Committente:

COMUNE DI GENOVA

Via Garibaldi, 9 - 16124 Genova

Oggetto:

OPERE DI PRESIDIO A MARE A PROTEZIONE DEL CORPO DI FRANA INTERESSANTE I TERRAZZAMENTI DI PERTINENZA DEI CIVV. 39,41,43,45,47 DI VIA AURELIA - LOC. CAPOLUNGO

STUDIO PRELIMINARE AMBIENTALE

Titolo elaborato:

STUDIO METEOMARINO PER L'IDENTIFICAZIONE DELLE CONDIZIONI DI ONDA A SUPPORTO DELLA PROGETTAZIONE DELL'OPERA DI DIFESA DELLA FALESIA DI CAPOLUNGO

(documento redatto da DHI s.r.l.)

Progettista:

INGEPRO Ingegneri Associati

Corso Torino 17/6 sc.A - 16129 Genova
Tel. 010.5740568 - fax : 010.4211059
e-mail: studio@ingepro.eu - PEC: studio@pec.ingepro.eu
C.F. e P. IVA: 02726060995

0	25.07.2022	ER	SC	RG	Emissione
Revisione	Data	Redatto da:	Verificato da:	Approvato da:	Descrizione

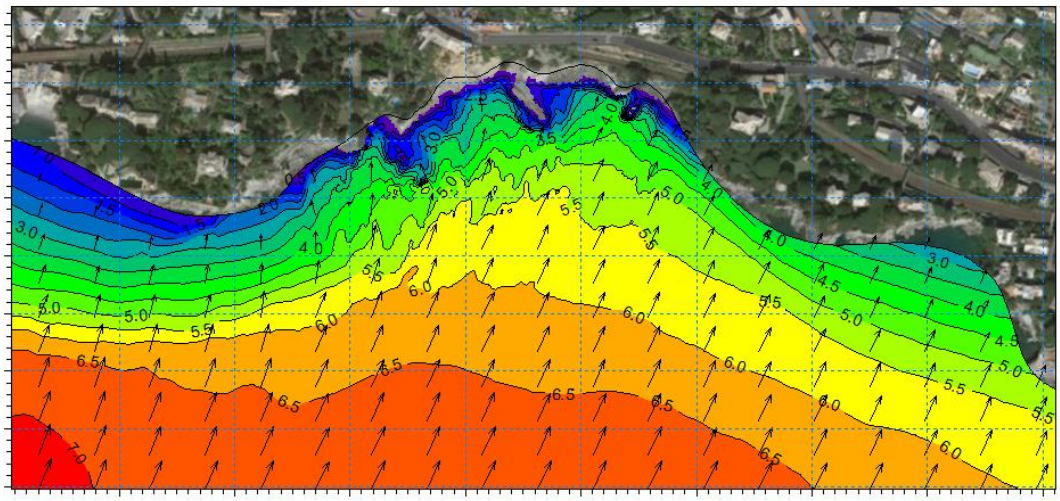
Nome file:	Scala:	Commessa:	Livello prog:	Elaborato:
P007.SA.R03.00_Studio meteomarino		P007	SA	R03

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Studio meteomarino per l'identificazione delle condizioni di onda a supporto della progettazione dell'opera di difesa della falesia di Capolungo

Relazione tecnica



inGEpro Ingegneri Associati

Relazione

Luglio 2022

The expert in WATER ENVIRONMENTS

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

This report has been prepared under the DHI Business Management System certified by Bureau Veritas to comply with ISO 9001 (Quality Management)



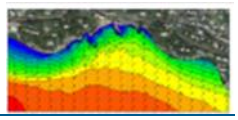
c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Studio meteomarino per l'identificazione delle condizioni di onda a supporto della progettazione dell'opera di difesa della falesia di Capolungo

Relazione tecnica

Committente inGEpro Ingegneri Associati

Referente del Committente ing. Riccardo Giammarini



Mappa di distribuzione dell'altezza d'onda

Project manager	Silvia Torretta
Quality supervisor	Andrea Pedroncini
Autore	Silvia Torretta

Codice progetto - elaborato	22803916
Data di approvazione	07/07/2022
Revisione	1.0
Classificazione	Open

DHI S.r.l. a socio unico• Via Bombrini 11/12• 16149 Genova• Italy•
Telefono: +39 010 84 81 220 • dhi-italia@dhi-italia.it • www.dhigroup.com

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

INDICE

1 Premessa 1

2 Dati disponibili 2
2.1 Dati meteomarini 2
2.1.1 Dati di moto ondoso 4
2.2 Dati di livello della superficie marina 8
2.3 Dati batimetrici 9

3 Analisi statistica degli eventi estremi al largo 10
3.1 Altezza d'onda significativa 10
3.2 Livello marino 13

4 Propagazione degli eventi estremi dal largo a costa 15
4.1 Condizioni d'onda associate agli eventi estremi al largo 15
4.2 Batimetria e dominio di calcolo 17
4.3 Risultati del modello d'onda 19

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

ALLEGATI

ALLEGATO A – Mediterranean Wind Wave Model
Descrizione tecnica

ALLEGATO B – MIKE 21 Spectral Waves (SW)
Descrizione tecnica

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

1 Premessa

Oggetto del presente studio sono le attività di modellazione numerica a supporto della progettazione degli interventi di difesa dall'azione erosiva del mare della falesia di Capolungo (Genova). Tali interventi si rendono necessari per la definitiva messa in sicurezza del sito: il 18 Gennaio 2014, a seguito di forti precipitazioni, la falesia è stata infatti interessata da una frana di notevoli dimensioni, che ha gravemente danneggiato parte degli edifici esistenti e mobilizzato il basamento roccioso della galleria della linea ferroviaria.



Figura 1-1 Sito oggetto di studio: nel cerchio bianco è evidenziata la zona interessata dalla frana del 2014

Al fine di mettere in sicurezza abitazioni ed area, le Autorità competenti hanno previsto due differenti tipologie di interventi, una con pali armati direttamente sul fronte in movimento, l'altra, al cui supporto è volta la presente analisi, relativa alla difesa dall'azione erosiva del mare al piede della falesia.

Le attività modellistiche a supporto della definizione delle caratteristiche dell'onda per il dimensionamento dell'opera a mare sono state affrontate utilizzando i software sviluppati da DHI, ed in particolare il modulo bidimensionale MIKE 21 SW – *Spectral Waves*, per lo studio della propagazione e dei campi d'onda degli eventi di mareggiata più intensi.

Per la caratterizzazione meteomarina al largo del sito di studio si è fatto riferimento al database Mediterranean Wind Wave Model (MWM), un complesso dataset di vento ed onda ad elevata risoluzione disponibile sull'intero bacino del Mar Mediterraneo, prodotto da DHI in collaborazione con HyMO*Lab* (Hydrodynamics and Met-Ocean Laboratory), struttura del Dipartimento di Ingegneria e Architettura dell'Università di Trieste.

La serie storica di 43 anni di dati di moto ondoso al largo, ricavata dal database MWM, è stata utilizzata per l'analisi statistica delle caratteristiche di onda, i cui risultati sono stati utilizzati come condizione al contorno di un modello locale a maggiore risoluzione, predisposto con lo scopo di propagare il moto ondoso fino a costa, tenendo conto delle principali trasformazioni che l'onda

subisce nella sua propagazione verso riva (rifrazione, shoaling, attrito col fondo, frangimento, diffrazione e riflessione).

I dati di onda propagati sono stati estratti sottocosta al fine di fornire le condizioni di riferimento per la progettazione delle opere di difesa, in carico ai tecnici di InGEpro Ingegneri Associati.

A seguire si riportano in dettaglio i dati utilizzati, la metodologia adottata, la descrizione delle impostazioni dei modelli numerici ed i risultati ottenuti.

2 Dati disponibili

2.1 Dati meteomarini

Tra le prime attività necessarie negli studi di dinamica costiera, vi è la caratterizzazione delle condizioni meteomarine di riferimento al largo del tratto di costa interessato, con particolare riferimento al moto ondoso.

Per quanto riguarda la disponibilità di registrazioni di moto ondoso, la principale fonte di riferimento nel nostro paese è la Rete Ondametrica Nazionale (RON) gestita dall'ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale). I dati di boa possono essere utilizzati come riferimento anche ad una certa distanza dal sito di interesse, qualora l'esposizione alle mareggiate per i diversi settori direzionali possa essere considerata simile tra il sito in esame ed il sito che ospita la boa ondametrica. Frequentemente, tuttavia, per la caratterizzazione meteomarina di un sito non è possibile fare affidamento alle misure. Questo avviene o perché i dati sono troppo frammentati a causa di malfunzionamenti dello strumento o periodi di manutenzione dello stesso, o perché le serie temporali disponibili coprono solo pochi anni (5÷10) oppure ancora perché per il paraggio in esame la boa non è disponibile o non è sufficientemente rappresentativa.

Sempre più spesso, pertanto, si fa ricorso ad una ricostruzione storica delle condizioni meteomarine attraverso modellistica numerica. Tale approccio, comunemente definito come "*wave hindcast*" permette di disporre di serie temporali, tra l'altro, di altezza d'onda, periodo e direzione, nel punto desiderato. Se da un lato la possibilità di disporre di ricostruzioni di condizioni meteomarine pregresse attraverso un approccio modellistico rappresenta oggi un formidabile supporto nell'ingegneria costiera ed offshore, dall'altro va sottolineata l'importanza di disporre di ricostruzioni modellistiche robuste, accurate e validate.

Tra i database disponibili, un esempio di ricostruzione storica di vento e moto ondoso per l'intero bacino del Mediterraneo è costituito dal database Mediterranean Wind Wave Model (MWM), prodotto da DHI in collaborazione con HyMO*Lab* (Hydrodynamics and Met-Ocean Laboratory), struttura del Dipartimento di Ingegneria e Architettura dell'Università di Trieste. Il database MWM deriva dall'implementazione di una catena modellistica che beneficia di due modelli che rappresentano lo stato dell'arte rispettivamente nell'ambito della modellazione atmosferica (WRF-ARW) e della modellazione del moto ondoso (MIKE 21 SW di DHI).

In Figura 2-1 e Figura 2-2 sono riportate rispettivamente la batimetria di riferimento per la componente modellistica di moto ondoso ed un dettaglio della "mesh" di calcolo adottata. La risoluzione del modello d'onda è variabile da circa 10 km al largo fino a circa 3 km sottocosta. I dati sono stati estensivamente validati con confronti con anemometri, boe, nonché con le stime di intensità del vento e altezza d'onda da satellite.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

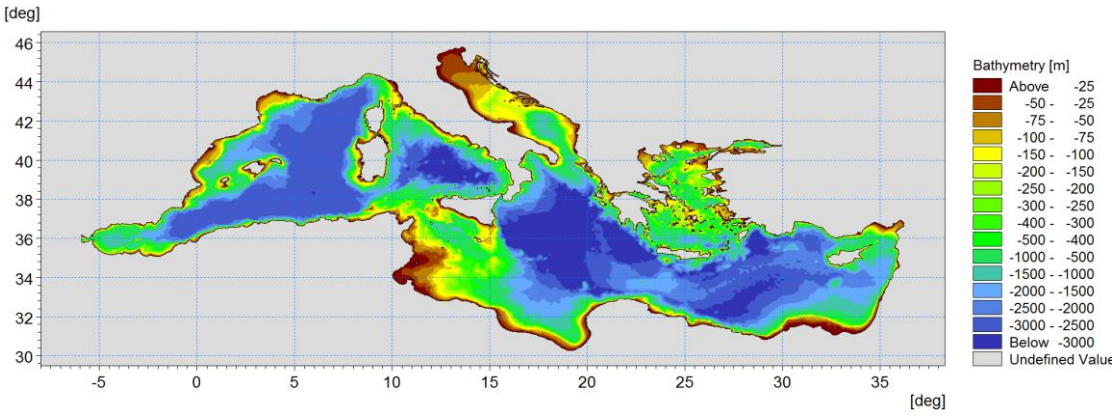


Figura 2-1 Batimetria di riferimento per la componente “onda” del database MWM

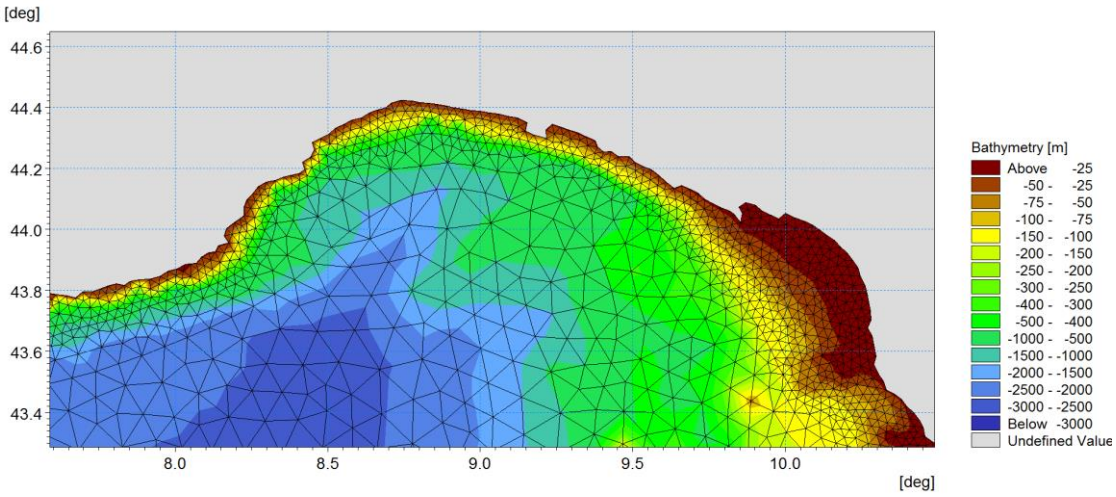


Figura 2-2 Batimetria di riferimento per la componente “onda” del database MWM – dettaglio sul Mar Ligure

Il database Mediterranean Wind Wave Model (MWM), descritto diffusamente in Allegato A al presente documento, è stato pertanto preso a riferimento per la caratterizzazione meteomarina al largo del sito di studio.

La selezione della cella del database MWM più adeguata a rappresentare il clima meteomarino al largo del tratto di costa oggetto di studio è stata effettuata tenendo in considerazione diversi aspetti:

- il punto deve essere ben rappresentativo dell’esposizione del sito al moto ondoso;
- in virtù della risoluzione del database MWM (circa 4 km), il punto deve essere collocato ad una profondità alla quale possa essere ritenuta trascurabile l’interazione dell’onda con il fondale, che viene pertanto demandata al modello di propagazione largo-costa descritto in seguito;
- la localizzazione del punto non deve essere troppo lontana dalla costa, in modo che il modello di propagazione largo-costa non presenti un dominio troppo ampio, con tempi di calcolo troppo onerosi.

Sulla base di tali prescrizioni e della risoluzione spaziale del database MWM è stato selezionato un punto per l’estrazione e la caratterizzazione dei parametri d’onda relativamente ai 43 anni (1979-2021) di ricostruzione storica (modalità *hindcast*) delle serie orarie ad oggi disponibili.

A seguire si riportano l’ubicazione grafica e le coordinate del punto selezionato.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E



Figura 2-3 Ubicazione del punto di estrazione da MWM (LON 9.029°E, LAT 44.340°N) i cui dati dal 1979 al 2021 sono stati utilizzati per la caratterizzazione del moto ondoso al largo

Tabella 2-1 Coordinate del punto selezionato dal dataset di MWM per la caratterizzazione meteomarina del sito

Punto	Lon [°E]	Lat [°N]
MWM	9.029	44.340

2.1.1 Dati di moto ondoso

In Figura 2-4 viene riportato l'andamento dell'altezza d'onda significativa per il periodo 1979-2021, per il punto MWM (LON 9.029°E, LAT 44.340°N), ubicato a circa 5 km dalla falesia di Capolungo.

Come si evince dai dati estratti, l'evento maggiormente gravoso nei 43 anni di dati orari a disposizione è stato registrato il 30 Ottobre 2008, con una altezza d'onda significativa Hs al largo pari a 7.14 m. Nei mesi di Dicembre del 2011, del 2017 e del 1999, si sono verificate le mareggiate rispettivamente identificate come la seconda, la terza e la quarta per valore di altezza d'onda significativa, tutte caratterizzate da valori di Hs superiori a 6.50 m.

Il più recente evento del 30 Ottobre 2018 risulta la quinta mareggiata per gravosità di altezza d'onda significativa rispetto alla serie di dati a disposizione (Hs=6.23 m nel punto MWM).

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

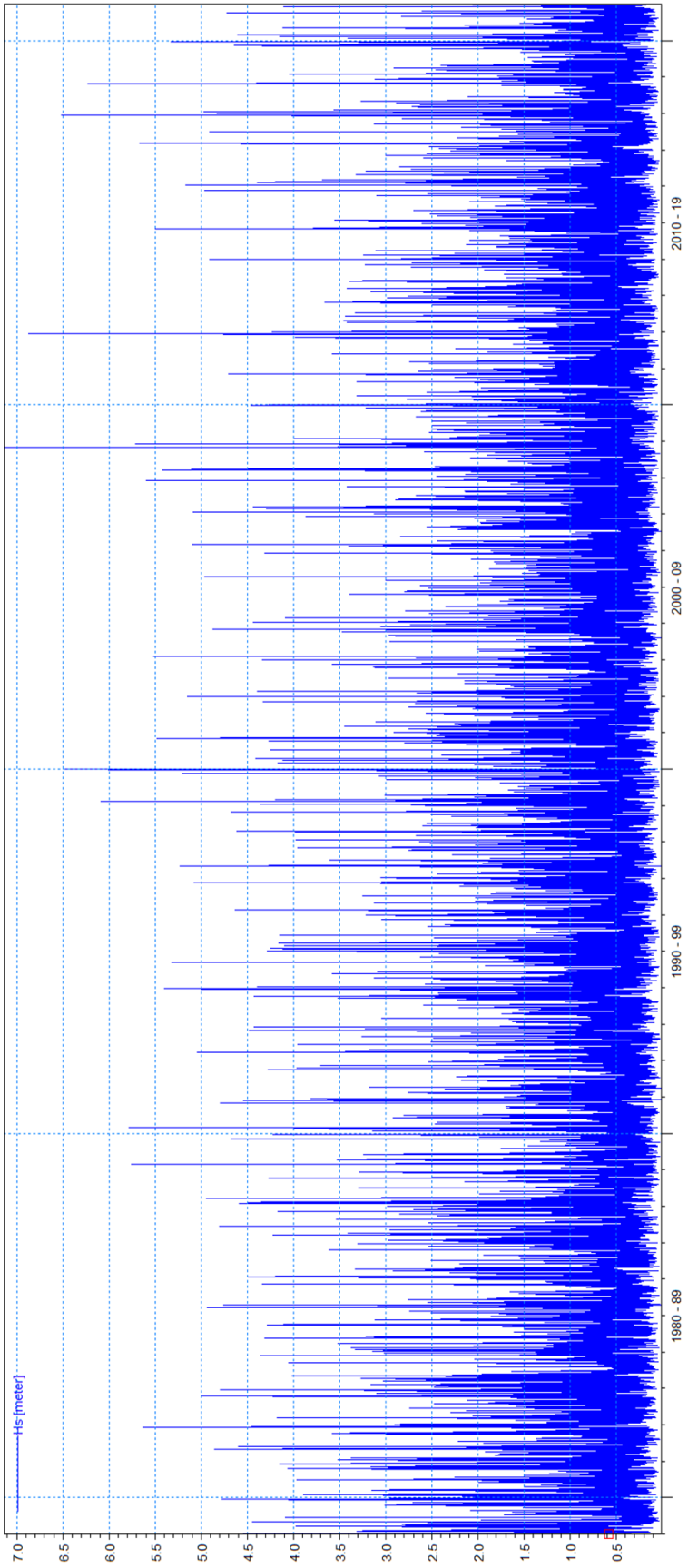


Figura 2-4 Serie di altezza d'onda significativa per il punto MWM (LON 9.029°E, LAT 44.340°N) per il periodo 1979 – 2021

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Dall'analisi della rosa del clima ondoso (Figura 2-5) e della tabella delle frequenze di occorrenza (Tabella 2-2) si evince che le mareggiate più frequenti e più intense provengono dal settore di Libeccio, con particolare riferimento alle direzioni comprese tra 200°N e 220°N. Complessivamente, tale settore racchiude circa il 26% delle onde, corrispondente in media a circa 3 mesi/anno. In questo settore direzionale l'onda raggiunge valori di altezza significativa anche superiori a 7 m.

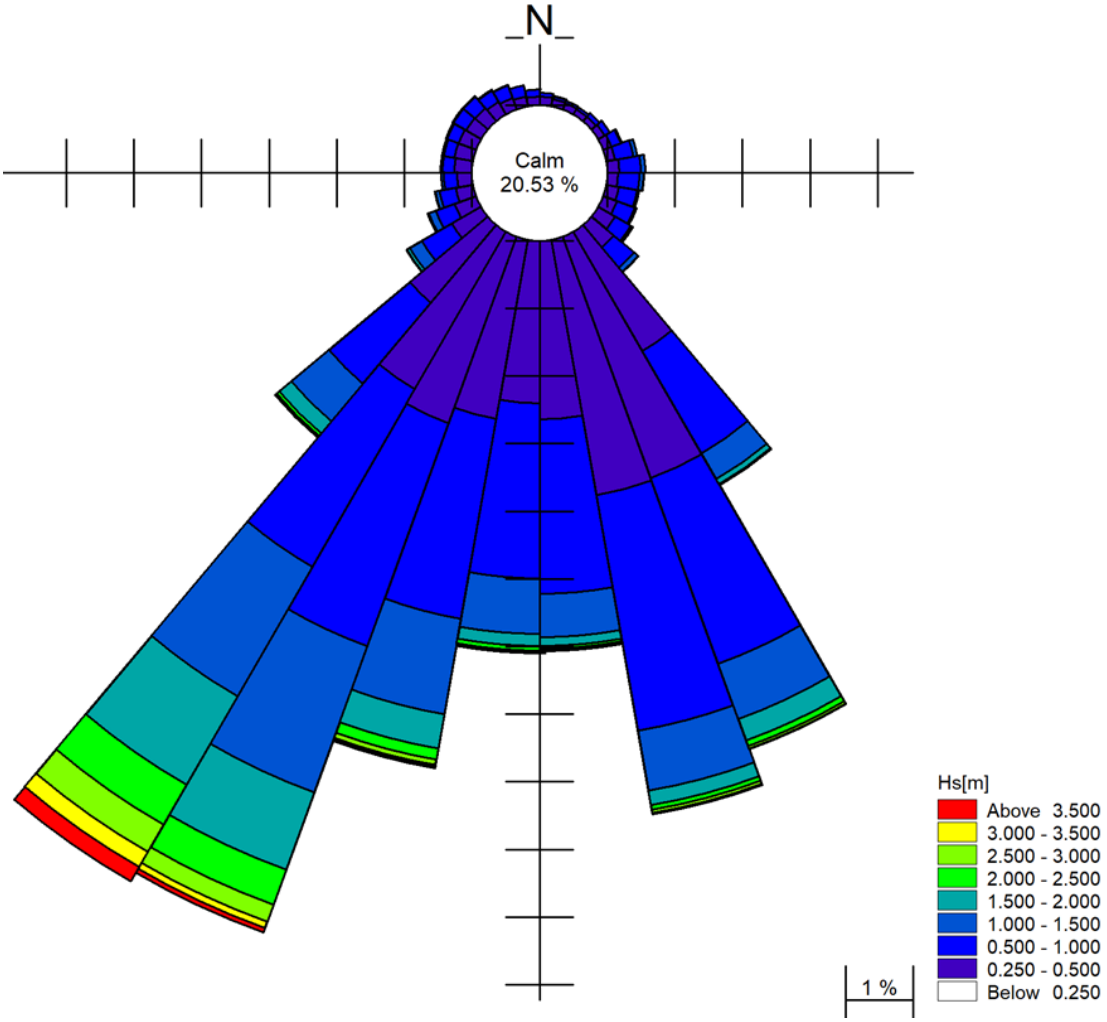


Figura 2-5 Rosa del clima ondoso al largo per il punto MWM (LON 9.029°E, LAT 44.340°N) per il periodo 1979 – 2021. La calma è riferita ad onde con altezza d'onda significativa H_s inferiore a 0.25 m

La condizione di calma, qui associata ad una altezza d'onda significativa inferiore a 0.25 m, si verifica per circa il 21% del tempo, corrispondente in media a circa 2 mesi e mezzo all'anno.

Tabella 2-2 Frequenza annuale per classi di altezza d'onda significativa Hs in funzione della direzione media di provenienza MWD per il punto MWM (LON 9.029°E, LAT 44.340°N) calcolata sul periodo 1979 – 2021

MWD[°] \ Hs[m]	<0.25	0.25-0.50	0.50-0.75	0.75-1.00	1.00-1.25	1.25-1.50	1.50-1.75	1.75-2.00	2.00-2.25	2.25-2.50	2.50-2.75	2.75-3.00	3.00-3.25	3.25-3.50	3.50-3.75	3.75-4.00	4.00-4.25	4.25-4.50	4.50-4.75	4.75-5.00	5.00-5.25	5.25-5.50	5.50-5.75	5.75-6.00	6.00-6.25	6.25-6.50	6.50-6.75	6.75-7.00	7.00-7.25	7.25-7.50
<10	0.929	11.71	4.02	0.48	0.1																									
10-20	0.786	9.262	3.98	0.21	0.12																									
20-30	0.595	8.69	3.45	0.43	0																									
30-40	0.595	7.452	3.81	0.31	0.05																									
40-50	0.619	8.167	4.88	0.95	0.17																									
50-60	0.81	9.429	5.57	2.12	0.21	0.02																								
60-70	0.595	11.05	8.45	4.69	1.67	0.17																								
70-80	0.857	11.83	13.1	11.1	3.74	1.02	0.05																							
80-90	0.738	15.43	17.6	10.1	4.98	1.26	0.33																							
90-100	0.833	13.88	20.4	7.55	4.26	0.9	0.43																							
100-110	2.429	16.52	16.2	7.79	2.05	0.55	0.29	0.02																						
110-120	6.167	19.62	16.7	7.05	1.9	0.33	0.33	0.05																						
120-130	13.95	25.48	16.2	7.07	2.02	0.88	0.14	0.24																						
130-140	31.33	38.6	24.4	9.31	5.14	1.79	0.5	0.48	0.05																					
140-150	189.1	178.5	98	55.2	27	11.8	4.76	2.5	1.02	0.57	0.14	0.05																		
150-160	235.1	333.2	172	84.2	48.8	27.6	18.3	11	4.52	3.45	1.83	1.17	0.33	0.26	0.24	0.02														
160-170	210.5	336.4	203	107	54.7	24.1	12.6	6.5	2.81	3.62	2.71	1.02	0.52	0.29	0.29	0.26	0.1	0.12	0.12	0.02										
170-180	170.4	232	146	79.3	39.5	16.8	7.62	3.62	1.52	2.12	1.05	1.07	0.31	0.14	0.19	0.29	0.12	0.19	0.19	0.02										
180-190	151.5	210.7	140	87.3	49.5	22.1	10.2	5.67	2.81	3.07	1.48	0.71	0.52	0.24	0.29	0.05	0.14	0.14	0.21	0.02	0.05	0.02	0.02							
190-200	145.7	235.7	158	106	77.8	47.6	26.3	18.9	7.79	7.05	3.45	3.07	1.45	0.33	0.52	0.6	0.57	0.21	0.17	0.17	0.05	0.1	0.02	0.02	0.05					
200-210	164.4	257.4	180	127	111	90.4	61.8	44.4	30.1	19	13.5	9.57	5.12	3.38	0.5	1.95	1.19	1	0.45	0.24	0.26	0	0.1	0.07	0.07	0.05	0.05	0.02	
210-220	174.1	236	151	115	106	88	75.2	57.6	41.9	17.6	22.8	18.3	13.2	9.14	3.36	1.33	5.5	3.69	2.45	1.88	1.33	0.79	0.67	0.38	0.12	0.14	0.05	0.07	0.02	
220-230	119.9	132.2	76.8	59.4	40.9	23.1	13	7.17	3.64	0.81	1.33	0.45	0.67	0.21	0.12	0	0.02	0.02	0.02	0.05	0.02	0.05	0.05							
230-240	38.19	43.62	25.4	19.4	11.6	6.69	3.21	1.52	0.6	0.14	0.05	0.02																		
240-250	27.21	29.43	16.6	10	6.48	2.93	1.05	0.31	0.02																					
250-260	24.48	23.12	13.3	7.55	3.95	2.07	0.31	0.02																						
260-270	23.74	19.52	10.8	6.26	2.36	1.02	0.14	0.02	0.02																					
270-280	26.19	22.4	10.9	5.26	1.81	0.43	0.12	0.02																						
280-290	21.67	24.83	9.48	4.43	1.57	0.21	0.1																							
290-300	8.286	24.24	11.7	3.81	1.45	0.14	0.07																							
300-310	3.095	22.93	14.5	4.48	0.74	0.31	0.1																							
310-320	1.857	22.31	15.7	3.86	0.86	0.14	0.05																							
320-330	1.31	18.74	14	3.24	0.9	0.12	0.02																							
330-340	0.714	15.93	13.9	3.29	0.6	0.14																								
340-350	0.69	13.26	11.6	2.6	0.38	0.05																								
>350	0.619	11.55	7.9	1.17	0.1																									

2.2 Dati di livello della superficie marina

Per la definizione dei livelli marini da considerare nella progettazione degli interventi si è fatto riferimento alla serie osservata del mareografo di Genova, il più vicino al sito e con maggior disponibilità di dati recenti (la monografia della stazione mareografica è riportata in Figura 2-6).

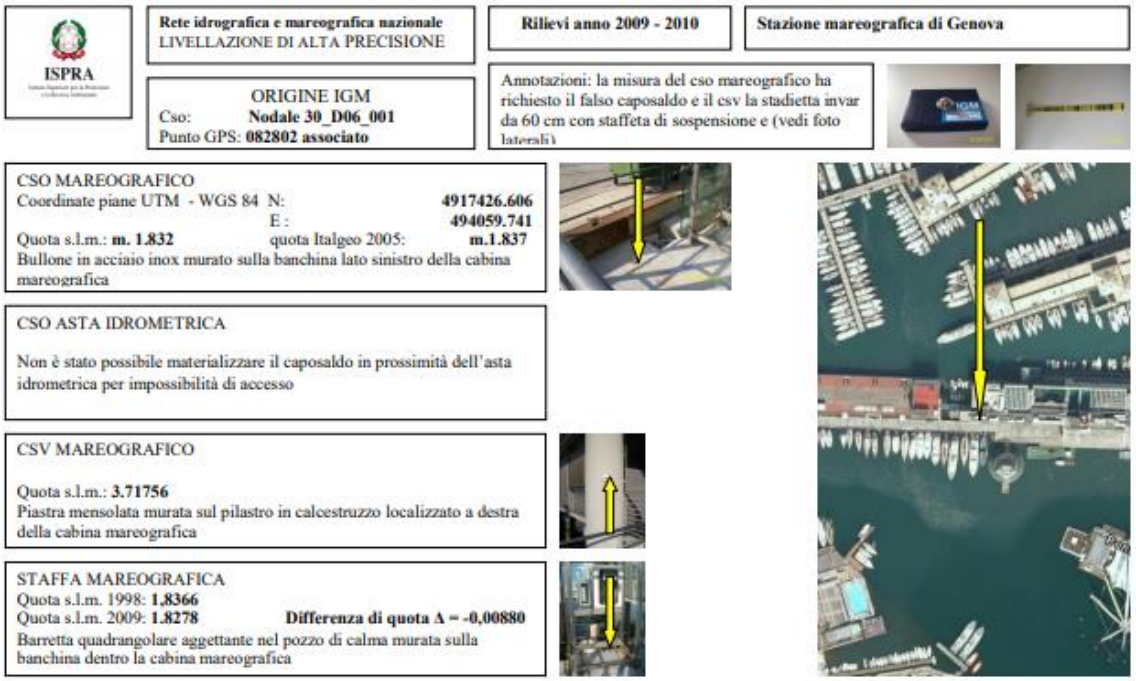


Figura 2-6 Monografia della stazione mareografica di Genova

In particolare, per le elaborazioni svolte nel presente studio si è fatto riferimento alle registrazioni disponibili nel periodo 1.1.2010 – 31.12.2019.

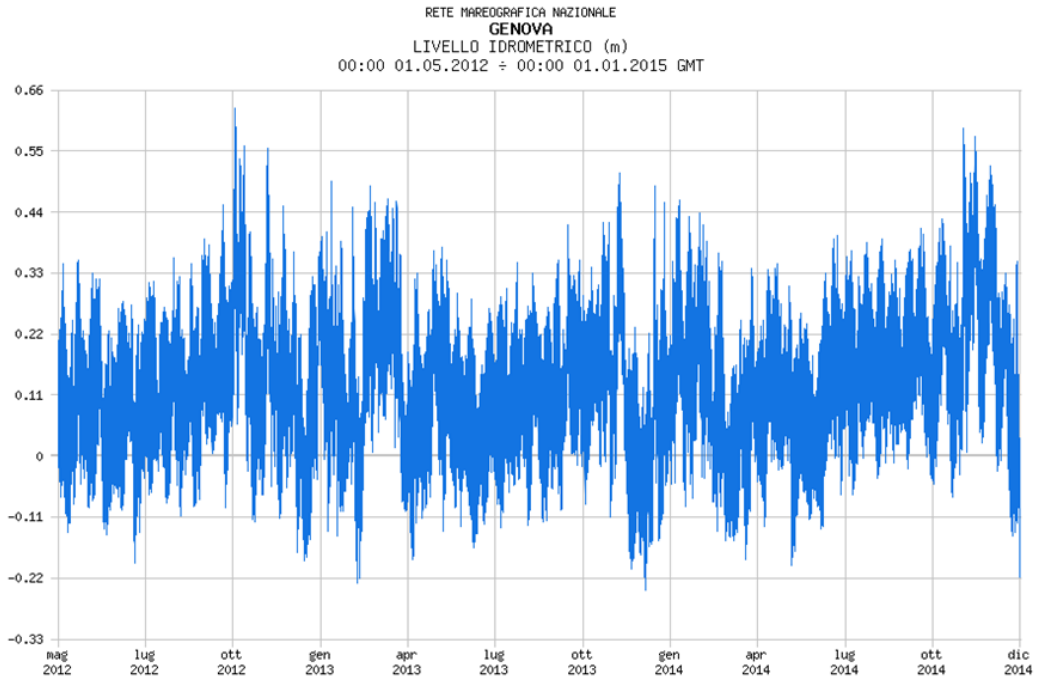


Figura 2-7 Osservazioni del livello idrometrico al mareografo di Genova (dettaglio dal 2011 ad 2015)

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

2.3 Dati batimetrici

Per la caratterizzazione topo-batimetrica del sito, è stato messo a disposizione un rilievo di dettaglio del tratto di costa comprensivo della falesia e della porzione di mara antistante, commissionato nell'ambito dello studio in oggetto e predisposto da Drafinsub nel Giugno 2022 (Figura 2-8).

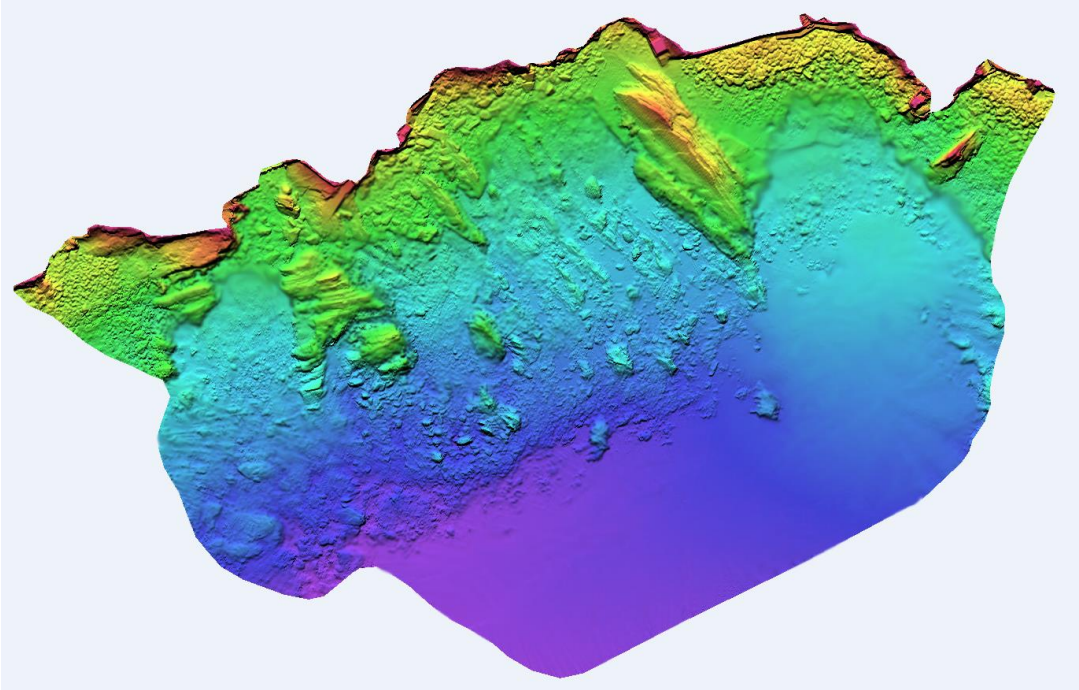


Figura 2-8 Rilievo di dettaglio del tratto di costa oggetto dello studio (Drafinsub, Giugno 2022)

Le dimensioni del dominio di calcolo del modello numerico implementato sono tuttavia più estese rispetto all'area per la quale risulta disponibile tale rilievo. A integrazione dei recenti dati locali, sono state pertanto utilizzate le carte nautiche digitali appartenenti al database CM-93 di C-MAP, un database globale di cartografia nautica in formato digitale, creato e continuamente aggiornato da Jeppesen (Figura 2-9). I dati forniti da questo database sono direttamente importabili nell'ambiente di lavoro dei codici di calcolo di DHI, consentendo quindi una rapida caratterizzazione batimetrica dell'area.

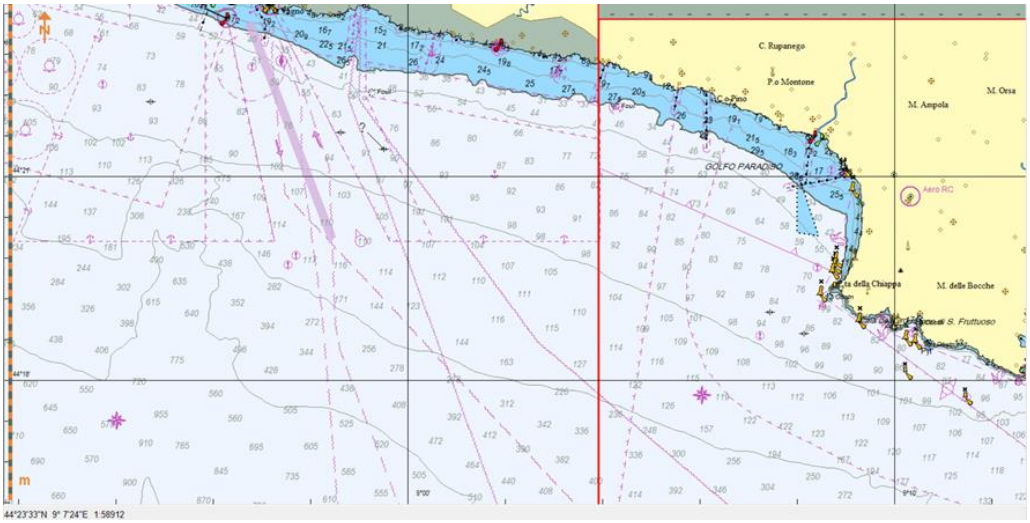


Figura 2-9 Rappresentazione della cartografia nautica digitale per il sito oggetto di studio (Jeppesen)

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

3 Analisi statistica degli eventi estremi al largo

Sulla base delle serie di dati estratti dal dataset MWM al largo di Capolungo si è proceduto con un'analisi statistica direzionale finalizzata alla definizione degli eventi estremi per assegnato tempo di ritorno, dai settori di provenienza più significativi.

I valori estremi associati a tempi di ritorno elevati sono in genere stimati applicando una distribuzione di probabilità alla serie di dati. In letteratura sono disponibili molte distribuzioni di probabilità, tecniche di selezione dei dati e di fitting e i risultati statistici risultano inevitabilmente dipendenti dalla metodologia selezionata.

Nel presente studio si è proceduto facendo riferimento ad una serie di diversi approcci, tutti opportunamente testati e confrontati, con la selezione del metodo che meglio approssimava i dati a disposizione.

L'analisi statistica è stata svolta sia per la serie di altezza d'onda significativa, che per i dati di livello idrometrico.

3.1 Altezza d'onda significativa

La procedura adottata è stata la seguente:

- estrazione, dalla serie temporale di dati orari in corrispondenza del punto MWM estratto al largo di Capolungo, di eventi statisticamente indipendenti. Il criterio di indipendenza degli eventi è legato sia all'intervallo di tempo che li separa (tipicamente non meno di 36 ore) sia all'evidenza che l'onda, tra due eventi indipendenti, scenda al di sotto di una determinata soglia (in genere pari al 70% del minore dei due valori associati agli eventi indipendenti);

- *fit* della distribuzione di probabilità con gli eventi selezionati. I parametri della distribuzione di probabilità possono essere stimati sia con metodi di massima verosimiglianza, sia con metodi ai minimi quadrati. Sono stati utilizzati i seguenti approcci di analisi:
  - fit dei dati con la distribuzione dei massimi annuali di Gumbel;
  - fit dei dati con la distribuzione di tutti gli eventi indipendenti sopra una determinata soglia (metodo "Peak Over Threshold"). Tra i tipi di distribuzione sono stati testati: l'esponenziale, la Weibull troncata e la Weibull a 2 parametri;

- stima degli intervalli di confidenza mediante tecniche di *bootstrap*.

Nel caso in esame, per modellizzare il comportamento del fenomeno di interesse in relazione alla popolazione di riferimento e alla finalizzazione dell'analisi è stata presa a riferimento la distribuzione statistica Weibull a due parametri, che meglio rappresentava l'andamento del campione.

A partire dall'intera serie temporale quarantennale si è proceduto ad estrarre, per settori direzionali di 30° di ampiezza, un numero sufficientemente rappresentativo di eventi statisticamente indipendenti, caratterizzati dai valori più elevati di altezza d'onda significativa in riferimento allo specifico settore. Gli eventi di volta in volta selezionati per ciascun settore sono stati pari a 54.

I quattro settori di 30° significativi per l'area di studio in esame sono in dettaglio:

- Settore Scirocco eventi caratterizzati da una direzione media di provenienza compresa tra 140°N e 170°N (MWD media di riferimento: 155°N);
- Settore Ostro: eventi caratterizzati da una direzione media di provenienza compresa tra 170°N e 200°N (MWD media di riferimento: 185°N);

- Settore Libeccio: eventi caratterizzati da una direzione media di provenienza compresa tra 200°N e 230°N (MWD media di riferimento: 215°N).

A seguire si riportano i risultati grafici della distribuzione statistica per ognuno dei settori identificati e una tabella riassuntiva con le altezze d'onda significativa per assegnato tempo di ritorno.

SETTORE SCIROCCO
ANALISI STATISTICA DEI VALORI ESTREMI DI ALTEZZA D'ONDA SIGNIFICATIVA

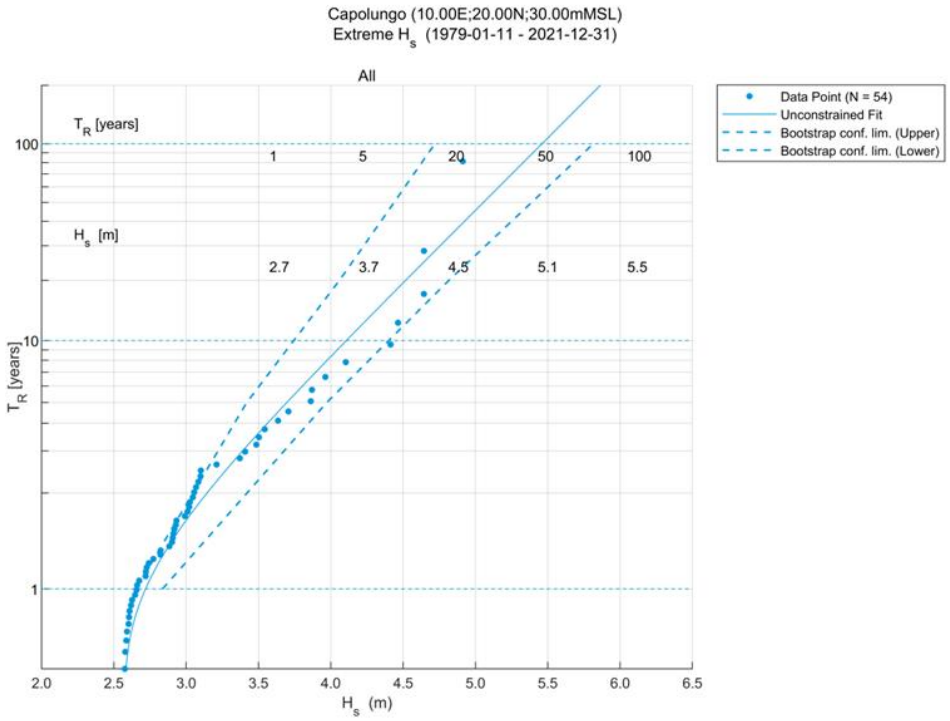


Figura 3-1 Distribuzione statistica di Weibull a due parametri per il campione di dati relativo ai 54 maggiori eventi degli ultimi 43 anni estratti nel punto MWM al largo di Capolungo, provenienti dalsettore di Scirocco (140°N<MWD<170°N)

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

SETTORE OSTRO
ANALISI STATISTICA DEI VALORI ESTREMI DI ALTEZZA D'ONDA SIGNIFICATIVA

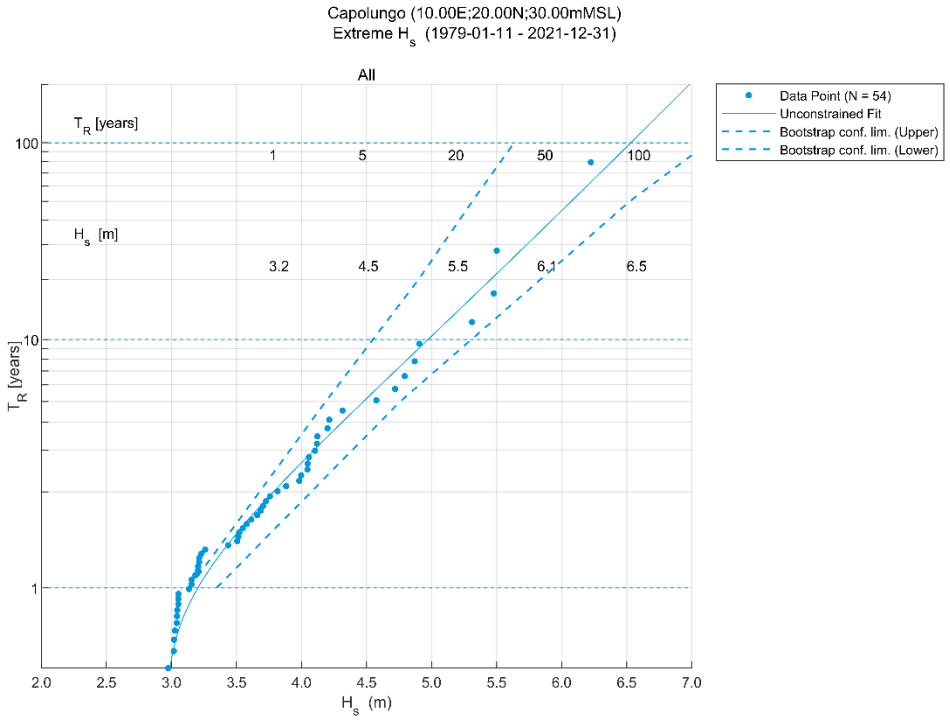


Figura 3-2 Distribuzione statistica di Weibull a due parametri per il campione di dati relativo ai 54 maggiori eventi degli ultimi 43 anni estratti nel punto MWM al largo di Capolungo, provenienti dal settore di Ostro (170°N<MWD<200°N)

SETTORE LIBECCIO
ANALISI STATISTICA DEI VALORI ESTREMI DI ALTEZZA D'ONDA SIGNIFICATIVA

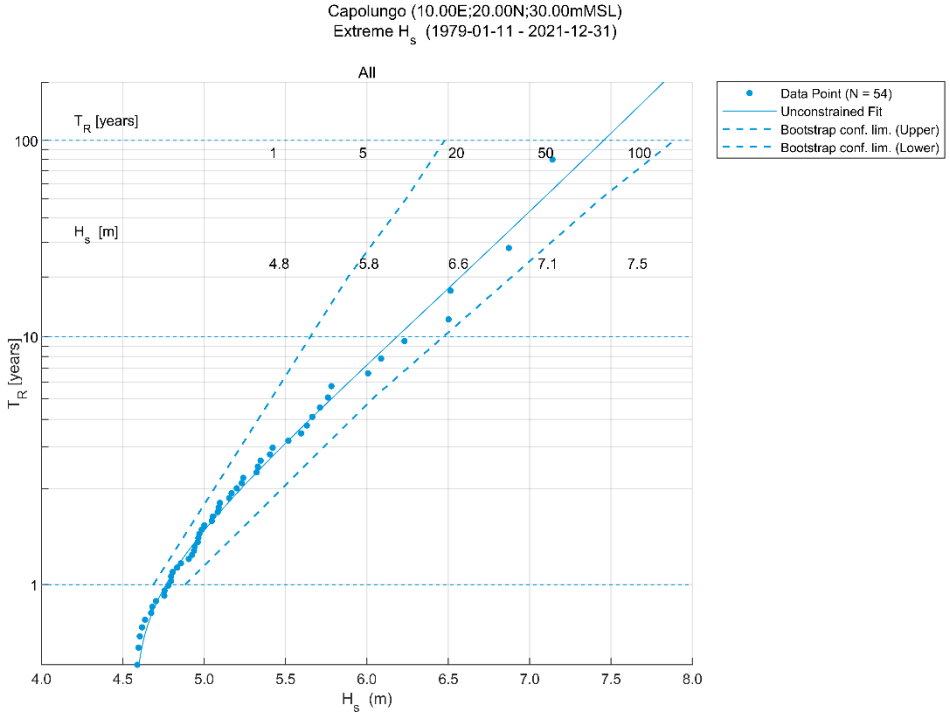


Figura 3-3 Distribuzione statistica di Weibull a due parametri per il campione di dati relativo ai 54 maggiori eventi degli ultimi 43 anni estratti nel punto MWM al largo di Capolungo, provenienti dal settore di Libeccio (200°N<MWD<230°N)

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Tabella 3-1 Valori risultanti dalla statistica degli estremi per l'altezza d'onda significativa Hs per i vari settori direzionali considerati, per i tempi di ritorno pari a 1 anno, 20 anni e 50 anni.

Settore	Hs[m]		
	TR 1 anno	TR 20 anni	TR 50 anni
Scirocco (140°N-170°N)	2.7	4.5	5.1
Ostro (170°N-200°N)	3.2	5.5	6.1
Libeccio (200°N-230°N)	4.8	6.6	7.1

3.2 Livello marino

L'analisi statistica dei dati di livello del mare si basa sulla serie di livello idrometrico registrata dal mareografo di Genova. Il mareografo è posto all'interno del bacino portuale, pertanto è in grado di tenere in considerazione i seguenti contributi alla composizione del livello superficiale totale:

- contributo della marea astronomica;
- contributo della pressione atmosferica (effetto di "barometro inverso");
- contributo del vento (effetto "*wind setup*", ovvero schiacciamento della massa d'acqua verso terra in concomitanza con intensi venti provenienti dal mare).

Per la sua posizione, il mareografo non misura l'effetto dell'onda ("*wave setup*") che, su costa aperta e in bassi fondali, laddove si verifica il frangimento, può ulteriormente contribuire ad innalzare (localmente) la superficie marina.

La statistica dei livelli per assegnato tempo di ritorno è stata impostata sui 100 valori più elevati registrati dal mareografo nel periodo di dati a disposizione, ed ha fornito i valori riportati in Tabella 3-2.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

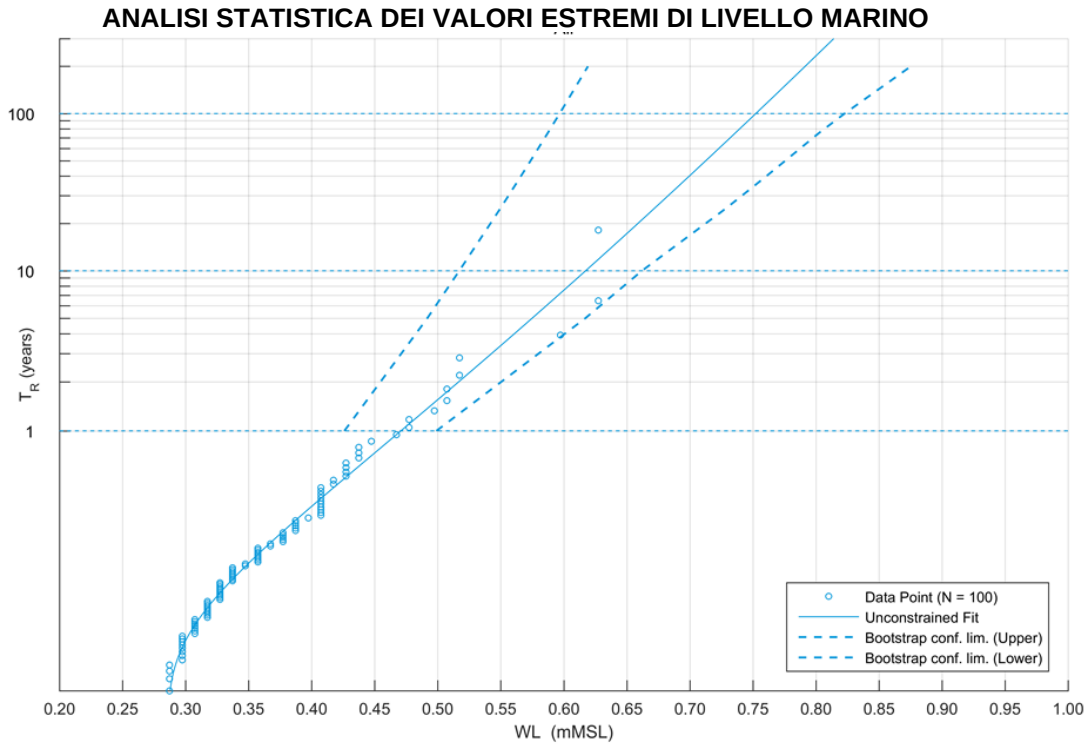


Figura 3-4 Distribuzione statistica di Weibull a due parametri per il campione di dati relativi ai livelli marini registrati dal mareografo di Genova (2000-2019)

Tabella 3-2 Valori di livello marino WL [m] per diversi periodi di ritorno TR, risultanti dall'analisi statistica

Livello marino	**TR 1 anno**	**TR 20 anni**	**TR 50 anni**
	WL [m]	**WL [m]**	**WL [m]**
Mareografo Genova	0.47	0.66	0.71

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

4 Propagazione degli eventi estremi dal largo a costa

Al fine di definire le condizioni di onda più cautelative per la progettazione dell'opera di difesa e di protezione dall'azione continua del moto ondoso al piede della falesia di Capolungo, in accordo con i progettisti dell'intervento, sono stati propagati gli eventi estremi caratterizzati da tempi di ritorno pari a 20 e 50 anni. A completamento del quadro informativo sul sito sono state riprodotte anche le mareggiate con TR pari a 1 anno, a rappresentazione di eventi intensi ma caratterizzati da frequenza maggiore.

Per propagare le mareggiate dal largo verso costa è stato implementato il codice di calcolo MIKE 21 SW - Spectral Waves di DHI, un modello spettrale per vento ed onde di terza generazione, basato su una griglia non strutturata in grado di simulare la trasformazione di onde generate dal vento ed onde di *swell* sia offshore, sia in aree costiere.

Tale modello, a maglia triangolare "flessibile", permette di utilizzare una risoluzione spaziale variabile, consentendo di impiegare una risoluzione elevata nelle aree per le quali si richiede un maggior dettaglio, laddove rifrazione, *shoaling*, attrito con il fondo e frangimento determinano una forte trasformazione delle caratteristiche dell'onda incidente su distanze relativamente limitate.

I fenomeni fisici che sono modellati con MIKE 21 SW sono i seguenti:

- generazione dell'onda ad opera del vento;
- interazione non lineare onda-onda;
- dissipazione dovuta al cosiddetto "*white capping";*
- dissipazione dovuta all'attrito con il fondo;
- dissipazione dovuta al frangimento;
- rifrazione e *shoaling* dovuti alle variazioni del fondale;
- interazione onde-correnti;
- diffrazione;
- riflessione.

Un'accurata descrizione del modulo MIKE 21 SW è riportata nell'Allegato B al presente elaborato.

I dati di input da inserire nel modello possono essere raggruppati in differenti categorie, ovvero:

- parametri di base (es. mesh di calcolo, durata della simulazione);
- tipo di formulazione, discretizzazione nel dominio delle frequenze e delle direzioni, tecniche di soluzione;
- forzanti (livelli, vento, correnti);
- parametri di dissipazione (frangimento, *white-capping*, attrito al fondo);
- condizioni iniziali (stato di mare iniziale);
- condizioni al contorno (onde al largo o alternativamente contorno chiuso).

I risultati ottenuti, per ognuno degli elementi della *mesh*, sono costituiti essenzialmente dai parametri caratteristici dell'onda: altezza d'onda significativa, periodo, direzione media, *radiation stress*.

4.1 Condizioni d'onda associate agli eventi estremi al largo

Ai valori di altezza d'onda significativa per TR 1anno, TR 20 anni e TR 50 anni (rif. Par. 3.1 Tabella 3-1) sono stati associati i valori di periodo di picco Tp, stimati attraverso le relazioni Hs-Tp definite sulla base del campione dati MWM per ogni settore direzionale di 30°.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

A titolo esemplificativo si riporta a seguire, Figura 4-1, il grafico relativo al Settore da Ostro con la nuvola dei punti rappresentanti le condizioni Hs-Tp per la serie ultra-quarantennale di dati a disposizione per gli eventi provenienti dallo specifico settore e le relative curve di fit dei dati al 5° - 50° e 95° percentile.

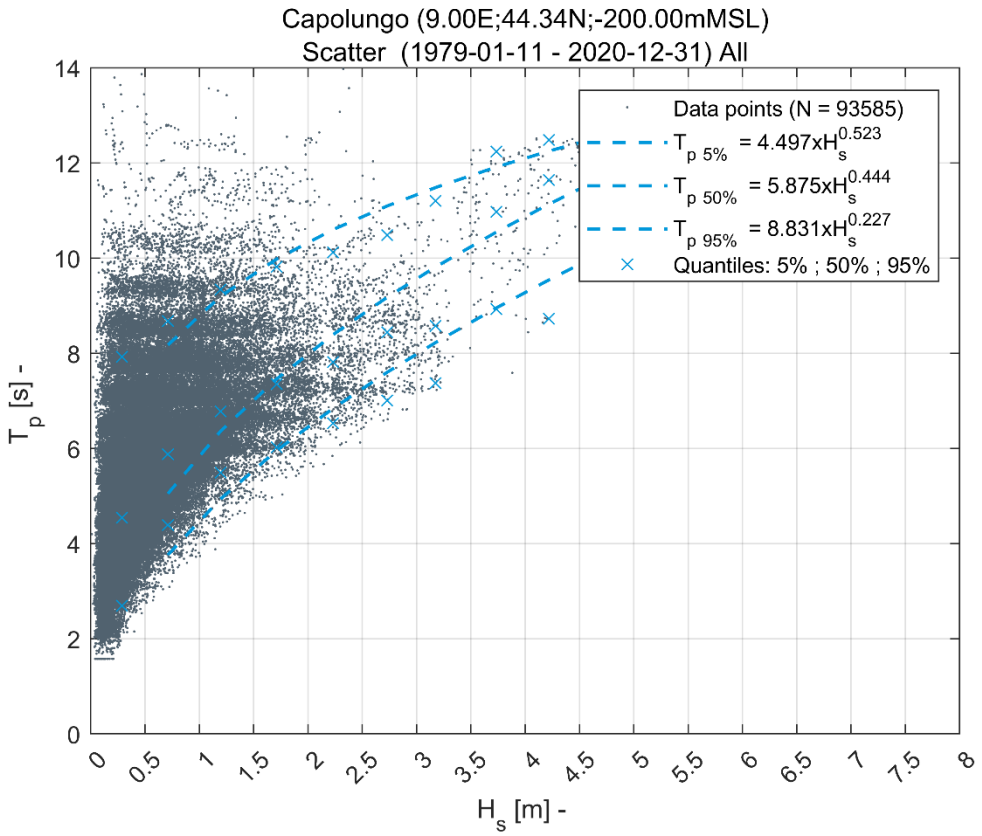


Figura 4-1 Dati di altezza d'onda significativa Hs e il periodo di picco Tp per gli eventi appartenenti al Settore da Ostro, con direzione media di provenienza MWD compresa tra 170°N e 200°N

Il Tp associato alle altezze d'onda per assegnato tempo di ritorno è stato calcolato sulla base della curva di fit al 50° percentile per le onde con TR 1 anno, mentre per le mareggiate con TR 20 e 50 anni si è adottato il fit al 95° percentile, al fine di garantire un approccio maggiormente conservativo.

Per tutti gli eventi la direzione di provenienza delle ondazioni è stata assunta pari alla direzione media del settore.

In Tabella 4-1 sono riportate le 9 mareggiate simulate con il dettaglio delle caratteristiche in termini di altezza d'onda significativa Hs, periodo di picco Tp e direzione media di propagazione MWD.

Si precisa che ad ogni evento è stato cautelativamente associato un livello del mare di riferimento pari al valore definito sulla base dei dati registrati dal mareografo di Genova e con pari tempo di ritorno (par. Tabella 3-2, ovvero 0.47 m per TR 1 anno, 0.66 m per TR 20 anni e 0.71 m per TR 50 anni).

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Tabella 4-1 Elenco delle condizioni d'onda estreme selezionate per il modello 2D di dettaglio (onda e conseguente circolazione locale)

ID onda	TR [anni]	Hs [m]	Tp [s]	MWD [°]
1	1	2.7	9.0	155
2	1	3.2	9.8	185
3	1	4.8	11.5	215
4	20	4.5	12.6	155
5	20	5.5	13.0	185
6	20	6.6	13.4	215
7	50	5.1	12.9	155
8	50	6.1	13.3	185
9	50	7.1	13.6	215

4.2 Batimetria e dominio di calcolo

Sulla base dei dati disponibili, descritti alla sezione 2.3, è stata predisposta una batimetria di calcolo a maglia triangolare che copre un tratto di costa caratterizzato da uno sviluppo complessivo di circa 18 km, da Quarto (Comune di Genova) a Ponente sino a Punta Chiappa (Comune di Camogli) a Levante, e un'estensione verso il largo di circa 7.5 km. Includere una porzione del promontorio di Portofino è risultato necessario al fine di considerare l'eventuale effetto schermante per il tratto di costa in esame esercitato dal promontorio per mareggiate provenienti dalle direzioni più oblique del secondo quadrante.

La dimensione e la risoluzione del dominio di calcolo sono state individuate al fine di rappresentare al meglio tutti i fenomeni che intervengono nella propagazione dell'onda da largo verso costa, ottimizzando al contempo i tempi di calcolo.

Per la caratterizzazione batimetrica dell'area oggetto di studio, come anticipato, si è fatto riferimento al database di carte nautiche digitalizzate CM-93 di CMAP e al rilievo batimetrico di dettaglio effettuato da Drafinsub nel mese di Giugno 2022. Il risultato finale del processamento dei dati batimetrici a disposizione è mostrato nelle immagini a seguire, in cui sono rappresentate l'estensione del modello e la batimetria di calcolo.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

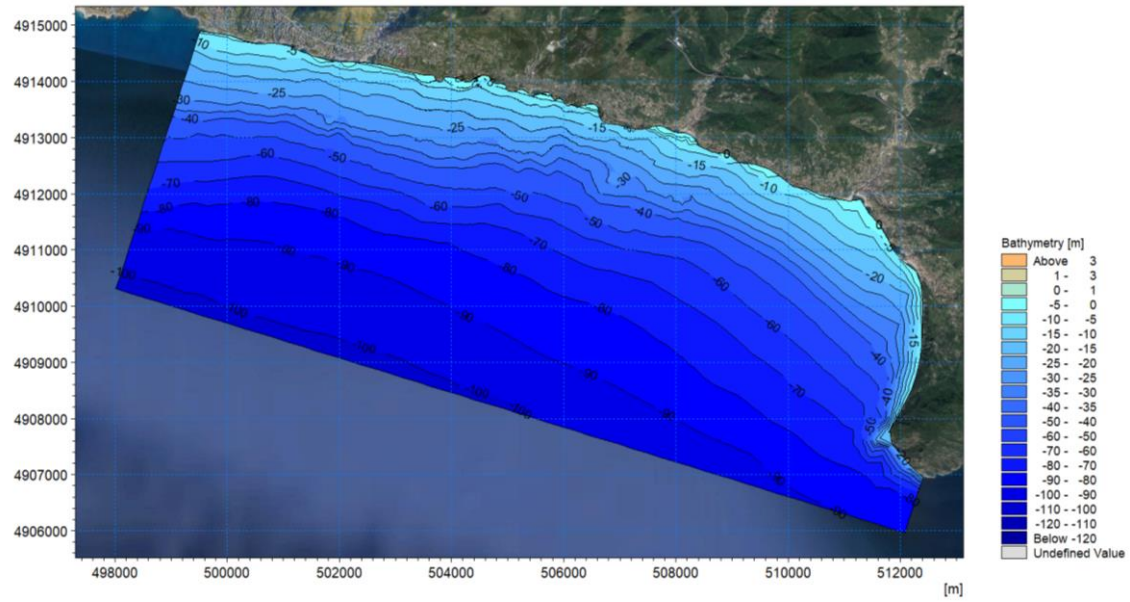


Figura 4-2 Batimetria ottenuta dal processamento dei dati a disposizione

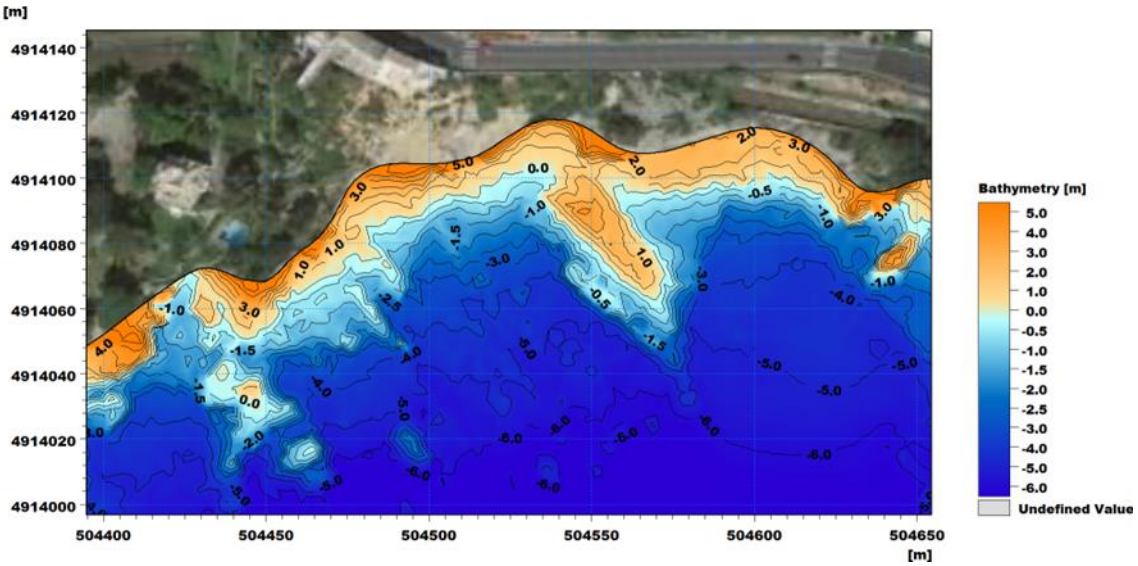


Figura 4-3 Dettaglio della batimetria sull'area limitrofa la falesia oggetto dell'analisi a Capolungo (GE)

La batimetria del modello è stata costruita utilizzando un approccio a maglia flessibile: la risoluzione spaziale al largo (lunghezza media dei lati dei triangoli) è di circa 270 m, per aumentare progressivamente a 90 m e 30 m, sino a 10 m in prossimità della costa e 3 m nell'area limitrofa alla falesia di Capolungo (Figura 4-4).

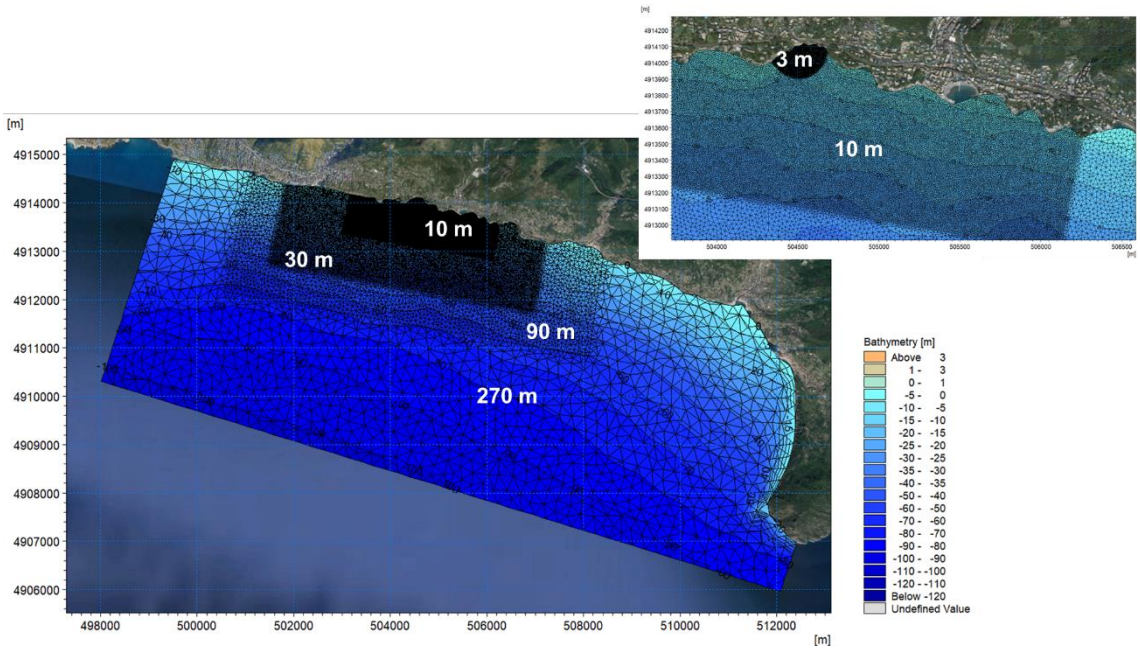


Figura 4-4 Rappresentazione della differente risoluzione spaziale della mesh di calcolo utilizzata nel modello di propagazione del moto ondoso con, in alto a destra, dettaglio sull'area di interesse

Complessivamente, la *mesh* di calcolo è costituita da circa 103.000 elementi.

4.3 Risultati del modello d'onda

Le simulazioni hanno permesso di ottenere la distribuzione delle principali grandezze di moto ondoso (altezza d'onda significativa, periodo medio e di picco e direzione media di propagazione) in tutti i punti del dominio di calcolo, rendendo pertanto possibile estrarre la serie di moto ondoso in qualsiasi punto sottocosta.

In queste mappe la scala cromatica e la lunghezza dei vettori, proporzionale in ogni punto all'altezza d'onda, e con direzione coincidente con la direzione media di propagazione, mostrano in maniera efficace le trasformazioni che l'onda subisce nella sua propagazione da largo verso costa.

Al largo i risultati del modello d'onda mostrano una distribuzione delle altezze d'onda piuttosto regolare con l'andamento dei fondali: le pendenze elevate determinano infatti ben poche dissipazioni dell'energia ondosa con l'avvicinarsi alla costa, mentre intorno all'isobata -25 m, la presenza di alcuni pianori influenza l'abbattimento dell'energia ondosa diretta verso costa.

Il tratto di costa in esame risulta caratterizzato da un settore di traversia abbastanza ampio, compreso tra 130°N e 270°N, quindi completamente esposto alle mareggiate da Libeccio e Mezzogiorno.

A seguire si riportano alcuni esempi di mappe di distribuzione dell'altezza d'onda per la mareggiata n°9, proveniente da Libeccio, e con associato tempo di ritorno pari a 50 anni.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

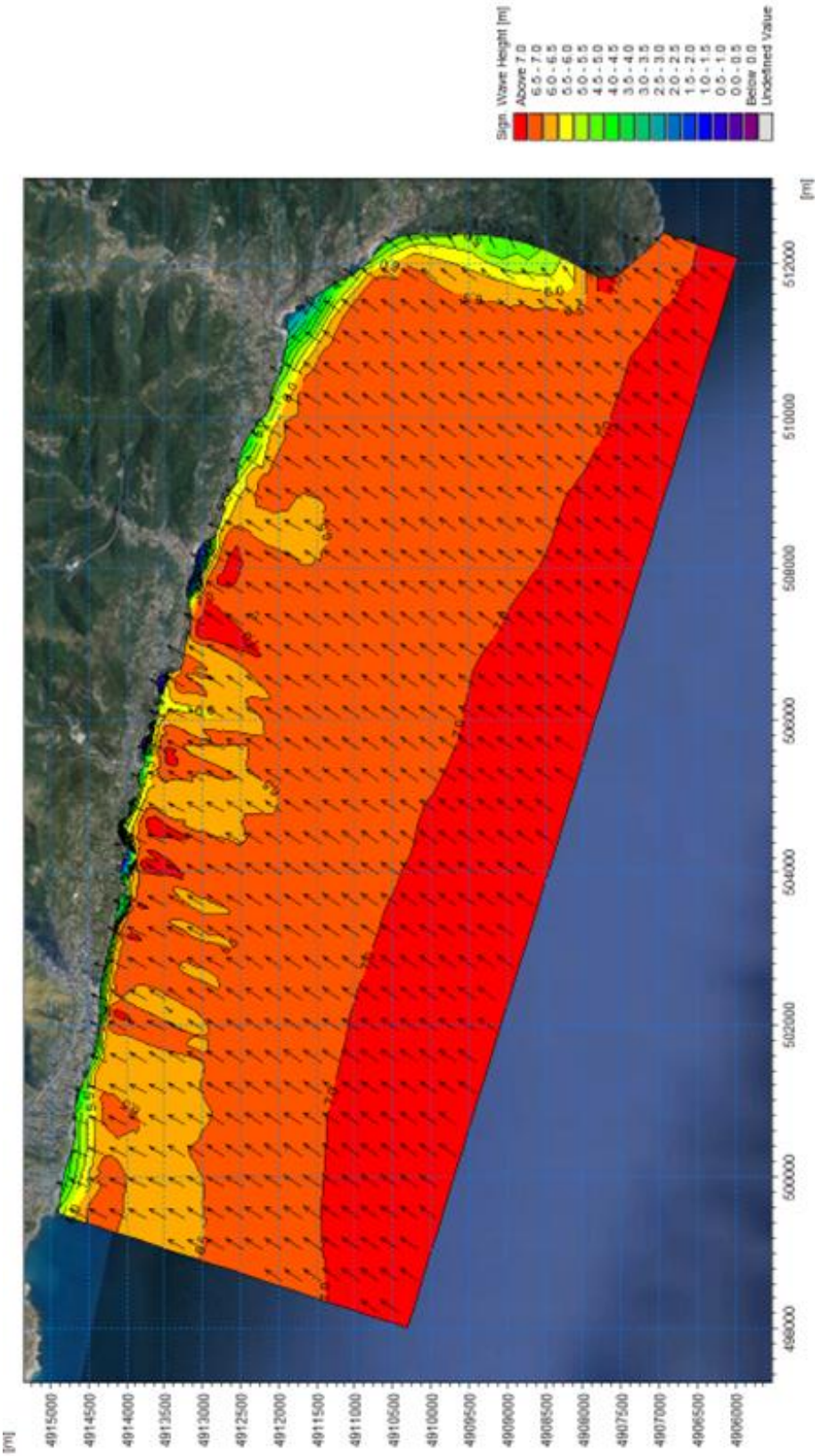


Figura 4-5 Distribuzione dell'altezza d'onda significativa nel dominio di calcolo per l'onda 9 da Libeccio con associato tempo di ritorno pari a 50 anni (Hs=7.1m, Tp= 13.6 s, MWD= 215°N)

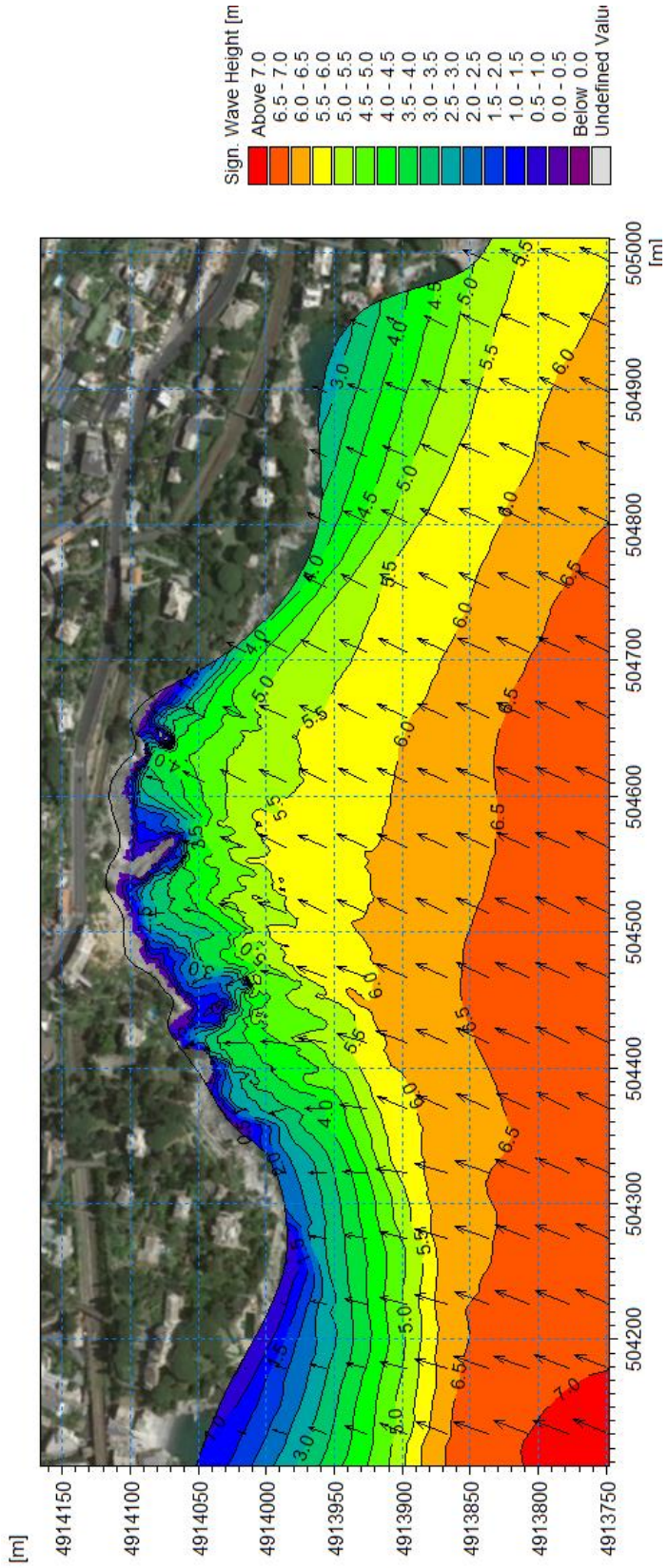


Figura 4-6 Dettaglio sulla zona di interesse della distribuzione dell'altezza d'onda significativa l'onda 9 da Libeccio con associato tempo di ritorno pari a 50 anni (Hs=7.1m, Tp= 13.6 s, MWD= 215°N)

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Per supportare la progettazione degli interventi si è proceduto con l'estrazione della serie di altezza d'onda significativa per gli eventi estremi selezionati in 6 punti sottocosta, denominati con le lettere dalla A alla F, scelti sulla base delle indicazioni ricevute dai progettisti incaricati per la definizione dell'intervento. Tali punti sono ad una distanza variabile tra 30 e 90 m dalla costa e sono ubicati a profondità comprese tra i 4.0 e i 6.5 m (Figura 4-7 e anagrafica in Tabella 4-2).

Tabella 4-2 Coordinate dei punti di estrazione del moto ondoso sottocosta

ID punto	X[m]	Y[m]
A	504504	4914057
B	504536	4914071
C	504482	4914027
D	504512	4914040
E	504542	4914057
F	504560	4914010

L'ubicazione dei punti è riportata in Figura 4-7, mentre le caratteristiche di onda estratte per i 9 eventi di riferimento sono dettagliate in Tabella 4-3.

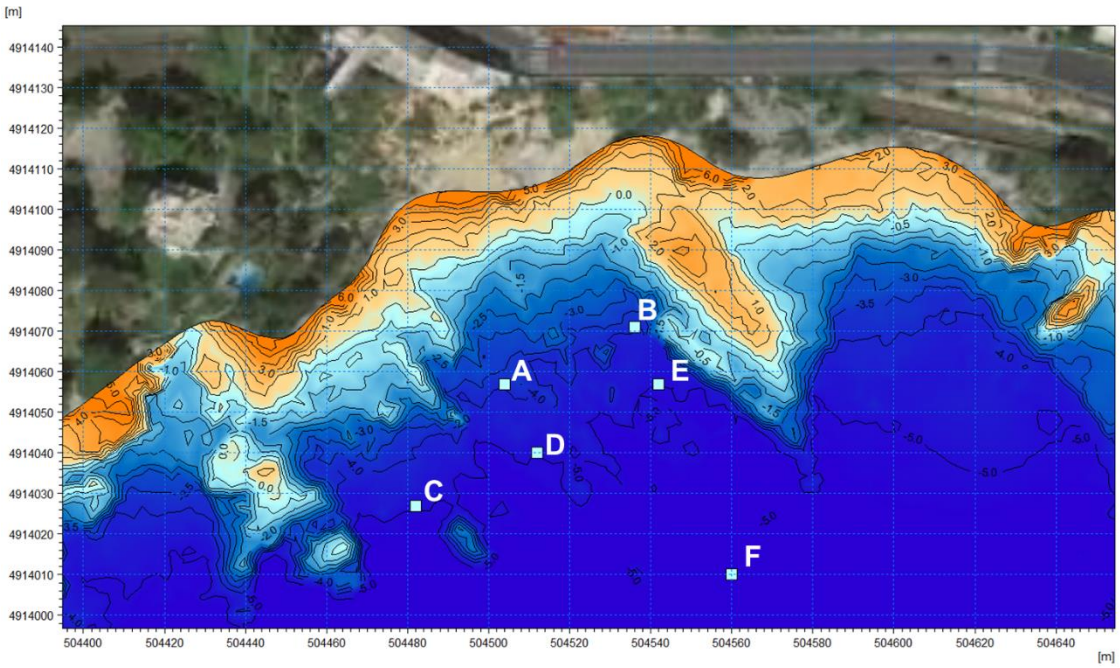


Figura 4-7 Ubicazione dei punti di estrazione delle condizioni di onda a supporto della progettazione dell'intervento

Tabella 4-3 Caratteristiche d'onda per gli eventi estremi con TR pari a 1, 20 e 50 anni, estratte nei punti A, B, C, D, E ed F

			A	B	C	D	E	F
TR 1 anno	Onda 1	Hs[m]	2.43	2.24	2.39	2.41	2.32	2.20
		Tp[s]	8.7	8.7	8.8	8.8	8.7	8.8
		MWD[°]	170.0	173.3	161.8	170.9	170.4	169.8
	Onda 2	Hs[m]	2.73	2.83	3.08	3.09	2.90	3.08
		Tp[s]	9.5	9.5	9.5	9.5	9.5	9.6
		MWD[°]	180.1	183.3	175.1	184.7	183.8	189.0
	Onda 3	Hs[m]	2.90	3.14	3.48	3.40	3.32	4.16
		Tp[s]	11.0	11.0	11.1	11.0	11.0	11.1
		MWD[°]	186.3	189.2	182.6	192.9	193.0	204.6
TR 20 anni	Onda 4	Hs[m]	3.55	3.33	3.86	3.82	3.56	3.74
		Tp[s]	12.1	12.0	12.1	12.1	12.1	12.2
		MWD[°]	172.2	174.8	165.8	173.7	173.1	174.4
	Onda 5	Hs[m]	3.66	3.71	4.53	4.36	3.97	5.03
		Tp[s]	12.4	12.3	12.5	12.4	12.4	12.5
		MWD[°]	179.6	182.4	176.7	183.6	183.2	189.1
	Onda 6	Hs[m]	3.35	3.58	4.19	3.98	3.81	5.02
		Tp[s]	12.7	12.7	12.8	12.7	12.7	12.8
		MWD[°]	185.5	188.4	182.8	191.5	191.9	203.1
TR 50 anni	Onda 7	Hs[m]	3.76	3.53	4.17	4.12	3.81	4.18
		Tp[s]	12.3	12.3	12.4	12.4	12.3	12.4
		MWD[°]	172.2	174.7	166.6	173.7	173.2	174.7
	Onda 8	Hs[m]	**3.76**	**3.81**	**4.68**	**4.49**	**4.08**	**5.24**
		Tp[s]	**12.6**	**12.6**	**12.7**	**12.7**	**12.7**	**12.8**
		MWD[°]	**179.6**	**182.4**	**176.9**	**183.5**	**183.2**	**189.2**
	Onda 9	Hs[m]	3.42	3.64	4.28	4.06	3.88	5.12
		Tp[s]	12.9	12.8	13.0	12.9	12.9	13.0
		MWD[°]	185.5	188.5	182.8	191.5	191.9	203.0

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

5 Sintesi e conclusioni

Il presente studio ha avuto come obiettivo la definizione delle condizioni di onda sottocosta necessarie per la progettazione degli interventi di difesa dall'azione erosiva del mare della falesia di Capolungo (Genova). Tali interventi si rendono necessari per la definitiva messa in sicurezza del sito interessato nel 2014 da una frana di notevoli dimensioni e causa di molteplici problemi strutturali per edifici e linea ferroviaria.

Le attività modellistiche sono state predisposte in stretta collaborazione e a supporto dei tecnici di InGEpro Ingegneri Associati, incaricati della redazione del progetto dell'intervento di difesa costiera.

Mediante l'utilizzo del database di ricostruzione delle condizioni di vento e onda nel Mar Mediterraneo (MWM - Mediterranean Wind Wave Model) è stato caratterizzato il clima ondoso al largo. Sulla base della serie di dati a disposizione è stata predisposta l'analisi degli eventi estremi direzionale, per settori di ampiezza pari a 30°.

In accordo con il gruppo di progettisti sono state selezionate e propagate 9 onde, caratterizzate da altezze d'onda con associato tempo di ritorno pari a 1, 20 e 50 anni. Si precisa che ad ogni evento è stato cautelativamente associato un livello del mare di riferimento pari al valore definito sulla base dei dati registrati dal mareografo di Genova e con pari tempo di ritorno.

Per ogni mareggiata simulata sono state estratte le condizioni di onda sottocosta, in 6 punti, ubicati a differente distanza e profondità dalla base della falesia in oggetto, che forniscono la base informativa sul moto ondoso a supporto della fase progettuale.

L'onda che arriva a costa con altezza maggiore è la 8, con associato tempo di ritorno pari a 50 anni proveniente da Ostro.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

ALLEGATI

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

ALLEGATO A–Mediterranean Wind Wave Model

Descrizione Tecnica

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

General description of the models' chain

The models and datasets used for the development of the MWM database are:

- the *CFSR* (*Climate Forecast System Reanalysis*) global re-analysis dataset, produced and freely published by NCEP (*National Centers for Environmental Prediction*) (Saha et al, 2010; http://rda.ucar.edu/datasets/ds093.0/index.html#description), hourly (re-forecast) data with a space resolution of 0.5°; these data are used as initial (IC) and boundary conditions (BC) of the *WRF-ARW model* (below);

- the atmospheric model *WRF-ARW – version 3.4.1* (*Weather Research and Forecast - Advanced Research WRF*), model developed by NCAR (*National Center for Atmospheric Research*) (Skamarock and Klemp, 2007; Michalakes et al, 2001; Michalakes et al, 2005); *WRF-ARW* is presently considered among the best state-of-the-art non-hydrostatic meteorological models; it is supported by a massive worldwide community that contributes to its local use and development (http://www.mmm.ucar.edu/wrf/OnLineTutorial/index.htm; http://www.wrf-model.org/index.php);

- the wave model MIKE 21 Spectral Waves (SW) developed by DHI (former Danish Hydraulic Institute) (Sorensen, O.R., Kofoed-Hansen, H., Rugbjerg, M. and Sorensen, L.S., 2004). MIKE 21 SW is among the state of the art wave models, widely used in thousands of offshore and coastal applications worldwide.

In the following a description of the CFSR dataset, the WRF-ARW and the MIKE 21 SW model is given, with specific interest to the implementation adopted in MWM.

CFSR Dataset

The CFSR dataset (Fig. A.1) is the result of a long and complex process performed by NCEP, an ensemble of nine weather prediction centers in the United States belonging to the NWS (*National Weather Service*) of the NOAA (*National Oceanic and Atmospheric Administration*). The simulation, completed in 2011, is based on a global atmospheric numerical model including atmosphere-ocean and sea-ice couplings, with a systematic ingestion of both conventional (point) and satellite observations with data assimilation procedures.

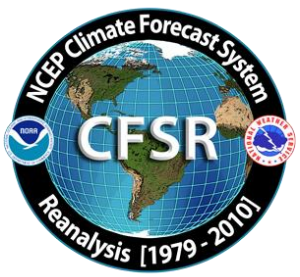


Figure A.1

The CFSR now covers a 35-year period from 1979 to 2013 (included) and is continuously updated with new recent data. The simulations were performed as 9 hours forecast simulations, initialized 4 times a day (at 00:00, 06:00, 12:00 and 18:00) between the 6-hourly re-analysis frames. The

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

results of these simulations, gathered in the CFSR dataset, consist in complete atmospheric data over ocean and lands with a one hour time resolution and a 0.5° horizontal resolution, while the vertical resolution changes greatly amongst the atmospheric variables, spanning from the single surface value up to values at 64 different isobaric levels.

MWM dataset ingest the 6-hourly CFSR data, specifically the *ds093.0* dataset.

Chawla et al (2013) presented a thorough analysis of the *CFSR* dataset against satellite and oceanic buoys data. The final goal of that study is the use of the U_{10} wind data from the *CFSR* dataset as the forcing term of *WWIII* to generate wave fields at global scale, without any assimilation of wave data. The analysis of the *CFSR* dataset shown in that paper includes the intrinsic performance of the model in terms of the seasonal and annual variability of the percentiles. A moving average is applied to smooth the altimeter data from the satellites and from the buoys. The normalized percentiles ("...normalized with the wind speeds at corresponding percentiles from the altimeters") computed over the satellite tracks exhibit an oscillatory behavior, never below 0.93 or 0.90 in the Northern and Southern hemisphere respectively. From that analysis, the wind and wave *CFSR* and *WWIII* data compare very well with satellite data in terms of normalized percentiles. The Q-Q plots at selected offshore buoys are generally good or very good, with some unexpected variations from case to case for some buoys close to the coast, with even a contradictory behavior between U_{10} and H_s in some locations.

The analysis of the wind field of the *CFSR* dataset is far beyond the scope of the present work but still some checks have been done in specific cases, like the event of November 1999 in Trieste (Italy). The performance of a local area model is directly related to the information contained in the global model used as boundary and initial conditions; Fig. A.2 after Contento et al (2014) shows the wind speed for the case of November 1999 in Trieste (Northern Adriatic Sea - Italy); the red dots are experimental data by NOAA (http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=hourly&layers=1&node=gis); the yellow line corresponds to the re-analysis data *CFSR d093.0* (Saha et al, 2010; http://rda.ucar.edu/datasets/ds093.0/index.html#description) interpolated at the same position of the station; the blue dots are related to a fully certified and verified measurement station of the Regional Agency for the Environment Protection (ARPA FVG-OSMER, http://www.osmer.fvg.it/home.php) located few meters far from the station used by NOAA (http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=hourly&layers=1&node=gis); the cyan line corresponds to the present hindcast dataset (model *WRF-ARW*). It is rather evident that the CFSR dataset ingests the experimental data from NOAA but there are some non-negligible discrepancies between the two experimental datasets (private communication with ARPA FVG-OSMER - Regional Agency for the Environment Protection – Friuli Venezia Giulia Region, Italy). In this case the local model *WRF-ARW* is able to develop the local wind field and matches correctly the measurement by ARPA, irrespective of the wrong assimilated data as BC and IC; this, however, cannot be always guaranteed.

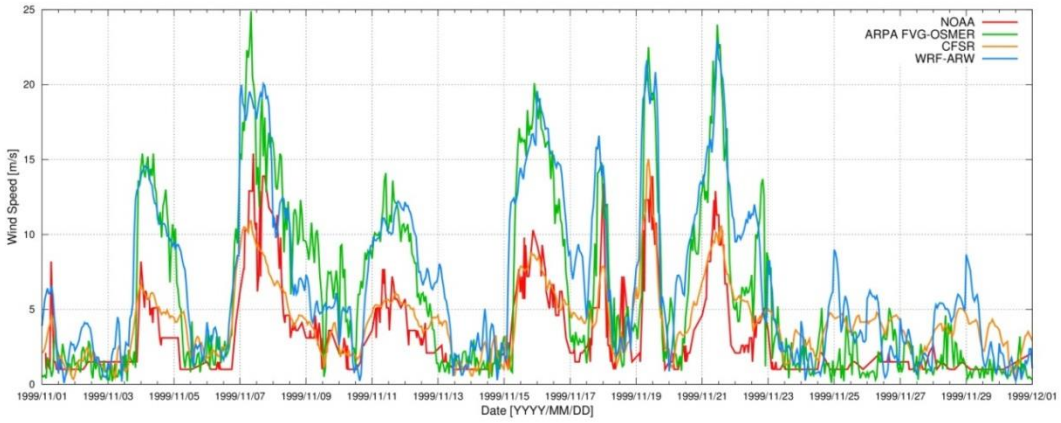


Figure A.2 Comparison between measured wind speed at two ground neighbor (few meters from each other) stations in Trieste (Italy - Northern Adriatic Sea) from the database of NOAA

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

(http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=hourly&layers=1&node=gis) (red line) and from ARPA-FVG OSMER (http://www.osmer.fvg.it/home.php) (blue line). Model data from *CFSR* (Saha et al, 2010) (yellow line) and the present simulations with *WRF-ARW* (cyan line) are overlapped.

The scope of these checks was solely to verify the sensitivity of the *CFSR* wind pattern to a complex steep geographic area facing the sea. The eastern coast of the Adriatic Sea is just an example among many others. The availability of certified wind data from the local Regional Agency for the Environment Protection – Friuli Venezia Giulia (ARPA FVG-OSMER, http://www.osmer.fvg.it/home.php) related to ground stations and to a fixed station in the middle of the Gulf of Trieste (Northern Adriatic Sea *http://www.ts.ismar.cnr.it/node/84*]), helped a lot in defining the set-up of the local area meteorological model. The aim of the set-up process was to let the model *WRF-ARW* develop mesoscale and local weather structures, thus using a domain large enough to develop these structures, but at the same time avoiding the use of too large a domain that may lead to a model drift from the experimental data. These undesired effects were observed along the entire Adriatic Sea, specifically on the eastern side (Contento et al, 2011; Contento et al, 2014).

WRF-ARW meteorological model

The WRF model is an open source mesoscale to microscale atmospheric model developed by the American atmospheric research center NCAR in cooperation with many other meteorological institutions. It is largely used worldwide for both atmospheric research and forecast or hindcast purposes due to its ability to perform atmospheric simulations over a wide range of length scales spanning from less then 1 kilometer to thousands of kilometers. This flexibility is further increased by its capability of performing two way coupled nested runs.

The WRF modelling system includes a pre-processor system (WPS), a data assimilation system (WRF-DA) and the dynamic solver. During this work the ARW dynamic solver, developed and maintained by the Mesoscale and Microscale Meteorology Division of NCAR, has been used. The ARW dynamic core is a fully compressible and non-hydrostatic model, based on a terrain-following hydrostatic pressure vertical coordinate system and on an Arakawa C-grid staggered evaluation of the vector quantities. The solver uses high order time integration and 3-D advection schemes.

The WRF model works internally with NetCDF files, a self-describing and machine-independent data format particularly suitable for the manipulation of long arrays of scientific data.

A WRF-ARW model run is a quite complex process, since it involves several different steps to be run in a precise order. First of all, WRF requires boundary and initial conditions; these conditions can be supplied by the GRIB files obtained from the CFSR dataset files described in CISL RDA: NCEP Climate Forecast System Re-analysis (CFSR) 6-hourly Products, January 1979 to December 2010." [Online] Available at http://rda.ucar.edu/datasets/ds093.0/index.html#description

GRIB files needed to cover completely the whole simulated period must be fed to the model to complete the simulation process successfully.

Moreover, since the atmosphere behaviour is strongly dependent on the soil characteristics, detailed data about these characteristics must be fed to the model too in order to let it develop the local weather phenomena correctly. However, there is no need to produce this type of data since suitable 30" resolved geographic data are included in the default WRF pre-processing (WPS). Since these data are time-independent they need to be downloaded only once, and they remain valid for every simulation unlike the GRIB files. Actually, some of the parameters contained in the geographic data cannot be considered as completely time-independent; in fact, some of the parameters show a time dependence which, however, is limited to seasonal changes, e.g. the

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

reduced vegetation cover in winter. The possible seasonal variability of the geographical parameters is included in the geographical data archive of WPS.

A complete WRF-ARW simulation needs the WPS (*WRF Pre-processor System*) to be run before the numerical solver (*wrf.exe*). The WPS pre-processor system deals with both the domain set-up and the preliminary input manipulations; it is composed by three main executables carrying out different tasks:

- *geogrid.exe* is responsible for the definition of the horizontal grid as well as for the interpolation of the geographic data on the user-defined grid. When performing nested runs, the *geogrid.exe* run produces a NetCDF file *geo_em.dxx.nc* containing the grid and geographic data for each domain, where xx stands for the code of the domain (01, 02, …).

- *ungrib.exe* is responsible for the decoding of the input GRIB files used as initial and boundary conditions. The GRIB files, which need to be linked to the work directory of WPS by means of the script *link_grib.csh*, are "ungribbed" and rewritten in an intermediate format suitable for further manipulations, excluding all the fields not needed for the following model run.

- *metgrid.exe* is responsible for the horizontal interpolation of the intermediate input files produced by ungrib.exe on the grid defined by geogrid.exe. Moreover, the geographic data contained in the *geo_em* files are ingested by metgrid and written on its output files. The output of metgrid.exe is in fact composed by the NetCDF files *met_em.dxx.YYYY-MM-DD_HH:00:00.nc*, each containing the interpolated boundary conditions and geographic data for the xx domain and for every timestep of the supplied GRIB files. In the case considered, as the CFSR dataset is composed of hourly data, the produced *met_em* files are hourly spaced too.

The whole WPS process is controlled by a single external configuration file: *namelist.wps*, which contains the user specified parameters defining the time length and the domain of the simulation as well as the time and space resolutions.

An additional manipulation is needed before launching the actual solver: the NetCDF data produced by metgrid.exe must be vertically interpolated onto the user- defined vertical levels of the WRF simulation. This task is performed by the *real.exe* executable, which, despite actually being a pre-processing routine, is not included in the WPS system. The real.exe run finally produces the NetCDF files needed by the bare solver: *wrfinput_dxx* and *wrfbdy_dxx*, containing respectively, for each of the nested domains under simulation, the initial condition inclusive of the domain geographic data and the boundary conditions forcing the domain over time.

The last step of a WRF-ARW model simulation is the *wrf.exe* solver run which performs the numerical integration and produces the final output files *wrfout_dxx_YYYY-MM-DD_HH:MN:SS,* one for each simulated domain and for every temporal frame in the total simulated period. Each wrfout file contains therefore the complete atmospheric variables set calculated by the ARW solver for every point of the user defined simulation 3-D grid at a single temporal frame.

Both real.exe and wrf.exe are controlled by *namelist.input*, an external configuration file gathering the user defined parameters regarding the vertical resolution of the simulation, the atmosphere microphysical parameters and, again, the time / length scales and resolutions of the simulation.

A script that makes all steps involved automatic in a WRF-ARW simulation procedure, from the set-up of the configuration files to the archiving of output files, was developed and tested extensively.

The above depicted working scheme is summarized in Figure A.3:

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

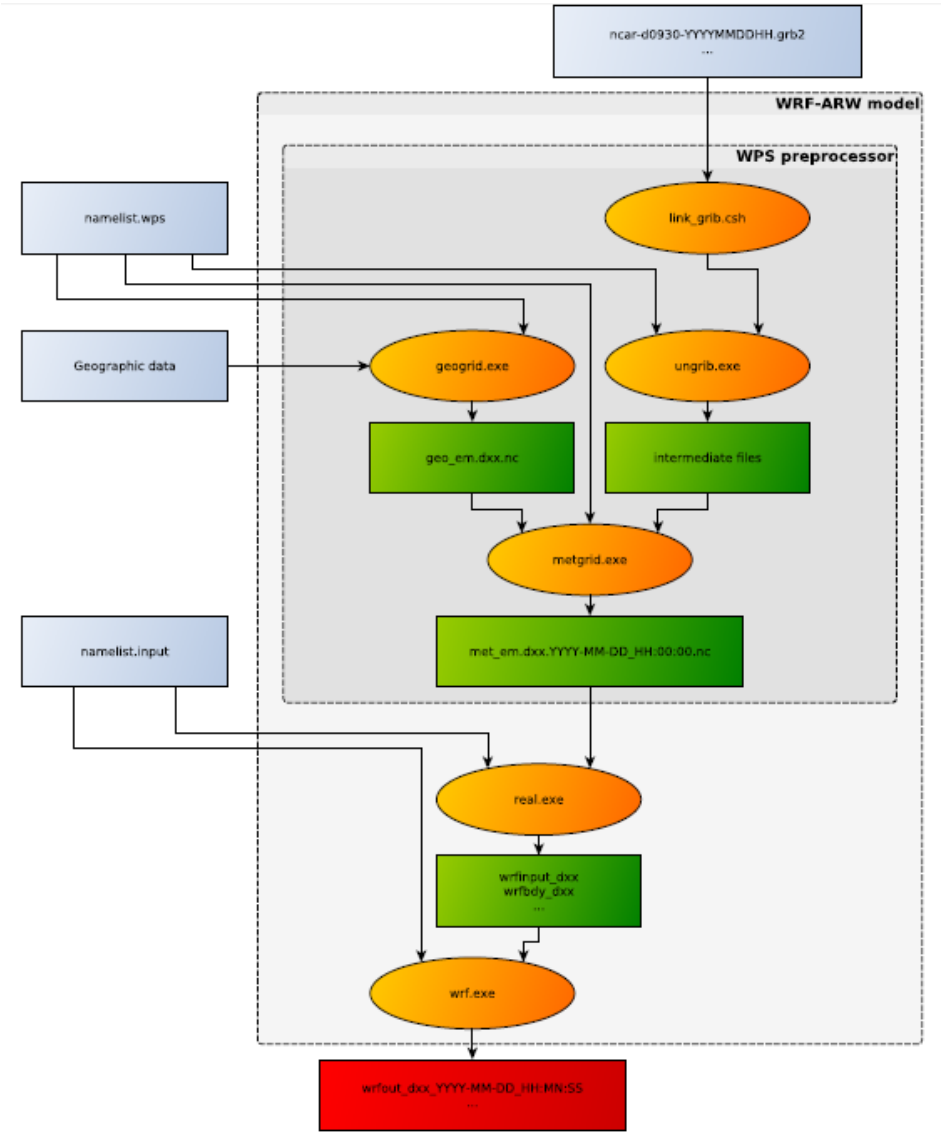


Figure A.3 Working scheme of the WRF-ARW model.

WRF-ARW domains, resolution, set-up in MWM

The preliminary set-up and tuning of the met-ocean models chain was performed simulating the month of November 1999, chosen for the remarkable number of very intense storms occurred over the Mediterranean Sea. The second step, before running the entire period 1979-2013, was done simulating one complete year, from November 1999 to October 2000, relying on 41 ground stations along the Mediterranean coast and 25 wave buoys for comparison. The results obtained in these steps are summarized in Contento et al. (2014), Contento et al. (2012-2014) and Donatini (2013).

The two-steps set-up started with the meteorological model *WRF-ARW*, adopting different configurations (domain size, resolution, run length, spin-up time) and comparing the wind speed and direction with observational data from ground stations. Since the *CFSR* (Saha et al, 2010) re-analysis dataset reproduces large scale events correctly, after several tests the final decision was to adopt three relatively small, overlapping domains, which cover respectively the Western, Eastern and Central Mediterranean Sea (Fig. A.4). Hereafter these domains will be referred as MEW, MEE and MEC respectively. The wind field obtained from the 3 domains was merged in a

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

single dataset by a bi-linear interpolation on a Lat-Lon grid and by a linear blending of the results inside the two overlapping zones (Fig. A.4).

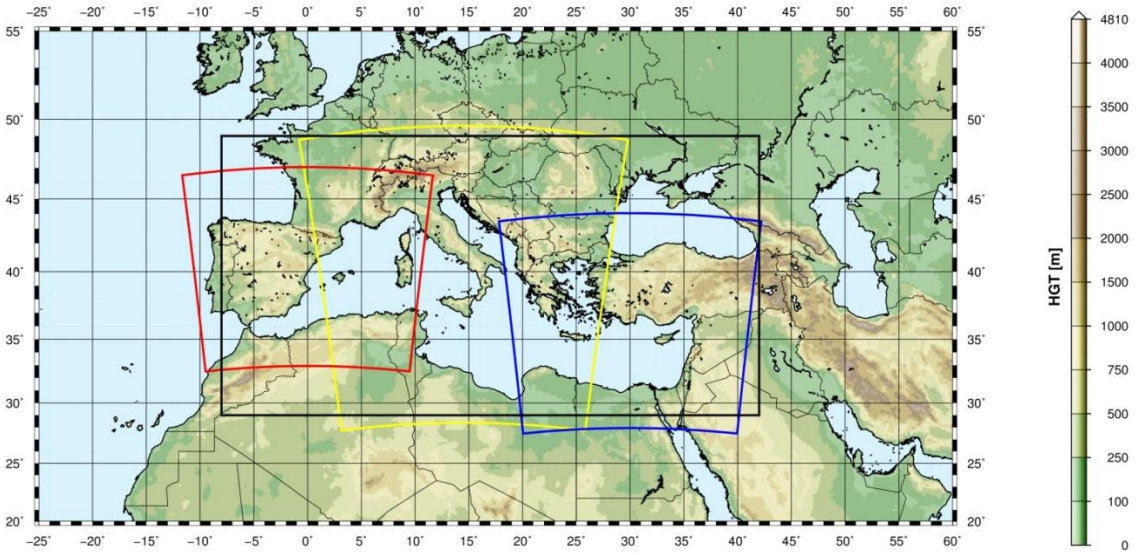


Figure A.4 WRF-ARW domains (red=domain MEW, yellow=domain MEC, blue=domain MEE) and interpolation/blending domain (black line).

The horizontal resolution of *WRF-ARW* was set to 10.53 km, with a grid ratio to the *CFSR* re-analysis data of 1:5 approximately. An additional domain (ITN) with a resolution of 3.51 km was run over Northern Italy as a nested domain of MEC.

The time length of the model run, in terms of hours simulated continuously between two consecutive model initializations with *CFSR* frames,proved to be among the most important parameters that influence the quality of the results. Keeping a small run length reduces the risk of model drift. On the other hand, shortening it excessively may lead to a too constrained behavior of the model, which prevents the correct development of the mesoscale weather structures. The problem of the model drift proved to be particularly tough over the Adriatic Sea where the orography is rather complex and the North-Eastern wind (Bora) can occasionally reach the speed of 150 km/h or more in very narrow zones.

A spin-up time window was used in order to let the model *WRF-ARW* ingest and process the coarser initial conditions from *CFSR*, thus letting it evolve and develop local weather structures. This spin-up window was overlapped with the tail of the previous run so that the data of the simulation during the spin-up window were discarded. The time length of this overlapping window is typically of few hours.

The Mediterranean Sea is a very complex basin from the meteorological point of view, with violent storms usually characterized by a short duration. The two examples given below show the importance of resolving the large space and time gradients of the variables.

Fig. A.5 shows a typical winter wind pattern (from the present simulations, 5 December 2009). The well-known 3 major narrow gates of the “Bora” wind over the Adriatic Sea are well captured by the model, i.e. Trieste (Italy), Rijeka and Sibenik (Croatia). The reference distance of these large variations is of 1° at most.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

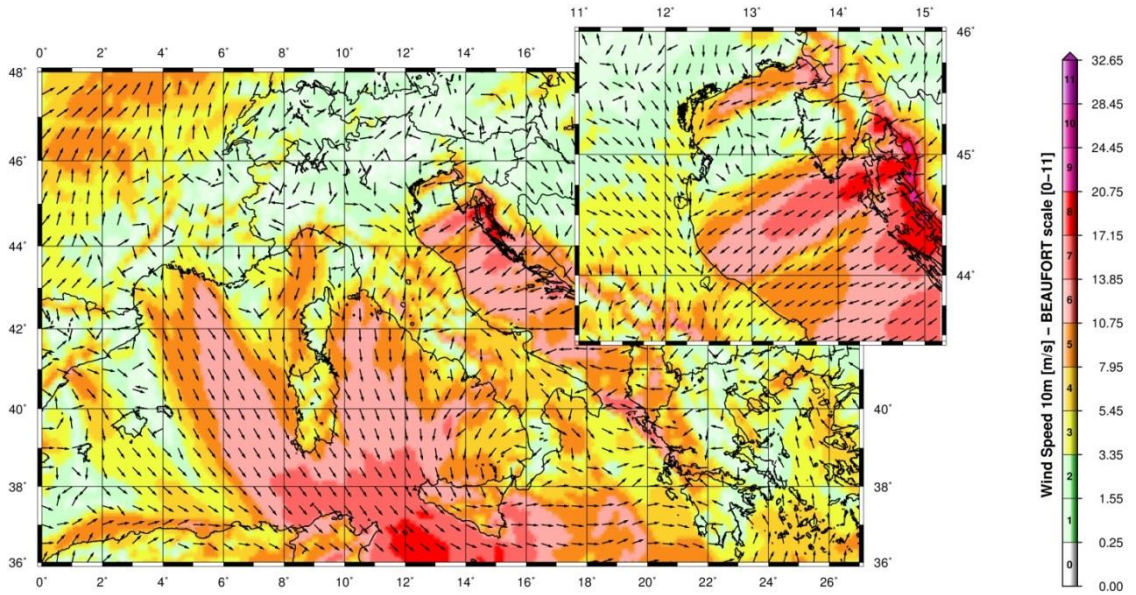


Figure A.5 A typical winter wind pattern over the Mediterranean Sea (from the present simulations, 5 December 2009). The well-known 3 major narrow gates of the "Bora" wind over the Adriatic Sea are well captured by the model, i.e. Trieste (Italy), Rijeka and Sibenik (Croatia). The upper-right figure shows a zoom over the Northern part of the Adriatic Sea (Istria peninsula).

Fig. A.6 (Contento et al., 2011) shows the time series of the wind speed during a squall event occurred on August 2008 in the Gulf of Trieste that caused the loss of two human lives and damages in the main harbor. The squall lasted about 10 min reaching more than 20 m/s from an almost calm situation. The red line corresponds to the results of the operational forecast meteorological model *WRF-ARW* run at that time by some of the authors of this work for ARPA FVG-OSMER, http://www.osmer.fvg.it/home.php. The black line corresponds to the measurement at the station PALOMA (45° 37' 06" N, 13° 33' 55" E) [*http://www.ts.ismar.cnr.it/node/84*]. The station is a fixed pole in the middle of the Gulf of Trieste. The measured wind speed is 5 min averaged with 5 min samples. The time step of the model is approximately 13 s. This situation is not uncommon in the Adriatic zone, mostly during the summer, with violent fronts from North and North-West then rotating to North-East.

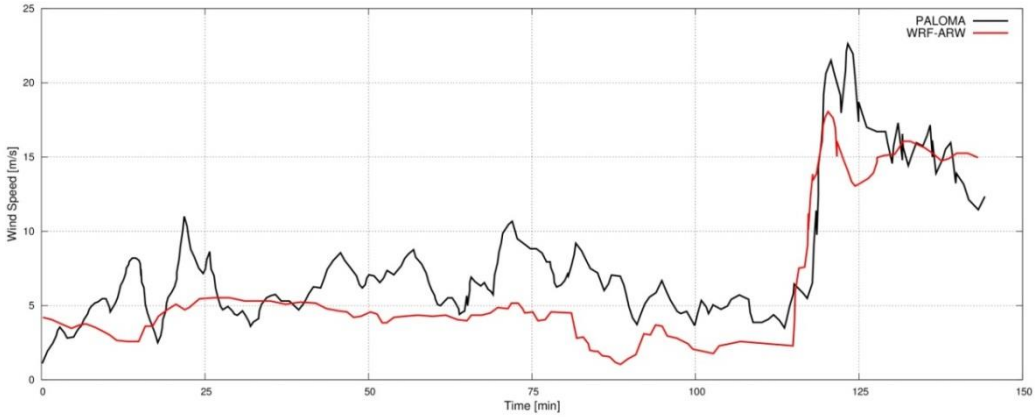


Figure A.6 Time series of the wind speed during a squall event occurred on August 2008 in the Gulf of Trieste. The squall lasts about 10 min reaching over 20 m/s from an almost calm situation. The red line corresponds to the results of the operational forecast meteorological model *WRF-ARW*. The black line corresponds to the measurement at the measurements station PALOMA (45° 37' 06" N, 13° 33' 55" E) [*http://www.ts.ismar.cnr.it/node/84*]. The measured wind speed is 5 min averaged with 5 min samples. The time step of the model is approximately 13 s.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

MIKE 21 SW wave model

The wave modeling system includes the state of the art third generation spectral wind-wave model MIKE 21 SW, developed by DHI. MIKE 21 SW simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas.

MIKE 21 SW includes two different formulations:

- Directional decoupled parametric formulation
- Fully spectral formulation

and includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction
- Effect of time-varying water depth

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multisequence explicit method is applied for the propagation of wave action.

For the production of the MWM database, the fully spectral formulation has been adopted, based on the wave action conservation equation, as described in e.g. Komen et al. and Young where the directional-frequency wave action spectrum is the dependent variable.

The time integration of the governing equations is done by using a dynamically determined time step. The time step is determined in order to verify the stability criteria (CFL number).

The only driving force is represented by the two components of wind fields U10 and V10, (x and y component of wind at the elevation of 10m). The process by which the wind transfers energy into the water body for generating waves is controlled by a uncoupled air-sea interaction.

The spectral discretization adopted in the wave model has been deeply investigated and the final configuration is able to guarantee at the same time a high level of accuracy of the results and a reasonable computational effort.

The model domain covers the whole Mediterranean Sea but the spatial resolution is not the same everywhere: while in the offshore areas the spatial resolution is around 0.1°, when approaching the coast the spatial resolution increases up to around 0.03°.

The wave model is forced by the wind fields coming from the WRF Atmospheric models, illustrated above. The wave model generated results in terms of wave parameters (Significant Wave Height, Wave Periods, Wave Directions, etc.) over the whole domain and, in addition, spectral parameters in predefined output locations have been stored, too.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

MIKE 21 SW domain, resolution, set-up in MWM

The model domain, covering the entire Mediterranean Sea, is illustrated in Figure A.7.

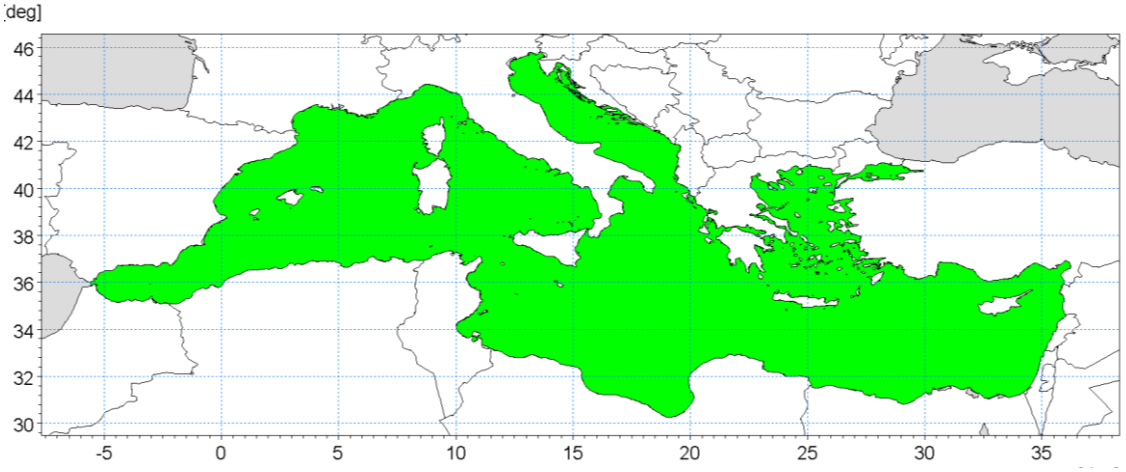


Figure A.7 Wave model domain filled in green

The unstructured mesh, generated over the entire domain by means of a specific tool included in MIKE 21 package, is characterized by different resolutions (in terms of mean length of triangle sides) over the domain. In particular the following criteria have been adopted:

- a coarser resolution of 0.1° (about 10 Km) is used for offshore areas;
- a finer resolution of 0.03° (about 3 Km) has been adopted in shallow water areas, where bathymetry is less than 100m depth or, in coastal areas characterized by very steep profiles, where the distance from the coastline is less than 5÷10 Km.

Figure A.8 illustrates the computational mesh of the Mediterranean wave model.

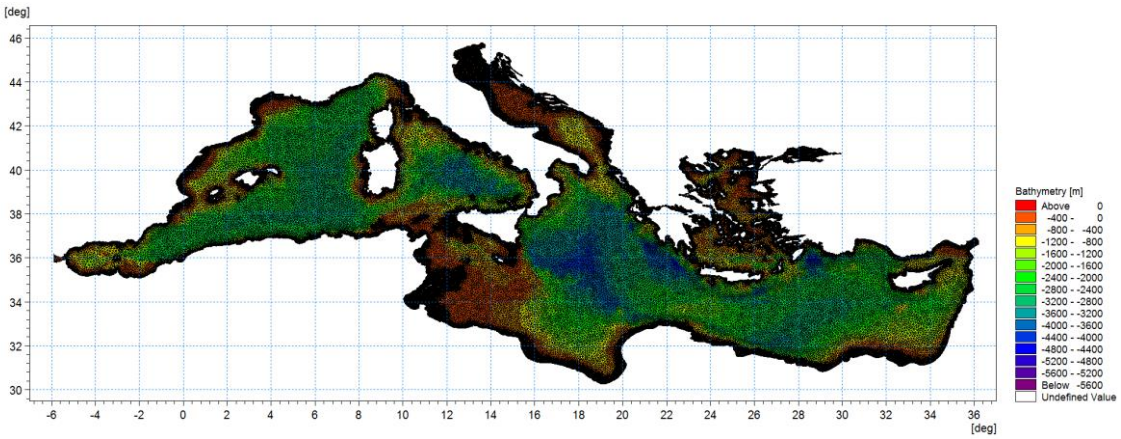


Figure A.8 - Mediterranean wave model computational mesh

Figure A.9 illustrates a detail of the above computational mesh, with special focus on the Adriatic Sea.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

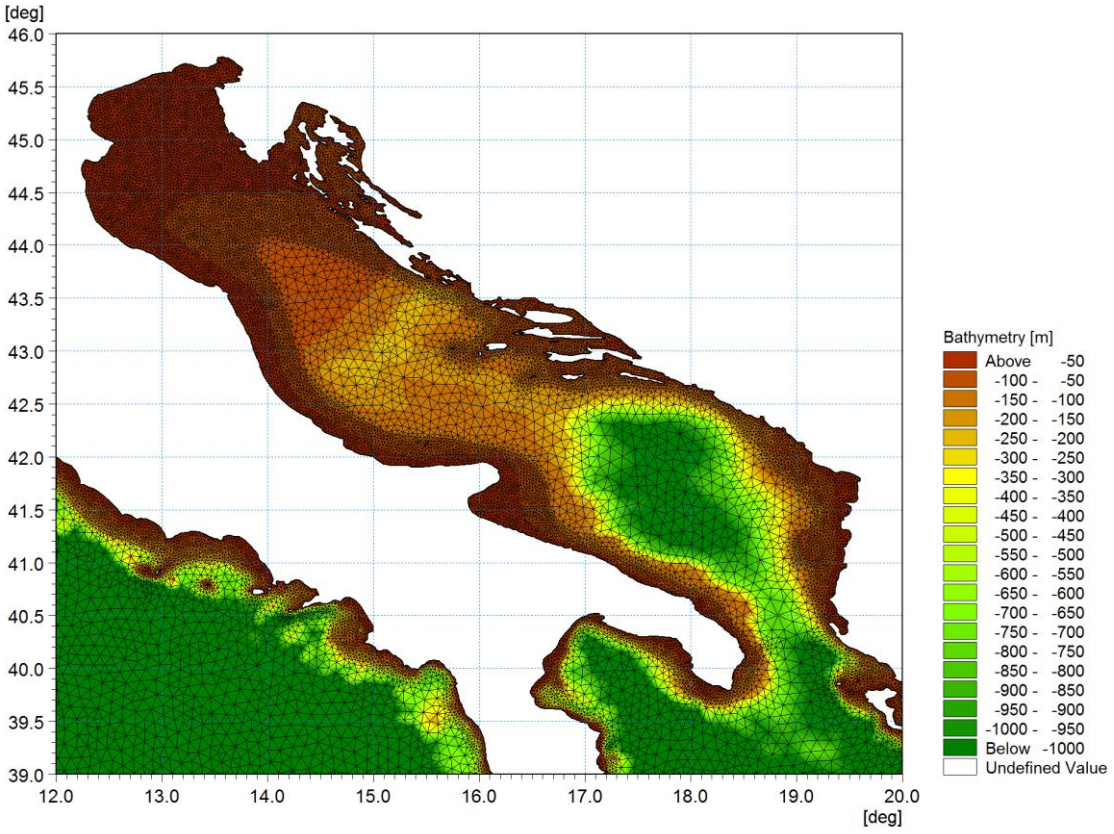


Figure A.9 - Detail of the mesh – Adriatic Sea

Scatter bathymetry data have been derived from GEBCO_08 database. The GEBCO_08 Grid is a 30 arc-second grid of global elevations and it is a continuous terrain model for ocean and land. The grid was generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data.

The gridded data are stored in a netCDF data file. Grids are stored as one dimensional arrays of 2-byte signed integer values. The complete data sets provide global coverage. Each data set consists of 21,600 rows x 43,200 columns, resulting in a total of 933,120,000 data points. The data start at the Northwest corner of the file, i.e. for the global file, position 89°59'45"N, 179°59'45"W, and are arranged in latitudinal bands of 360 degrees x 120 points/degree = 43,200 values. The data range eastward from 179°59'45"W to 179°59'45"E. Thus, the first band contains 43,200 values for 89°59'45"N, then followed by a band of 43,200 values at 89°59'15"N and so on at 30 arc-second latitude intervals down to 89°59'45"S. Data values are pixel centred registered, they refer to elevations at the centre of grid cells.

Figure A.10 illustrates GEBCO_08 scatter data for the entire area of the Mediterranean Sea.

GEBCO scatter data have not been used in the whole domain of the Mediterranean Sea. Following a detailed check of agreement and discrepancies between GEBCO database and nautical charts, it has been assumed to limit the use of GEBCO database for offshore areas (up to 500 m water depth) and to use nautical charts for shallower water areas (mainly coastal areas).

The nautical charts database which has been used is the CM93/3 database from CMAP.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

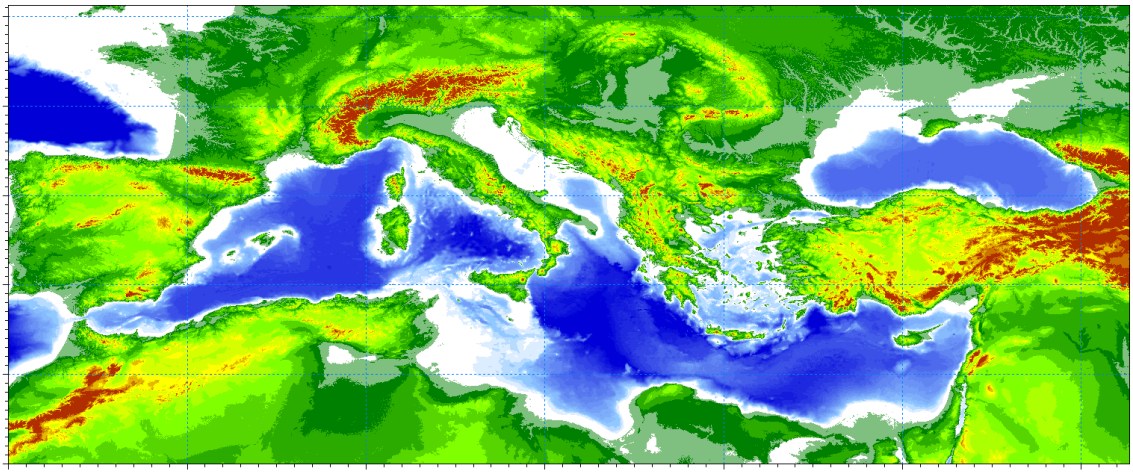


Figure A.10 - Scatter bathymetry data derived from GEBCO_08 database

The number of discrete frequencies and directions form the so called “spectral resolution”, which is a key parameter for wave models in general. The number of discrete frequencies and directions should in fact be high enough to properly represent the “real shape” of the wave spectrum and, on the other hand, it can’t be too high, since it would lead to unacceptable computational times and memory consumption.

In terms of frequency range, the minimum frequency f_{min} (which corresponds to the maximum wave period $T_{max,}$ according to the common relation $= \frac{1}{T}$) should be able to capture the longest wave periods that can occur in the Mediterranean Sea.

The analysis of ordinary and extreme waves in the Mediterranean Sea (from available data of wave buoys) has highlighted that almost all the wave energy associated to waves in the Mediterranean Sea are associated to wave periods between 1.5 seconds and 20 seconds.

In addition, a logarithmic distribution for the discrete frequencies acts better than a simple linear distribution, since most of the wave periods are concentrated below 8-10 seconds. A number of frequencies around 30 is widely considered as adequate for a proper discretization of wave energy spectra in the Mediterranean Sea. The following formulation has therefore been adopted:

$$f_{n=}0.04 \cdot 1.1^{n},$$

where n goes from 0 to 29 (30 frequencies in total). The discrete frequencies range from 0.04 Hz to 0.63 Hz (from 1.6s to 25.0s of Mean Wave Period T_m).

Also the choice of the number of discrete directions (directional discretization) is the result of detailed investigations and tests. In particular, a high number of wave model tests, each one characterized by a different spectral resolution (directional), i.e. by a different number of discrete directions have been setup and run.

Few examples of the results of the above model tests are illustrated from Figure A.11 to Figure A.13 in terms of short time series of wave heights extracted at 3 different locations where also measurements were available (La Spezia wave buoy, Ponza wave buoy, Cetraro wave buoy).

In all the below test cases, it appears that the two time series of wave height characterized by 24 and 36 discrete directions are almost coincident. Higher discrepancies can be found for a much limited number of discrete directions (12). After a high number of tests, the 24 directions solution has been assumed as a very good compromise between accuracy of results and computational time (the computational time of the wave model is linearly dependent on the number of discrete directions).

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Provided that wave directions can vary within the 360° rose, the directional resolution of the wave model is 360°/24 = 15°

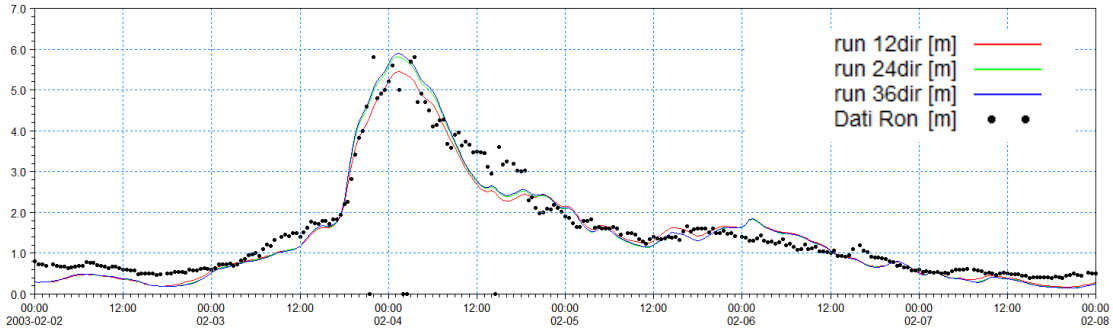


Figure A.11 - Time series of wave height at La Spezia buoy location for 3 different numbers of discrete directions

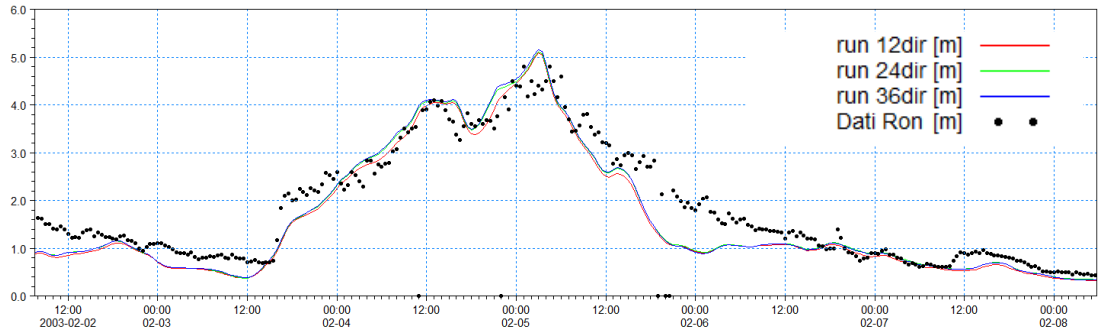


Figure A.12 - Time series of wave height at Ponza buoy location for 3 different numbers of discrete directions

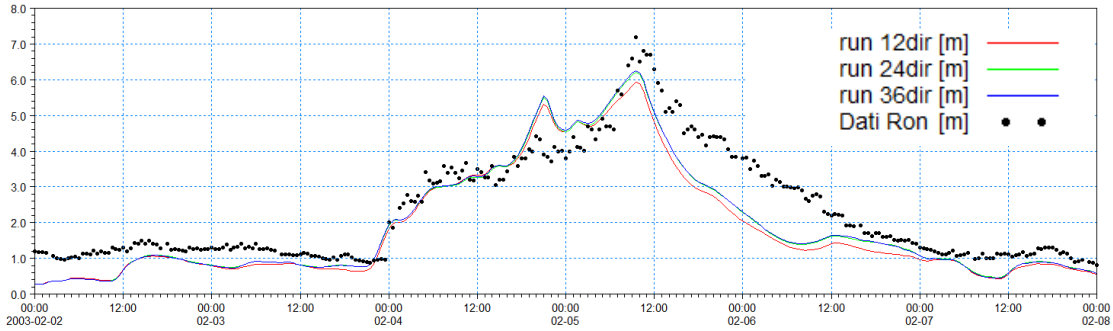


Figure A.13 - Time series of wave height at Cetraro buoy location for 3 different numbers of discrete directions

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Available products of the MWM database

The results of the wind and wave model are stored, in the whole domain, in terms of wind parameters and wave parameters averaged over the wave period ("phase averaged results"). In particular, the following hourly time series are available:

- Wind speed, WS [m/s]
- Wind direction, WD [deg]
- Significant Wave height, Hs [m]
- Mean wave period, Tm [s]
- Peak wave period, Tp [s]
- Zero crossing period, Tz [s]
- Mean wave direction, MWD [deg]
- Peak wave direction, PWD [deg]
- Directional standard deviation, DSD [deg]

In addition, hourly spectral results (in terms of wave energy associated to the frequency-direction bins) are saved on a regular grid with an equidistant spatial resolution of 0.1°.

Figure A.14 and Figure A-15 illustrate respectively an example of phase averaged results over a portion of Mediterranean Sea (Hs) and an local example of spectral results.

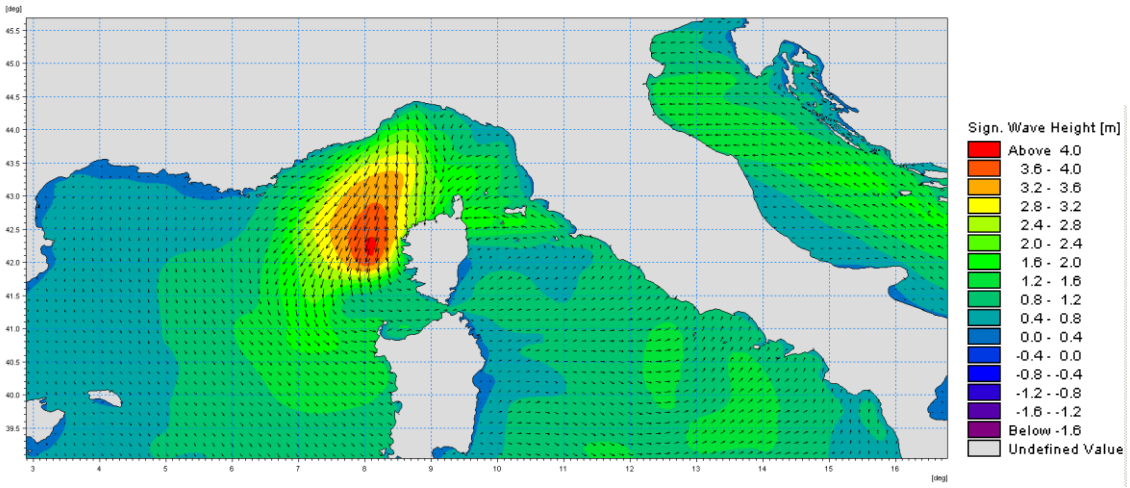


Figure A.14 Phase averaged results: Field of significant wave height and direction

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

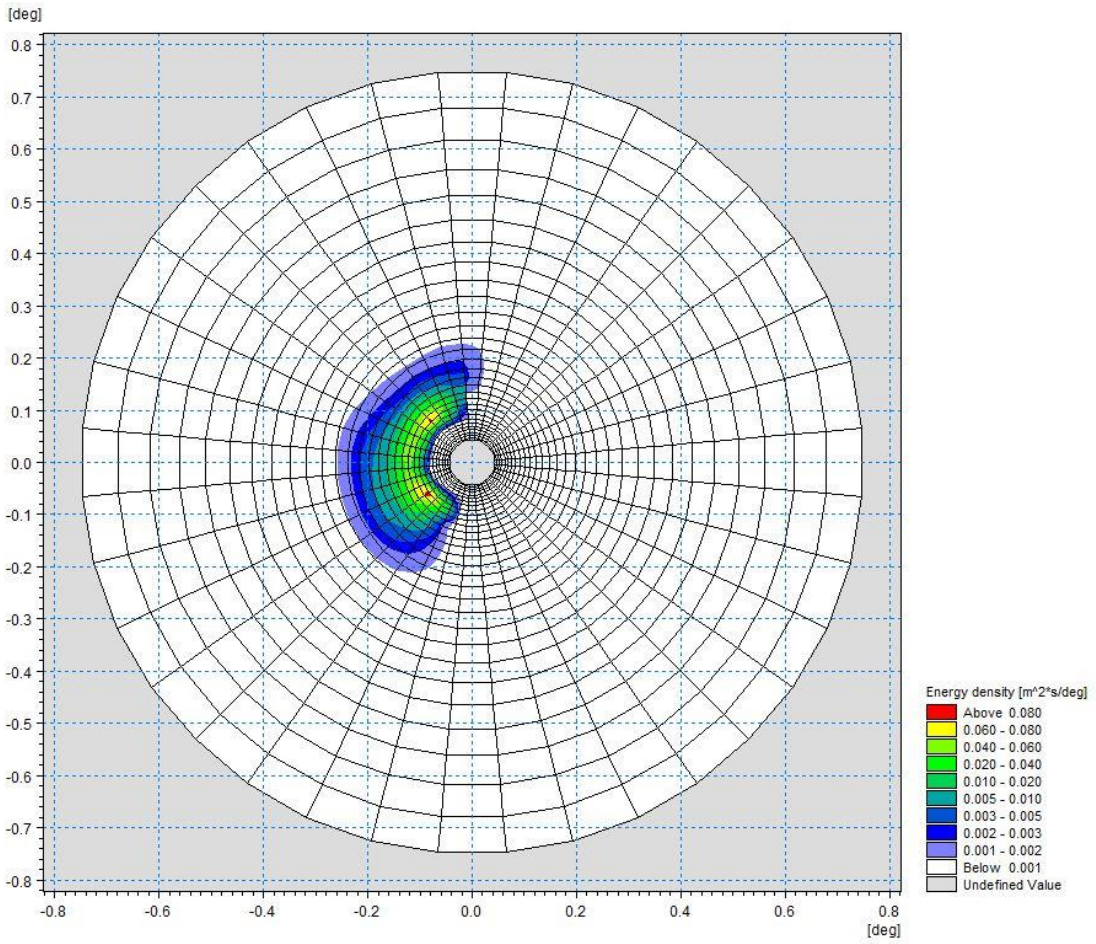


Figure A.15 Polar plot of spectral results. Wave energy density (coloured contours) as a function of directions (angular coordinate) and frequencies (radial coordinate)

References

Ardhuin, F., Bertotti, L., Bidlot, J.R., Cavaleri, L., Filipetto, V., Lefevre, J.M,, Wittmann, P., 2007, Comparison of wind and wave measurements and models in the Western Mediterranean Sea. *Ocean Engineering*, Vol. 34, pp. 526-541.

Athanassoulis, G., Stefanakos, Ch., Cavaleri, L., Ramieri, E., NoEL, C., Lefevre, J.M., Gaillard, P., 2004, RTP 10.10 / WW_MEDATLAS Scientific Report.

Battjes, J.A., Janssen, J.P.F.M., 1978, Energy loss and set-up due to breaking of random waves, Proceedings, 16th Int. Conf. Coastal Eng., ASCE, pp.569-587.

Bolaños-Sanchez, R., Sanchez-Arcilla, A., Cateura, J., 2007, Evaluation of two atmospheric models for wind-.wave modeling in the NW Mediterranean. *Journal of Marine Systems* 65:336-353.

Cavaleri, L., Bertotti, L., 2004, Accuracy of the modelled wind and wave fields in enclosed seas. Tellus, Vol. 56, pp. 167-175.

Cavaleri, L., 2005, The wind and wave atlas of the Mediterranean Sea – the calibration phase. *Advances in Geosciences*, Vol. 2, pp. 255-257.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Cavaleri, L., Sclavo., M., 2006, The calibration of wind and wave model data in the Mediterranean Sea. Coastal Engineering, Vol.53, pp. 613-627.

Chawla, A., Spindler, D.M., Tolman, H.L., 2013, Validation of a thirty year wave hindcast using the Climate Forecast System Reanalysis winds, Ocean Modelling, Vol. 70, pp. 189-206.

Contento, G., Lupieri, G., Venturi, M. Ciuffardi, T., 2011, A medium-resolution wave hindcast study over the Central and Western Mediterranean Sea, *Journal of Marine Science and Technology*, Vol. 16(2), pp. 181–201.

Contento, G., Lupieri, G., Donatini, L, Feudale, L, Pedroncini, A., Cusati, L.A., 2014, A state-of-the-art met-ocean model chain for wind&wave hindcast over the Mediterranean and Black Seas: implementation, tuning and validation against field data, accepted for presentation at the 21th Symposium Theory and Practice of Shipbuilding SORTA 2014, Oct. 2-4, 2014, Baška, Island of Krk, Croatia.

Contento, G., Lupieri, G., Donatini, L, 2012-2014, Project SEAPOL - Sistema modellistico ad Elevata risoluzione per l'Analisi storica e la Previsione del moto Ondoso nel mar Ligure, Department of Engineering and Architecture, University of Trieste, Technical Reports codes SEAPOL_UT_1.1.0 to SEAPOL_UT_5.1.0.

Donatini, L., 2013, Implementation of a state-of-art met-ocean model chain for hindcast wave simulations over the Mediterranean Sea and comparison of results with field data, Master Degree Thesis, Department of Engineering and Architecture, University of Trieste, Italy.

Donatini, L., Lupieri, G., Contento, G., 2014, A medium resolution wind&wave hindcast study for the Mediterranean Sea, Journal Paper, under review.

Hasselmann, K., Barnett, T.P., Bouws, E., Carlson, H., Cartwright, D.E., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E., Krusemann, P., Meerburg, A., Mueller, P., Olbers, D.J., Richter, K., Sell, W., Walden, H., 1973, Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Ergaenzungsheft zur Deutschen Hydrographischen Zeitschrift, Reihe, A(8), 12, 95 pp.

Hasselmann, S., Hasselmann, K., Allender, J.H., Barnett, T.P., 1985. Computations and parametrizations of the nonlinear energy transfer in a gravity-wave spectrum, Part II: Parametrizations of the nonlinear energy transfer for applications in wave models. J. Phys. Oceanogr. Vol. 15, pp. 1378–1391.

ISPRA (formerly APAT), 2004, Agenzia per la Protezione dell'Ambiente e per i servizi Tecnici, Dipartimento Tutela Acque Marine ed Interne, Servizio difesa delle coste, Analisi preliminare dei dati marini lungo le coste italiane – Atlante delle coste – Il moto ondoso al largo delle coste italiane, Technical Report (in Italian). http://www.apat.gov.it/site/_files/Atlante_coste/Introduzione.pdf.

Janssen, P.A.E.M., Abdalla, S., Hersbach, H., Bidlot, J.R., 2007: Error Estimation of Buoy, Satellite, and Model Wave Height Data. *J. Atmos. Oceanic Technol.*, Vol. **24**, pp. 1665–1677. doi: http://dx.doi.org/10.1175/JTECH2069.1

Michalakes, J., Chen, S., Dudhia, J., Hart, L., Klemp, J., Middlecoff, J., Skamarock, W., 2001, Development of a Next Generation Regional Weather Research and Forecast Model. *Developments in Teracomputing. In Proceedings of the 9th ECMWF Workshop on the Use of High Performance Computing in Meteorology.* Eds. Walter Zwieflhofer and Norbert Kreitz. World Scientific, 269-276.

Michalakes, J., Dudhia, J., Gill, D., Henderson, T., Klemp, J., Skamarock, W., Wang, W., 2005, The Weather Research and Forecast Model: Software Architecture and Performance. In *Proceedings of the 11th ECMWF Workshop on the Use of High Performance Computing in Meteorology.* Eds. Walter Zwieflhofer and George Mozdzynski. World Scientific, 56 - 168.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Ponce del León, S., Guedes Soares, C., 2008, Sensitivity of wave model predictions to wind fields in the Western Mediterranean Sea. *Coastal Engineering*, Vol. 55, pp. 920-929.

Puertos del Estado, Spain, 2009, – (http://www.puertos.es/oceanografia_y_meteorologia/), private communication.

Queffeulou, P., 2004, Long term validation of wave height measurements from altimeters. Marine Geodesy, Vol. 27, 495-510.

Queffeulou, P., Croizé-Fillon, D., 2010, Global altimeter SWH data set, version 7, Technical Report, Ifremer, ftp://ftp.ifremer.fr/cersat/products/swath/altimeters/waves/documentation/altimeter_wave_merge__7.0.pdf

Queffeulou, P., 2009, Altimeter Wave Height Measurements - Validation of Long Time Series.Poster: Ocean Surface Topography Science Team meeting, Seattle, Washington,USA.(http://www.aviso.oceanobs.com/en/courses/oststst/oststst-2009-seattle/posters/).

Saha, S., Moorthi, S., Pan, H., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Wollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y., Chuang, H., Juang, H., Sela, J., Iredell, M., Treadon, R., Kleist, D., VanDelst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C., Liu, Q., Chen,Y., Han, Y., Cucurull, L., Reynolds, R., Rutledge, G., Goldberg, M., 2010, The NCEP Climate Forecast System Reanalysis. *Bull. Amer. Meteor. Soc.*, Vol. 91, 1015–1057.

Skamarock WC, Klemp JB, 2007, A time-split nonhydrostatic atmospheric model for research and NWP applications. *J. Comp. Phys.* Special issue on environmental modeling.

Sorensen, O.R., Kofoed-Hansen, H., Rugbjerg, M. and Sorensen, L.S., 2004: A Third Generation Spectral Wave Model Using an Unstructured Finite Volume Technique. In Proceedings of the 29th International Conference of Coastal Engineering, 19-24 September 2004, Lisbon, Portugal.

Tolman, H.L., 2002a. Alleviating the garden sprinkler effect in wind wave models. Ocean Modelling, Vol. 4, pp. 269–289.

Tolman, H.L., 2002f, Validation of WAVEWATCH III, version 1.15 for a global domain. Tech. Note 213, NOAA/NWS/NCEP/OMB, 33p.

Tolman, H.L., 2008, http://cioss.coas.oregonstate.edu/CIOSS/workshops/Altimeter_workshop_08/Coastal_Alt_Presentations/18_Tolman_Sig_Wave_Ht.pdf

Sorensen, O.R., Kofoed-Hansen, H., Rugbjerg, M. and Sorensen, L.S., 2004: A Third Generation Spectral Wave Model Using an Unstructured Finite Volume Technique. In Proceedings of the 29th International Conference of Coastal Engineering, 19-24 September 2004, Lisbon, Portugal.

Komen,G.J., Cavaleri,L., Doneland,M., Hasselmann,K., Hasselmann,S. and Janssen,P.A.E.M., (1984). Dynamics and modelling of ocean waves. Cambridge University Press, UK, 560 pp.

Young,I.R., (1999). Wind generated ocean waves, in Elsevier Ocean Engineering Book Series, Volume 2, Eds. R. Bhattacharyya and M.E. McCormick, Elsevier.

WAMDI-group: S. Hasselmann, K. Hasselman, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky and J.A. Ewing, (1988) “The WAM model – a third generation ocean wave prediction model”, J. Phys. Oceanogr., 18, 1775-1810

General Bathymetric Chart of the Oceans (GEBCO) – www.gebco.net

CM-93 Edition 3.0, CM-93/3 - www.jeppesen.com/marine/commercial/professional/

Ole Baltazar Andersen (1995), Global ocean tides from ERS 1 and TOPEX/POSEIDON altimetry, J. of Geophys. Res., 100, C12, p. 25249-25260

Doodson, A. T., Warburg, H. D., 1941 “Admiralty manual of tides”

Web references

ARPA-FVG OSMER, [Online] http://www.osmer.fvg.it/home.php

ARW Online Tutorial.” [Online] Available at http://www.mmm.ucar.edu/wrf/OnLineTutorial/index.htm

CISL RDA: NCEP Climate Forecast System Re-analysis (CFSR) 6-hourly Products, January 1979 to December 2010.” [Online] Available at http://rda.ucar.edu/datasets/ds093.0/index.html#description

NOAA, Hourly/Sub-Hourly Observational Data.” [Online] Available at http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=hourly&layers=1&node=gis

The Weather Research&Forecasting Model Website.” [Online] Available at http://www.wrf-model.org/index.php

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

ALLEGATO B–MIKE 21 Spectral Waves (SW)

Descrizione tecnica

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E



MIKE 21 Wave Modelling

MIKE 21 Spectral Waves FM

Short Description

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

DHI headquarters
Agern Allé 5
DK-2970 Hørsholm
Denmark

+45 4516 9200 Telephone
+45 4516 9333 Support
+45 4516 9292 Telefax

mike@dhigroup.com
www.mikepoweredbydhi.com

© DHI

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

MIKE 21 SW - SPECTRAL WAVE MODEL FM

MIKE 21 SW is a state-of-the-art third generation spectral wind-wave model developed by DHI. The model simulates the growth, decay and transformation of wind-generated waves and swells in offshore and coastal areas.

MIKE 21 SW includes two different formulations:

- Fully spectral formulation
- Directional decoupled parametric formulation

The fully spectral formulation is based on the wave action conservation equation, as described in e.g. Komen et al (1994) and Young (1999). The directional decoupled parametric formulation is based on a parameterisation of the wave action conservation equation. The parameterisation is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum. The basic conservation equations are formulated in either Cartesian co-ordinates for small-scale applications and polar spherical co-ordinates for large-scale applications.

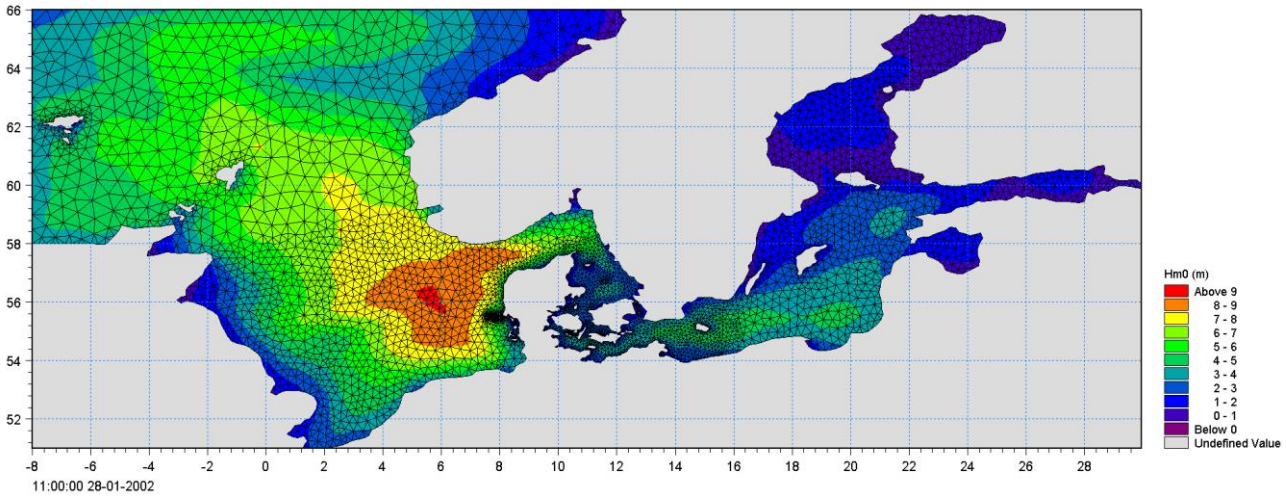
The fully spectral model includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction
- Effect of time-varying water depth
- Effect of ice coverage on the wave field

The discretisation of the governing equation in geographical and spectral space is performed using cell-centred finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.



MIKE 21 SW is a state-of-the-art numerical modelling tool for prediction and analysis of wave climates in offshore and coastal areas. © BIOFOTO/Klaus K. Bentzen



A MIKE 21 SW forecast application in the North Sea and Baltic Sea. The chart shows a wave field (from the NSBS model) illustrated by the significant wave height in top of the computational mesh. See also www.waterforecast.com

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Computational Features

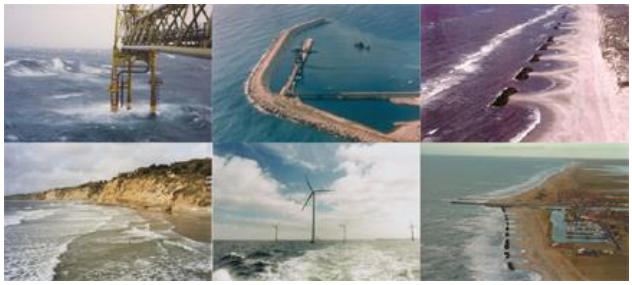
The main computational features of MIKE 21 SW - Spectral Wave Model FM are as follows:

- Fully spectral and directionally decoupled parametric formulations
- Source functions based on state-of-the-art 3rd generation formulations
- Instationary and quasi-stationary solutions
- Optimal degree of flexibility in describing bathymetry and ambient flow conditions using depth-adaptive and boundary-fitted unstructured mesh
- Coupling with hydrodynamic flow model for modelling of wave-current interaction and time-varying water depth
- Flooding and drying in connection with time-varying water depths
- Cell-centred finite volume technique
- Fractional step time-integration with an multi-sequence explicit method for the propagation
- Extensive range of model output parameters (wave, swell, air-sea interaction parameters, radiation stress tensor, spectra, etc.)

Application Areas

MIKE 21 SW is used for the assessment of wave climates in offshore and coastal areas - in hindcast and forecast mode.

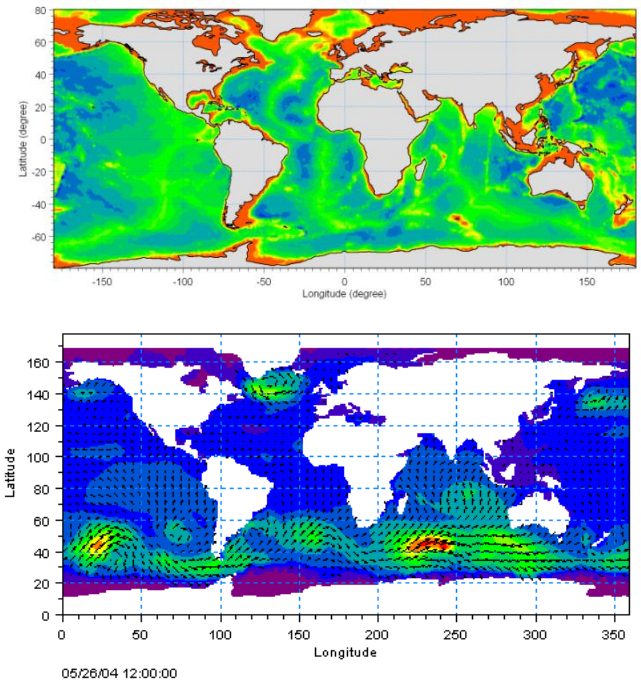
A major application area is the design of offshore, coastal and port structures where accurate assessment of wave loads is of utmost importance to the safe and economic design of these structures.



Illustrations of typical application areas of DHI's MIKE 21 SW – Spectral Wave Model FM

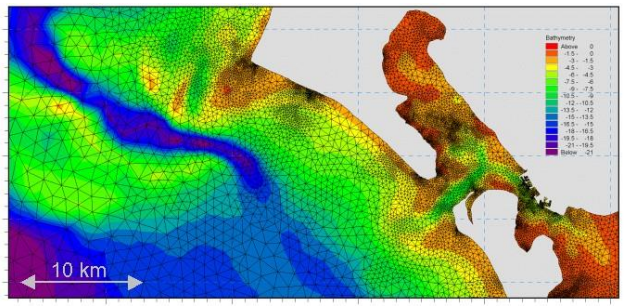
Measured data are often not available during periods long enough to allow for the establishment of sufficiently accurate estimates of extreme sea states.

In this case, the measured data can then be supplemented with hindcast data through the simulation of wave conditions during historical storms using MIKE 21 SW.



Example of a global application of MIKE 21 SW. The upper panel shows the bathymetry. Results from such a model (cf. lower panel) can be used as boundary conditions for regional scale forecast or hindcast models. See http://www.waterforecast.com for more details on regional and global modelling

MIKE 21 SW is particularly applicable for simultaneous wave prediction and analysis on regional scale and local scale. Coarse spatial and temporal resolution is used for the regional part of the mesh and a high-resolution boundary and depth-adaptive mesh is describing the shallow water environment at the coastline.

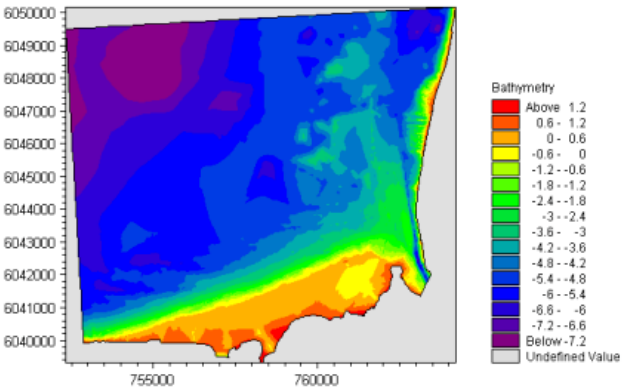


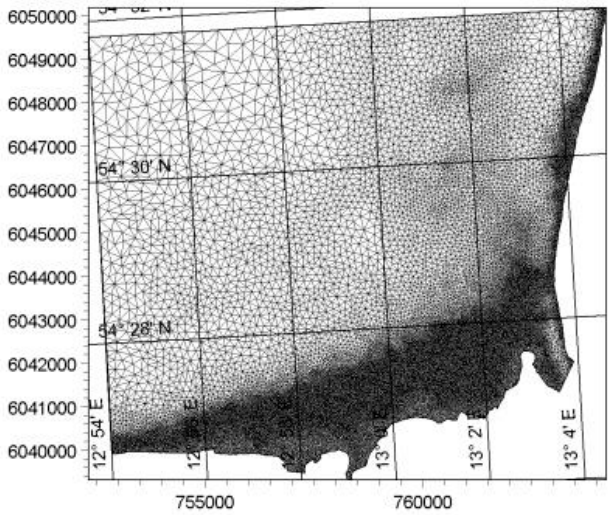
Example of a computational mesh used for transformation of offshore wave statistics using the directionally decoupled parametric formulation

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

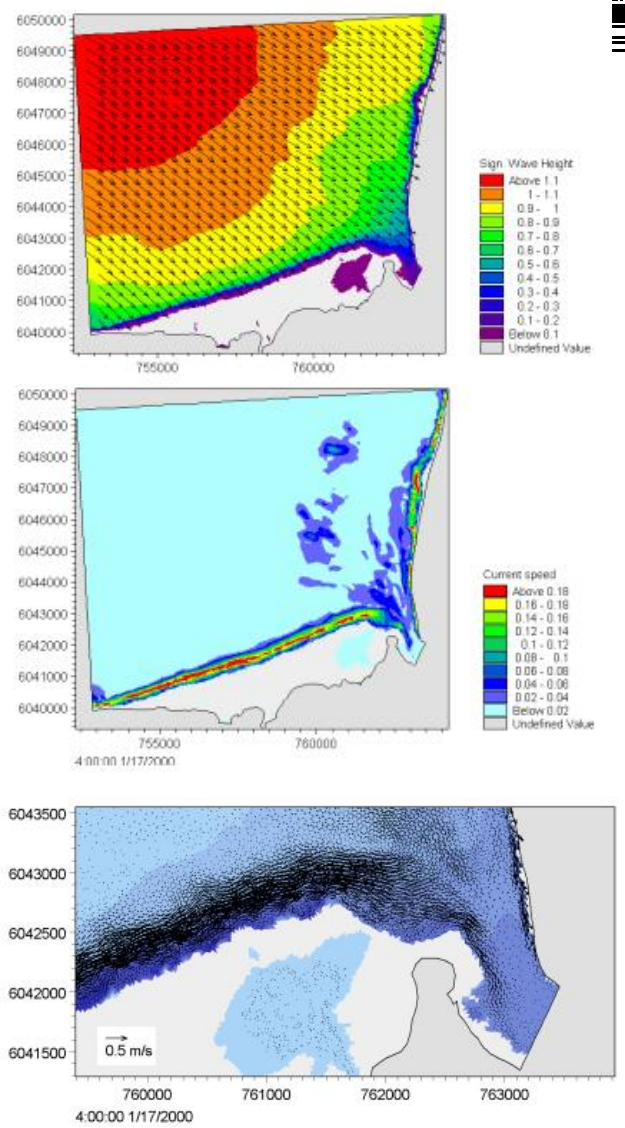
MIKE 21 SW is also used for the calculation of the sediment transport, which for a large part is determined by wave conditions and associated wave-induced currents. The wave-induced current is generated by the gradients in radiation stresses that occur in the surf zone.

MIKE 21 SW can be used to calculate the wave conditions and associated radiation stresses. The long-shore currents and sediment transport are then calculated using the flow and sediment transport models available in the MIKE 21 package. For such type of applications, the directional decoupled parametric formulation of MIKE 21 SW is an excellent compromise between the computational effort and accuracy.





Bathymetry (upper) and computational mesh (lower) used in a MIKE 21 SW application on wave induced currents in Gellen Bay, Germany



Map of significant wave height (upper), current field (middle) and vector field (lower). The flow field is simulated by DHI's MIKE 21 Flow Model FM, which is dynamically coupled to MIKE 21 SW

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Model Equations

In MIKE 21 SW, the wind waves are represented by the wave action density spectrum $N(\sigma,\theta)$. The independent phase parameters have been chosen as the relative (intrinsic) angular frequency, $\sigma = 2\pi f$ and the direction of wave propagation, θ. The relation between the relative angular frequency and the absolute angular frequency, ω, is given by the linear dispersion relationship

$$\sigma = \sqrt{gk\tanh(kd)} = \omega - \bar{k}\cdot\bar{U}$$

where g is the acceleration of gravity, d is the water depth and $\bar{U}$ is the current velocity vector and $\bar{k}$ is the wave number vector with magnitude k and direction θ. The action density, $N(\sigma,\theta)$, is related to the energy density $E(\sigma,\theta)$ by

$$N = \frac{E}{\sigma}$$

Fully Spectral Formulation

The governing equation in MIKE 21 SW is the wave action balance equation formulated in either Cartesian or spherical co-ordinates. In horizontal Cartesian co-ordinates, the conservation equation for wave action reads

$$\frac{\partial N}{\partial t} + \nabla\cdot(\bar{v}N) = \frac{S}{\sigma}$$

where $N(\bar{x},\sigma,\theta,t)$ is the action density, t is the time, $\bar{x} = (x,y)$ is the Cartesian co-ordinates, $\bar{v} = (c_x, c_y, c_\sigma, c_\theta)$ is the propagation velocity of a wave group in the four-dimensional phase space $\bar{x}$, σ and θ. S is the source term for energy balance equation. ∇ is the four-dimensional differential operator in the $\bar{x}$, σ, θ-space. The characteristic propagation speeds are given by the linear kinematic relationships

$$(c_x, c_y) = \frac{d\bar{x}}{dt} = \bar{c}_g + \bar{U} = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)\frac{\sigma}{k} + \bar{U}$$

$$c_\sigma = \frac{d\sigma}{dt} = \frac{\partial\sigma}{\partial d}\left[\frac{\partial d}{\partial t} + \bar{U}\cdot\nabla_{\bar{x}} d\right] - c_g\bar{k}\cdot\frac{\partial\bar{U}}{\partial s}$$

$$c_\theta = \frac{d\theta}{dt} = -\frac{1}{k}\left[\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial m} + \bar{k}\cdot\frac{\partial\bar{U}}{\partial m}\right]$$

Here, s is the space co-ordinate in wave direction θ and m is a co-ordinate perpendicular to s. $\nabla_{\bar{x}}$ is the two-dimensional differential operator in the $\bar{x}$-space.

Source Functions

The source function term, S, on the right hand side of the wave action conservation equation is given by

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf}$$

Here S_{in} represents the momentum transfer of wind energy to wave generation, S_{nl} the energy transfer due non-linear wave-wave interaction, S_{ds} the dissipation of wave energy due to white-capping (deep water wave breaking), S_{bot} the dissipation due to bottom friction and S_{surf} the dissipation of wave energy due to depth-induced breaking.

The default source functions S_{in}, S_{nl} and S_{ds} in MIKE 21 SW are similar to the source functions implemented in the WAM Cycle 4 model, see Komen et al (1994).

The wind input is based on Janssen's (1989, 1991) quasi-linear theory of wind-wave generation, where the momentum transfer from the wind to the sea not only depends on the wind stress, but also the sea state itself. The non-linear energy transfer (through the resonant four-wave interaction) is approximated by the DIA approach, Hasselmann et al (1985). The source function describing the dissipation due to white-capping is based on the theory of Hasselmann (1974) and Janssen (1989). The bottom friction dissipation is modelled using the approach by Johnson and Kofoed-Hansen (2000), which depends on the wave and sediment properties. The source function describing the bottom-induced wave breaking is based on the well-proven approach of Battjes and Janssen (1978) and Eldeberky and Battjes (1996).

A detailed description of the various source functions is available in Komen et al (1994) and Sørensen et al (2003), which also includes the references listed above.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Directional Decoupled Parametric Formulation

The directionally decoupled parametric formulation is based on a parameterisation of the wave action conservation equation. Following Holthuijsen et al (1989), the parameterisation is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum as dependent variables.

A similar formulation is used in the MIKE 21 NSW Near-shore Spectral Wind-Wave Model, which is one of the most popular models for wave transformation in coastal and shallow water environment. However, with MIKE 21 SW it is not necessary to set up a number of different orientated bathymetries to cover varying wind and wave directions.

The parameterisation leads to the following coupled equations

$$\frac{\partial(m_0)}{\partial t}+\frac{\partial(c_x m_0)}{\partial x}+\frac{\partial(c_y m_0)}{\partial y}+\frac{\partial(c_\theta m_0)}{\partial \theta}=T_0$$

$$\frac{\partial(m_1)}{\partial t}+\frac{\partial(c_x m_1)}{\partial x}+\frac{\partial(c_y m_1)}{\partial y}+\frac{\partial(c_\theta m_1)}{\partial \theta}=T_1$$

where $m_0(x, y, \theta)$ and $m_1(x, y, \theta)$ are the zeroth and first moment of the action spectrum $N(x, y, \sigma, \theta)$, respectively. $T_0(x, y, \theta)$ and $T_1(x, y, \theta)$ are source functions based on the action spectrum. The moments $m_n(x, y, \theta)$ are defined as

$$m_n(x,y,\theta)=\int_0^\infty \omega^n N(x,y,\omega,\theta)d\omega$$

The source functions T_0 and T_1 take into account the effect of local wind generation (stationary solution mode only) and energy dissipation due to bottom friction and wave breaking. The effects of wave-current interaction are also included. The source functions for the local wind generation are derived from empirical growth relations, see Johnson (1998) for details.

Numerical Methods

The frequency spectrum (fully spectral model only) is split into a prognostic part for frequencies lower than a cut-off frequency σ_{max} and an analytical diagnostic tail for the high-frequency part of the spectrum

$$E(\sigma,\theta)=E(\sigma_{\max},\theta)\left(\frac{\sigma}{\sigma_{\max}}\right)^{-m}$$

where m is a constant (= 5) as proposed by Komen et al (1994).



The directional decoupled parametric formulation in MIKE 21 SW is used extensively for calculation of the wave transformation from deep-water to the shoreline and for wind-wave generation in local areas

Space Discretisation

The discretisation in geographical and spectral space is performed using cell-centred finite volume method. In the geographical domain an unstructured mesh is used. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements. Triangle and quadrilateral shaped polygons are presently supported in MIKE 21 SW. The action density, $N(\sigma,\theta)$ is represented as a piecewise constant over the elements and stored at the geometric centres.

In frequency space either an equidistant or a logarithmic discretisation is used. In the directional space, an equidistant discretisation is used for both types of models. The action density is represented as piecewise constant over the discrete intervals, $\Delta\sigma$ and $\Delta\theta$, in the frequency and directional space.

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Integrating the wave action conservation over an area A_i, the frequency interval $\Delta\sigma_l$ and the directional interval $\Delta\theta_m$ gives

$$\frac{\partial}{\partial t}\int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i} N d\Omega d\sigma d\theta - \int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i}\frac{S}{\sigma}d\Omega d\sigma d\theta$$
$$= \int_{\Delta\theta_m}\int_{\Delta\sigma_l}\int_{A_i}\nabla\cdot(\bar{v}N)d\Omega d\sigma d\theta$$

where Ω is the integration variable defined on A_i. Using the divergence theorem and introducing the convective flux $\bar{F} = \bar{v}N$, we obtain

$$\frac{\partial N_{i,l,m}}{\partial t} = -\frac{1}{A_i}\left[\sum_{p=1}^{NE}(F_n)_{p,l,m}\Delta l_p\right]$$
$$-\frac{1}{\Delta\sigma_l}\left[(F_\sigma)_{i,l+1/2,m} - (F_\sigma)_{i,l-1/2,m}\right]$$
$$-\frac{1}{\Delta\theta_m}\left[(F_\theta)_{i,l,m+1/2} - (F_\theta)_{i,l,m-1/2}\right] + \frac{S_{i,l,m}}{\sigma_l}$$

where NE is the total number of edges in the cell, $(F_n)_{p,l,m} = (F_x n_x + F_y n_y)_{p,l,m}$ is the normal flux trough the edge p in geographical space with length Δl_p. $(F_\sigma)_{i,l+1/2,m}$ and $(F_\theta)_{i,l,m+1/2}$ is the flux through the face in the frequency and directional space, respectively.

The convective flux is derived using a first-order upwinding scheme. In that

$$F_n = c_n\left(\frac{1}{2}(N_i + N_j) - \frac{1}{2}\frac{c}{|c|}(N_i - N_j)\right)$$

where c_n is the propagation speed normal to the element cell face.

Time Integration

The integration in time is based on a fractional step approach. Firstly, a propagation step is performed calculating an approximate solution N^* at the new time level (n+1) by solving the homogenous wave action conservation equation, i.e. without the source terms. Secondly, a source terms step is performed calculating the new solution N^{n+1} from the estimated solution taking into account only the effect of the source terms.

The propagation step is carried out by an explicit Euler scheme

$$N^*_{i,l,m} = N^n_{i,l,m} + \Delta t\left(\frac{\partial N_{i,l,m}}{\partial t}\right)^n$$

To overcome the severe stability restriction, a multi-sequence integration scheme is employed. The maximum allowed time step is increased by employing a sequence of integration steps locally, where the number of steps may vary from point to point.

A source term step is performed using an implicit method (see Komen et al, 1994)

$$N^{n+1}_{i,l,m} = N^*_{i,l,m} + \Delta t\left[\frac{(1-\alpha)S^*_{i,l,m} + \alpha S^{n+1}_{i,l,m}}{\sigma_l}\right]$$

where α is a weighting coefficient that determines the type of finite difference method. Using a Taylor series to approximate S^{n+1} and assuming the off-diagonal terms in $\partial S/\partial E = \gamma$ are negligible, this equation can be simplified as

$$N^{n+1}_{i,l,m} = N^n_{i,l,m} + \frac{(S^*_{i,l,m}/\sigma_l)\Delta t}{(1-\alpha\gamma\Delta t)}$$

For growing waves ($\gamma > 0$) an explicit forward difference is used ($\alpha = 0$), while for decaying waves ($\gamma < 0$) an implicit backward difference ($\alpha = 1$) is applied.



MIKE 21 SW is also applied for wave forecasts in ship route planning and improved service for conventional and fast ferry operators

Model Input

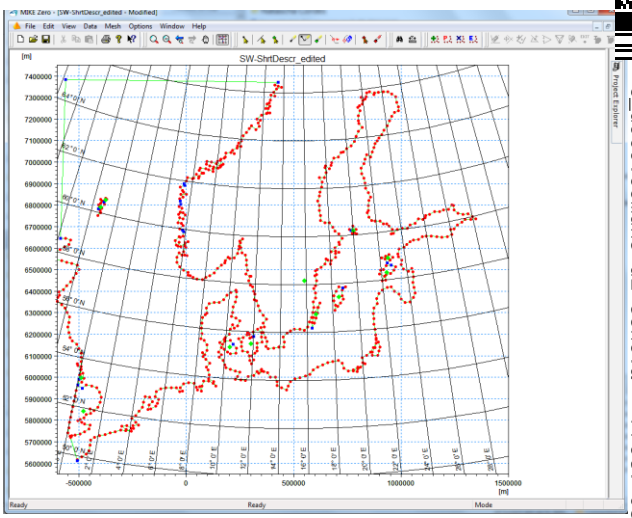
The necessary input data can be divided into following groups:

- Domain and time parameters:
  - computational mesh
  - co-ordinate type (Cartesian or spherical)
  - simulation length and overall time step
- Equations, discretisation and solution technique
  - formulation type
  - frequency and directional discretisation
  - number of time step groups
  - number of source time steps
- Forcing parameters
  - water level data
  - current data
  - wind data
  - ice data
- Source function parameters
  - non-linear energy transfer
  - wave breaking (shallow water)
  - bottom friction
  - white capping
- Structures
  - location and geometry
  - approach
  - structures coefficients
- Initial conditions
  - zero-spectrum (cold-start)
  - empirical data
  - data file
- Boundary conditions
  - closed boundaries
  - open boundaries (data format and type)

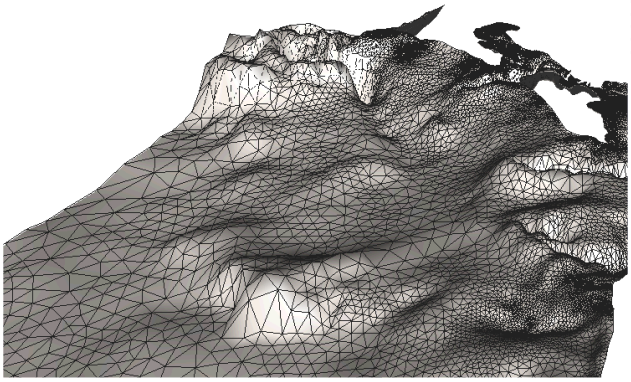
Providing MIKE 21 SW with a suitable mesh is essential for obtaining reliable results from the model. Setting up the mesh includes the appropriate selection of the area to be modelled, adequate resolution of the bathymetry, flow, wind and wave fields under consideration and definition of codes for essential and land boundaries.

Furthermore, the resolution in the geographical space must also be selected with respect to stability considerations.

As the wind is the main driving force in MIKE 21 SW, accurate hindcast or forecast wind fields are of utmost importance for the wave prediction.

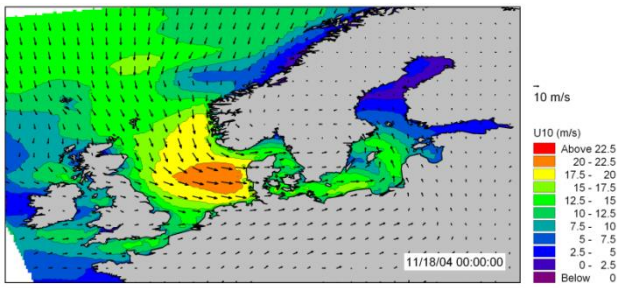


The Mesh Generator is an efficient MIKE Zero tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries



3D visualisation of a computational mesh

If wind data is not available from an atmospheric meteorological model, the wind fields (e.g. cyclones) can be determined by using the wind-generating programs available in MIKE 21 Toolbox.



The chart shows an example of a wind field covering the North Sea and Baltic Sea as wind speed and wind direction. This is used as input to MIKE 21 SW in forecast and hindcast mode

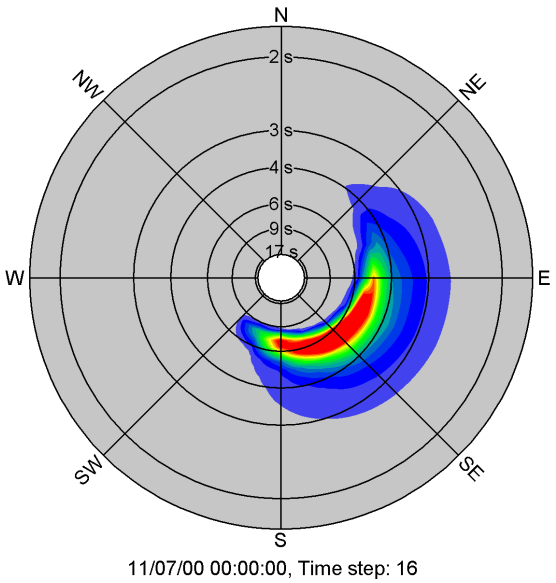
c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

Model Output

At each mesh point and for each time step four types of output can be obtained from MIKE 21 SW:

- Integral wave parameters divided into wind sea and swell such as
  - significant wave height, H_{m0}
  - peak wave period, T_p
  - averaged wave period, T_{01}
  - zero-crossing wave period, T_{02}
  - wave energy period, T_{-10}
  - peak wave direction, θ_p
  - mean wave direction, θ_m
  - directional standard deviation, σ
  - wave height with dir., $H_{m0} \cos\theta_m$, $H_{m0} \sin\theta_m$
  - radiation stress tensor, S_{xx}, S_{xy} and S_{yy}
  - particle velocities, *horizontal/vertical*
  - wave power, P, P_x *and* P_y



Example of model output (directional-frequency wave spectrum) processed using the Polar Plot control in the MIKE Zero Plot Composer

The distinction between wind-sea and swell can be calculated using either a constant threshold frequency or a dynamic threshold frequency with an upper frequency limit.

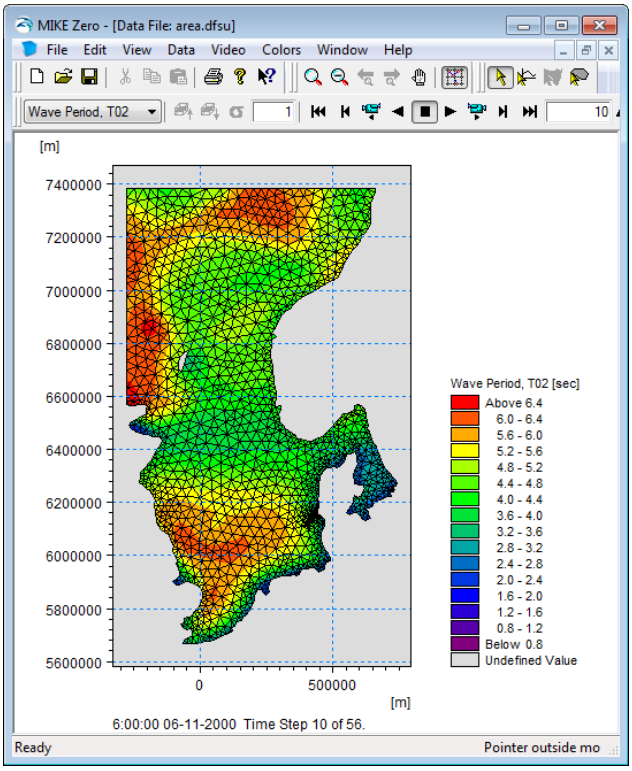
- Input parameters
  - water level, *WL*
  - water depth, *h*
  - current velocity, $\overline{U}$
  - wind speed, U_{10}
  - wind direction, θ_w
  - Ice concentration

- Model parameters
  - bottom friction coefficient, C_f
  - breaking parameter, γ
  - Courant number, *Cr*
  - time step factor, α
  - characteristic edge length, Δl
  - area of element, *a*
  - wind friction speed, u_*
  - roughness length, z_0
  - drag coefficient, C_D
  - Charnock parameter, z_{ch}

- Directional-frequency wave spectra at selected grid points and or areas as well as direction spectra and frequency spectra

Output from MIKE 21 SW is typically post-processed using the Data Viewer available in the common MIKE Zero shell. The Data Viewer is a tool for analysis and visualisation of unstructured data, e.g. to view meshes, spectra, bathymetries, results files of different format with graphical extraction of time series and line series from plan view and import of graphical overlays.

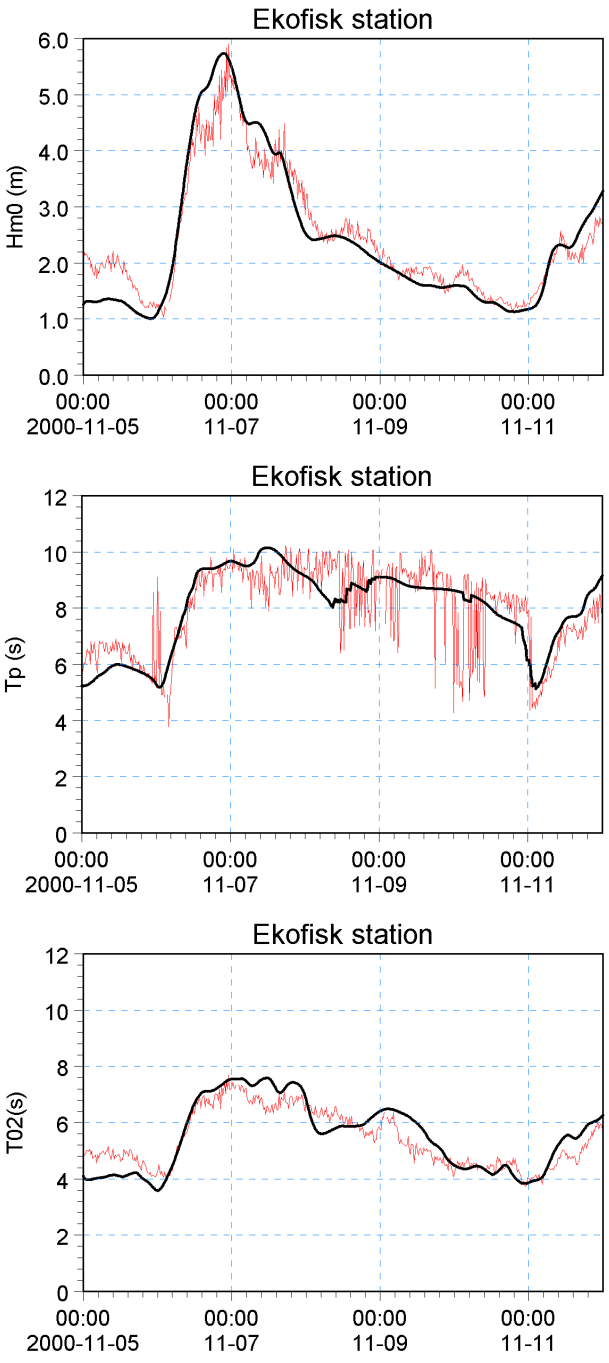
Various other editors and plot controls in the MIKE Zero Composer (e.g. Time Series Plot, Polar Plot, etc.) can be used for analysis and visualisation.



The Data Viewer in MIKE Zero – an efficient tool for analysis and visualisation of unstructured data including processing of animations

Validation

The model has successfully been applied to a number of rather basic idealised situations for which the results can be compared with analytical solutions or information from the literature. The basic tests covered fundamental processes such as wave propagation, depth-induced and current-induced shoaling and refraction, wind-wave generation and dissipation.

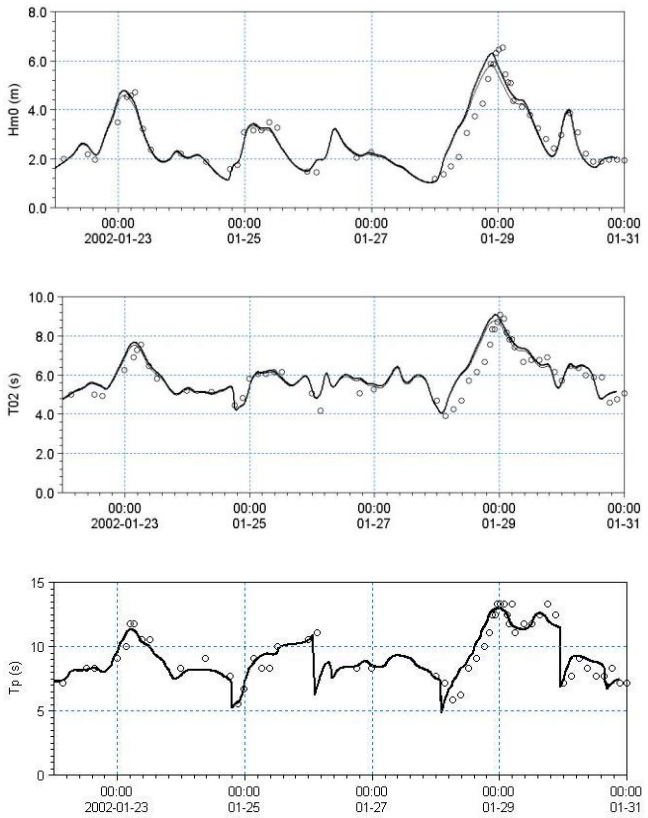


Comparison between measured and simulated significant wave height, peak wave period and mean wave period at the Ekofisk offshore platform (water depth 70 m) in the North Sea). (——) calculations and (——) measurements



A major application area of MIKE 21 SW is in connection with design and maintenance of offshore structures

The model has also been tested in natural geophysical conditions (e.g. in the North Sea, the Danish West Coast and the Baltic Sea), which are more realistic and complicated than the academic test and laboratory tests mentioned above.



Comparison between measured and simulated significant wave height, peak wave period and mean wave period at Fjaltring located at the Danish west coast (water depth 17.5 m).(——) calculations and (o) measurements

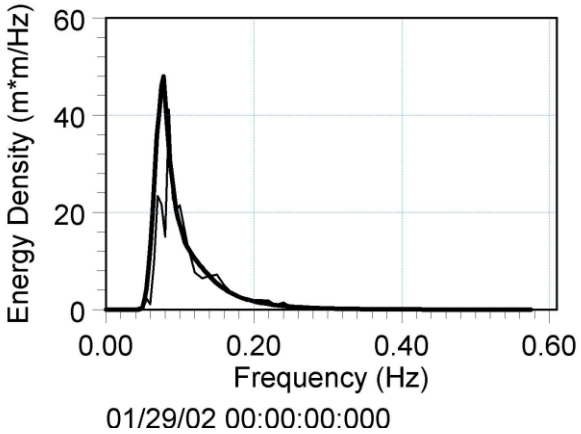
c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

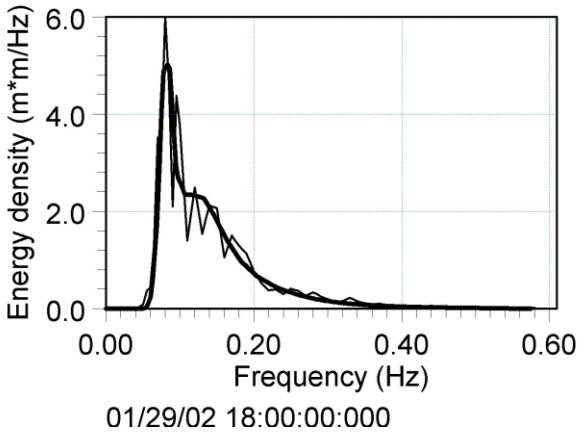
c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E



The Fjaltring directional wave rider buoy is located offshore relative to the depicted arrow

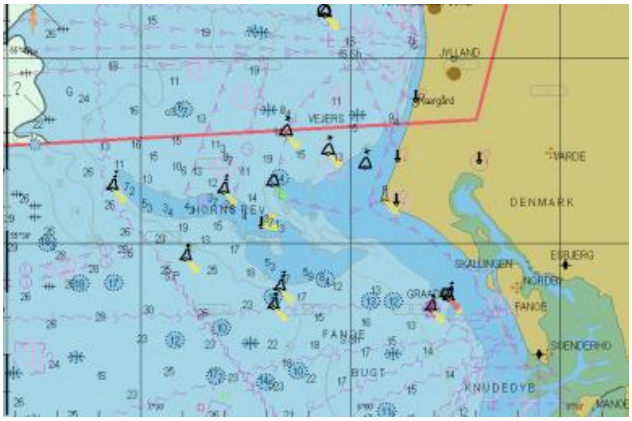
MIKE 21 SW is used for prediction of the wave conditions at the complex Horns Rev (reef) in the southeastern part of the North Sea. At this site, a 168 MW offshore wind farm with 80 turbines has been established in water depths between 6.5 and 13.5 m.

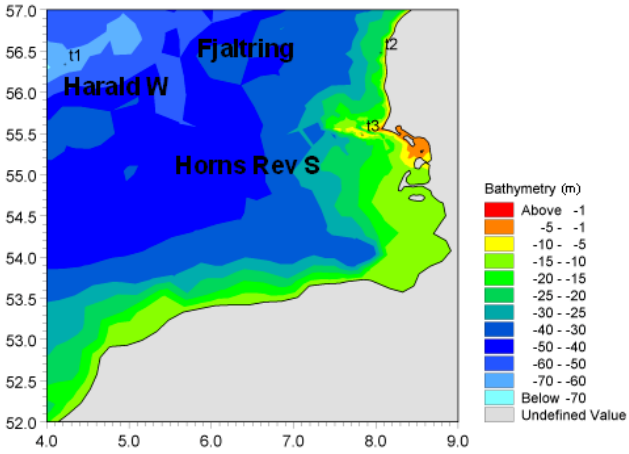


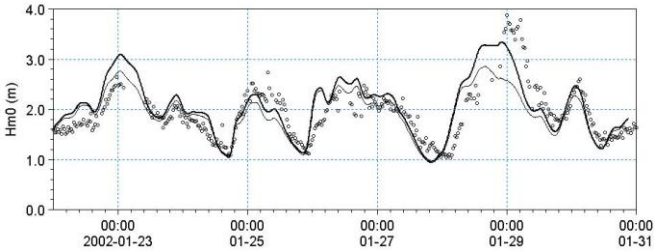


Comparison of frequency spectra at Fjaltring. (——) calculations and (——)measurements





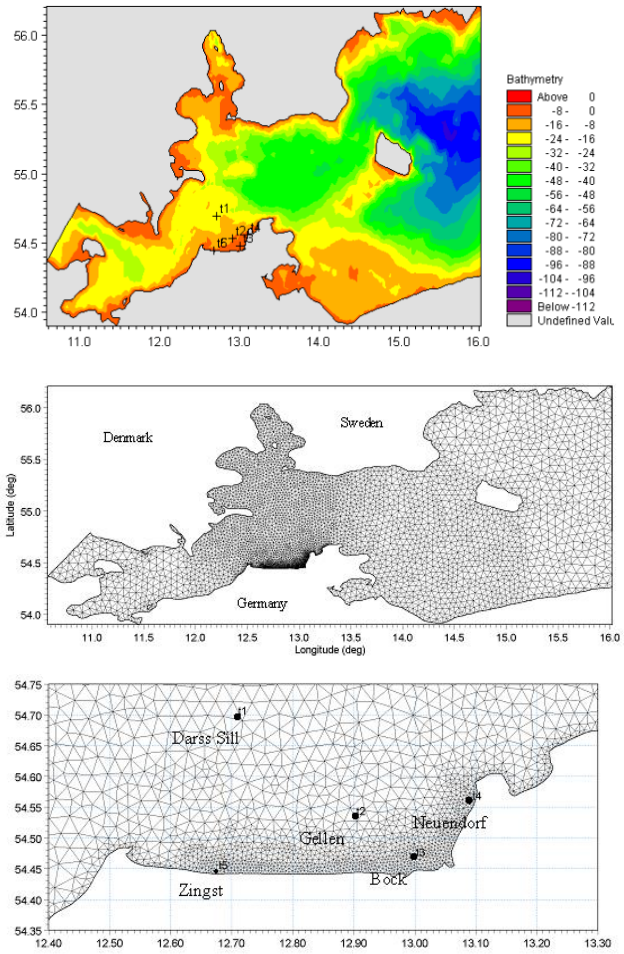




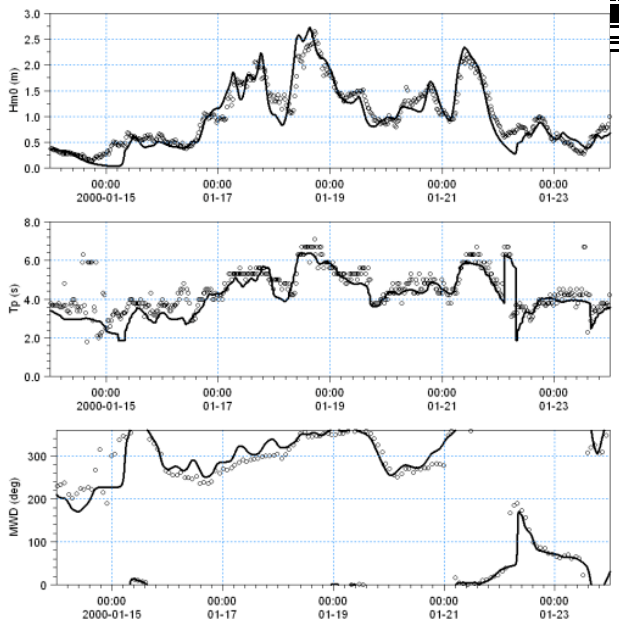
The upper panels show the Horns Rev offshore wind farm and MIKE C-map chart. 'The middle panel shows a close-up of the mesh near the Horns Rev S wave rider buoy (t3, 10 m water depth. The lower panel shows a comparison between measured and simulated significant wave height at Horns Rev S, (——) calculations including tide and surge and (—-) calculations excluding including tide and surge, (o) measurements

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

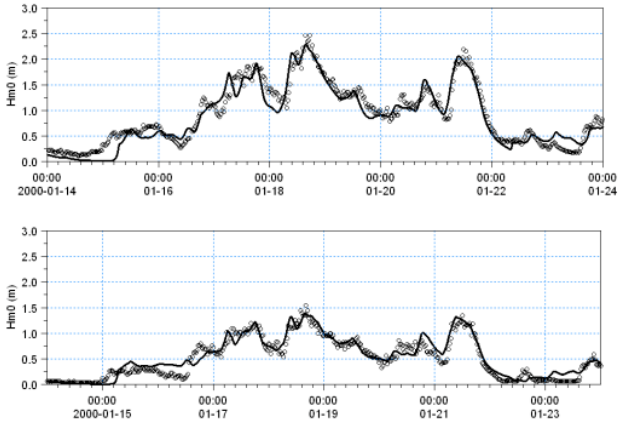
The predicted nearshore wave climate along the island of Hiddensee and the coastline of Zingst located in the micro-tidal Gellen Bay, Germany have been compared to field measurements (Sørensen et al, 2004) provided by the MORWIN project. From the illustrations it can be seen that the wave conditions are well reproduced both offshore and in more shallow water near the shore. The RMS values (on significant wave height) are less than 0.25m at all five stations.



A MIKE 21 SW hindcast application in the Baltic Sea. The upper chart shows the bathymetry and the middle and lower charts show the computational mesh. The lower chart indicates the location of the measurement stations

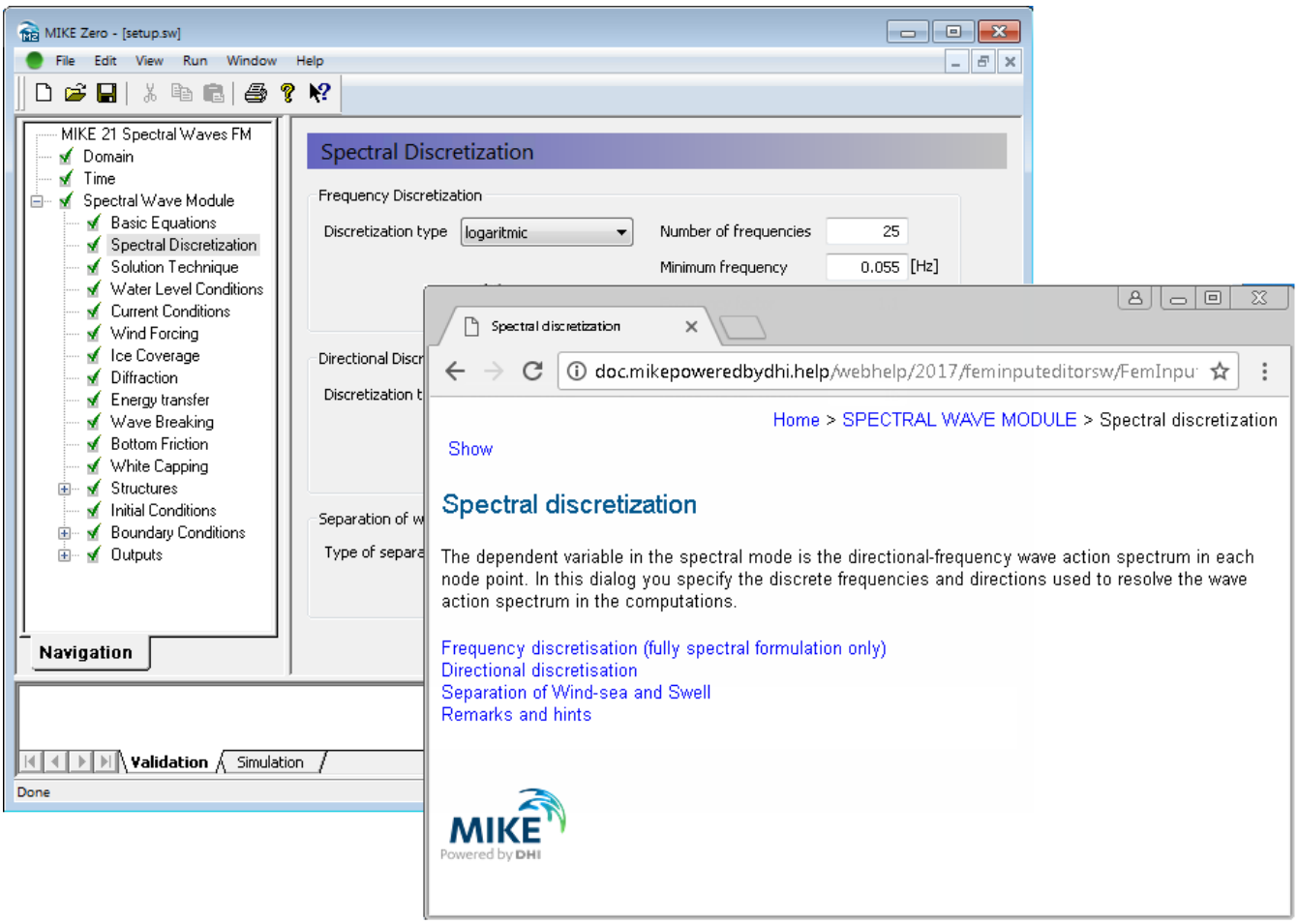


Time series of significant wave height, H_{m0}, peak wave period, T_p , and mean wave direction, MWD, at Darss sill (Offshore, depth 20.5 m). (——) Calculation and (o) measurements. The RMS value on H_{m0} is approximately 0.2 m



Time series of significant wave height, H_{m0}, at Gellen (upper, depth 8.3m) and Bock (lower, depth 5.5 m). (——) Calculation and (o) measurements. The RMS value on H_{m0} is approximately 0.15 m

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E



Graphical user interface of MIKE 21 SW, including an example of the Online Help System

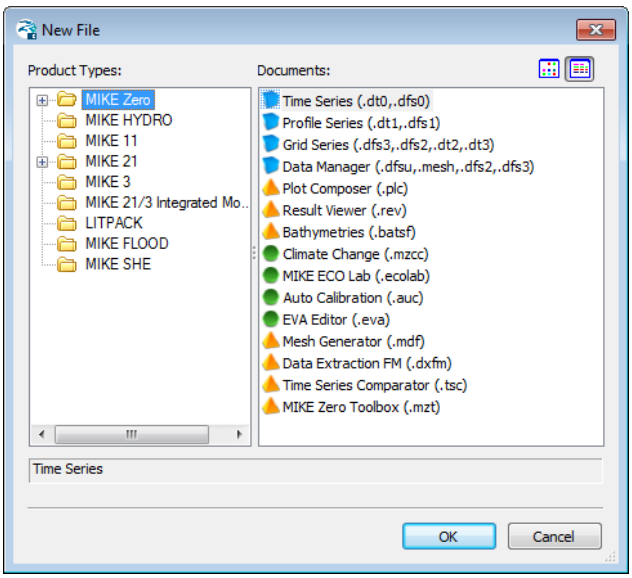
Graphical User Interface

MIKE 21 SW is operated through a fully Windows integrated Graphical User Interface (GUI). Support is provided at each stage by an Online Help System.

The common MIKE Zero shell provides entries for common data file editors, plotting facilities and a toolbox for/utilities as the Mesh Generator and Data Viewer.



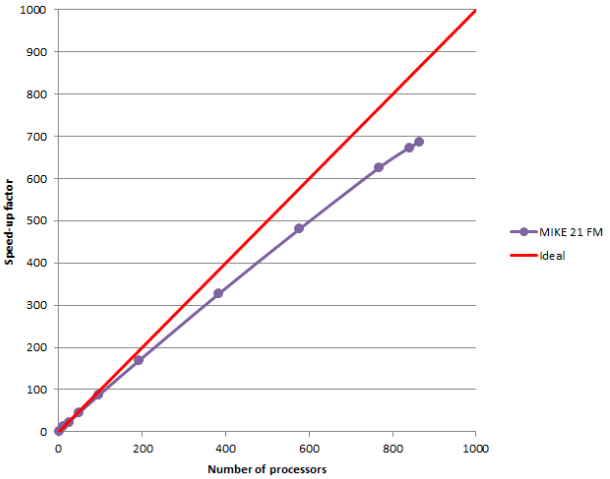
FEMA approval of the MIKE 21 package



Overview of the common MIKE Zero utilities

Parallelisation

The computational engines of the MIKE 21/3 FM series are available in versions that have been parallelised using both shared memory as well as distributed memory architecture. The latter approach allows for domain decomposition. The result is much faster simulations on systems with many cores.



Example of MIKE 21 HD FM speed-up using a HPC Cluster with distributed memory architecture (purple)

Hardware and Operating System Requirements

The MIKE Zero Modules support Microsoft Windows 7 Professional Service Pack 1 (64 bit), Windows 10 Pro (64 bit), Windows Server 2012 R2 Standard (64 bit) and Windows Server 2016 Standard (64 bit).

Microsoft Internet Explorer 9.0 (or higher) is required for network license management. An internet browser is also required for accessing the web-based documentation and online help.

The recommended minimum hardware requirements for executing the MIKE Zero modules are:

Processor:	3 GHz PC (or higher)
Memory (RAM):	2 GB (or higher)
Hard disk:	40 GB (or higher)
Monitor:	SVGA, resolution 1024x768
Graphics card: (GUI and visualisation)	64 MB RAM (256 MB RAM or higher is recommended)

Support

News about new features, applications, papers, updates, patches, etc. are available here:

www.mikepoweredbydhi.com/Download/DocumentsAndTools.aspx

For further information on MIKE 21 SW, please contact your local DHI office or the support centre:

MIKE Powered by DHI Client Care
Agern Allé 5
DK-2970 Hørsholm
Denmark

Tel: +45 4516 9333
Fax: +45 4516 9292

mike@dhigroup.com
www.mikepoweredbydhi.com

Documentation

The MIKE 21 & MIKE 3 FM models are provided with comprehensive user guides, online help, scientific documentation, application examples and step-by-step training examples.



c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

c_d969.Comune di Genova - Prot. 08/09/2022.0338008.E

References

Sørensen, O. R., Kofoed-Hansen, H., Rugbjerg, M. and Sørensen, L.S., (2004): A Third Generation Spectral Wave Model Using an Unstructured Finite Volume Technique. In Proceedings of the 29th International Conference of Coastal Engineering, 19-24 September 2004, Lisbon, Portugal.

Johnson, H.K., and Kofoed-Hansen, H., (2000). Influence of bottom friction on sea surface roughness and its impact on shallow water wind wave modelling. *J. Phys. Oceanog.,* **30,** 1743-1756.

Johnson, H.K., Vested, H.J., Hersbach, H. Højstrup, J. and Larsen, S.E., (1999). On the coupling between wind and waves in the WAM model. *J. Atmos. Oceanic Technol.,* **16,** 1780-1790.

Johnson, H.K. (1998). On modeling wind-waves in shallow and fetch limited areas using the method of Holthuijsen, Booij and Herbers. *J. Coastal Research,* **14**, 3, 917-932.

Young, I.R., (1999). Wind generated ocean waves, in Elsevier Ocean Engineering Book Series, Volume 2, Eds. R. Bhattacharyya and M.E. McCormick, Elsevier.

Komen, G.J., Cavaleri, L., Doneland, M., Hasselmann, K., Hasselmann S. and Janssen, P.A.E.M., (1994). Dynamics and modelling of ocean waves. Cambridge University Press, UK, 560 pp.

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 Engr*., **13**, 23-54.

References on Applications

Kofoed-Hansen, H., Johnson, H.K., Højstrup, J. and Lange, B., (1998). Wind-wave modelling in waters with restricted fetches. In: Proc of 5th International Workshop on Wave Hindcasting and Forecasting, 27-30 January 1998, Melbourne, FL, USA, pp. 113-127.

Kofoed-Hansen, H, Johnson, H.K., Astrup, P. and Larsen, J., (2001). Prediction of waves and sea surface roughness in restricted coastal waters. In: Proc of 27th International Conference of Coastal Engineering, pp.1169-1182.

Al-Mashouk, M.A., Kerper, D.R. and Jacobsen, V., (1998). Red Sea Hindcast study: Development of a sea state design database for the Red Sea.. *J Saudi Aramco Technology*, **1**, 10 pp.

Rugbjerg, M., Nielsen, K., Christensen, J.H. and Jacobsen, V., (2001). Wave energy in the Danish part of the North Sea. In: Proc of 4th European Wave Energy Conference, 8 pp.