# Safety of Navigation, Ballast Water and Meteo-marine Forecasting: Analysis and Reliability

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The objective of this paper is to study the possible use of meteo-marine forecasts for correct management of ships' ballast water, in order to improve the safety of navigation, having due consideration to the economical costs (wrong load/unload of water) and the possible performance impacts that could be generated. The analysis has been carried out verifying the operative forecasts used for crew training in the Italian yacht *Consorzio Prada* for the America's Cup 2000 and issued in the period April–July 1999. Studying the forecasts' quality, situations of potential incorrect load of ballast water have been examined together with the potential negative effects. It has been demonstrated that an accurate weather forecast is of paramount importance to safe navigation without economic loss while recognising the related performance aspects.

KEY WORDS

1. Marine. 2. Meteorology. 3. Safety.

1. INTRODUCTION. The use of ballast water has a crucial role in the performance growth of different types of craft (Buxton and Logan, 1986). However, the sensitivity of these craft to the meteo-marine conditions implies a need for more complicated decisions on whether to load or unload ballast to modify the trim of the boat (Bieker, 1996). From these considerations, it is possible to recognise the relevance of accurate meteo-marine forecasts for safe navigation while also reducing unnecessary performance impacts.

Bressani (1999) has already demonstrated that on medium-small sailing craft, characterised by a ballast water capacity of about 750–1500 litres, the water quantity to load, subject to the meteorological conditions, is a key point in determining the boat's performance, because of the effect of changes in draught on the boat's trim. At the same time, loading of water is not always possible or, rather, it is feasible only under certain conditions. For example, in the specific case of the sail craft *Giro 34 OD*, loading is performed dynamically during navigation by opening the ballast tanks under-sail (Bressani, 1999). The boat has to sail at a minimum speed of 7 kt and with a heeling angle of not more than 15°; the loading time in this instance is about two minutes. By contrast, loading is significantly slower if electric pumping is used. On reflection, it is clear that an error in the forecast hydro-marine conditions can strongly influence the time schedule and method of loading ballast water and, therefore, navigation safety.

This paper has broader application to many different types of craft, without entering into the details of each one. The type of craft considered does not constrain

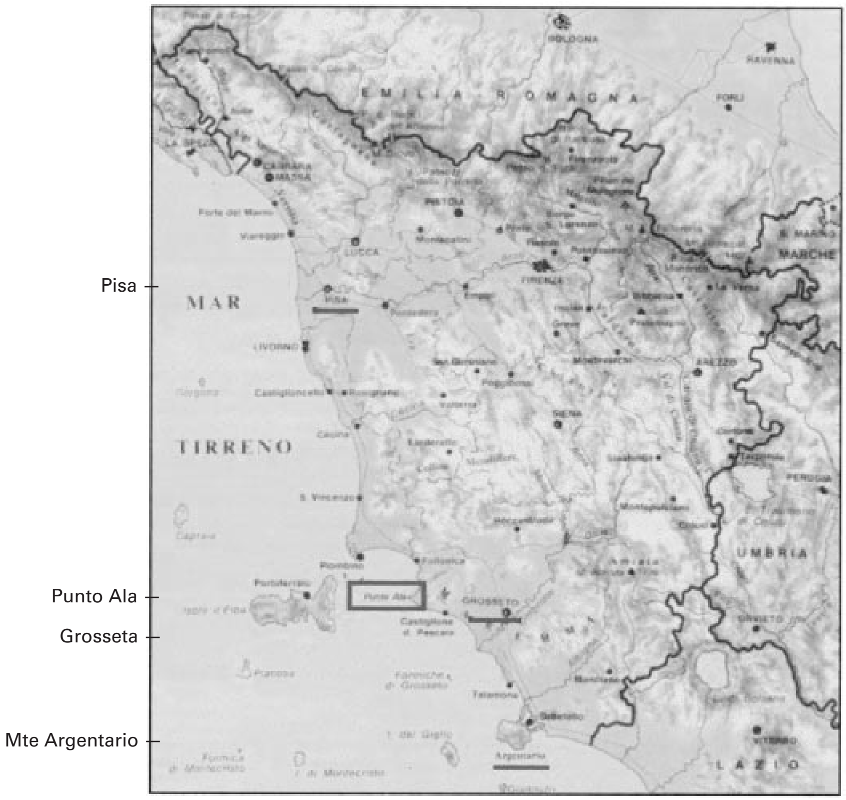

Figure 1. Punta Ala's position (scale 1:3300000)

the reliability of the analysis, but stresses even more the potential application of this work to broader navigational sectors.

## 2. VERIFICATION OF FORECASTS.

The weather forecasts, produced by D.I.T.I.C. Meteo-hydrological Laboratory of Turin Polytechnic, are subjective – meaning that the results obtained by the model at synoptic scale (GCM) and at mesoscale (LAM) are collected and analysed by the forecasters. The data is integrated with information from the 'just in time' measuring-net, and the forecasters' knowledge of average weather conditions, before the forecast is finalised. In fact, as demonstrated in several studies (Patteri and Pezzoli, 1999), despite a continuing improvement in the quality of computation offered by the mathematical models of the atmosphere (Kalnay and Dalcher, 1990), the achievement of satisfactory results has yet to be attained.

The dimensions of the grid used to integrate the data, and its complex interactions with different components of the atmosphere, make it necessary to use statistical relations, usually called MOS (Model Output Statistic), in order to reduce the effect of the errors in the forecasts. The operative weather forecasts (subjective) allow these problems to be overcome, with the achievement, on average, of better results than those offered by the mathematical models (Patteri and Pezzoli, 1999). In this paper, the weather forecasts for the area of Punta Ala (Grosseto, Italy, Figure 1) are analysed.

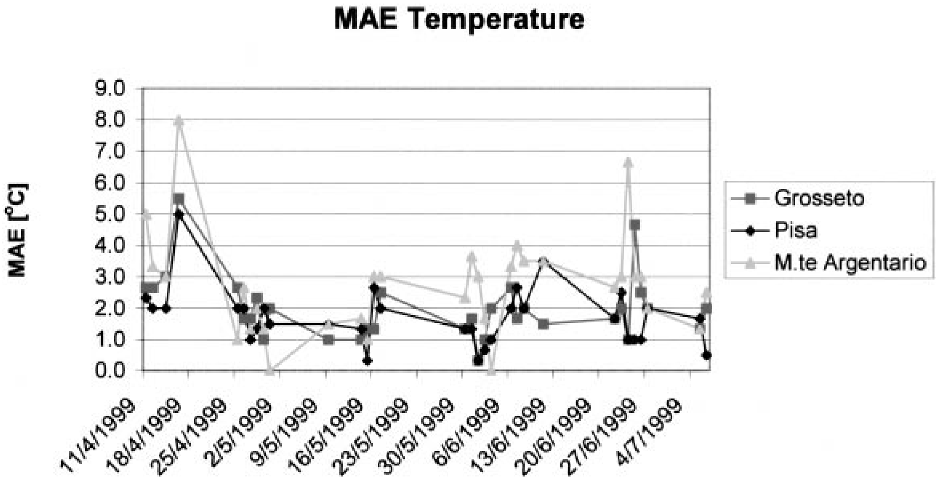

Figure 2. Comparison of MAE – temperature.

Verification was conducted by comparison of the forecasts for 12, 24 and 36 hours ahead with the actual conditions recorded at the meteorological stations of Pisa, Grosseto and M.te Argentario (Figure 1). The following atmospheric variables were analysed: temperature, pressure, maximum wind speed, average wind speed and wind direction. Verification used the mean absolute error (MAE) as described by Wilks (1995):

$$MAE = \frac{1}{n}\cdot \sum_{k=1}^{n} |y_k - o_k|, \tag{1}$$

where, $y_k$, $o_k$ are the $n$ paired $k$-th of forecasts and observations, and the $MAE$ is the arithmetic mean of the absolute value of the difference between each pair. Obviously, the $MAE$ will be equal to zero if the forecasts are perfect ($y_k = o_k$), and it will increase as the discrepancy between forecasts and observations increases. The $MAE$ is then the typical indicator of the forecast error for a data series and is often used as a measure of the verification for forecast variables.

In this specific case, since the verification has been carried out for the forecast values at 12, 24 and 36 hours ahead, it has used an index $n$ equal to 3. It is important to remember that the comparison is between the single forecast value and the observed one, obtained as an hourly average of all recorded measurements at a specific meteorological station. In order to provide a more detailed analysis of the results, a direct verification (not using the mean function) of the single data at 12, 24 and 36 hours ahead could also be undertaken.

It is clear that the weather forecast produced better results, in particular for wind speed and direction, in the short term (12h), while the largest errors are reported at 24 h and 36 h. It has to be taken into account that the meteorological bulletin was broadcast at about 16:00 hrs LT on the previous day. It follows that the 24 h weather forecast is set on the warmest hours of the day, when thermal phenomena can heavily influence the atmospheric situation. Since every site presents specific characteristics of thermal condition, the final result obtained is subject to minor changes that are a function of the geomorphology of the area under analysis.

The verification performed allows analysis of the true reliability of the weather forecast and the relative significance of each meteorological station in relation to the studied area of forecast, Punta Ala. The graphs show a comparison of the MAE of the forecast variables for each meteorological station (Figures 2–6).

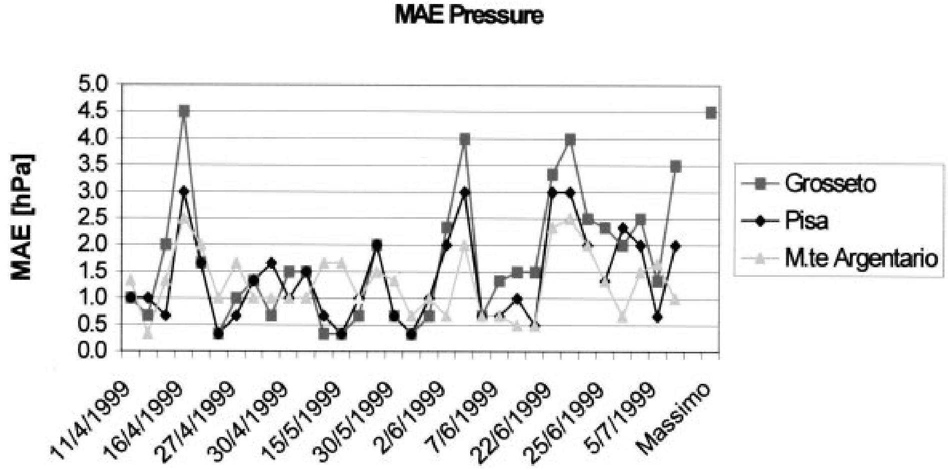

Figure 3. Comparison of MAE – pressure.

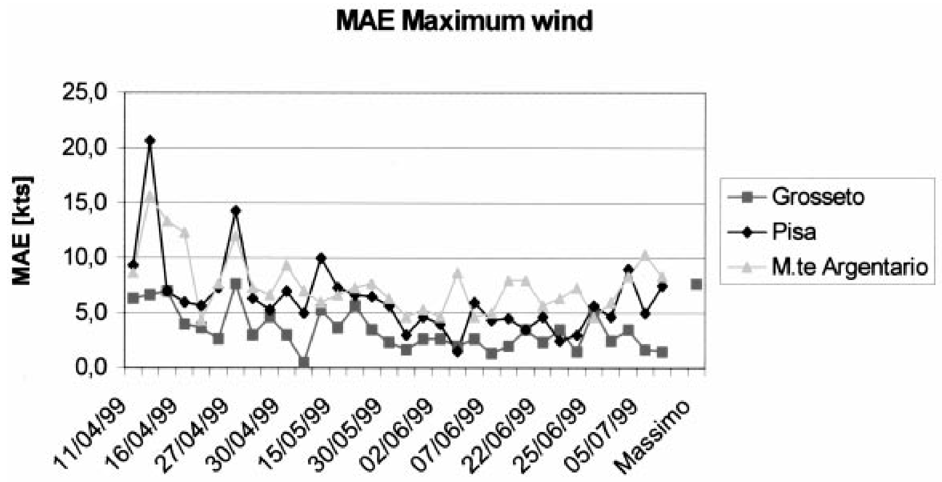

Figure 4. Comparison of MAE – maximum wind speed.

Grosseto was shown to be, on average, the most significant measuring station for verifying the weather forecast, thanks to its particular geographic location and the morphologic characteristics of the area.

It can be observed that the central period of forecasting is the one with higher precision for all the verified variables. This is due to the regularity and stability of the atmospheric conditions during Spring and to the better performance of the forecasting algorithms, used in the objective methods, when the synoptic conditions are predominant compared to the thermal ones.

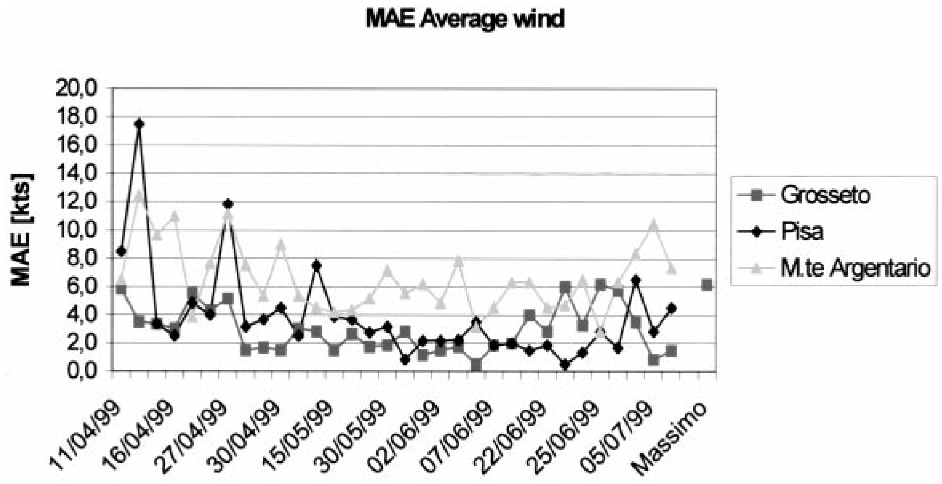

Figure 5. Comparison of MAE – average wind speed.

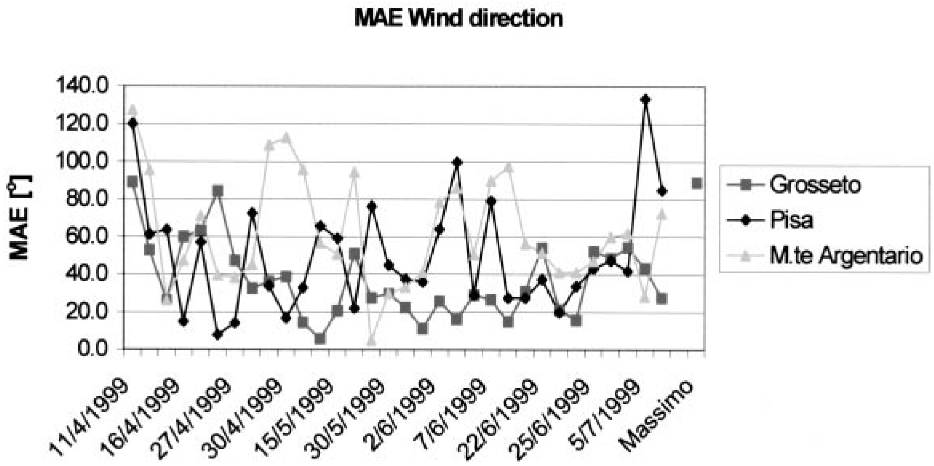

Figure 6. Comparison of MAE – wind direction.

The analysis of these graphs also shows that the variation of error for all the variables is inside a reasonable safety range presenting, to date, no problem for the safety of craft and crew. This conclusion can be also verified in the Section 3 – 'POD and FAR'.

Verification of wind direction has produced the least accurate results (Figure 6) because of the differences in ground morphology between the area of forecast (Punta Ala) and the observation.

Last, but not least, an indication of the quality of the weather forecast is provided by the reliability coefficient. It is a useful means of giving a realistic and clear view of the trustworthiness of the meteorological forecast to the end users (Del Prete *et al.*, 1999).

3. POD AND FAR. The POD (Probability of Detection) and FAR (False Alarm Rate) are parameters of great significance in evaluating the significance of

extreme events (such as storm, gale, etc…) (Wilks, 1995; Katz and Murphy, 1997). In an analysis, it is possible to draw conclusions concerning likely performance and economical consequences that can occur due to inaccurate meteorological forecasts. The two parameters are:

$$POD = \frac{a}{a+c} \tag{2}$$

$$FAR = \frac{b}{b+a} \tag{3}$$

where:

$a$ = number of cases forecast and occurred;
$b$ = number of cases forecast, but not occurred;
$c$ = number of cases not forecast, but occurred.

If a correspondence diagram is drawn, showing the values of maximum wind speed forecast against the values observed (in knots), when a gale warning is reported, it is possible to display the potential situations of danger that may occur (Figure 7). In fact, it is possible to define a safety band, inside which the located values do not cause any warning situations. The data located in the upper part of the graph, outside the safety band, highlights evidence of false alarm situations, with consequent probable economic results (such as, a decision to not undertake the navigation) and possible performance impacts (such as, an unnecessary load of ballast water). In the case of the data in the lower part of the graph, which is always outside the safety band, a missed alarm occurred with possible adverse consequences for crew safety and for the integrity of the craft.

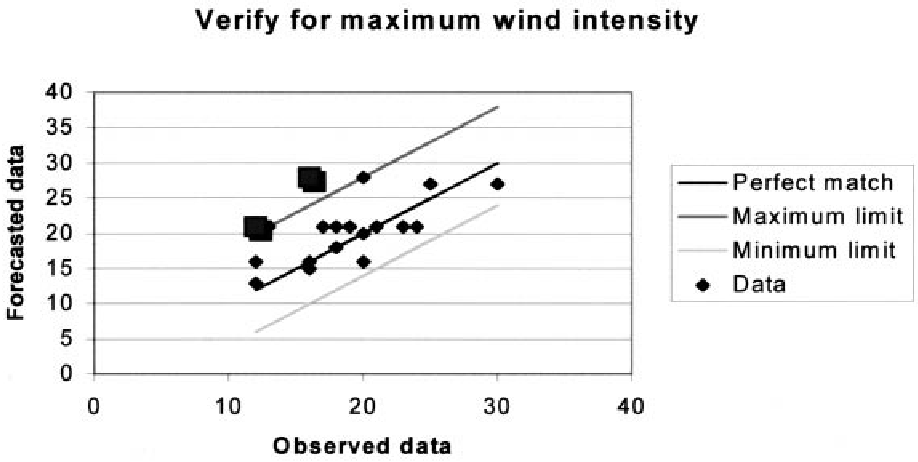

Figure 7. Verification of extreme events in locality of Grosseto.

In the case study, missed alarms never occurred for the meteorological station at Grosseto, meaning that the weather forecasts never set the conditions of possible jeopardy for the crew. The width of the safety band was determined using a variation between forecast and observed data of −6 kt (under-estimation) or +8 kt (over-estimation). The asymmetry is due to the need to consider, from the statistical point of view, the natural tendency of the forecaster to over-estimate the maximum wind intensity by about 10%. It is possible to discern this phenomenon directly from the diagram (Figure 7). Most of the data is located in the upper part, indicating that the forecast values are, on average, slightly higher than those observed.

The calculated data, as shown by the numerical value of the POD and FAR (Table 1), indicates the high level of reliability of the weather forecasts and the efficiency of the operative methodology used by the D.I.T.I.C. Meteo-hydrological Laboratory of Turin Polytechnic (Pezzoli, 1998). A false alarm has occurred on only two occasions:

Table 1. Contingency table.

| | | Observed | |
|---|---|---|---|
| | | Yes | No |
| Forecast | Yes | 13 | 2 |
| | No | 1 | 10 |
| | | POD | 0·93 |
| | | FAR | 0·13 |

(a) On 28 April 1999, with a forecast having a reliability coefficient of 75%, a wind of about 21 kt was forecasted, while it was measured at 13 kt;

(b) On 17 June 1999, with a forecast having a reliability coefficient of 70%, a wind of about 21 kt was forecasted, while it was measured at 12 kt.

## 4. SIMULATION.

As discussed in the introduction, the purpose of this paper was to consider how best to use the meteorological forecasts for correct water ballast management. To achieve this goal, it was decided to carry out a simulation of the behaviour expected of a sailing boat *Mini 6·5*, sailing throughout the area of Punta Ala, and characterised by the efficiency polar diagram shown in Table 2 and kindly provided to us by AMITeam. Taking into consideration the meteorological bulletin of 3 June 1999 at 19:00 LT (Table 3), it could be hypothesised that the boat would pass through the Punta Ala area around 10:00 UTC on the 4 June on course of 340° (sailing from South to North).

Table 2. Polar table for Mintransat AMITeam 1999 (b = loaded ballast).

| | Wind (kt) | | | | | | |
|---|---|---|---|---|---|---|---|
| Bowline | 4 | 8 | 12 | 16 | 20 | 24 | 30 |
| True Wind Angle | | | | | | | |
| 45° | 4 | 5·5 (b) | 6 (b) | 6 (b) | 6 (b) | 5·5 (b) | 5·5 (b) |
| 60° | 5 | 7 (b) | 7 (b) | 7·5 (b) | 7·5 (b) | 7·5 (b) | 7·5 (b) |
| 80° | 5 | 7 (1/2 b) | 8 (b) | 9 (b) | 9 (b) | 9 (b) | 9 (b) |
| 100° | 4 | 7 | 8 | 10 (b) | 10 (b) | 10 (b) | 10 (b) |
| 120° | 3 | 7 | 7.5 | 9 | 11 (b) | 11 (b) | 11 (b) |
| 140° | 3 | 6 | 7 | 8 | 11 | 12 | 12 |
| 160° | | 5 | 6 | 7 | 10 | 12 | 12 |

Considering the polar table, it might be expected that, with an angle between the heading of the boat and the true wind direction equal to 160° and with a wind speed of less than 16 kt, the ballast water load would be unnecessary. This means that, in the first part of the day, a water load can be avoided, in order to attain maximum performance. Furthermore, it is clear that a veer in the wind direction to 250°–290° and then, for the same route, reducing the true wind angle to 90°–100°, before 12:00 UTC and taking into account the time required, it would be recommended to load the water ballast. In fact, the weather forecasts are showing a steady increase in wind speed that will lead to average values of 15–20 kt with peaks of 25 kt. In this case, it is necessary to use the ballast water to increase the craft stability. At night, the wind will reduce to lower values, setting the conditions for sailing without ballast. After a comparison carried out between forecast and observation, the precision of the forecast was confirmed. In this situation, the crew safety would not have been threatened, and the ballast would have been managed in the correct manner. The likely performance impact that could be generated would be due only to safety issues.

A different result would ensue if weather forecasts, in which a false alarm occurred, had been used. This consideration is based on the fact that, according to the incorrect forecast, the ballast would have been loaded, causing a possible unjustified impact on performance.

Table 3. Meteorological Bulletin of D.I.T.I.C. (3/6/1999).

| MRF Forecast – Punta Ala Area Validity 04-05-06/06/1999 Emitted 03/06/1999 at 19:00 LT | | | | Hydraulic Department T.I.C. Meteohydrological Laboratory | | |
|---|---|---|---|---|---|---|
| Reliability coefficient | Date/UTC-(LOC) | Pressure/temp | WIND (°/kt) | Hs (m) | Ts (s) | Sea condition (Douglas) |
| val.: 70–75% | 04/0400–(0600) | | 030°–070°/2–7 | // | // | 0–1 (Calm-Rippled) |
| | 0700–(0900) | | var./3–8, from 110°–140°, max. 10 kt | | | 0–1 (Calm-Rippled) |
| | 1000–(1200) | | 180°–210°/5–10, max. 15 kt | SSW/0.2–0.3 | 1.6–2.1 | 2 (Smooth) |
| | 1300–(1500) | 1015–1016 hPa | 220°–250°/10–15 max. 20 kt | SW/0.4–0.5 | 2.0–2.6 | 2 (Smooth) |
| | 1600–(1800) | | 250°–290°/15–20 max. 25 kt rapidly decreasing to 10–15 kt | W/0.5–0.6 | 2.3–3.0 | 2–3 (Smooth-Slight) |
| val.: 65–70% | 05/0000–(0200) | 1015–1016 hPa | NE/1–6 | // | // | 0–1 (Calm-Rippled) |
| | 1200–(1400) | 1015–1016 hPa | SSW/10–15 max. 18 kt | S | | 2 (Smooth) |
| val.: 60–65% | 06/0000–(0200) | 1013–1014 hPa | ENE/3–8 | // | // | 1 (Rippled) |
| | 1200–(1400) | 1012–1013 hPa | SSE/5–10 rotating to SSW, max. 15 kt | S | | 1–2 (Rippled-Smooth) |

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Note: The forecast has to be considered valid between the signed time

Gale Warning signalled (validity until 08.00 LT of the 04/06/1999): NN.

Gale Warning forecasted (validity until 20.00 LT of the 04/06/1999): warning of fresh breeze force 5 Bft from SW on North Tirreno.

Situation on the 03/06/1999 – 12.00 UTC: the cold front is quickly coming nearer to the Alps and, focusing the analysis on the results of the numerical models and on the comparison between observations and forecast yesterday emitted, it is strongly possible that it will cross Italy already during the night.

17.00 LT – Pisa: 240° 8 kt, T = 27 °C, Hr = 50 %, 1016 hPa.
17.00 LT – Grosseto: 190° 14 kt, T = 28 °C, Hr = 69 %, 1015 hPa.
17.00 – M.te Argentario: 150° 10 kt, T = 24 °C, Hr = 69 %, 1018 hPa.

Weather Forecast for the 04/06/1999: during the night and the early morning the front will pass through the Alps with direction from NNW causing a rotation of the synoptic wind to SW on the Thyrrene. The front will pass close the border of the competent areas. The sky will appear, then, irregularly cloudy with a rapid pass of Ac-Cu to which will be alternated, especially in the inland, sparsely Cb that could cause localised shower. From the afternoon the weather will definitely improve having still fresh air and more unstable. This will trigger an increase in the wind speed. Beside it is important to consider that the sea breeze will be stronger than the other days. Tmin = 18–20 °C, Tmax = 27–28 °C, Tsea = 19–20 °C.

Weather Forecast for the 05/06/1999: the instability line will have crossed the whole Italy and a field of Highs will laying on the Sicily's channel. A second cold front will cross Central Europe. On the competent areas it will have a clear sky (also in the early morning) and the temperature will be slightly decreasing. The synoptic wind will blow southerly and then the sea breeze will be not in its "typical" direction from WSW, but will come from SSW.

Weather Forecast for the 06/06/1999: the situation is getting more complex and the cold front, that will be closer to the Alps, will not pass through because of the High located on the Sicily's channel. This High will be "pushed" by the front towards the Aegean Sea and, owing to a related Low that will take place on the Balearic, it will lead on the competent areas warm and more humid air from South. The sky will look then clear but veiled, the air will more humid and "heavier". The synoptic wind will blow from SE. The sea breeze will never be well developed. From the late afternoon it will start a partial covering of the sky with formation of Ci-Cs.

Tendency for the next 24h to the 06/06/1999: the instability line will cross Italy and, at the same time, warm air will flow on the South Thyrrhene. This joining situation of colder and more unstable air with warmer and more humid air, will lead to the formation of clouds with high water vapour content. On the competent areas the sky will be cloudy with possibility of rain in the early morning. An improvement it is likely to occur in the afternoon. The wind will blow from SE with speed between 7–12 kt

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5. CONCLUSION. In this paper, it has been demonstrated that weather forecasts are one of the most relevant tools for correct management of ballast water. However, the validity of weather forecasts is insufficient to avoid the occurrence of occasional performance impacts, but is still a most valuable tool to improve ballast water management, even from an economic point of view. At the same time, it is important to remember that, with an accurate weather forecast, the craft performance and safety will be increased, as the crew is able to set the right trim for the expected meteorological conditions.

## ACKNOWLEDGEMENT

Acknowledgement is given to the scientific contribution provided by the Maritime Research Centre at the Southampton Institute. MURST has to be acknowledged for the continued finance granted for the Scientific Research Programme of National Relevance 'Risk assessment of factors concerning beach protection and preservation' (COFIN 1998 – National Respresentative: Prof. Ing. E. Benessai), Turin UU.OO; and 'Risk assessment in the meteo-marine forecasts for limited area' (Local Respresentative: Prof. Ing. Giannantonio Pezzoli).

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