Coupled Ocean Circulation and Wind-Wave Models with Data Assimilation Using Altimeter Statistics

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Abstract

Coupled ocean wave and circulation models have been implemented under the IOEPAS program (*Integrated Ocean Environment Prediction and Assimilation System)*. The third generation wave model, WAM and the South East Asian Ocean Model (SEAOM) based on the Princeton Ocean Model (POM) are coupled through wave-current interaction terms. The modeling capability has been improved from the altimeter data in terms of better boundary inputs. Data assimilation of altimeter data and physical measurements, if any, is a new feature of the prediction system. WAM and SEAOM run in parallel, exchanging data as they execute. This work is aimed at a comprehensive ocean modeling system for the regional seas surrounding Singapore waters.

Keywords: wave modeling, circulation modeling, wave-current interaction, remote sensing data, and data assimilation

1. INTRODUCTION

In the realm of geophysical modeling the current state-of-the-art models have the capability to run at very high spatial resolutions. This has led to a drastic increase in the accuracy of the physics being predicted. Due to increased numerical accuracy, once neglected effects such as non-linear feedback between different physical processes no longer need to be ignored. The ocean's deep water circulation, surface gravity waves and atmosphere above can no longer be treated as independent entities, and must be considered as a coupled system. One solution to this problem is to link models together through a series of surface variables.

A regional scale modeling system is being developed for the South China Sea, adjoining seas and shelf waters. The modeling system consists of a three-dimensional circulation model and a wave model. This system will provide the means to forecast littoral circulation and surface waves while allowing for the appropriate coupling of the circulation and wave models. Assimilation capabilities will be integrated into the system to provide means of handling open boundary conditions for coupling with larger scale models, data for initializing the model, and surface forcing of different types.

A new interface component, called the bottom module, has been developed within the ocean modeling system that feeds back bottom wave stress to the circulation model. One-way coupling provides wave-stress fields to the circulation model to calculate wave-driven currents. This study concerns the coupling between the time-stepping circulation model and the wave model WAM.

Fig. 1 shows a set of hypothetical numerical models: ocean circulation model and surface gravity wave model. Each model provides information to the centralized server, sea surface temperature (SST), wave height and direction. The wind velocities at ten meters above the surface are available in the data bank through an external source. The wave information is transformed into stresses by the radiation stress and wave stress to drive the circulation.

Real-time satellite altimeter data and MCSSTs (Multi-Channel Sea Surface Temperature) are used to generate surface ocean temperature and salinity analyses. The analyses are then assimilated into the 3D primitive equations model to produce a nowcast.

The ocean model covers South East Asian waters from 9°S to 24°N and from 99°E to 121°E with 1/6° horizontal and vertical resolutions of 22 sigma layers. The model is restarted daily from previous nowcast fields. Once the model is restarted, it continuously assimilates the temperature/salinity fields constructed from altimeter sea surface height anomaly data, and is forced by the wind surface forcing to generate a nowcast. Forecasts up to 7 days are made available.

The data assimilation scheme is: incremental adjustment with a vertical weighing function based on the oceanic variability scales. One of the grand challenges in marine research is the design and implementation of an operational monitoring system, which comprises observation of physical and bio-geochemical variables and the integration of data into operational forecasting models, and oceanographic information systems. The establishment of information systems and prediction models is a prerequisite for a sustainable utilization and management of coastal zones and of the global ocean.

A coupled ocean wave-circulation model has been developed in the present study and applied for numerical experiments for wind waves and circulation of the South East Asian Seas in order to investigate the effect of their interactions. The coupled model is based on the synchronous one-way coupling of WAM and a three-dimensional ocean circulation model (SEAOM). SEAOM is an ocean circulation model taking into account the major physical features of shelf sea, such as waves, tides, wind, ocean currents and surface heat flux.

2. MODEL DESCRIPTION

2.1 The Wave Model (WAM)

WAM is an ocean wave model incorporating the effects of only steady and inhomogeneous currents and depth on ocean waves. WAM (The WAMDI group, 1988; Komen et al., 1994) estimates the evolution of the energy spectrum for ocean waves by solving the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. Hasselmann (1963) proposed an equation for the energy balance of the wave spectrum, which is the basis for the exact theory of wave spectrum dynamics. The source function is represented as superposition of source terms due to wind input, non-linear wave-wave interaction, dissipation due to wave breaking, and bottom friction. The amalgamation of these source terms signifies the current state of understanding of the physical processes of wind waves, namely the inputs from the processes of wind field, non-linear interaction, dissipation and bottom friction balance each other to form self similar spectral shapes corresponding to the measured wind wave spectra.

2.2 South East Asia Ocean Model (SEAOM)

SEAOM is a high-resolution coastal ocean model, with a free surface, a bottom-following vertical sigma coordinate and an embedded turbulence closure scheme, which is based on the POM (Blumberg and Mellor, 1987). The horizontal spacing of 1/6 by 1/6 degree and 22-vertical sigma coordinate levels. Consequently, the model contains 133x199x22 fixed grid points. The horizontal diffusivities are modeled using the Smagorinsky (1963) form with the coefficient chosen to be 0.2 for this application.

The model was spin up from the *Levitus98* annual mean temperature and salinity fields. The surface forcing uses ECMWF monthly mean winds and relaxation to the *Levitus98* seasonal surface temperature and salinity fields.

2.2.1 Boundary Conditions

Surface Forcing

The regional monsoon circulations in the atmosphere mainly influence the ocean heat content and the transport variability in the domain. The surface stress is one of the ocean circulation generating forces depends on the wind and the sea surface roughness. The wind forcing generates the surface waves. By using the WAM model, the surface wave stress can be predicted and coupled into SEAOM at the surface.

The near real time satellite remote sensed data from TOPEX/POSEIDON and ERS-2 altimeter data is employed as the observation data for the relaxation of the temperature. The short wave radiation incident output from WAM is also used as the surface condition of temperature and salinity.

Bottom Conditions

A kind of drag law is applied in the bottom layer to represent the turbulent frictional process. The form of the bottom friction term can take either a linear (Nowlin, 1967) or nonlinear (Blumberg, 1987). Many studies adopted a friction coefficient of 0.0025. However in our study, modified Grant-Madsen analytical model (Mathisen and Madsen, 1999) for wave-current interaction, which produces values of the bottom roughness experienced by a current, the apparent bottom roughness, from knowledge of wind-wave bottom, and current bottom shear stress characteristics. These values were determined during computation of the current from their transient behavior. The wave parameters, such as the bottom orbital velocity, peak frequency and mean direction of the wave, required in this bottom module are piped in from the WAM model.

Lateral Conditions

On closed lateral boundaries, i.e., solid coastal lines, no-flux and no-slip conditions are applied for heat, salt and velocity. Boundary condition requirements at open lateral boundaries are, however, complicated and problem specific. This is because open boundary conditions have to correctly reflect the momentum and mass exchanges between the enclosed region and the outside open ocean or river. It is believed that the reliability of the model is affected primarily by the uncertainty associated with specification of open boundary conditions especially those on cross-shelf and shelf-break boundaries. In the present application of the model, the radiative boundary condition with specified volume transport is applied. When the water flows into the model domain, temperature and salinity at the open boundary are likewise prescribed from the climatological data *Levitus98*. When water flows out of the domain, the radiation condition is satisfied.

In the present study, the tidal force is also considered. The tidal elevations along the boundaries are obtained from the *TotalTide* of UK Hydrographic Office.

3. APPLICATION OF REMOTE SENSING DATA

One important element of an operational observation system is satellite remote sensing. It provides rapid global and regional views of key variables such as surface wind and waves, sea surface temperature, ice, currents, distribution of water constituents, optical properties of the sea, characteristics of shorelines and coastal zone habitats, and land use, etc. NOAA's Polar-Orbiting Operational Environmental Satellite System (POES) AVHRR / HIRS, TOPEX and ERS-2 data are used for model boundary conditions and integration of remote sensing data into numerical models for SST, wind and wave forecast and for the data assimilation.

3.1 Data Sources and Description

3.1.1 POES AVHRR / HIRS data for SST

Fifty-kilometer resolution global Sea Surface Temperature (SST) data were collected from the NOAA Satellite Active Archive (SAA). SST were estimated by using NOAA's POES AVHRR/HIRS data. It is a composite gridded-image derived from 8-km resolution Global SST observations and is generated twice weekly (Tuesday and Saturday) on a global scale. SST is defined as the sea surface temperature tuned to *in situ* data at 1-meter depth.

An important objective in satellite remote sensing is the global determination of SST. The use of satellites for the estimation of the SST has provided an enormous leap in our ability to view the spatial and temporal variation in SST. The satellite SST provides both a synoptic view of the ocean and a high frequency of repeat views, allowing the examination of basin-wide upper ocean dynamics.

3.1.2 TOPEX/ERS-2 data for significant wave height and wind speed

Combined TOPEX and ERS data were collected from Colorado Center for Astrodynamics Research (CCAR) at the University of Colorado, Boulder. The near real-time altimeter significant wave height and wind data programs use the data from the ERS and the TOPEX/POSEIDON satellite. Data files can be generated from either of these two satellites or using data from both satellites combined. The data files are generated in the same form no matter which satellite is selected. Then the generated satellite track data files can be down loaded directly from their directory. The resolutions of the data set are 0.05~0.06^o for latitude and .01~0.02^o for longitude.

The active microwave sensors onboard ERS (altimeter, scatterometer, Synthetic Aperture Radar (SAR)) and TOPEX/POSEIDON offer clear advantages for the study of marine winds and sea state. Firstly, they allow homogeneous, global and continuous coverage, at an improved resolution over conventional observations from ships and buoys. Due to frequent revisits, global wind fields from the scatterometer are likely to detect 3-4 of approximately 10 major cyclonic depressions which are over the Earth's surface at any one time, hence improving atmospheric forecasts and resultant wave fields. Wave height observations, and measurements of the period of swells generated by a far-off storm (sometimes thousands of kilometers away), can be used to improve wave forecasts - as the future sea state is dependent on accurate knowledge of the current situation.

3.2 Driving the Model with Satellite Data

The availability of global high quality data on wind and wave fields in near real time through TOPEX/ERS require the development of a suitable scheme for the rapid efficient assimilation of a high volume of data, within the lifecycle of the operational forecast. In contrast to conventional observing systems which provide wind and wave data at fixed times and locations, satellite data are generated continuously at variable locations, requiring a two to four dimensional (both space and time dependent) assimilation method, achieved by assigning weights to the various data.

Assimilation efficiency also affects the resolution at which the gridded output from the model can be provided, although this is also dependent on the complexity of the model, the size of the geographical area covered and the available computing power.

4. MODEL COUPLING: DESIGN AND IMPLEMENTATION

This section describes the model coupling procedure. Fig. 1 depicts the coupling between the wave and the hydrodynamic models. Currently the WAM-SEAOM coupling essentially involves piping WAM output into SEAOM for a more accurate prediction of oceanic variables. The output from SEAOM may also be piped into WAM in a sort of feedback pattern. The exchange of generated data between the two models happens at specified model times. The coupling is implemented in two phases. In Phase 1, SEAOM is modified to read WAM data at specified times. In Phase 2, WAM will be modified to read SEAOM output at specified times.

Due to the asynchronous nature of the data exchange between WAM and POM, the data exchange is implemented using files. This design enables WAM and POM to run independently of one another, thereby facilitating the models able to run in parallel with each other. However, WAM should run slightly ahead of SEAOM since SEAOM requires data from WAM.

The outputs from WAM and SEAOM are then converted into a format ready for visualization using various software systems like Ferret, Vis5d and other GIS (Geographical Information System) software.

In phase 1 of coupling, few subroutines were added to SEAOM to enable it to read WAM-generated data. SEAOM is able to wait a configurable length of time for a given WAM-generated file. When the wait-time expires, SEAOM continues without reading the WAM data for that particular model time-step.

5. MODEL OUTPUT

The typical output of WAM includes all wave parameters. Fig. 2 shows the wave height and direct at a particular time.

By coupling the WAM model outputs and remote sensed data, the SEAOM can predict and forecast the ocean climate in the South East Asian Seas. The typical outputs of the model are shown in Fig. 3.

6. CONCLUSIONS

A coupled ocean wave-circulation model has been implemented for the regional seas of South East Asia. The system couples a wave model (WAM) and the South East Asian Ocean Model (SEAOM) through wave-current interaction terms, which provide the forecasting or nowcasting of the surface wave, the hydrodynamics and the thermodynamics parameters in the region. The modeling capability has been improved from the altimeter data in terms of better boundary inputs. Data assimilation of altimeter data and physical measurements is a new feature of the prediction system. WAM and SEAOM can run in parallel with the exchange of data. The coupled model would able to assist in the monitoring and assessing of the ocean environment in the region.

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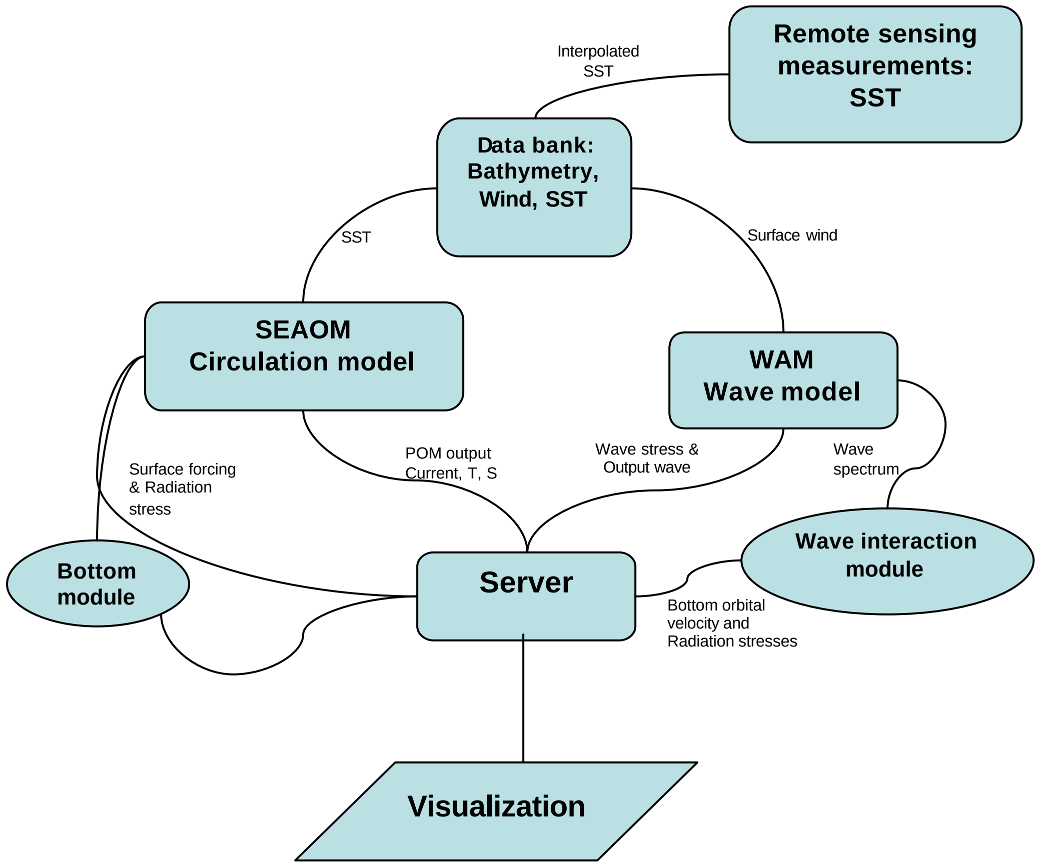

Figure 1 Coupled modeling system

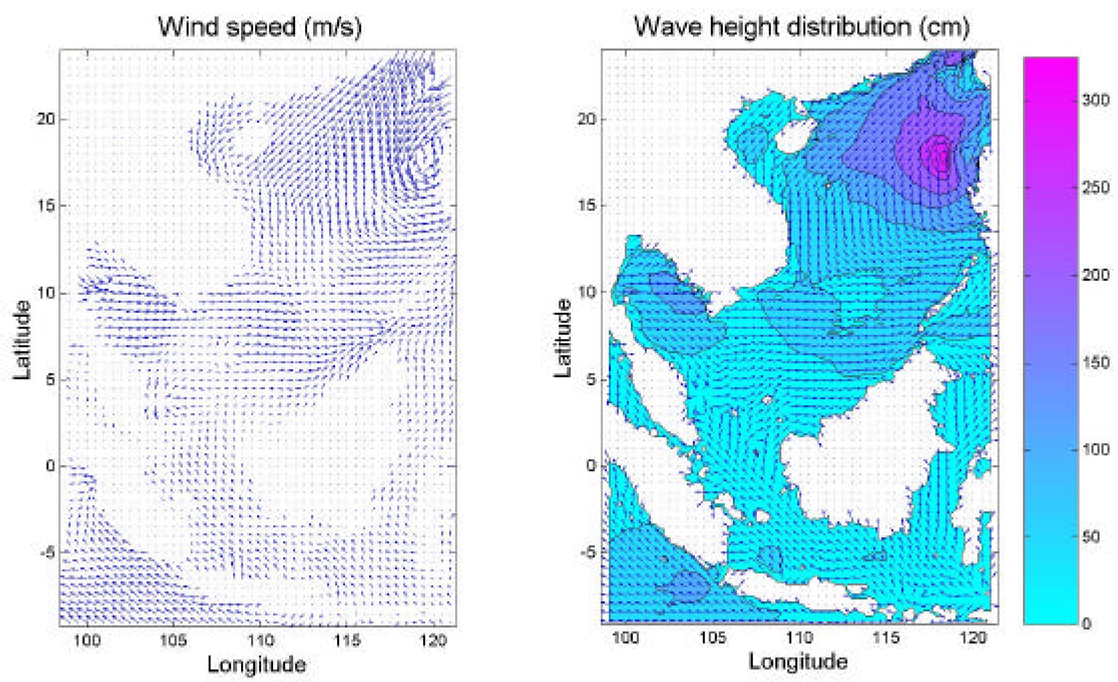

Figure 2 Typical wave height distribution for wind conditions at 00:00 hrs, 12 May 2001

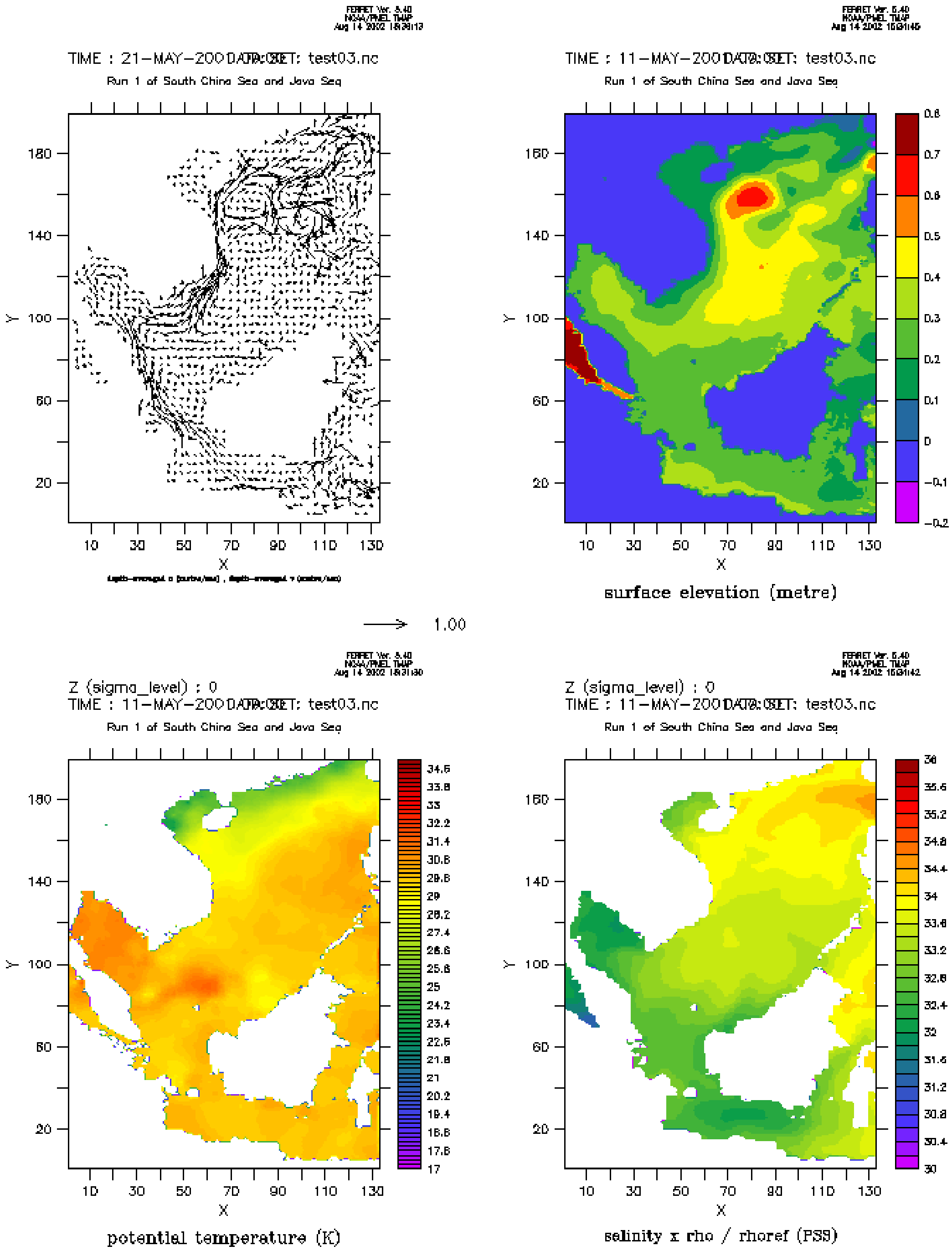

Figure 3 Typical snap shot of currents, sea surface height, temperature and salinity on 21st May 2001.