Wind Sea and Swell Delineation for Numerical Wave Modeling

Barbara Tracy
USACE Coastal and Hydraulics Laboratory, Vicksburg, MS

Eve Devaliere
University of North Carolina, Chapel Hill, NC

Jeffrey Hanson
USACE Field Research Facility, Duck NC

Troy Nicolini
NWS, WFO Eureka, CA

Hendrik Tolman
NOAA-NCEP-EMC, Camp Springs, MD

Introduction

Numerical wave modeling in the fields of hindcasting and forecasting produces output in the form of an energy spectrum. This energy spectrum is usually assigned a significant wave height calculated from the amount of energy in the spectrum, and a wave period and direction are assigned to this significant wave height from analysis of the energy spectrum. These definitions describe the overall situation but do not give a detailed picture of the spectrum. A spectrum is made up of an area of wind sea resulting from the prevailing winds at the same location as the spectrum in addition to many swell wave trains that have moved into the area from directions far from the site. It is helpful to know details of all the components of the spectrum to make judgments on the skill of a numerical model or to analyze wave conditions for navigation or a coastal process. A spectral partitioning method derived from the field of digital imaging (Vincent and Soille, 1991) has been adapted to produce wave partitions from a directional wave energy spectrum. This approach will be referred to as the Wave Spectrum Energy Partitioning (WaveSEP) method. A FORTRAN version of this algorithm was developed and tested at the Coastal and Hydraulics Laboratory and High Performance Computing Center at the Engineer Research and Development Center in Vicksburg, MS. This paper will discuss the implementation of the WaveSEP FORTRAN algorithm.

The WaveSEP approach has previously been implemented in a few MATLAB™ applications, including the commercial XWaves Ocean Surface Wave System Analysis Toolkit (http://www.oceanwavesystems.com/), the Wave Model Evaluation and Diagnostics System (WaveMEDS) (Hanson et al., 2006), and a new automated version (AutoMEDS) reported elsewhere in these proceedings (Devaliere et al., 2007). WaveMEDS was applied to numerical wave model output spectra and measured spectra to determine hindcasting skill between several different wave models for analysis of the Wave Information Studies (WIS)

Pacific basin hindcast (Hanson et al., 2006) and resulted in the selection of the Wavewatch III (WW3) (Tolman, 2002a) numerical wave model for WIS Pacific hindcasting. The new WaveSEP FORTRAN algorithm has been implemented in the output routines of the new Wavewatch III (W3) multi-grid numerical wave model code (Tolman, 2007) used by National Center for Environmental Prediction (NCEP) and National Oceanic and Atmospheric Administration (NOAA) for global wave forecasting applications. The WaveSEP algorithm has proven itself as a sturdy and efficient means of spectral partitioning and allows W3 to output partitioning information for all grid points in a wave hindcasting or forecasting grid. The previous version of the Wavewatch III model provided output in the form of spectral bulletins using a spectral partitioning method described by Gerling (1992). The Gerling partitioning approach identifies the various spectral peaks and assumes a parametric form for the spectral shapes. Spectral bulletin files defining the spectral partition by height, period and direction are available for the W3 output stations. The tracking and analysis was not guaranteed to work all the time (Chen et al., 1999) and required extensive computer resources.

The WaveSEP partitioning algorithm played a critical role in the development of a major new wave modeling system for use at Weather Forecast Offices (WFO) of the National Weather Service (NWS). These offices are responsible for marine forecasts extending from the shoreline to as many as 60 nautical miles out (Coastal Waters) and therefore deal with complex wind and wave climates. Meteorological features ranging in size from micro to meso scale combine with local effects to produce complex wind and wave fields over this region. The resultant locally generated wind seas and distance source swell both interact with the sea floor in this region, further complicating the job of the marine forecaster responsible for wave forecasts in the Coastal Waters. This paper will show an example of this NWS utilization of WaveSEP.

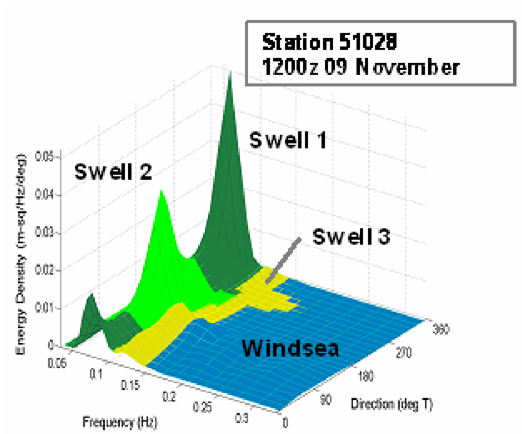

Figure 1. An example of a partitioned spectral density surface for a location near the NOAA Christmas Island buoy, 51028. Wind sea is shown in blue and several swell wave partitions are shown in two shades of green and yellow. Energy density is defined for each frequency-direction intersection.

Spectral Partitioning Method

Figure 1 shows an example surface plot of a directional wave spectrum at one geographic grid point at a specific time. The amount of energy density at each frequency-direction intersection is shown by this surface. The surface is divided into different colored areas or partitions representing energy from sub-peaks within the spectrum. Figure 1 shows four spectral partitions, an area of wind sea and three swell trains. The total energy represented by this spectrum can be defined by the bulk parameter, significant wave height. The four partition areas of the spectrum in Figure 1 can be defined by the partition wave height, peak period of partition (parabolic fit), peak wavelength of partition, mean direction of partition, wind-sea fraction of partition (W) using equation 1, and the number of partitions.

$$W = E^{-1} E |_{U_{p>C}} \qquad (1)$$

$$U_P = C_{mult} U_{10} \cos(\vartheta - \vartheta_w) \qquad (2)$$

The E in Equation 1 is the total spectral energy of a given partition. $E |_{U_{p>C}}$ represents the area in the spectral partition under direct influence of the wind. Wind influence is quantitatively determined from the wave-age relationship of Equation 2. Wave components traveling at wave phase velocities slower than U_p are considered to be forced by the wind. Here U_p is defined as the component of the wind in the wave direction multiplied by the wave age factor C_{mult} having a default value of 1.7. This representation of the wind-sea fraction, W, has been implemented in the W3 numerical wave model. W3 allows the option of changing C_{mult} to another value. The value of W allows each partition to be classified as pure wind sea (W=1), pure swell (W=0) or mixed seas.

Since the two-dimensional spectrum in Figure 1 looks very much like a topographical surface, it is logical to apply an image processing partitioning algorithm that treats the spectral surface like a topographical surface. The partitioning shown in Figure 1 is based on a digital image processing watershed algorithm (Vincent and Soille, 1991) first developed by Hanson (Personal Communication) and demonstrated by Hanson and Jensen (2004) for the analysis of ocean wave data. The continental divide where everything to the east goes into the Atlantic Ocean and everything to the west goes into the Pacific Ocean is a typical example of a watershed line. The oceans represent the bottom of the catchment areas or drainage basins. If the spectral surface is inverted, the spectral peaks become catchments and watershed lines or partition boundaries can be determined using the Vincent and Soille (1991) algorithm. This forms the basis of the WavSEP method.

Hanson and Jensen (2004) and Hanson et. al. (2006) used a MATLAB™ code to apply the WaveSEP approach. This code has now been transformed to an efficient FORTRAN routine for use in the new version of W3. Coding follows the Vincent and Soille (1991) paper but incorporates an efficient sort routine (*O*(n)) discussed in Tracy et al. (2006). In preparation for application of the algorithm, the input spectral matrix is redefined as a one-dimensional vector. The spectral values are then inverted based on the maximum and minimum energy values in the matrix. The next step is to change the one dimensional matrix to an integer vector using one hundred values. One hundred was selected after several trials. The values of the integer vector are now sorted in ascending order using the sort routine discussed in Tracy et al. (2006). The routine starts at the bottom of the integer vector and essentially "floods" the integer vector values one by one assigning partition values as it ascends. Each point has a pre-identified set of nearest neighbors to assist with location of each partition surface. All grid points within the original spectrum are now identified with a partition. Calculation of wave parameters for each spectral partition can then be accomplished and wave system analysis as described in Hanson and Phillips (2001) can be applied. Calculation of wind sea fraction, *W,* determines if the partition can be termed local wind sea. Height, period and direction parameters from analysis of the spectral partitions help to quantify the group of energy peaks that make up the full spectrum and assist with numerical model validation and comparison and the resulting analysis of the numerical model's source terms.

WIS Partitioning Example

Figures 2 and 3 show spectral partitioning results in the form of wave vectors from a W3 Pacific basin hindcast for November, 1990, at WIS station 125 (24 deg N, 157 deg W) located northeast of the island of Oahu. These results were derived from a test Pacific Basin hindcast as WIS transitions to the use of the new multi-grid W3 for WIS Pacific regional west coast hindcasts. Hanson et al. (2006) describes the WIS Pacific Basin hindcast setup. Figure 2 shows wave partitions greater than 0.5m for November, 1990. The length of each vector is proportional to the wave height of each partition and vectors show the direction the wave component is going. Each vector is also color-coded by wave height defined by a scale at the right of the plot. The y-axis sorts the wave vectors by wave period. A significant storm with 16-18 sec swell from the northwest shows up around November 25 in Figure 2. Figure 3 shows wave partitions less than 0.5m for the same time period and location using the same format as Figure 2. Small southerly swell contributions show up in this figure between November 8 and 12. Figure 4 shows the bulk wave parameters and wind information at this same station for November, 1990. WIS plans to add products to show the wave partitions at each of the WIS output stations so these can be utilized in coastal process calculations and analysis in addition to the existing bulk wave parameter descriptions already available on the WIS website: http://frf.usace.army.mil/cgi-bin/wis/atl/atl_main.html. ASCII files of these partitions will also be available. As testing continues with the WIS Pacific regional hindcast for 2000 through 2003, WaveSEP will allow extensive comparisons with all available measured information for validation of the numerical hindcast using W3.

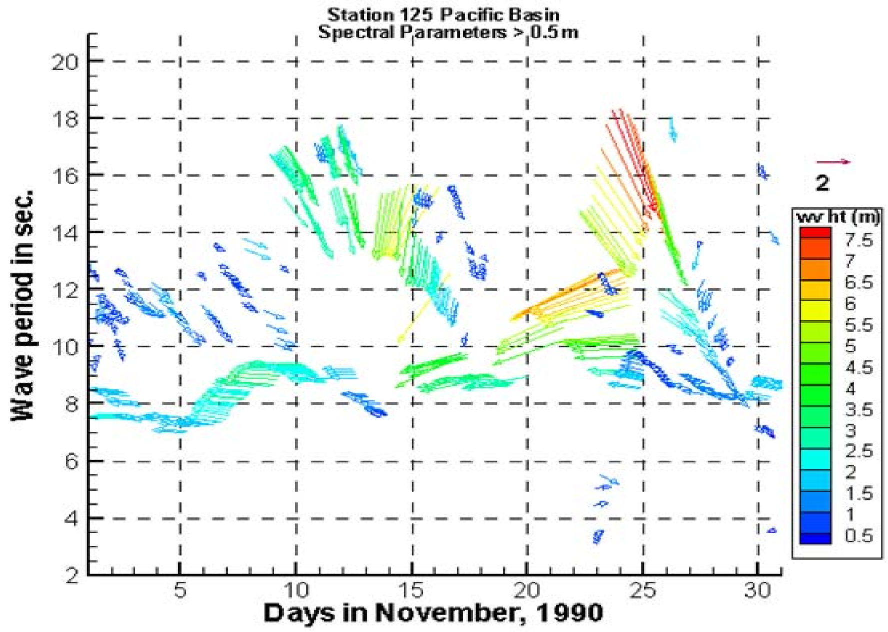

Figure 2. Spectral parameters greater than 0.5m at WIS station 125 for November, 1990.

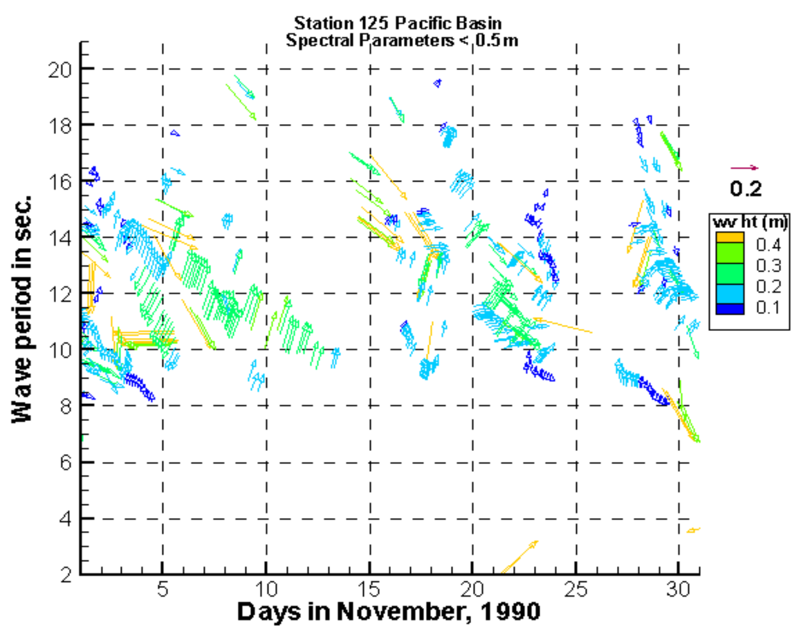

Figure 3. Spectral parameters less than 0.5m at WIS station 125 for November, 1990.

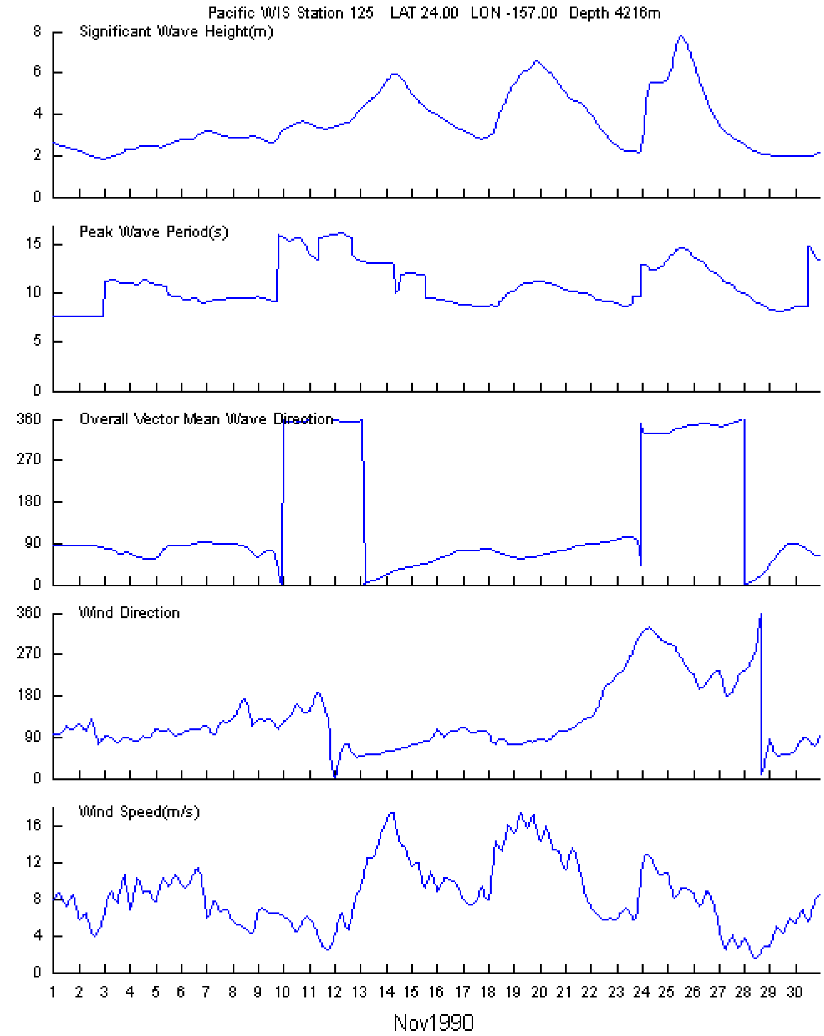

Figure 4. Plot of significant wave height, wave period, wave direction, wind speed and wind direction for WIS station 125 for November, 1990

W3 Global Hindcast Example

Global hindcast products showing results of NOAA/NCEP hindcasts using the new W3 are available on the internet: http://polar.ncep.noaa.gov/waves/index2.shtml. Spectral partitioning using the WaveSEP algorithm has been implemented and visual products showing the results of this partitioning are also available on the internet. A set of NOAA/NCEP figures showing forecasts for the northeastern Pacific Ocean has been selected to show the product display of the partitioning results. October 22, 2007, at 12Z has been selected as the example base time period and forecast results are shown for the 9, 30, 57, and 96 hour forecasts. In order to gain some understanding of the weather conditions over the Pacific at this time, Figure 5 shows the GOES-10 satellite image for 1430Z on October 23, 2007 (courtesy of Unisys/Purdue from the internet). Figure 6 shows surface level pressure fields including wind barbs (courtesy of University of Washington from the internet) for the same area for October 23, 2007. Note the Low pressure system southwest of Alaska.

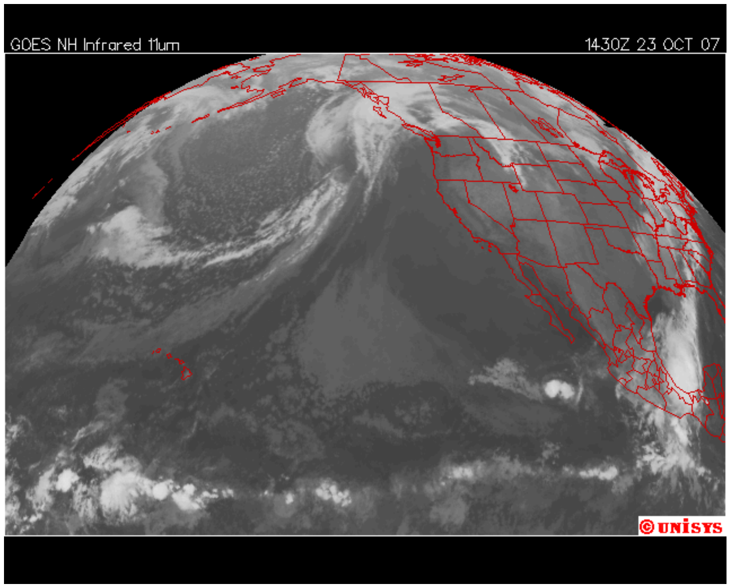

Figure 5. Northeast Pacific Ocean Infrared Satellite Image (from GOES-10 satellite)
Courtesy: UNISYS/Purdue

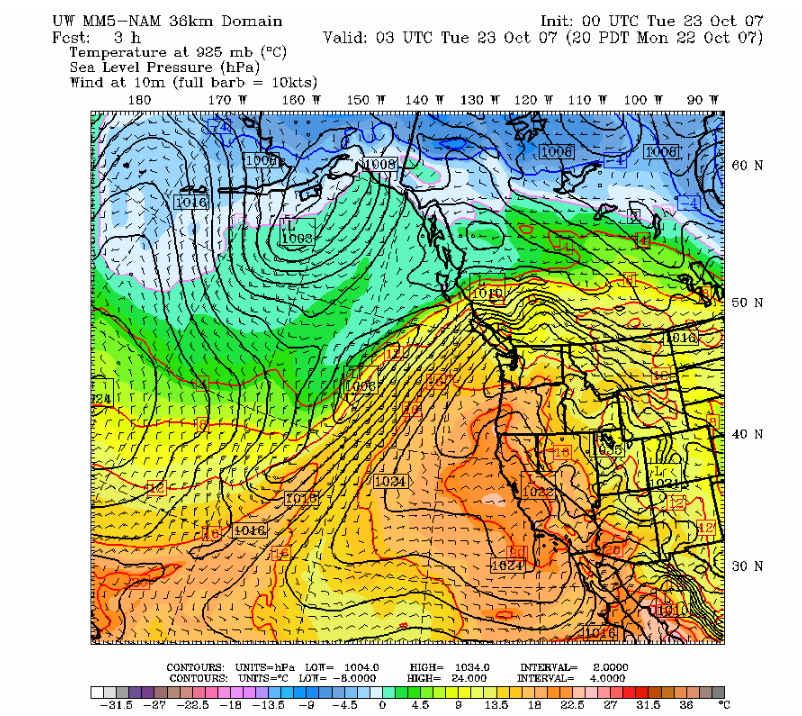

Figure 6. **Pacific MM-5 Model Surface Level Pressure (SLP) and Winds**
Courtesy: University of Washington

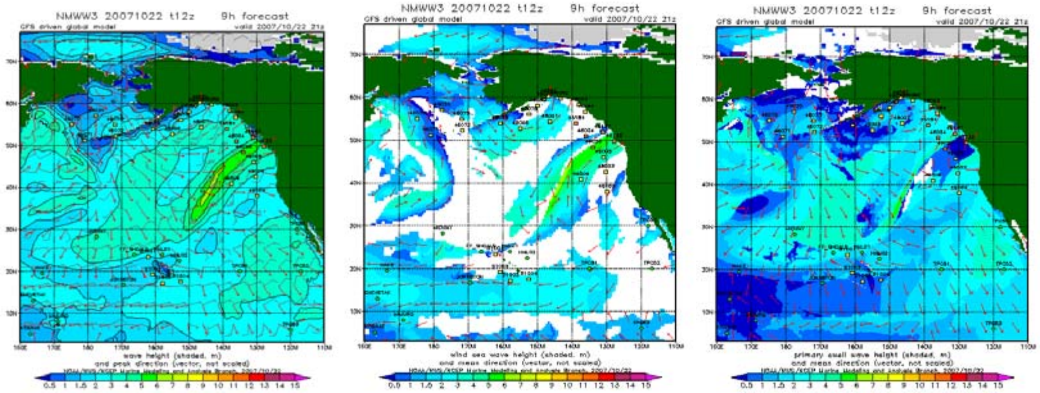

Figure 7. A 9 hour forecast for 20071022 at 12Z showing W3 numerical wave model significant wave height, wind sea wave height and primary swell wave height

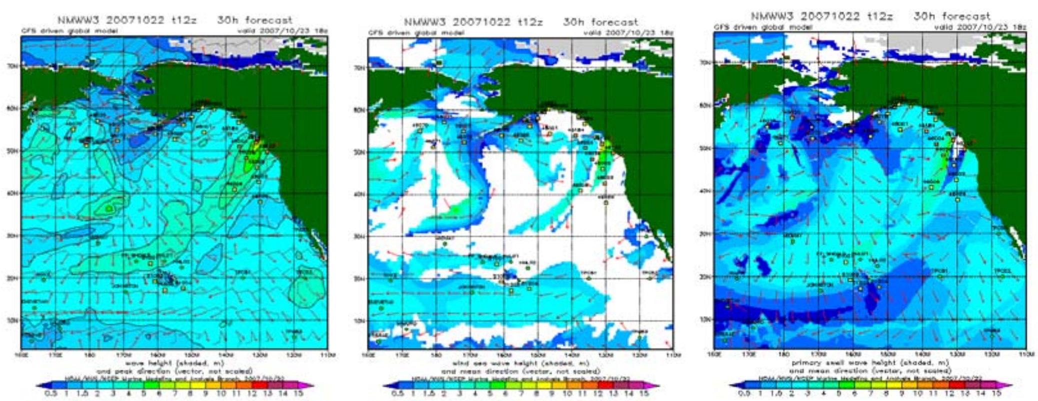

Figure 8. A 30 hour forecast for 20071022 at 12Z showing W3 numerical wave model significant wave height, wind sea wave height and primary swell wave height

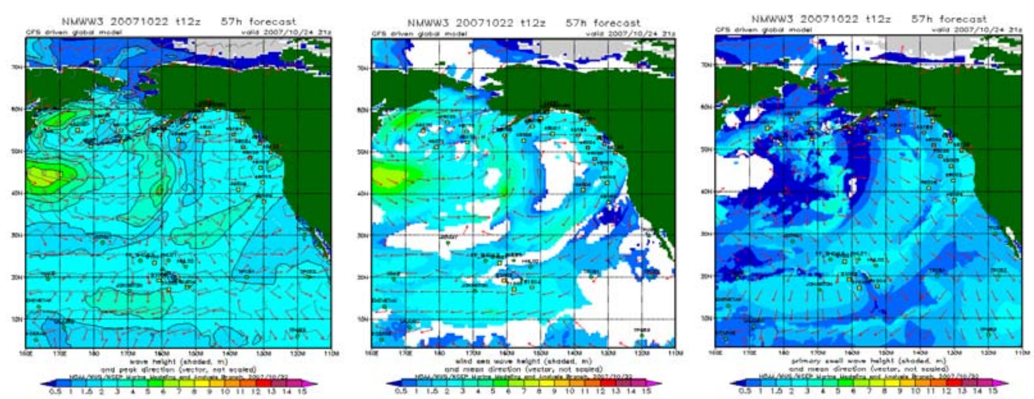

Figure 9. A 57 hour forecast for 20071022 at 12Z showing W3 numerical wave model significant wave height, wind sea wave height and primary swell wave height

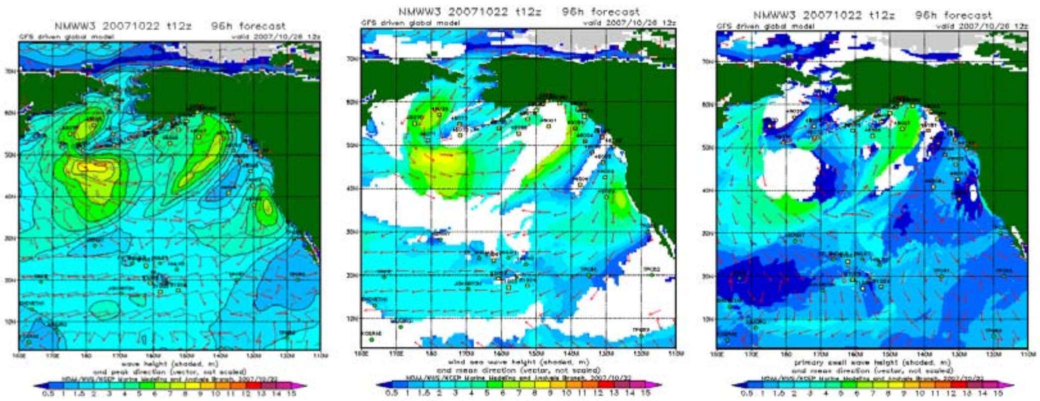

Figure 10. A 96 hour forecast for 20071022 at 12Z showing W3 numerical wave model significant wave height, wind sea wave height and primary swell wave height

Figures 7 through 10 show a series of display products available on the NOAA W3 product pages: http://polar.ncep.noaa.gov/waves/viewer.shtml? Figures 7 through 10 each show three plots for the specified hour of the forecast. The plot on the left hand side of each of these figures shows a contour plot of the significant wave height over the northeastern Pacific. Vectors are included to show the direction of the waves. The middle figure shows a contour plot of the wind sea conditions, and the plot on the far right shows a contour plot of the primary swell waves at this time. These two plots also include vectors to show the direction of the waves. These plots were taken from a series of animated plots available on the internet. Animated contour plots are also available for the Pacific, Atlantic, Gulf of Mexico and Great Lakes regions. Sub-areas close to the US coastline of these oceans are also available in addition to Australia. Contour plots of significant wave height, wind sea wave height, primary swell wave height, and secondary swell wave height are available. Wave period contour plots are also available for each of the previous wave height partitions. Wind speed and direction are also shown. WaveSEP has provided a host of products for definition and analysis of the NOAA wave forecasts.

NWS Implementation

NWS offices are using a tool developed for analysis of marine forecasts extending from the shoreline to as many as 60 nautical miles out (Coastal Waters) for areas all along the US coastline. The new wave modeling system, called Interactive Forecast Process- SWAN (IFP-SWAN), addresses the challenges of these complex wave climate areas by employing model improvements that capture the complex nearshore processes and show the results using a significantly improved partitioning approach based on the WaveSEP partitioning algorithm. Details of the SWAN numerical wave model can be found in Rogers et al., 2002. While the focus here is on the partitioning, one of the model improvements is worth mentioning because its benefits are only realized because of the enhanced partitioning. IFP-SWAN breaks from wave model tradition in that it does not only use raw atmospheric model wind data, but instead includes official gridded forecast wind data. This wind data is developed by WFO forecasters using model guidance that is blended with local knowledge of the complex wind environment in and around the Coastal Waters. Because WFO forecasters know that IFP-SWAN is being driven by their own wind forecast, they are confident that the wave output from IFP-SWAN is consistent with their official wind forecast. The real benefit of the IFP-SWAN approach, therefore, is that forecasters can use the wave model output directly in the generation of their official wave forecast with only minimal final quality control of the forecast. This benefit is only realized, however, because the enhanced partitioning approach converts the 2-D wave spectrum output from SWAN into a suite of gridded wave forecasts that are ready for direct use in the official NWS gridded wave forecast.

The partitioning approach used in IFP-SWAN begins with the basic WaveSEP partitioning but also includes spatial and temporal tracking of the wave partitions. These secondary steps are necessary to produce gridded wave forecasts logical and consistent through space and time. Typical output includes a wind sea grid and three or more swell grids with accompanying grids for each swell's direction and period. Guidance products are also produced for discrete points to help forecasters in their interpretation of the gridded wave forecasts. The wind-sea identification is based on the wave age criteria and the energy of the wind-sea is kept in the full spectrum for further swell analysis. Thus, one of the swell partitions can include the wind-sea energy. To initiate this process, WaveSEP is first applied to the full energy spectrum. The swells are then combined if necessary following a procedure that Eureka Weather Forecast Office developed. This procedure depends on the resulting steepness of the swells which reflects the degree of danger for a mariner. Low energy swells are discarded and the four most energetic partitions are kept. This method is applied in one point in space and time. Figure 11 shows the flow of the wave partitioning process. Figures 12 through 15 show example output products used in the NWS wave forecasting process using WaveSEP. The process begins with the forecaster developing their gridded wind forecast over their domain. The execution of IFP-SWAN includes wave calculations and basic partitioning and ends with the spatial and temporal tracking. Figure 12 shows a sample wave vector partitioning example for a July 9, 2007, forecast. The x-axis shows forecast dates extending up to July 15 and the y-axis sorts the wave vectors by wave period. Vectors show the direction and magnitude of the partitioned waves. A wind vector plot is shown below the plot for reference. Figure 13 shows an example wind barb plot for July 9, 2007. Figure 14 shows an example of a wind wave grid for July 9, 2007, and Figure 15 shows an example of a swell wave grid for July 9, 2007. Each wave component shown in the vector barb plot corresponds to a single wave grid. This helps the forecaster identify which wave grids should be used in their official gridded forecast to accurately communicate the wave hazard to the marine customers.

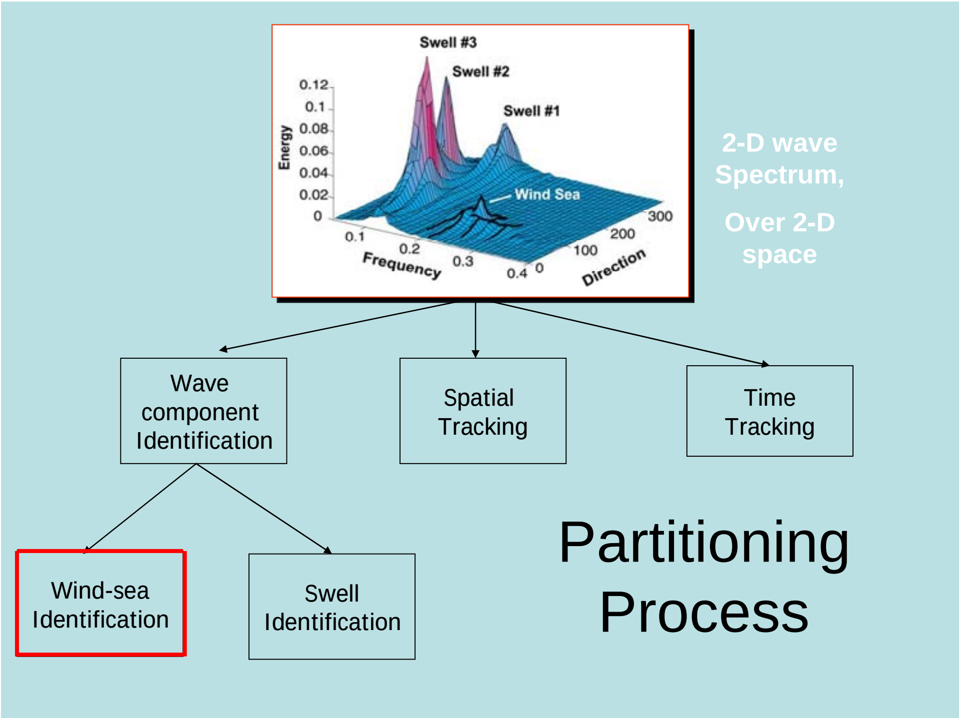

Figure 11. Flow chart showing the NWS partitioning process

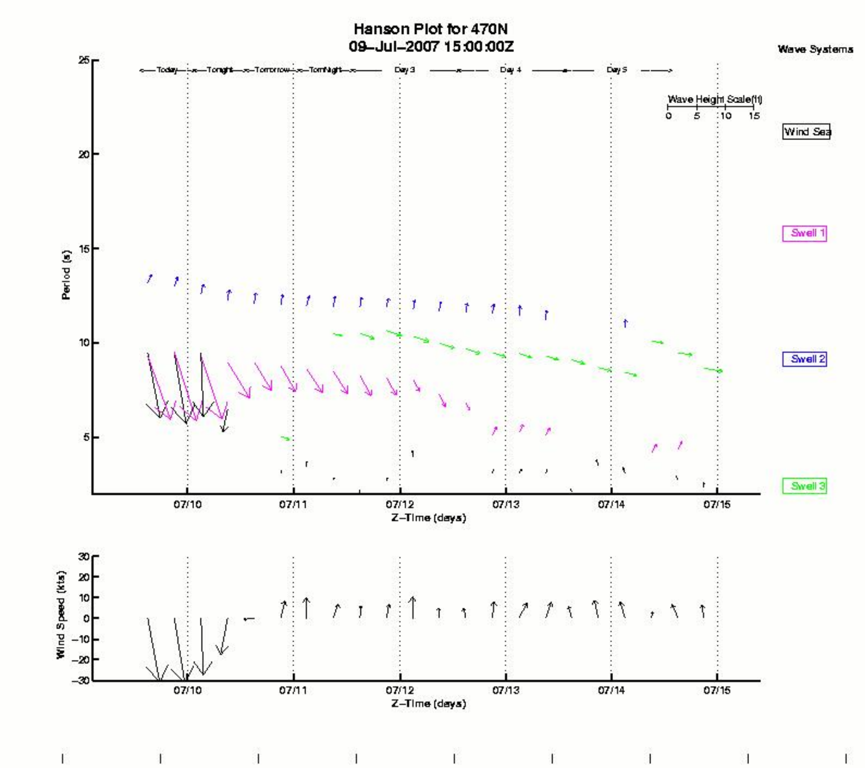

Figure 12. Partitioned wave vectors for a July 9, 2007, forecast ranging until July 15 with the corresponding wind vectors shown below the partitioning plot.

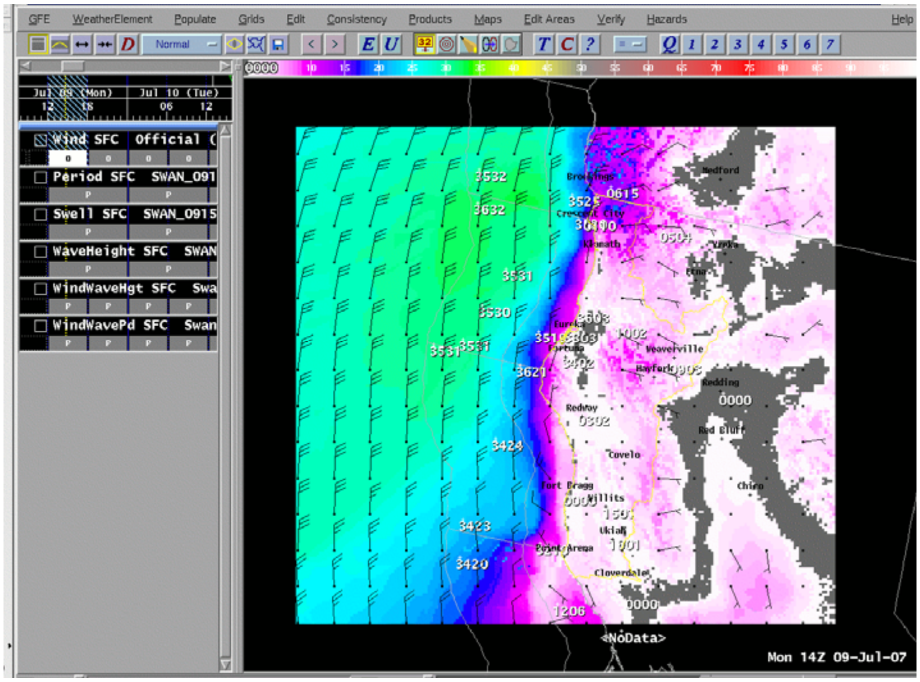

Figure 13. Wind plot (July 9, 2007) for area offshore from Eureka, CA

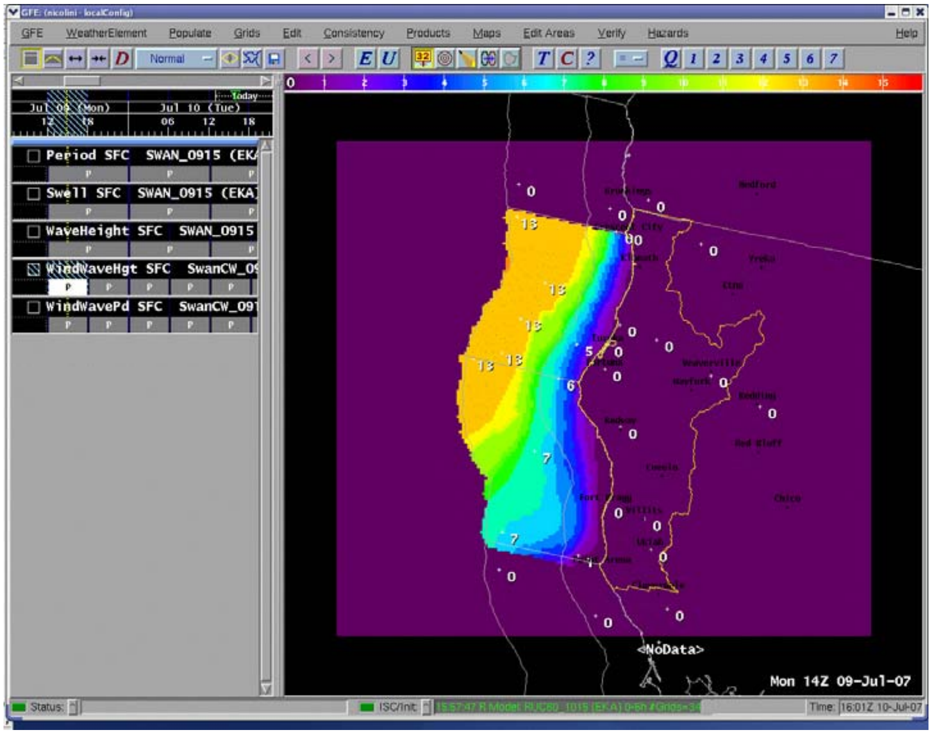

Figure 14. Wind wave contour plot (July 9, 2007) for area offshore from Eureka, CA.

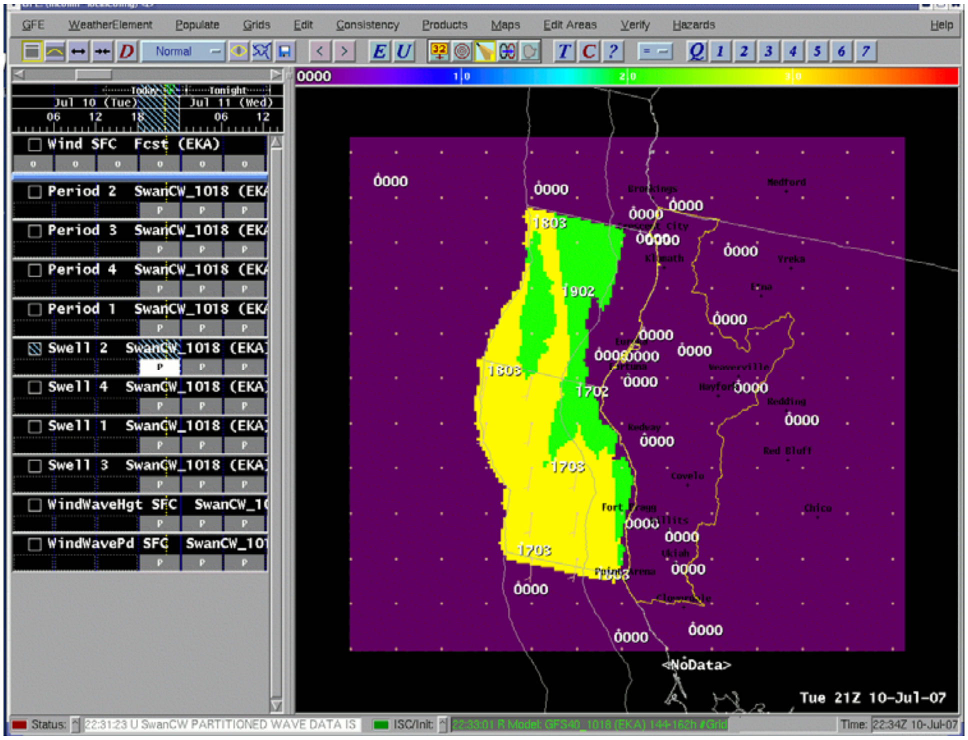

Figure 15. Swell wave heights for area offshore from Eureka, CA

The IFP-SWAN system has been deployed on all west coast offices of the NWS and is in the process of being deployed at offices on all other coasts and in Alaska and Hawaii. Forecasters in west coast offices are reporting that they are able to issue higher quality wave forecasts in a fraction of the time required with legacy methods.

Future Work and Conclusion

The NWS implementation of WaveSEP has already improved the NWS marine forecasts both in quality and efficiency, and the WIS and NOAA implementations have facilitated many useful products and analyses. The availability of a set of spectral partitions at each grid point of a numerical model grid will continue to facilitate many advances in the science of coastal engineering. The next logical step is to define paths and source zones for the various swell partitions that arrive from distant locations. Using this tracking technology in concert with measurements will advance the state of the art of numerical wave hindcasting and forecasting source terms. This work is currently in progress. Coastal process applications that previously based their calculations on a single significant wave height, period and direction can now utilize a set of wave parameters that define the full spectrum. Definition of storm waves using spectral partitioning should give new insight into risk analysis for coastal processes and the interaction of storm waves with a coastal structure. Full spectral calculations will still be necessary but many applications will be able to define the physics of the process by using the results of WaveSEP.

ACKNOWELEDGMENTS

This information will appear as a poster presentation at the 10th International Workshop on Hindcasting and Forecasting, November 11-16, 2007, at Turtle Bay, Oahu, HI. The development of FORTRAN WaveSEP algorithm was funded by NOAA. The Wave Information Studies work was completed under the Coastal Field Data Collection Program at the Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulics Laboratory, Vicksburg, MS.

REFERENCES

Chen, H.S., L.D. Burroughs, and H.L. Tolman, (1999): Ocean surface waves. *NWS Technical Procedures Bulletin No. 453*, NOAA, U.S. Department of Commerce, 6 pp.

Devaliere, E.M., J.L. Hanson, and R. Luettich (2007): Evaluation of wave model performance in a North Carolina test bed. 10th International Workshop on Wave Hindcasting and Forecasting, Oahu, Hawaii, November 2007.

Gerling, T.W., (1992): Partitioning sequences and arrays of directional wave spectra into component wave systems. *J. Atmos. Ocean. Techn*., **9**, 444-458.

Hanson, J. L., B. Tracy, H. Tolman, and D. Scott: (2006): Pacific hindcast performance evaluation of three numerical wave models, 9th International Workshop on Wave Hindcasting and Forecasting, Victoria, B.C., Canada, September 2006**.**

Hanson, J. L., and O. M. Phillips, (2001): Automated analysis of ocean surface directional wave spectra. *J. Atmos. Oceanic. Technol.*, **18**, 277-293.

Hanson, J.L. and R. E. Jensen, (2004): Wave system diagnostics for numerical wave models, 8th International Workshop on Wave Hindcasting and Forecasting, Oahu, Hawaii, November 2004, Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology Technical Report No. 29, WMO/TD-No. 1319.

Rogers, W.E., J.M. Kaihatu, H.A. H. Petit, N. Booij, and L.H. Holthuijsen, 2002: Diffusion reduction in a arbitrary scale third generation wind wave model, Ocean Engng., 29, 1357-1390.

Tolman, H. L. (2007): User manual and system documentation of WAVE-WATCH III version 3.xx. Technical Note (In preparation), U.S. Department of Commerce, NOAA, NWS, NCEP, Washington, DC.

Tolman, H. L. (2002a): User manual and system documentation of WAVE-WATCH III version 2.22. Technical Note, U.S. Department of Commerce, NOAA, NWS, NCEP, Washington, DC.

Tolman, H. L., (2002b): The 2002 Release of WAVEWATCH III. *7th International Workshop on Wave Hindcasting and Forecasting*, Meteorological Service of Canada, 188-197.

Tracy, Fred T., Barbara A. Tracy, Jeffrey L. Hanson, (2006): Sorting out waves with a fast sort algorithm. ERDC MSRC Resource, Fall 2006, Information Technology Laboratory, Vicksburg, MS, 8-14.

Vincent, L. and P. Soille, (1991): Watersheds in digital spaces: an efficient algorithm based on immersion simulations, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 13, No. 6, June 1991, p. 583-598.