The use of altimeter data to study wind and wave variability in the Mediterranean Sea and validate fine-mesh meteorological models

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ABSTRACT

First results of the comparison between altimeter-derived wind and wave parameters with data from fine-mesh meteorological models over the Mediterranean Sea are presented. On the basis of a qualitative analysis of some Geosat passes during February-March 1988, it is shown that the altimeter provides new capabilities: 1) for the study of wind and wave variability in the Mediterranean Sea; and 2) for the validation of fine-mesh wind and wave models.


RÉSUMÉ

Apport de l'altimètre pour étudier la variabilité du vent et des vagues en Méditerranée occidentale et valider les modèles météorologiques maille fine

Les premiers résultats de la comparaison entre paramètres vent/vague obtenus par altimétrie satellitaire et données de modèles météorologiques maille fine sur la Méditerranée occidentale sont présentés. A partir d'une analyse qualitative de quelques traces Geosat pour la période février-mars 1988, on montre que l'altimètre offre des possibilités nouvelles pour l'étude de la variabilité du vent et des vagues en Méditerranée occidentale et pour la validation des modèles maille fine de vent et de vagues.


INTRODUCTION

In the Western Mediterranean Sea, numerous local features are reported: these include the Mistral, blowing from the Rhône valley; the Tramontana, originating in the Pyrénées; the Sirocco from Libya; and the Libeccio from Tunisia. These wind regimes are all characterized by a large spatial variability due to the complex orography of the Mediterranean periphery and islands. The most noticeable feature is the wind acceleration in straits, as for example in the Bonifacio straits, where the Mistral dramatically accelerates, channeled by the high mountains of Corsica (2 710 m) and Sardinia (1 834 m). The masking of wind under the lee of islands is another well known characteristic.
However, because of the scarcity of in situ data, the extent and variability over the sea of such effects has not yet been studied. This limits our understanding of the physical processes governing the wind evolution in this very special climatic area; and many problems, including the influence of sea-surface temperature variations on the wind structure, cannot be addressed. Based on measurements by the Geosat altimeter (McArthur et al., 1987), the aim of this paper is to show how recent advances in remote sensing by satellite radar altimeter open a new chapter in the study of this Mediterranean wind and wave variability and how they provide a unique opportunity to validate surface wind and wave models. To this end, a detailed analysis of two Geosat tracks is presented, in which the altimeter measurements are compared with wind data from the fine-mesh atmospheric Peridot model (Imbard et al., 1986) and with wave data from the fine-mesh versions of the VAG model (Guillaume, 1987) and of the WAM model (the WAMDI Group, 1988). The paper is organized as follows: the second section describes the Geosat altimeter data that have been utilized. The wind and wave models are presented in the third section. The fourth section discusses the ability of the altimeter to study wind and wave variability. The fifth assesses the potential of using altimeter data to validate the wind and wave models. In the conclusion some indications are given concerning the organization of a more extensive experiment to obtain quantitative results.

**ALTIMETER DATA**

Work with Geosat-3 data (Mognard and Lago, 1979) and with Seasat data (Brown et al., 1981; Mognard et al., 1983) has demonstrated the capability of the altimeter to measure wind speed and significant wave height (SWH). But although Seasat has spawned a large quantity of literature, very little of it is devoted to the Mediterranean Sea (Guymer et Allan, 1984). The short life time of the satellite, moreover in summer, was a dramatic drawback for studying sea-state variability in this area. With data from the Geosat altimeter, in operation from 1985 to 1989, a wide range of sea-state conditions were measured. These data were used to study the wind speed and SWH variability over the world oceans in various weather conditions (Mognard et al., 1987; Mognard and Katsaros, 1990; Guillaume and Mognard, 1992). However, the study of a limited and complex area such as the Mediterranean Sea with an altimeter from an orbiting satellite such as Geosat has not been undertaken before.

To investigate its feasibility, a two-month data set (February-March 1988) was selected, based on climatological arguments and on the availability of wind fields from the fine-mesh (30 km) Peridot model. The altimeter data were extracted from the Geosat ERM-GDR (Exact Repeat Mission-Geophysical Data Records, Cheney et al., 1987). Because small variations in the satellite attitude affect the radar cross section (RCS) measurement, and thus the derived wind speed, data obtained with an attitude angle larger than 1° were discarded. The measurements of significant wave height (SWH) and RCS acquired along the satellite track (every second, over a distance of roughly 6.7 km) have been averaged over a 4s period for comparison with the model output. In a comparison with buoy data (Dobson et al., 1987), the SWH from the ERM-GDR were found to be 0.4 m too low on average. Such an underestimation is also found in a comparison with model results (Guillaume and Mognard, 1992) which suggests that it mainly affects the high waves. By fitting a detailed radar return model waveform to the Geosat waveform sampler data, Hayne and Hancock (1990) provide an independent estimate of the SWH, on average 12 % higher than the ERM-GDR SWH data. All these findings indicate an underestimation of the SWH in the Geosat ERM-GDR of the order of 10 %. To derive the wind speed from the RCS, the Brown algorithm (Brown et al., 1981) was used. Among several existing algorithms, this one is said to be the most accurate (Dobson et al., 1987; Guillaume and Mognard, 1992). But some discussion persists with regard to the proper algorithm to be used, mainly for high and low wind speeds, and the ability of the altimeter to measure wind speeds higher than 20 m/s.

The total Geosat coverage over the Mediterranean Sea for one cycle (17 days) is shown in Figure 1. For the Western Mediterranean Sea, 67 tracks are found in the two-month data set. From these 67 tracks, 27 (40 %) show waves higher than 3 m. These 27 tracks, being more likely to show significant sea-state variability, were selected. The total number of Geosat observations (averaged every 4s) for these 27 tracks is 489. The qualitative results we present next are from two representative tracks of this data set.

**WIND AND WAVE MODEL DATA**

Advances in regional fine mesh atmospheric modelling and its success over continental regions (Juvanon du Vachat et al., 1987) have led several meteorological institutions to extend its application to marine forecasts. Météo-France, after introducing the Peridot model (Imbard et al., 1986) for the main application of weather forecasting over France in 1985, extended its use to the Western Mediterranean in 1988 and to most of the basin in 1991. For February and
March 1988, the Peridot surface wind fields were collected every three hours on the stereographic grid of the model (30 km mesh size over the Mediterranean Sea), using the daily analysis of the model at 00 UTC, and then the short-range forecasts, up to 21:00 UTC. Because of the scarcity of conventional data, the ability of Peridot to reproduce highly variable structures over the Mediterranean Sea has not yet been fully studied, although it has been demonstrated over land (Juvanon du Vachat et al., 1987). The use of the altimeter wind speed measurements to validate the Peridot surface wind speeds is investigated.

The Peridot wind fields were used to run the fine mesh versions of two wave models: the VAG model (Guillaume, 1987) on the same grid as Peridot; and the WAM model (WAMDI Group, 1988) on a 0.5° by 0.5° latitude-longitude grid. The mesh size of the wave model is an important factor in the accurate description of the islands and the coastlines, and in the proper modelling the fetch. Validation studies carried out in the Atlantic (Guillaume, 1990; Guillaume, 1991) have shown that the VAG model was able to reproduce the dynamics of waves in rapidly changing situations. This is particularly required for the Mediterranean Sea. The evaluation of wave model results greatly depends on the accuracy of the model wind fields used as input. For the Mediterranean Sea, a fine description of the orography needs to be taken into account by the atmospheric model (Cavaleri et al., 1991). This is directly related to the fineness of the wind model grid and, to our knowledge, among operational models, Peridot has the finest grid (30 km) in this area. In a comparison against buoy data of two VAG hindcasts based on different wind fields (Guillaume, 1991) it was shown that...
the main differences between the VAG results and the buoy data could be explained by inaccuracies in the wind fields. A correct evaluation of the wind field over a large part of the Atlantic was found to be necessary to evaluate the wave model results further; but this could not be achieved with the available wind observations. With the altimeter, joint measurements of wind speed and SWH are made over a large area. We investigate how this helps in the validation of wave models.

WIND AND WAVE VARIABILITY IN THE MEDITERRANEAN SEA WITH THE GEOSAT ALTIMETER

During the two months February-March 1988, all the tracks from the selected altimeter data set (see the above section) show interesting features related to wind speed and SWH variability. Two representative tracks are analyzed in this section, in order to investigate the scale of the phenomena that are observed by the Geosat altimeter.

Wind and wave variability in the Tyrrhenian Sea (Fig. 2)

The track in Figure 2 corresponds to an ascending pass of Geosat in the Tyrrhenian Sea on 29 February 1988 at 08:15 UTC. The Mistral had started to blow six days earlier, as the result of a cold front moving from north to south. On 29 February, a flow with a western component is now well established over the whole basin. In the Tyrrhenian Sea, high wind variability is observed by the Geosat altimeter due to the orographic effects of Corsica and Sardinia on the wind flow (Fig. 2 a). From north to south, we may observe:
1) a wind acceleration near Cape Corsica (north of Corsica); 2) wind masking under the lee of Corsica; 3) a dramatic wind speed increase due to channeling in the strait of Bonifacio; 4) masking effects under the lee of Sardinia. The altimeter data show that this masking effect is more pronounced in the north, where the highest mountains are found. The wind speeds observed along this track are between 3 and 15 m/s, a range in which the Brown algorithm was tested against buoy data (Dobson et al., 1987) and, given the location of the fronts at that time and the land observations in the surroundings, no rain contamination is expected. Very reliable measurements of wind speed are made along this track by the Geosat altimeter. The SWH observations indicate a moderate sea state for which the Geosat altimeter is also very reliable. The SWH variations along the track follow the wind variations (Fig. 2 b). This shows that the waves are mainly wind-driven and that, even under the lee of the islands, they are not fetch-limited.

Wind and wave variability in the Gulf of Lions (Fig. 3)

The track on 22 March 1988 at 10:15 UTC (Fig. 3) corresponds to an ascending pass of Geosat overflying a typical early-stage Mistral situation. The wind had begun to blow in the Gulf of Lions twelve hours before (evening of 21 March), due to a frontal system reaching the Mediterranean Sea, and was now spreading out over the sea in the wake of the front. The front moved very quickly and at the time of the Geosat pass the frontal area was located beyond Sardinia and Corsica. This Geosat track (Fig. 3 a) matches the axis of the Mistral (Rhône Valley). The maximum wind speed could be quantified, but it reaches 15-18 m/s, a range in which the Brown algorithm might be more questionable as no verification against buoy data has ever been made (Dobson et al., 1987). Figure 3 b shows the SWH variability observed by the altimeter. The peak of SWH is shifted offshore compared to the peak of the wind speed (Fig. 3 a). For the higher sea state encountered along this track a 10% underestimation of the SWH by the altimeter (above section) would introduce a noticeable bias. However, at the beginning and at the end of this track, where moderate sea states are encountered, reliable wind speed and SWH measurements are made by the Geosat altimeter.

VALIDATION OF WIND AND WAVE MODELS WITH THE ALTIMETER

This section analyzes the results of the model hindcasts for the two Geosat tracks described in the previous section. Along these tracks the altimeter measured a high wind speed and SWH variability. We now investigate the use of the altimeter measurements to validate the wind and wave model results.

Modelling of the wind and wave variability in the Tyrrhenian Sea (Fig. 2)

For the Geosat pass in the Tyrrhenian Sea on 29 February 1988 at 08:15 UTC (Fig. 2 a), very reliable wind and wave measurements were made with the Geosat altimeter (see the first part of the third section). The wind variability is well reproduced by the Peridot model, except for the masking of the wind under the lee of Sardinia. In this area, the Peridot winds remain constant. The higher mountains of northern Sardinia do not seem to be taken into account in the modelling of the orographic effects. The SWH variability observed by the altimeter in the northern part of the track (beyond Corsica) is perfectly reproduced by the two wind hindcasts (Fig. 2 b and 2 c). However, under the lee of Sardinia, the WAM and VAG models give different results. On the basis only of the altimeter measurements (by comparing the wind speed variation with the SWH variation), we have shown (previous section) that in this area the waves are mainly wind driven. The higher SWH obtained by VAG, roughly 1 m, are explained by the higher Peridot wind speed. With the same Peridot winds the WAM SWH are 1 m lower. Part of this discrepancy can be explained by the lower resolution of the WAM model grid which might lead to fetch limited waves in this area. However the small differences in grid resolution do not appear sufficient to explain the 2 m difference between the two models.

Modelling of the wind and wave variability in the Gulf of Lions (Fig. 3)

On 22 March 1988 at 10:15 UTC (Fig. 3), reliable altimeter measurements are made by Geosat at the beginning and at the end of the pass. When the wind speed becomes higher than 15 m/s, the quality of the altimeter wind measurement is not fully validated (second section) and with higher SWH, a 10% underestimation of SWH by the altimeter (second section) should become noticeable. Along this track (Fig. 3 a), Peridot shows a higher wind speed variation than that observed by the altimeter, with higher wind speed in the northern part and lower wind speed near Africa. Low wind speed (less than 5 m/s) and high wind speed (more than 15 m/s) are only encountered on part of this track. Uncertainty about the altimeter-derived wind speed in these instances does not explain the whole along-track discrepancy. The Peridot model results and the altimeter wind measurements show slightly different spatial structures: Peridot gives a smaller extension of the mistral, and the altimeter measure a greater one. The lower high wind speed measured by the altimeter does not seem to be related to measurement errors but would rather indicate that both agree on the total wind energy. The SWH variations, including the shifting of the SWH peak compared to the wind speed peak, is well obtained by the VAG hindcast. In the northern part of the track the VAG model SWH are higher. This is mainly explained by the higher Peridot wind speeds, together with the altimeter SWH underestimation (10%, see second section) for the more noticeable discrepancy at the peak. With the WAM model hindcast, the peak of SWH coincides with the peak of wind speed and is not shifted offshore as observed by the altimeter. At the peak, and further offshore, the SWH from the WAM hindcast are lower than the altimeter-derived ones. These discrepancies do not appear to be related to the model wind errors, or to the uncertainty concerning the altimeter measurements for a high sea state. The WAM hind-
cast seems rather to show an earlier stage of wave field development. In the most southern part of the track the two hindcasts agree and show SWH 1 m higher than the altimeter-derived SWH. This SWH discrepancy is not related to the model wind errors and suggests some background swell in the two model hindcasts.

CONCLUSION

The Geosat altimeter furnishes the first wind and wave measurements over the Mediterranean Sea for studying the spatial variability of wind and waves. Qualitative analysis of some Geosat passes shows that the altimeter measurements provide much valuable information. Masking and channeling effects inferred by the islands can be investigated with high spatial accuracy which could not be achieved with previous in situ data. The altimeter can be used to observe the offshore extension and intensity of the mistral. Due to the fact that along any track crossing the Mediterranean sea, a wide range of wind speed and sea state is encountered, by focusing on the wind speed range for which the altimeter-derived wind speed are assessed, we were able to highlight in the mistral event studied in the above section that the Peridot model and the Geosat altimeter were showing slightly different spatial structures. During February and March 1988, 27 Geosat passes with SWH higher than 3 m are found that can be used to study wind and wave variability. It is expected that with the five-year data set obtained by Geosat, completed by the ongoing ERS-1 records, progress will be made in our understanding of the wind and wave variability over the Mediterranean Sea.

In this study, the spatial wind variability observed by the altimeter was well obtained by the Peridot fine-mesh model. With the altimeter data it was possible to highlight even minor inaccuracies in the Peridot results such as, for example, the apparent lack of differentiation in the orographic effects between north and south Sardinia or, as in the mistral event described in the second part of the fourth section, the fact that too active a structure seems to build up in this early stage of mistral. The unique capacity of the altimeter to provide joint wind and wave measurements is very useful for the validation of the wave models in order to distinguish between wind model errors and wave model errors. A good agreement is found between the VAG model and the altimeter-derived SWH and the discrepancies seem related to errors in the model winds. With the WAM model, only part of the SWH variability observed by the altimeter is obtained. The discrepancies do not seem to be related to model wind errors but appear rather to indicate some under-development of young sea state by the WAM model. These qualitative results demonstrate the high potential of the altimeter-derived wind speed and SWH observations for the accurate study of wind and wave variability in the Mediterranean sea and the validation of wind and wave models. On the basis of these results, it was decided to carry out more investigations on an extended data set, including ERS-1 data, to determine how significant qualitative results at this level of accuracy can be obtained. The present study indicates a need to evaluate the altimeter-derived wind speed for each wind speed range better than on average, as was already suggested by Guillaume and Mognard (1992).

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REFERENCES


