Panel Discussion: Is There a Clear Need for a Global Wave Monitoring System?

The major objective of the panel discussion was to explore whether global wave monitoring from space is (a) practical, and (b) likely to improve operational wave forecasting. The panel was encouraged to recommend viable courses of action for the time frame of the mid 1990s. More specifically, should the ocean-wave community propose, and can it scientifically or operationally justify, a system to monitor ocean waves over global scales sometime during the next decade? The panel, chaired by William Plant, consisted of G. Komen, V. Cardone, B. Green, E. Mollo-Christensen, O. Phillips, S. Kitaigorodskii, L. Zambresky, W. Pierson, S. Bales, and M. Donelan.

Panelists	*Affiliation*
Susan L. Bales	David Taylor Naval Ship R&D Center
Vincent J. Cardone	Oceanweather, Inc.
Mark Donelan	Canada Centre for Inland Waters
Bert Green	Naval Ocean R&D Activity
Sergei A. Kitaigorodskii	The Johns Hopkins University
Gerbrand J. Komen	Royal Netherlands Meteorological Institute
Erik Mollo-Christensen	NASA/Goddard
Owen M. Phillips	The Johns Hopkins University
Willard J. Pierson, Jr.	City College of CUNY
William J. Plant	Naval Research Laboratory
Liana F. Zambresky	Fleet Numerical Oceanographic Center
Audience Participants	
Thomas Allan	Institute of Oceanographic Science, Wormley, England
Robert C. Beal	Applied Physics Laboratory
Merrill Skolnik	Naval Research Laboratory
Stanley Wilson	NASA Headquarters

William Plant: The question before the panel is whether global wave monitoring from space is both practical and likely to improve operational wave forecasting. I would interpret the question of practicality in terms of whether or not this meeting convinced you that there are techniques available that could do the job. There are some problems with various techniques. The synthetic aperture radar (SAR) could distort the spectra it measures and may not yield a totally viable wave spectrum. The radar ocean-wave spectrometer (ROWS) may introduce contamination, at least across track. How important is it that the spectra collected from orbit have absolute fidelity? With regard to improvements in operational wave forecasting, probably anything of a scientific nature that one learns about waves from a global monitoring system would improve ocean-wave forecasting, although perhaps not immediately. So please consider even those scientific aspects that may eventually have some practical application to wave forecasting, even if not immediately.

Gerbrand Komen: I have been impressed by the observed spectra shown at this symposium. They will no doubt have an impact on ocean-wave modeling. In my talk I have already tried to indicate how I think progress could be achieved.

First, the model validation aspect is very important. We have now seen spectra that have not previously been measured. The SWAMP model comparisons in 1981 were run for idealized situations, and we hardly expected to be able someday to measure two-dimensional spectra for those cases. But now it seems feasible for the right geophysical situation. Spatial evolution of spectra would be very valuable in validating our models. It really is a revolution.

Second, for operational forecasting, which is one purpose of this meeting, I have shown an example where data assimilation paid off significantly. There must be more such examples. I am confident that it will be possible to improve the quality of ocean-wave forecasting on the basis of satellite observations. People criticize sometimes, saying that if your wave model is perfect, you don't have to do any data assimilation. But that is too fast a conclusion. Even if your wave model is perfect, the winds are not. Atmospheric modeling is actually more difficult than wave modeling. Perfect wave models will still yield imperfect results, so there will always be a need for wave measurements. Combined assimilation of both wind and wave data from satellites will be extremely valuable.

One should think beyond operational or real-time applications. The strength of satellites is that they can observe globally, so they will also help us to understand air–sea interactions on a global scale. That is very important for understanding the climate system of the world.

Vincent Cardone: With regard to the two aspects of the posed question, I tend to agree with Dr. Komen. It is difficult not to be impressed with our present capability for measuring ocean waves, but how does that capability affect wave forecasting? There is no simple answer. I suggest three areas that should be addressed to get ready for the next decade. First we must continue evaluation and development of global and regional wave models. Although much progress has been made in the last five years, the models are not perfect. The model physics needs to be developed in the areas of the input and the dissipation terms. The third-generation models are computationally expensive. Perhaps the nonlinear source term can be made more efficient.

There is much potential for model validation, as has been shown at this meeting. Examples are the Norwegian Sea data from the ROWS, the Josephine SIR-B data, and also GEOSAT, with its ability to produce global long-term data sets. The data sets will allow us to investigate the trade-offs between relatively simple first-generation models up through the more recent third-generation models. When should one use a third-generation model? For significant wave-height forecasts, they may not be necessary, but for detailed swell predictions, they may be vital. Preparation of wind fields for these cases will be extremely critical. We have to get beyond the point where we allow errors to propagate into validation tests from incorrect wind fields.

Work is also required in the development of data assimilation methods for wave models. There are alternate approaches to this. To borrow some jargon from meteorologists, there are the so-called direct insertion method and the dynamic assimilation method. One has to address the total three-dimensional time/space problem and various input combinations: wind only; wind and significant wave height; or wind, significant wave height, and vector wavenumber spectrum.

The third area is in observing system simulation experiments. We need to design a set of experiments to investigate systematically what will happen with the assimilation of NROSS* scatterometer (NSCAT) data alone, NSCAT plus Spectrasat, Spectrasat alone, or even NSCAT, Spectrasat, and TIROS. Wave forecasting is critically dependent on weather forecasting, so an integrated approach is essential.

Bert Green: The forcing function of the models for wave prediction is the most important issue in terms of data input. Cardone responded earlier to the relative value of (a) a perfect wind field or (b) a perfect third-generation model. He chose a perfect wind field in conjunction with a first-generation model as having the larger potential for improvement. We have little capability to monitor the predictions or, at best, can only qualitatively evaluate them. There are apparently only two systems now available that can be used to validate wave prediction models: the surface contour radar (SCR) and the ROWS. With those systems and the eventual follow-up of a ROWS/SAR/altimeter combination, in the Spectrasat concept, we could begin to envision the "ultimate" system. But since there is only one SCR in existence and it is not readily available, we should consider how we might expand our resources in wave validation studies at scales and resolutions that would allow true model validation so that we can determine whether our models are predicting the physics correctly.

One of the areas of physics that needs to be explored in more detail is the effects of current-shear distributions on wave-height distributions in regions such as the Agulhas Current, the Gulf Stream, and western boundary currents in general. In these regions of intense currents, significant focusing of wave energy may occur. We are not yet in a position to incorporate the conditions into the third-generation models. So we might describe the "fourth generation" as the stage where wave–current interactions are included. The fourth-generation model should also have an improved representation of the wave dissipation process.

Finally, we need to assess the problem of funding for the desired wave-measuring satellite. Seasat was discussed for several years before it appeared as a valid budget item. GEOSAT was in the discussion stage from the mid 1970s until shortly before launch. Now is the time to identify potential sponsors of a wave-measuring satellite. Right now, I cannot do so. As scientists and as research managers, we need to start "shaking the trees" to locate a sponsor or sponsors.

Erik Mollo-Christensen: I agree with the previous speakers. I am impressed by the wave-prediction models. I am familiar with both the ROWS and the SCR. When we can measure the wave field with such precision, we need to think of how we can verify the wind predictions. With a modification of the ROWS, we could also operate it as a scatterometer and validate both the wind field and the wave field. With the success of the models that Komen reported on, we are starting to understand the energy input into the wave field pretty well, including the wave–wave interactions. So we are understanding one aspect of the sea surface: fluxes in the air–sea interaction process.

In oceanic frontal regions where you are liable to have cyclogenesis, wind field predictions are especially difficult. With an ability to observe both the wind and the wave field, we may be able to understand cyclogenesis much better also. Combining the wave prediction models and the physical understanding that goes into it with observations of wind and wave fields may enable us to start understanding and assessing global sea-surface processes of kinetic energy. Also, perhaps, with additional measurements we may be able to get at some of the other fluxes passing through the sea surface.

Owen Phillips: My interests are primarily in the research aspects of this topic, but I have two comments of an operational kind. I ask myself who really cares about measuring spectra on an operational basis from space. I am reminded, and I hope I can say this without offense to my very good friends in the waves community, that under typical conditions in which ships operate, there is really no such thing as a Bretschneider spectrum, or a Wallops spectrum, or a SWOP spectrum, or even a JONSWAP spectrum. These are representations of

*Panelists refer in their comments to NROSS, a U.S. program for global wind-field monitoring that was cancelled in December 1986. The prognosis for its revival is unclear as this goes to press.

highly idealized cases; they certainly do not represent the range of conditions encountered at sea, particularly the sorts of conditions that Bales was talking about in her presentation.

It is going to be of great benefit to naval architects to build up a global climatology of waves on a much more detailed basis than is available now. If ship designers had some idea of the extreme conditions—not only of wave height and period, but also of the directional distribution of waves—that their ships would have to encounter during their lifetime, we might have ships that could perform a little better than they do now.

We have discussed the question of comparing modeling results with observations. There is no doubt that the more observations we have, the better the models will be. But there are also other areas in which operational measurements of wave spectra are going to be very important. For example, for those who are interested in the acoustic background in the ocean, one of the contributing causes is wave activity. In order to be able to predict areas in which background levels will be unusually high, we need to know not only the wave spectrum but also the wind. I would hope that those members of the community who are concerned with questions of this kind would find it important to undertake continuing operational measurements throughout the areas of the world's oceans in which they are interested.

Sergei Kitaigorodskii: I consider global wave monitoring from space not only practical but the *future* of satellite oceanography. My reasons are based on the fact that the asymptotic forms of the wavenumber spectra of ocean waves that can be measured (if you consider the recent results from the ROWS and SCR, for example) demonstrate that the expressions for the wavenumber spectra have at least two important fluxes in their form: action and energy. These fluxes are directly related in one way or another to the energy input, which has a cubic dependence on wind. It may be possible to calibrate this dependence even for different stages of wave development. Therefore, I believe that by observing the wave spectrum, even over a narrow wavenumber range, it is possible to reconstruct the wind field.

By observing the wave spectrum in a certain range of wavenumbers, it is possible to define the total amount of energy lost from the waves due to breaking. The conservation of energy requires that the amount of energy lost be equal to the energy dissipation in turbulent patches, and the dissipation is the governing factor for determining the gas transfer between the ocean and the atmosphere. So again, by observing the wave spectra in the proper wavenumber range, you are able to reconstruct not only the wind speed but also the turbulent dissipation in turbulent patches; this permits you to estimate the gas-transfer rate quantitatively.

The amount of energy lost from waves, which one can determine from the forms of the spectrum predicted by the asymptotic theory, can give not only the amount of energy entering the upper ocean in the form of turbulence but also the amount that is dissipated. This is important in determining the intensity of turbulence in the upper ocean and, with some reservation, may also be important in the deepening of the mixed layer. I can see some historic analogy with what occurred in the atmosphere. By measuring the intensity of spectra in a narrow frequency range, one can determine the intensity of free-atmosphere turbulence, which is very important on a global scale. I see a bright future for having global information about wavenumber spectra, not for the sake of waves, but for the sake of many important quantities in the ocean. So wave measurements from space are not only practical, but necessary.

On the other hand, I do not believe that this information will improve operational wave forecasting very much. For that, we must continue to make detailed studies of the JONSWAP type, where all sources can be determined experimentally and one can develop a refined theory based on the observations. Then the theory can be applied to operational forecasting with the expectation that it will cover all external conditions.

In the real world, the global behavior of waves can be influenced by so many factors that it would be very difficult to verify a model.

Liana Zambresky: The observation of waves from space would be extremely useful. Wave models need to be initialized. They also need to be validated. We have only begun to touch the two-dimensional validation of wave models even though two-dimensional wave models have been around for quite a few years. We have been developing theories about the evolution of the wave spectrum with hardly any validation.

The modeling of the atmosphere is certainly not perfect. We will probably always have errors in the winds. But with better initialization, the impact of the errors will be much less. Also, better observations of the two-dimensional spectrum could help to improve our understanding of wave–current interactions.

Willard Pierson: The wave-measuring systems that have been described in this symposium should be thought of as parts of a much larger system that is needed to characterize more completely the planet Earth from orbiting spacecraft. They are very important parts. Wave measurements will not be adequate from either NROSS or TOPEX because they will yield only significant wave height.

During the meeting, I have talked to people who are already using some remotely sensed wind and wave data and are discovering things just from wave-height data that were not known earlier. One cannot send an expedition to Antarctica each year to measure waves in the Antarctic winter. We may be a bit too pessimistic about estimating wind fields in the future. Certainly when NROSS data become available we will obtain excellent wind fields that could be used with tremendous success as an initial-value update in numerical weather prediction models in a way similar to the study that Cardone did with Seasat. If the initial-value-specification error can be reduced by a factor of two, probably a three-day weather forecast will be as accurate as a two-day forecast now is.

In most normal wave-forecast models, an initial-value update is not available. Usually, the last part of the model is exercised using past winds that are assumed correct. Next, the forecasted winds are used. The analyzed winds are not quite correct, and so the initial-value specification of the spectrum is not quite correct. The forecasted winds then rapidly degrade the wave forecasts. If one tries to extend this to two days, a pretty nasty problem results.

Of course, the advantage of having measured global wave spectra is that one can update or correct each of the spectra in a field with the same sort of concept that the meteorologists call a "region of influence." Then when one starts the new forecast, it will be much better.

Another big advantage of the wave-monitoring systems that have been described here is their available degrees of freedom for a single spectral estimate. One is on the horns of a dilemma when measuring waves as a function of time. If the record is too long, the waves change too much; if the record is too short, confidence intervals are too large. There is an order-of-magnitude improvement in the degrees of freedom for spectral estimates made with the remote-sensing techniques discussed here because they are averaged over area rather than time. With this degree of averaging, if the forecasted spectrum does not agree with the measurement, the forecast is wrong. One cannot blame poor verification data. I am reasonably sure that is what we will find out most of the time with most models.

There are climatologies of winds, clouds, precipitation, tornadoes, and thunderstorms that are useful in making decisions. We cannot hope to predict the weather six months in advance, but we must have some idea of what has happened in the past. One of the biggest contributions that a wave-monitoring satellite can make is to start building up a good wave climatology.

Susan Bales: We really do not have a clear statement of the requirement to measure directional waves from space. Waves are about halfway down on the Navy priority list, and funding is usually available for only the top third or quarter of the list in the Navy and probably also in NASA. We all believe that wave measurements are desirable, that they are good science, and that there will be many spin-offs. But what is the real national requirement? We ought to address that issue. We should identify what will be lost if we do not have directional wave measurements from space. We could develop a very specific list from scientific, engineering, commercial, and national defense viewpoints.

It is important that we break out of our traditional boundaries as oceanographers and naval architects and look at other areas that are of high interest and high priority. For example, we can tie requirements for wave measurements to related interests in both acoustics and in the Arctic (for example, ambient noise or ice dynamics).

We ought to consider doing more comparisons of instrument data using a broader variety of instruments. Comparing one remote sensor to another is good but not enough. We have to look back toward traditional instruments such as wave buoys and conduct a more conclusive comparison of remote and in-situ sensors.

In the next decade, we need to go beyond just wave-height measurement and prediction comparisons; we are interested not only in the wave height but also in the spectral shape. Any wave height can have an infinite number of associated spectra, but often it is the shape of the spectrum that drives the application of the data.

There is no doubt that measurement of waves from space has the potential for greatly improving our operational wave-forecasting ability. These richer data sets could also significantly improve our global climatologies. The climatologies are the input-forcing functions for marine vehicle and structure engineering studies. We have insufficient climatology for most of the world oceans. From the sea-based wave forecasting viewpoint, we're going to see a tremendous increase of activity by 1990. Until now, the oil industry has been one of the leaders in regional wave forecasting. Now, the Navy is moving into an era where, in order to accomplish tactical missions, it will be absolutely necessary for mariners to have good space-based measurements coupled with land-based forecasts, both of which can then be massaged into a meaningful prediction of mission success.

Wave prediction in shallow water can also benefit from space-based wave measurements. There are many harbors throughout the world that have ship-grounding problems. A tremendous investment is going on in this area, using less than state-of-the-art techniques to monitor the air–sea environment.

Mark Donelan: On the question of the practicality of global monitoring of waves from space—being an outsider in this business, I have just a brief comment. The two methods, SAR and ROWS, both appear promising in that they both provide good areal coverage of rather general aspects of wave information that would be suitable for updating models. The SCR is in a completely different class, in that it is basically a research tool, and shows great promise for giving detailed information about waves that can be used for developing a better physical understanding of how waves grow and develop. I would like to see more of these wave-monitoring systems, particularly when a JONSWAP-like experiment is run again.

On the question of improving ocean-wave and weather forecasting, there are two distinct aspects. I showed earlier in the meeting that there is a pronounced effect on the short waves of the presence of long waves. It is no longer simply a question of forecasting the wind and the waves independently of each other. A swell propagating from a distance that is the result of a poor, non-updated forecast may have an effect on local wind-generated seas that will change the stress, affect the scatterometer's impression of the wind, and make it more difficult to get a suitable wind for forecasting waves losort of feedback mechanism. But, more importantly, the stress itself is perhaps materially changed by the presence of long waves propagating at odd angles with respect to the wind. If this is so—and I believe we are now able to show that it is—we will have incorrect stress estimates as input to wind models unless we know the wave field. The wind models therefore will provide poor forecasts of the winds, and the loop will be closed quite quickly, with subsequent poor wave forecasts.

Finally, changes in the roughness Reynolds number or in stress also affect the transfer of other properties. As Kitaigorodskii mentioned, there is the effect of breaking waves on gas transfer, but more importantly, there is a change in the transfer rate for moisture, or latent heat, and sensible heat. And this drives the atmospheric circulation. If you estimate the stress and heat fluxes wrongly, you will never forecast the development of local storms correctly.

Therefore, unless we know the present wave field on the ocean rather well, we will be unable to forecast it. We will need to be able to update the forecasts with global monitoring in order to keep ourselves honest in the long term.

William Plant: Reiterating, the panel agrees that the presently available wave-measuring techniques are impressive and that our impending ability to measure spectra from space is exciting. There is also general agreement that measured directional wave spectra would have an impact on wave forecasting. There was one dissenting view, that of Kitaigorodskii. Donelan and Komen have both mentioned the need for wave measurements to obtain better wind fields, and I would second that. Our measurements show that, at least to some extent, microwave backscattering is impacted by the longer waves.

We do need some sort of feedback system such as Donelan was suggesting. Wind and waves are intimately tied together and our measurements of them need to be tied together also. Several people have mentioned that we need to build up a climatology of waves and that global wave monitoring from satellites would be a good way to do it. I would like to second that also. Bales mentioned the importance of spectral shape. I, too, am very impressed by our impending ability to estimate wave spectra from space. But I am also concerned, to some extent, by SAR, which obtains its azimuthal resolution by mapping Doppler shifts. The ocean contains many types of moving scatterers that give Doppler shifts. Several theories indicate that those moving scatterers do something to the long-wave spectrum that is measured. How important is that? Bales seemed to indicate that it might be quite important. Is it important that we know if the spectral shape is distorted by a SAR measurement? In all the measurements that the APL researchers have made, no spectral distortions have been detected beyond the azimuth falloff. They interpret that as evidence for the usefulness of a SAR for measuring waves. We have other ways of measuring waves, as you have heard here. SAR, because of its ability to do other things in addition to measuring waves, is most likely to be the technique first flown in space. So how much will it affect our operational and our scientific conclusions if we misestimate spectral shapes a bit from our measurements in space?

Willard Pierson: You have to remember that we are aware that the problem exists. By the time a dedicated spacecraft gets built, the problem may have been solved.

William Plant: It is true that in many cases, it is not a serious problem even now. So you're saying "full speed ahead"?

Willard Pierson: For example, how long have we had the pass over Hurricane Josephine—about a year? You see the most interesting things occurring in that one hurricane. We need to do some model comparisons. It is much too early to form any conclusions now.

William Plant: That's an excellent point. There is now a much higher quality in the spectral estimates, even given the possibility of some distortion. We can measure direction much more accurately than we have ever been able to before. The data coming from these systems are very exciting.

Gerbrand Komen: I am concerned about the accuracy of the SAR images if there is distortion. The ERS-1 people guarantee image spectra, but they don't guarantee wave spectra. It may be helpful in image interpretation to have a real-time forecasting system running. The first guess from the model could be used to improve the algorithm for estimating distortion. One should really start working on this, so that the distortion problem can also be examined from that perspective.

Willard Pierson: The Spectrasat design has a built-in check. The ROWS spectrum will be collected adjacent to the SAR spectrum. If they do not agree, then there is a problem. But I think the problem will go away before it ever comes up.

Erik Mollo-Christensen: You are going to have the ROWS spectra only if someone asks for it.

Owen Phillips: I would like to echo Pierson's points about the pace at which this field is going. Just a few years ago, the idea of measurements of this kind was just a gleam in a few wild men's eyes. And people said, "Oh, yes, that's very interesting." But now we're at a point where we're pretty sure these things can be done, and we're pretty sure about the performance. If this kind of progress is extrapolated in the next few years, then I do share Pierson's confidence that some of the things that are now troublesome will go away. I would emphasize that it is terribly important that they do go away, for if these measurements are to have the usefulness they might have—if we're interested in the sort of flux questions that Kitaigorodskii was talking about and the sound generation and sound scattering in the ocean—we do need to have these spectra fairly accurately. At least we need to know how accurate they are. I would hope that all the instrument developers charge right ahead and anticipate that they will have a very interested group of users.

William Plant: But *who* is interested? Who is going to pay the bill?

Susan Bales: I raised the requirement issue for just that reason. Instruments are being demonstrated. A high measurement capability is emerging. Whose responsibility is it to justify an operational system? With all the recent budget constraints in Washington, my concern is that the evolution will go to a certain point, and then NASA and other potential sponsors will lose interest because they do not have a charter to develop operational systems. High-resolution spectral wave measurements are not in the Navy program now and may never be, with the Navy's ever-changing management. NOAA has expressed little real interest. What will happen then? As a user, I feel a great deal of apprehension that we need to look further into the future. Will the 1995 time frame yield an operational system that can give directional wave spectra several times a day in those parts of the ocean in which we have a great interest? I do not see that capability emerging, at least not in the U.S.

Willard Pierson: I do not want to wait even until 1995 for global wave spectra estimates. They ought to be available along with NROSS, and I can give you some good arguments for that. A wave-monitoring spacecraft could be in orbit by the time NROSS is operating.

William Plant: That is an excellent idea, but how do we convince people and whom should we convince?

Willard Pierson: We should at least document our scientific and professional opinion that a global wave-monitoring system is necessary, and we should also produce a clear justification for it.

Susan Bales: I think we have to show clearly what is lost in the absence of such a capability.

Willard Pierson: The argument should be put in a positive framework, showing how global wave-monitoring can support and enhance NROSS.

Vincent Cardone: One of the initial questions on the table was "Will global wave monitoring improve wave forecasting?" The initial comments have shown that this question is much too narrow. We have broadened our interests, and we should think in terms of those broader interests as well as of longer time frames. A wave-monitoring system has to be scientifically or operationally justified to a viable sponsor. We should be thinking of wave forecasting as one justification, but broader scientific issues should be stressed as well. Isn't TOPEX justified in terms of basic science? When the NASA Announcement of Opportunity for the NROSS Scatterometer was issued, only basic science was stressed. So we should stress that too. Finally, we have to take a longer term view. The proposed Spectraset is just a three-year experiment, as is NROSS. In the long term, we should be planning for the operational earth-observatory system in the next century. This is just an intelligent step along the way. If we combine those three justifications, we might have a viable program.

Gerbrand Komen: I have made a list of users of wave forecasts and related satellite observations. In my country, much of the justification for wave forecasting comes from coastal engineering and coastal defense. The Netherlands is below sea level, so we have to rely on dikes. That is pretty sophisticated work. A major storm-surge barrier is still under construction. The work can be done only with very accurate wave forecasts, which have at least five applications.

First, there are the coastal engineering, harbor construction, and coastal defense interests, in addition to the off-shore industry. In this class of application, government agencies and oil companies are the main users.

Second, there is ship routing, which not only has commercial aspects, in the sense of fuel economy, but safety aspects as well. Because the ships are quite deep, reliable wave forecasts are necessary for supertankers to enter Rotterdam harbor safely. They have to go through a channel. If the tankers resonate with the waves, they could strike the bottom, leading potentially to major catastrophies, with all the associated pollution problems. Actually, the ships now have to wait when the waves are too high.

The third application on my list is algorithm improvement. If we could get better winds from space, that would certainly increase the possibility of making better weather forecasts. Having the waves available would increase the possibility of getting reliable winds from space. This application should be supported by weather forecasters.

Fourth, waves have an impact on climate research, as has been mentioned several times already. During a recent meeting at the European Center for Medium Range Weather Forecasting that was organized at the request of the World Ocean Circulation Experiment, it became clear that we need satellite observations for those experiments to better understand the global climate system, including the coupling to the oceans.

Wave climatology is a fifth application of wave models and wave observations. In fact, a lot of the interest involves insurance inquiries, where a knowledge of sea conditions during special events is needed.

There are many different sources and organizations that would have an interest in accurate wave forecasting and wave modeling.

Sergei Kitaigorodskii: It must not be forgotten that, as I understand it, you can measure only two things from space: the ocean-surface elevation and the ocean-surface temperature. Therefore, the oceanographic community is obligated to extract as much information as possible from observations of wave spectra. This can at least partially improve operational wave forecasting, but it is only a part of the whole problem of extracting everything. With the observation of surface elevation, one can hope to measure geostrophic currents from space. Measuring waves is just part of the spectrum of surface elevation. We can and must extract everything possible in order to understand air–sea interaction processes in the upper ocean. That is why I consider it necessary, if only from this viewpoint. There are no substitutes.

Erik Mollo-Christensen: We must not forget the opportunity being offered by the European ERS-1, which will have a SAR as well as other instruments. We cannot change the instruments on ERS-1, but we can learn to understand them better by underflights, by using aircraft instruments to learn more about the detailed wind and wave fields, and by developing better algorithms. So we do not need in-situ measurements; we can also use aircraft.

William Plant: We need to keep checking the accuracy of our measurements in as many ways as we can, particularly on the satellites that make the measurements. We should never forget that there may be problems there.

With that comment, let me open the discussion to the general audience.

Thomas Allan: One of the most important customers in Europe for directional wave spectra is the off-shore oil industry. As the industry moves into deeper, more remote, and possibly more hostile marine environments, the need for wave climate information will increase. At present, the long-term predictions of extreme conditions—especially over remote areas of the southern hemisphere—are based on very sparse observations. So, at a stroke, satellite observation of waves will produce an enormous improvement in long-term wave forecasts over present methods.

Turning to Europe's ocean satellite, ERS-1, presently set for launch at the end of 1989, an Announcement of Opportunity has just been issued and it already appears that there will be a strong response from North America. One of the greatest interests is in the measurement of winds and waves. However, if the ERS-1 SAR is operating, the wind scatterometer is switched off (since they share the same circuits). So an overlap with NROSS may be particularly desirable in that respect.

May I make a final point? Spectrasat is designed for a low orbit to reduce the range-to-velocity ratio and hence the amount of image distortion of azimuthal-traveling waves. But even for comparatively high-flying satellites such as ERS-1 it may still be possible to go part of the way to reconstructing the wave spectrum by taking two "looks" with SAR, one on an ascending pass and another descending. If there were two SARs in tandem, 180 degrees apart—something now being considered by NASA/ESA as the polar-orbiting element of the space station—surely some useful information on wave spectra would emerge. Also, by then we might have a better understanding of the physics.

Merrill Skolnik: I have two technical comments, one of which has been addressed, the other not. The former has to do with SAR and what it shows. Ocean surface patterns from SAR look like waves but they are not. That has been recognized. SAR targets in motion look nothing like they are supposed to. So if you are satisfied with the SAR images of the sea, it must be fortuitous. You have to make sure that you really are able to use those images. I know people in this room have worried about that, and Pierson may be right when he says we will solve that problem before long. But sometimes we can be too complacent. We always have to remember that SAR does not image moving targets. If you think it does, come to my office and I can show you lots of examples that you will not recognize.

Willard Pierson: That is not quite true. SAR does image moving targets, but it shows that they are moving.

Merrill Skolnik: An image of a ship does not look like a ship. The only way you get a proper image of a ship is if it is stationary. But a ship that is rolling and pitching can look like a line, a blob, a blur, or a crescent, but not like a ship. You cannot believe a SAR when the target is moving.

My second point, perhaps more controversial, has to do with Bragg scatterers. Bragg scattering is the theory of choice at the moment. It has two very nice things going for it. First, it explains very well the sea-scatter effects one sees with high-frequency radar, that is, long-wave radar looking at water waves on the order of tens of meters wavelength. There is no question that Bragg scattering describes what goes on there. Second, Bragg scattering is a nice theory. People can work with it. But when one looks at the higher microwave frequencies (an L-band radar might be high enough), there is nothing that resembles Bragg scattering.

One wonders why people are not more concerned about the sea spikes that Phillips mentioned on the first day. Little waves do not ride on big waves. Pictures of capillary waves or small waves riding on large waves always show a lot of discontinuities. There are "wedges" of radar scatter from discontinuities comparable to a wavelength. A discontinuity can be expanded into a Fourier series, and a component of that discontinuity will have a Bragg-scattering component. But observations of short, high-resolution microwaves show that the sea spikes last for a few seconds. They are nonstationary in time and they are discontinuous in space. Again, Bragg-scattering theory might give satisfactory answers, but it does not reflect the real world.

Willard Pierson: I concur with everything you have said, but I do not think it is a particularly difficult problem to solve. There is some good work by Lyzenga, by Kwoh and Lake, and also by Mike Banner in Australia on all those effects. They can be combined with Bragg scattering and specular backscatter in a logical way to help explain radar images of the ocean. So things will probably soon become clear. For example, many scientists are working to perform the kind of experiments that will help resolve some of the questions that you have raised. I am sure everybody is aware of them and has some pretty good ideas of what to do about them.

William Plant: With respect to Skolnik's comments on Bragg scattering, he is used to looking at scattering from very shallow grazing angles. At those angles, Bragg scattering is certainly suspect. But at the higher incidence angles, we have a lot of evidence that Bragg scattering is the major contributor to the backscatter, although certainly not the only one. Doppler spectra exhibit the expected splitting that you would predict from Bragg scattering. In other words, Bragg scattering from a slightly rough surface will show lines that have been Doppler shifted. If the wave is traveling toward you, it will be shifted in one direction; if its traveling in the other direction, it will be shifted away. The splitting is very well defined. It is twice the frequency of a wave that is in Bragg resonance. We have observed those kinds of things on the ocean with L band on a pier off the coast of North Carolina. There is quite a bit more evidence for Bragg-scattering theory in the intermediate range of incidence angles.

Robert Beal: There were reasons why our agenda here did not include the scattering problem. It is certainly a very active and important field of research. But this symposium is more directed toward the question of whether, in spite of all the uncertainties in the scattering models, the macroscopic (6-kilometer-on-a-side averaged) measurements can provide useful estimates of the spectra. Within certain bounds that we are beginning to understand, it appears that they can. Unfortunately, those bounds appear to dictate a low-altitude orbit. Nevertheless, once we understand the bounds, we simply have to abide by them. Our understanding of SAR for making wave measurements now is probably similar to our understanding of the scatterometer about a decade ago, when we first decided to put one in Seasat. We certainly did not understand the scattering mechanism then. Even now, models for the scatterometer algorithm are still under development.

Bert Green: Putting one satellite up is not going to solve all of our data-input problems for wind or waves, but it will certainly improve our understanding of some of the scientific problems that have been mentioned. Could we launch a network of several satellites for a reasonable cost? Do we need more than one satellite?

William Plant: I think we do.

Robert Beal: The answer depends partly on the temporal and spatial decorrelation of the ocean-wave fields. Global models can give some insight, but a model output is not as reliable as measured data. The data do not yet exist to answer the question unambiguously. Certainly we will never be able to monitor a rapidly evolving storm adequately with a single satellite.

Willard Pierson: If we get one spacecraft we have done a lot. Two spacecraft will double our ability. But the first step is the most important. A small amount of information can make a tremendous advance in studying a problem. We do not now even get that small amount of information with data-buoy networks. Our present methods are inadequate simply because the earth is too large. A data buoy cannot be maintained off Antarctica to measure waves. We cannot use the large number of data buoys that would be required to replace just one spacecraft for this problem. So, in order to understand the problem—in order to start a climatology—we have to have at least one satellite. A single satellite would permit us to get an adequate annual climatology of waves.

Mark Donelan: The best way to a detailed wave climatology is through meteorology and wave modeling. A single satellite observing global waves can provide a check on the system. Eventually we hope to be in a position where we can forecast the waves accurately. That is our final objective. It may be that we will not need more than one wave-observing satellite, but we will not know that until we have that one and find how well we forecast waves. If we find that the forecasting systems always agree with the satellite, clearly we will not need another.

Susan Bales: Returning to the fundamental issue of requirements, a demonstration with existing satellite data would be quite valuable and apparently it has not been done. We have comparisons of various instruments, but has anyone taken data from one instrument either to update a forecast model or to apply it to a fleet or coastal engineering problem? I don't think so, at least not conclusively. I still do not see that we are demonstrating a national requirement to measure directional waves from space. We can define some specific reasons why it would be helpful to have wave spectra. But that by itself is not a convincing argument to justify a satellite system. We should focus on a demonstration. The Labrador Extreme Wave Experiment (LEWEX), being planned by some of us here for March, 1987, could serve as such a demonstration. There will be an ensemble of different in-situ wave-measuring instruments, some better understood than others. There will be two ships deploying a number of buoys and two aircraft employing radar remote sensors. Unfortunately, because of the Challenger accident, there will be no spacecraft. We will try to validate the GSOWM and later-generation wave models. A number of wave modelers will be involved in the exercise.

William Plant: The best way to promote a system is to get one operating, to use it, to make some dramatic advances or, at least, incremental steps in understanding it. It then becomes a powerful case for continuing in that direction.

Robert Beal: We already have some unique data and some enlightening results from SIR-B. One of the major reasons for this symposium is to share them with a broader community. We would like as many people as possible to ponder the data. Komen will take some data back so that the Europeans can try their third-generation wave model on hindcasting the wave field of Hurricane Josephine. Clearly, none of us is willing to state the value of the wave data until we ourselves are convinced of the extent to which it offers an improvement. We now have one key data set and will be in the interpretation phase for some time. However, LEWEX is critical to extending our database into high and actively growing sea states. Further, if we can manage to collect global spectra with ERS-1 and SIR-C around 1990, we should be able to get an even better idea of wave-model performance.

William Plant: Could anyone use Beal's SIR-B data now to improve what they are doing?

Vincent Cardone: Wave modelers could certainly use them. But I think we have to go beyond just exciting the interest of the scientific community. We need financial support. The sources of support are no more evident for that activity than they are for the other areas of demonstration. We do not seem to have a balanced effort. There is an effort to develop sensor algorithms and sensor technology, but none to demonstrate the utility or benefits of the information. We cannot do that in a meeting. There are systematic scientific studies that should be conducted, but they require a little time and some support. As an outcome of this meeting, there should be a plan for ground-based experiments involving computer studies that could help develop answers to the questions that are being raised here. For example, which sensors should be used, how accurate should they be, and how many satellites should there be? Then we have a way to proceed.

Robert Beal: We intend to exploit the SIR-B data set as much as possible; we have only just begun. But it is available for others to examine. The LEWEX experiment that Bales mentioned may also address some of the questions that Cardone has raised.

Liana Zambresky: I have a question for Bales. This morning, in your talk, you outlined the accuracy with which a ship captain might like to know the two-dimensional spectrum. You said the significant wave height should be known to 0.3 meter, the period to 1 second, and the directional resolution to 7½ degrees. How great is the need for a ship captain to have a wave forecast?

Susan Bales: Those were all plus or minus estimates, so they represent a total error window. They are actually a goal. The values will permit adequate prediction of the response of any ship to any type of swell-corrupted wind-generated seas. One can demonstrate that a ship transfer function having the errors in wave height that I mentioned, with perhaps a 2-second error in period and 40 to 50 degrees error in direction, can cause an error of a factor of two to four in the prediction of ship performance. Clearly, that is unacceptable to a captain. He wants guidance, not just rough trends.

Liana Zambresky: But how *important* are the requirements for this performance?

Susan Bales: We will never be able to predict motions of a ship at sea unless we achieve that kind of resolution. We cannot do it with the JONSWAP spectrum or the Bretschneider spectrum "directionalized" by the cosine-squared law. We might hit the correct response or we might be off by orders of magnitude. That is the problem. Significant wave-height estimates are completely inadequate. One needs the full directional spectrum. I quoted optimum resolutions that perhaps are a little idealistic. But they are goals to move toward.

Erik Mollo-Christensen: There are many research uses of wave data beyond just determining their spectra. One may be able to see the development of the wave field in other terms. One can look at more local measures of the wave field and, perhaps, find that there are fewer frequency components present in a local area than are present in the spectra. The spectrum is a spatial average, of course, so locally a wave field may have just a few really dominant components. Locally, there may be just two or three wave components in a maximum likelihood estimate. That may be informative for ship design too. With the information that is becoming available, we can start asking questions we did not dare ask before, and perhaps understand the likelihood of breaking a little more. One has to look at the wave fields more in order to start thinking of good questions to ask and to get quantitative answers.

William Plant: This is a trend that often accompanies new instrument development. One begins to be able to get information that has not been available before. We are seeing that trend now with the remote sensors of directional wave spectra. And we can begin asking questions for which previously we had no way of obtaining data to answer.

Merrill Skolnik: Just a suggestion about requirements. There are a lot of "requirements" in the Navy, but a requirement generally is not promulgated until the operational Navy believes there is a solution. If you are going to pursue operational Navy sponsorship, which may be necessary with a system as expensive as this, Pierson's argument about going from zero to one satellite will not be adequate. You have to know you need *x* number of satellites, whether it is one or two or three.

Mark Donelan: It is clear that weather forecasting is considerably more difficult than wave forecasting, given the correct winds. We need global wind-observing systems, but we may not need global wave observations, if we completely understand the physics of the process. If we have all the winds that we need to initialize the weather forecasting system properly, we may eventually forecast the winds correctly; until we do, we cannot forecast the waves anyway.

Willard Pierson: Didn't you just state that errors in wave estimates would lead to errors in wind estimates?

Mark Donelan: Given the right initial condition, one can forecast the waves from then on. If one understands the system, one can keep on getting them right. Only an occasional check might be necessary.

Willard Pierson: Will you concede that we do not understand the system well enough to do that now?

Mark Donelan: Yes, but as you said earlier, by the time the satellite goes up, our understanding will be much improved.

Willard Pierson: I was only referring to the peak of the spectrum as measured by two different instruments. We will not solve all the planetary boundary-layer problems in the next two or three years.

Mark Donelan: I would like to think that while the technical people are working on improving instruments and estimating ocean-wave spectra, the theorists and experimentalists are working on the problem of trying to understand how waves behave. Perhaps we will get a little further ahead by the time they do. Perhaps we do need a lot of global monitoring of waves and perhaps we need only one wave-measuring satellite, but we will not know until we try. Clearly you should not argue for 10 until you know that you need that many. You cannot possibly say that you need them now, whether that is good marketing strategy or not, until you have performed some sort of test. I think the most useful test is to orbit one satellite and find out what it tells you. In a sense, the better we succeed at understanding the physics of waves and wind-wave interaction, the less we will need global observing systems to update our predictions, assuming, of course, that the meteorologists get better at their predictions too.

Stanley Wilson: I have a few comments on this symposium from the NASA perspective. I think the group here has accomplished a necessary first step. It is one I have not seen taken for a number of years, that is, to collect all the interested parties and to decide what needs to be done. But talking among yourselves can be fairly incestuous. You need to convince the external community of what needs to be done. You can measure directional spectra and you can outline the science that could be accomplished by a satellite system with particular characteristics. You can justify it on its scientific basis. We at NASA would be receptive to listening to arguments developed along that line. I think Bales' summary comments regarding "what are the requirements?" were most appropriate. Perhaps one wants to sell a satellite system primarily on the basis of operational requirements. The Navy and NOAA, in addition to a huge commercial community not represented here, may have operational requirements. You can develop observational requirements to meet certain operational and scientific needs. If you can convince the different groups to work together to develop an advocacy and a commonality of approach, then you will have as good a chance as any other community of getting your needs met.