ISSN 0736-5306

SCIENCE OF
TSUNAMI HAZARDS

The International Journal of The Tsunami Society

Volume 19 Number 2 2001

P. O. Box 37970,
Honolulu, HI 96817, USA

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ISSN 0736-5306 **http://www.ccalmr.ogi.edu/STH**

Published by The Tsunami Society in Honolulu, Hawaii, USA

USING A SATELLITE TELEPHONE TO RETRIEVE TSUNAMI DATA FROM TIDE SITES IN THE PACIFIC BASIN

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ABSTRACT

The tsunami warning centers require accurate, timely and reliable tide data during a large potentially tsunamigenic earthquake. At the present time tide gauge data in remote parts of the Pacific Basin are often not available to view during a potential tsunami event or the data may be transmitted hours after the expected tsunami arrival time. This delay can adversely affect state and local emergency officials who require lead times for placing their areas in a warning status. The West Coast/Alaska Tsunami Warning Center conducted a feasibility study, which showed that a satellite telephone link can be used to collect tide gauge data from remote sites in a timely manner.

INTRODUCTION

The primary mission of the West Coast/Alaska Tsunami Warning Center (WC/ATWC) is to provide timely tsunami watches and warnings to Alaska, British Columbia, Washington, Oregon, and California for potentially tsunamigenic earthquakes that occur in the Pacific Basin. Seismic data are received in real time and automatically processed to determine an earthquake's parameters. Based upon these parameters, watch, warning and advisory messages are sent to predetermined recipients.

Tide gauge data are critical in confirming the existence or nonexistence of a tsunami and its degree of severity. The data from sites in remote parts of the Pacific are sometimes not available during a possible tsunamigenic event, or the data transmission may be delayed for hours after the expected tsunami arrival time at a site. Under the current procedures, the sites data are scheduled transmissions via satellite, every 1, 2 or 3 hours via telecommunications, or via dial up modem where data can be delayed up to an hour. A feasibility study was conducted by the WC/ATWC to decrease this delay by using satellite telephone technology to receive tide/tsunami data from remote sites upon demand. This paper discusses the method used in this feasibility study to retrieve tide gauge data from National Ocean Service (NOS) tide sites in the Pacific Basin.

METHODOLOGY TO RETRIEVE NOS TIDE DATA

Currently, the warning centers use dial-up telephone lines or delayed satellite transmission to interface with tide gauges in the Pacific Basin. A modem in the tide gauge is connected to a telephone line. A personal computer (PC) at the WC /ATWC receives the data via a dial-up modem and contains software to display it for viewing. Unfortunately, the data are not always available on demand, and cannot be immediately retrieved to confirm the existence of a tsunami at a particular tide gauge. This delay adversely affects the geophysicists at the warning centers, emergency officials and the public who are in designated watch and warning areas. Figure 1 shows a diagram of how tide data are currently transmitted from a remote site to the WC/ATWC. Figure 2 shows the integration of a satellite phone and the International Maritime Satellite (INMARSAT) into the configuration.

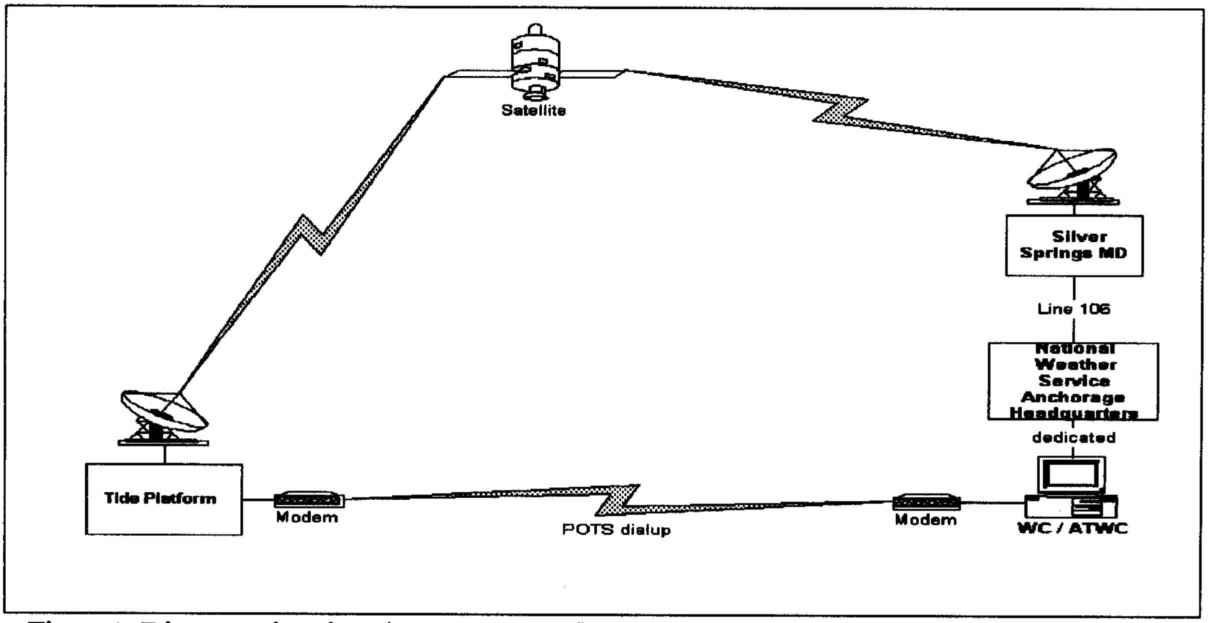

Figure1. Diagram showing the current configuration to retrieve tide data.

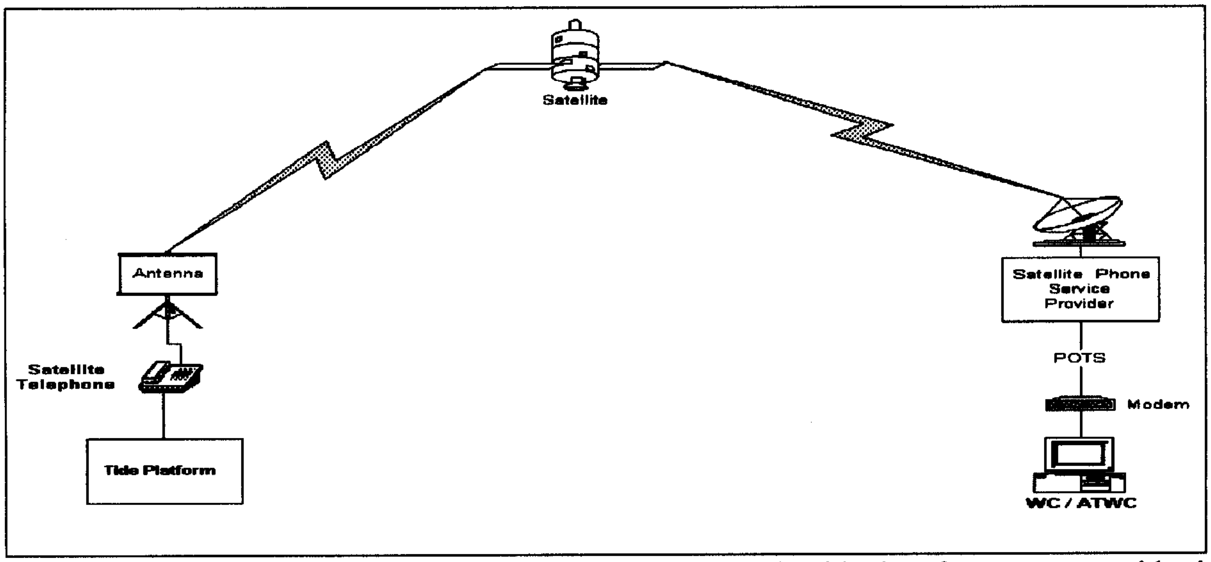

Figure 2. This diagram shows the configuration to retrieve the tide data from a remote tide site located at Seward, Alaska. The modem in the satellite phone is connected to a NOS tide gauge via its serial port. The data are transmitted via INMARSAT, upon demand, to a modem at the WC /ATWC where a PC displays the data.

The INMARSAT system used in this feasibility study uses satellites to provide four different services, called INMARSAT A, B, C and M. Each service targets a particular user. Each unit, called a satphone, uses ether a parabolic or flat satellite antenna with a diameter between 90cm and 1.3 m. Unlike cellular telephones, where near range is important, the INMARSAT phone system communicates directly via satellite to the international telephone network replacing current direct telephone lines. The satellite phone has its own onboard modem. The present cost of a Mini-M satellite phone at a tide gauge is approximately US$4,000. The government charge per minute is approximately US$2.50. These costs depend upon the vendor and quantity of equipment purchased.

In this study, we use, at the remote site, a mini-M system whose dimensions are H=57mm, W=235mm and D=190mm. It weighs 2.4 kg including batteries. It has power requirements of 0.8W to receive and 12W to transmit. It has 4.8 kbps voice and 2.4 kbps data rates. The beam antenna is small and unobtrusive. This systems footprint has Pacific-wide coverage for all NOS sites. Although the primary power source of the Mini-M is AC, it can also be powered by battery or solar panels, which makes it ideal for remote areas where AC power is not reliable or non- existent. Since its interface device uses a serial port, this enables attachment of non-proprietary equipment to a satphone. It is simple to install and retrieve NOS tide data to a PC. In an iteration of our study, we constructed a data logger using a stamp micro-controller. This was interfaced between the tide gauge and the satphone. This data logger, located at the remote site, recorded and made available the most recent two hours of data for viewing and further processing.

The tide site selected for this study was Seward, Alaska, approximately 200 miles from Palmer. A satellite phone was placed at the site and interfaced to the resident NOS tide gauge software. On demand, the data were retrieved and downloaded into a PC for display and/or further processing. Figure 3, on the next page, shows a graph of the tide data retrieved from the Seward tide site.

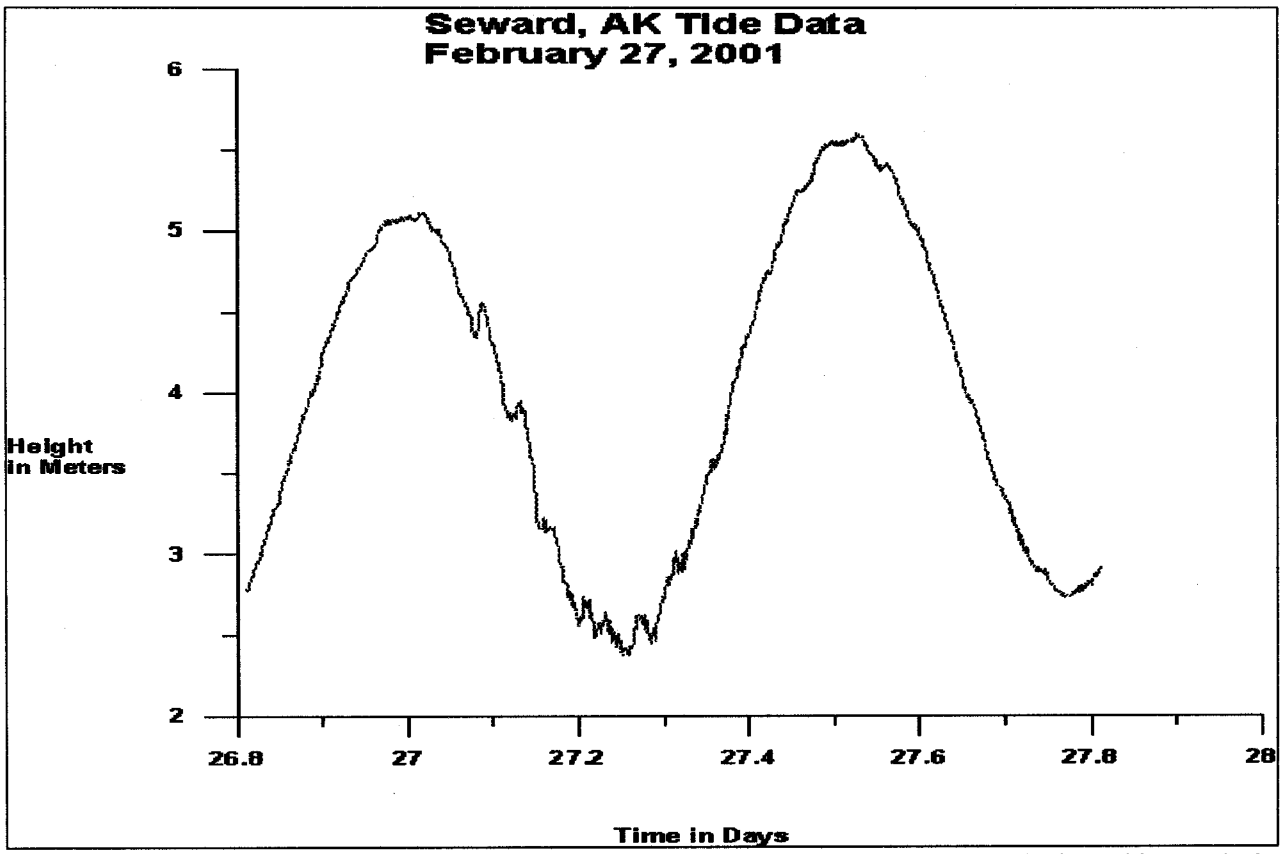

Figure 3. Graph of tide data retrieved from an NOS tide site located in Seward, Alaska. This graph shows the relative tide height collected over a 24 hour time period on February 27, 2001. Time is given in UTC and Julian Day.

DISCUSSION

There are many tide sites throughout the Pacific for which the U.S. Tsunami Warning Centers rely upon to confirm the existence or non-existence of a tsunami. The data from these sites are not available upon demand, often being delayed for hours after the expected tsunami arrival time at a site. Some of the advantages of using a method like this to retrieve tide/tsunami data via satellite are:

- X Obtaining tide/tsunami data upon demand
- X Placement at remote sites, and independent of local telephone and power lines
- X Independent of international telephone circuitry
- X Independent of local communications outages near an epicenter

Delays in obtaining tide data would be reduced considerably by having the data retrieved upon demand from a remote tide site to confirm the existence of a tsunami. This retrieval could be done in periodic lengths of time and repeated as many times as necessary. The retrieved data could be displayed by a PC and/or further processed to enhance the operations of the U.S.Tsunami Warning System (TWS). Eliminating the current significant delays would be beneficial to the TWS geophysicists who must issue and conclude warnings and watches; and, for emergency officials who have the task of evacuating people or avoiding unnecessary evacuations.

ACKNOWLEDGMENTS

The authors wish to thank Mr. R. Przywarty, Alaska Regional Director for his continued support in our efforts to improve the WC/ATWC. The authors also thank Mr. M. Moss (NOS, Pacific Operations Group), and the WC/ATWC staff Paul Whitmore, Tony Tix, and Bruce Turner for their constructive criticism in the preparation of this article.

A MULTI-SENSOR RESEARCH PROGRAM TO IMPROVE TSUNAMI FORECASTING

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ABSTRACT

While the warning systems do an increasingly good job of warning of all probable events, there are still apparent false alarms and a lack of magnitude prediction. History shows that major advances in technology occur when several components mature to be combined into a final system. An example is the communications satellite: around 1960, the silicon solar cell, the RF transistor, the integrated circuit, the large rocket, knowledge of the synchronous orbit, reliable components, and supporting systems came together to produce systems so workable that the early ones are still usable and the current ones just have more channels. We are now in a "1960 position" in tsunami work. Deep ocean sensors are in place, numerous tide gauges and sea level gauges are telemetered (via satellite), real-time numerical analysis programs are under development, Mw can now be calculated in an hour and Mwp in a minute, a global infrasonic network has been deployed, T-phase data are readily available, and so are ionospheric sounders. We have the capability to cheaply and quickly record, correlate, analyze, transmit, and discard data from all these sensor systems. Thus, we should have the means to develop the ability to evaluate a tsunamigenic earthquake and early tsunami waves, reliably and even quantitatively. I suggest the ideal way to accomplish this is to establish a small, dedicated laboratory which will bring together a selection of data from these sensor systems to evaluate every possible tsunamigenic event. It is now easy to temporarily store these data in volatile memory for analyses, retention, and discard. An earthquake that would be checked and discarded by the warning center can provide the trigger for storage and evaluation. Most of the data are low frequency, easy to transmit (part of it is on the Internet now), and store. Information on prior experiments with some of the components, current status, and processing estimates is provided, along with ample references.

THE WARNING PROBLEM

While the warning systems do an increasingly good job of warning of all probable events, there are still unnecessary evacuations and a lack of magnitude prediction. Warnings are binary, with a very fine line between "warn" and "no warn"; the decision is usually conservative and produces false alarms from the public viewpoint if not in fact. This occurs because we still have not achieved the ability to forecast a damaging event accurately and rapidly. Yet, we have more seismic stations than ever, more sea level stations, more computers with faster, more capable programs, and better communication systems. Our use of modern technology is good, but more can be incorporated into a systems approach. Curtis (1993) reviewed the progress at that time and pointed out some research which might be cost-effective. How can we accomplish more improvements? History shows that major advances in technology occur when several components mature to be combined into a final system (Curtis et al, 1986). An example is the communications satellite: around 1960 the silicon solar cell, the RF transistor, the integrated circuit, the large rocket, knowledge of the synchronous orbit, and highly reliable components, came together concordantly to produce systems so workable that the early ones are still usable and the current ones just have more channels. We are now in a "1960 position" in tsunami work. Deep ocean sensors are in place, numerous tide gauges and sea level gauges are telemetered (via satellite), real-time numerical analysis programs are under development, Mw can now be calculated in an hour and Mwp in a minute, a global infrasonic network has been deployed, T-phase data are readily available, and so are ionospheric sounders. We have the capability to cheaply and quickly record, correlate, analyze, transmit, and discard data from all of these sensor systems. Thus, we should have the means to develop the ability to evaluate a tsunamigenic earthquake and early tsunami waves, reliably, and even provide a quantitative warning. If we bring all appropriate technology to bear on the problem, we can surely advance that capability nearer to the goal.

THE CONCEPT

I suggest that the ideal way to accomplish this is to establish a small, dedicated laboratory which will bring together a selection of data from these sensor systems to evaluate every possible tsunamigenic event. It is now easy to temporarily store these data in volatile memory for analyses, retention, and discard. An earthquake that would be checked and discarded by the warning center can provide the trigger for storage and evaluation. Most of the data are low frequency, easy to transmit (part of it is on the Internet now), and store. A precept was provided by Najita and Yuen (1978). The reference includes a full description of tsunami generation by earthquakes and of detection of tsunamigenic events by HF ionospheric sounding. The laboratory they set up at the University of Hawaii is described; the sounding was continuously plotted on a chart recorder at slow speed activated to a high speed when seismic waves from the UH seismometer exceeded a threshold similar to the alarm at the Pacific Tsunami Warning Center (PTWC). A significant problem was in disregarding the natural perturbations occurring at dawn and dusk. These could only be partially be removed by the band pass filter used, and the project was eventually discontinued. Was an important opportunity missed when this work was not carried further? Most of the technology involved has now grown and advanced so it will be much easier to carry out the work in the future. Plus, with more geophysical sites in use, far more good data are readily available. In fact, it is likely that this and other ideas can be done as a hindcast experiment with the large amount of sensors and recordings from them currently stored in accessible data banks.

SENSORS AND SOURCES

Ionospheric:

Ionospheric sounders indicate the height of the ionosphere, the upper portion of the atmosphere that is heavily ionized and which enables "short wave" radio transmission by reflection of the signals. Earthquakes with a significant component of vertical deformation perturb this layer in a manner that is readily measured using precise radio signals in the high frequency region broadcast by standard stations around the world. The vertical displacement travels toward the ionosphere (100 meters altitude or more) as a Rayleigh wave, faster than the speed of sound; the radio measurements are of course instantaneous. Weaver et al, (1969) report such measurements for an earthquake in the Kuriles and Furumoto (1970) discusses using them to evaluate the source mechanism of tsunamis. These investigators used 5 and 10 MHZ transmissions from WWVH on Kauai, received in Honolulu and utilized as described by Najita. Fitzgerald and Walcott (1985), reported the ionospheric disturbances from the Coalinga earthquake; there are numerous other similar recordings. The actual data of interest is between 2 seconds and 300 seconds. It appears that there are at least 12 HF sounding stations around the Pacific in the US, Canada, and Japan which can provide real time or recorded data for this purpose. Figure 1 shows the location of some. A newer but widely used method of measuring ionospheric changes is by their subtle changes in SHF radio transmissions from satellites; Navstar GPS is usually used. Calais et al (1997) obtained signatures from a mine blast by this method while others have described the effects of earthquakes on the signals. Romans and Hajj, (1996) give a general view of the methodology. Since the satellites transmit on two frequencies it is feasible to obtain an excellent differential measurement. These receivers can be set up for real time use wherever telemetry is available.

Infrasonic Sensors:

Project "Vela" a set of ARPA programs to detect nuclear explosions produced many standard seismic systems around the world, but also a number of infrasonic receiving systems (microbarographs) were established. (Of course many such geophysical labs had existed for years). These sensors added to the ability of research in atmospheric detection of events such as hurricanes, tornados, earthquakes, and other disturbances. It was known that earthquakes sometimes were reported to produce a noise, and Nakamura (1988) described the sound of an approaching tsunami and analyzed how it might be produced. Miller (1968) had earlier brought up the possibility of predicting tsunami height from atmospheric wave data, mentioning the effect of the vertical component. In the same symposium, Donn (1968) discussed sources of infrasonic waves and their detection [this writer developed the sensors then in use by Donn at Lamont Geophysical Observatory and recalls their detection of hurricanes as well as nuclear explosions]. Bedard and Georges (2000) and Bedard (1998) discuss the varied applications of infrasonic detection (the 1998 paper alone has 31 references) including earthquake detection and analysis. An example of recording both infrasonic and acoustic waves for geophysics is provided by Tihara, et al (1997). There are a number of microbarographs around the Pacific of varying capability whose records might be used for analysis, if not in real time. Ironically, the Honolulu Observatory (which became the Pacific Tsunami Warning Center) had a microbarograph, which apparently was disgarded long ago. The Comprehensive Test Ban Treaty (CTBT) has resulted in establishment of an enhanced Vela-type global network by the U.S. Department of Defense. These microbarographic stations are extremely sophisticated, have a large wind noise reduction system (detection is limited by wind noise, not the sensor elements) , and are well equipped and manned. The pass band of the microphone is 8 to 0.02 Hz (period of 0.125 to 50 sec) less some noise reduction effect, and the data are telemetered to a central location in Virginia. There are systems now reported to be in operation in the Pacific region, as part of the International Monitoring System (IMS). Because they are wide band, low noise, and on line, they are probably the best sources of earthquake-effect data. Figure 2 maps some of the various microbarographs in the Pacific. Since the signals travel at roughly the speed of sound, it is necessary to utilize sensors as near the source as possible.

T-phase Sensors:

The T-phase signal from an earthquake is propagated via the SOFAR (SOund Fixing And Ranging) channel in the ocean and couples into the earth near the coast to be detected by a seismograph. Since most of the path is acoustic (1500 m/sec) it arrives after the P and S waves and so is referred to as the tertiary wave. It can of course be readily detected by hydrophones in the sound channel (U.S. Navy) and also by other hydrophones. The use of the T-phase signals in the warning system was proposed by Ewing et al, in 1950. Considerable work was done on seismic T-phase evaluation for that purpose (Johnson, 1970) but with limited success. Johnson pointed out that if an array of hydrophones were available, he could have combined directivity with duration and accurately determined rupture length. The SOSUS can now provide just what Johnson needed, in the desired band of 2 to 30 Hz. Walker et al, (1991, 1992) revived interest in application of T-phase data to tsunamigensis by gathering extensive data from abandoned military hydrophones of the Wake Island MILS (missle impact locating system). They did extensive examination of the correlation of these waves (in frequency, amplitude and duration) with source, path, and moment magnitude and concluded that variables such as the acoustic path limited reliable analysis of tsunamigenisis in many cases. However, he was limited to a single receiving location and no directivity. With the end of the Cold War the Navy began to close many of their submarine tracking SOSUS (SOund SUrveillance System) stations, and made data from others available to the scientific community. Fox and Hammond, 1994, describe the VENTS program under NOAA which provides T-phase and other data via SOSUS in the North Pacific. The several SOSUS stations, each with an array of many hydrophones, offers a means to deal with the path discrepancies encountered with a single location. It should be possible to evaluate predetermined paths to likely seismic locations and make a more valid analysis of tsunamigensis of an event in near-real time. Figure 3 shows the approximate locations of some SOSUS stations; some are part of the IMS and some are connected to NOAA via a Navy processing station at Whidby Island, Washington.

Other Sensors:

An open scientific mind may suggest other sensors not yet considered or which, though not feasible in the past, may now be possible. Satellite altimetry has improved since Seasat and the fortuitous detection of waves may occur if we look and analyze carefully. The use of differential GPS on a buoy with satellite transmission is a possible method of observing a wave. Improvements in evaluating the source in real time the seismic moment, the rupture length from wave arrival time at area gauges, the deployment of more deep ocean sensors will certainly continue and will offer more means to promptly evaluate a possible tsunami, while at same time make the job more complex.

THE TSUNAMIGENISIS EXPERIMENT

The above descriptions of past and current programs related to tsunamigenisis indicate that a) there are technologies available or known that can help define the onset of a significant tsunami but b) we have not combined them into a working system. The other vital technology available but not mentioned as it is known to all is rapid data handling systems. We now have relatively cheap, fast, high volume, digital communication, storage, and analytical equipment not available to many of the investigators cited above. We should utilize these capabilities along with careful consideration of the science that has been done and that is now in use, to develop a more reliable tsunami forecasting system. This is the sort of concurrent approach outlined in the introduction and can move the 1960's point into this century.

I suggest that the ideal way to carry this out is to establish a small, dedicated laboratory which can gather, correlate, and evaluate a selection of data from every possible tsunamigenic event. The extensive and very capable seismic network now deployed provides the basis for experiments by triggering the data collection scheme. Inputs from several sensors temporarily stored in volatile memory of ample duration may then be stored for analysis, archiving, or discard. It is easy to save before as well as after. This writer designed a system 20 years ago which keeps four channels of data plus WWVH time for 4 minutes before and 6 minutes after an event. It is still in use but could be done much better with present technology. This is a good approach to our data problem. As in any good experiment, the negative data (no significant tsunami) can be as important as the positive results. Examination of the possible sensors and data makes it clear that some very productive work can be accomplished by hindcasting with existing data. A good example already accomplished is the evaluation of moment analysis as a tsunamigenic indicator (Walker et al, 1991; Tsuboi et al, 1999). This has not provided a satisfactory answer yet, but if it is correlated with other data may eventually yield a better solution. Other examples might be microbarographic data after an earthquake, from Japanese and U.S. archival sources. The optimum approach is to establish a small, dedicated laboratory at a location where essential real-time data are available and staff and analytical capability exist even part time. Because most pertinent data can be saved automatically by this system for later analysis,,attendance would not be mandatory. Certainly, a combination of on-line data, recorded data, and retrievable data can be used to present the coordinated information to knowledgble scientists, present or not. Figure 4 outlines a system intended to be comprehensive what should be planned for, not necessarily what can be done this year. But, none of it is technically difficult. Funding for new projects is often difficult but we have far more available to solve this problem than we had ten or twenty years ago (Curtis 1993). Much of the data are "free" for the connection or retrieval.

A carefully chosen committee of "customers" (warning centers and advisors), experienced tsunami scientists, and data suppliers as overseers will enable the laboratory to achieve the goal of almost eliminating "false alarms" without endangering public safety. The cost of one unnecessary evacuation would pay for years of its operation.

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Note: copies of most of the above references are in this writer's files, and can be made available to other users.

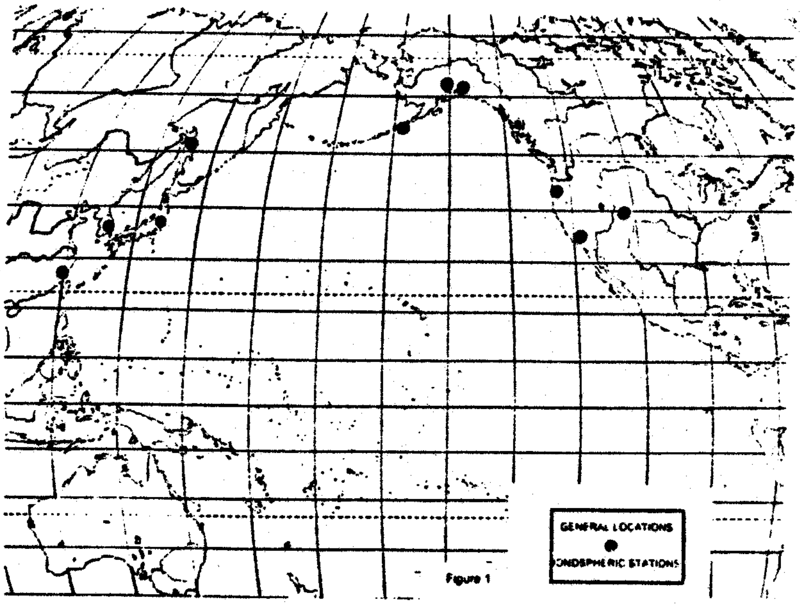


Figure 1 - General locations, ionospheric stations

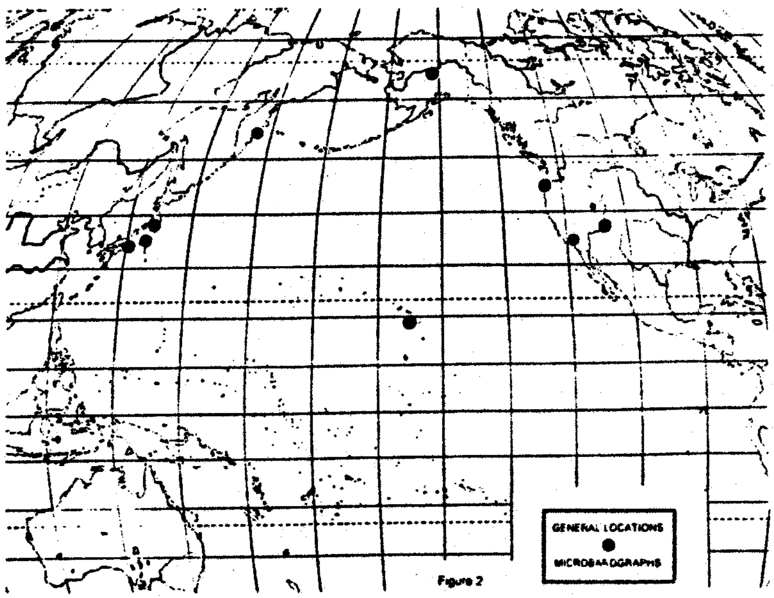


Figure 2 - General locations, microbarographic stations

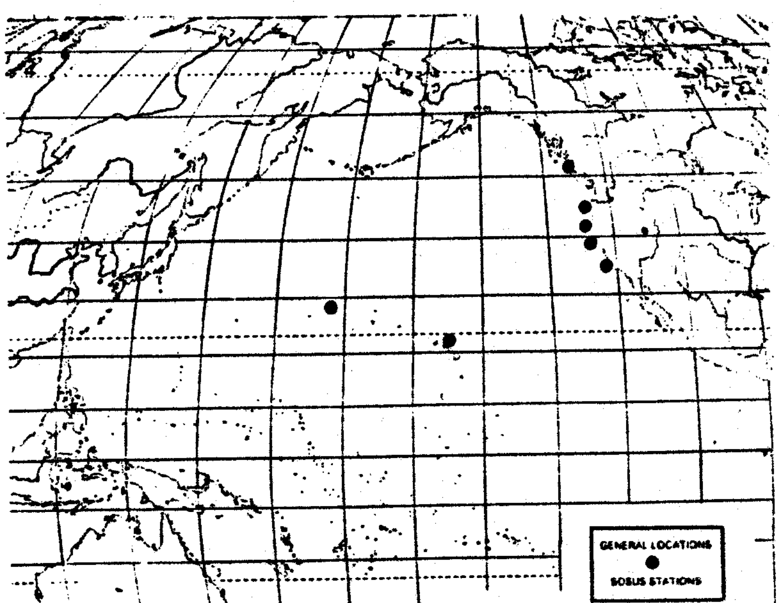
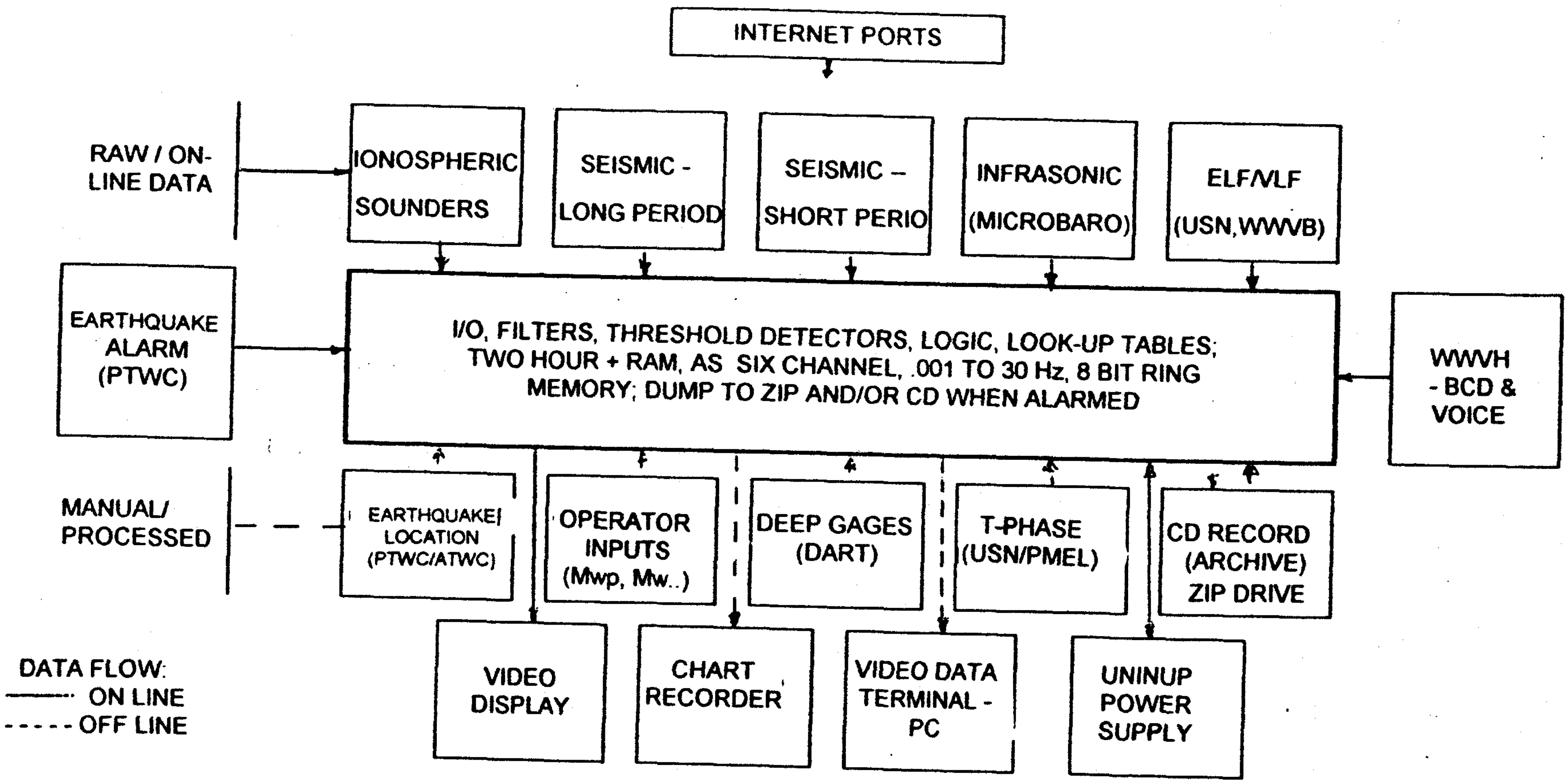


Figure 3 - General locations, SOSUS/hydroacoustic stations



DUE TO THE LOW DATA RATE — 30 Hz MAXIMUM — STORAGE REQUIREMENTS FOR SIX CHANNELS REAL TIME DATA FOR TWO HOURS ARE MODEST; APPROXIMATELY 20 Mbyte (VOICE OPTIONAL). MULTIPLE INTERNET ACCESS IS PROBABLE.

Figure 4 - Data Flow in a Proposed Tsunamigenisis Laboratory

THE INAPPROPRIATE TSUNAMI ICON

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ABSTRACT

The supposition that the Japanese printmaker Hokusai intended to represent a tsunami in his print of the "Great Wave at Kanagawa " is unfounded, and the use of his "Great Wave" as a tsunami icon gives a false impression of the nature of tsunami waves.

HOKUSAI AND HIS PRINT OF THE "GREAT WAVE OFF KANAGAWA"

The artist most widely known as Hokusai was born in Edo (now Tokyo) in 1760 and died in 1849. When adopted as an infant by Nakajima Ise, he was given the name Nakajima Tamekazu, but he took many different names later including Katsuhika from the district of Tokyo in which he was born, and Hokusai, which he used as a surname beginning about 1797.

At least outside of Japan, Hokusai has been considered the greatest of the artists of the Popular School (Ukiyo-e) of that nation, although Japanese have tended not to rank him so high. He is best known for his illustrations of books, particularly the *Mangwa*, a 15 volume pictorial encyclopedia of Japanese life, for his color prints, many of which were published in sets, and for his "Hundred Views of Mount Fuji", monochrome prints published in three volumes.

The print commonly referred to as the "Great Wave off Kanagawa" (Figure 1) was one of the colored prints in the set of the "Thirty-six Views of Mount Fuji" that Hokusai made between 1823 and 1829. (The wording within the cartouche on the print is essentially a combination of the title of the individual print and the title of the set of which it was a part. It might be translated more or less literally as: "Mount Fuji, Thirty-Six Views -- From within the waves of the open sea off Kanagawa).

The dominant feature of the print is a breaking peak on the crest of a steep wave that is moving from the left toward the center; the back of a similar wave is shown at the extreme right; and a subsidiary wave peaks in the left foreground. There is a fishing boat with eight crewmen in the trough between the subsidiary wave and the wave at the right; what appears in a reduced-sized version of the print to be a part of the same boat to the left of the subsidiary wave may be distinguished in an unreduced version as a separate boat; and in the background, sliding down the back of the wave to the right, there is a third boat, again with eight crewmen. Mount Fuji is shown in the distance behind this third boat.

In this print, as in the case of most of his prints, Hokusai exercised considerable artistic license. The title he used for this print suggests, however, that he intended to represent in it a typical scene. Combined with the title, the position of Fuji in the print and the direction in which the waves are moving in it suggest that the scene was that of a viewer looking west-northwest from a point in the Sagami Wan (Sagami Bay) off the coast of the Kanagawa Prefecture in the vicinity of Kamakura (Figure 2). Neither the Kanagawa shore nor the hills and lower mountains southeast of Fuji are shown in the print, but that they are beyond the horizon cannot be certain because the viewpoint is clearly in the trough of the waves.

ERRONEOUS IDENTIFICATION OF THE "GREAT WAVE" AS A TSUNAMI WAVE AND ITS INAPPROPRIATE USE AS A TSUNAMI ICON

Some have supposed that Hokusai intended the "Great Wave" to represent a tsunami wave; and during the last few decades it has been used by individuals and organizations involved with research on tsunamis and the mitigation of tsunami hazards as an icon symbolizing such endeavors.

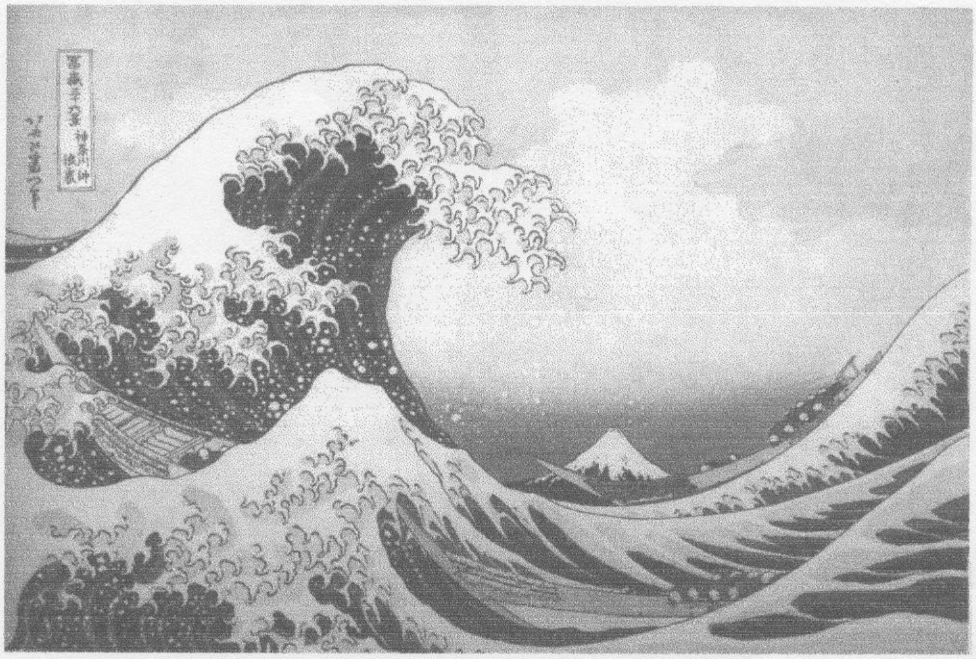

Figure 1. Hokusai's "Great Wave off Kanagawa".

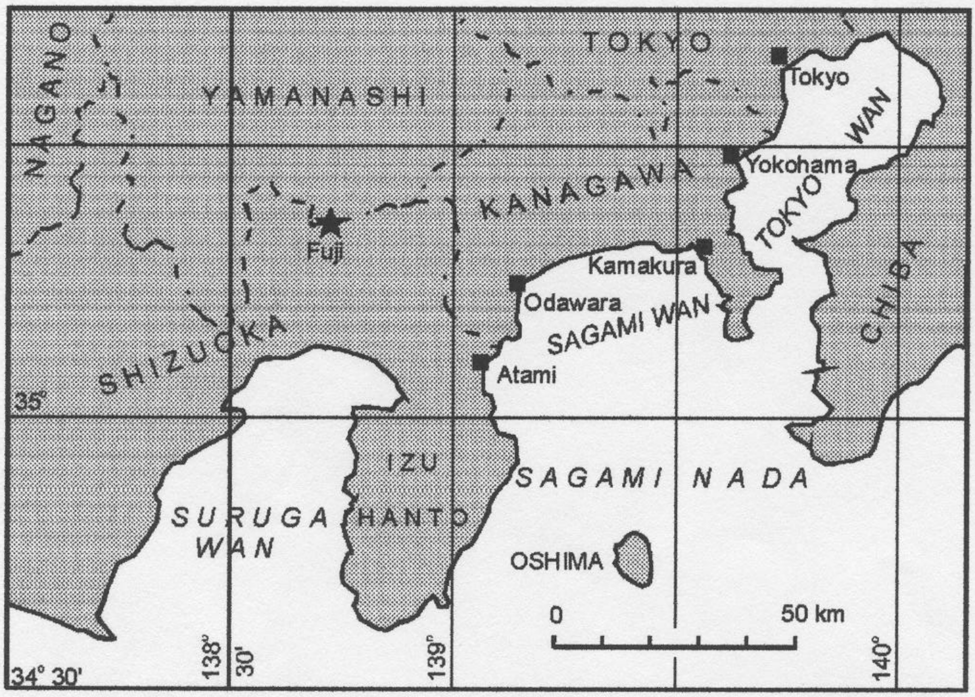

Figure 2. South coast of central Honshu, Japan, showing Kanagawa, Fuji, Sagami Wan, and surroundings.

I am not certain when the "Great Wave" was first associated with tsunamis. I was given a copy of Hokusai's print by Ryutaro Takahasi, the Director of the Earthquake Research Institute of Tokyo University in 1961, when I first went to Japan as the geophysicist in charge of the newly established Tsunami Research Program at the Institute of Geophysics of the University of Hawaii. It was my impression, however, that Takahasi selected the gift in recognition of our mutual oceanographic interests in general and perhaps because I had expressed an admiration for Japanese prints, and not because he attached any special tsunami significance to the print. I can neither recall nor find evidence for any reference to the Hokusai print at the tsunami meetings sponsored by various organizations associated with the Pacific Science Congress in 1961.

The association had, however, been made by 1964, the year of publication of the Japanese version of *Studies on Oceanography*, a collection of papers dedicated to Koji Hidaka, the then retiring Director of the Ocean Research Institute of the University of Tokyo. In one of those papers Hokusai's print was described as portraying "The crest of a great tsunami wave off Kanagawa" (Wilson, 1964, 1965). I have since heard Hokusai's print described many times as intended to represent a tsunami and, recently, as intended to represent specifically the Sanriku tsunami of 1896. This last rumor may have been based on similarities between Hokusai's "Great Wave" and representations of waves of the 1896 tsunami in a number of contemporary drawings by other artists that were reproduced in a pamphlet published for the 100th anniversary of the event (Nanashita, 1995).

Since the 1970's at least, various monochrome versions of Hokusai's print or the "Wave" from it have been used as symbols for tsunamis. For example, small, much simplified versions of the "Wave" without Fuji in the background and with the initials ITIC superimposed have been used since 1972 as an icon by the International Tsunami Information Center appearing somewhere on the cover of each issue of the Center's *Tsunami Newsletter*. In addition, large but slightly cropped copies of the print, generally including Fuji, have appeared on the cover of each *Newsletter* issued from1993 through 1999. Other uses noted before 1996 when I prepared a first version of this paper, include small, simplified versions appearing on the fronts of brochures describing the International Tsunami Warning System and on the front of a brochure of the Hilo (now Pacific) Tsunami Museum. A very small version, greatly simplified and with a palm tree replacing Fuji in the background, appeared on a handsome pin of which copies were distributed to participants in a conference on tsunamis held so long ago that I cannot now remember its date or sponsors. What seems to be a highly stylized version of the wave was the base of a symbol used at an international tsunami symposium held in at Novosibirsk in 1989 and again on the cover of a Tsunami Hazard Mitigation Plan prepared by a USA Federal/State Civil Defense working group.

It would, of course, have been impossible for Hokusai to have included in any of his prints a wave of the Sanriku tsunami that occurred 55 years after his death, and in any case the "Great Wave" he portrayed was off the coast of the Kanagawa Prefecture, not the coasts of the Sanriku prefectures of northeastern Honshu. The record of tsunamis known to have affected the Kanagawa coast in the 18th and 19th centuries (Table 1) includes none occurring during the period when Hokusai was portraying various aspects of Fuji in his set of "Thirty-Six" prints (there were actually 46).

Table 1. Tsunamis affecting the coast of Kamagata Prefecture, Japan, 1700-1900.

Date		Earthquake				Tsunami	
			Epicenter, °				
Gregorian	Japanese	Time (local)	N Lat.	E Lon.	Mag.*	Source	Mag.#
1703 Dec 31	Genroku 16 XI 23	~ 02:00	34.7	139.8	8.2	Sagami Nada	4
1782 Aug 22	Tenmei 2 VII 15	~ 02:00	34.5	138.8	7.3	Sagami Nada	1
1854 Dec 23	Ansei I XI 4	09:00-09:15	33.2	135.6	8.4	S. of Wakayama Hanto	4

* Earthquake magnitude, authority: Tokyo Astronomic Observatory

\# Tsunami magnitude: m =1, maximum runup ~ 1 m
m = 2, " " ~ 2 m
m = 3, " " ~ 4 m
m = 4, " " ~ 8 m

Sources of information: Iida *et al*., 1967.
Solov'ev and Go, 1974, 1984.

Indeed the last major tsunami significantly affecting the Kanagawa coast had accompanied a major earthquake occurring nearly 50 years before Hokusai's birth on 31 December 1703. That tsunami is reported to have caused 600 deaths at Kamakura where it had a runup height estimated at 8 m, and 230 deaths at Odawara, where it had a runup height estimated at 4 m. Another earthquake that was felt strongly in Kanagawa and Tokyo Prefectures and that caused considerable damage at Odawara in 1782 was accompanied by a tsunami. However, little is known about the effects of that tsunami, which occurred when Hokusai was 22, 21 years before he began preparing the "Thirty-Six Views". What is known as the Great Ansei Tokaido Tsunami did not occur until December 1854, five years after Hokusai's death.

The characteristics of the "Great Wave" are shared with waves in other Hokusai prints, for example a wave traveling in the opposite direction in another of the "Thirty-Six Views of Mount Fuji" that is titled simply "A Wave". There is no evidence that Hokusai intended to represent non-wind generated waves in any of his Fuji prints, and if he had wished to commemorate the occurrence of one of the tsunamis that affected Kanagawa by incorporating one of its waves in the foreground of one of the prints, it seems very doubtful that he would have done so without identifying the wave as that of a tsunami (or kaisho).

Regardless of Hokusai's intent, the use of his "Great Wave" as a tsunami icon gives a false impression of the nature of tsunami waves. Even as a representation of a wind-generated wave. Hokusai's "Great Wave" has a steepness that is exaggerated. As such, the exaggeration is not only within the bounds of artistic license but in accord with how ordinary waves are often perceived. However, the steepness of tsunami waves in the ocean and even as they approach many coasts is so small that they cannot be perceived as waves. If not accompanied on such coasts by wind-waves, they may best be described on these coasts as gradual rises and falls of water level whose most dramatic effects are the high water velocities that result from their inundation of and recession from the shore. Their tide-like behavior under these circumstances is undoubtedly the reason that they have been referred to as "tidal waves" in non-technical language.

Where a tsunami wave approaches the shore in shallow water it may convert to a bore with one or more steep, step-like fronts; and the steepness of the fronts of waves inundating the Sanriku coast in some of the drawings of the 1896 tsunami to which reference was made earlier

(Nanashita, 1995) cannot be considered inappropriately exaggerated. .However, for a considerable distance behind the steep wave front of a bore, the water level is characteristically nearly flat whereas the backslope of Hokusai's "Great Wave" is apparently as steep as its foreslope. There is, in any case no evidence that his "Great Wave" is approaching shore in shallow water and the general impression given by the print is that the scene portrayed is well offshore.

Failure to realize that tsunami waves often have such small steepness that they cannot be recognized as waves has undoubtedly contributed to the loss of life associated with tsunamis. The adoption of representations of steep waves as symbolic of tsunamis therefore seems unfortunate. I must admit, however, that I can think of no substitute whose artistic attractiveness would approach that of representations of Hokusai's "Great Wave". Hence it seems unlikely that these representations will be replaced as tsunami icons. In my opinion, however, each use of such an icon should at least be accompanied by explicit recognition that real tsunami waves do not resemble the icon.

ACKNOWLEDGEMENTS

I acknowledge with gratitude the help I have received from several people in the preparation of this note. George Curtis, Augustine Furumoto, and Charles McCreery provided information on uses of Hokusai's "Great Wave" as an icon, drew to my attention the drawings of waves of the 1896 tsunami, or both. Phillip Roach of the Honolulu Academy of Arts provided information on Hokusai and the provenance of his "Great Wave off Kanagawa". Diane Henderson, Editor, School of Ocean and Earth Science and Technology, University of Hawaii, provided valuable editorial services.

The preparation of this paper was supported in part by National Science Grant BCS 9208173.

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MODELING THE 1755 LISBON TSUNAMI

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ABSTRACT

The generation and propagation of the November 1, 1755 Lisbon earthquake generated tsunami is of current interest to the IOCARIBE Tsunami Scientific Steering Committee.

The November 1, 1755 Lisbon earthquake generated a tsunami with a period of one hour and amplitudes of 20 meters at Lisbon and along the African and south European coasts, of 4 meters along the English coast, and of 7 meters at Saba in the Caribbean after 7 hours of travel.

The modeling was performed using the *SWAN* code which solves the nonlinear long wave equations. The tsunami generation, and propagation was modeled using a 10. minute Mercator grid of 600 by 640 cells.

The observed tsunami wave characteristics were approximately reproduced using a source 300 kilometer in radius with a drop of 30 meters located in the region of the 1969 earthquake near the Gorringe bank.

The east coast of the U.S.A. and the Caribbean received a tsunami wave off shore in deep water about 2 meters high with periods of 1.25 to 1.5 hours. The maximum wave amplitude after run-up would be about 10 feet. The Gulf of Mexico would have a wave with less than half that amplitude.

INTRODUCTION

The earthquake that destroyed the city of Lisbon at about 9:40 a.m. on November 1, 1755 is estimated to have had the unheard of magnitude of 8.75-9.0 as described in reference 1. It was felt over a million square miles and appears to have had at least two foci, one of which in North Africa caused ground motion that damaged cities 400 miles south of Lisbon. The epicenter may have been close to the February 28, 1969 earthquake epicenter located south of the Gorringe bank as postulated in reference 2.

The November 1, 1755 earthquake generated a tsunami which arrived at Lisbon between 40 minutes and one hour after the earthquake as a withdrawing wave that emptied the Lisbon Oeiras Bay to more than a mile out. Then a tsunami wave with an amplitude of about 20 meters arrived followed by two more waves about an hour apart as described in reference 1. The tsunami wave had a period of one hour and amplitude of up to 20 meters at Lisbon and along the African and south European coasts, of 4 meters along the English coast, and of 7 meters at Saba in West Indies after 7 hours of travel as described in references 1, 2 and 3.

In comparision, the May 23, 1960 Chile earthquake had a magnitude of 8.5 and generated a tsunami with a 25 minute period from a source about 150 kilometers wide and 800 kilometers long or 120,000 sq kilometers. The March 26, 1964 Alaskan earthquake near Prince William sound had a magnitude of 8.4 and generated a tsunami wave with a 30 minute period from a source about 300 kilometers wide and 800 kilometers long or 240,000 square kilometers. To a first approximation the tsunami wave period is determined primarily by the width of the ocean floor displaced by the earthquake and the wave amplitude by the height of the ocean floor displacement. To generate a tsunami wave with a 1 hour period requires an ocean floor width, area and displacement larger that either the 1960 or 1964 events.

MODELING

Since we do not have seismological information for the 1755 earthquake to determine the location and area, we have used the tsunami wave characteristics to determine the possible source characteristics. While large uncertainities are associated with the procedure, the amplitudes of the tsunami wave at deep water locations in the Caribbean and along the U.S. East Coast are probably adequate for determining the hazard presented by a large tsunami such as the 1755 Lisbon tsunami.

To generate a tsunami with an initial negative wave of 1 hour period and 20 meter amplitude at Lisbon about 40 minutes after the earthquake requires an ocean floor region about 300 kilometer in radius (282,000 square kilometers) dropping 30 meters. The location needs to be in the region of the 1969 tsunami epicenter which was near the Azores-Gibraitor fracture zone and the Gorringe bank as described in reference 2. The intitial earthquake displacement region is shown in Figure 1.

The modeling was performed using the *SWAN* non-linear shallow water code which includes Coriolis and frictional effects. The *SWAN* code is described in Reference 4. The calculations were performed on 233 Mhz Pentium personal computers with 48 megabytes of memory.

The 10 minute Atlantic topography was generated from the 2 minute Mercator Global

Marine Gravity topography of the earth of Sandwell and Smith of the Scripps Institute of Oceanography and described in Reference 5. The grid was 600 by 640 cells with the left hand corner at 20 S, 100 W. The grid extended from 20 N to 65 N and from 100 W to 0 W. The time step was 10 seconds.

The source used in the calculations to simulate the 1755 Lisbon tsunami and the Table 1 locations are shown in Figure 1. The units of the X and Y axis are 10 kilometers. The travel time chart is shown in Figure 2.

The maximum deep water amplitudes at various locations are given in Table 1. The negative wave arrives first followed by several waves with the first wave usually having the maximum amplitude. The periods of the waves along the European and Africian coasts are from 1.0 to 1.2 hours.

As shown in Reference 4 the run-up amplification may be from 2 to 3 times the deep water wave amplitude. Locations with depths less than 1000 meters have some of the run-up amplification included.

The east coast of the U.S.A. and the Caribbean receive a tsunami wave off shore in deep water about 2 meters high with periods of 1.25 to 1.5 hours. Such a wave would give waves along the shore about 10 feet high with Saba being unique with about a 20 feet high wave after run-up. After the wave travels into the Gulf of Mexico the wave amplitudes are less than one meter.

Computer generated animations of these calculations are available from the author.

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TABLE 1
CALCULATED DEEP WATER WAVE HEIGHTS
FOR 1755 LISBON TSUNAMI

No	Depth Meters	Location	Maximum Amplitude Meters	Minimum Amplitude Meters
1	953	Off Lisbon	+20.	-20.
2	4747	East of Saba	+2.5	-3.2
3	825	East of Saba	+5.	-4.
4	3446	North of San Juan	+2.	-3.5
5	783	East of Miami	+2.	-3.5
6	2922	East of Washington	+2.	-3.5
7	178	South West of England	+6.	-9.
8	4574	West of Lisbon	+9.	-13.
9	3868	West of Lagos	+7.	-11.
10	3923	West of Gibraltar	+5.	-13.
11	4376	West of Gibraltar	+10.	-13.
12	1717	West of Casablanca	+15.	-15.
13	3314	West of Source	+7.	-8.

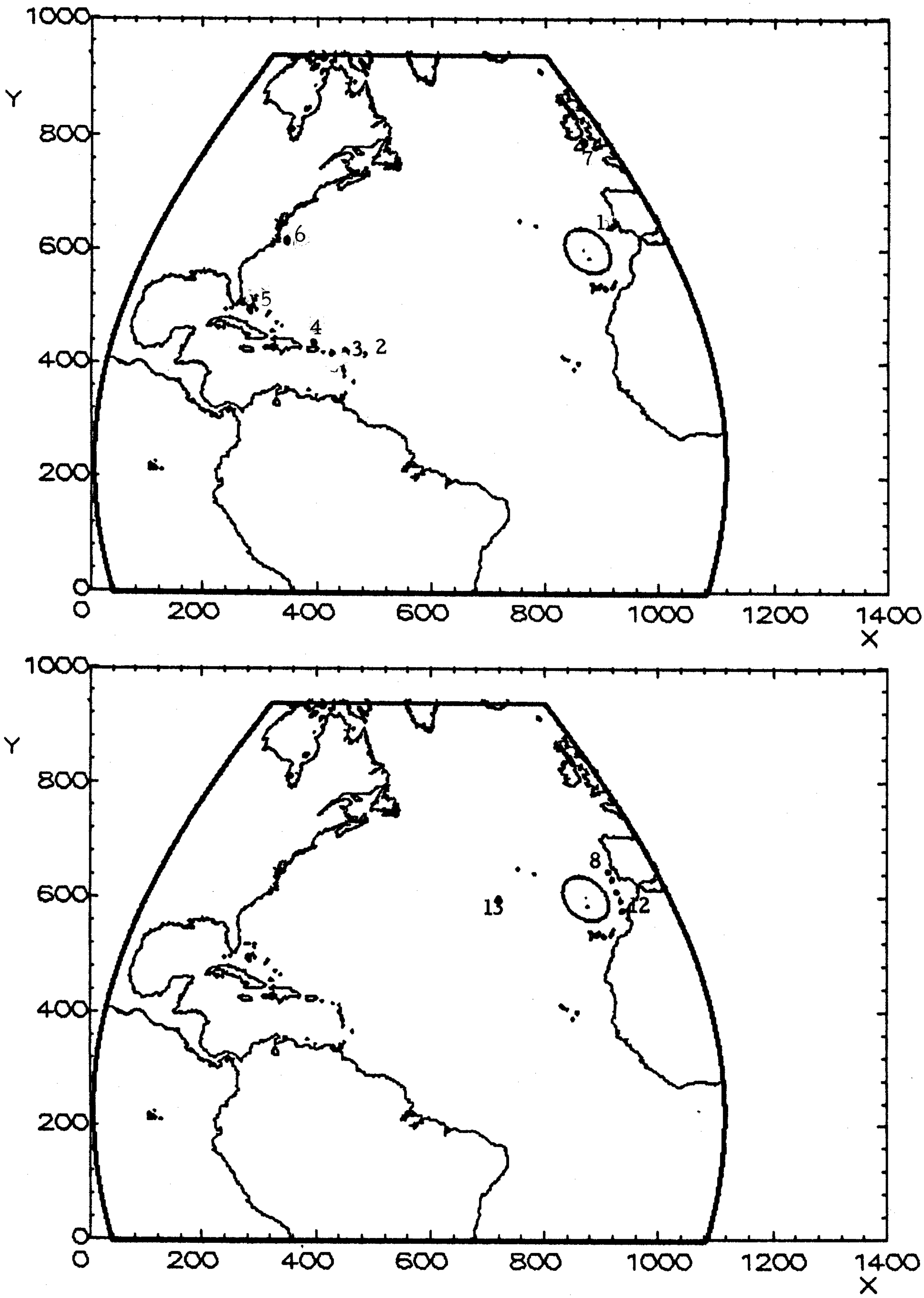

Figure 1. The source region and Table 1 locations. The X and Y axis units are 10 kilometer

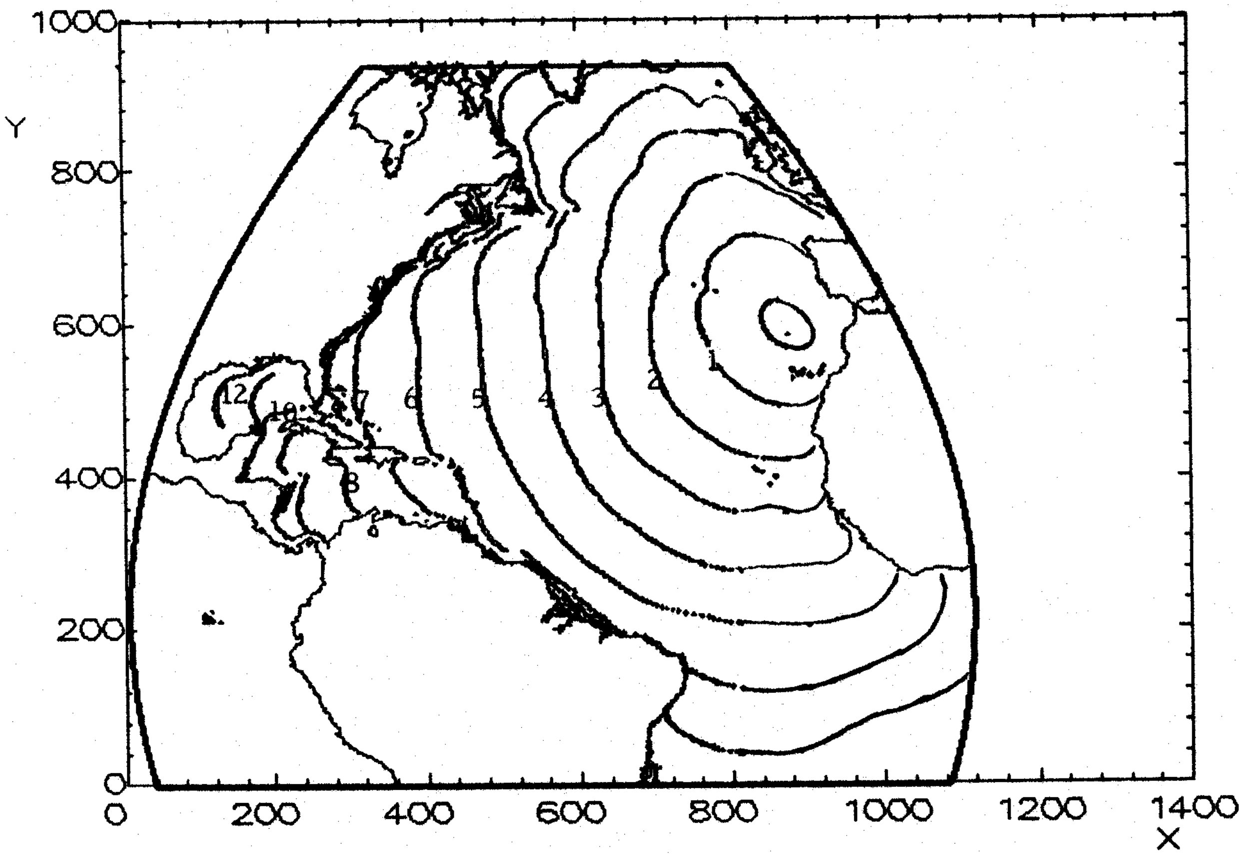

Figure 2. The Travel Time Chart at one hour intervals.

BASIC RELATIONS BETWEEN TSUNAMI CALCULATIONS AND THEIR PHYSICS

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ABSTRACT

Basic tsunami physics of propagation and run-up is discussed for the simple geometry of a channel. We will try to understand how linear and nonlinear processes occurring in a tsunami should influence approach taken to numerical computations.

1. Introduction

While stability of a numerical scheme for tsunami computations seems to be a straightforward notion, achieving of a proper spatial and temporary resolution is a goal which is closely related to the tsunami wave physics. A process of tsunami wave propagation is considered in the deep 6000 km long channel. It is demonstrated how to choose time step and space step to avoid numerical dissipation. Examples are given for tsunami and tsunami-tide propagation. This simple numerical tool is quite useful in delineating sluggish tide-tsunami interactions. Influence of the nonlinear terms in equations of motion and continuity is explored in the sloping channel. Both amplification and dissipation of the tsunami wave is demonstrated. These phenomena are related to the travel distance and tsunami period. In the tsunami spectra, the shorter waves are first to be transformed through the process of nonlinear interactions. This process leads to dissipation and breaking of the shorter period waves and leaving in the spectra the longer period waves only. Numerical approach helps to delineate spatial and temporal domains in which the long wave approximation remains valid, i.e., the long wave propagates without breaking. The run-up problem is studied for the cases, when the channel response is either resonant or non-resonant. Whenever the period of an incident wave is close to the natural period of the channel, the resulting run-up is amplified. The generation of the resonant modes require longer times of interaction of the incident wave so it can pump energy into the resonant mode. This underlines the fact that the strong run-up in the local water bodies is quite possible not only at the time of arrival of the first tsunami wave but at the time of arrival of second or third wave as well, due to pumping action. Since run-up processes in certain local water bodies are related to the resonance, it is prudent to start calculations by investigating natural oscillations of these local water bodies.

2. Propagation in channel

In order to identify important steps in the construction and analysis of a numerical scheme we shall study first propagation of the long wave in a channel.

Consider the numerical solution of the equations of motion and continuity

$$\frac{\partial u}{\partial t} = -g\frac{\partial \zeta}{\partial x} \tag{1}$$

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial}{\partial x}(Hu) \tag{2}$$

Solution of this system is usually searched by the two-time-level or the three-time-level numerical schemes (Kowalik and Murty, 1993a). For construction of the space derivatives in the eqs. (1) and (2), a space staggered grid (Figure 1) is usually used (Arakawa C grid). The two-time-level numerical scheme

$$\frac{(u_j^{m+1} - u_j^m)}{T} = -g\frac{\zeta_j^m - \zeta_{j-1}^m}{h} \tag{3}$$

$$\frac{\zeta_j^{m+1} - \zeta_j^m}{T} = -\frac{(u_{j+1}^{m+1}H_{j+1} - u_j^{m+1}H_j)}{h} \tag{4}$$

is of the second order of approximation in space and only the first order in time. For a quick reference, we shall call it the Fisher's scheme. All notations are standard: u is velocity, ζ denotes sea level change, t is time, x denotes horizontal coordinate, g is Earth's gravity acceleration (g=981 cm s^{-2}), and H is depth.

The space-staggered grid given in Figure 1 is used to construct space derivatives in the above equations. Variables u (dashes) and ζ (crosses) are located in such a way that the second order of approximation in space is achieved. The depth is taken in the sea level points. The space step along the x direction is h. Index m stands for the time stepping. In the Fisher scheme the time step is T.

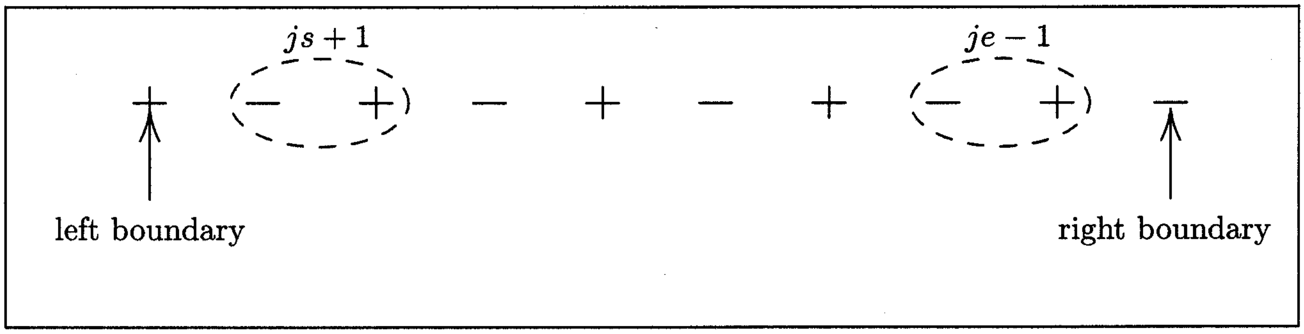

Figure 1

Staggered grid for the wave propagation problem. Sea level is given at the left boundary as a sinusoidal wave. Radiation condition is used at the right boundary.

The space index runs from $j = js$, at the left–hand boundary, to the $j = je$ at the right–hand boundary. The velocity computation starts at $j = js + 1$, i.e. one grid point away from the left boundary, and proceeds up to the point $j = je$ (see Figure 1). Sea level computation starts at the left boundary ($j = js$) but it runs only to the $j = je - 1$ point. Sea level at the left boundary will be given by a sinusoidal sea level signal and velocity at the right boundary is specified by the radiation condition (Reid and Bodine, 1968),

$$u^m_{je} = \zeta^m_{je-1}\sqrt{\frac{g}{H}} \tag{5}$$

Tsunami wave distortion generated by the finite differencing is caused by approximation errors. These are consequences of the finite spatial and temporal steps. The first problem in constructing a numerical scheme is achieving stability of the numerical scheme. As shown in Kowalik and Murty (1993a), a stability condition for the above numerical scheme requires that the time step and space step fulfill the following inequality

$$\sqrt{gH} \leq \frac{h}{T} \tag{6}$$

This is the so-called Courant – Friedrichs – Lewy or CFL stability condition. Unfortunately this condition does not guaranty a proper reproduction of the wave. A signal reproduced by the eqs. (1) and (2) will be altered mainly in phase. The phase change Φ of the signal over one time step is

$$\tan\Phi = \tan\omega T = \frac{\sqrt{4Q - Q^2}}{(2 - Q)} \tag{7}$$

Where: $\omega = 2\pi/T_p$, and T_p denotes wave period.

Parameter

$$Q = 4gH(\frac{T}{h}\sin\frac{\kappa h}{2})^2 \tag{8}$$

includes both space and time resolution through the nondimensional numbers

$$\frac{T}{h}\sqrt{gH} \qquad \text{and} \qquad \frac{L}{h} \tag{9}$$

The nondimensional number L/h defines a spatial resolution and is connected with the wave number $\kappa = 2\pi/L$. For the well resolved processes the wave length is covered by many space steps ($\kappa h \to 0$). In such a case $Q \to 0$, and from eq. (7) follows that this numerical scheme will not change the phase ($\Phi = 0$) of the signal. Taking into account both stability and spatial resolution leads to a difficult choice: while diminishing of the time step diminishes parameter Q and makes stability stronger, diminishing of the space step introduces better spatial resolution but may cause, accordingly to formula (6), instability of the numerical scheme. Errors of approximation increase over the longer time of integration and over the longer propagation distance. The choice proposed here is to test both stability and resolution through the application of the proposed numerical schemes to the tsunami wave propagation in a channel.

Let us consider a simple problem of a sinusoidal wave propagating over the long distance in the channel of the constant depth. At the left end of the channel a sinusoidal wave is given as

$$\zeta = \zeta_0 \sin(\frac{2\pi t}{T_p}) \tag{10}$$

Here the amplitude is ζ_0=100 cm, and the period T_p will be taken from 5 min to 0.5 h range. Propagation of this monochromatic wave toward the right end of the channel will be studied through eqs (3) and (4). The computational program named fisher.f is given on the website: http://www.sfos.uaf.edu/pubs/kowalik/tsunami_physics_01.pdf. The right end of channel is open, and a radiating condition will be used so that the wave can propagate beyond the channel without reflection (eq. 5). At the left end of the channel, eq (10) is applied for one period only; after that, the radiating condition is used as well. The channel is 6000 km long and 4077 m deep. The wave period under consideration is 10 min, which results in a 120-km wavelength. The time step of numerical integration will be taken equal to 5 s or 0.5 s. The initial space step is chosen equal to 10 km (close to 5′ represented by PDP5 gridded topography). The 10-km space grid sets 12 steps per wavelength (SPW). Such a resolution will slowly introduce numerical errors into reproduced waves. In Figure 2, results of computation are given for the space step of 10 km (SPW=12) and the time step 5 s (upper panel), for the space step of 10 km and the time step 0.5 s (middle panel), and for the space step of 2 km (SPW= 60) and the time step 5 s (bottom panel). The wave propagation from the left end has been depicted at distances of 2000 km, 4000 km, and 6000 km. The relatively poor space resolution in the upper and middle panels results in the wave damping along the channel.

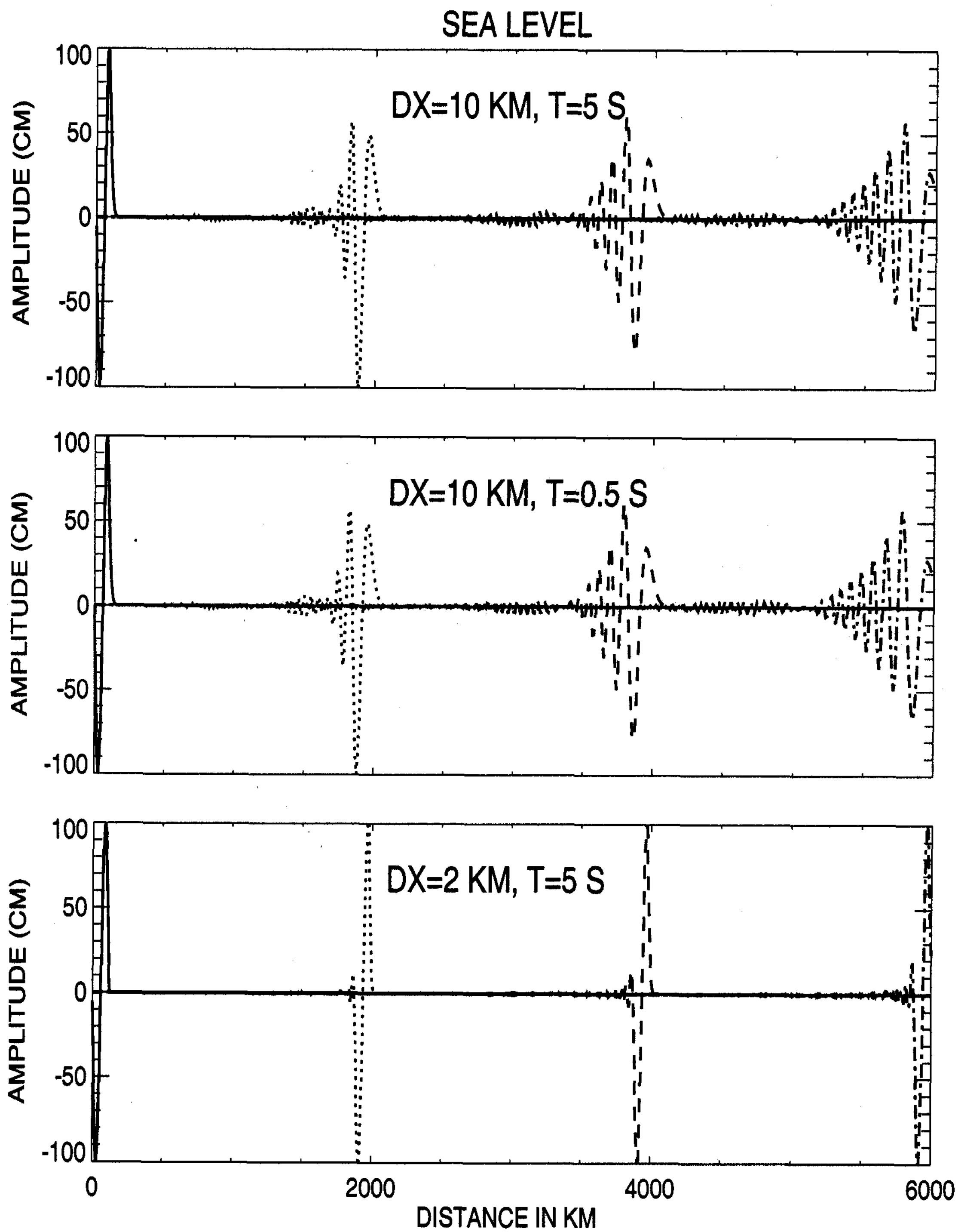

Figure 2

Propagation of the monochromatic wave of 10 min period along the channel of constant 4077 m depth. DX denotes spatial step and T is time step.

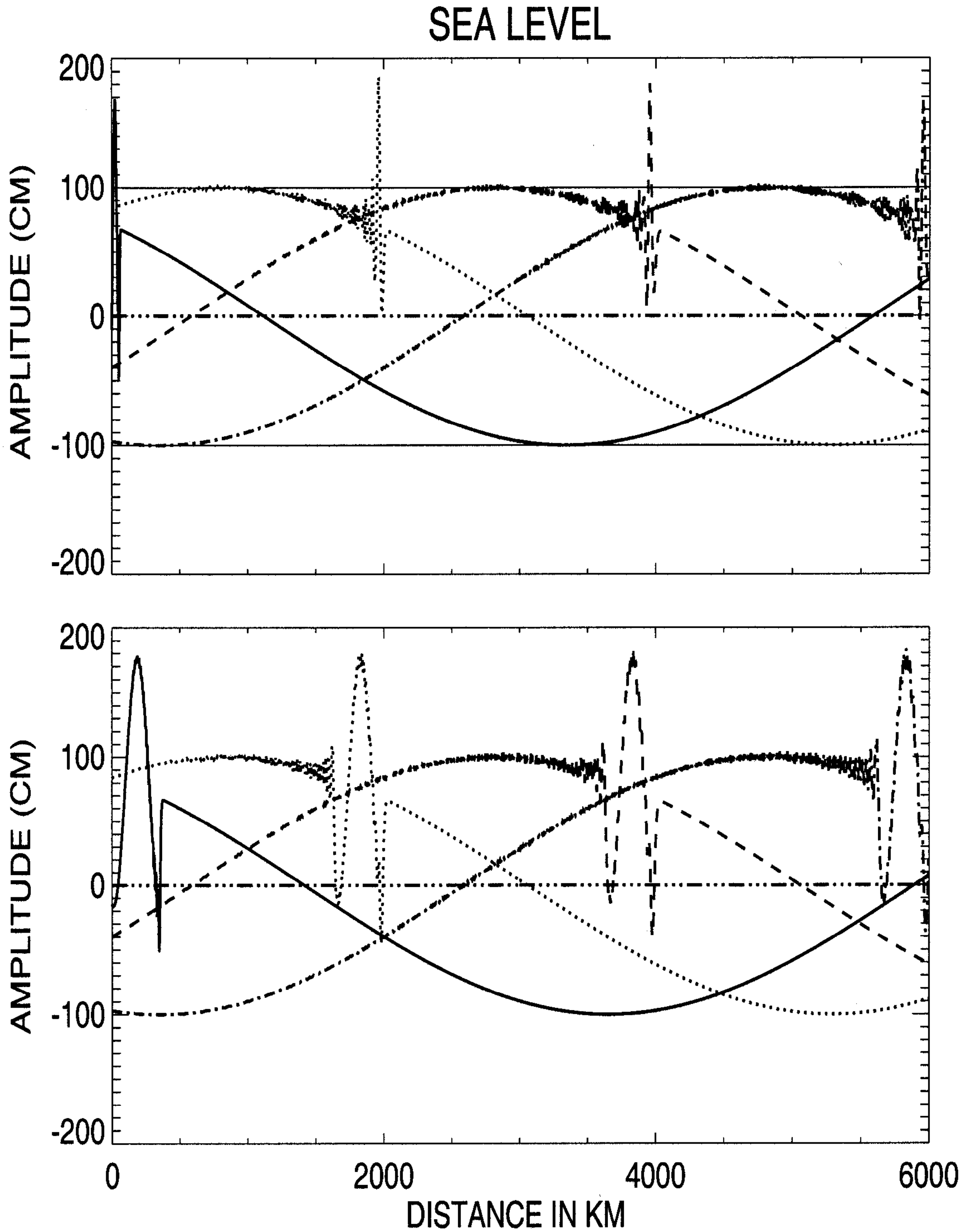

Figure 3

Interaction of M_2 tide with tsunami of 10 min period (upper panel) and with tsunami of 30 min period (lower panel). Waves travel from left to right.

At approximately 1500 km, the amplitude of the first wave became smaller than the amplitude of the second wave. Traveling wave train has a tail of secondary waves trailing behind the main wave. The shorter time step does not correct dispersive behavior (see the middle panel), only the shorter space step which increases the number of SPW, allows the nondispersive propagation. Dispersive numerical error is cumulative, i.e. for the longer travel distances it will become large enough to generate dispersive waves again. Therefore, the choice of the SPW index will depend on the propagation distance as well.

Numerical dispersion of the numerical scheme, can be defined through the Taylor series (Kowalik and Murty, 1993a). Its analytical expression is of the same form as the physical dispersion described by the Boussinesq equation. Imamura (1996) proposed to use the numerical dispersion to simulate physical processes of dispersion. Approach is quite easy to apply in the rectangular system of coordinate. In the spherical system the varying numerical grid introduces too many parameters and simulation of the physical dispersion through numerical dispersion is less successful.

A simple model that we use, can also shed some light on the question of tide-tsunami interaction. Results of such interaction are demonstrated in Figure 3. Here the M_2 tide wave, period 12.42 h and 9000 km wavelength, travels together with tsunami of 10 min period (upper panel in Figure 3) and with tsunami of 0.5 h period (lower panel in Figure 3). In this experiment SPW=60 (for the 10 min period) and time step is 5 s. The dispersive tail behind tsunami waves did not occur in the previous numerical experiments; therefore, its origin is related to the linear interaction of tsunami and tide wave. Linear superposition of the two waves (periods T_1 and T_2) leads to the two new periods T_s and T_l :

$$T_l = \frac{2T_1T_2}{T_2 - T_1} \quad \text{and} \quad T_s = \frac{2T_1T_2}{T_1 + T_2} \tag{11}$$

Assuming T_1 is the tsunami period and T_2 is the tidal period, it follows that $T_1 << T_2$. Therefore, from eq (11), $T_l \simeq T_s \simeq 2T_1$. Two new periods are very close, and approximately two times longer than the tsunami period. Analysis of the main tsunami wave and the tail behind this wave suggests that tsunami is modulated by the new period. Derived results of tsunami-tide interaction lead to the conclusion that in the process of propagation tide and tsunami interact slowly and that this interaction leads to sluggish change of the tsunami spectra.

3. Propagation in sloping channel

We shall proceed to construct a simple algorithm for the propagation along the up-sloping channel. This numerical scheme allows to elucidate processes occurring across the shelf. We also will be able to pinpoint an influence of the friction and nonlinear term on the process of propagation and dissipation. Consider equation of motion and continuity along x direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \zeta}{\partial x} - \frac{ru|u|}{D} \tag{12}$$

$$\frac{\partial \zeta}{\partial t} = \frac{\partial}{\partial x}(Du) \tag{13}$$

Solution of this system will be searched through the two-time-level numerical scheme. The nonlinear (advective) term will be approximated by the upwind/downwind scheme. D in the above equations denotes the total depth $D = H + \zeta$.

The following numerical scheme is used to march in time:

$$\frac{(u_j^{m+1} - u_j^m)}{T} + up\frac{(u_j^m - u_{j-1}^m)}{h} + un\frac{(u_{j+1}^m - u_j^m)}{h}$$
$$= -g\frac{(\zeta_j^m - \zeta_{j-1}^m)}{h} + \frac{ru_j^m|u_j^m|}{0.5(D_j^m + D_{j-1}^m)} \tag{14}$$

Here: $up = 0.5(u_j^m + |u_j^m|)$, and $un = 0.5(u_j^m - |u_j^m|)$

$$\frac{\zeta_j^{m+1} - \zeta_j^m}{T} = -[(u_{j+1}^{m+1}0.5(D_j^m + D_{j+1}^m) - u_j^{m+1}0.5(D_{j-1}^m + D_j^m)]/h \tag{15}$$

The Fortran program for propagation in sloping channel, named channel.f90 is given on the website: http://www.sfos.uaf.edu/pubs/kowalik/tsunami_physics_01.pdf.

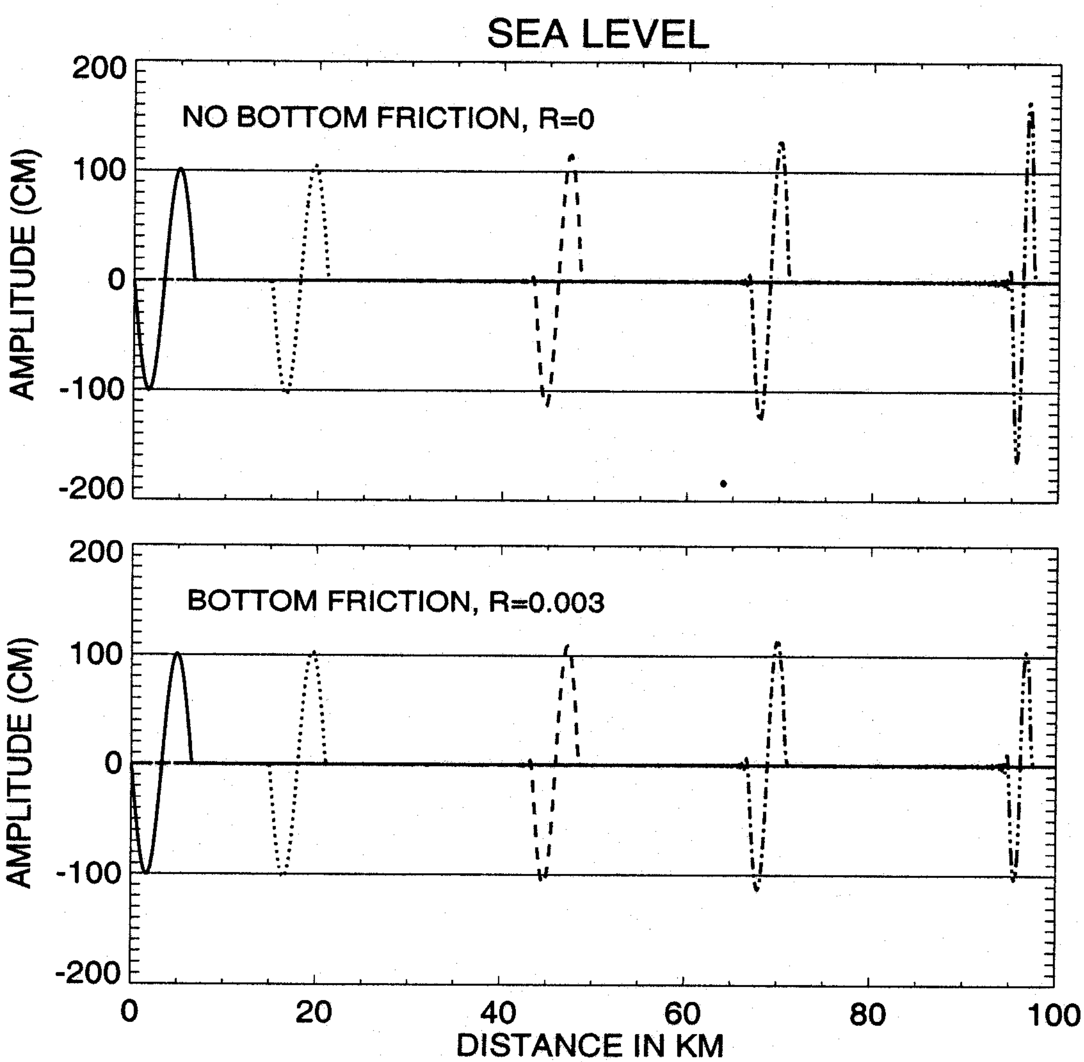

Figure 4

Tsunami propagation in upsloping channel of 100 km long. In the upper panel the bottom friction and advective terms are neglected. In the lower panel the bottom friction is included.

In this experiment the upsloping channel of 100 km length is considered. Depth is changing from 50 m at the entrance to 5 m at the end of the channel. We start by computing propagation of a 5 min period tsunami wave from the deep water towards the shallow water. The bottom friction and nonlinear (advective) terms are neglected in equation of motion.

The results are given in Figure 4, upper panel. The wave traveling towards shallow water increases amplitude and diminishes wavelength. In the lower panel, the same wave is considered with the bottom friction included into equation of motion (the advective term is equal to zero). Here due to the bottom friction and shallowing of the water, the amplitude of the wave practically does not change along the entire channel.

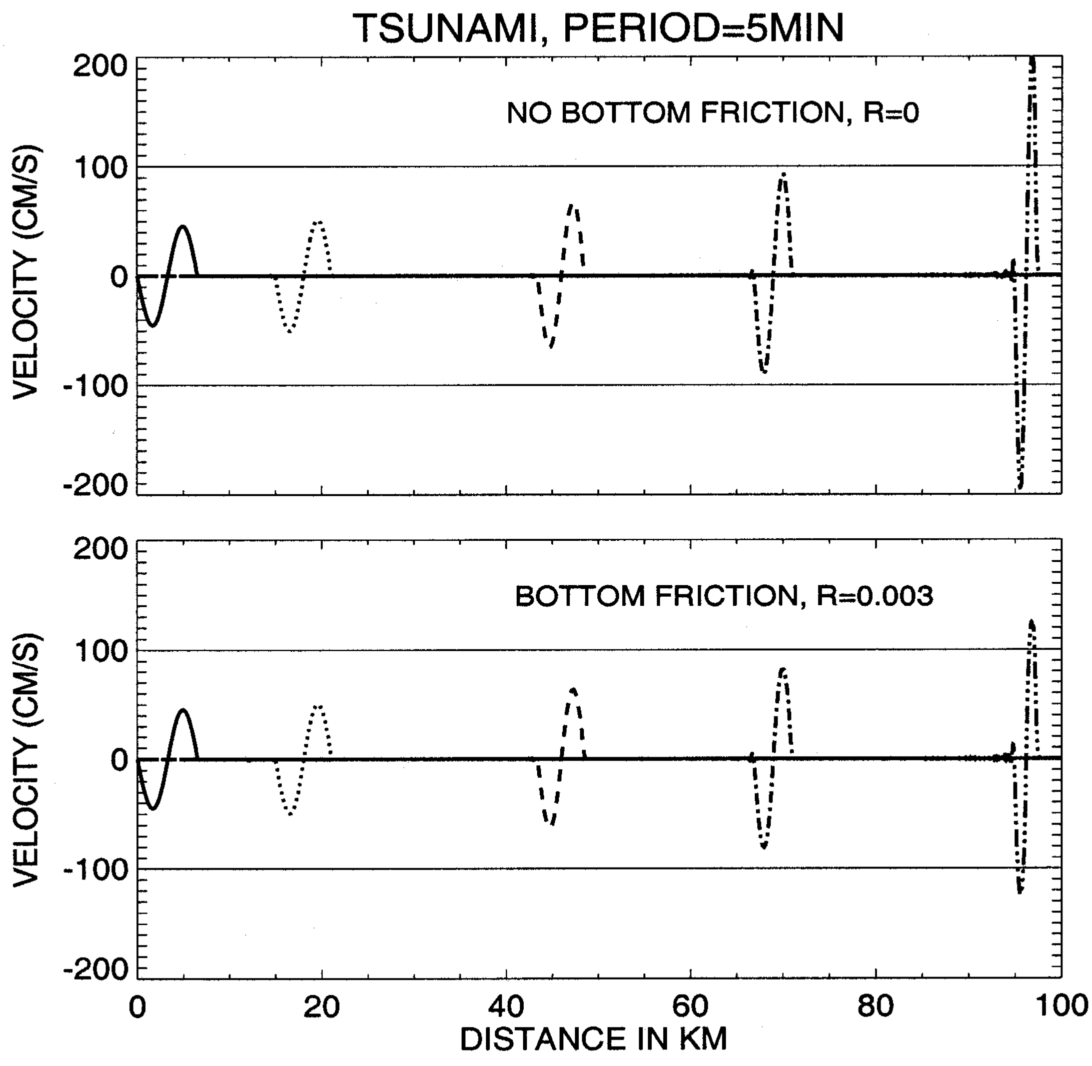

Figure 5

Tsunami velocity in upsloping channel of 100 km long. In the upper panel, the bottom friction and advective terms are neglected. In the lower panel, the bottom friction is included.

Figure 5 depicts a distribution of the wave velocity along the channel during the same experiments. Changes of velocity both with and without bottom friction are very substantial. While the sea level amplitude changes over a small range along the channel, velocity, on the other hand, displays much greater variations; for the nonfrictional propagation, it increases four times and for the frictional propagation, it increases 2.5 times. The wide range of changes in the velocity field offers better opportunity to compare models and observations. The comparison of the models against the sea level amplitude only, often show that the lack of the bottom friction increases amplitude, but the results are not very different from the frictional models (Titov and Synolakis, 1998).

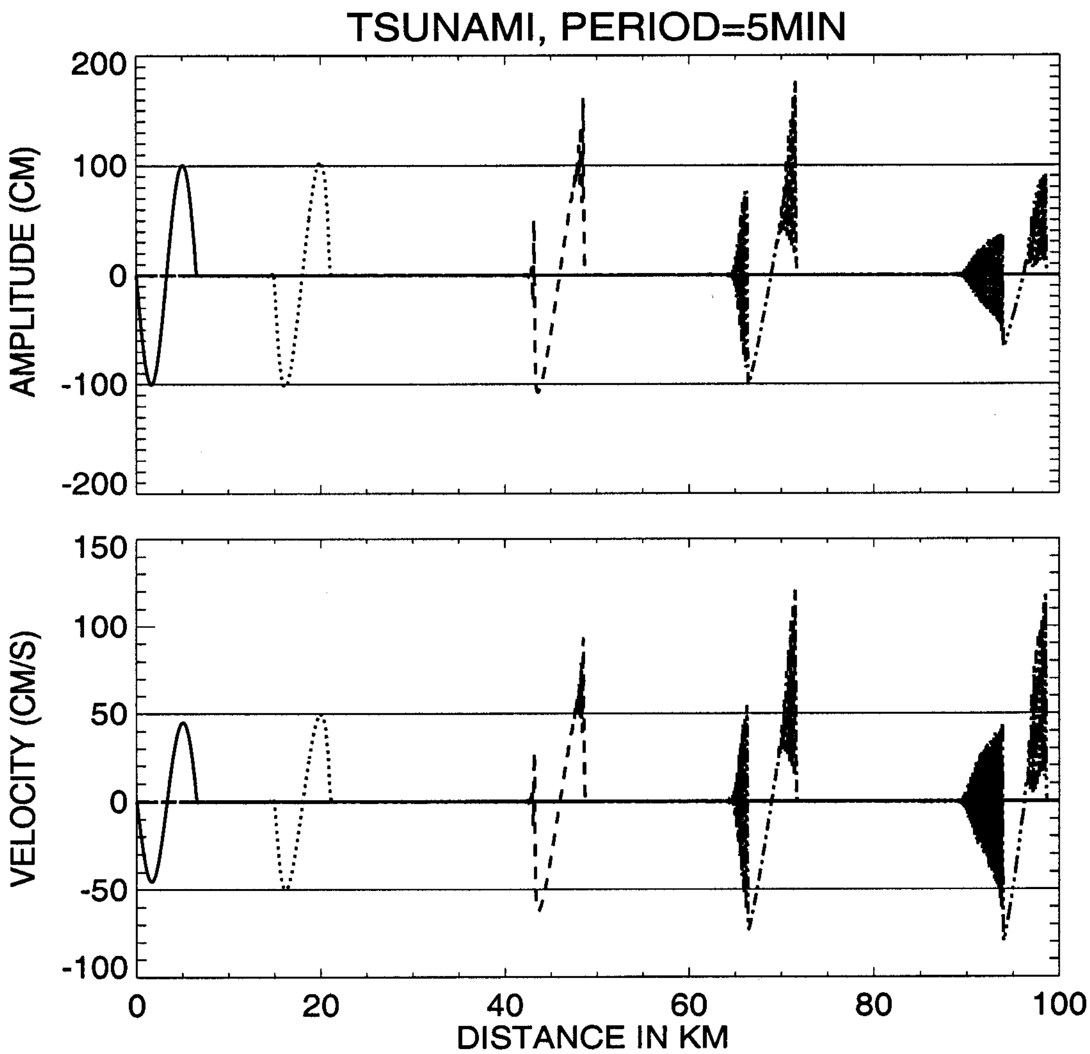

Figure 6

Amplitude (upper panel) and velocity (lower panel) of 5 min period wave. Advective term and bottom friction are included.

An experiment which takes into account all terms in equation of motion, including advective (nonlinear) term, is described in Figure 6. Amplitude of the wave is given in the upper panel and velocity in the lower panel. Only over the first 20 km of propagation, the incident wave remains symmetrical. In the middle portion of the channel, the wave steepens so strongly that the process of wave breaking begins. It occurs in the computation in the form of short waves which precede and trail the main wave. Again, the destruction of the wave amplitude and velocity occurs differently. It is of interest to understand what these nonlinear processes bring to the tsunami physics and how the computational approach ought to be modified. Initial sinusoidal wave, while traveling towards shallow water starts to exhibit strong asymmetry in which the positive values of velocity by far exceed the negative values. The time average over tsunami velocity will result in the strong residual current which induces flow towards the shore. It is obvious that the interaction of this short period tsunami with the remaining tsunami spectra is very complex and it occurs through the bottom friction and advective terms.

An important question is, can we use the long wave equation for numerical computations if the wave breaking occurs? Even the best numerical resolution is not going to improve this situation because our equations are not valid for the wave breaking physics. Numerical experiments can be helpful in answering basic questions; i.e., which part of the tsunami spectra is going to be modified through the nonlinear processes and where the long-wave approach will be still valid?

Repetition of the above experiments for the various tsunami periods in the chosen channel geometry shows that the waves of the 20 min period and greater depict very small tendency for breaking. Computation of the non-breaking waves (including tide) suggests that to estimate the wave parameters along the channel a simple formula given by eq. (5) can be used. It relates the sea level ζ and the particle velocity u to the depth H and the phase velocity $\sqrt{(gH)}$:

$$\frac{\zeta}{u} = \frac{H}{\sqrt{(gH)}} \tag{16}$$

Denoting parameters at the beginning of channel by 1 and parameters at the end of channel by 2, we arrive at

$$\frac{\zeta_1}{\zeta_2} = \frac{u_1}{u_2}\sqrt{\frac{H_1}{H_2}} \tag{16a}$$

Computations for the M_2 tide wave show that the wave amplitude in the channel remains approximately constant, i.e., $\zeta_1 \simeq \zeta_2$, and from eq.(16a) $u_2 = u_1\sqrt{(10)}$. Thus, velocity is amplified three times over the length of channel. In Figure 7, as an illustration of the propagation of the longer waves, the sea level and velocity are given for the M_2 tide at the beginning and at the end of the channel. Here instead of spatial distribution, the time distribution is given for 40 hr of process at the left end of the channel (continuous line) and at the right end of the channel (dotted line). The processes of the nonlinear wave deformation and breaking will differ for the various channel geometry. Generally, the longer the travel distance, the stronger the wave will be distorted by the nonlinear interactions. The above procedure can be aided through the theoretical conclusion related to the breaking waves. Unfortunately, the results have been obtained only for the upsloping beach whose length is shorter than the tsunami wavelength. For such a case Pelinovsky (1996), extended the Carrier and Greenspan (1958) theory. The condition for the nonbreaking wave is defined through a dimensionless parameter (Br),

$$Br = \zeta_o\omega^2/(g\alpha^2) \tag{17}$$

Here, ζ_o is amplitude of the incident wave, ω denotes frequency $(2\pi/T_p)$ and α is slope of the beach. If $Br < 1$, the nonbreaking waves will occur; in case $Br > 1$, the waves will break while climbing up the sloping beach.

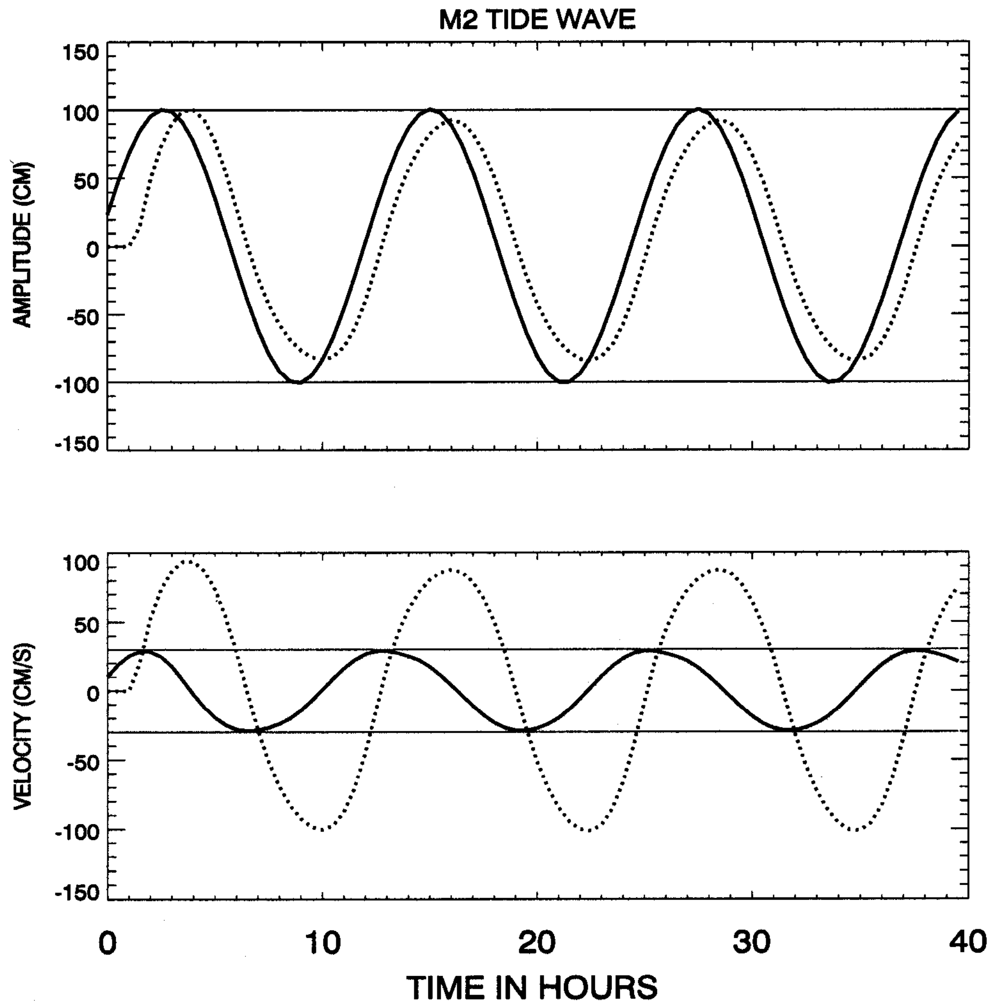

Figure 7
M_2 tide wave traveling in upsloping channel. Upper panel depicts amplitude in time at the entrance (continuous line) and at the end (dotted line) of the channel. Lower panel depicts velocity in time.

4. Run-up in channel

We shall proceed to construct a simple algorithm for the run-up in the channel by using eqs. (12) and (13) The solution of this system will be searched through the two-time-level numerical scheme. The numerical form of the equation of motion is expressed by eq. (14). The major problem arises when the wave starts to move into and out of the dry domain. Obviously none of the second order symmetrical space schemes can be used, because the movement is defined only in the wet domain. Strong nonlinearity and discontinuity are often sources of computational instabilities (Lewis and Adams, 1983;

Kowalik and Murty, 1993b; Imamura, 1996). One of the major new assumptions is that equation of continuity can be approximated by the upwind/downwind approach as well. This approach introduced by Mader (1986) makes equation of continuity quite stable at the boundary between wet and dry domains. The following numerical scheme is used to march in time for the equation of continuity:

$$\frac{\zeta_j^{m+1} - \zeta_j^m}{T} = -(upj1 \times D_j^m + unj1 \times D_{j+1}^m - upj \times D_{j-1}^m - unj \times D_j^m) \tag{18}$$

In the above equation:

$$upj1 = 0.5(u_{j+1}^{m+1} + |u_{j+1}^{m+1}|) \quad \text{and} \quad unj1 = 0.5(u_{j+1}^{m+1} - |u_{j+1}^{m+1}|)$$

$$upj = 0.5(u_j^{m+1} + |u_j^{m+1}|) \quad \text{and} \quad unj = 0.5(u_j^{m+1} - |u_j^{m+1}|)$$

To simulate the run-up and run-down, the variable domain of integration is established after every time step by checking whether the total depth is positive. This was done through a simple algorithm proposed by Flather and Heaps (1975) for the storm surge computations. To answer whether u_j is a dry or wet point, the sea level is tested at this point;

$$\begin{cases} u_j \textit{ is wet point}, & \text{if } 0.5(D_{j-1} + D_j) \geq 0; \\ u_j \textit{ is dry point}, & \text{if } 0.5(D_{j-1} + D_j) < 0 \end{cases} \tag{19}$$

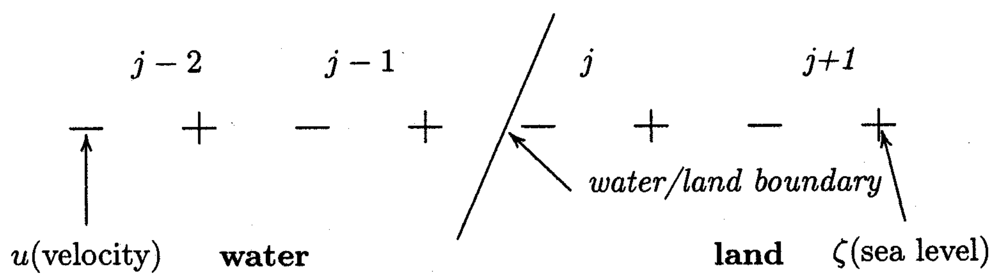

Figure 8
Grid distribution for the run-up problem.

Next, Sielecki and Wurtele's (1970) extrapolation of the sea level and velocity to the first dry point was used.

$$(\zeta_j^{m+1})_{ext} = 2\zeta_{j-1}^{m+1} - \zeta_{j-2}^{m+1} \tag{20a}$$

$$(u_j^{m+1})_{ext} = 2u_{j-1}^{m+1} - u_{j-2}^{m+1} \tag{20b}$$

Linear extrapolation is easy to program but caution should be used in the case of a rough beach.

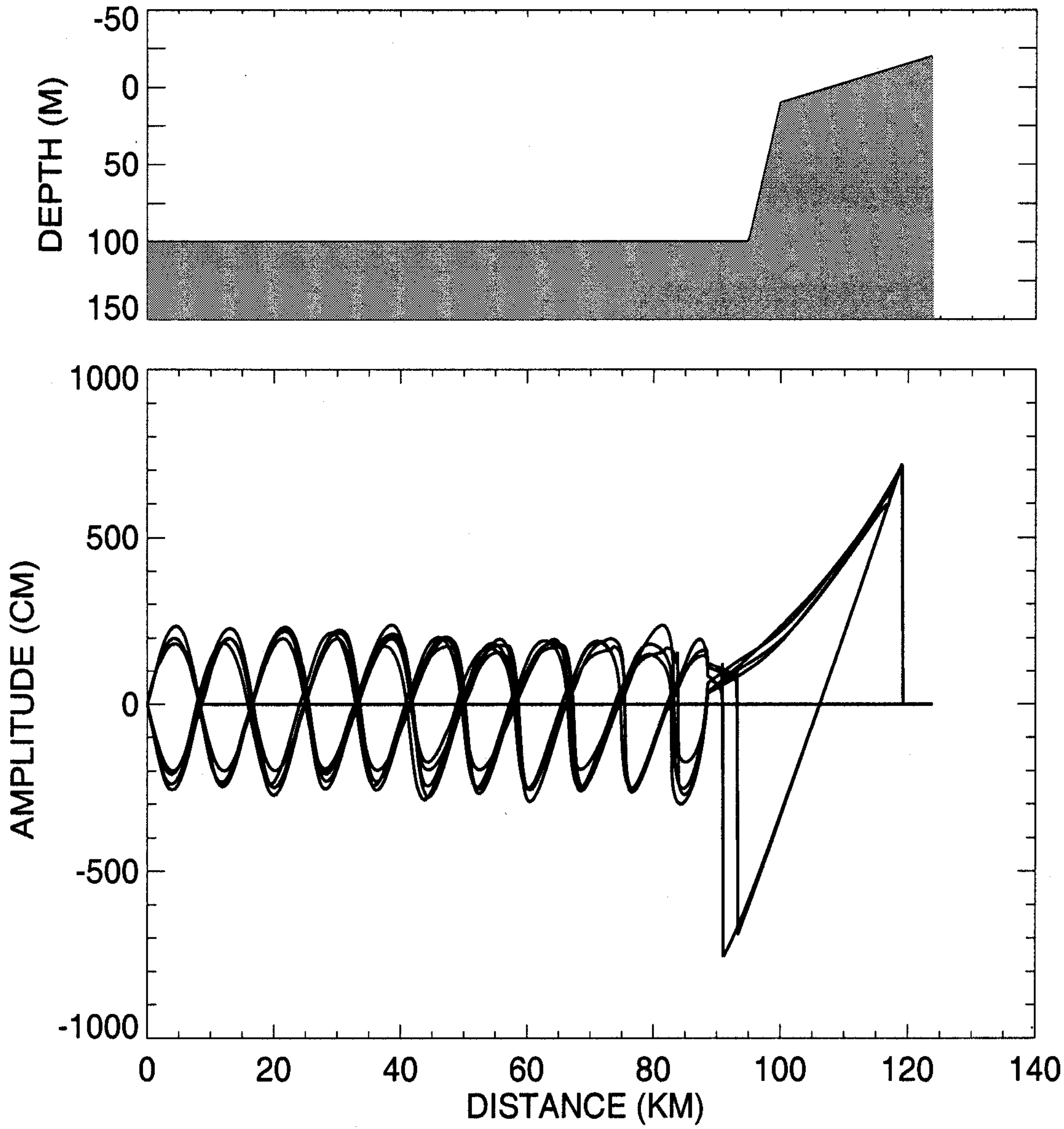

Figure 9

Upper panel: depth distribution in the channel. The distance along upsloping beach has been magnified. Lower panel: amplitude of the wave at the time of the maximum and minimum run-up.

The space-staggered grid given in Figure 8 is used to construct the space derivatives and to visualize procedures at the wet/dry boundary. At the left end of the channel, a sinusoidal wave is given:

$$\zeta = \zeta_0 \sin(\frac{2\pi t}{T_p})$$

Here the wave amplitude is taken as 200 cm. The 90 km long channel has constant 100 m depth (Figure 9, upper panel). Over the distance of 10 km from 90 km to 100 km, the channel is sloping from 100 m to 10 m and finally the channel is sloping into the beach. The beach depth changes linearly from 10 m at the 100 km to -10m at the 102 km (the 2 km distance is magnified in all figures to better resolve the run-up and run-down processes). In tsunami problem the positive value of depth is related to the wet domain. The fine space grid of 5m is used; the time step is 0.1s. The fortran program runup.f is given on the website: http://www.sfos.uaf.edu/pubs/kowalik/tsunami_physics_01.pdf.

Figure 9, lower panel, describes an experiment in which a 10 min period wave of 2 m amplitude is continuously generated at the open end of the channel. After this signal is reflected from the sloping boundary, a standing wave is settled in the constant bottom domain. In this domain the signal is described by superposition of incident and reflected waves,

$$\zeta = \zeta_i \sin(\frac{2\pi t}{T_p} - \frac{2\pi x}{\lambda}) + \zeta_r \sin(\frac{2\pi t}{T_p} + \frac{2\pi x}{\lambda}) \qquad (21)$$

Here: ζ_i amplitude of an incident wave; ζ_r amplitude of a reflected wave and, λ denotes the wavelength.

Along the sloping beach (its length has been exaggerated in Figure 9), the run-up of approximately 7 m high is generated. After the first wave arrival and reflection, a stationary distribution of the wave amplitude along the channel is achieved. Subsequent reflections do not change this stationary distribution (in the lower panel four reflections have been reproduced).

A different picture emerges from experiments with tsunami of 0.5 h period (wavelength 56 km). In the upper panel of Figure 10, propagation of one wave (continuous line) towards the sloping beach, together with reflection from the shore at the time of the run-up maximum (dotted line) and reflection at the time of the lowest water (dashed line) is given. The maximum wave amplitude in the constant bottom domain is approximately 2 m. The maximum run-up of 6.5 m is approximately equal to the run-up for the 10 min period (see Figure 9). In the middle panel, propagation and reflection of the second wave is considered. Again, continuous line denotes an incident wave, dotted and dashed lines denote reflected waves at the time of the highest and lowest sea levels along the sloping beach. The maximum amplitude in the channel over the constant bottom has increased from 2 m to approximately 4 m. Such steep growth of the wave amplitude indicates conditions close to resonance, and indeed the two wavelengths of the incident wave are close to the channel length (approximately 102 km). To find out how this process will develop in time, results for the continuously generated wave signal are given in the lower panel. After about 10–15 reflections the process arrived to a stationary state with the wave amplitude in the channel of approximately 7 m and run-up of 13 m. A simple method for investigation of natural mode of oscillations in the semi-closed water bodies has been discussed by Kowalik (1997).

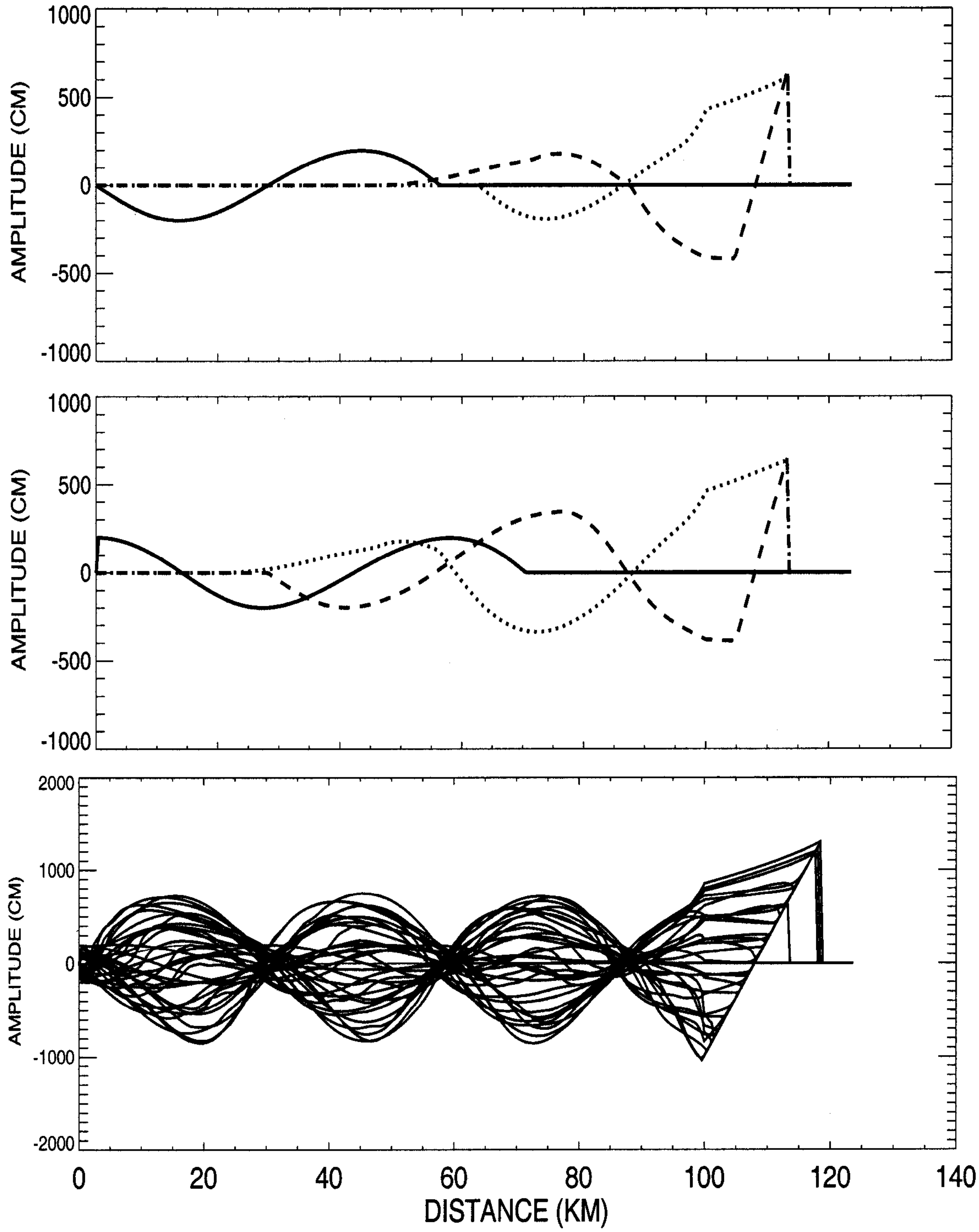

Figure 10

Tsunami of 30 min period running upsloping beach. Upper panel describes first wave: incident wave (continuous line), reflected wave at the time of maximum run-up (dotted line), reflected wave at the time of the lowest water (dashed line). Middle panel: second wave, same notation. Lower panel: continuous wave generation and reflection.

Two conclusions can be deduced from the above experiments: a) a water body whose own periods of oscillations are close to an incident tsunami wave period will respond by generating higher run-up and higher reflected waves, and b) resonance response will depend on the time span of the incident tsunami wave train. The longer tsunami wave train the stronger resonance response will occur. This should direct our attention to the fact that the strong run-up in the local water bodies is quite possible not only at the time of arrival of the first tsunami wave but at the time of arrival of the second or third wave as well due to the pumping action. A simple method for investigation of natural mode of oscillations in the semi-closed water bodies has been discussed by Kowalik (1997).

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BOOK REVIEW

Landslides and Tsunamis

Barbara H. Keating, University of Hawaii
Christopher F. Waythomas, Alaska Volcano Observatory
Alastair G. Dawson, Coventry University
ISBN 3-7643-6300-2

Birkhauser Verlag AG, Basel Switzerland
http://www-birkhauser.ch

In recent years the study of tsunamis has shifted away from theoretical modeling of tsunami source, wave propagation and run-up toward multidisciplinary investigations, with a clear emphasis on field studies. These studies produce a much more comprehensive understand of the various earth surface processes that generate tsunamis and the ways that tsunamis modify coastlines often destroying property and producing fatalities. This collection of papers highlights the varied approaches now being utilized to study landslides and tsunamis including: the documentation of the geomorphic effects of tsunami run-up and backwash, seismological studies of tsunamigenic earthquakes, sonar mapping of submarine landslide scars and debris fields resulting from continental margin and ocean island edifice collapse, and the study of both ancient and modern tsunami deposits.

Dr. Barbara Keating is chairing a special session on **GAS HYDRATE VENTING AND TSUNAMIS** at the Second Tsunami Symposum, May 28-30, 2002.

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The meeting will be held at the University of Hawaii East-West Conference Center Asian Room. Economical Waikiki tour packages including air-room-car are available from many tour agencies.

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For additional information call the Tsunami Symposium Chairman, Mr. James Lander at 303-497-6446, e-mail JFL@ngdc.noaa.gov; the Tsunami Society Secretary, Mr. Michael Blackford at 808-532-6423, e-mail Michael.blackford@noaa.gov; or the Tsunami Society Treasurer, Dr. Barbara Keating 808-956-8143, e-mail Keating@soest.hawaii.edu. call the Program Chairman, Dr. Charles Mader, at 808-396-9855 or e-mail MCCOHI@aol.com.

Please send abstracts of papers to be presented by September 1, 2001 and complete papers by January 1, 2002 to Dr. Charles Mader, 1049 Kamehame Drive, Honolulu, HI 96825-2860. Abstracts may be sent by e-mail to MCCOHI@aol.com.

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http://www.ccalmr.ogi.edu/STH

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http://epubs.lanl.gov/tsunami

and on a CD-ROM from the Tsunami Society. A collection of computer generated tsunami animations is also on the CD-ROM.

The International Tsunami Information Center maintains a web site with current information of interest to the Tsunami community. The web site has the following URL:

http://tgsv5.nws.noaa.gov/pr/hq/itic.htm

The West Coast and Alaska Tsunami Warning Center maintains a web site with tsunami information. The web site has the following URL:

http://www.wcatwc.gov/main.htm/

A beautiful web site about Tsunamis is being published by **Tsunami Society** member, Dr. George Pararas-Carayannis. His tsunami web site has the following URL:

http://www.geocities.com/capecanaveral/lab/1029

A web site about The National Tsunami Hazard Mitigation Program is maintained by **PMEL**. The web site has the following URL:

http://www.pmel.noaa.gov/tsunami-hazard

Several members of **The Tsunami Society** have helped develop a web site for the **Pacific Tsunami Museum** in Hilo, Hawaii. The web site has the following URL:

http://planet-hawaii.com/tsunami

A remarkable website by Michael Paine on Tsunamis from Asteroid Impacts from the Australian perspective has the following URL:

http://www1.tpgi.com.au/users/tps-seti/spacegd7.html

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