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An Assessment Study on Technical Development Of Coastal Wave Models from Meteorological Aspects

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An Assessment Study on Technical Development Of Coastal Wave Models from Meteorological Aspects

by

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A. Introduction

The purpose of this study is to suggest the feasibility of improvement of the current wave model and of future development of an advanced Coastal Wave Model (CWM). Associated manpower to achieve this effort will be estimated.

As computers evolve ever faster in speed and larger in size, sophisticated models for the coastal waves may become feasible with much higher resolution to predict those waves accurately along the coast.

For the near-term planning purpose, an upgrade of the current operational ocean wave model is strongly recommended due to the increasing accuracy of the newly implemented models at various operational centers to forecast sea states, particularly the recent developments of the nested ocean surface wave model at the National Centers of Environmental Prediction (NCEP) of the US National Oceanic and Atmospheric Administration (NOAA).

B. Operational Forecast System

An advanced operational forecast system for ocean surface waves should be an integrated system including an ocean wave model, a marine boundary-layer model, data processing software, and a verification package.

Model resolutions and effective forecast durations depend heavily on the computers the forecast system will be running.

B.a Ocean Wave Model

This model is primarily to forecast ocean surface waves over the western Pacific (coarse resolution) and the sea surrounding the Island of Taiwan (fine-resolution).

The most advanced model to forecast ocean surface waves currently running at operational forecast centers is the two-domain nesting NWW3 (NOAA Wave Watch III) model at NCEP. It is suggested to adapt the NWW3 model to the Marine Meteorology Center of the Central Weather Bureau (MMC/CWB) for operational use. The two-domain nesting configuration is arranged in the following manner. The inner domain for the sea surrounding the Island of Taiwan is nested inside of the western Pacific region (Fig, 1).

(i) Western Pacific Region:
This outer domain covers a region between 0N and 45N, and between 100E and 150E with a resolution between 0.25 and 0.5 degree. The forecast of this domain will provide not only interfacing boundary condition to the inner domain, but also the wave forecast for the western pacific region.

(ii) Taiwan Region:
This inner domain is bounded by 15N, 30N, 115E, and 130E with a resolution between 0.1 and 0.125 degree. Its lateral boundary conditions are provided by the results from the outer domain calculation.

The wave model with both outer and inner domains should be conducted twice a day at the starting times of 00Z and 12Z. Each run should include a 12-hour hindcast to assimilate available observations to a previous forecast in order to generate a better initial condition. A 120-hour (5-day) forecast should follow immediately. Computer resources should allow enough lead-time to complete these calculations and to post-process these results.

The details of the NWW3 model system and its forecasts can be found in the web-page address:

NOAA/NWS/NCEP/EMC/OMB:
http://polar.wwb.noaa.gov/waves/Welcome.html

Forecasts:
http://polar.wwb.noaa.gov/omb/products.html#waves

Model:
http://polar.wwb.noaa.gov/waves/wavewatch/wavewatch.html#documentation

References:
http://polar.wwb.noaa.gov/waves/references.html

http://polar.wwb.noaa.gov/omb/omb.notes.html

B.b Marine Boundary-Layer Model

Surface wind fields have dominant control on the surface wave calculations. Using outputs from a high-resolution numerical weather prediction (NWP) model will be ideal. However, to include high vertical resolutions in a NWP model to produce an accurate surface wind field is almost unlikely under normal NWP forecast cycles. Model vertical resolutions are not particularly designed for providing adequate surface wind field for storm surge and wave models, because NWP models generally produce model forecasts for general weather forecasts. The purpose of this model is to enhance the numerical weather products from any NWP model such that the enhanced surface wind field will provide a better input to the storm surge and ocean wave models operated at CWB/MMC. Furthermore, this marine boundary layer (MBL) model should compute the buoyancy fluxes at the ocean surface based in its vertical profiles of temperature and humidity and precipitation. Both stress and flux fields will be very useful for ocean circulation models that will be discussed later. The emphasis here is the marine boundary layer above the ocean surface. If the structure in the MBL cannot be well modeled, the hope to have an accurate wind stress and buoyancy flux fields usually diminishes quickly. Thus, a MBL model is crucial for accurate wind stress and buoyancy flux fields. Such a model will have much higher vertical resolution in the MBL than that in the free atmosphere above. Even though the MBL model will be prognostic rather than diagnostic, it will be operated offline from any NWP model operations, but will use their outputs to dynamically adjust the flow and thermal fields in the MBL to produce better wind stress and buoyancy flux fields. This model should be operated either during the NWP forecast period or some of its sub-periods.

B.c Data Collection

In any modeling system, data are required to provided initial and boundary conditions to the model and to verify model results. Idealized data are mainly for research purposes, but any operational forecast model has to have data from real observations. Although data collection over the ocean usually is much more difficult and expensive than its counterpart over the land, it is nonetheless necessary.

For ocean models, wave amplitude, wave direction, wavelength, temperature, salinity, and current are considered to describe the sea states models compute. Surface wind stress and buoyancy fluxes (such as heating/cooling and precipitation/evaporation) are computed based on the variables observed in the lower atmosphere right above the ocean. Therefore, wind, temperature, humidity, pressure and precipitation are the required parameters to be measured in the atmosphere.

Obviously, it is impossible to have observation station at each model grid to gather all those variables mentioned above. But, the more the observed data, the better the data set to initialize the model and to verify the results. One way to reduce the cost to obtain observed data sets is to exchange these data internationally with neighboring countries and major foreign forecast centers under careful arrangements.

To ensure the minimum requirement for the success of the advanced ocean wave models to be implemented at CWB/MMC, it is strongly suggested to install four operational buoy stations at the locations of NNW, NEE, SE, and SW of Taiwan within the inner domain of the nested modeling system, but far away enough from the near-shore observation stations. Combining with the existing stations of Japan (Stations 22001 and 21004) and three planned stations of PRC over Yellow Sea, East China Sea and South China Sea, these four proposed buoy stations will establish an observation network for the nested ocean wave model to be implemented at CWB/MMC.

It is well known that the observation stations (such as buoys) and the instruments installed or attached to them are extremely expensive. Usually it takes long time to repair and/or replace them, if they should be damaged or lost. Therefore, it becomes crucial to educate fishermen the importance of these equipments because they are the people is benefited the most. Furthermore, if they are willing to be trained to help some incidental maintenance, perhaps with incentive financial supplements.

Quality control (QC) of incoming data to be analyzed and used as initial and boundary conditions and for the model results verification purpose is quite critical to the success of any operational forecast. The QC methodology is to automate the analysis a human observer would use to assess the quality or acceptability of incoming data. The procedure developed for the data is to maximize the detection and flagging of erroneous data while minimizing the flagging of actual features in the data. The operational procedure to QC incorporates automation of process of quality assurance in a manner that minimizes human interaction while maintaining a high degree of flexibility through the use of configuration files with a simple and robust set of algorithms.

QC on data should occur concurrently with the ingest process and before data are used. Initially, one may ask the following questions to design a QC procedure:

- Is the observation close enough in value to the previous observation?
- Does the observation lie within a reasonable or expected range of values?
- Have this and previous observations changed enough over some past interval? And
- Is the observation close in value to the neighboring observation?

B.d Verification

Objective verification of any forecast is a necessary gauge to measure the performance of the operational forecast system. Without such a verification package, it is extremely difficult to access the success of the forecast. For future developments, it would be hard to estimate where the focus of improvements should be placed. Standard statistical tools to measure forecast accuracy, whenever observation is available, are good starting points. Bias, root-mean square error, and mean absolute error are just few examples.

C. Presentation of Marine Forecasts

The present web display at CWB/MMC has progressed significantly during last year. Display of forecast is a very important component of any forecast system. It is un-avoidable not to consider an easy and understandable display of marine observations and forecasts on line through a web page, because of the public access to the internet has become more convenient and the public demand for update information from government organizations will become more urgent than before. Of course, there are many levels of display of information. An additional internal web page containing various observations and model outputs will be a good addition and will be very helpful to weather forecasters. Furthermore, an attractive and colorful web page displaying some fundamental observations in near real time and basic forecasts of tides and wave heights. Next step should include some special warnings of severe sea states, such as typhoons during summer and northeast monsoons during winter. This effort will have high pay-off, because it not only shows the usefulness of marine observation and prediction but also demonstrate the importance of this operation. Of course, there is always worry on the accuracy of the forecasts. However, the public awareness of the accuracy and their demand for high accuracy actually are excellent support to future improvements and developments of the operational forecast system. The improvement of forecast accuracy requires more professional people and better hardware and software.

D. Future Developments

With ever increasing demand of better forecasts in accuracy and more details in items, future developments are anticipated. For CWB/MMC, the following three subjects are recommended for an early planning. They are a coastal wave model, a coastal circulation model, and a data assimilation package.

D.a Coastal Wave Model

When open-ocean waves approach the coastal waters, and when the water depth is less than a half of wavelength, the shallow water effects such as shoaling, refraction and wave breaking become important, as the waves start to feel the bottom topography along the coast.

For the Island of Taiwan, the water depth varies significantly along its unevenly curved coastal line. The influence of the bottom topography and coastal shape on surface waves are much more complex than that on its deep-water counterpart. Although basic physical processes for the coastal surface waves may not greatly different from those for the open-ocean waves, the designs of both gridnet arrangement and grid resolution for the coastal wave model require much more attention. It is therefore to suggest a fine-resolution (1-3 km) coastal wave model to cover an area about 400 km X 600 km. This model should be nested inside the nested ocean wave model described earlier to take advantage of the forecast fields from the ocean wave model as time-varying boundary conditions (Fig. 2). This effort will not only provide detailed wave forecasts over the Taiwan coastal region, but also be useful to even finer-resolution applications, such as studies of harbor design, coastal shape evolution, coastal water pollution, and off-shore development for industry use.

D.b Coastal Circulation Model

The Island of Taiwan is positioned on the western edge of the Pacific Ocean, and the famous Kuroshio running northward along the eastern coast of the island. Over the western side of Taiwan, the southward cold current and northward warm current over the shallow Taiwan Strait have their clearly seasonal variations. In addition to localized upwelling events around the island, the coastal currents are definitely not uniform. Both temporal and spatial variability of circulation is complex. Thus, a three-dimensional time-dependent ocean circulation model is necessary to describe such variability.

Over coastal waters, the interaction between waves and currents become stronger than that over the deep ocean, as the water depth becomes shallow. The coupling between waves and currents is a significant process over coastal waters. Thus, coastal circulation model should be an integral part of the operation-forecast system. The challenge to establish a coastal circulation model is great. The dynamics and thermodynamics of a coastal circulation model and model's numerical structures have been studied and matured during last 20 years to a point that such a model can supply meaningful forecasts of coastal circulations, although substantial improvements still are needed to increase the forecast accuracy.

Just like other models, this kind of models requires initial, boundary and forcing conditions. It is therefore recommended that a nested regional circulation model to be placed at the same locations of the ocean wave model. The lateral boundary conditions for the regional model can be obtained from an ocean basin model for the Pacific Ocean somewhere else. The forcing conditions at the ocean surface (both wind stress and buoyancy fluxes) can be computed by the marine boundary-layer model driven by the NWP forecast at CWB (Section B.b).

Furthermore, this set of circulation models can produce currents, temperature, and salinity in three dimensions at different time scales, i.e., short-term forecast for the coastal waters and long-term forecast for the open ocean. Cargo shipping industry and fishery business will be tremendously benefited. Moreover, the computed results from both wave and circulation models can be utilized as the lower boundary conditions for climate models. Eventually, direct coupling between ocean and atmosphere models is envisioned.

D.c Data Assimilation

With increasing availability of different observed data sets in an almost real-time fashion, to assimilate incoming data to the model execution has become an effective scheme to increase the accuracy of model results. The range of methods to assimilate real-time data is from the simple nudging, the three-dimensional variational assimilation, to the full adjoint model. Not only aggressive research is still required for the full adjoint model of any ocean wave or circulation model at this time, but also the prohibitive computer resource required should be taken into consideration. On the other hand, to test the methodology of the read-time data assimilation with simple nudging is quite feasible in the present environment, and is strongly encouraged.

E. Recommended Schedule

Year 1:

a. Implement and test NWW3 ocean wave model over the western Pacific,

b. Adapt near-surface wind fields from CWB NWP model outputs for the NWW3 ocean wave model over the western Pacific,

c. Test marine boundary-layer model over the western Pacific,

d. Plan research program for the coastal wave and circulation models,
e. Plan to acquire new observations stations (buoys).

Year 2:

a. Start operational forecast with NWW3 ocean wave model over the western Pacific,
b. Implement and test NWW3 ocean wave model over the Taiwan region,
c. Adapt near-surface wind fields from CWB NWP model outputs for the NWW3 ocean wave model over the Taiwan region,
d. Implement marine boundary-layer model over the western Pacific,
e. Test marine boundary-layer model over the Taiwan region,
f. Continue research program for the coastal wave and circulation models,
g. Continue to acquire new observations stations (buoys).

Year 3:

a. Start operational forecast with NWW3 ocean wave model over the Taiwan region,
b. Start operational use of marine boundary-layer model over the western Pacific,
c. Implement marine boundary-layer model over the Taiwan region,
d. Continue research program for the coastal wave and circulation models,
e. Start to install new observation stations (buoys),
f. Test simple verification methods.

Year 4:

a. Start operational use of marine boundary-layer model over the Taiwan region,
b. Test simple data assimilation scheme by nudging real-time data,
c. Test regional ocean circulation model over the western Pacific,
d. Continue research program for the coastal wave and circulation models,
e. Continue to install new observation stations (buoys),
f. Improve verification methods.

Year 5:

a. Implement simple data assimilation scheme to NWW3 ocean wave model over the western Pacific,
b. Implement regional ocean circulation model over the western Pacific,

c. Test regional ocean circulation model over the Taiwan region,
d. Test the coastal wave model,
e. Continue research program for the coastal wave and circulation models,
f. Finish installation new observation stations (buoys),
g. Continue to improve verification methods.

Year 6:

a. Start operational use of simple data assimilation scheme to NWW3 ocean wave model over the western Pacific,
b. Start operational forecast with regional ocean circulation model over the western Pacific,
c. Implement simple data assimilation scheme to NWW3 ocean wave model over the Taiwan region,
d. Implement regional ocean circulation model over the Taiwan region,
e. Continue to test the coastal wave model,
f. Continue research program for the coastal wave and circulation models,
g. Continue to improve verification methods.

Other remaining tasks:

a. Start operational use of simple data assimilation scheme to NWW3 ocean wave model over the Taiwan region,
b. Start operational forecast with regional ocean circulation model over the Taiwan region,
c. Implement coastal wave and circulation models, and start operational forecasts,
d. Develop simple data assimilation scheme for coastal wave and circulation models will be completed in the successive years.

Of course, during the period of this program, adjustments to this schedule may happen, and they depend on the progress of each task.

F. Estimated Manpower

The required manpower to achieve this undertaking can be estimated. CWB/MMC is in charge of the program with the assistance of experts in their respective specialties. The personal assigned to the task should take full responsibility. The details of each task depend on the purpose, method and workload, and should be planned with task leader, members and advising experts. With the understanding on the restriction on the size of governmental employees, additional personal should be added as governmental contractors. Furthermore, each task group should be retained to maintain and improve each aspect of the operational forecast system, even if this proposed program were completed. The following personal is referred to as the full-time employee (FTE).

a. Ocean wave model, coastal wave model, and data assimilation (5 FTEs),
b. Ocean circulation model and coastal circulation model (2 FTEs),
c. Marine boundary-layer model (2 FTEs),
d. Data analysis and quality control (2 FTEs),
e. Data management (1 FTE),
f. Post-processing, model output displays (1 FTE).

Each FTE is required to document each respective task.

G. Required Hardware

For the operational forecast system, not only computers for the model calculations have to be fast enough, but also the local storage facility has to be large enough for both model outputs and observed data. The local network should be well designed and tested to ensure the smooth operation of the entire system.

To enhance the quality of the initial and boundary conditions to the ocean and marine boundary-layer models, four observation stations (buoys) are strongly recommended to be installed.

H. Conclusion

The Island of Taiwan is surrounded by ocean. Ocean provides vast resources for the people on the island, such as food, energy, recreational activities and others, but it can generate large amplitude waves to damage boats, port facilities, and other destructions along the coast. It is necessary to provide sea state forecast as accurate as possible to mitigate such destruction. Numerical modeling system is a critical tool to produce such forecast, and has been constantly improved to meet the challenge of the ever-increasing use of the ocean.

For the near-term phase, the focus should be the upgrading of the current operational system itself, primarily the implementation, maintenance and verification of the advanced nested ocean-wave modeling system.

The improvements and further developments of various aspects of the system are encouraged as resources allow.

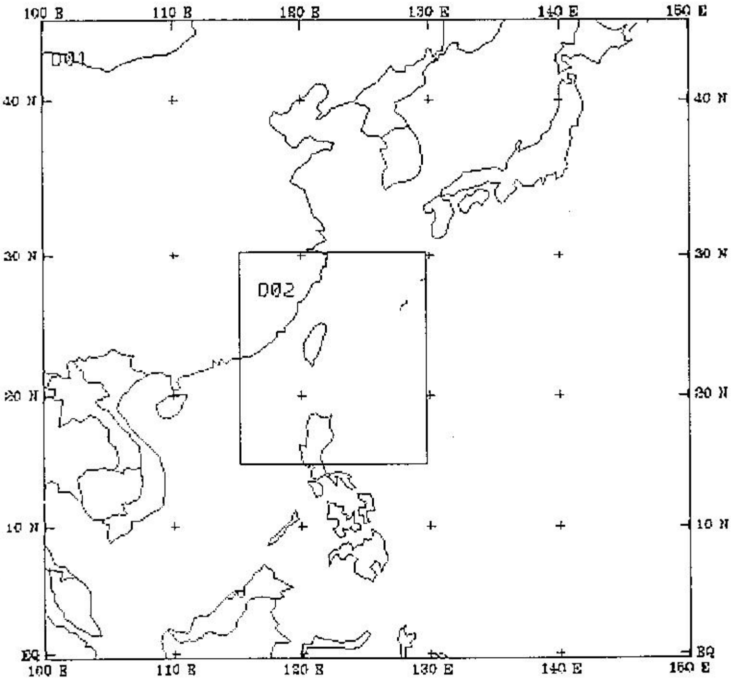

Fig. 1 The doubly nested model configuration of the western Pacific and the Taiwan regions for the ocean wave model.

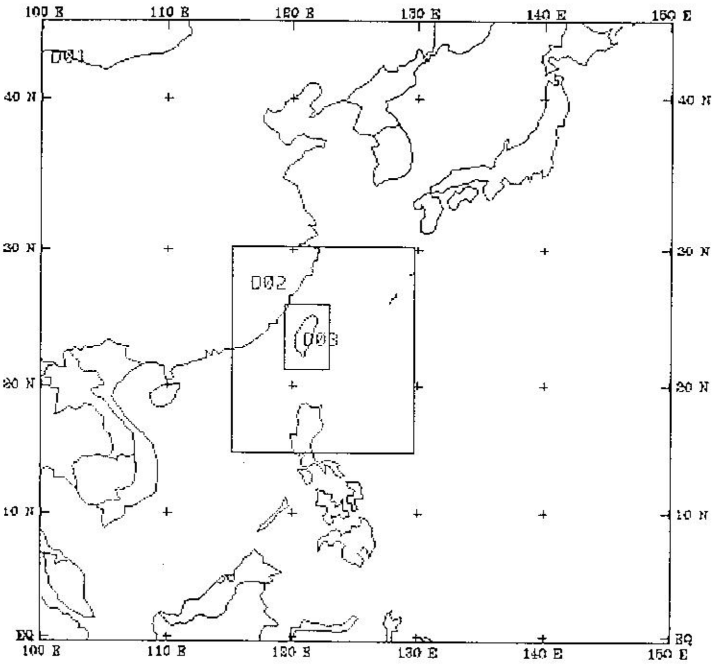

Fig. 2 The triply nested model configuration of the western Pacific, the Taiwan regions for the ocean wave model, and the Taiwan vicinity region for the coastal wave model.