SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	**The role of orography and model resolution in the underestimateof modelled offshore blowing winds**
Computer Project Account:	SPITWM
Start Year - End Year :	2023 - 2025
Principal Investigator(s)	Luciana BERTOTTI
Affiliation/Address:	ISMAR-CNR Arsenale, Tesa 104 Castello 2737/F 30122 Venice, Italy
Other Researchers (Name/Affiliation):	Luigi Cavaleri ISMAR-CNR Arsenale, Tesa 104 Castello 2737/F 30122 Venice, Italy Jean Bidlot Nils Wedi Josh Kousal ECMWF

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

This line of research arose from some preliminary results by Luciana Bertotti and Luigi Cavaleri who had obtained undeniable evidence that in their daily wave forecast in the Adriatic Sea (East of Italy) the speed of the ECMWF wind fields had to be regularly increased to match the scatterometer measured values and consequently to get the correct modelled wave heights. This turned out to be a regular feature of all the coastal winds (when blowing to offshore) and it led to the previous Special Project where a number of interesting results emerged. For instance it was soon clear, as progressively confirmed along the successive increases of resolution of the ECMWF high resolution meteorological model. Indeed in the years the required “enhancement” factor decreased from 1.50 (with T213) to 1.35 (T511), 1.27 (T799), 1.21 (T1279), 1.16 (Tco1279).

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The activities derived from the previous project, terminated at 31 Dec 2022, have implied and imply a strong interaction between ECMWF and UKMO, with exchange of respective results that we have analysed in details. While the picture of the situation is pretty clear, with a marked underestimate of the ECMWF wind speeds blowing to offshore from the coast, the reasons are not yet clear. There is definitely a strong role of orography whose physics is not yet clear, mainly because touching this subject we are moving into the basic meteorological/orographic problem of the quantification of the surface orography drag as a compromise between the correct local surface wind speed values and the optimisation of the forecast quality.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

No particular problem. Rather, the information is always timely and very clear. We much appreciate.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

1 – The area of interest

In our previous Special Project (2020-2022) two areas had been selected. The Mediterranean Sea, with a highly varied coastline, displaying all the possible orographic features. The English southern part of the North Sea, facing (East Anglia) a very flat coast, hence suitable to check contrary-wise the effect of orography on coastal winds. In this project. Aiming at the specific role of orography, our attention has been focused mainly on the Mediterranean Sea, although, and done for the purpose of clarifying the emerging problems, we have also extended part of our analysis to the Red Sea. Although with a different shape, most of the problems encountered in the Mediterranean Sea appear to exist also in the Red Sea.

2 – Data to be analysed

All the required data have been made available, for ECMWF concerning the operational system data (high resolution). All these data have been retrieved and stored as monthly files in standard format.

3 - Present results

Before focusing on the specific results of this project it is convenient to summarize the one of the previous project as propedeutical to the actions taken in this project. Our first attempt was to plot the ratio model/measured wind speed versus fetch, i.e. the sea distance run by wind over the sea after "leaving" land. The reference measured data are scatterometer ones. While confirming the results of Cavaleri and Bertotti (2004), although with a different resolution, it was clear that a different approach and representation was required.

This has been found in the representation of Figure 1. Focused in this case on the Mediterranean Sea and on the 9 km, short term forecast ECMWF results, we show here the ratio model/scatterometer wind speeds as a function of "fetch". The blue lines represent the unstable conditions, the red ones the stable ones. The variously dotted-dashed lines (see synopsis) refer to different wind speed ranges, the continuous line to the full range of wind speeds.

It is clear that there is a substantial underestimate by the ECMWF model, the more so when in unstable conditions.

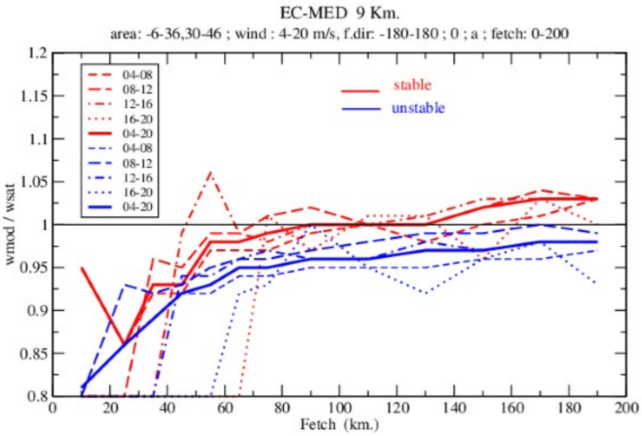

Figure 1 – Ratio model/scatterometer wind speeds as a function of "fetch". The blue limes refer to unstable conditions, the red ones to stable ones

Much of the attention during this past year has been focused on the coastal orography. In particular, we checked how the ECMWF underestimate depends on the orography of the land the wind blows from. Looking for an ample zone with these characteristics we have focused our attention on the eastern part of the Mediterranean Sea, on its southern coast, where the Sahara desert reaches the coast with behind a vast extent of practically flat terrain. Here we have considered both the outgoing (from land to sea) wind cases as the incoming ones, i.e. when the wind reaches the coast blowing from the sea, hence in principle without any orographic effect. The first case is shown in Figure 2.

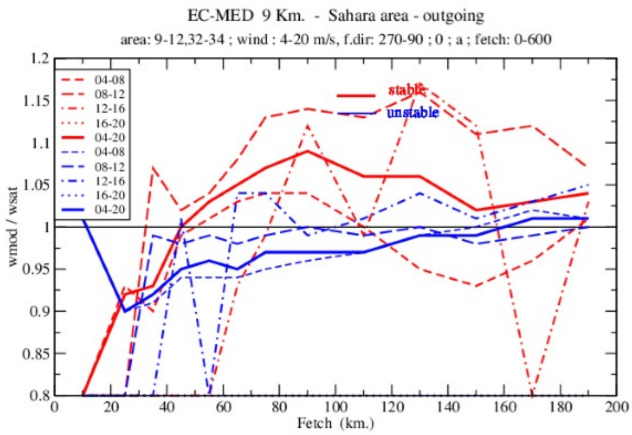

Figure 2 – As Figure 1, but for Sahara coast in the Mediterranean Sea.

There is an obvious tendency to a better fit with scatterometer data than for the general Mediterranean case. The reason is obviously the different orography of Lybia and Egypt with respect to the ones that characterises the northern coasts of the Mediterranean Sea (Pyrenees, Massif Central, Alps, Appennines, Dynaric Alps, etc). As a comparison, we show in Figure 3 the same area of incoming winds, i.e. winds blowing from the sea towards the coast.

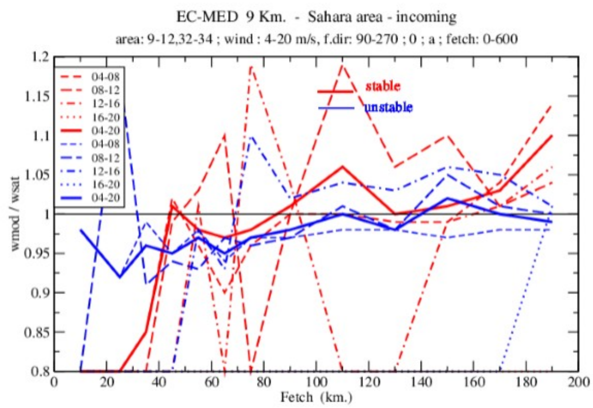

Figure 3 – As Figure 2, but for wind blowing from sea to land.

It is immediately evident that the model winds show a better fit with the scatterometer data, and again this strongly suggests a dominant effect of the local terrain in slowing down the surface wind, and its slow catch-up when on the sea.

This has shifted our attention to the specific orography. Then the question is how to characterize the local orography. Our latest discussions at ECMWF have clearly pointed out that the problem of the ECMWF wind underestimate when blowing to offshore is not only related to the passage from land to sea, but also to the characteristics of the orography the wind comes from. The question has a double face. For a long while the practical evidence along the successive increases of resolution of the ECMWF operational model showed that coastal wind quality was steadily improving with resolution. This had led to think that a better orographic description was the key to improvements. However, the various tests by Nils Wedi and his temporary Japanese visitor have clearly shown that the key to improvements is given by the increased resolution of the meteorological model. As a matter of fact, it has also turned out that an increased resolution of the orographic description leads to reduced wind speeds because of the higher drag along the mountains. Then an increase of resolution has a double effect: on one hand the coastal wind speeds are decreased because of an increased orographic drag. On the other hand the better resolution leads to a more rapid increase with fetch of the offshore blowing winds, this latter effect dominating on the first one, whence the improvement we found in the years with each increase of the ECMWF meteorological model.

All this has shifted the attention to the orography, wondering how to quantify the orography effect on the surface wind on the base of the specific orography. This has led to formulate a drag expression for a specific coastal orographic profile. This result will be going to be a key part of the final analysis and specification of the characteristics of the offshore blowing wind. We have experimented with many different profiles, checking how the various features affect the final drag value of the profile.

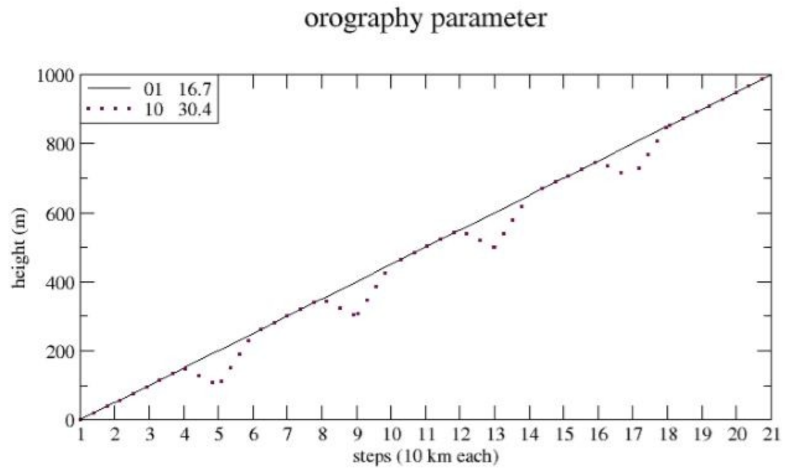

Figure 4 – A linearly sloping orographic coastal profile versus a more articulated one. In the figure there is the specification of the respective resulting drags.

A first example is given in Figure 4 where the more rugged terrain leads to doubling the resulting overall drag.

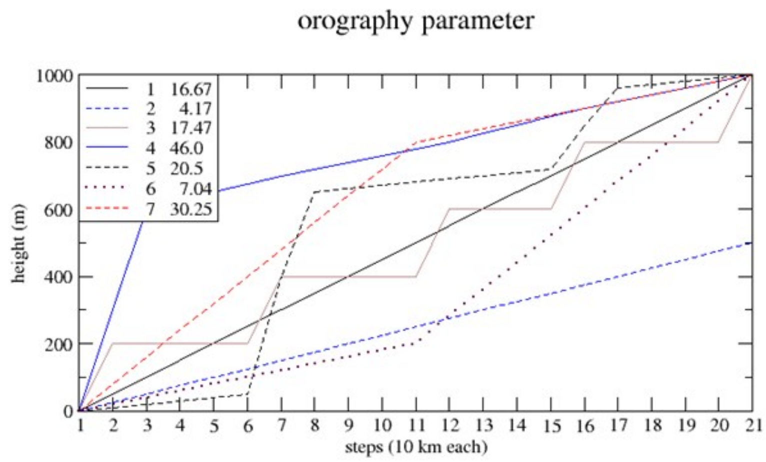

Figure 5 – As Figure 4, but with different orographic profiles

A more articulated example is in Figure 5 where, for the same height (1000 m) after 200 km inland (20 ten km steps) the different shapes of the slope leads to drag parameters with up to an order of magnitude difference.

It is therefore clear that the profile of the orography while descending towards the coast has a fundamental importance to determine the overall orographic drag, hence the characteristics of the offshore blowing wind. We are presently at the stage of characterising all the Mediterranean and southern North Sea coasts for a full evaluation of the drag, hence a new interpretation of the results we have for so long seen from the ECMWF model.

4 – The relevance of orography

The relevance of orography in determining the coastal underestimate has been explored using the ECMWF Tco1279 model wind in different areas of the Mediterranean Sea. Figure 6 provides a) the overall results for the Mediterranean, b) the ones off the French coast when the Mistral wind is blowing, c) a North blowing wind off the coast of Algeria (high mountain range in the interior), d) a North blowing wind off the Libyan coast (with the flat Sahara desert in the interior). It is evident that the higher the interior orography, the higher the model wind underestimate and the longer the "recovery" time and distance while blowing to offshore.

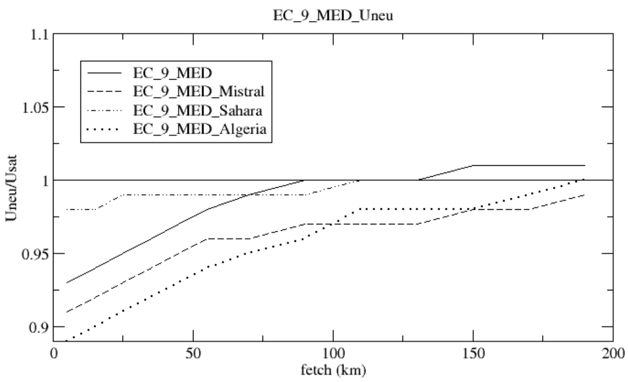

Figure 6 - Ratio between model neutral and scatterometer wind speed values as a function of fetch (km) and of the wind speed at the measurement point. Note the differences between the overall results (EC_9_MED) and the ones for areas characterized by high mountains (Mistral, Algeria) and flat terrain (Sahara) on the back coastal zone.

6– A different perspective of the problems

A final attack to the problem was to explore if the reported results were general or characteristics of the Mediterranean Sea. As we reported in our last intermediate report, we have extended our analysis also to the Red Sea. The Red Sea has a peculiar shape, relatively narrow and elongated, but with specific orographic features along all its coasts. These strongly condition the characteristics of the wind field in the basin. A representative and summary plot is the one reported in Figure 7 where the analysis has been pushed further with respect to the Mediterranean and Adriatic seas. In particular, in Figure 7 we show that, although averaged on the basin, the underestimate is strongly directionally dependent. In turn this shows the dependency on the orography, implicitly confirming the results we have all along found and reported for the Mediterranean Sea. This has opened a new line of research that will focus on the role of the air-sea stability conditions.

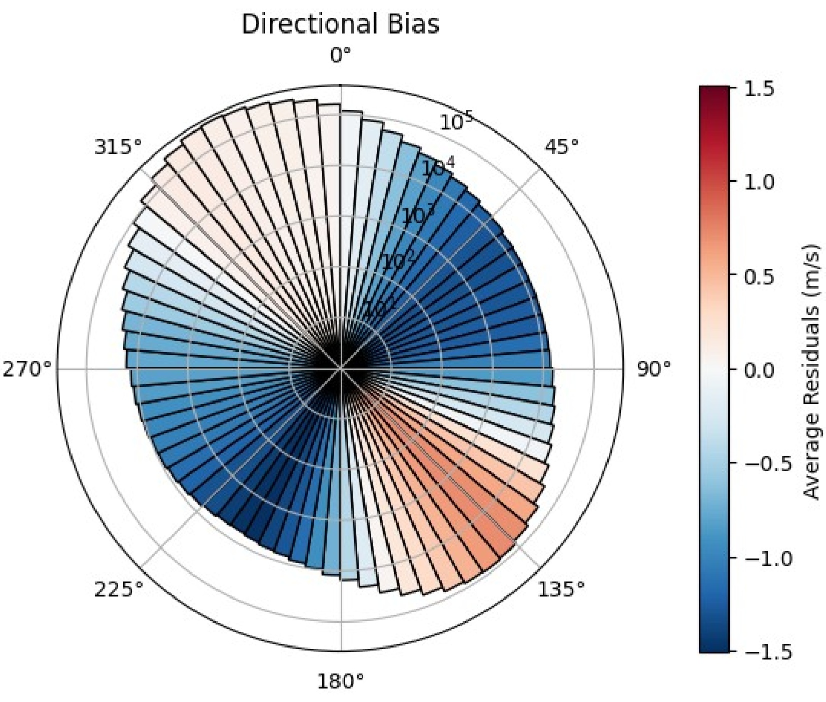

Figure 7 – Bias of ECMWF surface wind fields on the Red Sea.

7– Computer allowance

All our experiments, being always in new conditions with continuous adjustments of the handling ECMWF software, require a strong interaction both with the local meteorologists to discuss the progressive steps of advance and User Support team. All this can be done only during our presence at ECMWF. It follows that no experiment has been done during the passed time of this project.

List of publications/reports from the project with complete references

2023 Langodan, S., L.Cavaleri, L.Bertotti, A.M.Qasem, S.P.Razak, A.Pomaro, and I.Hoteit
"Winds and waves in the Arabian Gulf: Physics, characteristics and long-term hindcast", *Int.J. of Clim.*, 1-14. https://doi.org/10.1002/joc.8043

2023 L.Cavaleri, G.Balsamo, A.Beljaars, L.Bertotti, S.Davison, J.Edward, T.Kanehama, and N.Wedi,
"ECMWF and UK Met Office offshore blowing winds: impact of horizontal resolution and coastal orography" – J.Geoph.Res Atm, https:10.1029/2023JD039673

2024 Bidlot, J.-R., J.Kousal, O.Breivik, F.Barbariol, and L.Cavaleri
"Wind wave and atmosphere-ocean coupling at weather and climatic scales", BAMS, Oct 2024, DOI:10.1175/BAMS-D-24-0202.1

2025 Cavaleri, L., L.Bertotti, L.De Nat and A.Papa
"45 years of directional wave recorded data at the Acqua Alta oceanographic tower", Scientific Data, 2025, 12:224, https://doi.org/10.1038/s41597-025-04541-8

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Special Project 2026-2028 – We plan to focus our attention on the air-sea interaction as derived from accurate open sea wave data taken from the ISMAR offshore tower "Acqua Alta" (AAOT), with the purpose of verifying the wind input used in the present ECMWF operational WAM wave model.