**US Army Corps
of Engineers**
Waterways Experiment
Station

Wave Information Studies of US Coastlines

Annotated Bibliography on Coastal and Ocean Data Assimilation

by   *Jon M. Hubertz, Edward F. Thompson, Harry V. Wang*

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19970303 069

Prepared for   Headquarters, U.S. Army Corps of Engineers

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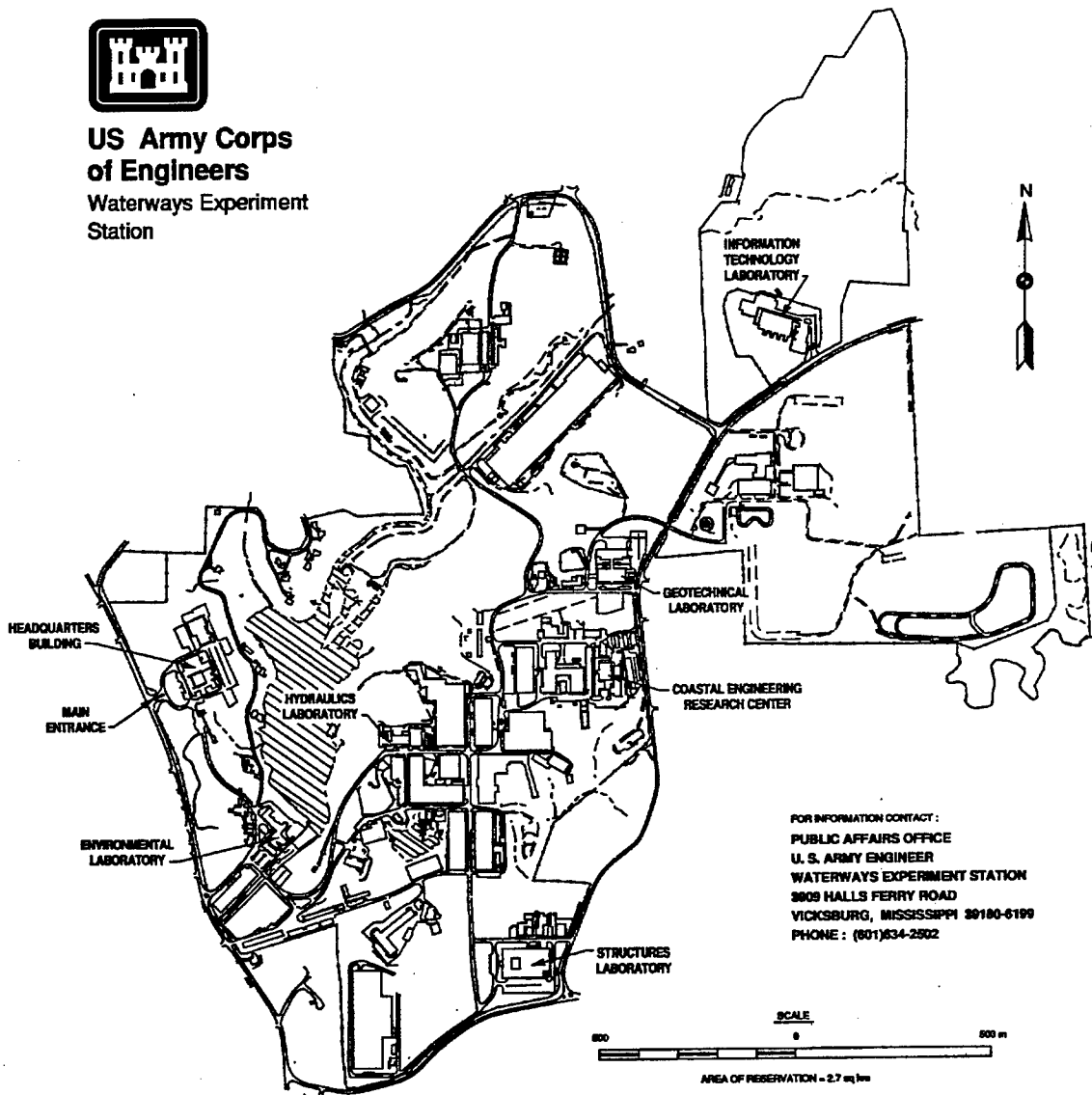3909 Halls Ferry Road
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Final report

US Army Corps
of Engineers
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Preface

In late 1976 a wave climate study for U.S. coastal waters was initiated at the U.S. Army Engineer Waterways Experiment Station (WES). The Wave Information Study (WIS) was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Coastal Field Data Collection Program, which is managed by the WES Coastal and Hydraulics Laboratory (CHL). The CHL was formed in October 1996 with the merger of the WES Coastal Engineering Research Center and Hydraulics Laboratory. Dr. James R. Houston is the Director of the CHL and Messrs. Richard A. Sager and Charles C. Calhoun, Jr., are Assistant Directors. Messrs. John H. Lockhart, Jr., Charles B. Chesnutt, and Barry W. Holliday, HQUSACE, are Program Monitors for the Coastal Field Data Collection Program; Ms. Carolyn M. Holmes, CHL, is Program Manager; and Dr. Jon M. Hubertz, CHL, is WIS Project Manager.

This report, the 36th in a series, is part of an effort to include data assimilation in the WIS hindcast procedure. The effort began in fiscal year 1995 (FY 95). WIS data assimilation milestones for FY 96 include preparation of an annotated bibliography as related to WIS needs. The scope of the bibliography is broad, including winds, water levels, and currents, as well as waves. This document serves as the milestone report. The study was conducted during the period November 1995 through April 1996.

This report was prepared by Drs. Jon M. Hubertz, Edward F. Thompson, and Harry V. Wang, all of the Coastal Oceanography Branch (COB), Research Division (RD), CHL. The work was performed under the direct supervision of Dr. Martin C. Miller, Chief, COB, and Mr. H. Lee Butler, Chief, RD.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

1 Introduction

Background

Due to advances in both measurement techniques and numerical modeling, the assimilation of atmospheric and oceanic data has experienced a remarkable growth in popularity during the last decade. In coastal engineering, with an increasing database of routine measurements supplemented by data from a number of intensive, multi-purpose experiments held at the U.S. Army Engineer Waterways Experiment Station (WES) Coastal and Hydraulics Laboratory (CHL), Field Research Facility (FRF), and several other coastal areas, and the progress made in coastal modeling systems, data assimilation is a promising tool for integrating data collection and modeling efforts.

Data assimilation is the process of incorporating observations of a dynamic system into a model of the system. The purpose is to correct a numerical simulation of a process by comparison with observations of the process. In the context of wave modeling, this is the process of incorporating observed wave information (e.g. heights and peak periods from buoys over time) into a wave model (e.g. WISWAVE, Hubertz (1992)). In the context of water level modeling, this is the process of incorporating observed water level information (e.g. tide and surge levels from gauges over time) into a hydrodynamic model (e.g. CH3D, Johnson et al. (1991)). The purpose is to use the technique to bring model results into closer agreement with observations.

Data assimilation in the geophysical sciences was first applied to the atmosphere for numerical weather forecasting. The purpose was to improve forecasts by more accurately initializing weather models and sequentially updating the models as new observations became available. It has subsequently been applied to the hydrosphere to improve water level and current predictions on water bodies of various size. The most recent application, within about the last 5 years, has been in wave forecasting.

The success of assimilation is dependent on the amount of observed data available. In weather forecasting, there is a relatively large amount of data from observations of temperature, pressure, and humidity on land and sea, and from satellites. In hydrodynamic forecasting, there are few in situ observations, but an increasingly accurate set of satellite data. Satellite data consist of sea surface elevation and temperature measurements. There is a network of tide gauges around the United States, but few current

measurement sites. Those available current measurements are near major ports to improve forecasts for navigation. Wave forecasting is similar to hydrodynamic forecasting in the amount of observed data available. There is a network of buoys near the U.S. coasts, originally designed to aid weather forecasts, but also making measurements of wave conditions. Satellite measurements of radar backscatter are translated into estimates of wave height. No wave period or direction information is generally available from satellites.

Present applications of data assimilation in the atmosphere and hydrosphere are aimed at improving *forecasts*. This is done by improving the accuracy of the initial conditions of a model before it marches forward in time. In weather forecasting, the set of observed variables used to improve input conditions and predicted variables are the same. In hydrodynamic and wave modeling, surface winds drive the models as well as initial conditions such as elevations, currents, and wave energy spectra. Thus, there is the opportunity to improve the driving force (surface winds) as well as other initial conditions.

Data assimilation techniques can also be used in *hindcasting* hydrodynamic and wave conditions. Hindcasting can be viewed as successive applications of a forecast model at an initial state. Weather forecasters produce an analysis of the atmosphere every 12 hr using all available observations. This analysis is the initial state for the weather forecast model. The surface winds from these analyses can be input successively to hydrodynamic and wave models to reproduce water levels, currents, and wave conditions coincident with the surface winds. These results constitute a hindcast for the historical period of record. It is in this mode that the Wave Information Study (WIS) group seeks to improve hindcasts of wave and hydrodynamic conditions.

Assimilation techniques will be used to improve both input to models and model products, namely surface wind fields, wave and water elevations, and current conditions. The Coastal Engineering Data Retrieval System (Jones 1995) provides a convenient source of measured data to use with the assimilation techniques.

Assimilation Techniques

All data assimilation techniques attempt to improve the results of a model by using some technique to minimize the difference between model results and a set of observations of model variables in space and time that are considered more accurate than model values.

Data assimilation approaches can be grouped into two general categories. One is referred to as *sequential* and the other *variational*. A number of different approaches are included in the sequential method. These are, in ascending order of complexity: direct insertion, blending, nudging, optimal interpolation, successive corrections, and Kalman filtering.

Direct insertion consists of simply replacing the value of a variable calculated by a model by a measured value of the variable. In wave and water level applications, this would consist of replacing a modeled wave height, period, or direction at a grid point by values measured at a nearby buoy at the same time, or water level at a node by a nearby tide gauge measurement. If one assumes the error in measurement is less than modeling error, this certainly improves the answer at the location and time, but does nothing for surrounding points or subsequent times. It will also most likely introduce an unsmooth character to the variable in time and space. There is generally a sparseness in space of wave and water level data, so any improvement in model results would be limited.

Blending consists of combining model and measured values at a point and time by weighting their value. For example, if a measurement were available interior to four grid points, a spatially weighted value could be calculated to modify values at the grid points. This would also apply to time, if the measured value was between model output time levels. This approach would spread the influence of measurements, but be limited by their distribution in space and time.

Nudging is a technique which introduces an extra term in the prognostic equation for a variable of the form: (relaxation function) times (difference between model value and measured value of variable). The nudging term is intended to adjust the solution for model variable to agree with observations available in space and time. Since this is done as part of the calculation in the prognostic equation, the measured data have a broader influence over the grid region. The relaxation function is usually chosen by trial and can be a constant or function of space and time.

Optimal interpolation (OI) is a technique, which as the name implies, produces a model result in which the differences between measurements and model results are minimized. These differences are referred to as cost functions. OI is dependent on developing a matrix of interpolation weights which is optimal in reducing differences between model and measured data. This matrix is developed from a statistical model of the error covariances under certain assumptions. If the information contained in the error covariance matrix is based on empirical weights, optimal interpolation is referred to as a successive correction method. If the error covariances are calculated explicitly, the optimal interpolation is referred to as a Kalman filter.

The above techniques are termed *sequential* since they use observations to improve model results only at the times they occur. Current observations are discarded as soon as they are assimilated. Their success increases with the number of observations in space at each time data are assimilated. However, as the number of observations increases, computational cost also increases, especially for techniques like the Kalman filter where covariances are calculated.

An alternative to the sequential, statistical methods is the *variational* approach. The *adjoint method* is a commonly used variational approach. The adjoint method considers a set of observations in space over a certain time interval which by ergodicity is equivalent to a distribution in probability space. Again, the objective is to minimize the difference between

model results and observations or a cost function. This is done by solving a set of equations consisting of the model equations and adjoint equations. The adjoint equations are formed by differentiating the cost functions with respect to a control variable and setting the result equal to zero. (Recall from differential calculus that a minimum of a function is equivalent to the derivative equal to zero.) This differentiation can be very difficult due to the dynamical coupling between state variables in the cost function (e.g. wave height) and control variables (e.g. wind speed). However, there are mathematical approaches for addressing these problems.

Objectives in Using Data Assimilation

The most important components of the Field Data Collection Program are the support provided by the Field Wave Gaging Program to continue wave measurements along the U.S. coasts, and the WIS, which provides hindcast wave information continuously in time at fixed locations. To date, the measured products have only been used to establish error bounds for the hindcast data through validation studies. One objective of pursuing data assimilation is to make more extensive use of the measurements to improve wave hindcast results.

The measurement program also includes wind information. Using data assimilation with this information and the global surface winds in the WIS database can improve the wind products used by WIS to drive the wave and water level models used in the nowcasts. The accuracy of ocean response models is directly related to the quality of wind input. Thus, a second objective is to improve both wave and water level information by improving input to these models.

A third objective is to continue to build a knowledge base of data assimilation and develop ties with others working in the area. This will ultimately benefit those who attempt to *predict* wave and water level conditions, including military applications at CHL.

Description of Annotated Bibliography

The following chapters provide an annotated bibliography on the subject of coastal and ocean data assimilation. Items included in the bibliography are selected to represent the present state of the art relative to the desired WIS applications. No effort is made to provide a complete listing of items in the field. Although most of the bibliographic items were published in the 1990's, several historical items of particular importance are also included.

Each bibliographic item includes the following information:

a. Complete citation.

b. List of key words relative to the objectives of this report.

c. Summary, with emphasis on areas which relate to the objectives
       of this report.

   d. A brief statement of the significance of the item to coastal
       engineering applications, particularly the WIS effort.

   Chapter 2 gives items with broad coverage of data assimilation tech-
niques and detailed explanations. These comprehensive items are helpful
introductory and reference works on the general subject of data assimila-
tion. Chapter 3 deals with wind data assimilation. This chapter is highly
selective. Much has been published on the subject of wind data assimila-
tion. The few items included in this report are focused on a kinematic
analysis approach, which holds promise for improving WIS wind fields.

   Chapter 4 covers wave data assimilation. Since the literature on this
subject is relatively recent and sparse, the items included provide a rela-
tively complete overview of the state of the art. Chapter 5 presents items
related to water level and current data assimilation. As with winds, the
items have been selected from a fairly extensive body of literature, but
with primary focus on the coastal ocean.

   All literature cited in the report, including the bibliographic items, is
listed in the References section, which follows Chapter 5. Appendix A is
a list of all key words used in the bibliographic items and Appendix B is a
supplementary list of additional recent references relative to water levels
and currents.

2 Annotated Bibliography – Comprehensive

BENNETT, A.F. (1992). *Inverse Methods in Physical Oceanography*, Cambridge University Press, 346 pp.

Key words: *oceanography; data assimilation; inverse methods*

Summary. Inverse methods are presented as a tool for combining oceanic observations with theoretical models of ocean circulation. The need for these methods in oceanography arises mainly from the voluminous satellite data now available. Possibilities for inverse theory are emphasized over rudimentary applications. The presentation is strongly based in mathematics, presupposing that the reader is conversant with linear algebra and advanced calculus. The material is based on lectures given to advanced graduate students in physical oceanography and to advanced undergraduates in applied mathematics.

Coastal Engineering Significance. This book gives a relatively advanced and complete development of methods for reconciling data and model dynamics to effectively estimate ocean circulation.

DALEY, R. (1991). *Atmospheric Data Analysis*, Cambridge University Press, 457 pp.

Key words: *meteorology; data assimilation*

Summary. The methodologies of atmospheric forecasting are developed. Procedures for analyzing diverse and scattered atmospheric data with concurrent modeling to produce optimum estimates of atmospheric behavior are presented in detail. Emphasis is on theoretical foundations and most of the development is analytic, but attention is also given to practical considerations. The first half of the book deals mainly with spatial analysis. The remaining chapters focus on temporal concerns, with some discussion of data assimilation. The book is intended to be suitable for graduate and upper level undergraduate students with no prior knowledge of the subject.

Coastal Engineering Significance. This book is notable for its thorough introduction to the subject of atmospheric data assimilation. It includes background material on statistical and mathematical methods to enable a novice, with careful study, to progress to a relatively sophisticated understanding of the subject.

GHIL, M., and MALANOTTE-RIZZOLI, P. (1991). "Data assimilation in meteorology and oceanography," *Advances in Geophysics*, 33, pp. 141-266.

Key words: *meteorology; oceanography; data assimilation; inverse methods*

Summary. Assimilation of atmospheric and oceanographic data is reviewed and discussed. Data assimilation in oceanography includes aspects of the stationary, solid-earth problem, in which available data can be treated with an inverse modeling approach. However, oceanography also includes some needs for data assimilation into nonstationary, dynamic models, as in meteorology. Oceanographic data assimilation is compared and contrasted with meteorological data assimilation. Main sections include a historical review of data assimilation in meteorology, comparison between the atmosphere and ocean in terms of physics and data, mathematical framework of estimation theory, meteorological applications of data assimilation, present status of oceanographic data assimilation including a literature review, and a critical discussion of the state of the art and future research needs.

Coastal Engineering Significance. This work gives a helpful perspective on the commonalities and differences between applications in meteorology and oceanography. It also gives a good and relatively complete overview of relevant data assimilation approaches. It does not address the subject of ocean waves.

KOMEN, G.J., CAVALERI, L., DONELAN, M., HASSELMANN, K., HASSELMANN, S., and JANSSEN, P.A.E.M. (1994). *Dynamics and Modeling of Ocean Waves*, Cambridge University Press, 532 pp.

Key words: *meteorology; ocean waves; wave modeling; data assimilation; inverse methods*

Summary. This book is the final report of the international Wave Modeling (WAM) group. It is designed to be a comprehensive introduction to the state of the art in wave modeling, including basic physics, modeling techniques, hindcasting/forecasting applications, satellite wave measurements, and data assimilation. An entire chapter (78 pages) is devoted to wave data assimilation and inverse modeling. An overview of the subject and methodologies is followed by more specific adaptations to wave modeling. Included are an optimal interpolation scheme for assimilating altimeter data into the WAM model, a wind and wave data assimilation scheme based on the adjoint technique (applied to a *second* generation wave model rather than the more complex third generation WAM model), and data assimilation using a Green's function approach.

Coastal Engineering Significance. This book is the primary comprehensive reference on wave data assimilation. It is relatively recent and complete in its coverage.

3 Annotated Bibliography – Winds

DEMARIA, M., ABERSON, S.D., and OOYAMA, K.V. (1992). "A nested spectral model for hurricane track forecasting," *Monthly Weather Review*, 120, pp 1628-1643.

Key words: *meteorology; hurricanes; kinematic analysis*

Summary. A numerical method for analyzing and forecasting a wide range of horizontal scales of motion is tested in a barotropic hurricane track forecast model. The system, named VICBAR (Vic Ooyama Barotropic Model), is based on the Spectral Application of Finite Element Representation (SAFER) method (Ooyama 1987) applied to a variable resolution multi-nest domain. It is tested and evaluated relative to forecasting hurricane tracks during the 1989 and 1990 hurricane seasons. Up to five nested grids with nodal spacings between 50 km and 800 km are used.

Coastal Engineering Significance. This paper describes the kinematic analysis system used by the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, for hurricane winds.

FRANKLIN, J.L., LORD, S.J., FEUER, S.E., and MARKS, F.D. (1993). "The kinematic structure of Hurricane Gloria (1985) determined from nested analyses of dropwindsonde and Doppler data," *Monthly Weather Review*, 121, pp 2433-2451.

Key words: *meteorology; hurricanes; kinematic analysis*

Summary. The structure of Hurricane Gloria is investigated by objective analysis of data from airborne Doppler radar and Omega dropwindsondes. The analysis is represented in the three-dimensional, multi-nest model of DeMaria et al. (1992) and Lord and Franklin (1987), based on the objective analysis approach of Ooyama (1987). Small-scale motions are filtered from analyzed winds according to the spatial density of observations and model nest constraints.

Coastal Engineering Significance. This paper illustrates the kinematic analysis system used by the NOAA Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, for hurricane winds. It is a powerful system for reconstructing hurricane wind fields.

LORD, S.J., and FRANKLIN, J.L. (1987). "The environment of Hurricane Debby (1982); Part I: Winds," *Monthly Weather Review*, 115, pp. 2760-2780.

Key words: *meteorology; hurricanes; kinematic analysis*

Summary. The mechanical interpolation method of Ooyama (1987) is extended to a nested kinematic analysis system to take advantage of denser data coverage in regions of greater spatial variability. Horizontal wind fields at different levels are combined and adjusted for vertical continuity to produce a three-dimensional analysis. High-resolution analyzed wind fields produced by the system with three nested grids are used to diagnose and forecast tropical cyclone motion for Hurricane Debby.

Coastal Engineering Significance. This paper is a key step in the development of the kinematic analysis system of the NOAA Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division, for hurricane winds.

LORENC, A.C. (1981). "A global three-dimensional multivariate statistical interpolation scheme," *Monthly Weather Review*, 109, 701-721.

Key words: *meteorology; data assimilation*

Summary. A three-dimensional optimum interpolation scheme for data assimilation is described and tested. The scheme was developed in conjunction with the European Centre for Medium Range Weather Forecasts (ECMWF) operational forecast model. Its development was also motivated by a need to analyze data from the first GARP global experiment.

Coastal Engineering Significance. This paper is a frequently referenced, seminal work in the field of meteorological data assimilation.

OCEANWEATHER, INC. (1993). "Development and initial test against SWADE of an interactive objective kinematic analysis program for marine surface wind field analysis," final report submitted under contract DACW 3992-C-0091 (unpublished).

Key words: *meteorology; kinematic analysis; data assimilation*

Summary. The Interactive Objective Kinematic Analysis (IOKA) method is a tool for generating accurate vector wind fields for numerical modeling. The method takes advantage of three key sources of information: wind measurements, judgement of a meteorologist, and initial model wind fields. The IOKA attempts to assimilate information from all three sources in an optimum way. An analyzed wind field is determined such that differentially weighted squared differences between the analyzed wind field and available information are minimized. The objective analysis is based on the approach of Ooyama (1987). The IOKA method is briefly described and illustrated with test case IOP-1 from the Surface Wave Dynamics Experiment (SWADE).

Coastal Engineering Significance. The IOKA has potential for being an affordable, practical tool for upgrading wind analyses in coastal engineering

applications. It can be used to adjust model surface wind fields (such as the NMC nowcasts) to be more consistent with measurements taken at and near synoptic times. It also provides a convenient mechanism for introducing judgement about the actual, detailed wind field structure at times of special interest, such as major storms or field experiments.

OOYAMA, K.V. (1987). "Scale-controlled objective analysis," *Monthly Weather Review*, 115, pp. 2479-2506.

Key words: *meteorology; kinematic analysis; data assimilation*

Summary. Objective, kinematic procedures are presented for developing optimum wind fields from available, undersampled data. Detailed consideration is given to determining spatial scales which can be resolved from the data and removing smaller scale variations from the analyzed wind fields. The study arose from the need for spatial analysis of upper-air sounding data from the GARP Atlantic Tropical Experiment. A general method for spatially filtered mechanical interpolation of irregularly distributed data in a finite domain is presented in the appendix. The method uses a least-squares fitting algorithm combined with a spatial derivative constraint term. The derivative constraint acts as a spatial low-pass filter.

Coastal Engineering Significance. The developments regarding resolvable spatial scales in data assimilation are pertinent to wind fields for wave modeling. The methodology given in the appendix is especially flexible and adaptable to subregions over which winds are often needed for coastal engineering applications. The method is purely mechanical and does not include any consideration of process dynamics.

4 Annotated Bibliography – Waves

BAUER, E., HASSELMANN, S., HASSELMANN, K., and GRABER, H.C. (1992). "Validation and assimilation of SEASAT altimeter wave heights using the WAM wave model," *Journal of Geophysical Research*, 97(C8), pp. 12671-12682.

Key words: *wave data; data assimilation; SEASAT; WAM*

Summary. Most of this paper compares winds and waves derived from the SEASAT scatterometer and altimeter to wind products from Goddard Laboratory for Atmospheres (GLA), the European Center for Medium Range Forecasts (ECMWF), and results from the international Wave Modeling group (WAM). A smaller section is devoted to data assimilation. Wave heights from the SEASAT altimeter are compared to those from WAM. A correction factor is determined based on the difference between the two wave heights, and the distance of the WAM grid point from the location of the altimeter measurement. The WAM spectrum is adjusted across frequencies and direction by the correction factor. The WAM results were improved particularly in the swell portion of the spectrum, but the wind sea portion continued to be biased low with respect to the altimeter data when additional data in time was not introduced to correct the model.

Coastal Engineering Significance. This approach is good in the sense that it treats a spectrum, but lacking in the assumption that energy at all frequencies and directions is adjusted uniformly based on the integrated quantity wave height. There is also some subjectivity in the spacial scales of influence. If spectral data were available, for example from buoys, the model spectra could be adjusted by frequency and direction to the measured data through the same approach. The problem then would be how to influence model spectra away from the measurement point to spread the correction in space.

BAUER, E., HASSELMANN, K., YOUNG, I.R., and HASSELMANN, S. (1996). "Assimilation of wave data into the wave model WAM using an impulse response function method," *Journal of Geophysical Research*, 101(C2), pp. 3801-3816.

Key words: *wave data; data assimilation; spectra; SAR; ERS*

<u>Summary.</u> Directional wave spectra derived from synthetic aperature radar (SAR) measurements from the earth remote sensing satellite (ERS) are used with results from the third generation wave model WAM to improve both wave model results and the wind fields forcing the wave model. It is assumed that wave spectra are the result of, and respond quickly to, local winds. A linearized relation between the wind and wave spectrum is solved for the wind producing the SAR-derived wave spectrum. The modified wind field can then be reintroduced to the wave model to generate improved wave results.

<u>Coastal Engineering Significance.</u> This approach potentially allows one to improve both wind and wave results, including the full wave spectrum. However, it is limited by the assumption that waves are the immediate result of local winds. One would have to treat swell arriving from a distant storm separately. It also relies on directional spectra which are available, but less so than in situ, nondirectional measurements. If measurements were frequent and well-distributed in space, this technique might address the total spectrum including swell.

DE LAS HERAS, M.M., BURGERS, G., and JANSSEN, P.A.E.M. (1994). "Variational wave data assimilation in a third-generation wave model," *Journal of Atmospheric and Oceanic Technology*, 11, pp. 1350-1369.

Key words: *wave data; data assimilation; adjoint technique; WAM*

<u>Summary.</u> The major information in this paper is a discussion of calculation of the adjoint equations for the WAM, testing them with synthetic data, and comparing to assimilation using an optimal interpolation (OI) scheme. Tests were conducted using one grid point. The tests showed improved results over no assimilation and the OI technique, but give no indication of success in an operational mode using available measured data input. An appendix provides a detailed explanation of the construction of the adjoint for the input and dissipation terms.

<u>Coastal Engineering Significance.</u> The method discussed is certainly desirable, since it preserves the connection between winds and waves, and seems to give better results than a sequential approach such as OI. In practice, however, only the potential for improved results can be inferred. The scheme is untested in a realistic application with thousands of grid points, and a lack of data to assimilate.

DE LAS HERAS, M.M., and JANSSEN, P.A.E.M. (1992). "Data assimilation with a coupled wind-wave model," *Journal of Geophysical Research*, 97(C12), pp. 20261-20270.

Key words: *data assimilation; adjoint technique; boundary value; iterative scheme*

<u>Summary.</u> The feasibility of assimilating wind data into a coupled wind and wave model using the adjoint technique is investigated. A very simple wave model is coupled to the wind through the drag coefficient. The objective is to minimize the deviations of model results from observations by varying the wind stress as a control function. Prescribed, so-called true stress fields, are input to the wave model to obtain true wave results. Alternate stress fields, which depart from the

true, are input to the wave model to obtain model results. A cost function, which consists of the departure of the wind and wave model results from the true, is minimized by solving the adjoint of the wind and wave model to obtain improved wind and wave results. The technique works in this simple application, but depends on how often "observations" are available for assimilation, and is limited to wind sea versus swell.

Coastal Engineering Significance. The method is more of academic interest than practical application at this time. It is not clear that it could be applied to any but a simple wave model, and then the computational and memory requirements would be large. Observed data are generally not available frequently in space and time as in this hypothetical application.

ESTEVA, D. (1988). "Evaluation of preliminary experiments assimilating SEASAT significant heights into a spectral wave model," *Journal of Geophysical Research*, 93(C11), pp. 14099-14105.

Key words: *data assimilation; SEASAT; direct replacement; wave height*

Summary. This paper reports on an early remotely sensed wave data set (SEASAT 1978) assimilated into a global wave model. Significant wave height was remotely sampled every second along a track with a footprint of 2-7 km. Values were quality controlled and averages used every 3 hr and 2.5 deg when available to replace model values. Simple replacement of model values with measured values worked better than spreading the influence of measurements by blending. Improvements of results using the technique were small, and increased with more frequent insertion of values.

Coastal Engineering Significance. Improvements in the quality and quantity of satellite data, and wind and wave models may make it worthwhile to revisit this approach. Remote sensing seems to be the only way to obtain data on a global basis. The objection is that it will probably not be available on a continuous enough basis in space and time to make a really significant improvement everywhere all the time. However, this may improve in time as better data are gathered, so experiments should be made periodically to test the scheme with current data and models.

FOREMAN, S.J., HOLT, M.W., and KELSALL, S. (1994). "Preliminary assessment and use of ERS-1 altimeter wave data," *Journal of Atmospheric and Oceanic Technology*, 11, pp. 1370-1380.

Key words: *data assimilation; ERS; iterative scheme; wave height*

Summary. Wind speed and wave height sensed from the Earth Remote-sensing Satellite -1 (ERS-1) during November 1991 to January 1992 were verified with buoy measurements mainly from the NOAA program. After a calibration phase, significant wave heights were assimilated in a wave model used operationally by the United Kingdom Meteorological Office (UKMO). An iterative correction scheme was used with data collected over 12-hr periods along tracks separated by about 30 deg. Little difference in model results before and after assimilation was noted,

except for an improvement in swell energy. Wind sea at a point was scaled to the local wind speed. Sufficient swell was added to result in the ERS-1 wave height. Most improvement was noted in the central Pacific, which is subject to swell from the Northern and Southern Hemispheres.

Coastal Engineering Significance. More accurate hindcasts and forecasts of swell are important for coastal engineering. Present wave models (3G WAM and WISWAVE) seem to be deficient in this respect. Improvements using this technique would require a continuous, accurate, relatively dense set of satellite measurements for operational use. Experiments along this line of investigation should be continued using the latest satellite data.

FRANCIS, P.E., and STRATTON, R.A. (1990). "Some experiments to investigate the assimilation of SEASAT altimeter wave height data into a global wave model," *Quarterly Journal of the Royal Meteorological Society*, 116, pp. 1225-1251.

Key words: *data assimilation; SEASAT; wave height; weighted interpolation*

Summary. Five days of SEASAT data are analyzed to compare wind speed and wave height values to modeled and measured values, and to assimilate wave height data into model results. The deficiencies of satellite altimeter data are reviewed, namely large areas of ocean unsampled, infrequent resampling of the same areas in time, the experimental nature of algorithms to translate backscattter into wind speed and wave height, sampling problems transitioning from land, ice to sea, the absence of swell detection, since backscatter is related to the local wind. The assimilation scheme used is based on scaling the model spectra using the altimeter-derived wave height or wind speed, then spreading the scaled spectra to surrounding grid points using an exponential function based on distance and assumed correlation length. The greatest improvement from the scheme is in the Southern Hemispere. Modeled winds and waves in the Northern Hemisphere are generally accurate enough that the SEASAT data did not give significant improvement. Assimilation of altimeter data in shallow water areas is an unsolved problem.

Coastal Engineering Significance. Use of this early ocean remote sensing data set demonstrates the potential for improvement in model results through assimilation. The largest gains are in the Southern Hemisphere, where observations are lacking. Use of current satellite data and models may improve hindcasting of Southern Hemisphere swell.

LIONELLO, P., GUNTHER, H., and HANSEN, B. (1995). "A sequential assimilation scheme applied to global wave analysis and prediction," *Journal of Marine Systems*, 6(1-2), pp. 87-107.

Key words: *data assimilation; ERS; wave height; optimal interpolation*

Summary. This paper discusses assimilation of wave heights, from ERS-1 altimeter data on a global basis, into the WAM model for February 1992. The procedure is that of Lionello, Gunther, and Janssen

(1992). Results from the assimilation are compared to results from reference data not using assimilation, and to buoy data. There is little difference in the distribution by height category of wave heights between the reference and assimilated results. There is also little difference in scatter index based on comparison to buoy data between reference and assimilated results. Measures of bias with respect to buoy data are not consistently improved by assimilation. This apparent lack of improvement may be due to the different measurement techniques, buoy versus altimeter, space and time inconsistencies in the measurements, and adjustment of the assimilation scheme.

<u>Coastal Engineering Significance.</u> This study confirms results of a similar nature in showing the potential for improvement of results, especially in remote areas. It also emphasizes the shortcomings of altimeter data, namely lack of direction, the different response to wind sea and swell, and lack of the structure of a wave spectrum.

LIONELLO, P., GUNTHER, H., and JANSSEN, P.A.E.M. (1992). "Assimilation of altimeter data in a global third-generation wave model," *Journal of Geophysical Research*, 97(C9), pp. 14453-14474.

Key words: *data assimilation; SEASAT; spectra; optimal interpolation*

<u>Summary.</u> Wave heights derived from altimeter measurements aboard SEASAT (1978) and GEOSAT (1988) are used with a first guess global (3-deg spacing) field of wave heights from WAM to arrive at an analyzed global wave height field using optimal interpolation. WAM spectra are reconstructed using the OI wave heights to adjust the model spectra. The scheme is tested for three cases (wind sea growth, decay, and evolution in the presence of swell) using a one-grid-point version of WAM. These simple cases all showed marked success in improving results. Application to actual conditions also resulted in improvements, especially in representation of swell. Results were compared to satellite data not used in the assimilation scheme and buoy data. Some discrepencies were noted between altimeter and buoy data. It is noted that WAM has a tendency to overpredict wind sea, underpredict swell, decay energy too rapidly after a storm, and propagate energy inadequately.

<u>Coastal Engineering Significance.</u> The use of satellite data can improve wave model results, and point out weaknesses in the model. Current data should provide better coverage in space and time than that used in this study, making potential improvement even more likely. Significant improvement should be possible in Southern Hemisphere regions, which are a source of swell in mid- and northern latitudes. The joint use of buoy, satellite, and model data to determine a wave climate should result in a better product than use of only one source of information.

SNYDER, R.L., LAWSON, L.M., and LONG, R.B. (1992). "Inverse modeling of the action-balance equation; Part I: Source expansion and adjoint-model equations," *Journal of Physical Oceanography*, 22, pp 1540-1555.

Key words: *adjoint technique; wave equation*

<u>Summary.</u> The action balance equation, without propagation, is expressed in terms of series expansions for each of the source terms. These are wind input, whitecapping, and wave interactions. Bottom

friction is neglected, and deep water and a uniform wind speed and direction are assumed. The form of solution is examined for four cases. Three cases involve wind input and whitecapping, the fourth includes wave interactions. In the three cases whitecapping is uncoupled, coupled (Hasselmann's second order), and weakly coupled between frequency bands. It is noted that in the Hasselmann case, energy may dissipate rapidly in one band and not adjacent bands. The adjoint wave model equations are derived for the fourth case.

Coastal Engineering Significance. The paper gives some insight to possible forms of the source functions in a wave model, and how they may interact. Adjoint equations for a wave model are derived, which may be potentially useful. The paper does not offer any immediately useful techniques for production of improved wave results in a production hindcast or forecast mode.

THOMAS, J. (1988). "Retrieval of energy spectra from measured data for assimilation into a wave model," *Quarterly Journal of the Royal Meteorological Society*, 114, 781-800.

Key words: *data assimilation; spectra; wave data*

Summary. Three different schemes for scaling model spectra using measured spectra are discussed. Results using one of the methods are presented based on data from two buoys in the North Sea. The methods differ from simple scaling of all frequencies equally based on differences between measured and modeled wave height in that they attempt to treat only the wind sea portion of the spectrum. This portion of the spectrum is defined as those frequencies greater than 0.8 times the peak frequency and within ± 90 deg of the wind direction. Improvements were obtained using the method, but only apply to the model grid point close to the measurement. The scheme is limited by the availability of spectral data in space and time over a region, and does not treat swell specifically.

Coastal Engineering Significance. The schemes are an advance over simply scaling spectra by the differences in model and measured wave height. They would be best applied when one had data for use as a boundary condition driving a wave model. This would ensure a more accurate input wave spectrum than one without adjustment to measurements. However, unless the measurements are directional, one has to make assumptions about the directional distribution.

5 Annotated Bibliography – Water Levels and Currents

Introduction

As with winds and waves, data assimilation is a potentially valuable tool for combining data collection and modeling efforts to improve prediction of coastal currents and water levels. Therefore, a thorough literature review of the state of the art in data assimilation technology, particularly in conjunction with CHL's coastal modeling and data collection programs, is warranted. The review is focused on coastal engineering applications rather than related, broad interdisciplinary areas in which data assimilation can also be a useful tool. Selection of material is guided by three criteria: (1) availability of data; (2) candidate coastal models at CHL; and (3) associated techniques for data assimilation.

Availability of data

The largest data program at CHL is the Coastal Field Data Collection Program (CFDCP), which supports measurements along many U.S. coasts. Within CFDCP, several regional programs are coordinated with local state governments, including the Coastal Data Information Program (CDIP) along the west coast and Hawaii, and the Florida Wave Gage Program (FWGP) along Florida's east and gulf coasts. The National Oceanic and Atmospheric Administration (NOAA), National Data Buoy Center (NDBC), with partial support from the Corps of Engineers, operates intermediate-depth gauges to supplement the nearshore gauges. Additionally, NOAA's water level measurement system along all U.S. coastlines routinely provides data. Besides these large, multi-year measurement programs, CHL periodically hosts intensive multi-agency, limited area experiments at the Field Research Facility (FRF), located at Duck, NC. Past experiments include DUCK'82, DUCK'85, SUPERDUCK(1986), DELILAH (1990), and DUCK'94.

Models

The following circulation models are available at CHL:

a. DYNLET1: one-dimensional, dynamic (time-dependent) tidal model at inlets. The model is capable of simulating one-dimensional fluid flow from the ocean through a tidal inlet into back-bay regions and up tributaries. An important feature of the model is the ability to represent multi-channel inlets and over-wash in the barrier island.

b. WIFM: two-dimensional, depth averaged WES Implicit Flooding Model. The model solves a finite difference approximation of the Navier-Stokes equations for water surface displacement and vertically integrated velocity field. The model can include flooding/drying and sub-grid barriers and can simulate flow induced by wind, river discharge, and tidal forcing. Its primary application is in storm surge modeling.

c. CH3D-WES: curvilinear boundary-fitted, three-dimensional model which solves external and internal modes of the Navier-Stokes equations. The external mode consists of equations for water surface elevation and vertically integrated contravariant unit flow. The internal mode consists of three velocity components, salinity, and temperature with a turbulence closure scheme for calculating the fluctuating terms. It simulates flow induced by wind, river discharge, and tidal forcing. It has been used extensively for estuarine simulation.

d. ADCIRC: advanced circulation model for shelves, coasts, and estuaries using a finite element numerical scheme. The present version is a two-dimensional vertically averaged model which can simulate large computational domains (for example, the entire east coast of the United States) over long time periods. It has been refined for high computational efficiency and has been tested extensively for both hydrodynamic accuracy and numerical stability. It has been used for large-scale tidal calculation.

Data assimilation techniques

Data assimilation techniques can be categorized into two major approaches: (a) variational analysis, and (b) Kalman filter sequential method. Variational analysis finds the solution which provides a best fit to both the model equation and data. Best fit is defined in a weighted least-squares sense, with weights reflecting prior estimation of the various standard errors. In Kalman filtering, the model is embedded into a stochastic environment, within which system noise is introduced to take into account inaccuracy of the underlying deterministic system. Then, by using a Kalman filter, the information provided by the measured data and stochastic-dynamic model are combined to obtain an optimal estimate of the state of the system in a sequential manner. Error statistics of the numerical model are determined recursively from each previous time-step.

Since coastal engineering concerns are generally in shallow water, barotropic motions are the primary focus in choosing bibliographic items for this report. In this respect, publications by Heemink and Metzelaar (1995), Lardner (1993), and Zahel (1995) reflect general interests of applying data assimilation techniques in tidal, storm surge, and wind-driven circulation. One of the outstanding issues in coastal data assimilation is that most of the data were collected near the coast, not in the open ocean. Given the fact that numerical model solutions typically progress from open ocean toward the boundary at the coast, this means that data are generally not available inside the model domain. Thus the Kalman filter approach, which requires initial conditions to be updated from the interior, is often impractical. Items by Bennett and McIntosh (1982), Navon and Legler (1987), and Thacker and Long (1988) provide insight into the working of variational analysis with data taken at or near the model domain boundary.

For data sets collected with detailed spatial and temporal resolution, albeit in a limited area and for a relatively short duration (such as the FRF experiments), the Kalman filter method is a realistic possibility. Evensen (1992) and Heemink and Metzelaar (1995) applied Kalman filter techniques in shallow water with quasi-geostrophic equations. Holland and Malanotte-Rizzoli (1989) used a simplified version of the Kalman filter, referred to as *nudging*, in their investigation of the ocean circulation. The limited-area models are usually integrated over only a portion of the open ocean, so correct lateral boundary conditions are very important as illustrated by Seiler (1993). The item by Oliger and Sundström (1978) addresses the importance of the initial boundary value problem formulation, whether it is well- or ill-posed. Bennett (1985) has implications for measurement array design in limited-area experiments.

Data assimilation technology is progressing rapidly in terms of both methodology and observation techniques. Recent success in retrieving satellite GEOSAT data and acoustic tomography are examples. The item by Greiner and Perigaud (1994) illustrates the usage of alternative data resources. Bennett and Bauch (1992) describe development of a parallel algorithm methodology. Krüger (1993) presents an innovative optimization technique using simulated annealing. A supplementary listing of recent references related to water level and current data assimilation is included as Appendix B.

Bibliographic Items

BENNETT, A.F. (1985). "Array design by inverse methods," *Prog. Oceanog.*, 15, pp. 129-156.

Key words: *experiment design; inverse methods*

Summary. The generalized inverse method is used to assess the efficiency of instrument arrays which observe deterministic fields. Arrays considered are a combination of points at which bottom pressure is observed plus paths along which averaged barotropic velocities are observed by the acoustic tomography technique of reciprocal shooting.

The barotopic M_2 tide is used as an example of a field which is being observed by the array and for which an interpolation or smoothing is required. Treatment of individual inter-annual event observations would be similar. It is shown that the generalized inverse method for objective analysis of deterministic fields is formally identical to the Gandin (1965) method for objective analysis of random fields. Construction of the generalized inverse requires the inversion of a Hermitian positive definite matrix. Array efficiency is characterized by the number of significant eigen-values of the matrix. The admission of errors in observations and dynamics necessitates the choice of weights in a variational principle. The choice is made by prior estimation of the relative error variances. It is also necessary to choose locally singular weighting functions for the dynamics, in order to ensure non-singular interpolating or smoothing fields. Dominant array modes are defined and constructed. These are interpolating fields which make the most stable contribution to the generalized inverse. An example of inversion is carried out using simulated data.

Coastal Engineering Significance. The generalized inverse method was used to assess the efficiency of the instrument arrays. This could be beneficial for obtaining the optimal experiment design strategy for CHL and other data collection programs.

BENNETT, A.F., and BAUCH, J.R. (1992). "A parallel algorithm for variational assimilation in oceanography and meteorology," *Journal of Atmospheric and Oceanic Technology*, 9(4), pp. 426-433.

Key words: *parallel algorithm; variational assimilation*

Summary. A parallel algorithm is described for variational assimilation of observations into oceanic and atmospheric models. The algorithm may be coded first for execution on a serial computer and then modified for execution on a parallel computer such as the Intel iPSC/860. The speedup factor for parallel execution is roughly $P(2M + 3)(2M + 3P)^{-1}$, where P is the number of processors and M is the number of observations ($M \geq P$). The speedup factor approaches P from below as $M/P \rightarrow \infty$. For the sake of simplicity, the parallel algorithm is described here for a model consisting of a linear, first-order wave equation with initial and boundary conditions plus a dataset consisting of observations at isolated points in space and time. However, measurements of parallel performance are given for a nonlinear quasi-geostrophic model.

Coastal Engineering Significance. When solving the Euler-Lagrangian equations in variational assimilation, the calculation could be greatly accelerated by using a parallel algorithm for the representer function. The method could be a significant step toward developing a computationally efficient scheme for data assimilation.

BENNETT, A.F., and McINTOSH, P.C. (1982). "Open ocean modeling as an inverse problem: Tidal theory," *Journal of Physical Oceanography*, 12, pp. 1004-1018.

Key words: *weighted variational formulation; inverse methods; sea level data*

Summary. Classical models of tides in open coastal regions employ ad hoc conditions on the open boundaries instead of reliable sea level data on the coastline in order to achieve a well-posed problem. A weighted variational formulation is described here, employing both open boundary conditions and coastal data and also any flow or sea level data at isolated deepwater locations. The procedure for solving equations of the first variation is an infinite-dimensional generalization for the least-squares inverse theory for finite-dimensional systems. The classical solution is obtained as a variational solution in the limit of vanishing data weights. A more rational choice of weights may be made, based on known errors in the dynamics, boundary conditions, and data. The variational formulation provides a procedure for design of observational arrays.

Coastal Engineering Significance. This paper addresses tidal theory, inverse problem, and a theoretical technique which will permit modification of model results by using measured data in the interior and reduce dependence on unsatisfactory open boundary conditions. Coastal models DYNLET1, WIFM, and CH3D can potentially benefit from this technique for reconciliation of model results with data.

EVENSEN, G. (1992). "Using the extended Kalman filter with a multilayer quasi-geostrophic ocean model," *Journal of Geophysical Research*, 97, pp. 17905-17924.

Key words: *Kalman filter; multi-layer; quasi-geostrophic model*

Summary. Formulation of the extended Kalman filter for a multilayer nonlinear quasi-geostrophic ocean circulation model is discussed. Nonlinearity in the ocean model leads to an approximation equation for error covariance propagation, where the transition matrix is dependent on the state trajectory. This nonlinearity complicates the dynamics of the error covariance propagation, and effects which are nonexistent in linear systems contribute significantly. The transition matrix can be split into two parts, where one part results in pure evolution of error covariances in the model velocity field, and the other part contains a statistical correction term caused by nonlinearity in the model. This correction term leads to a linear unbounded instability, which is caused by the statistical linearization of the nonlinear error propagation equation. Different ways of handling this instability are discussed. Further, nonlinear small-scale instabilities also develop, since energy is accumulated at wavelengths 2 Δx, owing to the numerical discretization. These small-scale oscillations are removed with a Shapiro filter, and the effect they have on the error covariance propagation is discussed. Some data assimilation experiments are performed using the fully extended Kalman filter, to examine properties of the filter. An experiment where only the first part of the transition matrix is used to propagate the error covariances is also performed. This simplified experiment actually performs better than the full extended Kalman filter because unbounded instability associated with the statistical correction term is avoided.

Coastal Engineering Significance. Coastal engineering problems involve nonlinearity. When changing from a linear to nonlinear model representation, new, possibly significant phenomena may emerge. This

paper uses a Kalman filter technique to investigate nonlinear dynamics in the context of data assimilation.

GREINER, E., and PERIGAUD, C. (1994). "Assimilation of GEOSAT altimetric data in a nonlinear reduced-gravity model of the Indian Ocean; Part 1: Adjoint approach and model-data consistency," *Journal of Physical Oceanography*, 24, pp. 1783-1804.

Key words: *altimeter data; reduced-gravity model; adjoint technique*

Summary. GEOSAT sea-level variations are assimilated into a nonlinear shallow-water model of the Indian ocean. After spin-up, the model forced by observed winds over 1985-1988 provides a first guess for initial conditions in November 1986 and a mean thermocline depth used as a reference surface for altimetric observation. Data are assimilated during one year and north of 20 deg S. The model-data misfit is minimized using the adjoint model with respect to initial conditions and a reference surface. The assimilation algorithm converges quickly and steadily. The monthly rms difference between model and data for depth of the thermocline is reduced from 21 m to 16 m. The optimal thermocline surface is significantly affected by assimilation. Large changes occur along the paths of the through-flow and South Equatorial Current. It is found that the optimal mean state is valid only for the period of assimilation. It degrades the agreement between observations and simulations for the following year because of the large interannual event that took place over 1986-1988. With an assumed 7-cm observation error, model and data are overall consistent. But the model is fundamentally inconsistent with data in the Bay of Bengal or in the Indonesian through-flow region. Examples of erroneous conclusions about model-data consistency are given when data are assimilated with faked assumptions on the observation error structure.

Coastal Engineering Significance. GEOSAT altimetric data provide a viable data resource for use with coastal models, such as ADCIRC, WIFM, and CH3D, to obtain a realistic open boundary and initial conditions with data assimilation.

HEEMINK, A. W., and METZELAAR, I.D.M. (1995). "Data assimilation into a numerical shallow water flow model: A stochastic optimal control approach," *Journal of Marine Systems*, 6(1-2), pp. 145-158.

Key words: *storm surge; shallow-water model; stochastic optimal control approach*

Summary. Kalman filtering and model fitting can be employed to assimilate water level data into numerical shallow-water flow models. An advantage of Kalman filtering is its stochastic nature. By introducing a noise process into the system equations, it is possible to take into account inaccuracies of the underlying deterministic system. However, Kalman filtering can only be employed for linear or weakly nonlinear problems. Model fitting is more suitable for nonlinear problems but it is a deterministic method. To combine the best of both approaches, a data assimilation procedure based on stochastic optimal control theory has been developed. The new approach is applied to assimilate water level data into a storm surge prediction model.

Coastal Engineering Significance. Prediction of storm surge dealing with uncertainties from both wind field and the open boundary condition are discussed. An interesting methodology combining the best of Kalman filtering and model fitting is developed to assimilate water level data into a storm surge model.

HOLLAND, W.R., and MALANOTTE-RIZZOLI, P. (1989). "Assimilation of altimeter data into an ocean circulation model: Space versus time resolution studies," *Journal of Physical Oceanography*, 19, pp. 1507-1534.

Key words: *altimeter data; ocean circulation model; nudging technique*

Summary. The crucial question addressed in this study is: What is the effect of changing space or time resolution or both upon the success of a numerical model in reconstructing a four-dimensional picture of the ocean circulation through the assimilation of altimetric data? To answer this question, a series of numerical assimilation experiments is carried out with a three-layer, eddy-resolving, quasi-geostrophic model of ocean circulation in which space and time resolution of available data are systematically varied. In principle, assimilation of altimetric data with a simple relaxation (*nudging*) technique can be very successful in driving the assimilation model to the control run, even in the deep layer for which no data are supplied. This is achieved with a nearly perfect space-time resolution surface height data set in which data are supplied at every model grid point and every 0.5 day in time. Residual errors after 1 year of continuous assimilation amount to less than 10 percent in all three layers. These results depend on the space and time scales of motion in the region to be studied. Moreover, conclusions reached here depend, to an unknown extent, on the assimilation technique used. Better techniques might allow better differentiation between the space-time choices for TOPEX and more faithful reproduction of actual oceanic circulation.

Coastal Engineering Significance. The nudging technique, a simplified version of the Kalman filter, is used with altimeter data to investigate effects of time and space resolution on model performance. A good description of the nudging technique is presented in the Appendix.

KRÜGER, J. (1993). "Simulated annealing: A tool for data assimilation into an almost steady model state," *Journal of Physical Oceanography*, 23, pp. 679-688.

Key words: *simulated annealing; almost steady-state model*

Summary. A new method is used to calculate a steady-state best fit of a given strongly nonlinear time-dependent model to observed data. The proposed technique has a statistical nature and is known as simulated annealing. It is described in detail and two examples are presented. In the first example a simple but highly nonlinear model is considered. It is shown that simulated annealing is robust and converges to the solution, whereas the adjoint technique, a sophisticated optimization method, fails. The second example illustrates that simulated annealing is also able to handle a problem with many degrees of freedom (~4,000). The required amount of computer time is acceptable.

<u>Coastal Engineering Significance.</u> The simulated annealing technique is suggested as an alternative optimization tool because of two problems with analytic optimization methods: (1) it is not clear whether the solution belongs to a global or local minimum of the cost function; and (2) the method may fail when numerics of the model result in non-smooth behavior of the cost function. One such example in coastal engineering is the wave breaking problem.

LARDNER, R.W. (1993). "Optimal control of open boundary conditions for a numerical tidal model," *Computer Methods in Applied Mechanics and Engineering*, 102, pp. 367-387.

Key words: *optimal control; open boundary condition; tidal model*

<u>Summary.</u> A major difficulty faced by numerical models of tidal flows concerns the treatment of open boundaries. It is shown that effective control of open boundary conditions in a depth-averaged numerical tidal model can be achieved by assimilation of data from tide gauges in the interior of the region occupied by the water body. The tidal model considered is a semi-linearized one in which kinematic nonlinearities are neglected but nonlinear bottom friction is included, and the numerical scheme consists of a two-level leapfrog method. The adjoint scheme is constructed on the assumption that a certain norm of the difference between computed and observed elevations at the tidal gauges should be minimized. Numerical minimization is completed using the BFGS (Broyden-Fletcher-Goldfarb-Shanno) quasi-Newton algorithm. Effectiveness of the procedure is verified on three test problems, the first involving flow in a long narrow inlet, the second, flow in a rectangular gulf with one open side and the third, flow in a bay with a long open boundary.

<u>Coastal Engineering Significance.</u> This paper uses a variational adjoint method for assimilating interior surface elevation data into a tidal model and thus improves surface elevations on the open boundaries. The approach is important for coastal modeling such as in tidal inlets and in gulf and bay areas with a long open boundary.

NAVON, I.M., and LEGLER, D. (1987). "Conjugate-gradient methods for large-scale minimization in meteorology," *Monthly Weather Review*, 115, pp. 1479-1502.

Key words: *conjugate-gradient methods; minimization*

<u>Summary.</u> During the last few years new meteorological variational analysis methods have evolved, requiring large-scale minimization of a nonlinear objective function described in terms of discrete variables. The conjugate-gradient method was found to represent a good compromise in convergence rates and computer memory requirements between simpler and more complex methods of nonlinear optimization. In this study different available conjugate-gradient algorithms are presented with the aim of assessing their use in large-scale typical minimization problems in meteorology. Computational efficiency and accuracy are principal criteria. Four different conjugate-gradient methods, representative of up-to-date available scientific software, are compared by applying them to two different meteorological problems of interest. Conclusions

are presented as to the adequacy of the different conjugate-gradient algorithms for large-scale minimization problems in different meteorological applications.

Coastal Engineering Significance. The conjugate-gradient method is a powerful tool for large-scale, nonlinear minimization. In terms of scientific software, particular concerns are computational efficiency and accuracy. This paper addresses these important issues.

OLIGER, J., and SUNDSTRÖM, A. (1978). "Theoretical and practical aspects of some initial boundary value problems in fluid dynamics," *SIAM, Appl. Math.*, 35, pp. 419-446.

Key words: *well/ill-posedness; initial-boundary value problem*

Summary. Initial-boundary value problems for several systems of partial differential equations from fluid dynamics are discussed. Both rigid wall and open boundary problems are treated. Boundary conditions are formulated and shown to yield well-posed problems for the Eulerian equations for gas dynamics, the shallow-water equations, and linearized constant coefficient versions of the incompressible, anelastic equations. The primitive hydrostatic meteorological equations are shown to be ill-posed with any specification of local, point-wise boundary conditions. Analysis of simplified versions of this system illustrate the mechanism responsible for ill-posedness.

Coastal Engineering Significance. The treatment of open boundaries is important for modeling the finite ocean coastal area. This paper shows that local treatment of open boundaries for primitive equation models is an ill-posed problem in that it is difficult to prove that a unique solution exists that is continuously dependent on available observations.

SEILER, U. (1993). "Estimation of open boundary condition with the adjoint method," *Journal of Geophysical Research*, 98, pp. 22855-22870.

Key words: *adjoint technique; open boundary condition*

Summary. The adjoint method is used to assimilate observations into a quasi-geostrophic ocean model for a middle-latitude jet. The domain has four open boundaries. Control variables used in this study are the lateral boundary values of stream function and relative vorticity. As a basic step, simulated data are assimilated and the effects of reducing the amount of observations as well as changing their distribution in space and time are investigated. Special attention is paid to the problem of how well the unobserved parts of the model trajectory are resolved. First, data are assimilated as two-dimensional maps at certain time intervals. Subsequently, continuous assimilation is performed along satellite ground tracks. The solution deteriorates somewhat in the satellite scenario, for which the data set is relatively sparse. However, the model can still be well fitted to the "true." It is also shown that the deeper layers are constrained by the upper layer information.

Coastal Engineering Significance. The variational adjoint method is used to investigate the open boundary condition effect on the interior solution. The technique is useful for CH3D and ADCIRC dealing with open boundary conditions.

THACKER, W.C., and LONG, R.B. (1988). "Fitting dynamics to data," *Journal of Geophysical Research*, 93(C2), pp. 1227-1240.

Key words: *fitting dynamics; equatorial oceanic model; wind stress*

Summary. A formalism is presented for fitting dynamic forecast models to asynoptic data. Because of the importance of wind stress forcing in oceanic models and of the inadequacies of wind stress observations, the formalism allows an oceanic model to be fit to both oceanographic and meteorological data. Within the context of this formalism the important question of whether an asynoptic data set contains sufficient information to determine the model state completely and unambiguously is discussed. Because the information travels along wave characteristics, it is clear that for the data to be sufficient to determine the model state, they must be distributed so that every feature of the flow is seen at some time or another. Such widespread coverage of the ocean requires a data collection system that relies heavily on satellites. The formalism is illustrated using a highly truncated model of the wind-driven equatorial ocean and computational examples demonstrate how surface elevation and wind stress observations might be used to recover the model state.

Coastal Engineering Significance. Wind stress is a major forcing in coastal dynamics. Frequently the inadequacy of wind stress observations requires that coastal models be fitted to both wind and oceanic data. Surface elevation and wind data are both used in this study to fit the dynamics. A conjugate gradient descent algorithm proves to be reasonably efficient. Most coastal engineering data assimilation is done in a hindcast mode. Therefore, demands of a sequential assimilation scheme may be relaxed in favor of the best fit over a fixed time interval, as is done in this paper.

ZAHEL, W. (1995). "Assimilating ocean tide determined data into global tidal models," *Journal of Marine Systems*, 6(1-2), pp. 3-13.

Key words: *tidal model; pelagic tidal data*

Summary. A data assimilation procedure, which has successfully been applied to fictional and realistic scenarios, is applied to a 1-deg model making use of an effective iterative method for the solution of the minimization problem. Two sets of ocean tide data are used for the purpose of assimilation, the more extensive one mainly comprising pelagic together with some coastal sea surface elevation data, and the other consisting of loading gravity data. The computed O_1 and M_2 global tidal oscillation systems, namely fields of tidal elevation and loading gravity, are compared with numerous additional pelagic and coastal elevation data and with a selected number of proper gravity data, respectively. Assimilation of the two data sets leads to an enormous reduction of model errors in all oceans. Assimilating this altogether still-restricted number of data allows studying the generation of realistic tidal oscillation phenomena by individual data and comparing these data effects with those having been obtained by previous data assimilation experiments using a model with coarser grid spacing. The field of dynamical residuals resulting from data assimilation reflects the far-reaching influence of the data, and it is shown that spatially integrated work done by the

residuals contributes to an overall reduced rate of dissipation in the tidal power balance.

Coastal Engineering Significance. Improvement of prediction in global tidal models using data assimilation is of great interest to coastal model ADCIRC, which uses results of a global tidal model as open boundary conditions to simulate coastal tide and storm surge phenomena.

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References

Appendix A
Key Words

The following keywords are used with the annotated bibliography.

      Adjoint technique
      Almost steady-state model
      Altimeter data
      Boundary value
      Conjugate-gradient methods
      Data assimilation
      Direct replacement
      Equatorial oceanic model
      ERS (European Remote Sensing Satellite)
      Experiment design
      Fitting dynamics
      Hurricanes
      Initial-boundary value problem
      Inverse methods
      Iterative scheme
      Kalman filter
      Kinematic analysis
      Meteorology
      Minimization
      Multi-layer
      Nudging technique
      Ocean circulation model
      Oceanography
      Ocean waves
      Open boundary condition
      Optimal control
      Optimal interpolation
      Parallel algorithm
      Pelagic tidal data

Quasi-geostrophic model
Reduced-gravity model
SAR (Synthetic Aperture Radar)
Sea level data
SEASAT
Shallow-water model
Simulated annealing
Spectra
Stochastic optimal control approach
Storm surge
Tidal model
Variational assimilation
WAM (Wave Modeling Group)
Wave data
Wave equation
Wave height
Wave modeling
Weighted interpolation
Weighted variational formulation
Well/ill-posedness
Wind stress

Appendix B
Supplementary List
of References Related
to Water Levels and Currents

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1996	3. REPORT TYPE AND DATES COVERED Final report

4. TITLE AND SUBTITLE
Annotated Bibliography on Coastal and Ocean Data Assimilation

5. FUNDING NUMBERS

6. AUTHOR(S)
Jon M. Hubertz, Edward F. Thompson, Harry V. Wang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
WIS Report 36

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Appoved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Data assimilation, the process of incorporating observations of a dynamic system into a model of the system, is a promising tool for integrating data collection and modeling efforts. This report is an annotated bibliography on the subject of coastal and ocean data assimilation. Items included in the bibliography are selected to represent the present state of the art relative to selected applications under the Wave Information Studies (WIS) authorized by Headquarters, U.S. Army Corps of Engineers. Although most of the bibliographic items were published in the 1990's, several historical items of particular importance are also included.

14. SUBJECT TERMS
Coastal data assimilation
Data assimilation
Ocean data assimilation

15. NUMBER OF PAGES
43

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102