeed, one may thus include the effect of waves and ocean. Deterministic methods do not yet exist to combine these effects, and it is hence natural to experiment non-deterministic or statistical approaches to solve surface drift problems.

In the present study, the hyper-ensemble approach developed in Rixen and Ferreira-Coelho (in press) is applied to (1) forecast at short time scale surface drifts from combined atmospheric ocean, wave models and local drifter observations in the Adriatic during a “Bora” event that occurred in February 2003, a wind responsible for the deep water formation in the area in winter (*e.g.* Signell et al, 2005) (2) to derive uncertainty/probability areas for drifter positions. Data, models and the hyper-ensemble methodology are detailed in section 2. Results are presented in section 3 and conclusions are drawn in section 4.

2
Data and models

2.1 Data - drifters

Lagrangian drifters provide a broad, basin-scale, coverage of mesoscale surface circulation and surface temperatures to study the movement of water masses (*e.g.* Kovacevic *et al*, 1999; Poulain *et al*, 2003). Typical drifters that track the top one-meter of the ocean surface show excellent coupling to the surface layer and exhibit little wave rectification. Between fall 2002 and spring 2003 covering field experiments ADRIA02 and ADRIA03 with R/V ALLIANCE, some 144 drifters were launched in the Adriatic, building a comprehensive database used in this study.

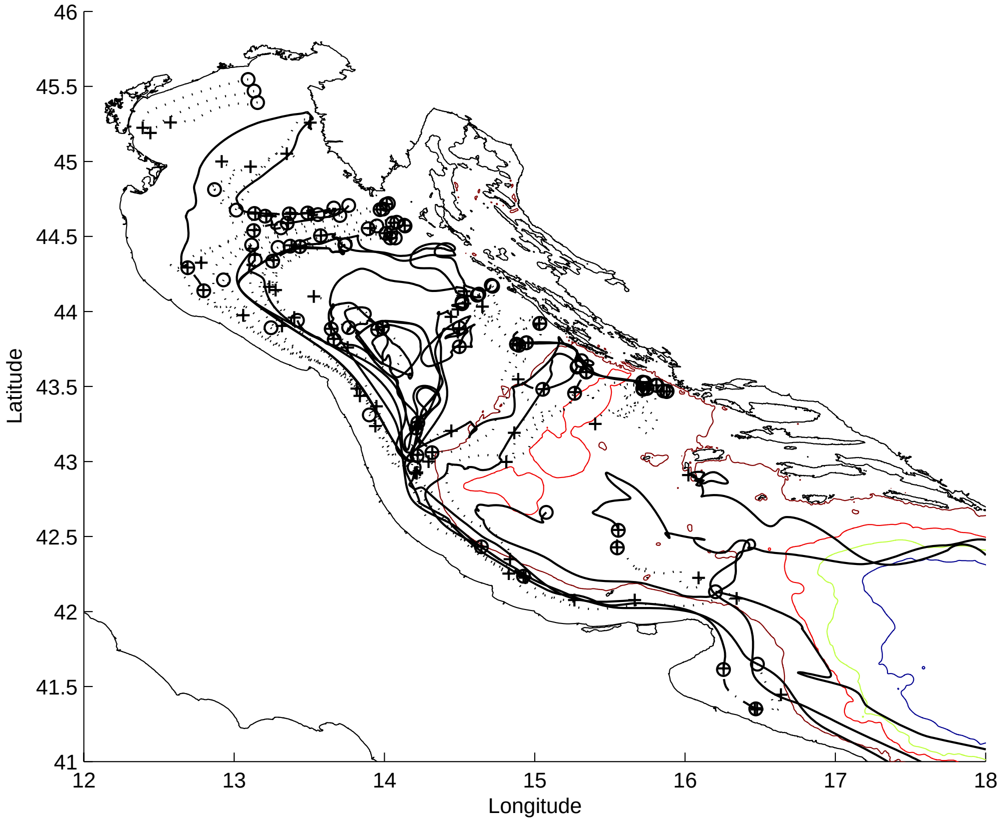

Figure 1 *Selected trajectories of drifters in the Adriatic Sea for period January-February 2003. The dashed line shows the 48 hours track after 10-Feb-2003. The dotted line shows the remaining track after that time. Circles and crosses indicate start and end position.*

2.2 The atmospheric, ocean and wave models

ROMS Circulation Model

To simulate near-surface ocean circulation, the Regional Ocean Modeling System (ROMS) version 2.1 was used. This model was selected because it has several features of potential benefit for the study of near-surface currents. The s-coordinate allows more flexibility than the sigma coordinate in specifying vertical grid spacing, allowing thin layers near the surface to have a more uniform thickness. Additionally, version 2.1 contains the Generic Length Scale (GLS) mixing scheme of Umlauf and Burchard (2003), which can be configured with parameters that allow the model to represent the correct dissipation profile under strong wind driving with breaking surface waves. The model was configured in curvilinear coordinates with variable grid resolution ranging from 3-4 km in the northern Adriatic to 7-9 km in the southern Adriatic. The model was initialized in mid September, 2002 using *in situ* observations and driven with tides and no-gradient temperature and salinity open boundary conditions at the narrow entrance to the Adriatic Sea. Wind, air temperature, air pressure, cloud fraction, short-wave radiation and relative humidity were used from LAMI (see below) with sea surface temperature from ROMS to compute bulk momentum and heat fluxes using the COARE 2.6 algorithms. The model was run from September 17, 2002 to June 13, 2003, and output saved every 3 hours. For further details on the model implementation, see Signel et al (2005) and references therein.

LAMI Model

LAMI (Limited Area Model Italy) is the Italian operational implementation of LOKAL MODELL, the limited area model originally developed by the German Meteorological Service (Deutscher WetterDienst, DWD) for meso/micro scale weather prediction and simulation developed by several European meteorological services belonging to COSMO (COnsortium for Small scale MOdelling). LAMI is managed by SMR-ARPA-EMR, UGM (Ufficio Generale per la Meteorologia, Italian Airforce) and Regione Piemonte. It has been operational since the beginning of 2001 at the CINECA super-computing Centre in Bologna. It has a 7 km grid spacing and 35 vertical terrain-following levels. It is a fully compressible, non-hydrostatic 3D model in which initial and boundary conditions are obtained from the DWD global circulation model GME (Majewsky, 1998; Majewsly et al., 2002). LAMI gives output every 3 hours and produces a 48 hours forecast daily. We therefore used forecast winds at 03, 06, 09, … 24 (00 + 03, 00 + 06, 00 + 09, … 00 +24). For further details, see Doms and Shatter (1999), Cacciamani et al. (2002) or the COSMO web site (http://www.cosmo-model.org).

COAMPS Model

The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) is a 3D finite difference, non-hydrostatic, sigma-coordinate model developed by the Naval Research Laboratory (Hodur, 1997). The version adopted was run in a re-analysis mode using three nested grids with the finest 4 km grid mesh centred over the Adriatic Sea. The two outer meshes are a 12 km grid covering the majority of the Mediterranean and a 36 km resolution European grid. The global NOGAPS model provides lateral boundary conditions for the 36 km grid at 6-hour intervals. In the reanalysis configuration, analyses are performed twice daily with forecasts for the following 15 hours. Forecast winds at 03, 06, 09, … 24 hours (00 + 03, 00 + 06, 00 + 09, 00 + 12, 12 + 03, 12 + 06, 12 + 09, 12 + 12) were used. Further details are documented in Hodur et al. (2001) for an evaluation of the COAMPS system and in Pullen et al. (2003) for the Adriatic re-analysis.

SWAN Model

In order to simulate the wave characteristics, a third-generation wave model, SWAN (Simulating WAves Nearshore), has been implemented for the Adriatic Sea with COAMPS wind forcing. The SWAN model was developed for shallow waters at Delft University Technology (TU Delft), with support from the Office of Naval Research (USA) and the Ministry of Transport, Public Works and Water Management (The Netherlands). The basic model used in this paper was SWAN version 4.41.

Waves in SWAN are described with the two-dimensional wave action density spectrum, the balance equation of which takes into account the local rate of change in time, the propagation in geographical space, the shifting of the relative frequency due to variations in depths and currents and the depth-induced and current-induced refraction. The sink-source terms take into account the generation by wind, dissipation by white-capping, dissipation by depth-induced wave breaking, dissipation by bottom friction and redistribution of wave energy over the spectrum by non-linear wave-wave interactions. A full description of the SWAN model is given by Holthuijsen et al. (1989), Booij et al. (1999) and Ris et al. (1999), and http://www.swan.ct.tudelft.nl.

Thirty-six uniformly distributed directions were used with 26 frequencies geometrically distributed: f_{n+1}=1.1*f_n, and f_1=0.05 Hz. The model time step was 10 min and the spatial grid had a uniform resolution of 2 km over the Adriatic. The bathymetry for the 2 km grid was interpolated from the finite element tidal model of Cushman-Roisin and Naimie (2002). The wind components from the four wind models were linearly interpolated onto the 2 km wave model grid prior to running the simulations. Incoming waves at the open southeastern boundary of the Adriatic were assumed to be zero. The model was run in non-stationary mode with wave breaking enabled and Madsen bottom friction with default parameters.

Further details on these models and their respective implementations may be found in Signell et al (2005).

Figure 2 shows the model velocities before and during a BORA event for the ocean surface currents, stokes drift from waves (e.g. Rixen et al, in press), wind velocities at 10m and the drifter velocities optimally interpolated in space at time with 30km spatial and 3 days temporal correlation lengths. LAMI shows weak winds on the 8 February 2003 followed by strong BORA conditions on the 16 February 2003. ROMS surface currents and SWAN stokes drift respond accordingly with strong NE-SW currents and Stokes drift components in the Northern Adriatic and a strong signature of the Western Adriatic Current (*e.g.* Poulain and Raicich, 2001). These model outputs agree qualitatively with the surface drift as derived directly from the drifter data showing strong velocities in the Northern Adriatic and along the Western Adriatic coast from day 12 Feb onward. They have been interpolated on a common 5km by 5 km grid.

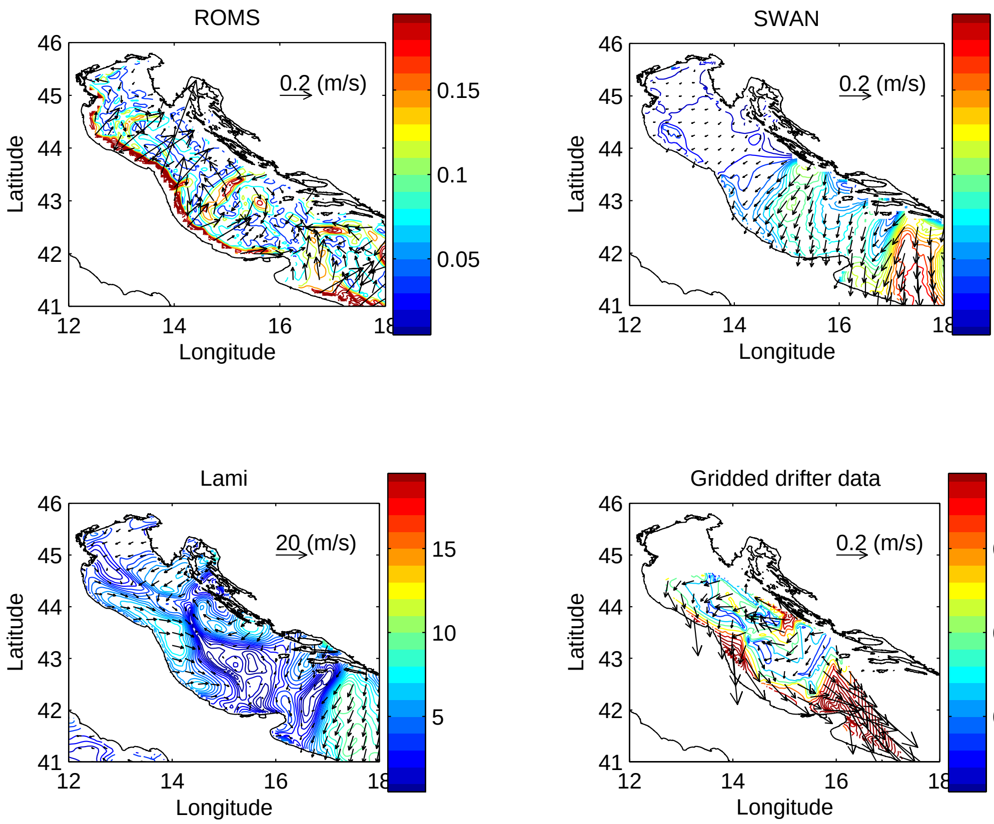

Figure 2a *ROMS ocean currents (top-left, surface), SWAN derived Stokes drift (top-right, surface), LAMI winds at 10m (bottom-left) model nowcasts and gridded drifters velocities (m/s) at days 8 (top) and 20 (bottom) February 2003, 00:00.*

Surface drift 48 hrs forecast errors from traditional approaches are presented in Figure 3 for day 10 February (corresponding to day 12 February) and include simple ocean advection (top left), the rule of thumb imposing 3% of the wind magnitude rotated by 15 degrees to the right, the combination of both (bottom left) and the subsequent addition of the Stokes drift (bottom right). ROMS ocean currents show larger errors along the Croatian coast. The rule of thumb on the contrary shows large discrepancies along the Italian coast. The combination of the rule of thumb and ocean currents and the subsequent addition of the Stokes drift contribution increase the errors further. Results for other days and lead times show qualitatively similar results.

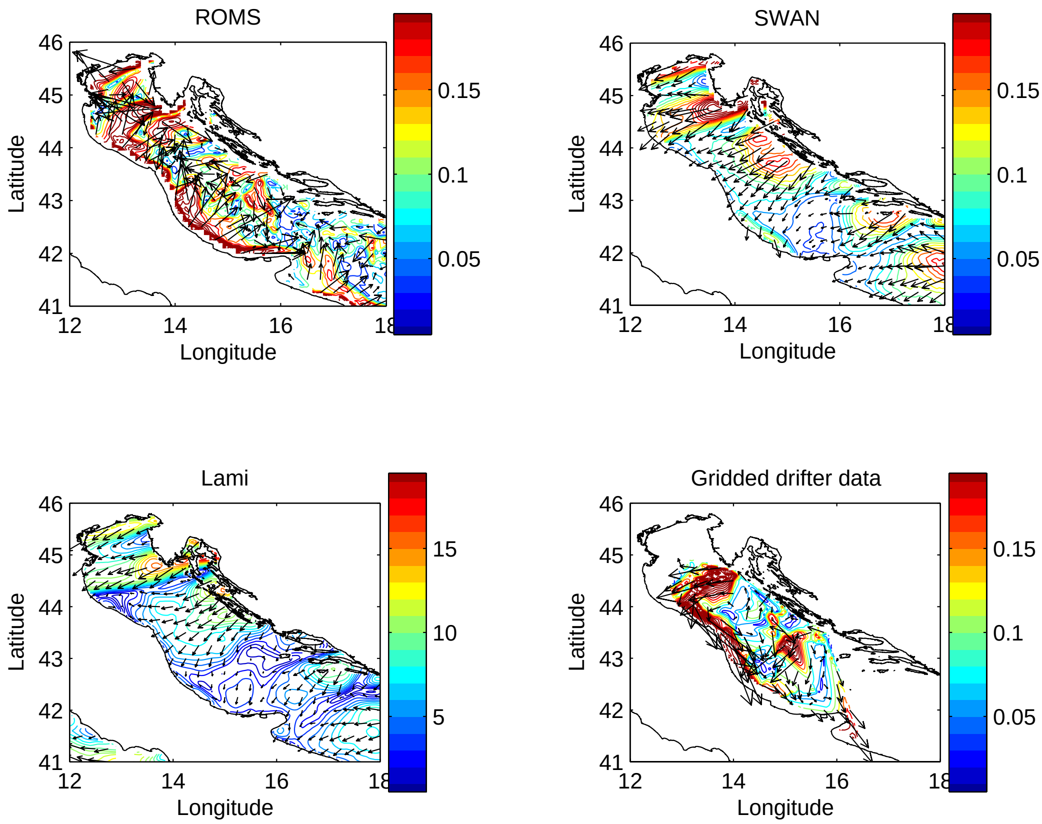

Figure 2b *ROMS ocean currents (top-left, surface), SWAN derived Stokes drift (top-right, surface), LAMI winds at 10m (bottom-left) model nowcasts and gridded drifters velocities (m/s) at days 8 (top) and 20 (bottom) February 2003, 00:00.*

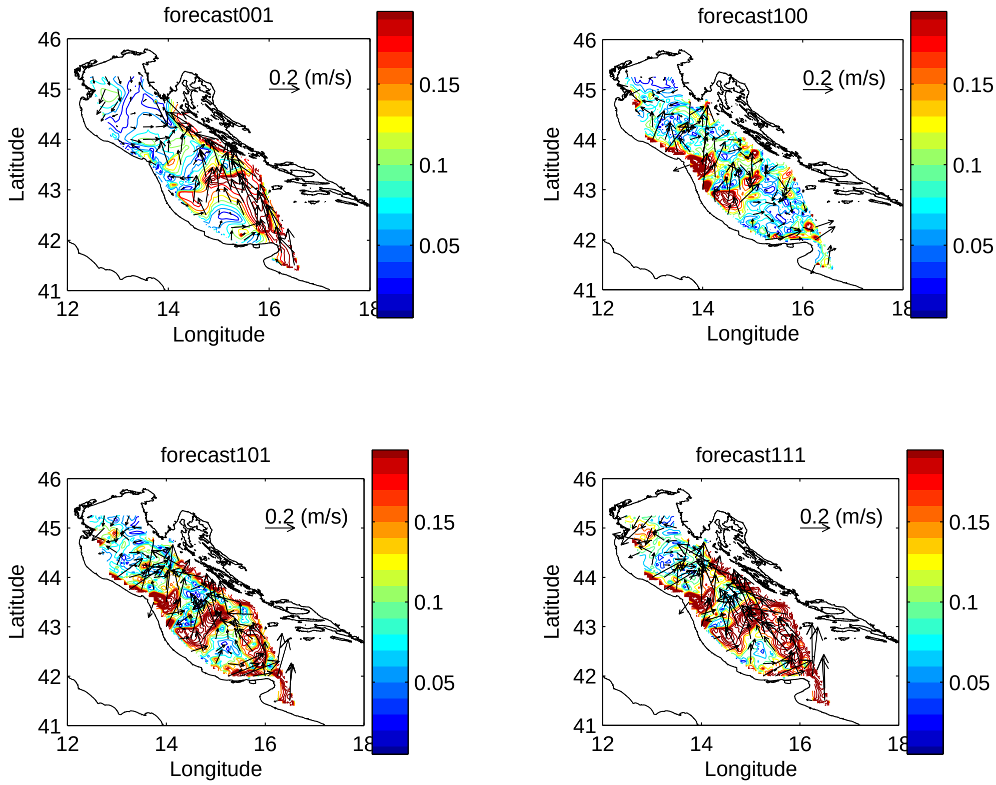

Figure 3 *Raw model surface drift 48 hrs forecast errors (m/s, vectors and magnitude in the color scale) at day 10 February 2003 corresponding to day 12 February 2003 for simple ocean advection (top left), the rule of thumb (top right), the combination of both (bottom left) and the subsequent addition of the Stokes drift (bottom right).*

3
The hyper-ensemble

Super-ensemble methods aim at combining models of the same kind (*e.g.* Krishnamurti *et al* 2000a, 2000b). This technique has been recently extended by Rixen and Ferreira-Coelho (in press) to the concept of *hyper-ensemble*, where models of different kinds are combined. Indeed, surface drift is a complex combination of a wide variety of processes. The overall strategy is to find an optimal weighting of the ocean, atmospheric and wave models based on past/*a priori* information during a learning cycle at all grid points and use them locally to compute new predictions in a forecast cycle. In the present study, this optimum is obtained using linear regression (with bias) in a least square sense with various learning periods, from 5 to 10, 25, 50 days. For non-linear methods and further details on the hyper-ensemble strategy, we refer to Rixen and Ferreira-Coelho (in press).

Figure 4 shows instantaneous 48 hrs forecast errors from day 10 February 2003, using unbiased ocean currents (top-left), unbiased rule of thumb (top-right), an unbiased combination of both (bottom-left), and the inclusion of the Stokes drift (bottom-right). Errors remain similar among the different methods, large along the coast, but generally speaking lower than the traditional forecast methods shown in Figure 3. Results for other days, lead times and combinations of models show qualitatively similar results.

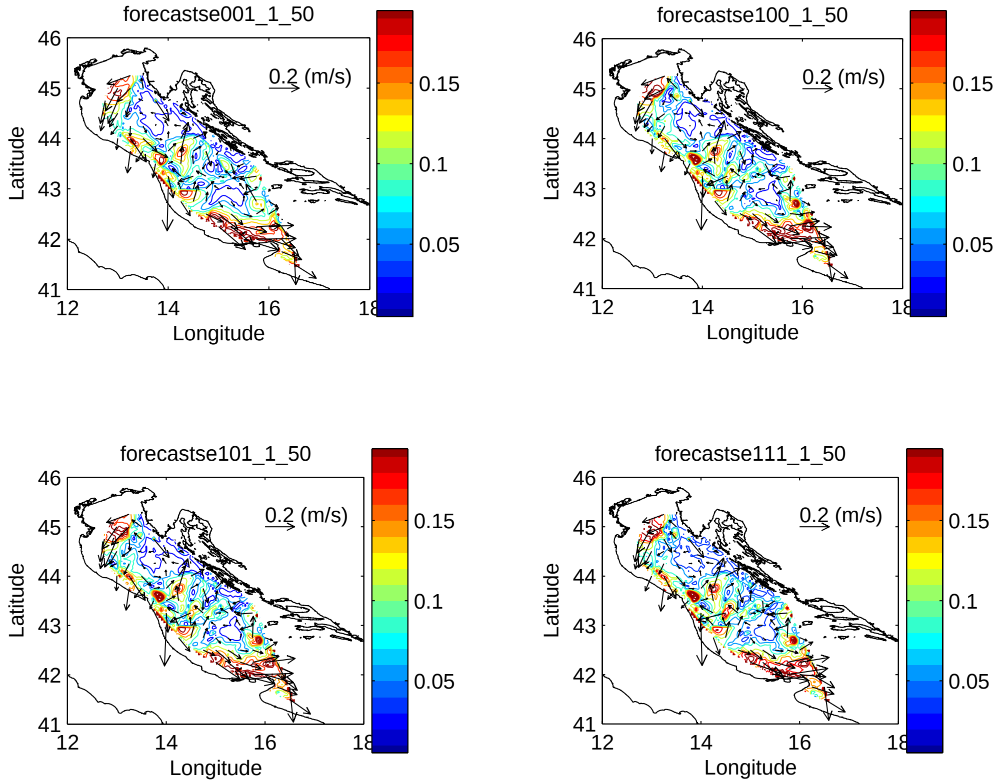

Figure 4 *Hyper-ensemble surface drift 48 hrs forecast error (m/s, vectors and magnitude in the color scale) at day 10 February 2003 corresponding to day 12 February 2003 with a 50 days learning period, using locally unbiased ocean advection (top left), rule of thumb, the combination of both (bottom left) and the subsequent addition of the Stokes drift (bottom right).*

Local RMS forecast errors provide a simple measure of the uncertainty associated with the traditional methods (Figure 5) and hyper-ensemble methods (Figure 6) corresponding to Figures 3 and 4 respectively. These errors are computed over a 48 hrs period around day 12 February 2003. Although the ocean currents had lower instantaneous errors (fig 3, top-right), the uncertainty of the rule of thumb is lower than any other standard method.

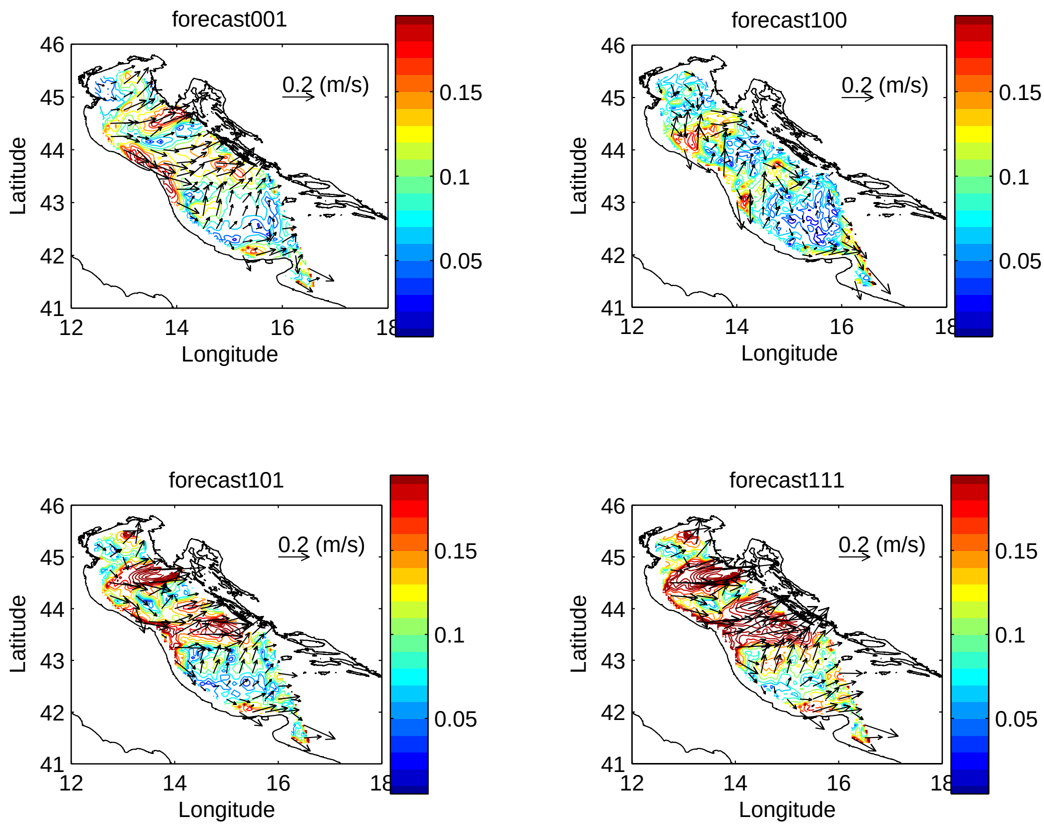

Figure 5 *Local RMS forecast error (m/s, vectors and magnitude in the color scale) corresponding to traditional methods depicted in Figure 3.*

The corresponding RMS forecast errors for the hyper-ensemble methods (Figure 6) show an overall reduction of the uncertainty. The consistency throughout the different methods suggests that the correction is essentially a bias correction. The combination of different models has a minor impact on the hyper-ensemble skills. Again, results for other days, lead times and combinations of models show qualitatively similar results.

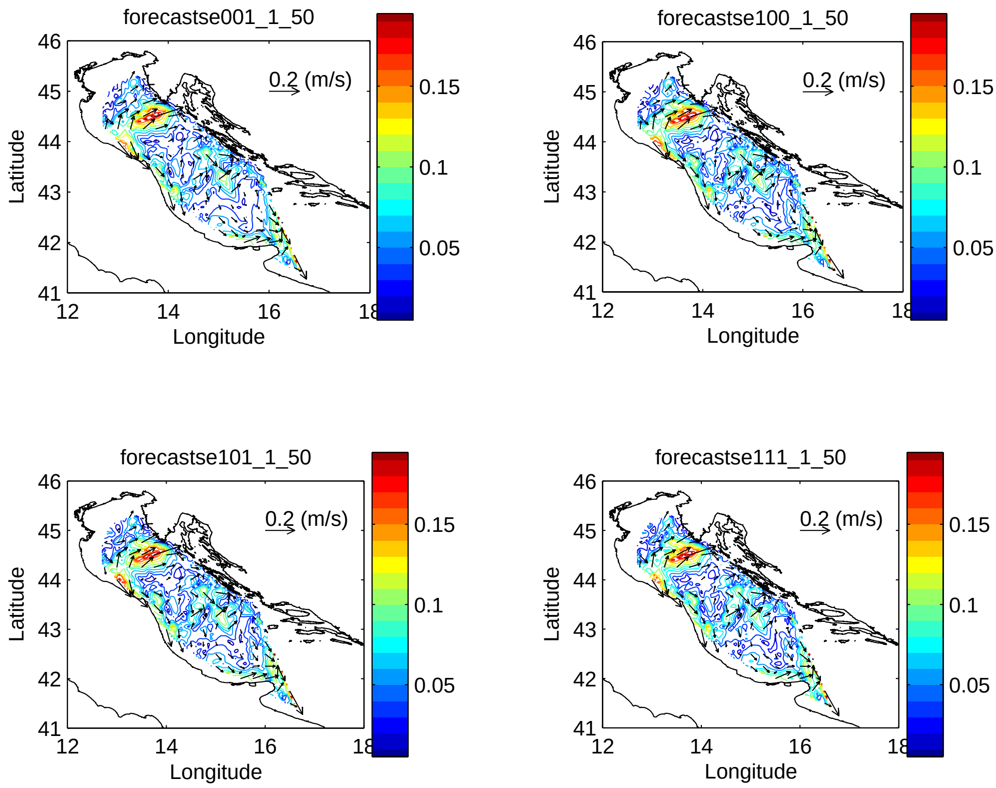

Figure 6 *Local RMS forecast error (m/s, vectors and magnitude in the color scale) corresponding to hyper-ensemble methods depicted in Figure 4.*

At this stage, some wider statistical analyses are needed to compare quantitatively the skills of the different surface drift forecasts. Figure 7 shows some standard statistics for the different methods on the two components of velocity. In hindcast mode, the bias should ideally vanish: statistics are compared here to the true drifter values instead of the interpolated values. Hence some minor bias remains. Statistics are consistent between the hindcast and the forecast, implying that the weights remain roughly valid and useful in predicting surface drift. The rule of thumb (the second bar) remains usually the more robust of the traditional methods but is outperformed by the hyper-ensemble methods, especially for long training periods (50 days) in the hyper-ensemble using all models (last bar). Again, results for other days, lead times and hyper-ensemble combinations of models show qualitatively similar results.

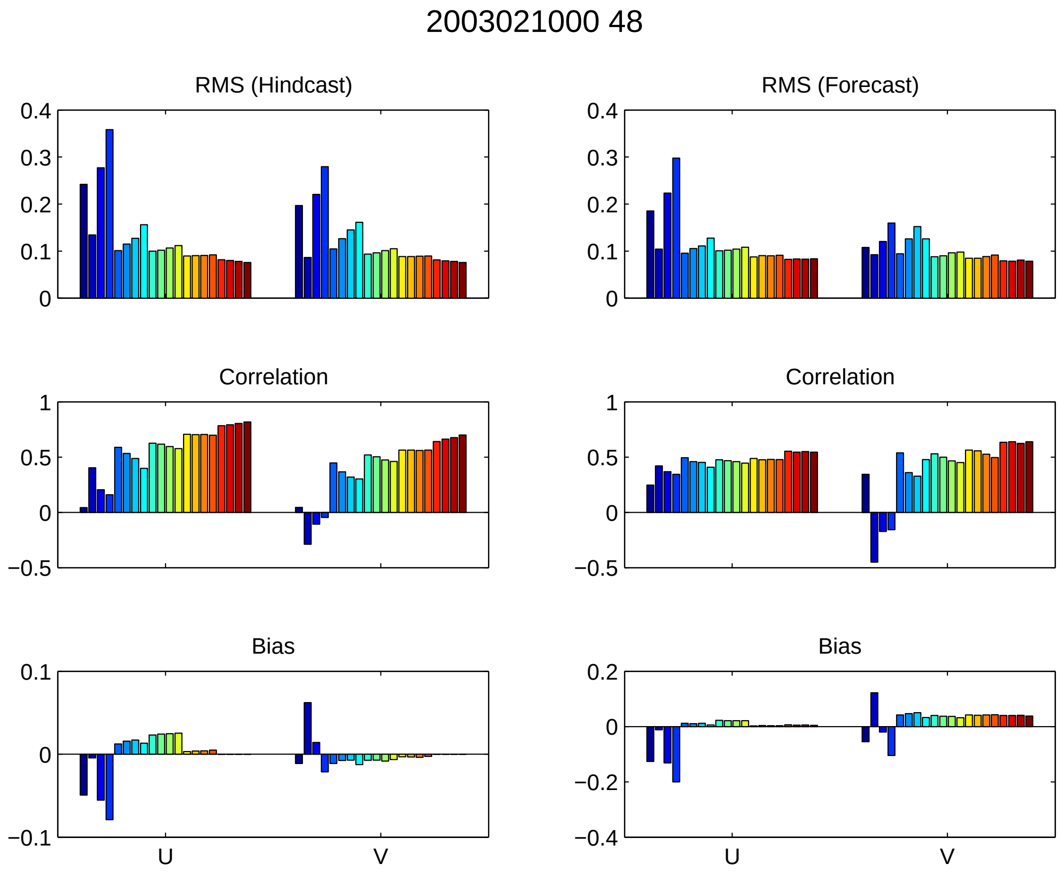

Figure 7 *Hindcast and 48 hrs forecast RMS errors (m/s), correlation and bias (m/s) on U and V components of velocity for the different methods for day 10 February 2003 corresponding to 12 February 2003. Bars from left to right represent respectively: (1) ocean currents, (2) wind rule of thumb, (3) the addition of (1) and (2), (4) the addition of the Stokes drift, and the corresponding hyper-ensemble combinations for a 5 (bars 5-8), 10 (bars 9-12), 25 (bars 13-16) and 50 (bars 17-20) days learning period.*

Uncertainty maps as derived previously from the recent 48 hrs forecast may be used to associate two-dimensional probability distribution areas with single drifter tracks instances. Ensembles of 100 members were generated by a random walk procedure, adding Gaussian velocities with standard deviation equal to the uncertainty velocities derived as above, from which encompassing convex hulls of 100, 75, 50 and 25% of the end position are identified with a shrinking of the convex hull shape down to the mean position of the ensemble. Several examples are illustrated in fig 8. The persistence might provide useful and quite robust information if the drifter is not undergoing a radical direction change just afterwards. Ocean currents are overestimated and potentially in a wrong direction. The rule of thumb method in these examples is not very robust either. Only the hyper-ensemble solutions have tracks similar to the observed drifters. Their probability distribution areas sometimes capture the true drifter end position, which is not the case for the standard methods.

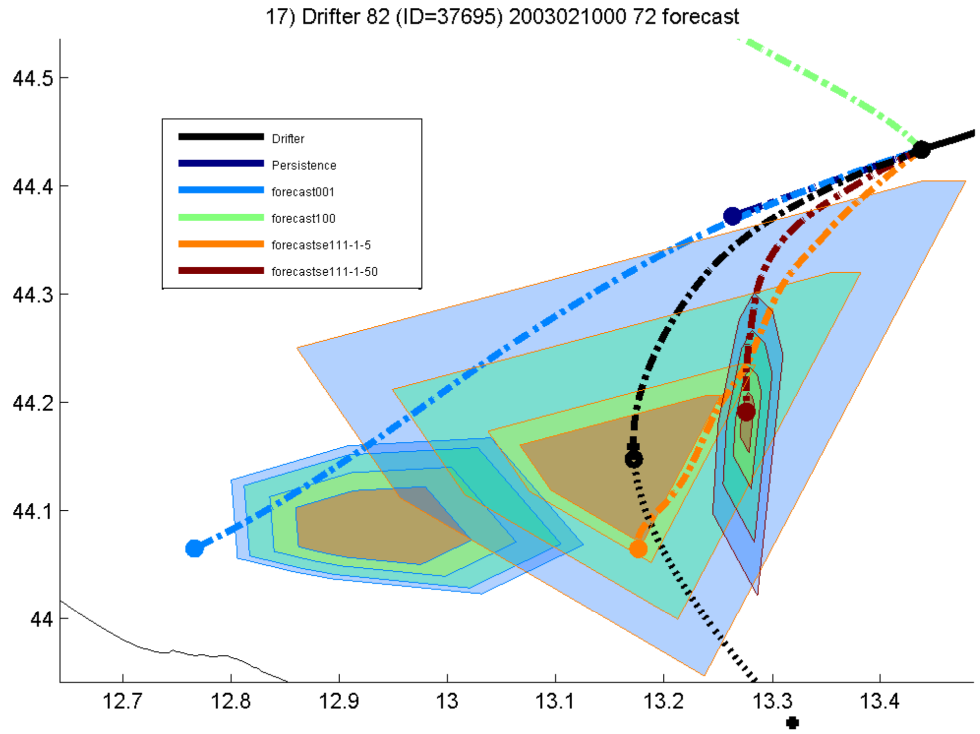

Figure 8a *Some examples of true drifter tracks at different days (past - continuous line, 72 hrs forecast - dashed line) and associated probability distribution areas for different methods: true drifter track (black), persistence (dark blue), ocean current (blue), rule of thumb (green), hyper-ensemble with all models using 5 days (orange) and 50 days (brown) learning period. Convex hulls in decreasing order represent the estimation of the 100, 75, 50 and 25% probability distribution areas corresponding to the different methods.*

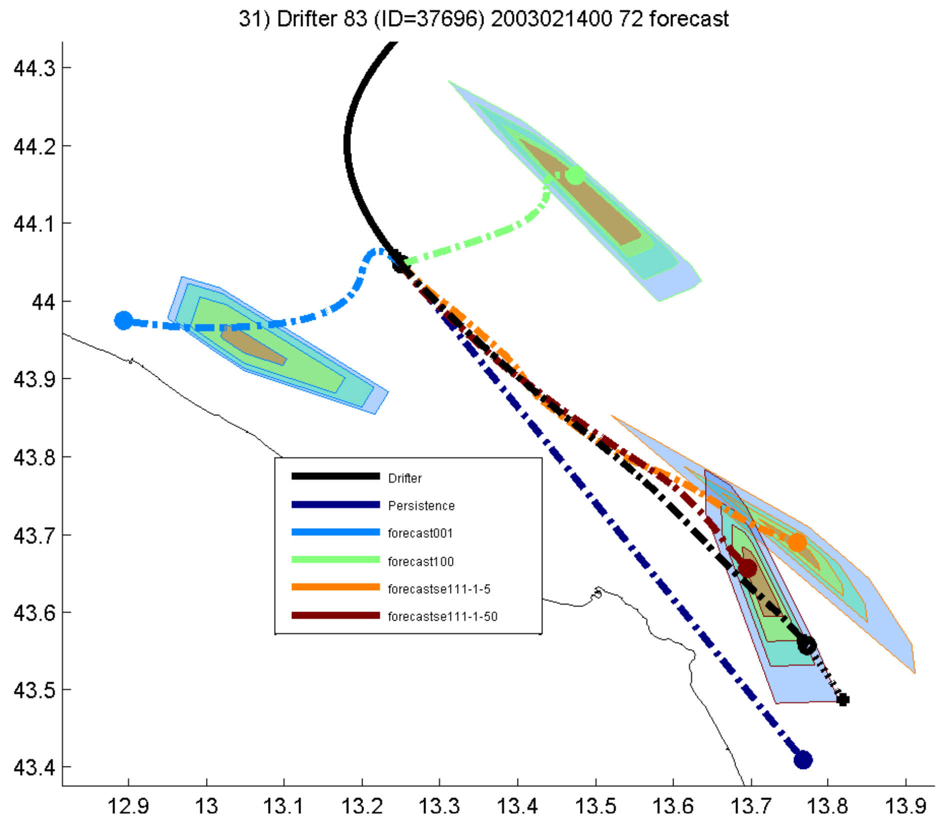

Figure 8b *Some examples of true drifter tracks at different days (past - continuous line, 72 hrs forecast - dashed line) and associated probability distribution areas for different methods: true drifter track (black), persistence (dark blue), ocean current (blue), rule of thumb (green), hyper-ensemble with all models using 5 days (orange) and 50 days (brown) learning period. Convex hulls in decreasing order represent the estimation of the 100, 75, 50 and 25% probability distribution areas corresponding to the different methods.*

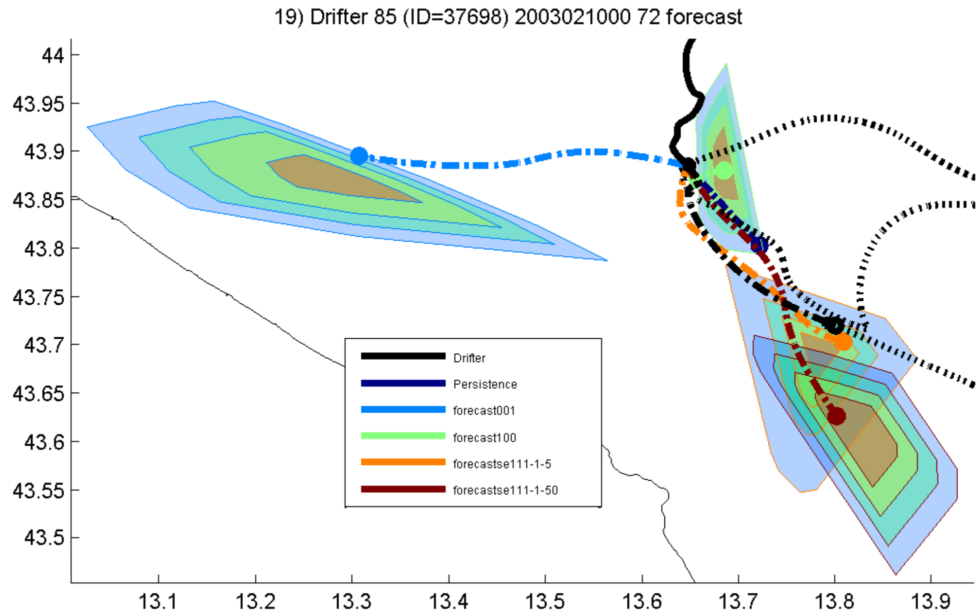

Figure 8c *Some examples of true drifter tracks at different days (past - continuous line, 72 hrs forecast - dashed line) and associated probability distribution areas for different methods: true drifter track (black), persistence (dark blue), ocean current (blue), rule of thumb (green), hyper-ensemble with all models using 5 days (orange) and 50 days (brown) learning period. Convex hulls in decreasing order represent the estimation of the 100, 75, 50 and 25% probability distribution areas corresponding to the different methods.*

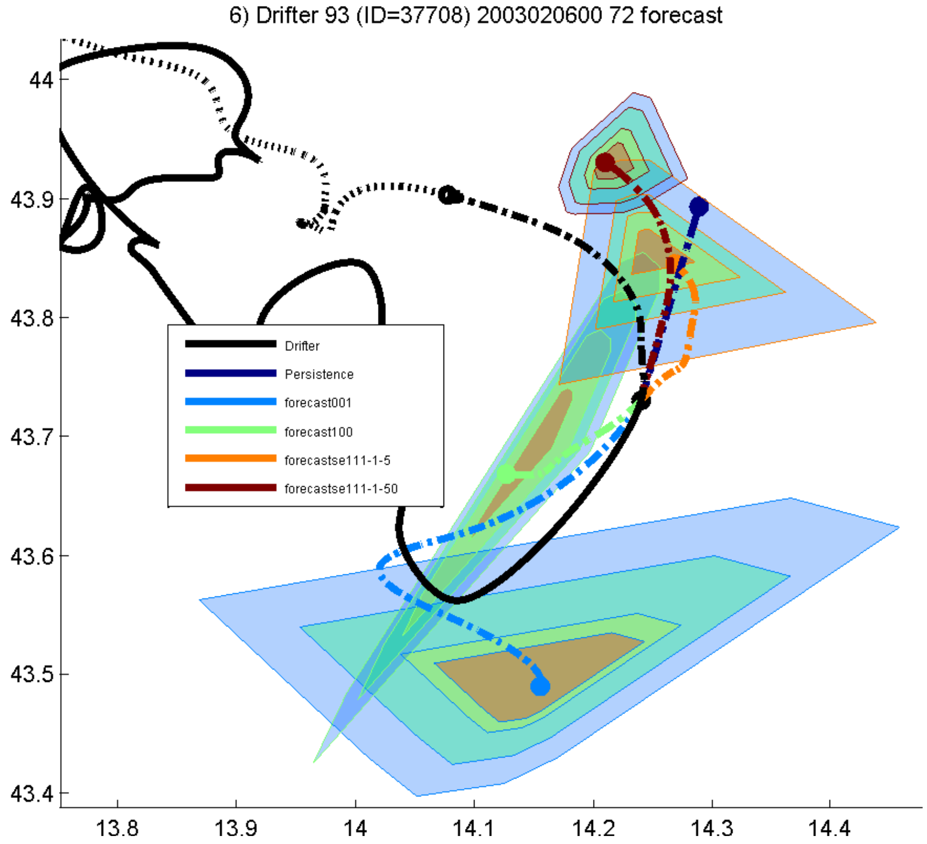

Figure 8d *Some examples of true drifter tracks at different days (past - continuous line, 72 hrs forecast - dashed line) and associated probability distribution areas for different methods: true drifter track (black), persistence (dark blue), ocean current (blue), rule of thumb (green), hyper-ensemble with all models using 5 days (orange) and 50 days (brown) learning period. Convex hulls in decreasing order represent the estimation of the 100, 75, 50 and 25% probability distribution areas corresponding to the different methods.*

Figure 9 summarizes the reliability of the estimation of the probability distribution areas for the different methods. The traditional methods (first 4 bars) provide unreliable end positions, far from the true position and almost a null probability of capturing the true position in the ensemble convex hull. On the contrary, the hyper-ensemble end positions, ensemble histogram maximum (in 5km*5km bins) and gravity center are much closer to the true drifter end position. The results are slightly better for shorter learning period, which contradicts somewhat the optimal 50 days found previously. The probability of capturing the true end position in the ensemble convex hull is usually 0 for the traditional methods and ranges from 20% to 35% for the hyper-ensemble solutions.

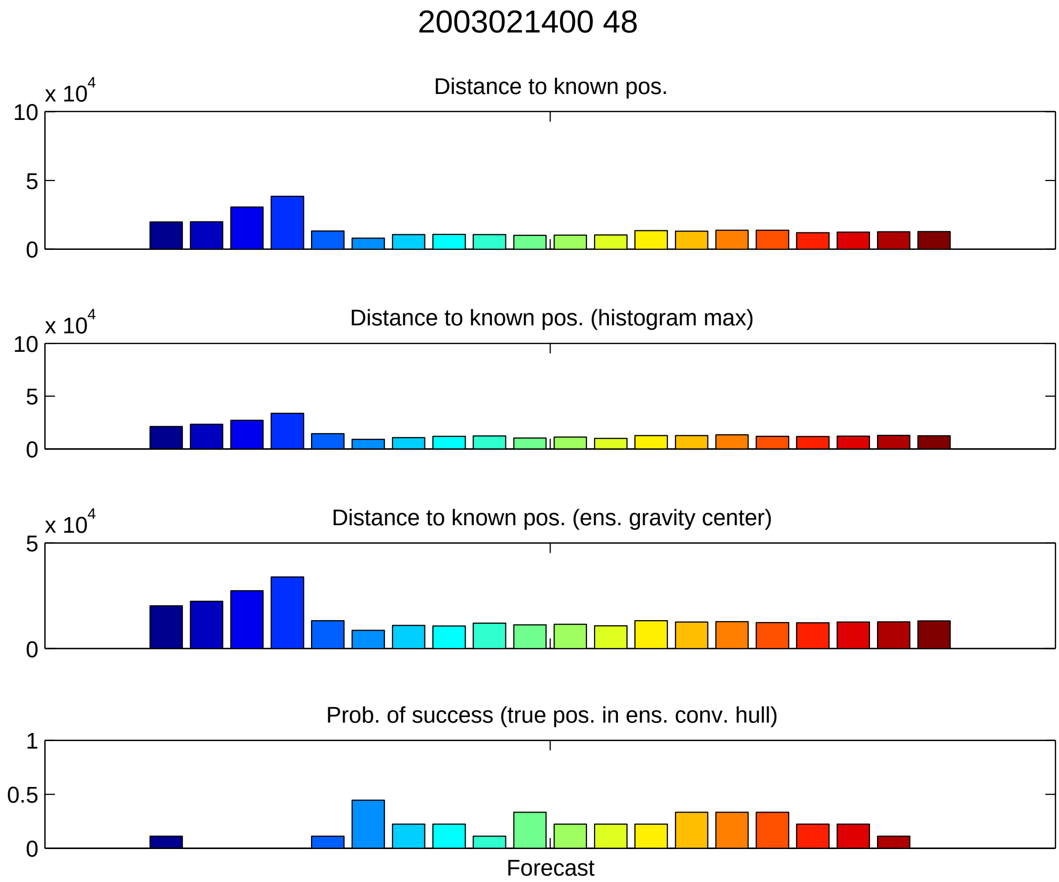

Figure 9 *Summary of reliability of the estimation of probability distribution areas for the different methods (as in Figure 7) for 48 hrs forecast on day 14 February: (top) mean distance of single instance end position to the true end positions; (top-middle) mean distance of ensemble end position histogram maximum to the true end positions; (bottom-middle) mean distance of ensemble gravity center of end positions to the true positions; (bottom) probability that the convex hull captures the true end position.*

4
Conclusions

The hyper-ensemble approach is a very generic tool for geophysical applications. This statistical approach makes the best use of all available data, with a marginal effort, provided underlying models and data are available. The application of the hyper-ensemble technique in the challenging area of the Adriatic Sea during a Bora event has shown significant improvements in surface drift forecast, both on field estimates, integrated drifter tracks and probability distribution area estimation. However, results also suggest that this technique is still very far from a very reliable surface drift forecasting system to be used in search and rescue cases or dramatic oil spills pollutions.

Two major limitations of the existing surface drift approaches may be identified, which require further improvements. On the one hand, comprehensive observational networks are needed to cover the spatio-temporal and spectral range of processes found in a specific area. On the other hand, individual models also require further improvement of their respective forecast skills. Only a joint observational and modeling effort may improve directly the hyper-ensemble approaches which require both components. The consistency between the different hyper-ensemble combinations has shown that the major correction arises from the local bias removal. Only a marginal improvement has to be expected from the inclusion of two or more processes in the hyper-ensemble.

Acknowledgments

This work was performed at NURC and funded by the North Atlantic Treaty Organization. All people who contributed to the observational and modeling effort during the ADRIA02 and ADRIA03 field experiments are deeply acknowledged.

References

Booij, N., Ris, R.C. and Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions. Part I- Model description and validation. J. Geophys. Research, 104(C4):7649-7666.

Cacciamani, C., Emiliani, P., Ferri, M. and Minguzzi, E., 2002. High Resolution Verification of Hydrostatic and Non-Hydrostatic LAM Precipitation Forecasts in Italy. COSMO Newsletter n°2 (February 2002), 176:186. In: G. Doms and U. Shatter (Editors), Deutscher WetterDienst (DWD), Offenbach (Germany).

Carniel, S., Umgiesser, G., Sclavo, M., Kantha, L., and Monti, S. (2002). Tracking the drift of a human body in the coastal ocean using numerical prediction models of the oceanic, atmospheric and wave conditions. *Science and Justice*, 42(3):143-151.

Cushman-Roisin, B. and Naimie, C.E., 2002. A finite element model of the Adriatic tides. J. Mar. Syst., 37(4): 279-297.

Doms, G. and Shattler, U., 1999. The Nonhydrostatic Limited-Area Model LM (Lokal-Modell) of DWD. Part I: Scientific Documentation. Deutscher WetterDienst (DWD), Offenbach (Germany).

Gill, A. E., 1982: *Atmosphere-Ocean Dynamics*. Academic Press, 662pp.

Hodur, R. M. (1997). The Naval Research Laboratory Coupled Ocean/ Atmosphere Mesoscale Prediction System (COAMPS). *Monthly Weather Review*, 125(7):1414-1430. DOI:10.1175/1520-0493(1997).

Hodur, R.M., Pullen, J., Cummings, J., Hong, X., Doyle, J.D., Martin P. and Rennick, M.A., 2001. The Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), Oceanography**,** 15**:**88-98.

Holthuijsen, L.H., Booij, N. and Herbers, T.H.C., 1989: A prediction model for stationary, short-crested waves in shallow water with ambient currents, Coastal Engineering, 13:23-54.

Kovacevic, V., Gacic, M., and Poulain, P.-M. (1999). Eulerian current measurements in the Strait of Otranto and in the Southern Adriatic. *Journal of Marine Systems*, 20:255-278.

Krishnamurti, T., Kishtawal, C., Shin, D., and Williford, E. (2000b). Improving tropical precipitation forecasts from a multianalysis superensemble. *Journal of Climate*, 13:4217-4227.

Krishnamurti, T., Kishtawal, C., Zhang, Z., Larow, T., Bachiochi, D., and Williford, E. (2000a). Multimodel ensemble forecasts for weather and seasonal climate. *Journal of Climate*, 13:4196-4216.

Kumar, T. V., Krishnamurti, T., Fiorino, M., and Nagata, M. (2003). Multimodel superensemble forecasting of tropical cyclones in the Pacific. *Monthly Weather Review*, 131:574-583.

Majewsky, D., 1998. The new global icosahedral-hexagonal grid point model GME of the Deutscher Wetterdienst. Recent developments in numerical methods for atmospheric modelling, ECMWF Seminar Proceedings, 173-201.

Majewsky, D., Liermann, D., Prohl, P., Ritter, B., Buchhold, M., Hanisch, T., Paul, G., Wergen, W. and Baumgardner, J., 2002. The operational global icosahedral-hexagonal gridpoint model GME: description and high resolution tests. Monthly Weather Review, 130:319-338.

Poulain, P.-M., Mauri, E., and Zanasca, P. (2003). Upper thermal structure and intermediate currents in the Adriatic and Northern Ionian as measured by a Lagrangian profiler in 1995 and 1996. *Bollettino di Geofisica teorica ed applicata*, 44(2):139-154.

Pullen, J., Doyle, J., Hodur, R., Ogston, A., Book, J., Perkins, H. and Signell, R.P., 2003. Coupled ocean-atmosphere nested modeling of the Adriatic Sea during winter and spring 2001. J. Geophys. Res., 108(C10):3320. doi:10.1029/2003JC001780.

Ris, R.C., Booij, N. and Holthuijsen, L.H., 1999. A third-generation wave model for coastal regions. Part II- Verification. J. Geophys. Res., 104(C4):7667-7681.

Rixen, M. and Ferreira-Coelho, E. (2005a). Operational prediction of acoustic properties in the ocean using multi-model statistics. Ocean Modeling, 11(3-4):428-440. doi:10.1016/j.ocemod.2005.02.002.

Rixen, M. and Ferreira-Coelho, E. (2005b). Operational surface drift prediction using linear and non-linear hyper-ensemble statistics on atmospheric and ocean models. Journal of Marine Systems. In press.

Shin, D. and Krishnamurti, T. (2003a). Short- to medium-range superensemble precipitation forecasts using satellite products: 1. Deterministic forecasting. *Journal of Geophysical Research*, 108(8). 8383, DOI 10.1029/2001JD001510.

Shin, D. and Krishnamurti, T. (2003b). Short- to medium-range superensemble precipitation forecasts using satellite products: 2. Probabilistic forecasting. *Journal of Geophysical Research*, 108(8). 8384, DOI 10.1029/2001JD001511.

Signell, R. P, Carniel, S., Cavaleri, L., Chiggiato, J., Doyle, J.D., Pullen, J., Sclavo M. (2005). Assessment of wind quality for oceanographic modelling in semi-enclosed basins. *Journal of Marine Systems, Vol 53(1-4), 217-233.*

Umlauf, L., Burchard, H. 2003. A generic length-scale equation for geophysical turbulence model. J. Mar. Res. 61: 235–265.

Document Data Sheet

Security Classification		Project No.
NATO UNCLASSIFIED		1A5
Document Serial No.	**Date of Issue**	**Total Pages**
NURC-FR-2006-012	May 2006	28 pp.

Author(s)

Rixen, M.,, Ferrerira-Coelho, E., Signell, R.

Title

Surface drift prediction in the Adriatic Sea using hyper-ensemble statistics on atmospheric, ocean and wave models: uncertainties and probability distribution areas

Abstract

.

Despite numerous and regular improvements in underlying models, surface drift prediction in the ocean remains a challenging task because of our yet limited understanding of all processes involved. Hence, deterministic approaches to the problem are often limited by empirical assumptions on underlying physics. Multi-model hyper-ensemble forecasts, which exploit the power of an optimal local combination of available information including ocean, atmospheric and wave models, may show superior forecasting skills when compared to individual models because they allow for local correction and/or bias removal. In this work, we explore more in detail the potential and limitations of the hyper-ensemble method in the Adriatic Sea, using a comprehensive surface drifter data base. The performance of the hyper-ensembles and the individual models are discussed by analyzing associated uncertainties and probability distribution maps. Results suggest that the stochastic method may reduce the position errors significantly for 12 to 72 hours forecasts and hence compete with pure deterministic approaches.

Keywords

forecast – surface drift – ocean models – atmospheric models – wave models – multi-model super-ensembles – linear regression

Issuing Organization

NATO Undersea Research Centre
Viale San Bartolomeo 400, 19138 La Spezia, Italy

[From N. America:
NATO Undersea Research Centre
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int