7. Array Summary

Now that all elements of U.S. array, as envisioned at the DART® Siting Workshop, have been deployed and have been returning data for some time, it is appropriate to report some measures of the performance of the array as a whole. This is likely to be an ongoing process as factors such as data return rate, ambient current patterns, commercial and fishing vessel traffic patterns, become evident.

7.1 The Final Array

The distribution of the 39 elements of the U.S. array, and of the five cooperatively deployed instruments as of October 2008 is provided in Fig. 5 and Table 11 below. The U.S. sites were chosen in light of available knowledge so as to optimize the detection of seismically generated tsunamis that pose a threat to U.S. interests. The data used to compile the data availability statistics presented in Table 11 are based on 15-min data readily obtained from the NDBC web site `www.ndbc.noaa.gov/dart.shtm`; other historic BPR data beginning in the 1980s, including those with higher sampling rates, can be found at the NGDC (National Geophysical Data Center) site `www.ngdc.noaa.gov/hazard/DARTData.shtml`. It should be noted that the percent completeness values in Table 11 are, in many instances, related more to the logistics of reestablishment cruises which can result in major data gaps. Data return statistics, more relevant to instrumental performance and environmental impact, are provided in Tables 2–10 of Section 6.

Some statistics relating to the data return are presented in Section 7.2 and have led to consideration of the impact of individual instrument failure on the array. This is done in Section 7.3, though an interim report on the impact of multiple failures in the Gulf of Alaska has been provided to the Warning Centers. The other factors, such as the impact of ambient currents or ship track and fishing activity on mooring survivability, may suggest revisions to the array layout as data acquisition from the array progresses. Two sites, 42408 and 44402, have already been adjusted from their initially recommended locations due to their exposure to the Loop Current and Gulf Stream, respectively, and as noted earlier 42408 was disestablished in December 2008 in favor of a new site 42409. The isolation of the Gulf of Mexico from the Atlantic and Caribbean limits the impact of this change on the joint array statistics reported below, and insufficient data have been acquired at 42409 to warrant reporting its return statistics. Section 7.3 includes some preliminary results from recently acquired datasets on ship tracks and fishing pressure.

Table 11: Array layout and data availability as of 30 October 2008. Asterisk denotes a non-U.S. site.

Region	DART®	Latitude	Longitude	Depth (m)	Data Availability
Aleutians-AK	21414	48.958°N	178.266°E	5431	11 Aug 2006 (90.8%)
	46413	48.868°N	175.586°W	5504	11 Aug 2006 (81.4%)
	46408	49.623°N	169.848°W	5372	14 Aug 2006 (98.0%)
	46402	51.062°N	164.002°W	4712	1 Jan 2003 (79.8%)
	46403	52.637°N	156.932°W	4508	1 Jan 2003 (89.5%)
	46409	55.301°N	148.495°W	4187	29 Sep 2005 (98.2%)
	46410	57.503°N	143.989°W	3742	28 Jul 2006 (72.5%)
U.S./Canada West Coast	46419	48.798°N	129.584°W	2773	25 Jul 2006 (75.0%)
	46404	45.863°N	128.776°W	2740	11 Jan 2003 (63.3%)
	46407	42.595°N	128.894°W	3266	10 Dec 2007 (97.7%)
	46411	39.329°N	127.011°W	4266	27 Sep 2005 (89.0%)
	46412	32.246°N	120.699°W	3777	29 Sep 2005 (98.8%)
Central and South America	43412	16.031°N	107.001°W	3239	21 Mar 2007 (87.3%)
	43413	10.841°N	100.085°W	3468	24 Mar 2007 (97.5%)
	32411	4.924°N	90.685°W	3247	27 Mar 2007 (98.2%)
	32412	17.970°S	86.392°W	4326	2 Nov 2007 (99.9%)
	32401*	19.577°S	74.814°W	4881	23 Mar 2005 (98.2%)
Northwest Pacific	21415	50.166°N	171.836°E	4709	28 Jul 2007 (87.3%)
	21416	48.046°N	163.490°E	5782	26 Jul 2007 (99.5%)
	21417	43.187°N	157.140°E	5483	24 Jul 2007 (32.3%)
	21418	38.707°N	148.694°E	5665	23 Jul 2007 (77.6%)
West Pacific	21413	30.550°N	152.093°E	5822	27 Nov 2006 (90.0%)
	52401	19.256°N	155.759°E	5569	12 Dec 2006 (69.1%)
	52402	11.564°N	154.585°E	5799	15 Dec 2006 (99.6%)
	52403	4.023°N	145.580°E	4436	19 Dec 2006 (93.7%)
	52404	20.942°N	132.307°E	5925	1 Dec 2006 (98.6%)
	52405	12.884°N	132.317°E	5967	4 Dec 2006 (99.2%)
Southwest Pacific	52406	5.340°S	165.078°E	1849	4 Mar 2008 (94.1%)
	51425	9.499°S	176.246°W	4962	28 Feb 2008 (98.7%)
	51426	22.982°S	168.100°W	5637	11 Feb 2008 (96.2%)
	54401	33.005°S	172.968°W	5837	17 Feb 2008 (96.2%)
Coral Sea	55012*	15.800°S	158.500°E	3284	27 Mar 2008 (99.1%)
Tasman Sea	55015*	46.932°S	160.461°E	4944	27 Apr 2007 (91.0%)
Equatorial Pacific	51406	8.489°S	125.017°W	4473	1 Jan 2003 (95.6%)
Hawaii	51407	19.627°N	156.526°W	4718	28 Jun 2005 (97.5%)
Atlantic	41420	23.302°N	67.662°W	5659	27 Apr 2006 (80.6%)
	41421	23.401°N	63.912°W	5802	11 Apr 2006 (89.2%)
	41424	32.928°N	72.468°W	5252	7 Apr 2006 (69.4%)
	44401	37.551°N	49.985°W	5391	31 Aug 2007 (96.0%)
	44402	39.487°N	70.595°W	2434	28 Aug 2007 (65.0%)
Caribbean	42407	15.255°N	68.236°W	4486	11 Apr 2006 (86.8%)
Gulf of Mexico	42408	25.410°N	86.797°W	3259	17 Apr 2006 (58.7%)
Indian Ocean	23401*	8.907°N	88.540°E	3546	4 Dec 2006 (93.7%)
	53401*	0.051°N	91.900°E	4481	27 Sep 2007 (97.9%)

7.2 Array Detection Capability

To summarize the capabilities of the array for the detection of seismically generated tsunamis we rely on statistics derived from the propagation database (Gica *et al.*, 2008). This contains MOST model simulations for the propagation of waves generated by "unit sources" each consisting of an $M_w = 7.5$ event whose slip is distributed over a rectangular region, measuring 100 km along the strike and 50 km along the descending plate. When complete the database will span all potential sources (subduction zones and segments of oceanic convergent plate boundaries) worldwide. Currently those sources of greatest threat have been computed, and are available to the SIFT tool for use in tsunami forecasting. What remains is to expand the width of the unit source tiling in some regions and add coverage of more remote sources in the eastern Atlantic and South Shetland Islands.

To quantify the utility of a DART® site in tsunami monitoring, two parameters are employed. The first is the arrival time, T_f, of the first peak of the tsunami wave train. This can be computed from the propagation database and is usually taken as the earliest time at which a peak exceeding 20% of the overall maximum for wave train occurs at a location (see Fig. 51.) The 20% (or other) requirement is to exclude spurious low-level peaks that might exist in the numerical solution. The other parameter needed quantifies the amplitude of the signal expected at the site. Tsunami waves of low amplitude may be difficult to detect in the presence of background pressure fluctuations and residual seismic noise. As noted earlier, the unit source model solutions, while computed for a magnitude 7.5 event, may be linearly scaled and combined in the open ocean. The scale factor is related to source magnitude through the relationship

$$\text{Scale} = 10^{1.5(\text{M}_\text{w}-7.5)} \tag{4}$$

This relationship (see also Fig. 51) is used to define a "detectable magnitude" for each combination of unit source and DART® location. Based on past experience, a tsunami signal is visible in a BPR record if its amplitude exceeds a detectability threshold A_t of about 0.5 cm. If the predicted amplitude for a unit source ($M_w = 7.5$) at a DART® location is A_u then, using the relationship (4) above with a threshold of 0.5 cm, the source is detectable at a magnitude of

$$\text{M}_\text{wd} = 7.3 - 0.667\log(A_u) \tag{5}$$

Small values for M_{wd} are desirable since they imply that weaker tsunami events are detectable by a DART® site, thereby facilitating early warning cancelation. Large values, on the other hand, indicate that only strong tsunamis emanating from that source region can be detected.

For the purpose of evaluating detection time and detectable magnitude the unit sources are treated individually; this is realistic for lower magnitude events, but less so for event magnitudes of 8.0 and greater where more than a single unit source is involved. Nonetheless T_f and M_{wd} together allow a straightforward means of representing the ability of the array to detect

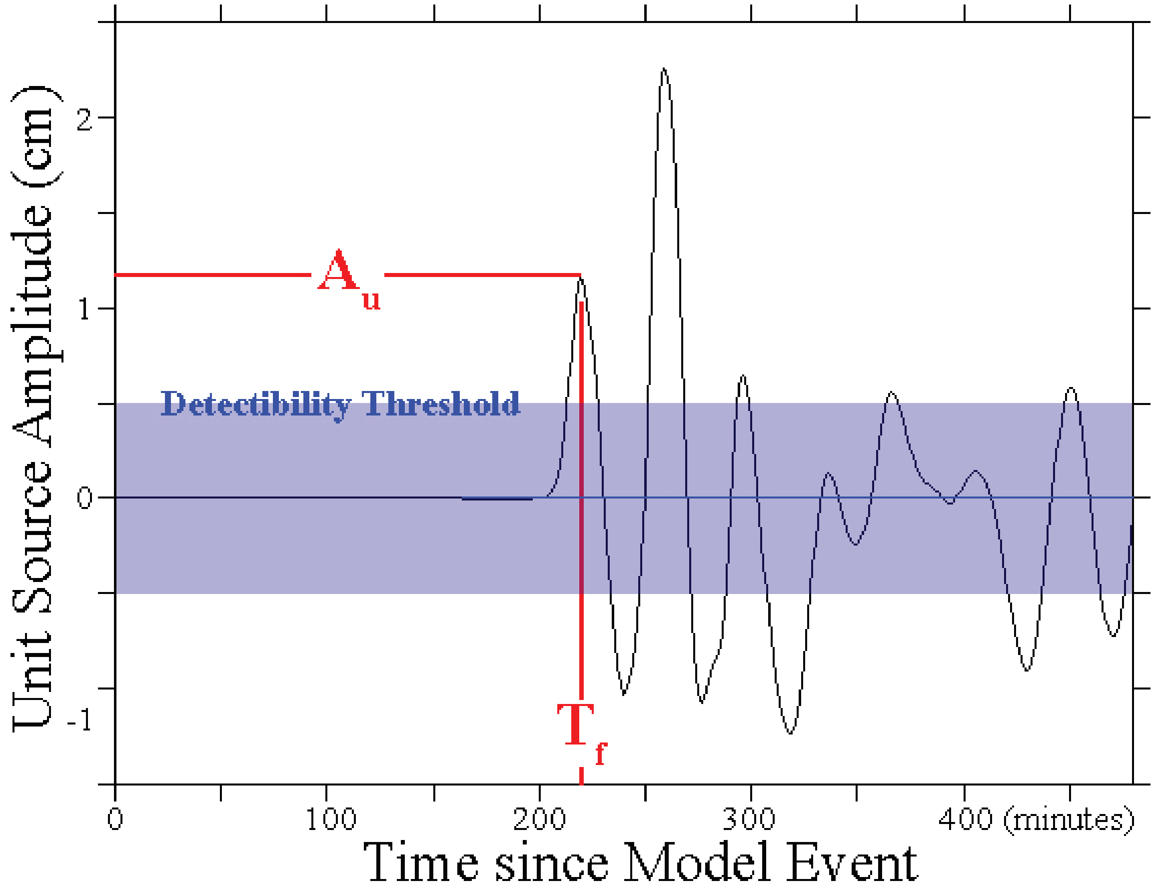

Figure 51: Definition of first wave arrival time and amplitude. The latter, based on a unit source magnitude $M_w = 7.5$ and an assumed threshold of 0.5 cm at a DART®, can be used to determine the lowest magnitude event at the source location that is detectable.

tsunamis generated in the far-flung distribution of potential sources. The results are tabulated in Table 12 and illustrated graphically in Figs. 52–56.

In Table 12, the Pacific and Atlantic Oceans are partitioned into regions for purposes of discussion, though the statistics presented consider all pairings of DART® site and B-row unit source. For each instrument the number of (B-row) unit sources for which it provides the primary and secondary detection are given. The importance of a site combines its ability to provide an early warning and to serve as backup in the event of failure of a neighboring site. Use of the word backup is not intended to imply redundancy; a SIFT inversion can proceed once the first wave peak is resolved but the quality of the forecast is improved when tsunami detection results from two or more locations are assimilated. For those unit sources for which it provides the primary (earliest) detection, the mean detection time (in minutes) is given. This is followed by a degraded detection time, for those unit source locations, in the event the primary instrument fails. The quality of the detection and the impact of loss of the instrument are given by the mean detectable magnitudes, with and without the DART® site in question. For the Aleutians and Alaska, both the primary and secondary DART®s are capable of providing

Table 12: Source detection contributions for elements of the U.S. DART® array. Three non-U.S. sites, indicated with an asterisk, are included, since their presence influences Pacific array performance.

		# Sources Detected As		Mean Detection Time (min)		Mean Detectable Magnitude (M_w)	
Region	**DART®**	**Primary**	**Backup**	**With**	**Without**	**With**	**Without**
Aleutians and Alaska	46413	3	5	17	26	6.87	7.15
	46408	4	4	17	25	6.87	7.10
	46402	5	4	17	28	6.91	7.15
	46403	5	4	17	33	6.92	7.20
	46409	4	15	18	30	6.85	7.15
	46410	13	4	34	57	7.03	7.19
West Coast	46419	9	3	34	57	7.10	7.18
	46404	4	9	29	36	6.90	7.11
	46407	2	4	32	37	6.97	7.15
	46411	2	1	25	35	7.02	7.11
Central and South America	43412	9	5	45	89	7.11	7.41
	43413	10	30	61	89	7.14	7.39
	32411	29	8	109	174	7.44	7.76
	32412	11	67	109	124	7.46	7.64
	32401*	59	8	154	209	7.70	7.57
Northwest Pacific	21418	19	15	49	78	7.19	7.28
	21417	7	11	34	48	6.97	7.18
	21416	11	7	37	57	7.02	7.11
	21415	9	8	26	42	7.06	7.12
	21414	4	6	17	26	6.89	7.15
West Pacific	21413	11	16	70	89	7.27	7.43
	52401	8	7	68	77	7.43	7.38
	52402	8	19	67	81	7.33	7.50
	52403	38	21	87	145	7.60	7.73
	52404	21	24	72	118	7.39	7.59
	52405	32	28	70	107	7.25	7.35
Southwest Pacific	52406	5	22	67	76	7.32	7.25
	51425	5	5	54	86	7.27	7.63
	51426	12	26	49	81	7.21	7.64
	54401	22	14	60	126	7.26	7.58
Coral Sea	55012*	32	8	94	127	7.47	7.84
Tasman Sea	55015*	7	1	32	309	7.00	8.32
Equatorial	51406	0	0	n/a	n/a	n/a	n/a
Hawaii	51407	0	0	n/a	n/a	n/a	n/a
Atlantic	41420	13	58	55	69	7.53	7.56
	41421	20	13	79	95	7.51	7.65
	41424	0	0	n/a	n/a	n/a	n/a
	44401	0	0	n/a	n/a	n/a	n/a
	44402	0	0	n/a	n/a	n/a	n/a
Caribbean	42407	43	21	75	136	7.53	8.12
Gulf Mexico	42408	16	0	104	155	7.87	8.20

early detection of low-magnitude events. Loss of 46410, at the end of the line (see Fig. 52), would have a noticeable impact on array performance for sources off the Alaskan panhandle and Canada.

Note that the southern California DART® provides neither primary nor secondary coverage for any of the (seismic) sources in the propagation database. This is true of other sites in the table, in the mid-Pacific and in the Atlantic. These sites were chosen to provide warning of non-seismic or remote tsunami sources (or other less-well characterized threats).

Off Central and South America, some of the statistics in Table 12 (and Fig. 55) indicate weaknesses in the array. Sites 43413 and those further south must each cover long stretches of the source line. The mean detection times for 32411, 32412 and the Chilean tsunameter 32401 are long, reflecting poorer coverage of sources off Panama, Colombia and Ecuador in the north and the extensive tsunami-prone central and southern coastline of Chile. The hazard is more local than remote due to the long travel time to points of direct U.S. impact, but the degraded detectable magnitudes will increase the basin-wide uncertainty for events in these regions. It is hoped that these weaknesses will be addressed through the addition of Ecuadorean and further Chilean tsunameters. There has been some discussion (see the site recommendation reports in the Appendices) of the possibility of reallocating one of the U.S. array elements (likely 51406) to southern Chile. There appears to be some reluctance to do so, given the long history of the site and its potential to provide validation of SIFT predictions for a wide range of sources. Preferable would be a modest expansion of the number of instruments in the U.S. array, should the anticipated Chilean sites not be realized.

The close spacing along the Aleutian/Alaskan and West Coast source regions is evident in the early portion of the table. With the exception of 46410, which provides primary cover from the northern Gulf of Alaska to the Queen Charlotte Islands, each DART® need only cover 300–500 km of the source line.

Proceeding to the northwestern Pacific, the statistics provided in Table 12, and illustrated graphically in Fig. 52, show that this region is comprehensively covered, too. The orientation of the Kamchatka and Kuril trenches, while directing tsunami energy toward the Hawaiian Islands and the U.S. West Coast, does permit them to be detected by western elements of the Aleutian/Alaskan DART® line. The situation is somewhat poorer in the west and southwest, where increased detection intervals and poorer detectable magnitudes are encountered. This may be of greater concern for local than for remote impacts. The region with its many island chains may limit the basin-wide broadcast of tsunami energy. For example, both ends of the New Guinea to Vanuatu source line (see Fig. 53) are poorly detected due to the screening effect of New Guinea itself and New Caledonia. The Australian site 55012 in the Coral Sea is better placed to detect sources in the center section of the line than is 52406 to the north of the island chain. The New Zealand to Tonga source line is well served by 51425, 51426, and 54401. Australia's Tasman Sea tsunameter 55015, in addition to its primary role of monitoring Puysegur Trench off New Zealand's South Island, is better

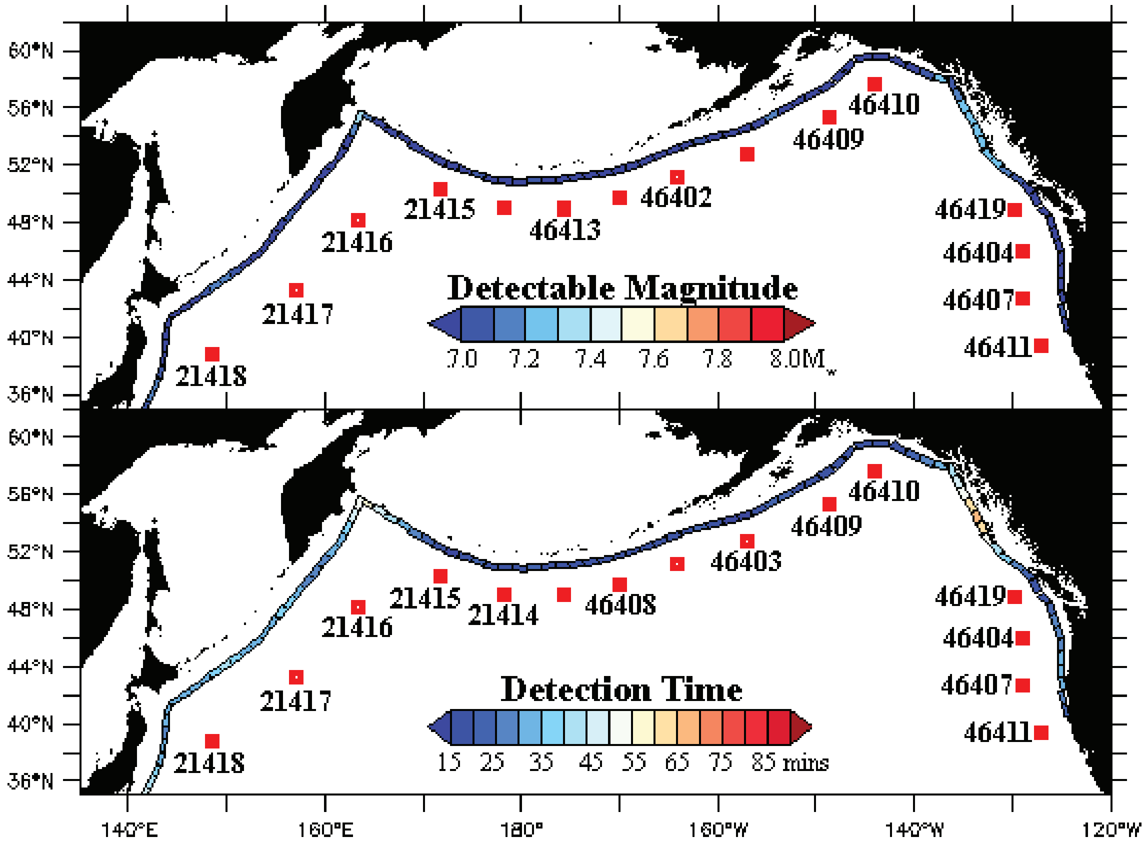

Figure 52: Detectability and detection time for seismic sources in the North Pacific.

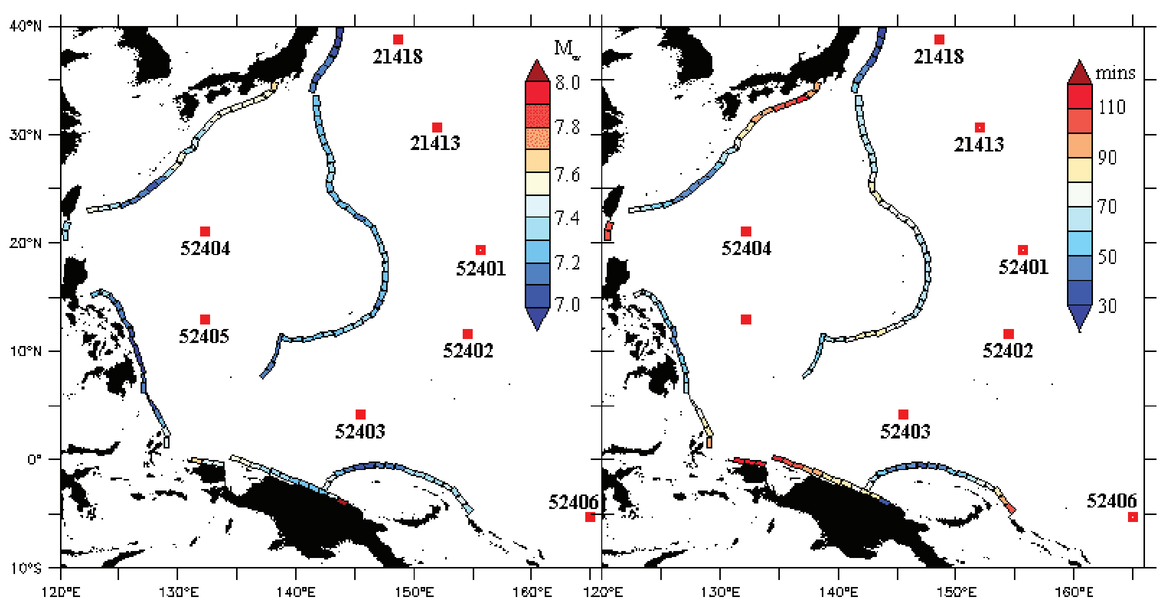

Figure 53: Detection capability in the Western Pacific.

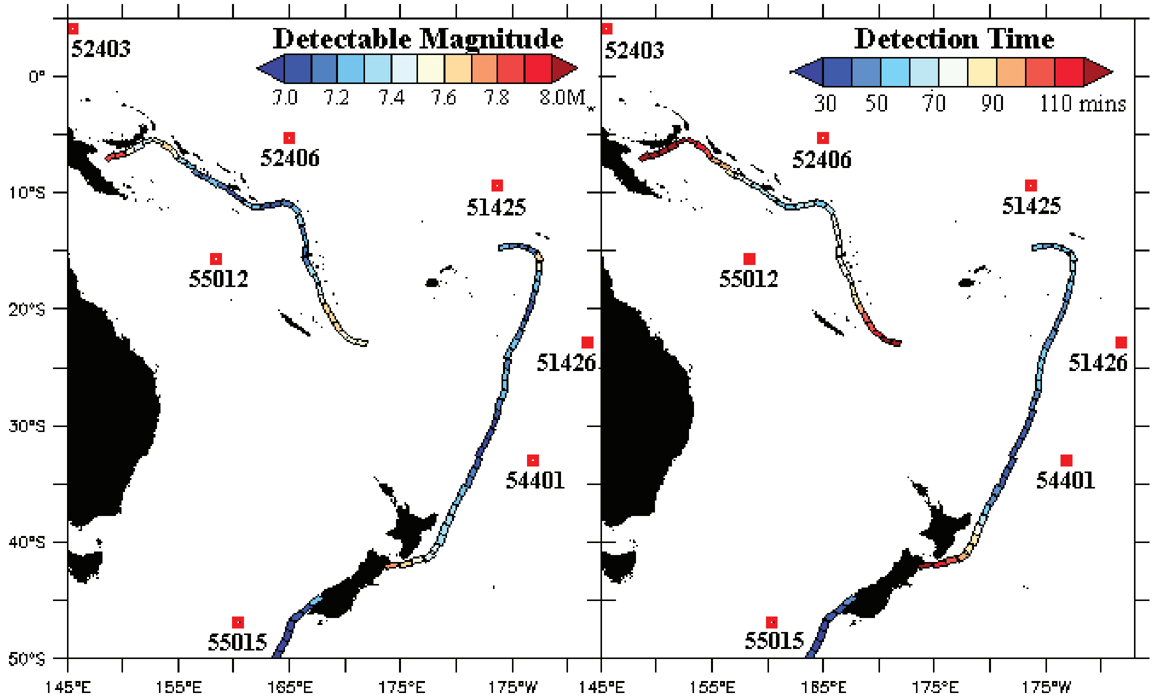

Figure 54: Detection capability in the Southwest Pacific.

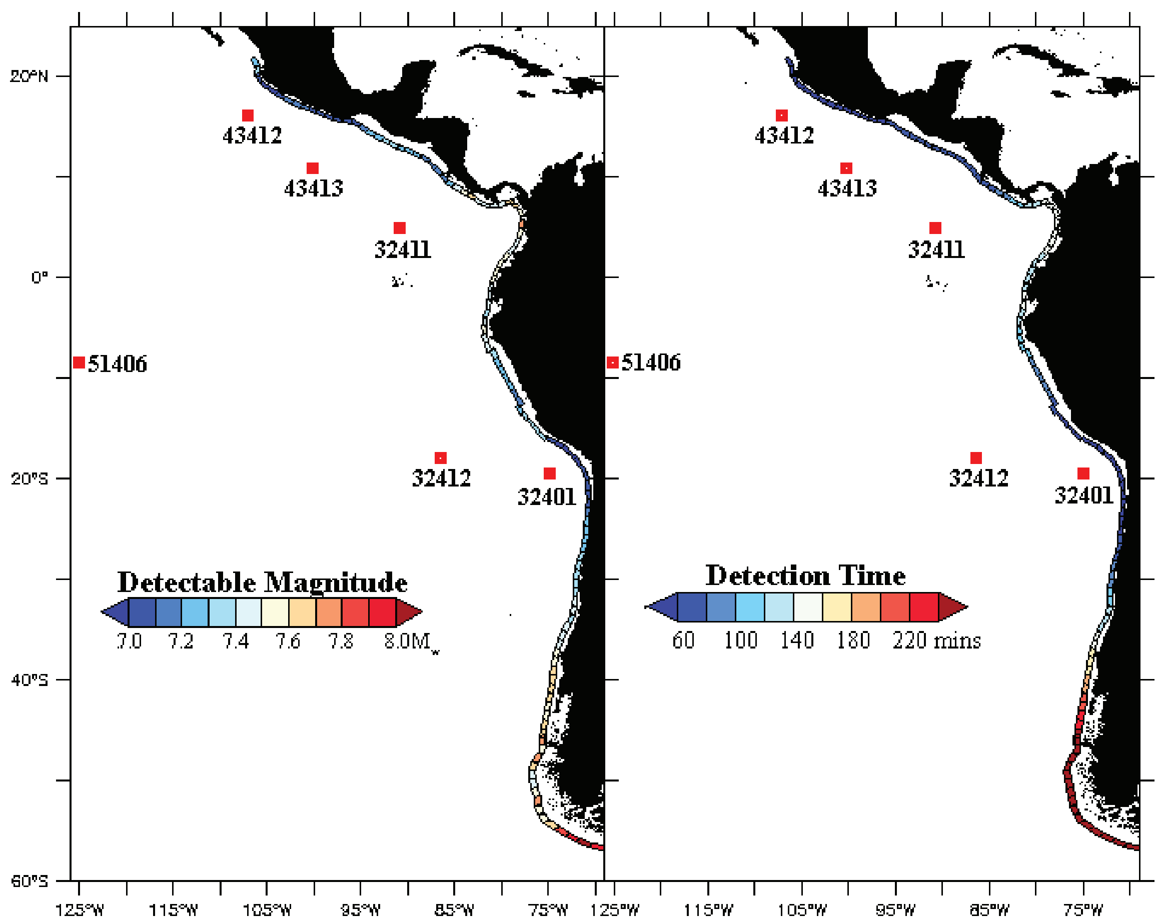

Figure 55: Detection capability in the Eastern Pacific.

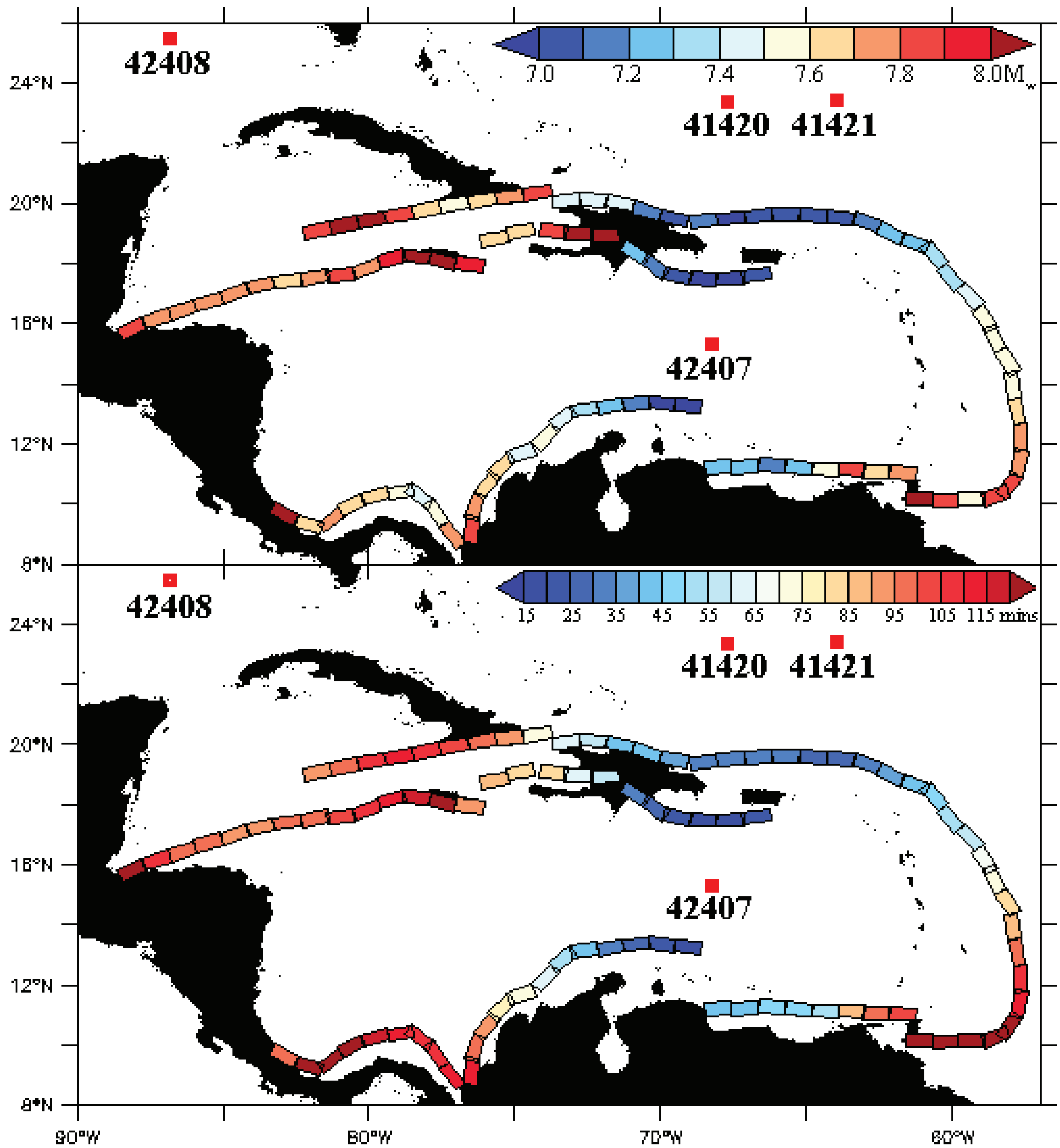

Figure 56: Detection capability for Atlantic and Caribbean seismic sources.

placed to detect waves generated near Macquarie Island, or other segments of the plate boundary further south, than is DART® 54401 to the northeast of New Zealand. These sources are of major concern to Tasmania and New South Wales but may direct some energy into the Pacific.

In the Atlantic basin the primary threat to the U.S. East Coast for seismically generated events comes from sources between Antigua and Hispaniola. The DART® pair 41420/42421 north of Puerto Rico primarily covers these. The timing and quality of the detection degrades somewhat in moving away from Puerto Rico, though this is somewhat compensated for by the presence of shielding shallows (Turks and Caicos and Bahamas) to the west and the orientation of the main tsunami beam in the east. Puerto Rico, in addition to being threatened (and monitored) to the north, is exposed to a range of sources to its south. The Muertos Trough is perhaps of greatest concern to Puerto Rico and the U.S. Virgin Islands, but there is the potential for tsunami generation off Venezuela, with relatively short travel times. The sole DART® site in the Caribbean, 42407, provides some cover for many of these sources but with late detection and less than desirable quality in many instances (see Fig. 55.) There are further sources in the western Caribbean basin that are not well served. Given the almost total EEZ ownership, siting in the western Caribbean would be impossible except in a collaborative mode. Further north in the Atlantic, sites 41424 and 44402 can provide delayed observations of remote events impinging on the East Coast as well as local landslide-generated events not fully treated in this report. The easternmost site, 44401, was selected to give approximately 3 hours warning of waves that might originate in the eastern Atlantic: Lisbon or possibly Las Palmas.

7.3 Data Return Statistics

Overall data return statistics for each element of the array are summarized in Fig. 57. Although the data return rate has been substantial, there are occasions when severe intermittency or complete loss of data occurs. The reasons for such occurrences are not always completely known, though weekly status reports from NDBC attempt to classify them. Apart from instrument failure or damage during deployment, intermittency may be due to communication interruptions between the surface unit and the BPR, or the satellite link. Sea state or strong ambient currents are external factors that may be responsible for such intermittency. Total loss on the other hand, though it may be due to a hostile natural environment, can arise through vandalism or collision with merchant or fishing vessels.

The issue of intermittency, as possibly the result of ambient currents, has been addressed to some extent in the individual site descriptions of Section 6. This analysis is not complete to the extent that contemporaneous, in situ, current observations are not available and the NLOM hindcast currents do not substantially overlap the DART® records. In some locations NDBC meteorological and wave buoys lie in the vicinity of a DART® and will in the future be used in an attempt to associate intermittency with environmental factors.

7.4 Commercial and Fishing Vessel Considerations

Total loss of the data stream is occasionally the result of a collision with a surface vessel. Two sources of relevant data in this regard have recently been considered. The first is an analysis of VOS (Voluntary Observing Ship) Program data conducted by Halpern *et al.* (2008) as part of a study of human impact on the marine environment. VOS vessels are estimated to comprise some 11% of traffic for vessels in excess of 1,000 tons, and perhaps a greater

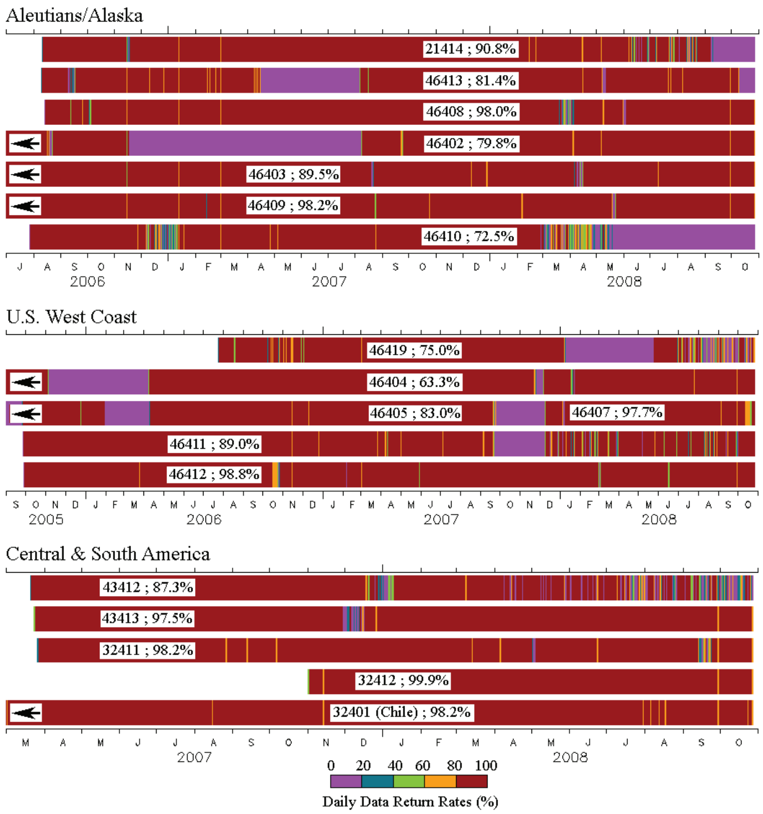

Figure 57a: DART® data return statistics.

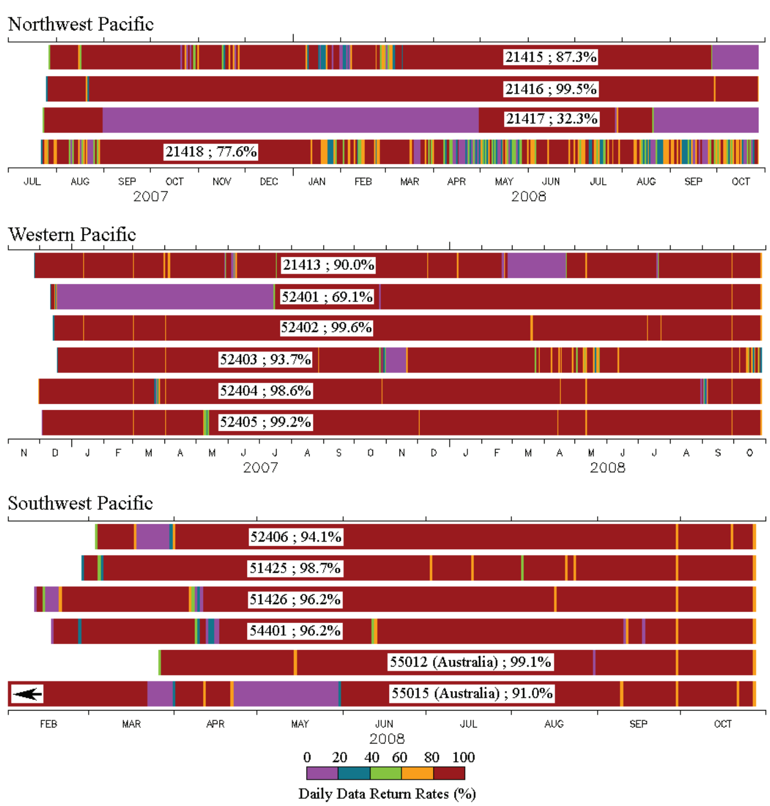

Figure 57b: DART® data return statistics (cont.).

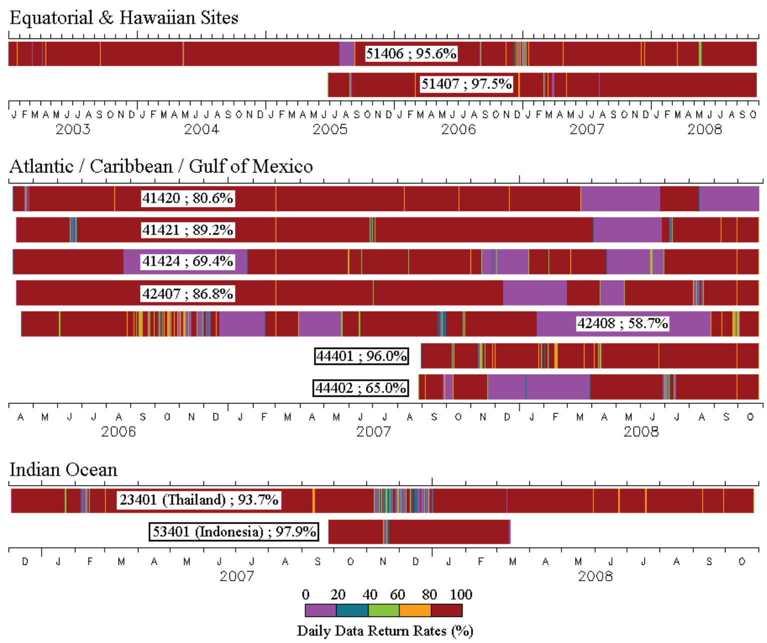

Figure 57c: DART® data return statistics (cont.).

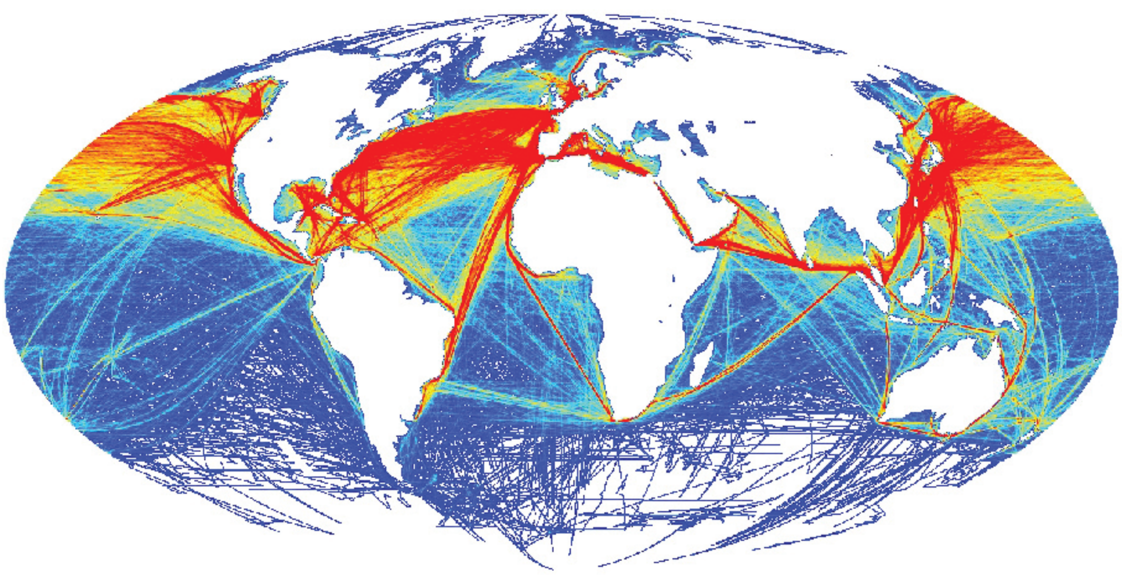

Figure 58: Global commercial vessel activity, derived from VOS ship reports by Halpern *et al.* (2008).

proportion in such heavily traversed regions as the North Pacific and Atlantic. By interpolating between successive reports from individual vessels, Halpern *et al.* (2008) achieve resolutions of about 1 km in their estimates of vessel transits per square kilometer per year, and so finely delineate the shipping lanes, as seen in Fig. 58.

Fishing boat activity is not included in the VOS traffic analysis. However, another product, "Lights At Night," available from NGDC and the Defense Mapping Satellite Program, identifies transient lights over water and

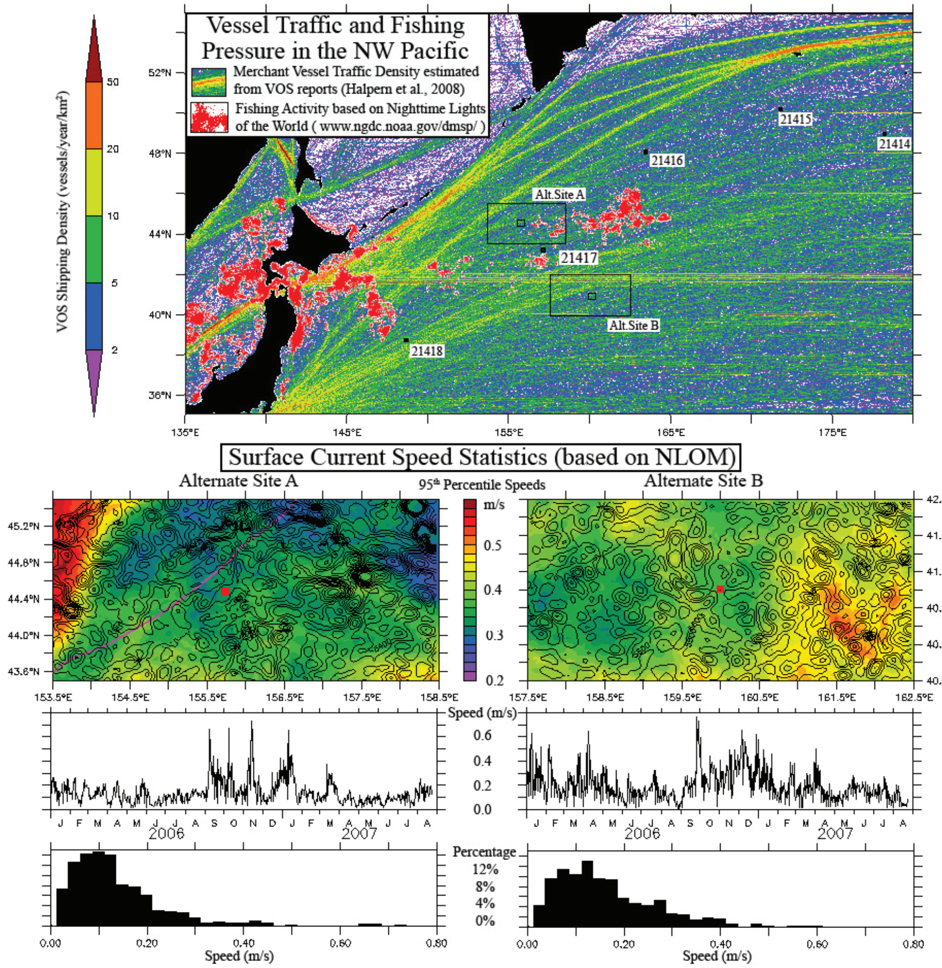

Figure 59a: Sea-lanes and fishing activity near DART® Site 21417.

discriminates between those due to gas flares from drilling platforms and those associated with fishing boats. Among the regions than stand out in the fishing activity results is the area east of the Kuril Islands where DART® 21417 has twice been lost in circumstances that suggest a collision. Another "hot spot" of fishing pressure appears south of the Galapagos. While these products have not yet been systematically included in the DART® siting process at NCTR, a case study for DART® 21417 has been performed and the instrument will be relocated when the site is next visited. Figure 59 is a composite of sea-lane and fishing activity generated during that study.

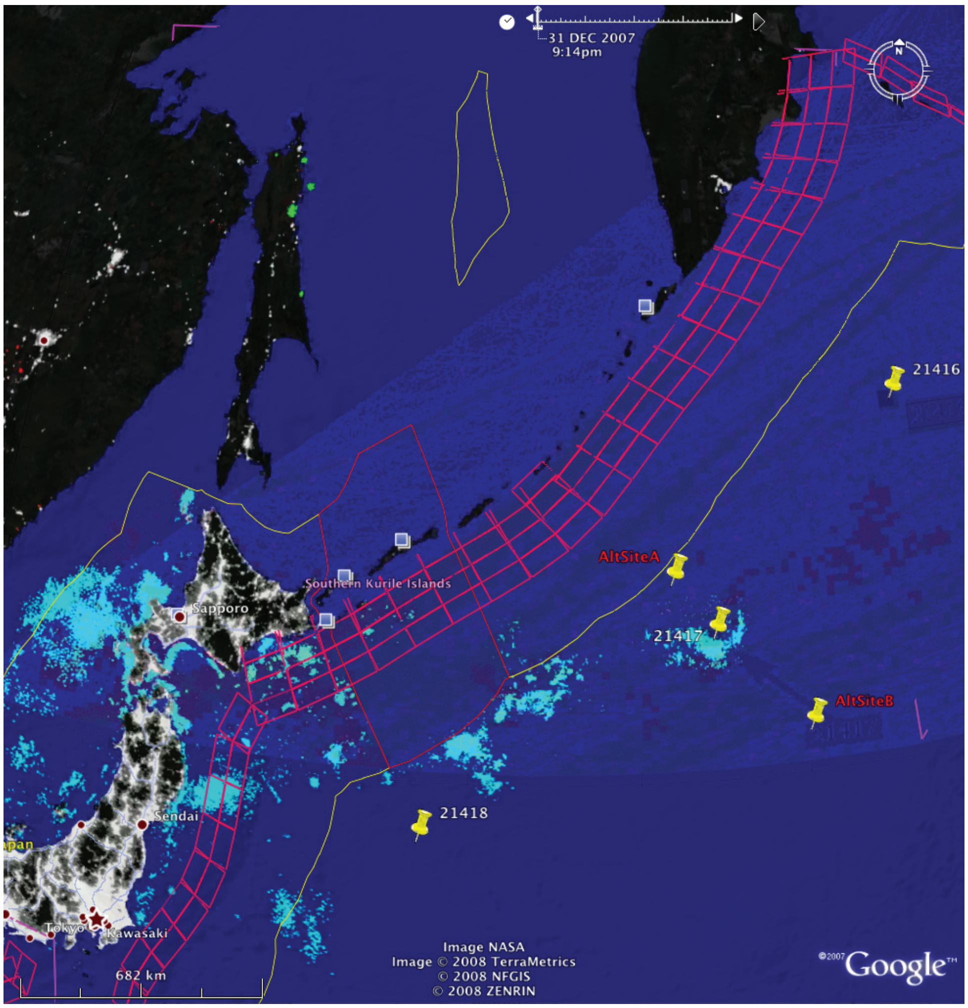

Figure 59b: Sea-lanes and fishing activity near DART® Site 21417 (cont.).

8. Conclusions

8.1 Major Considerations in DART® Siting

Some of the major issues involved in site selection for an array of DART® instruments are:

1. **Water Depth and Strong Current Regimes:** the DART®s currently in use can only be deployed in water depths between 1500 and 6000 m. Because of the need for a surface buoy, strong current regions where it is difficult to maintain the tethered surface buoy are to be avoided.
2. **Bottom Roughness:** A DART® needs to communicate acoustically with its surface unit. For this to work it must lie on a reasonably flat seabed. This is a local bathymetric constraint, as is the need to avoid areas of strong depth gradients, or where submarine landslides may occur.
3. **Seismic waves:** If a DART® is located too close to the seismic event that generates the tsunami, the shaking of the sea floor can cause spurious BPR fluctuations unrelated to the passage of tsunami water waves. This seismic noise can be largely avoided by locating the instruments no closer than 30-min of tsunami travel time from the closest source.
4. **Tsunami Scattering:** While consideration (2) above relates to the local bathymetry, the presence of seamounts or other major seafloor features between a DART® and likely tsunami sources is also to be avoided. The complete detection/forecast system works by "inverting" the waveform of a passing tsunami wave train to extract the characteristics of the tsunami source. This process involves comparison with modeled waves that in complex regions may not fully represent scattering by rugged bathymetry.
5. **Timing issues:** Consideration (3) above suggests that DART®s not be placed too close to potential tsunami sources. Conversely, if sited too far from the action, too much time is lost between the seismic event, which is detected almost instantly and the arrival of an unambiguous sea surface disturbance at a DART® site. Suitable sites must therefore be close, but not too close, to potential sources.
6. **Detectability:** Until it reaches the coast, a tsunami wave in the open ocean may have only an amplitude of a few centimeters. While the influence of the larger (but much shorter period and wavelength) wind waves is largely filtered out in a BPR record, there is a noise threshold of a few millimeters that limits the detectability of weak tsunami signals. Given the lobed or beamlike pattern of tsunami energy, the best location to observe the tsunami is somewhat "in the beam" rather than too far to the side. Actually, though, observations directly off-

shore of a source can complicate the discrimination of the unit sources it represents.

7. **Number of Systems:** For the U.S. DART® system that will monitor the Pacific and Atlantic it was decided that 39 instruments would be deployed. Potential tsunami sources span virtually the entire perimeter of the Pacific and the Atlantic has sources in the Caribbean as well as to the east (between Portugal and the Azores, and perhaps landslide or volcanic sources elsewhere).
8. **EEZ Issues:** For source regions along the Aleutians, and the Alaskan and U.S. west coast mainland, likely DART® sites are either in international waters or within U.S. EEZ (Exclusive Economic Zone) limits. Elsewhere, notably in the Caribbean and western Pacific, the seafloor is a patchwork of differing ownerships. Other related issues include shipping routes, seafloor infrastructure, piracy, or a history of damage to unattended buoys that make some areas less desirable for DART® siting.
9. **Logistics:** Although DART®s are typically deployed for 2-year stints, there is considerable expense associated with deploying and maintaining them in remote regions. For some potential sites in the equatorial Pacific, where the TAO (`www.pmel.noaa.gov/tao/`) buoy array or elsewhere where meteorological buoys exist, there may be efficiencies in collocation if there is not conflict with special DART® requirements.
10. **Redundancy:** Either the bottom unit or the surface buoy of a DART® may fail and, in remote locations, repair/replacement may not be an immediate option. Of course tsunamis do not occur every day but nonetheless it would be desirable to have some redundancy in the array. Not in the sense of having DART®s virtually side-by-side (the bottom units have dual systems to partially achieve this), but more in having a sufficient density of DART®s that failures near source regions of particular risk are partially compensated for by having more than one DART® capable of providing a timely, high-quality signal.

Other nations, Chile and Australia, have deployed DART® in the Pacific, which extend the coverage, and some Indonesian plans in the Western Pacific may assist the detection of sources in the vicinity of the Philippines and Bird's Head. Nevertheless some gaps remain, most notably off central and southern Chile where some assumptions of the DART® Siting Workshop have not as yet been met. Now that the full U.S. array is in place, as seen in Fig. 5, it is probably time to revisit these assumptions and decide whether additional buoys may be forthcoming or whether an existing instrument, such as 51406, whose role in the expanded array is altered, should be reallocated.

8.2 Future Directions

With the U.S. DART® array in place and, together with similar instruments put in service by other nations, providing input data to the Tsunami Warning Centers, it is appropriate to identify the ongoing efforts and additional products or analyses that might improve performance and reliability into the future. Chief among these would be the identification of regions that are poorly covered, for example the southeast Pacific, where an ongoing discussion may lead to a relocation of DART® 51406 to a site south of Chile's Juan Fernandez Island.

The design of the U.S. array described in this report is mainly aimed at detecting seismically generated tsunami waves, and providing adequate forewarning of their far-field impact. Seismic noise and geometric/bathymetric constraints to siting make local impacts more difficult to cover, though the duration of tsunami impacts give value to even a "late" forecast. A recent analysis of the detection in the Western Mediterranean of tsunami waves generated off North Africa (Schindelé *et al.*, 2008) highlights the difficulty. The NCTR propagation database employed, while well suited to estimating DART® arrival times and amplitudes, is less satisfactory to quantify local coastal impact; a database of higher-resolution propagation solutions, appropriate to Cascadia, the Caribbean, and other regions with local threats, is needed to refine the analysis.

Considerable effort within the tsunami research community is being directed toward landslide-generated waves whose dynamics are far more difficult to model. The distribution of the landslide threat has been considered by McAdoo *et al.* (2000) and others, and a case study of the Currituck landslide off North Carolina (geologic age ∼25–50 ka) by Geist *et al.* (2008) suggests that the local impact of such events need to be considered in ongoing refinements and expansion of the array.

Technological improvements in tsunami detection will likely need to be considered in the future. An effort underway at NOAA/PMEL involves the development and intercomparison of the DART®-ETD (Easy To Deploy) buoy configuration with the standard DART®-II. The ETD version is considerably more compact, allowing it to be deployed from smaller vessels, reducing costs, and providing options for expanding the array and speeding replacement when a failure occurs. Part of the intercomparison effort involves attempts to quantify and explain differences between neighboring instruments. The impact of environmental factors is part of this effort and should lead to insights that might routinely be applied at other sites.

While it is hoped that the material in this report may assist site selection processes by other nations to serve their own needs, the global nature of the threat suggests that NCTR staff should stand ready to cooperate in foreign decision-making, since the U.S. will benefit from array synergies. Likewise the audience for this report may be aware of other information sources that could be usefully employed in site selection.

9. Acknowledgments

This publication is contribution 3192 from NOAA/Pacific Marine Environmental Laboratory and was [partially] funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington under NOAA Cooperative Agreement No. NA17RJ1232, JISAO contribution 1607. The authors would like to acknowledge the contributions of the USGS and NDBC for information pertinent to the siting choices, and to online data sources used in the analysis and graphics.

The authors benefited from discussions with Diana Greenslade of the Australian Bureau of Meteorology in regard to their methodology for site selection and forecast procedures. Dr. Benjamin Halpern of the UCSB National Center for Ecological Analysis and Synthesis, and coworkers, are gratefully acknowledged for permission to reproduce their graphic of VOS shipping lanes and for the data it represents. Technical assistance and editing suggestions from Ryan Layne Whitney of PMEL were invaluable in the production of this report.

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Appendix A. The DART® Siting Workshop

This two-day meeting, 6–7 July 2005, was conducted jointly by NOAA and USGS at NOAA's Pacific Marine Environmental Laboratory, and was attended by staff from the Tsunami Warning Centers, members of the tsunami, seismological, and oceanographic research communities, and engineers from PMEL and NDBC knowledgeable in DART® design and operational matters. Speakers with their affiliations were as follows:

Frank González, NOAA Center for Tsunami Research, PMEL
Eddie Bernard, NOAA Center for Tsunami Research and PMEL Director
Sam Johnson, USGS Western Coastal and Marine Geology Team
Paul Whitmore, NWS West Coast and Alaska Tsunami Warning Center
Shannon MacArthur, NOAA/National Data Buoy Center
Hal Mofjeld, NOAA Center for Tsunami Research, PMEL
John Dennis, Rice University (Consultant on optimization methods)
Mick Spillane, NOAA Center for Tsunami Research, PMEL
Eric Geist, USGS
Ken Hudnut, USGS Earthquake Hazards Program
Brian Atwater, USGS
Uri ten Brink, USGS
Aurelio Mercado, University of Puerto Rico
Chris Newhall, USGS Volcano Hazards Program
Vasily Titov, NOAA Center for Tsunami Research, PMEL
Doug Luther, University of Hawai'i

Other experts, including Peter Bird, David Jackson, and Yan Kagan of UCLA, though unable to attend, communicated their views through the participants.

The discussion was very fruitful, beginning with the practical needs of an operational warning system, then focusing on the distribution and associated threat levels associated with various tsunami sources with a goal of narrowing and refining the initial network concept. Logistical considerations bearing on maintenance of a virtually global array were described, together with options for incorporating the needs and resources of other oceanic observational programs. The potential application of optimization techniques to array design were described. A concept of a fully-featured warning system, melding data from seismometers and DART® buoys with pre-computed numerical models of tsunami propagation and tuned site-specific inundation models (now available in the SIFT system), was presented.

The workshop concluded with a consensus-building discussion in which Frank González (then Program Leader of PMEL's Tsunami Research group) sought an assignment of the 39 U.S. DART® buoys in the Pacific and Atlantic/Caribbean basins which would achieve the best coverage of the perceived threat. The resulting allocation, encapsulated in Fig. 4 of the body of this report, assigned 7 buoys to the Atlantic region (including one each to the Caribbean and Gulf of Mexico), with the remaining 32, including several existing instruments, distributed in several groupings throughout the Pacific. The Workshop recommendations included priorities for the sequence of deployments at the new sites, and agreement on the distribution of effort among those involved in order to make the expanded array a reality. The completion of the array in March 2008 marks the success of the Workshop deliberations.

More specific detail on the content of the Workshop discussions, summarized by Geist *et al.* (2005), are available online from the USGS at `soundwaves.usgs.gov/2005/10/meetings.html`.

Reference

Geist, E., F. González, and U. ten Brink (2005): Workshop on Optimizing the DART Network for Tsunami Forecasting. Sound Waves Monthly Newsletter, October 2005 (`soundwaves.usgs.gov/2005/10/meetings.html`).

Appendix B. West Pacific DART® Location Assessment (Stations 2-1 to 2-6)

Hal Mofjeld, Mick Spillane, Frank González, Vasily Titov
NOAA/PMEL National Center for Tsunami Research
(Originally circulated on 21 October 2005)

Introduction

NDBC has scheduled the deployment of six new DART® stations in the West Pacific, with the deployment cruise set to begin February–March, 2006. At the request of Shannon McArthur (NDBC), PMEL conducted a highly accelerated evaluation of a set of candidate locations developed by the Tsunami Warning Centers (TWCs). The rapidity of this evaluation was driven by the lead time needed to secure advance permission from other nations to deploy DART® systems in their territorial waters, if such deployments prove necessary in order to meet DART® Network operational requirements. The purpose of this effort is to recommend refinements in the DART® locations to the TWCs and NDBC, as well as to identify choices that will need to be made before the final locations can be established.

Analysis

The assessment and subsequent recommendations were guided by the following set of criteria:

(a) Tsunami travel times from potential tsunami sources,
(b) Positions relative to tsunami propagation paths to U.S. impact sites,
(c) Suitability of bottom conditions for hardware deployment,
(d) Avoidance of wave scattering islands, seamounts, and ridges,
(e) Location relative to political boundaries.

Overall, only minor changes in location appear to be necessary in order to meet these criteria. The original TWC candidate sites, the recommended locations, and relevant comments and issues are listed in Table B1, and a graphical representation is provided in Fig. B1.

To better understand the role of these recommended DART® stations in observing tsunamis from the full suite of possible subduction zone sources in the West Pacific Region, it is helpful to view the tsunami beam patterns from the sources. These patterns are available at the website: `nctr-people.pmel.noaa.gov/spillane/WestPacAnim.html`.

Table B1: Original and recommended DART® positions in the West Pacific Ocean.

	Original Sites			Recommended Sites			
DART® Station	Latitude (°N)	Longitude (°E)	Depth (m)	Latitude (°N)	Longitude (°E)	Depth (m)	Issue/Comment
2-1	18.30	152.10	5873	18.30	152.10	5873	Unchanged
2-2	18.28	155.57	5678	18.00	157.00	5722	Scatterers nearby
2-3	11.20	154.60	5740	11.20	154.60	5740	Unchanged
2-4	20.84	134.97	5849	21.00	134.00	5934	Ridge nearby
2-5	02.38	145.65	4570	04.00	145.50	4414	Beam coverage
2-6	13.00	132.00	5695	13.00	132.00	5695	Unchanged

Summary and Recommendations

Each individual DART® Station is addressed here in turn, together with a recommendation to either leave the candidate location unchanged or to move it, based on the analysis criteria listed above.

2-1. Placed on the 1.0-hr travel time curve from South Honshu Ridge and Japanese sources, the original location appears to be fully adequate. It is located in International Waters.

2-2. Suggest moving to the east to avoid scattering centers near the original location. This does increase the minimum travel time slightly from 1.0 hour to 1.25 hour. Location within the Northern Marshall Islands. Moving it eastward beyond 158°E would place it in the Marshall Islands.

2-3. Also on the 1.0-hour travel time curve, the original location appears to be fully adequate. Location is within the Northern Marshall Islands. Moving it eastward beyond 158°E would place it in the Marshall Islands and moving it southward below 10.5°N would place it in the Federated States of Micronesia.

2-4. This station is in a difficult location because it is between the Kyushu Palau Ridge and water to the west with depths >6000 m; the latter are beyond the depth limit of the DART® bottom units. The suggested location is farther away from the ridge but in deeper water. A local bathymetric survey during the deployment cruise will be necessary to find a suitable location in terms of water depth. The station is within waters claimed by Japan.

2-5. Suggest moving the station northward to get within the main beam of more sources to the south. Location is within the Federated States of Micronesia. Moving it westward a relatively short distance will place it within waters claimed by the Palau Islands.

2-6. Well-located. The station is in international waters. Moving it farther west will eventually place it within 200 nm of The Philippines.

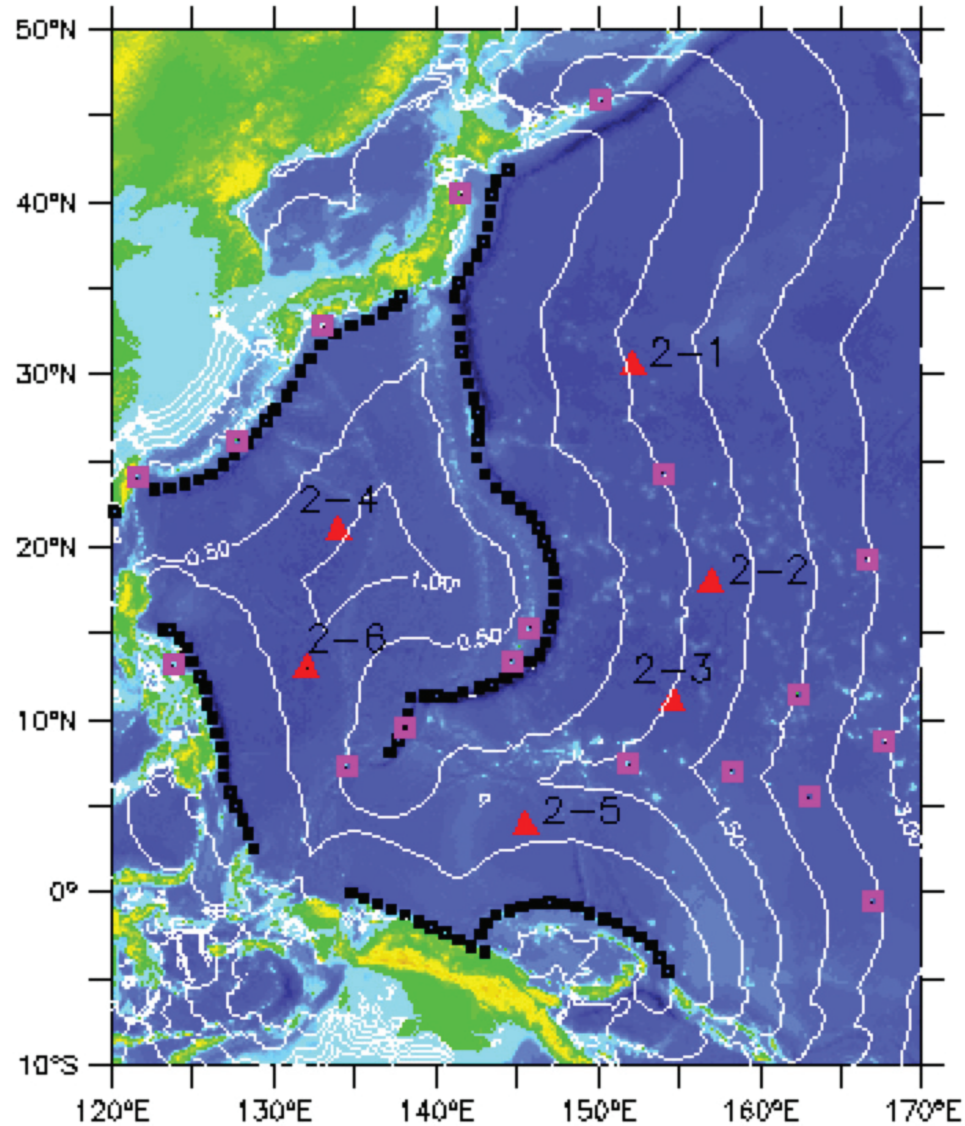

Figure B1: Recommended DART® locations in the western Pacific Ocean. Also shown are tsunami travel times to nearest tsunami source (white lines, in hours), potential tsunami sources (black squares), TWC warning points (pink squares), and bathymetry (indicating islands, seamounts, and mid-ocean ridges).

Note on EEZ Issues

Even modest changes in some of the candidate locations can move these locations from the territorial waters claimed by one nation (Fig. B2) into those of another. In addition, some of the borders separating these waters are in dispute.

It may be that the NOAA/NWS already has existing relationship with some of the Island Nations that will facilitate getting permission for the DART® deployments in their waters. It may be that the NWS Pacific Region HQ in Honolulu has experience in dealing with instrumentation deployments and maintenance in these nations that would be useful in this

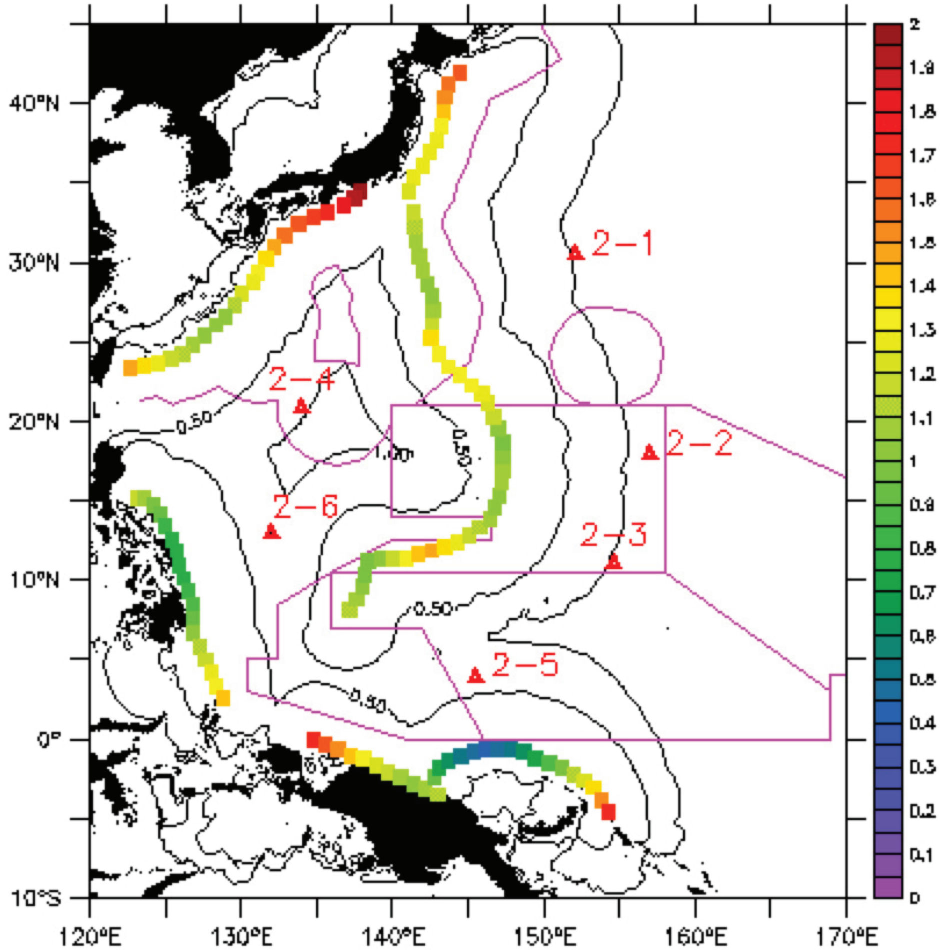

Figure B2: Recommended DART® station locations and territorial waters. Minimum tsunami travel times are shown in black, while political boundaries are shown as magenta lines. Color code refers to the earliest DART® network detection of a tsunami generated by the associated source. The EEZ boundaries for Japan are from the online source `www.gdrc.org/oceans/un-seahorse/maps.html`; the island nation boundaries are extracted from The New International Atlas (Rand McNally, 1991).

regard. This possibility needs to be explored further, since delays associated in getting permission from other nations can be substantial, potentially delaying the DART® deployments in the west Pacific or leading to a less-than-optimal DART® array there[1].

[1]Further discussion following this recommendation, coupled with a more accurate representation of the EEZ boundaries, led to minor adjustments that placed all of the sites in International waters.

Appendix C. Atlantic/Caribbean/Gulf of Mexico DART® Location Assessment (Stations 3-1, 3-2, 3-3, 7-1, 7-2, 7-3, 8-1)

Hal Mofjeld, Mick Spillane, Frank González, Vasily Titov
NOAA/PMEL National Center for Tsunami Research
(Originally circulated on 2 February 2006)

Introduction

NDBC has scheduled the deployment of five new DART® stations in the Atlantic/Caribbean/Gulf of Mexico Region, with the deployment cruise scheduled to begin on 24 March. At the request of Shannon McArthur (NDBC), PMEL has conducted an accelerated evaluation of candidate locations of all seven DART® stations that have been allocated for the region. Alternate locations are suggested for some stations as well, based on various technical considerations. This evaluation is meant to serve as a guide to the Tsunami Warning Centers (TWCs) who will make the final decision of the locations or who may request additional analyses for some locations. Having the seven locations, Shannon can then plan the deployment cruise, taking into account the relative costs of ship time for the various choices of the five stations.

The original DART® locations were established at the DART-NOW Workshop. The priorities for each group of stations were also established relative to the overall U.S. DART® Network. In the Atlantic/Caribbean/Gulf of Mexico Region, the stations in the Caribbean/Puerto Rico area were assigned third priority in the overall DART® network based on the frequency and damage potential of regional tsunamis. The stations off the East Coast have seventh priority, and the Gulf of Mexico station eighth priority. However, it should be noted that NOAA is committed to deploying all seven stations by the end of FY07 and that logistical contributions must largely determine the order in which the stations are deployed.

Analysis

The DART® location assessment and resulting recommendations were guided by the following set of criteria:

(a) Tsunami travel times from potential tsunami sources,
(b) Positions relative to tsunami propagation paths to U.S. impact sites,
(c) Suitability of bottom conditions for hardware deployment,
(d) Avoidance of wave scattering islands, seamounts and ridges,
(e) Avoidance of strong current regimes,

Table C1: Original and recommended DART® positions in the Atlantic/Caribbean/Gulf of Mexico Region.

	Original Sites			Recommended Sites			
DART® Station	**Latitude (°N)**	**Longitude (°W)**	**Depth (m)**	**Latitude (°N)**	**Longitude (°W)**	**Depth (m)**	**Comment**
7-1	28.46	56.69	5413	37.55	50.00	5454	Moved NNE
7-2	38.57	67.95	4112	38.21	67.93	4317	Moved South
7-3	31.72	73.55	5158	32.93	72.47	5283	Moved NE
3-1	21.50	66.81	5374	23.33	67.64	5750	Moved North
3-2	15.00	73.00	3144	15.26	68.23	4462	Moved East
3-3	21.28	62.79	5498	23.40	63.90	5840	Moved North
8-1	25.41	86.80	3312	25.41	86.80	3312	Unchanged

(f) Location relative to political boundaries.

The database of tsunami propagation model runs was expanded to cover potential earthquake sources in the Atlantic/Caribbean/Gulf of Mexico Region, with the guidance of Uri Ten Brink of the USGS. Unit sources with 100 km spacing were sited along the major known faults. Off the East Coast and in the Gulf of Mexico, submarine landslides are the most likely sources of tsunamis. Travel times appropriate to such sources were computed based on the TTT program (Geoware), but amplitude information for the landslide-generated tsunamis is as yet unavailable. Preliminary results from an analysis of the submarine landslide hazard, being prepared by the USGS, were employed in the revisions to the East Coast DART® locations (7-2 and 7-3).

The original locations were established during the DART-NOW Workshop. They, and the recommended locations, are listed in Table C1; a graphical representation is provided in Fig. C1. Further graphical information relevant to site selection in the Caribbean Sea (3-2) and Gulf of Mexico (8-1) are provided in Fig. C2.

Note added during the writing of this Technical Memo

The surface buoy of the Gulf of Mexico DART® 8-1 (46408), which was deployed as recommended here, broke loose in November 2007. The loss was likely due to strong currents associated with the Loop Current sweeping across the site. The mooring for DART® 7-2 (44402) has been similarly impacted by strong currents of the Gulf Stream. Clearly the treatment above, based on a climatological representation of these strong currents, was inadequate to appropriately represent the major excursions they exhibit. A full treatment of siting should include actual current observations, preferably moored but perhaps supplemented with drifter data; Such data are, however, sparse.

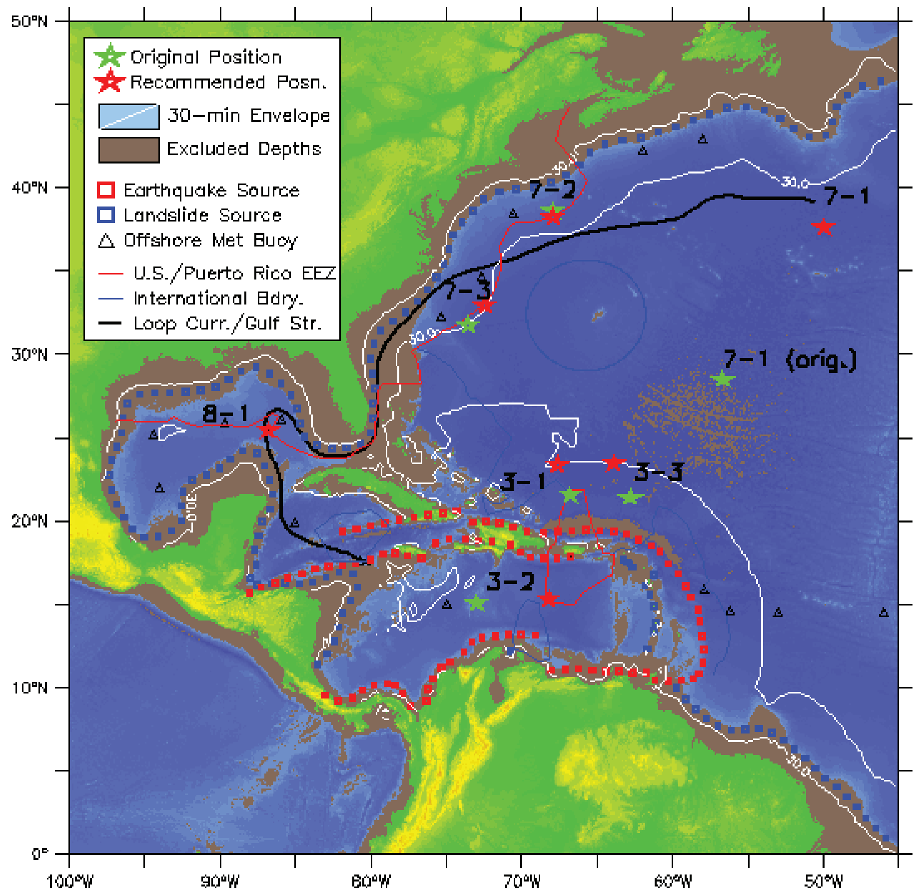

Figure C1: DART® site selection in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico. Also shown are the 30-min tsunami travel times to nearest tsunami source, potential tsunami sources, bathymetry, and boundaries of international waters.

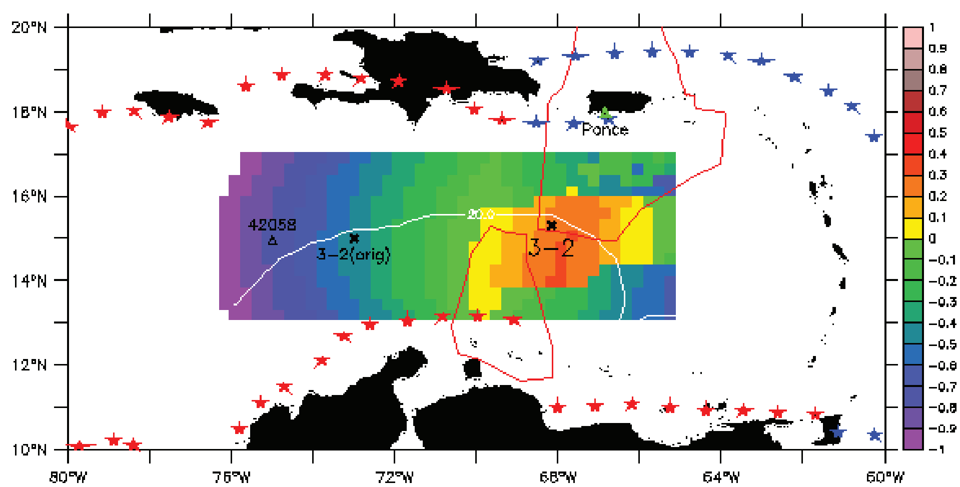

Figure C2: Detection times as a factor in Caribbean site selection. The position recommended for a single DART® in the Caribbean lies in the southwest of the Puerto Rico EEZ. Color-contoured is the advance arrival (in hours) at potential buoy locations when compared to Ponce for the tsunami sources indicated by red stars. Sources shown as blue stars are excluded from the computation because their detection relies on other DART®s (north of Puerto Rico), or other methods (for the closest Muertos Trough sources and those off the chart to the east of the Lesser Antilles.) The original 3-2 site, while providing greater advance warning of tsunamis originating near Panama, provides no lead time for events to the south and near Hispaniola.

In attempting to address this issue and quickly generate revised recommendations for the 46408 and 44402 sites, hindcasts from the Navy Layered-Ocean Model (NLOM, Shriver *et al.* (2007)) have been employed (see Appendix D of this report). For data and visualizations see `www7320.nrlssc.navy.mil/global_nlom32/skill.html`.

Reference

J.F. Shriver, H.E. Hurlburt, O.M. Smedstad, A.J. Wallcraft, and R.C. Rhodes. 2007, 1/32° real-time global ocean prediction and value-added over 1/16° resolution. *J. Marine Systems, 65*, 3–26.

Appendix D. Revised Siting Recommendation for the New England DART® (44402)

Mick Spillane
NOAA Center for Tsunami Research, Seattle WA
(Originally circulated on 6 March 2008)

Introduction

The initially recommended site for the northernmost of the two DART®s along the U.S. East Coast has proved to be too often in the path of the Gulf Stream and is, in consequence, difficult to maintain. A revised recommendation, based on the surface current statistics of the Navy Layered-Ocean Model (NLOM, Shriver *et al.*, 2007), is proposed that should substantially reduce the risk of mooring loss. The revised site, **39.30°N, 70.65°W**, is closer to shore, which may improve the warning time somewhat in the case of locally generated tsunami waves caused by submarine landslides, but possibly degrade the detection of slides at intermediate distances. However, it should still permit an updated forecast, two hours or so in advance of coastal impact, for waves from remote seismic sources off Puerto Rico or in the Eastern Atlantic that have already been detected by other elements of the DART® array.

Analysis

An initial report (Mofjeld *et al.*, 2006; Spillane *et al.*, 2008) that led to the deployment of DART® 44402 at 38.196°N, 67.851°W employed a representation of the climatological mean path of the Gulf Stream that has proved inadequate. The surface buoy broke loose in November 2007, severing communications with the sea floor pressure recorder, and a replacement was lost shortly after deployment. It is believed that strong currents from the meandering Gulf Stream were responsible for the losses.

While a thorough mooring design and selection of a new site should include an analysis of all available current meter data for the region, this is precluded by the urgency of restoring tsunami coverage. Instead, surface current hindcasts from an operational U.S. Navy circulation model NLOM, available online for the period January 2005 through August 2007, were analyzed. The overall maximum and median speed statistics, displayed in Fig. D1, confirm that the original 44402 site is frequently in the path of the Gulf Stream with excessive current speeds. The meandering nature of the

Stream can be readily visualized at the NLOM website and exposes a wide area off New England to its influence. Sorting the daily model speeds over the 965 days available allows the computation of a the 99th percentile speed for each grid point. This is the speed (denoted by $S_{1\%}$) that is likely to be exceeded during 1% of the days of a long-term deployment. In Fig. D2, $S_{1\%}$ is plotted for the Gulf Stream region, south and east of Cape Cod. The inshore bathymetry and 1,500–3,000-m isobaths are based on Smith and Sandwell (1997). The latter indicate the presence of the New England seamount chain to the east that should be avoided as potential scatterers of tsunami wave energy. Color contours show the 1% exceedance level for speed in units of meters/second, south of the stepped boundary which represents the inshore boundary of the NLOM domain. The initial site of DART® 44402 is shown, as is the site of a NDBC wave and meteorological buoy 44004 at which some knowledge of environmental conditions should be available.

Highlighted in red in Fig. D2 is the 1 m/s $S_{1\%}$ contour. This encloses a region that has a considerable extent to the south of the Stream but is more constrained to the north. The 0.75 m/s contour is shown in blue. Based on these, two tentative sites, marked in red, were circulated to the DART® user group with an estimate of their impact on warning times. Based on the positive response, via e-mail and the DART® teleconference of 5 March 2008, a more detailed study of this sub-region enclosed in black was performed. The results are shown in Fig. D3. Here the underlying bathymetry is from the NGDC (2005) and has 9-arcsecond resolution; the color contour interval is 100 m. Submarine canyons are clearly evident, cutting through the continental slope and in places incised into the more gradually sloping plane on which the DART® will be placed. Cross-hatching is used to display the $S_{1\%}$ statistic. Regions where speeds of 2 m/s and 1 m/s might be exceeded during 1% of deployment days are hatched in red and orange. These are clearly unsuited as survivable DART® sites. Further inshore, and hatched in yellow, are the regions of minimum $S_{1\%}$, with levels between 0.4 and 0.5 m/s. Considering these and the isobath spacing, highlighted in red, the location **39.30°N, 70.65°W** with water depth ∼**2644 m** is recommended as the new DART® 44402 site.

In addition to reduced exposure to strong currents, the warning characteristics of the site must be considered. Potential sources for tsunami hazard for the U.S. East Coast include local submarine landslides and remote seismic events. For the latter, the subduction zone of the Puerto Rico Trench is probably of greatest concern. Considering travel times, to the initial and revised 44402 site from unit sources of the propagation database near Puerto Rico, it is estimated that a reduction of approximately 12 min in arrival time will result from the move. However, detection at the revised 44402 site still comes 2 hours in advance of coastal impact along the northern portions of the East Coast, and the primary warning of such events will have been produced hours earlier by DART® 41420 or 41421. Being 270 km westward of the initial site, a delay of 20–30 min might be expected in waves originating in the eastern Atlantic (Portugal or the Azores), but again the role of DART® 44402 in such a situation is to refine the estimate of waves initially detected by DART® 44401.

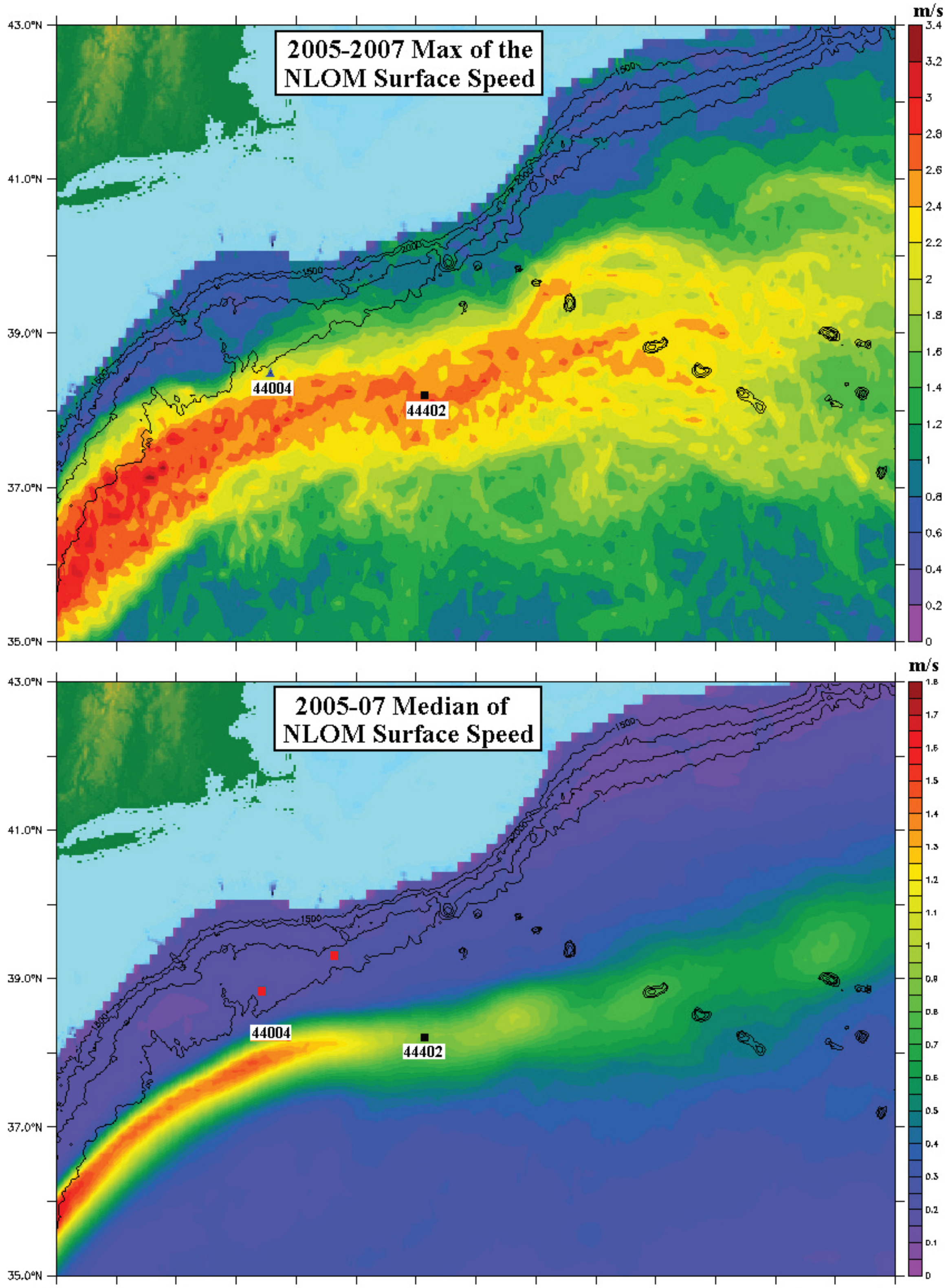

Figure D1: Maximum and median surface current speeds from the Navy Layered-Ocean Model (based on 965 days of hindcasts: 1 January 2005 to 23 August 2007.)

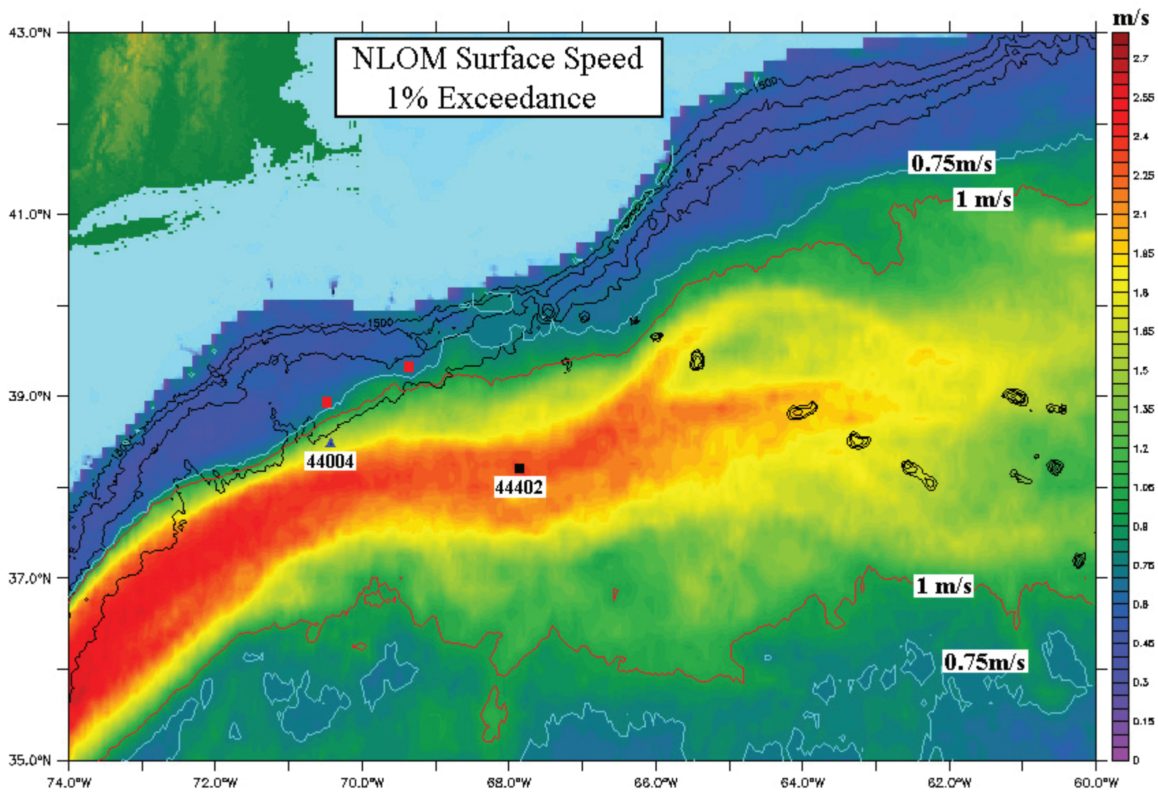

Figure D2: 99th percentile of NLOM surface speed distribution (m/s) expected to be exceeded on 1% of days during a long-term deployment. Details of the region within the box are presented in Fig. D3.

In the absence of a complete characterization of the local submarine landslide hazard, both in terms of location and the waves that might be generated, it is not possible to do more than comment generally on the result of the 44402 re-siting. For events in the immediate vicinity the move inshore might improve matters, but slower alongshore propagation and the reduction in the length of shoreline effectively monitored might degrade the detection of other landslide events.

Conclusion

A revised location for DART® 44402 deployment in the vicinity of **39.30°N, 70.65°W** is recommended. The precise location may be subject to revision by NDBC staff on consideration of seafloor infrastructure, sea lanes, or seafloor surveys during deployment. The new site is expected to greatly reduce the currents to be expected, though no site in sufficiently deep water can be expected to completely escape the meandering path of the Gulf Stream.

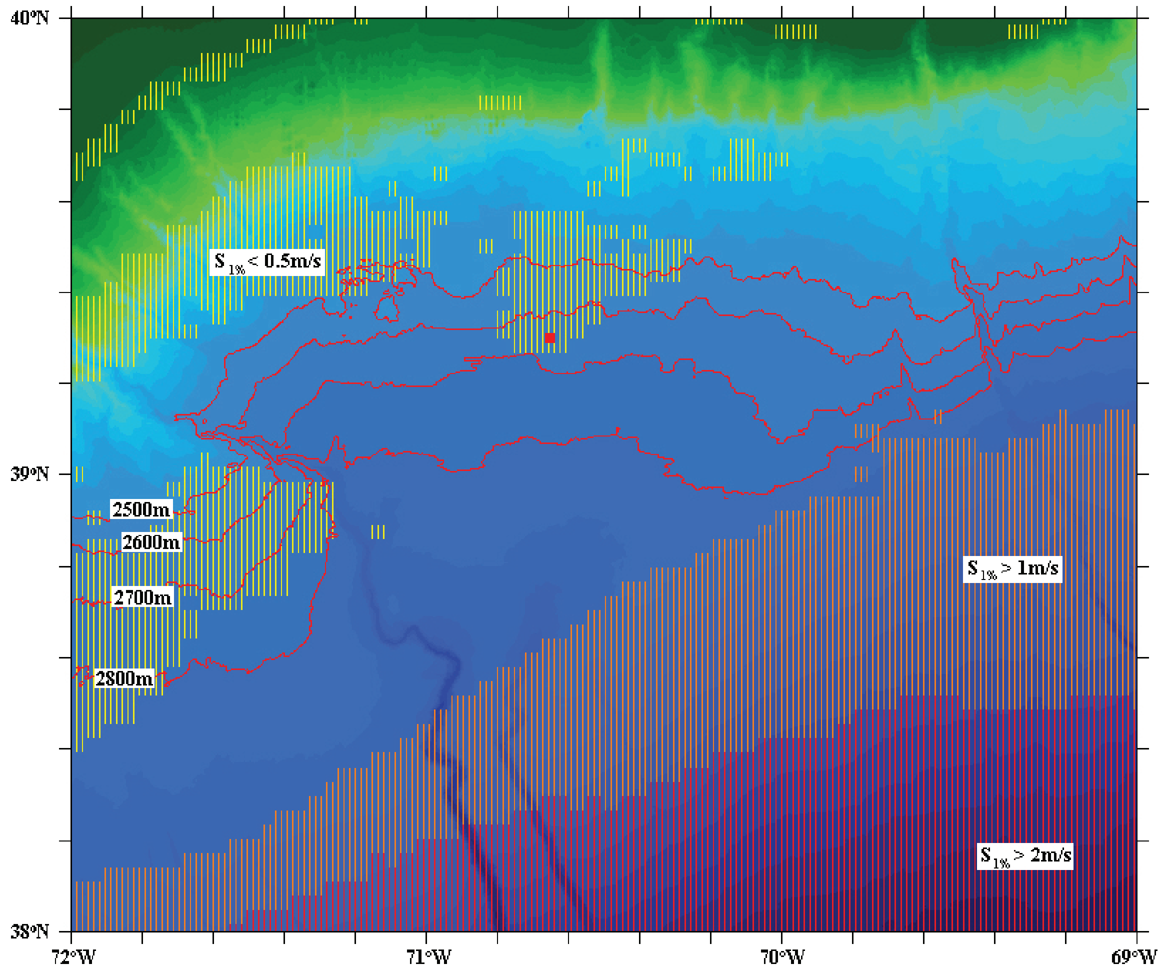

Figure D3: Bathymetry in the vicinity of the revised site recommendation for DART® 44402. The statistic $S_{1\%}$ estimates the surface current speed that may be exceeded on 1% of days during a long-term deployment and is computed from NLOM hindcasts. At the recommended site, 39.30°N, 70.65°W, $S_{1\%}$ is less than 0.5 m/s.

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Appendix E. Aleutian/Alaska/West Coast DART® Location Assessment (Stations 4-a, 46401, 1-2, 1-1, 5-3, and 46405)

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NOAA/PMEL National Center for Tsunami Research
(Originally circulated on 31 March 2006)

Introduction

The NDBC is scheduling a cruise to deploy four new DART® stations in the Aleutian/Alaska/West Coast region and to service, and possibly redeploy in new locations, some others. This report is intended to provide guidance as to likely sites, which best meet the goals of the Tsunami Warning Centers with regard to coverage of potential tsunami sources and satisfy operational constraints of the instruments. Precise siting is generally determined by NDBC, taking into account detailed bathymetry, the presence of seafloor infrastructure, national boundaries, etc. In this case all but one of the locations lie within U.S. waters. The exception, P26/5-3, lies within the Canadian EEZ.

The DART® network design combines the legacy of the originally instrumented sites, the conceptual array that emerged from the DART-NOW Workshop, and the results of tsunami propagation studies that are ongoing at PMEL. The Workshop assigned priorities to the recommended sites but, since all of the sites are to be instrumented in the next year or two, the order of deployment is in large part dictated by instrument production and ship scheduling. One location (P1/4-b) discussed below will not be instrumented at this time. However it seemed appropriate to include it, and existing DART®s unaffected by the cruise, in this report in order to fully reflect the current concept for the regional array.

Note on DART® Site Naming: Unfortunately there is more than one name associated with each site. The initial array concept for the Pacific was described with labels P1–P32. The workshop employed names, such as 5-3, to provide regional and local index information for the planning process. Finally, when a DART® is deployed it gets a NDBC buoy name, such as 46401. Where more than one name is appropriate to the likely users of this report, all the relevant ones are given.

Analysis

The DART® location assessment and resulting recommendations in this report were guided by the following set of criteria:

(a) Tsunami travel times and amplitudes for potential tsunami sources,
(b) Positions relative to tsunami propagation paths to U.S. impact sites,
(c) Suitability of bottom conditions for hardware deployment,
(d) Avoidance of wave scattering features such as seamounts and ridges,
(e) Provide timely data for real-time forecasting of tsunami amplitudes, as well as early warning cancelation capability.

The database of tsunami propagation model runs for the Pacific Ocean basin is essentially complete and allows the estimation of the travel time and amplitude of the first wave crest arriving offshore at any location from all potential sources. It should be noted that these model results do not extend to the beach but, in addition to serving as primary information for DART® siting studies, provide input to more detailed real-time models of inundation. The 15- and 30-min minimum travel time envelopes that result from the propagation database are shown as light blue lines in Fig. E1. These lines show the arrival time at a location from the closest source in the database. DART® locations are generally sited close to one or other of these lines. In the case of the Aleutian DART®s, the 15-min envelope is preferred since the detection and computation time needed to estimate impacts on the Hawaiian Islands make the 3-hour notice desired for evacuation difficult to achieve. Elsewhere the 30-min envelope is generally chosen, except where frequent but rarely damaging events are expected. Here placement of instruments closer to the sources is important for rapid cancelation of local tsunami warnings as needed.

Summary and Recommendations

The Tsunami Warning Centers have indicated that an even distribution of DART® sites best provides coverage of a largely unpredictable hazard. This has been a major consideration in the choice of Aleutian and Alaskan sites, as has their positioning along the 15-min line as dictated by travel times to the Hawaiian Islands. In particular, the Aleutian sites P1 through P14 will, after adjustments, have a nominal 6° zonal spacing. Details of the rationale for sites involved in the cruise being planned are given below.

P26/5-3. The area to the west of Vancouver Island, and northward toward Queen Charlotte Island, has frequent earthquake activity. While the tsunami amplitude associated with such events is generally low, it is desirable to have a DART® site in the vicinity to verify that the warning issued on the basis of the seismic signal can be canceled. For this reason it is recommended that the original DART® site be moved inshore to the location shown in Fig. E2. The sea floor is relatively flat and scattering features to the west and southwest do not rise much closer than 2000 m to the surface. Earlier work by Hal Mofjeld suggests that features need to

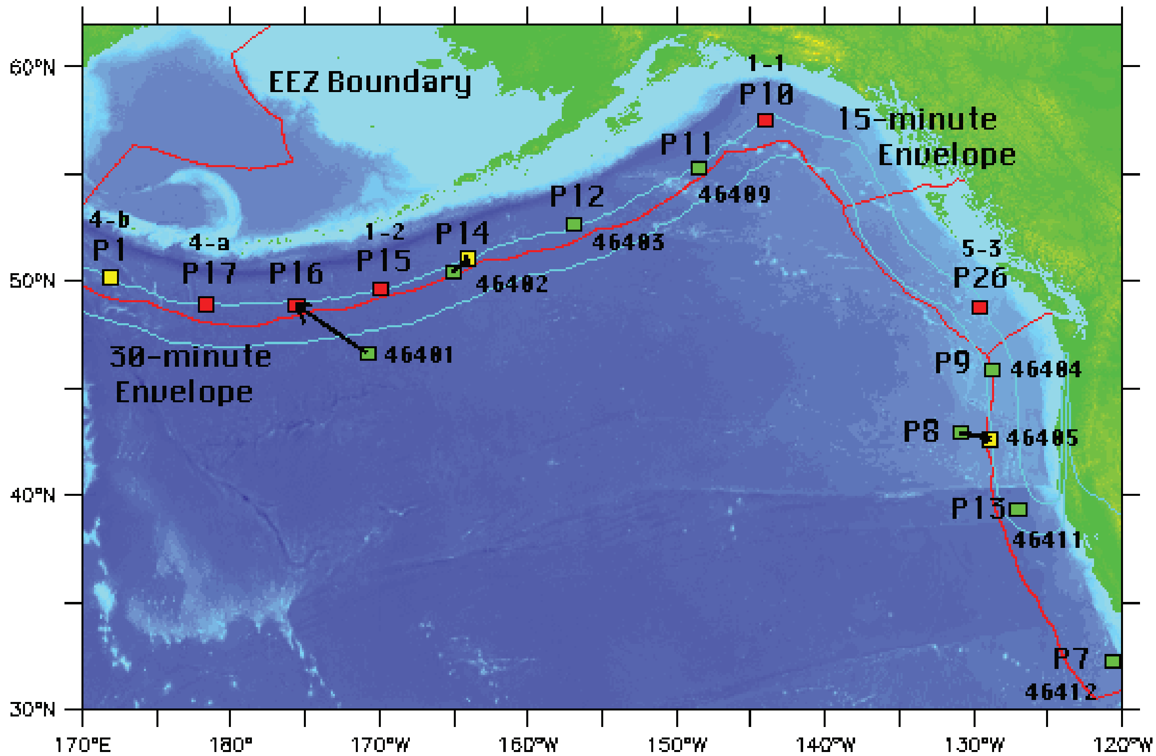

Figure E1: The current design for the DART® array in the Aleutian/Alaska/West Coast region. Red squares indicate instruments to be installed or repositioned in upcoming cruises; green marks those already in place, and yellow future deployments or repositioning actions. Arrows indicate recommended moves. Instruments at P8/46405 and P9/46404 will be serviced in the April 2006 cruise; the repositioning of P8/46405 may await the following servicing cruise.

rise to within 1200 m of the surface to cause significant scattering. The tsunami beam patterns of nearby sources in the propagation database were examined. They tend to be quite directional but, given their proximity to the recommended P26 site, their amplitude should be adequate for detection. The overall distribution of DART®s (Fig. E1), and the presence of faults for the entire shelf northward to Yakutat, suggests that an additional DART® to the north, perhaps in the vicinity of 55°N, 138°W, would be desirable to provide some redundancy to P10/1-1. P26/5-3 does add redundancy for P9 and P8, lying in the path of waves propagating from the northern Gulf of Alaska toward the West Coast. Its recommended location is however within the Canadian EEZ; all others discussed below are in U.S. waters.

P8/46405. This should be moved from its current location near the 45-min line to a point on the 30-min line, approximately midway between P9/46404 and P13/46411. In Fig. E3, the Smith-Sandwell bathymetry shows a relatively flat valley, separated from the open ocean by a low ridge (which might provide an alternate site, in the vicinity of 42.8°N, 129.5°W). To the east, where the plate boundaries are seen in the wider view, there are some minor seamounts that should not cause significant scattering of Cascadia events. Waves originating off California are likely to be distorted by the Mendocino escarpment and other features to the south and southeast, as

Table E1: Original and recommended DART® positions in the Aleutian/Alaska/West Coast region. Bold text highlights positions to be visited in the upcoming cruise. Other stations, existing or planned, are included, here and in Fig. E1, to show the overall array design for this region. Several naming conventions are in use for DART® positions; those most appropriate to likely readers are included here.

DART® Station		**Original Position**			**Recommended Position**			
		Latitude	**Longitude**	**Depth (m)**	**Latitude**	**Longitude**	**Depth (m)**	**Comment**
4-b	P1	50.667°N	171.961°E	5000	50.175°N	171.850°E	4681	Future deployment (Fig. E6)
4-a	P17	47.273°N	179.709°E	4899	48.920°E	178.300°E	5714	New DART® (Fig. E3)
46401*	P16	46.638°N	170.790°W	5658	48.870°E	175.580W	5502	Substantial move (Fig. E4)
1-2	P15	48.727°N	168.814°W	3686	49.610°N	169.900°W	5184	New DART® (Fig. E8)
46402	P14	50.442°N	165.028°W	4900	51.060°N	164.000°W	4687	Future adjustment (Fig. E9)
46403	P12	52.649°N	156.940°W	4517	52.649°N	156.940°W	4517	No action
46409	P11	55.300°N	148.500°W	4175	55.300°N	148.500°W	4175	No action
1-1	P10	56.455°N	143.971°W	3890	57.500°N	144.000°W	3771	New DART® (Fig. E7)
5-3	P26	48.787°N	130.896°W	3289	48.800°N	129.600°W	2838	New DART® (Fig. E2)
46404	P9	45.849°N	128.778°W	2765	45.849°N	128.778°W	2765	Service visit
46405*	P8	42.903°N	130.909°W	3500	42.600°N	128.900°W	3243	Possible move (Fig. E3)
46411	P13	39.349°N	127.008°W	4320	39.349°N	127.010°W	4320	No action
46412	P7	32.246°N	120.699°W	3782	32.246°N	120.700°W	3782	No action

*Note that, subsequent to their resiting to the recommended locations, 46401 and 46405 were given the WMO buoy numbers 46413 and 46407, respectively.

are trans-Pacific tsunamis, but this is unavoidable for any site in the region. A more precise characterization of the sea floor is desirable to avoid the risk of submarine landslides. The recommended location is within the U.S. EEZ.

P16/46401. The current and recommended locations for P16/46401 are shown in Fig. E4. The original site was south of the 30-min minimum travel time envelope, a location chosen perhaps to monitor sources near Kamchatka and the West Aleutians as well as those to the north. This need is reduced by the placement of other DART®s to the west, including others, not seen in Fig. E1, off Kamchatka and east of Japan. By moving P16/46401 north, close to the 15-min envelope, earlier forecasts and/or warning cancelation are achieved, particularly for Hawaii. The recommended site lies in relatively flat topography within the U.S. EEZ boundary; the feature to the NNW lies some 4000 m below the surface and ought not cause significant tsunami wave scattering.

P17/4-a. This site was chosen to extend westward the picket line of DART® instruments monitoring Aleutian tsunami sources to the north. In addition it will provide some backup and another reading on events whose origin lies further west for which the DART® at P1/4-b (see Fig. E1) and other instruments (not shown) are the primary detectors. The recommended

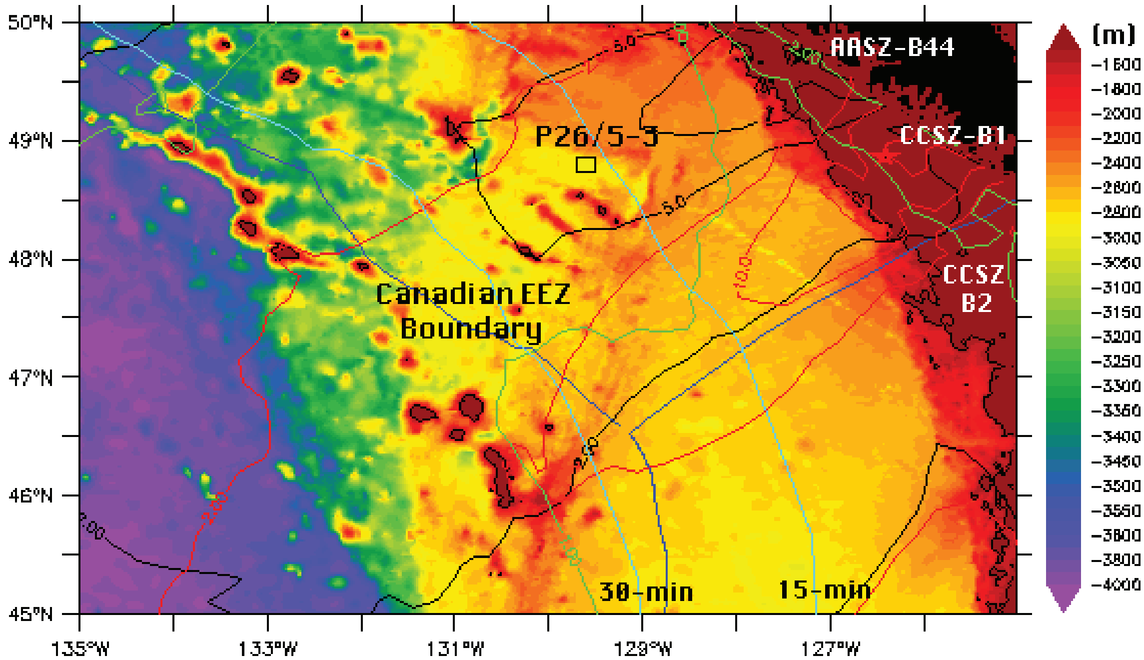

Figure E2: Smith-Sandwell bathymetry in the vicinity of the recommended location for P26/5-3. This site is in Canadian waters and is intended to enhance early warning cancelation capability for the Pacific Northwest and British Columbia for local events. Light blue lines show the 15- and 30-min minimum travel time envelopes; black, red, and green contour lines characterize the beam of three unit sources in the region (AASZ-B44, CCSZ-B1, and CCSZ-B2).

site (see Fig. E5) is on the 15-min envelope and lies within the U.S. EEZ boundary. When placed, P17/4-a will be for a while the westernmost of the DART® array. It lies near the dateline in broken, but not too rugged topography, within the U.S. EEZ.

P1/4-b. DART® site P1/4-b, when deployed in a future cruise, will be the westernmost of the array in U.S. EEZ waters. Its location (see Fig. E6), near the 15-min envelope, maintains the nominal 6° spacing of the DART®s to the east. Farther west, DART®s 4-c, 4-d, and 4-e of the group (not shown in Fig. E1) will be aligned parallel to the Kuril-Kamchatka subduction zone. However, P1/4-b is well placed to monitor the northern portion of this subduction zone and its junction with the Aleutian subduction zone. The recommended location is within the U.S. EEZ.

P10/1-1. This station is intended to monitor potential tsunami sources at the eastern end of the Aleutian/Alaska subduction zone, as well as the Yakutaga Zone and a range of other faults extending southward toward Queen Charlotte Island. Because of the vee-shaped distribution of these sources, reflected in the shape of the 15- and 30-min envelopes, P10/1-1 provides early detection for quite a few sources. In addition to providing the primary detection capability for waves propagating toward Hawaii, it should provide coverage for West Coast impact sites, too. However, while other DART®s to the west provide some redundancy for Hawaii, this is less

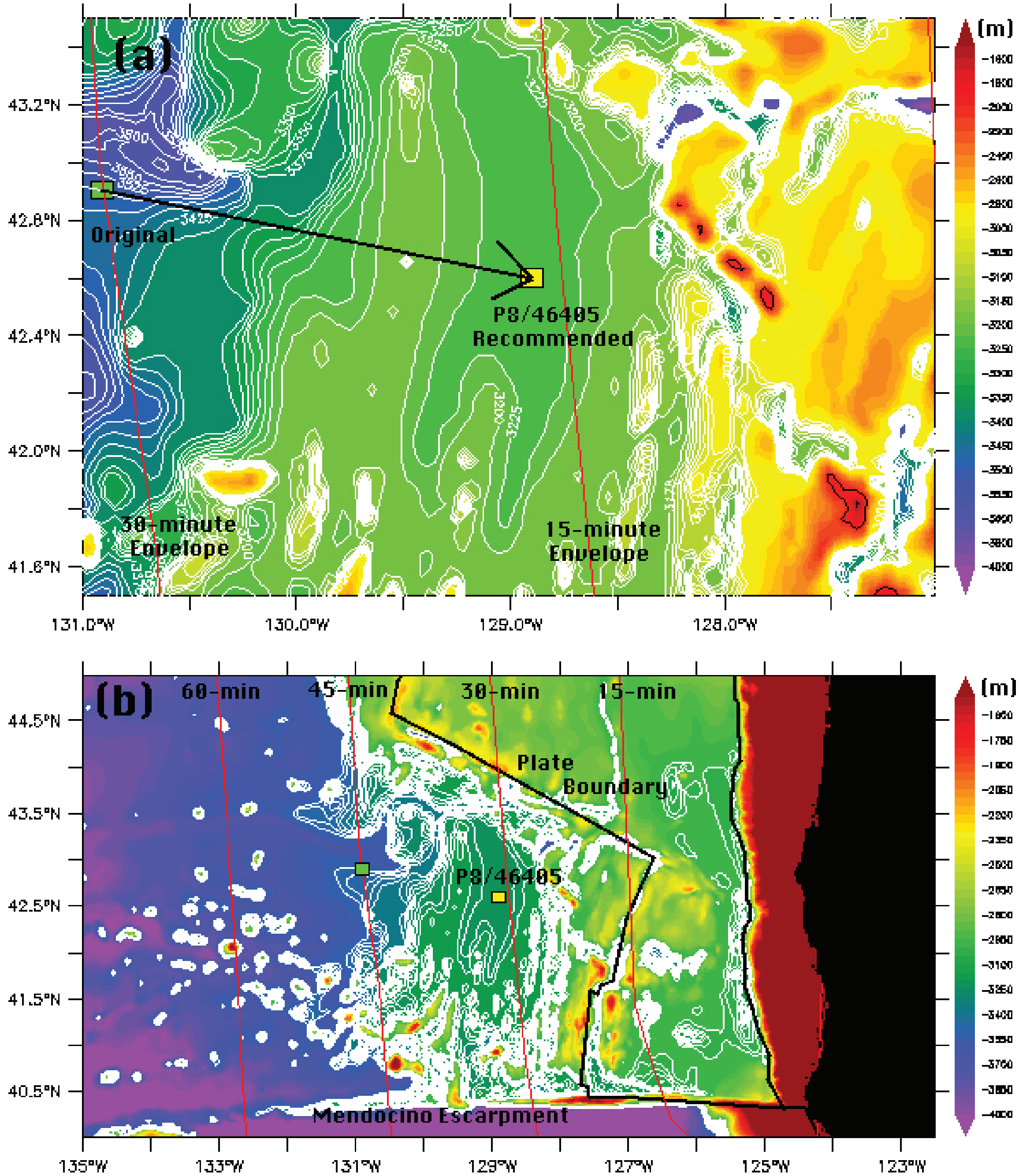

Figure E3: Current and recommended locations for P8/46405. The bathymetry of the region in the local (a), and wider view (b) is based on the Smith-Sandwell topography.

true for the West Coast, and an additional DART® between P10/1-1 and P26/5-3 (off Vancouver Island) would be desirable.

P15/1-2. This is a new DART® site whose location was chosen to continue the nominal 6° spacing of the sites to the west, and placement near the 15-min minimum travel time envelope. The Smith-Sandwell bathymetry shows a relatively smooth sea floor in the region, without significant scattering features.

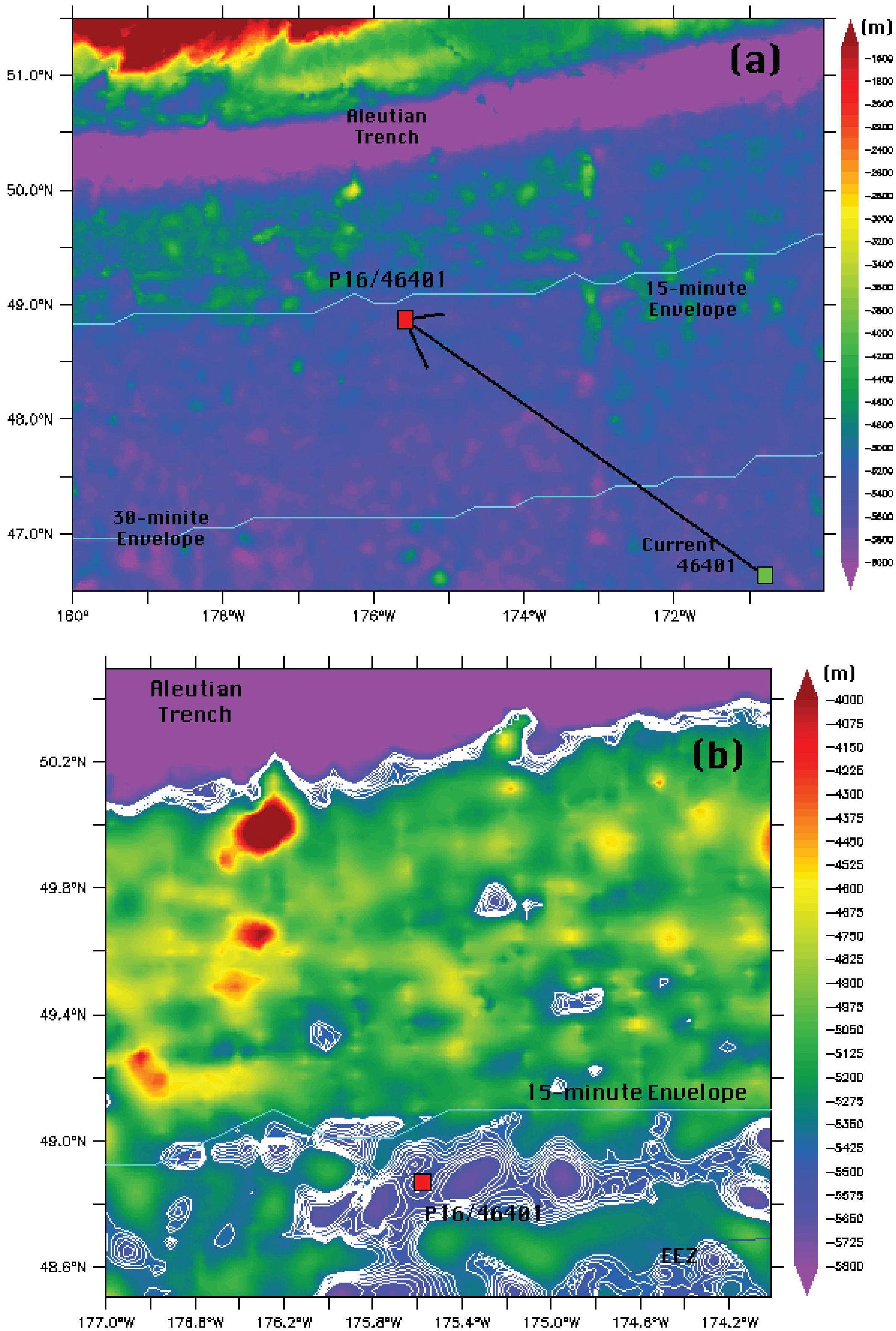

Figure E4: Repositioning of DART® P16/46401 from its current position outside the 30-min line (panel a) to the position recommended in this report will improve early detection and hence the forecast and warning cancelation capability. The bathymetry shown is from Smith-Sandwell.

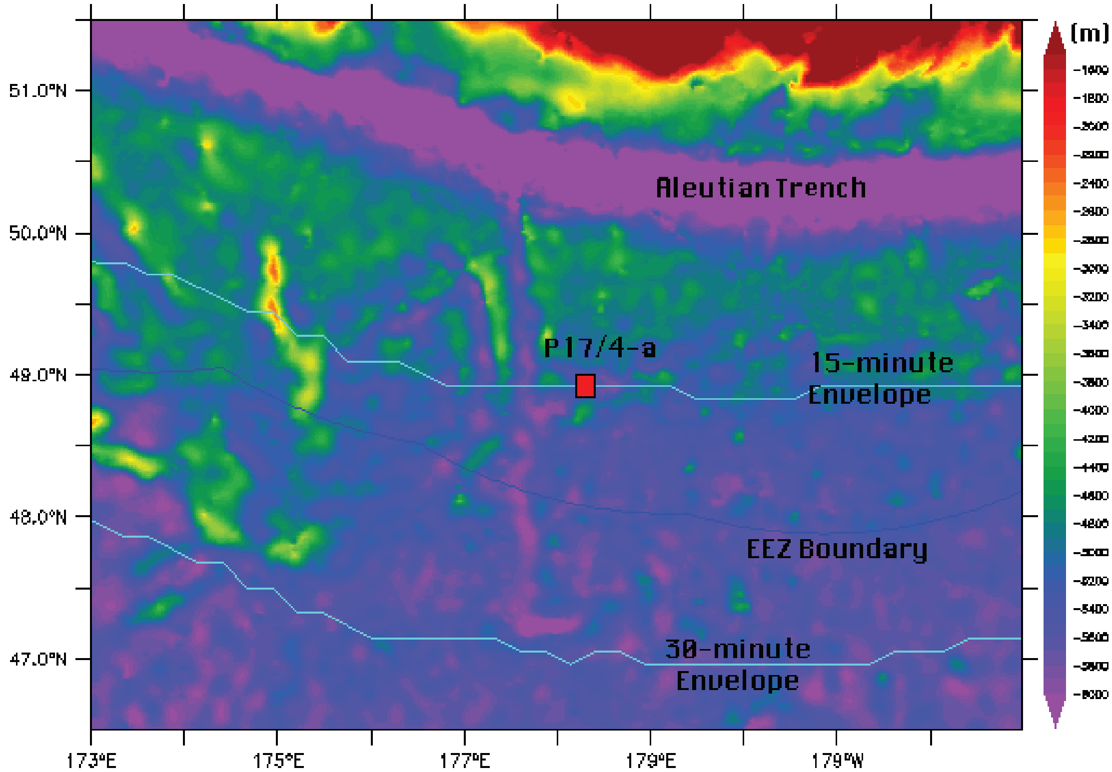

Figure E5: Siting recommendation for DART® P17/4-a. The bathymetry data is from Smith and Sandwell (1997).

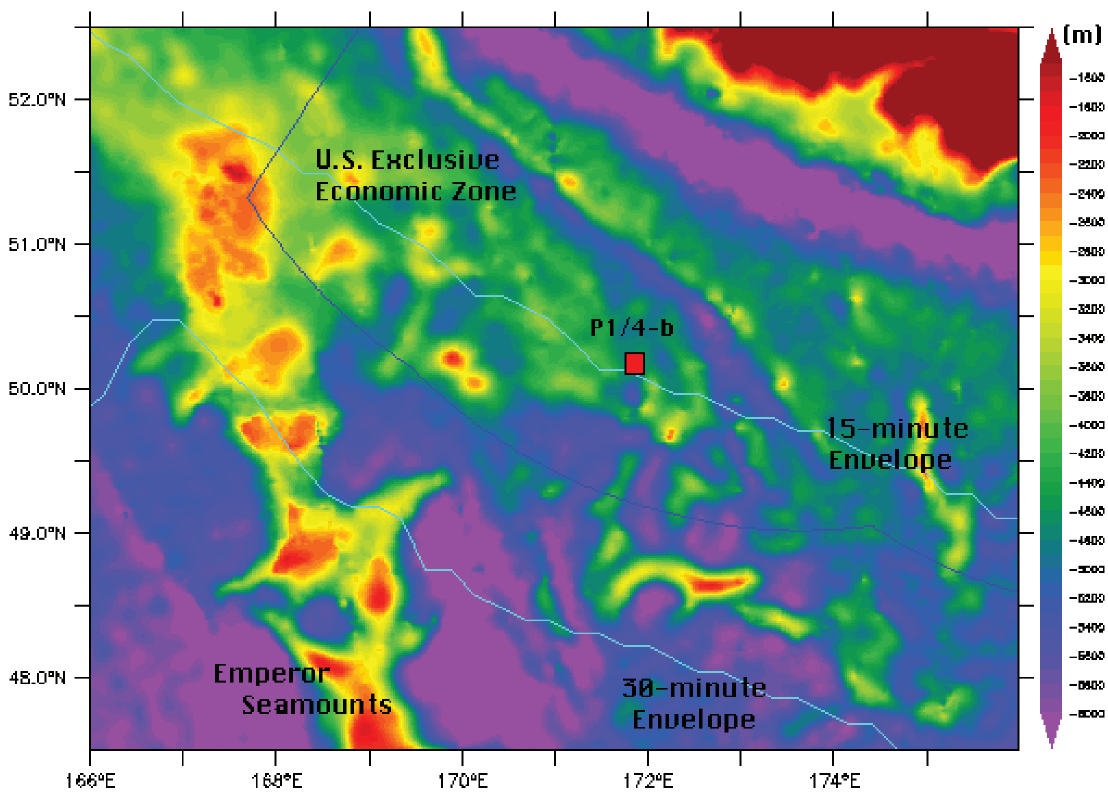

Figure E6: Siting recommendation for P1/4-b, which will be deployed in a future cruise, with bathymetry from Smith-Sandwell.

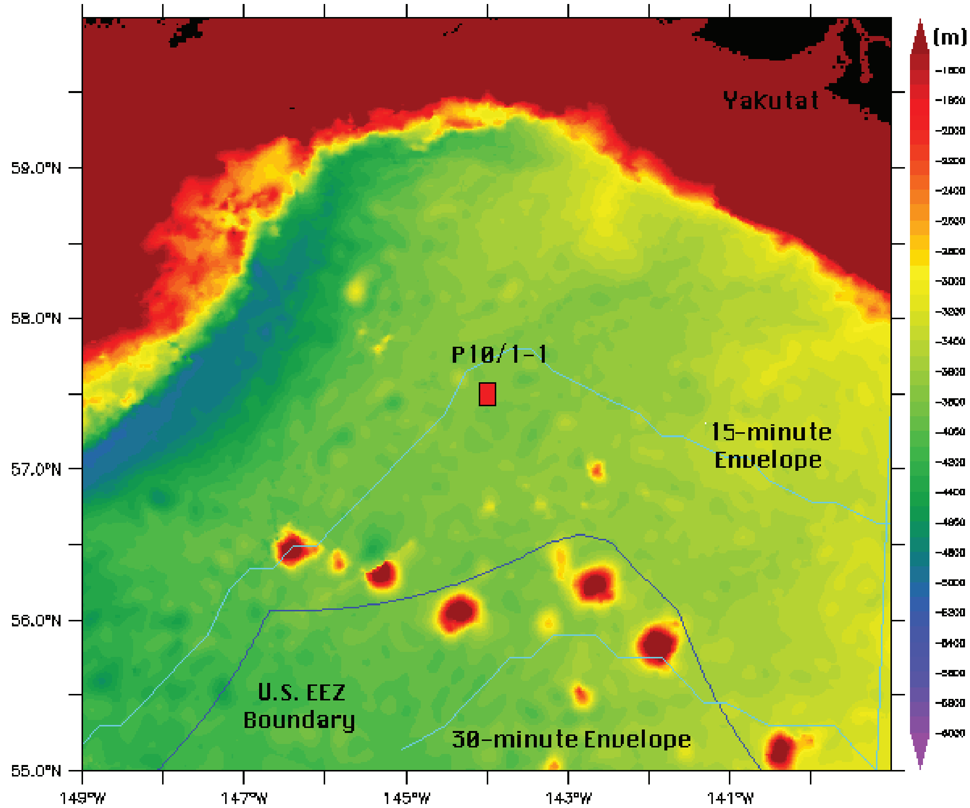

Figure E7: Siting recommendation for P10/1-1 in the northern Gulf of Alaska, with bathymetry from Smith and Sandwell (1997).

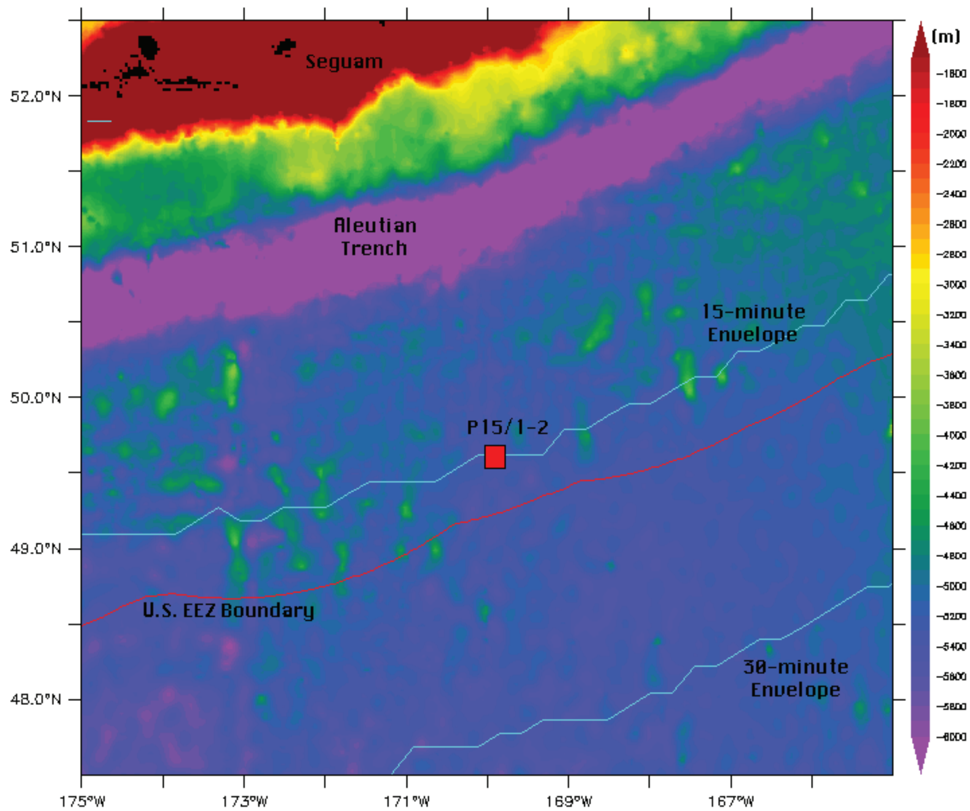

Figure E8: Siting recommendation for P15/1-2 with bathymetry from Smith-Sandwell.

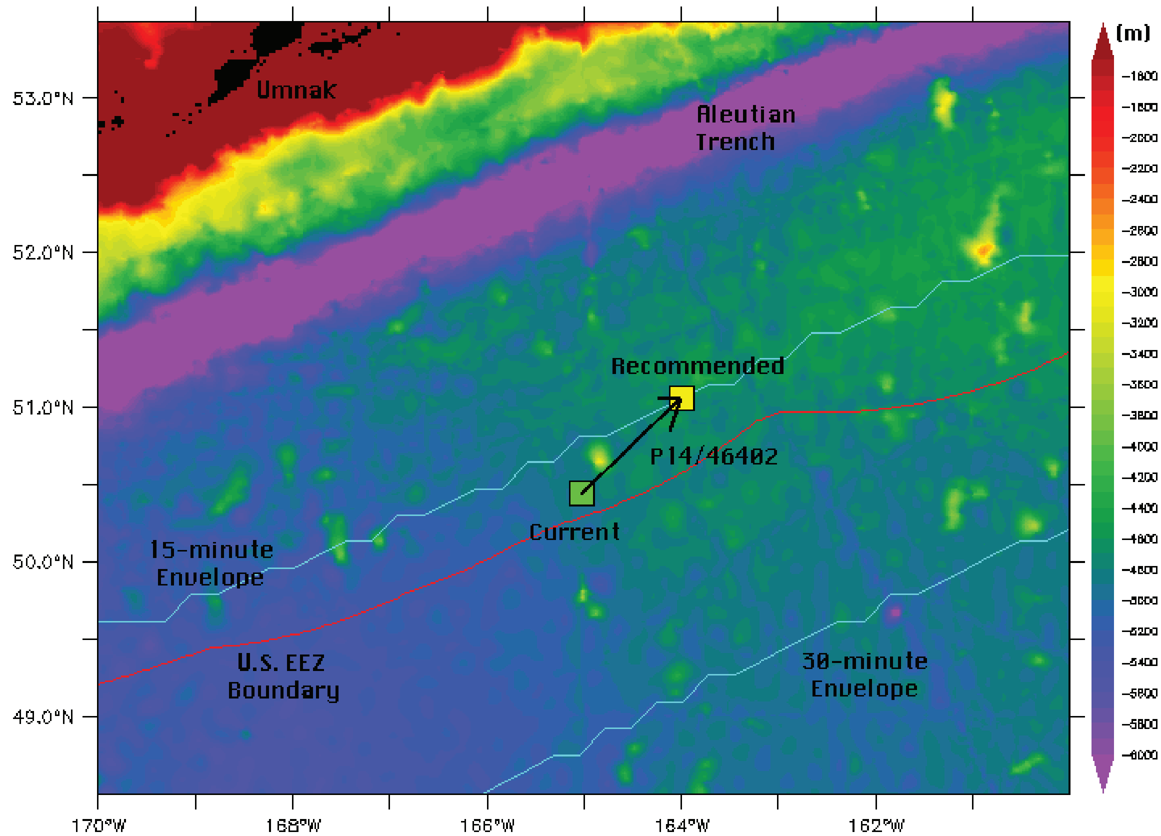

Figure E9: Potential future adjustment of the P14/46402 DART® with bathymetry from Smith-Sandwell.

P14/46402. The current cruise does not entail servicing this DART® location. The current position is generally quite suitable and only slightly removed from the alternate location, which was picked to achieve 6° spacing. There may be merit in maintaining the continuity of observations at the current P14/46402 site.

Appendix F. Central/South America DART® Location Assessment (Stations 6-1, 6-2, 6-3, 6-4, and relocated 51406)

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(Originally circulated on 29 December 2006)

Introduction

NDBC is working toward the completion of the DART® array in the Pacific during 2007. This report recommends locations suitable for DART® siting in the eastern Pacific, between the now complete U.S. West Coast array and the existing Chilean tsunameter 32401. The sites discussed include the four designated as Group 6 in previous planning documents, and a relocation of the existing DART® 51406 from its current position near 8.5°S, 125°W. Site recommendations for DART®s in the northwest Pacific and southwest Pacific will be provided in separate reports.

The "Equatorial" DART® 51406 (previously named 46406) was intended to warn Hawaii of events either in the Chile or the Tonga region. The Southwest Pacific DART®s of Group 9, to be sited north and east of Tonga, will greatly improve the coverage of events in that area, allowing 51406 to be better employed in the eastern Pacific where it essentially becomes an extra element of Group 6.

Analysis

Site recommendations are based on the following considerations:

- Water depth and sea floor slope and roughness: Instruments must be deployed in water depths of 1,500–6,000 m and the seafloor unit must be level to communicate with the surface satellite link.

- Proximity to tsunami sources: Early warning cancelation or accurate forecasts of expected impacts require each DART® to lie close to the source region it is intended to monitor. The finite number of DART® systems available, the extent of potential source regions, and the need to provide backup in the event of instrument failure, limit this.

- Signal quality: In the open ocean tsunami amplitudes are quite small and their beam patterns complex. Scattering features such as seamounts between the source and DART® are to be avoided; extreme proximity to a potential source is to be avoided to prevent contamination of the true tsunami signal by seismic seafloor shaking. High-quality time series from one or more DART®s are needed to accurately forecast impacts.

- Deployment/servicing efficiencies: To facilitate routine servicing or repair in the event of failure, DART®s should, where possible, be placed within U.S. or International waters. Coordination with the cruise plans of other U.S. research programs or NDBC's other buoy activities may lead to efficiencies. Areas with a history of vandalism should be avoided.

To quantify the above considerations, Smith-Sandwell seafloor bathymetry, the database of precomputed tsunami propagation solutions, a database of EEZ boundaries, and known buoy locations are employed in producing the following recommendations.

The recommended locations are given in Fig. F1 and Table F1. Shown as blue triangles are the closest DART®s to the north and south; blue squares and lines are the TAO array sites with typical servicing cruise tracks (dark blue for the *Ron Brown*, Chile-Panama via the WHOI Stratus buoy; light blue for the *Ka'imimoana*, San Diego–Manzanillo.)

Tsunami Source Distribution in the Region

Virtually the entire west coast of Central and South America is a potential source of tsunamis with several notable events in the historical record. The propagation database contains unit sources representing $M_w = 7.5$ events in 100 km segments from Manzanillo, Mexico to Cape Horn and provides useful information to aid in site planning for DART® instruments to monitor the region. Figure F2 shows, for each unit source, its potential risk for the Hawaiian Islands; squares at each unit source have areas proportional to the relative amplitude to be expected offshore from Hilo. Contour lines, for selected sources posing the greatest risk, show the extent to which the first wave from a unit source has a readily DART®-detectable 1-cm amplitude. These patterns have lobes, which illustrate the complexity of tsunami detectability and impact at remote locations.

An alternate presentation, in Fig. F3, contrasts timing and **offshore** amplitude at Hilo and San Diego. Note that the amplitude scales refer to offshore conditions and that SIM results are needed to reflect conditions at the beach. While the amplitudes (indicated by bar length) at the two locations are not directly comparable, first wave arrival times are; arrival times at San Diego for Central American sources are considerably earlier so that DART® placement needs to be closer to those sources than those further south to enable early warning cancelation and forecasts for the west coast.

Table F1: Locations recommended for Group-6 DART® deployment and 51406 relocation.

DART®	Latitude	Longitude	Water Depth	Comments
6-1	16.033°N	107.000°W	3468 m	Rugged bathymetry; avoid seamounts
6-2	4.924°N	90.685°W	3216 m	Close but outside Peru/Ecuador EEZ
6-3	10.840°N	100.085°W	3304 m	Near TAO 95°W–110°W transit track
6-4	17.980°S	86.350°W	4359 m	Relatively smooth bathymetry
51406	7.000°S	93.943°W	4013 m	Plan in relation to TAO schedule

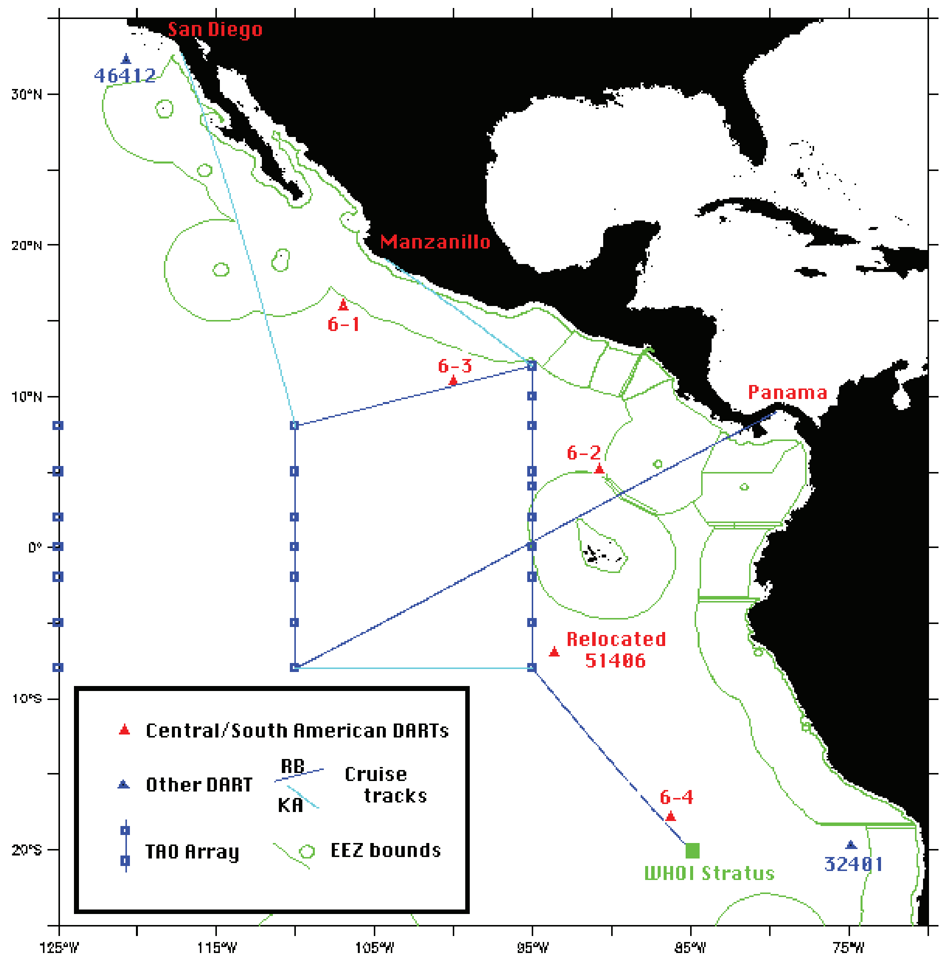

Figure F1: Recommended locations for the four Group-6 DART®s and the relocated 51406.

Summary and Recommendations

The suggested layout and locations of the Central and South American DART®s were given in Fig. F1 and Table F1 above. Further detail and site-specific graphics are provided below.

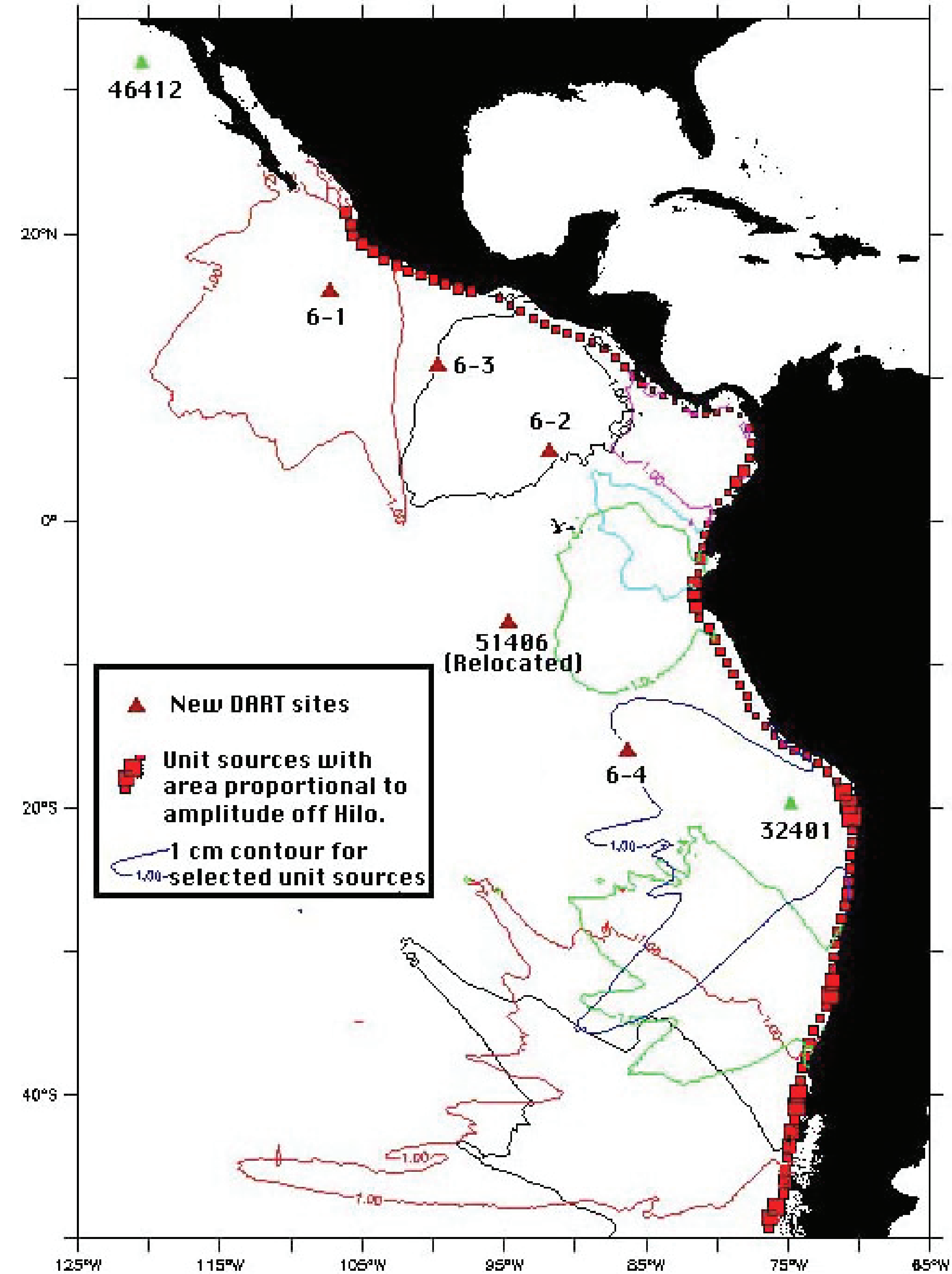

Figure F2: Relative impact offshore at Hilo for East Pacific Sources.

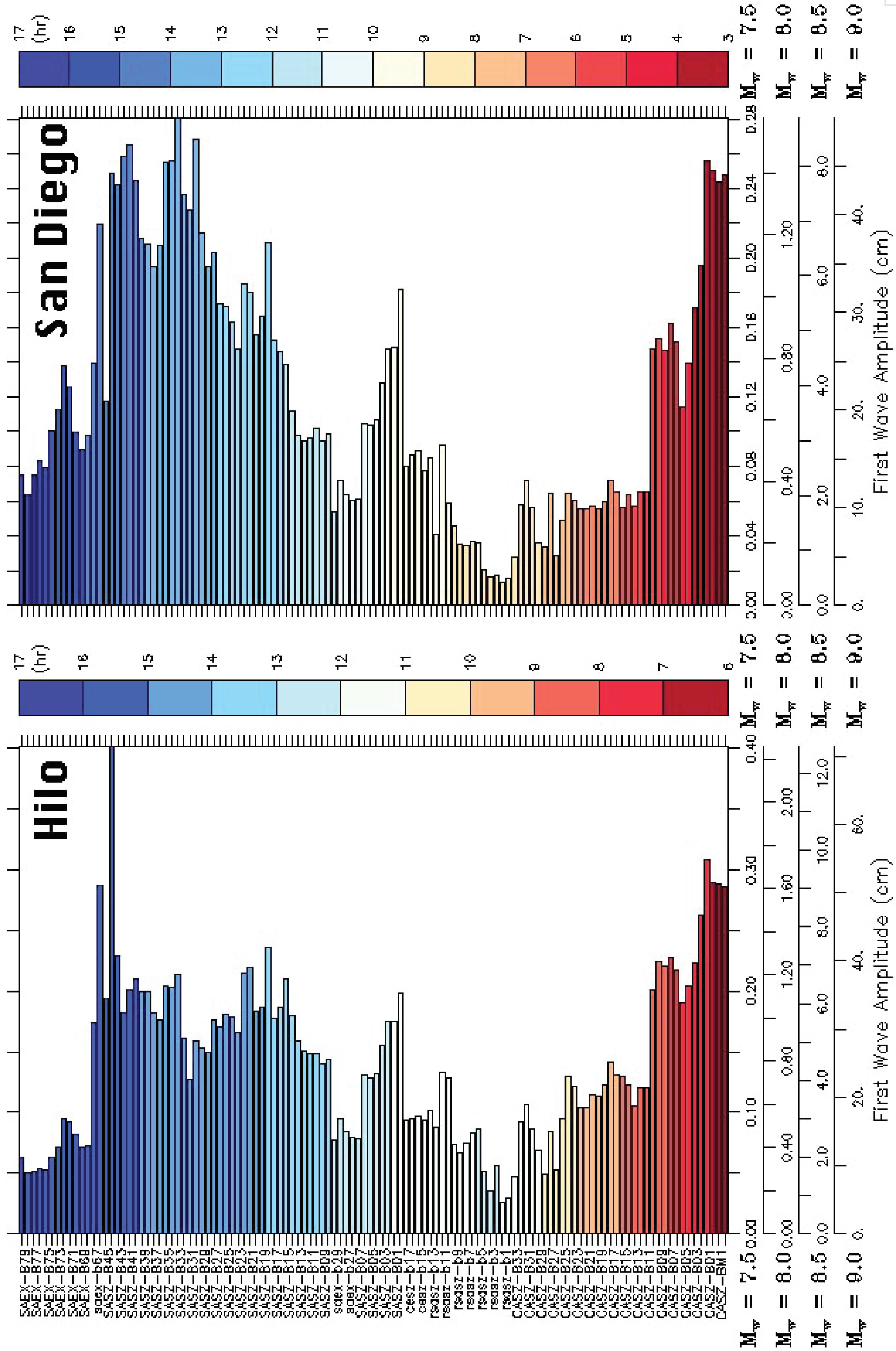

Figure F3: Offshore amplitude (indicated by bar length) and arrival time (color coded.)

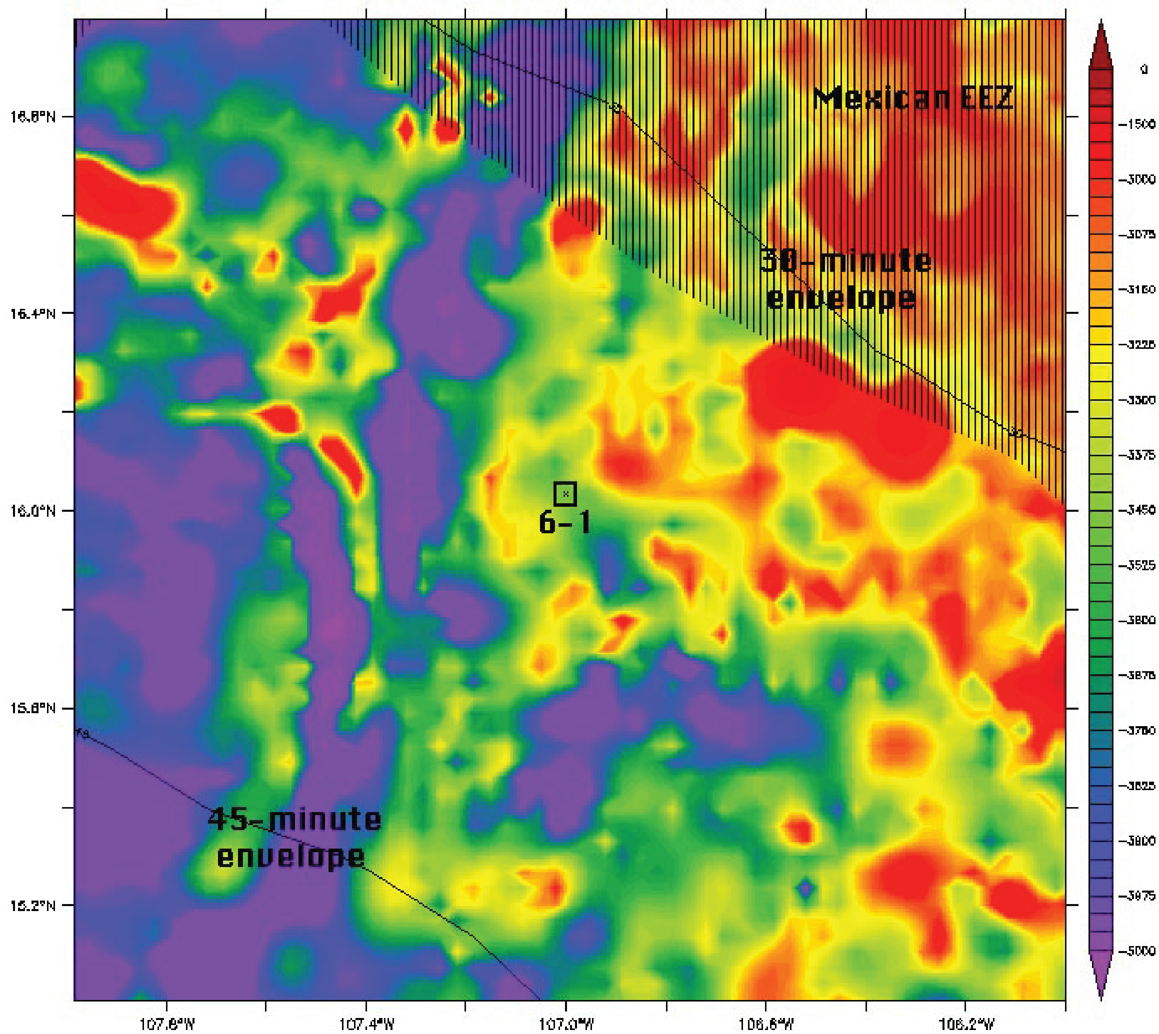

Figure F4: Recommended location for DART® 6-1.

Site 6-1. Figure F4 shows the recommended location for DART® 6-1. The site is in International waters with a travel time of about 36 min from the nearest source. The bathymetry is quite rugged in the area though only a few features rise close enough to the surface to scatter tsunami waves. Tsunami waves from the sources that this site is intended to monitor could reach San Diego within 3 hours, and the resort areas of western Mexico even earlier. Were the array to be augmented in the future, sites within the Mexican EEZ should be considered.

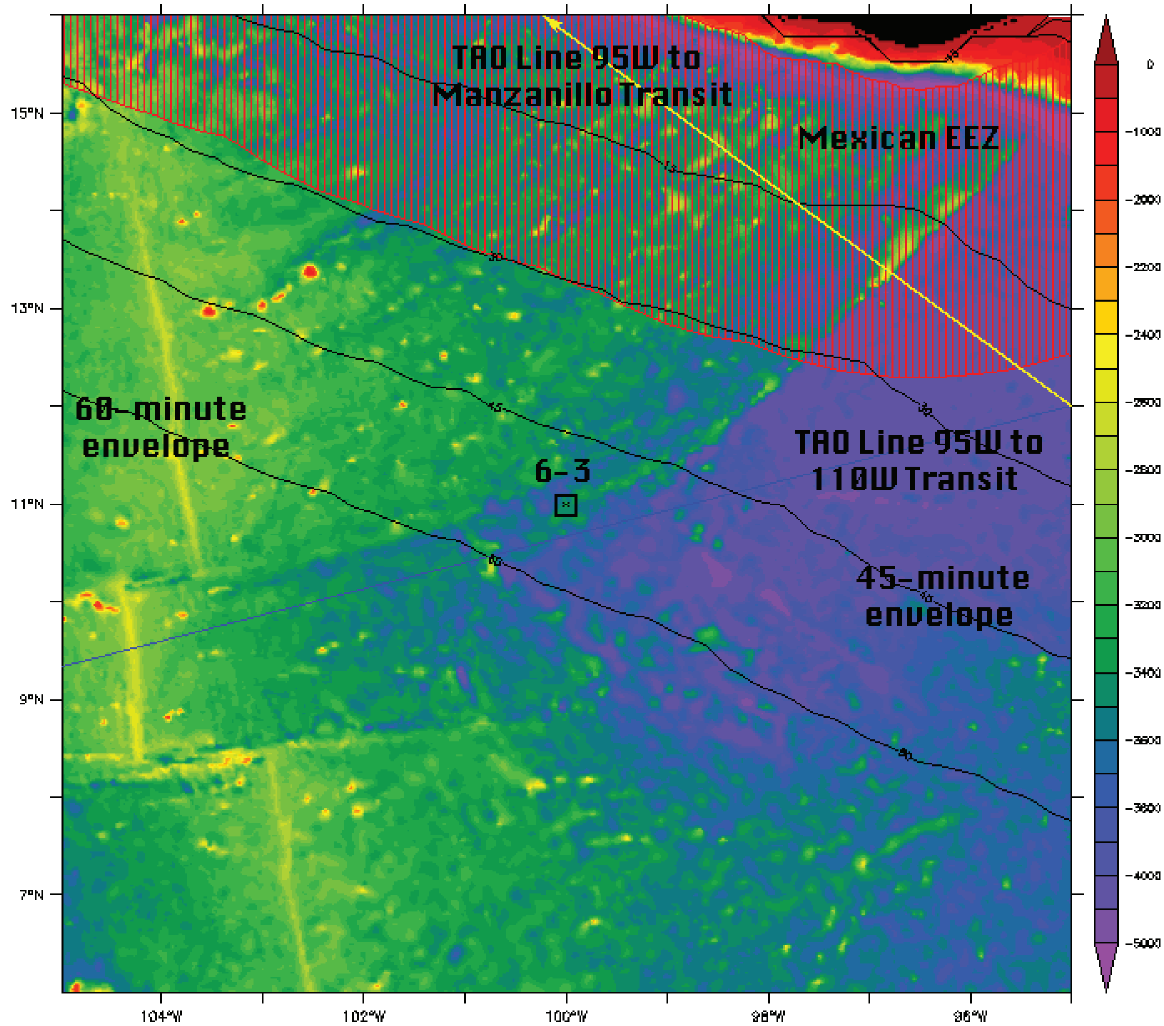

Figure F5: Recommended location for DART® 6-3.

Site 6-3. The next DART® to the south of 6-1 has been designated 6-3 in planning to date. The bathymetry in its vicinity, shown in Fig. F5, is quite smooth and free of seamounts so that there is some flexibility to choose the site in relation to the TAO servicing ship tracks. When the TAO servicing of lines 95°W and 110°W is done on a cruise from Chile to Panama, the transit between lines is east to west at the north (the blue line). Visiting DART® 6-3 involves no added steaming; its location is about 300 nm west of the 12°N, 95°W buoy. The other mode of servicing is on a Manzanillo to San Diego cruise where the transit between 95°W and 110°W is done at 8°S. In this case a departure from the cruise track from Manzanillo (shown in yellow) would be required, adding about 170 nm (25%) to that leg. Site 6-3 is approximately 53 min from the closest unit source.

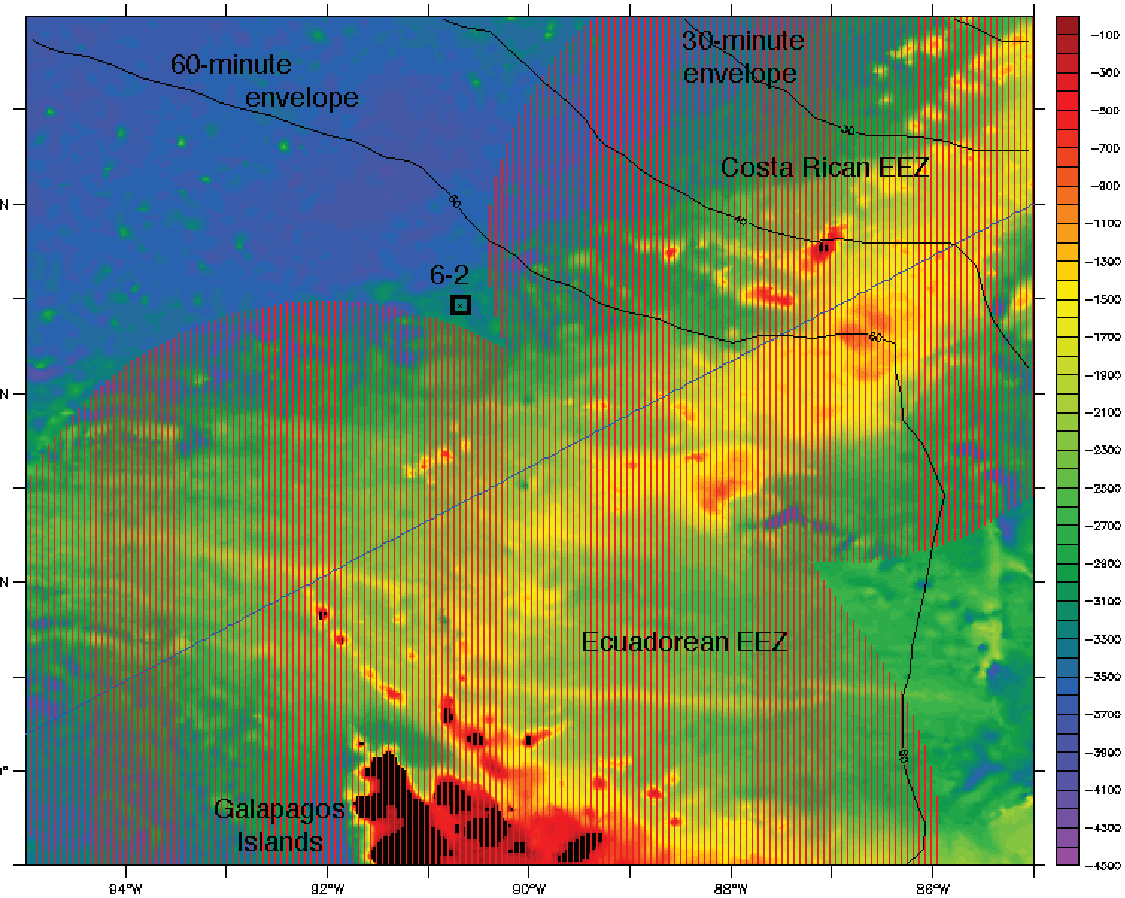

Figure F6: Recommended location for DART® 6-2.

Site 6-2. Proceeding south, the next DART® site of Group-6 is 6-2, which serves the dual role of monitoring sources in Central America and those off Colombia, Ecuador, and northern Peru. The recommended site (see Fig. F6) is in International waters close to the EEZ boundaries of Ecuador and Costa Rica, about one degree east of the "placeholder" site (5°N, 92°W). This position reduces somewhat the travel time (68 min) to the closest sources, gives a clearer view to the southeast, and places it closer to the *Ron Brown*'s route from TAO buoy 8°S, 110°W to Panama. A position closer to the 5°N, 95°W TAO buoy would place 6-2 more in the lee of the Galapagos Islands, resulting in more complex time series for likely tsunami sources.

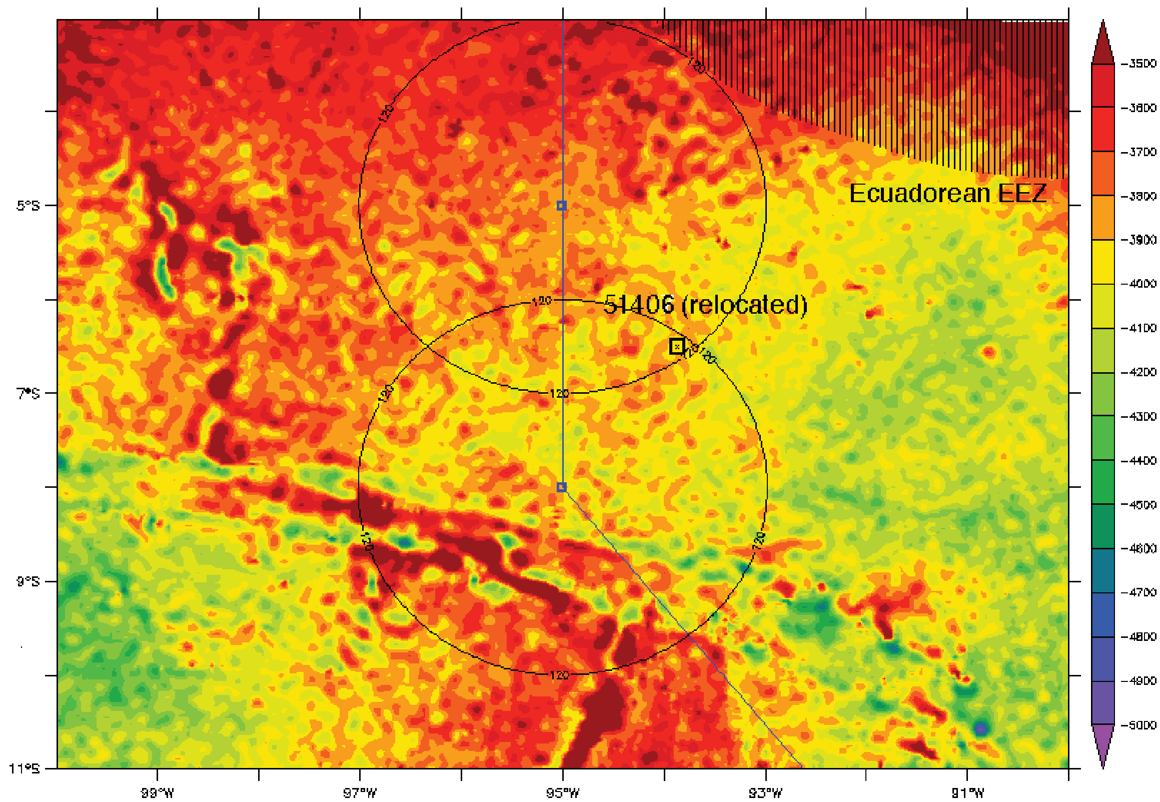

Figure F7: Recommended relocation of DART® 51406.

Relocated 51406. As noted earlier, the Group-9 DART®s will detect tsunami waves from the Tonga or southern Chilean sources covered by the current 51406 location (8.5°S, 125°W). By moving it eastward, 51406 could improve the coverage of South American sources that historically have impacted U.S. interests. A likely location SSE of the Galapagos Islands is detailed in Fig. F7. In the absence of strong scattering features, the suggested site was chosen approximately 120 nm from the TAO buoys at 8°S, 95°W and 5°S, 95°W to facilitate overnight steaming between site visits during servicing cruises of either the *Ron Brown* or the *Ka'imimoana*.

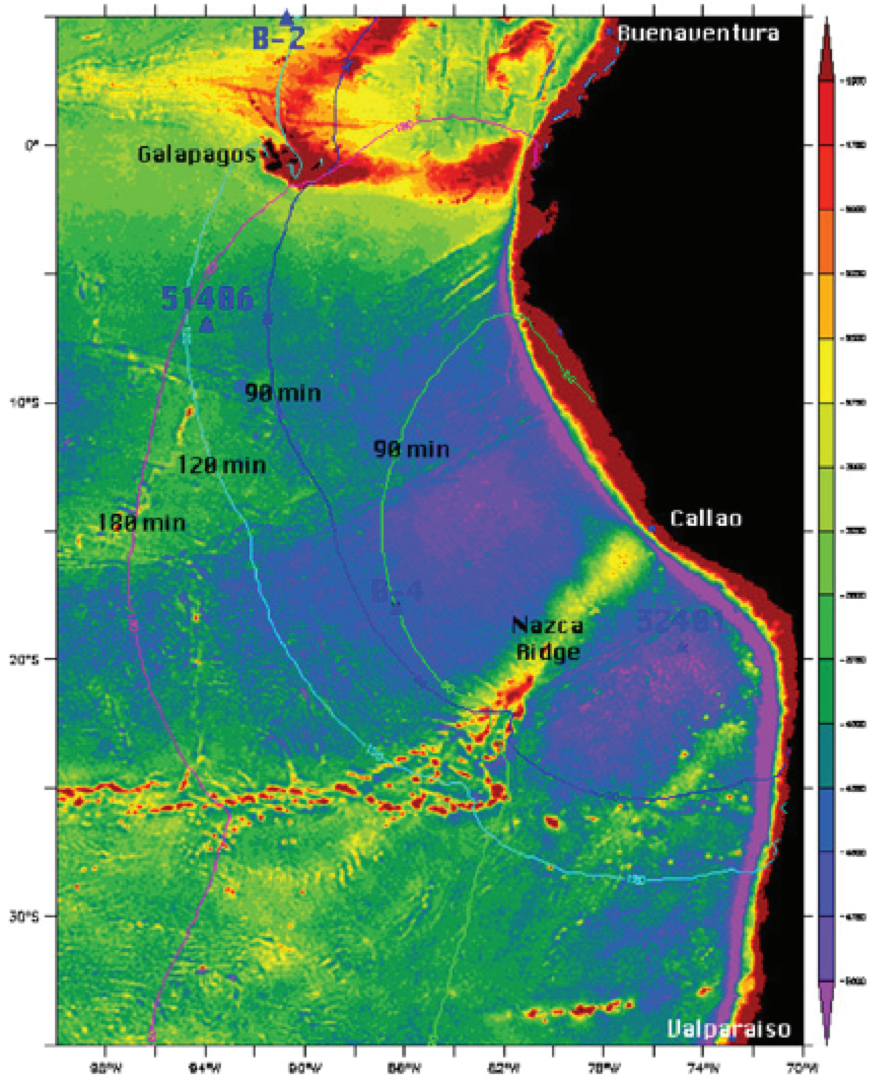

Figure F8: Suggested location for DART® B-4.

Site B-4. The southernmost site of the Central/South American group of U.S. DART®s is designated B-4. Its location, well removed from any EEZ boundaries and in a region of relatively smooth sea floor, is less constrained than most of the other sites. The suggested location was chosen to be close to the servicing cruise track from the WHOI Stratus buoy to the southernmost TAO buoy in the 95°W line and on the 90-min minimum travel time envelope for sources south of Callao. It acts as a backup to 32401 and benefits from the presence of the Nazca Ridge, which appears to focus the energy from sources far to the south, thereby improving their detectability. It also provides backup coverage to the relocated 51406 for sources between Callao and Buenaventura. The bathymetry allows some flexibility in the precise location; the suggested location is some 140 nm northeast of the WHOI Stratus buoy.

Appendix G. Northwest Pacific DART® Location Assessment (Stations P1/21415, P18/21416, P3/21417, P19/21418)

Mick Spillane and Vasily Titov
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(Originally circulated on 19 June 2007)

Introduction

NDBC plans to complete the tsunami-warning array in the north Pacific with the deployment of four new DART® systems during July 2007. The positions, as recommended in this report, will extend the Aleutian line of DART® sites, which currently ends at 21414 near the dateline, and bridge the gap along Kamchatka, the Kuril Islands, and northern Japan to link with the western Pacific group of DART® sites whose northernmost member is 21413. The current Aleutian line has successfully detected some moderate tsunamis emanating from the Kuril region in November 2006 and January 2007. The signals received, however, were not in the main beam of these events; the additional sites to be instrumented will reduce the detection time and, by improving the spatial sampling of future events, improve the quality of the source characterization and forecasts derived from it.

Analysis

Site recommendations are based on the following considerations:

- Water depth and sea floor slope and roughness: Instruments must be deployed in water depths of 1,500–6,000 m and the seafloor unit must be level to communicate with the surface satellite link.
- Proximity to tsunami sources: Early warning cancellation or accurate forecasts of expected impacts require each DART® to lie close to the source region it is intended to monitor, and to provide backup in the event of instrument failure.
- Signal quality: In the open ocean tsunami amplitudes are quite small and their beam patterns complex. Scattering features such as seamounts between the source and DART® are to be avoided; extreme proximity to a potential source is to be avoided to prevent contamination of the true tsunami signal by seismic seafloor shaking. High-quality time series from one or more DART®s are needed to accurately forecast impacts.

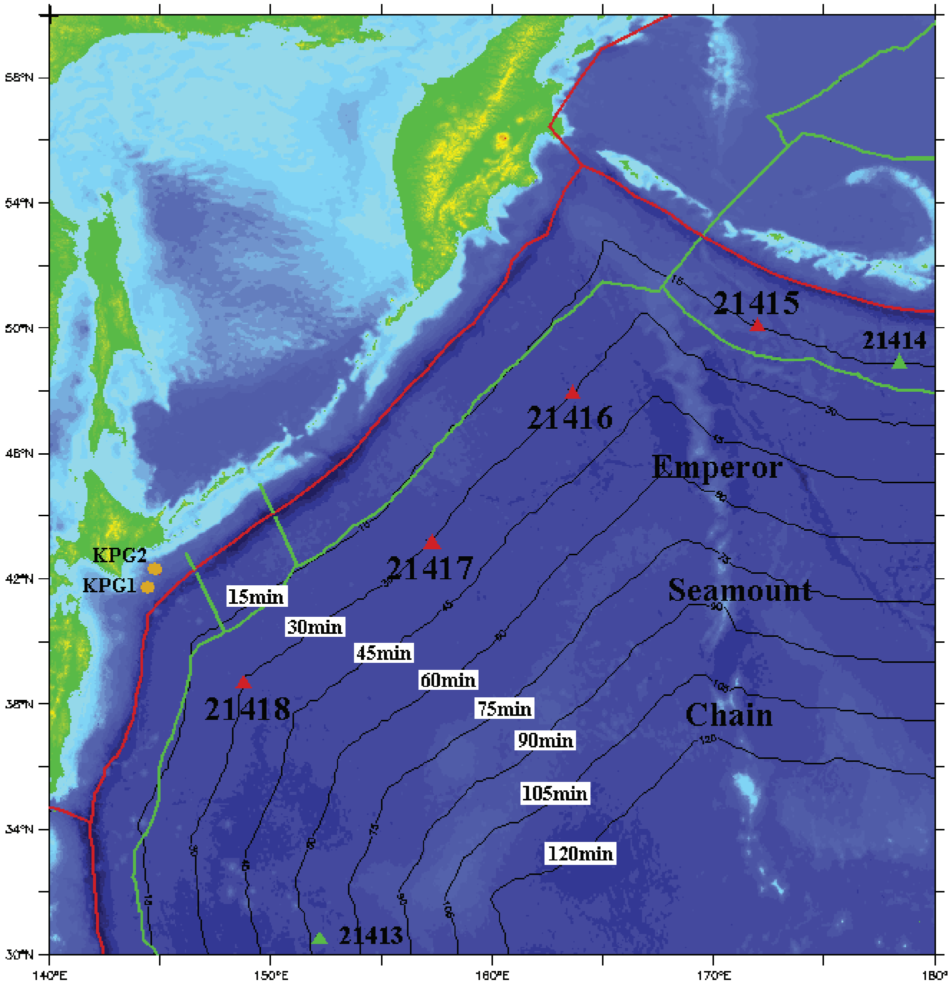

Figure G1: The recommended sites for the Northwest Pacific are shown as red triangles, with the closest existing DART® sites to the south (21413) and east (21414) marked in green. Green lines indicate EEZ boundaries, red the plate boundaries. Minimum travel time envelopes for the first wave are drawn at 15-min intervals and are based on the B row of unit sources in the propagation database for the northwest Pacific.

- Deployment/servicing efficiencies: To facilitate routine servicing or repair in the event of failure, DART®s should, where possible, be placed within U.S. or International waters.

To quantify the above considerations, Smith-Sandwell seafloor bathymetry, the database of pre-computed tsunami propagation solutions, a database of EEZ boundaries, and existing DART® locations are considered. The recommendations are summarized in Fig. G1 and Table G1 below, and supported by the text and graphics that follow.

Analysis

P1/21415. This site will be the westernmost element of the DART® array in U.S. waters, south of the Near Islands. It was described in and accepted

Table G1: Characteristics and comments for the four recommended northwest Pacific DART® sites.

DART®	Latitude	Longitude	Water Depth	Comments
P1/21415	50.175°N	171.850°E	4681 m	Extend Aleutian Trench coverage
P18/21416	48.011°N	163.503°E	5858 m	Assist 21415; Kamchatka-Kuril cover
P3/21417	43.188°N	157.125°E	5510 m	Kamchatka-Kuril cover
P19/21418	38.710°N	148.670°E	5712 m	Kamchatka-Kuril cover; assist 21413

following an earlier report (Mofjeld *et al.*, 2006), but some of the content is repeated here for convenience, and illustrated in Fig. G2. The site maintains the nominal 6° spacing of its neighbors to the east and lies, as they do, along the 15-min minimum travel time envelope for the closest sources. The latter choice, in the case of 21415, is dictated less by the need to minimize the warning time for Hawaii than to avoid the more serious wave scattering features of the Emperor Seamount Chain. Mofjeld *et al.* (2001) have shown that the potential for scattering by submarine features increases as the summit approaches the surface; the threshold for major scattering in the water depths of the NW Pacific is about 1500 m. The Detroit Seamount (∼1500 m, some 340 km to the WNW of 21415) and the Meiji Guyot off Kamchatka (∼3000 m, visible in Fig. G1) should not cause major scattering. However, younger members of the chain: Suiko (45°N), Nintoku (41°N), Koko (36°N), and Kimmei (34°N), could induce substantial scattering that increases the uncertainty in modeled tsunami signals. The intent is then that 21415 monitor potential local tsunami sources in the Aleutian subduction zone as well as those to the west in the corner region where that subduction zone joins those off Kamchatka and the Kuril Islands. DART® 21415 can provide backup and a second look at events in the Kuril region but, for these, the primary detection will come from the remaining three sites that are not in the lee of the seamount chain.

P18/21416 to P19/21418. The role of 21416 (and its neighbors to the south: 21417 and 21418) is to cover the active tsunamigenic region off Kamchatka, the Kuril Islands, and northern Japan. DART® 21413, the northernmost of the western Pacific DART® sub-array, provides further coverage for events off Japan, as do Japanese pressure gages and seabed seismometers connected to shore via cable in an alternate methodology for tsunami detection (see KPG1 and KPG2 in Fig. G1). The bathymetry is relatively smooth in this region, allowing considerable flexibility in the choice of sites. Those chosen are essentially evenly spaced along the 30-min minimum travel-time envelope for local potential sources in the interests of permitting early warning cancellation for the relatively frequent events that originate in the Kuril region.

The bathymetry in the vicinity of the recommended sites is shown in Figs. G3–5. In the case of 21416, the strong bathymetry of the Emperor Seamount Chain, evident in the upper right of Fig. G3, but extending south

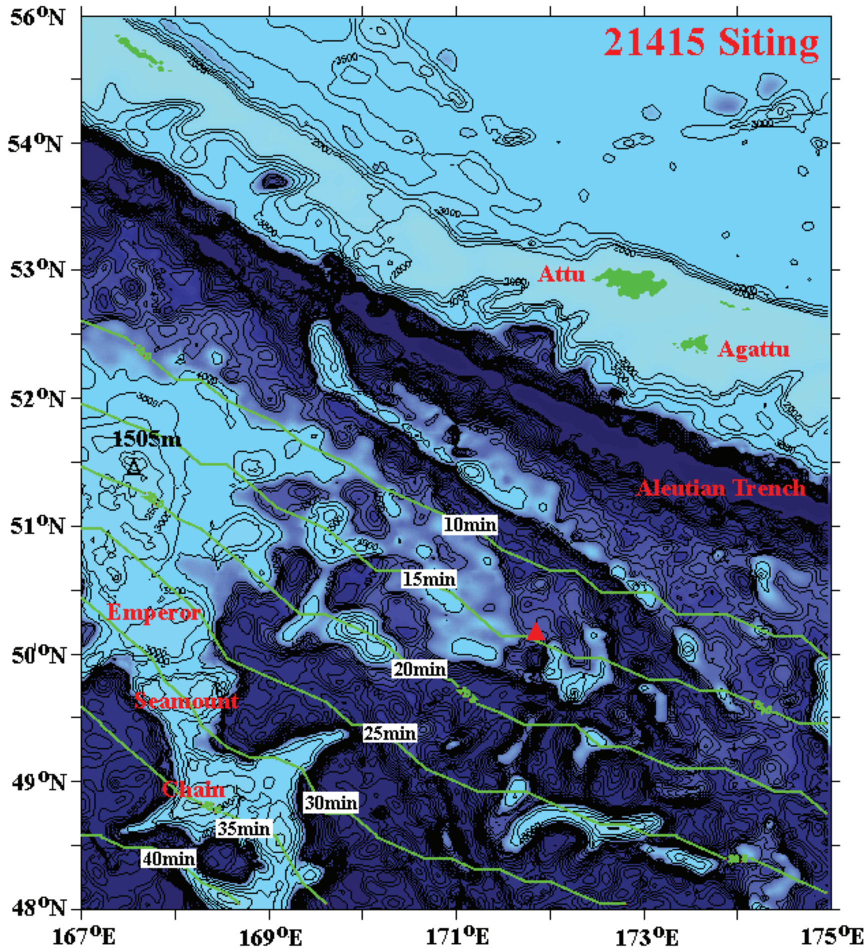

Figure G2: Topography and minimum travel-time envelopes near the recommended 21415 site.

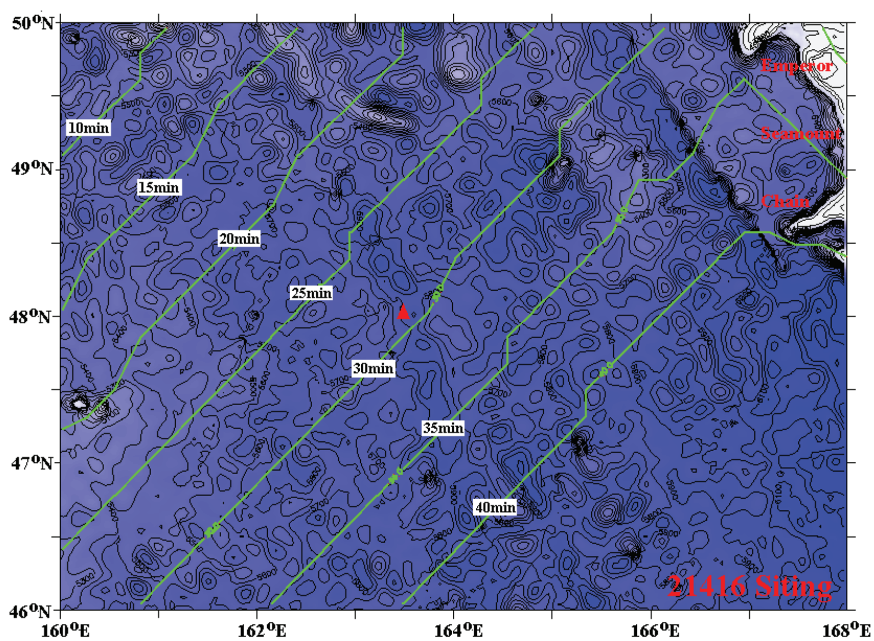

Figure G3: Recommended site for DART® 21416 which, together with 21417 and 21418, provide an essentially uninterrupted view of the Kamchatka, Kuril, and north Japan subduction zone sources.

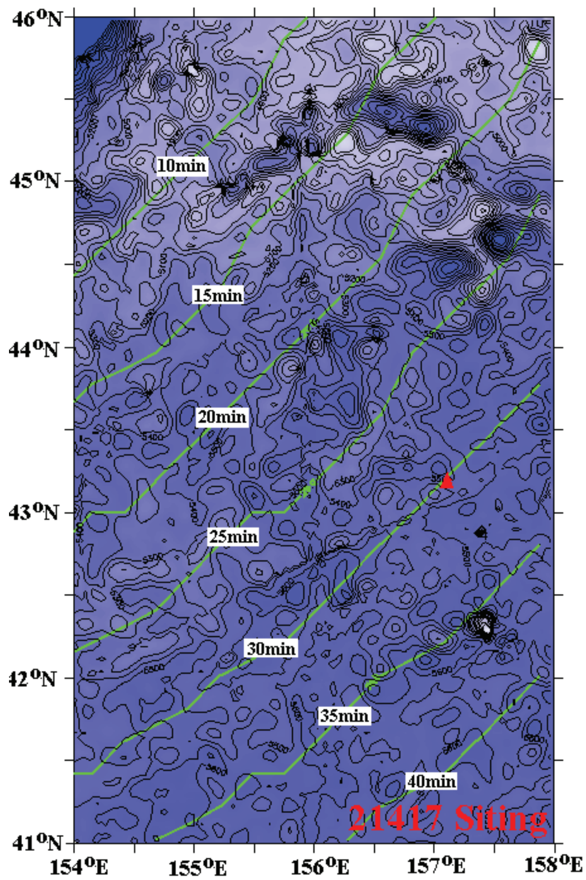

Figure G4: Recommended site for DART® 21417.

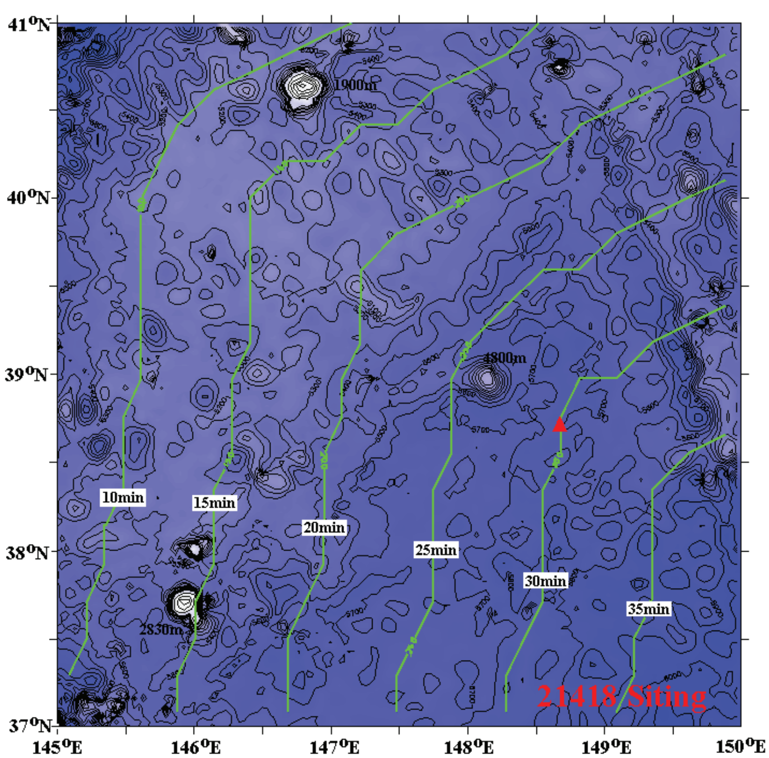

Figure G5: Recommended site for DART® 21418. Three topographic features have been labeled, but none rise sufficiently close to the surface to induce major scattering of tsunami waves.

to near Midway then east to the Hawaiian Islands, is “downstream” of the Kamchatka-Kuril-Japan sources this DART® and its neighbors to the south are intended to monitor. In the case of 21418, three topographic features have been labeled, none of which should cause significant scattering. All three DART®s are located on the 30-min minimum travel-time envelope. There is a possibility that seismic noise may overlap the actual tsunami signal and need to be removed during data processing, particularly in the case of the DART® closest to the source, but the relatively frequent occurrence of medium-sized events in this region suggests a need for early detection and, hopefully, early warning cancelation.

References

Mofjeld, H.O., V.V Titov, F.I. González, and J.C. Newman (2001): Tsunami scattering provinces in the Pacific Ocean. *Geophys. Res. Lett., 28*(2), 335–337.

Mofjeld, H.O., M. Spillane, and V.V. Titov (2006): Aleutian/Alaska/West Coast DART® Location Assessment (Stations 4-a, 46401, 1-2, 1-1, 5-3, and 46405) (Appendix E of this report).

Note added in the production of this report:

Following deployment at the recommended location, DART® 21417 has apparently been involved in two collisions with vessels. As described in Section 7.4, sea lanes and fishing activity ought to be a greater consideration in site selection.

Appendix H. The U.S. DART® Array: Recommendations for the Remaining Stages of the Initial Deployment

M.C. Spillane and V.V. Titov
NOAA Center for Tsunami Research
(Originally circulated on 5 November 2007)

Introduction

The initial deployment of the U.S. array of DART® tsunameters in the Pacific Ocean is nearing completion; only 5 of the 39 instruments allocated to the array remain. By and large the deployment has followed the arrangement shown in Fig. H1, which is an annotated version of an image produced in September 2005 to encompass the recommendations of the DART® Siting Workshop held that year. Instruments yet to be deployed are the Southwest Pacific group (designated 9-1 to 9-4) and one DART® (6-4) of the Central/South American group. The allocation of DART® buoys in the Pacific was predicated on the expectation of further Chilean tsunameters south of that designated 24 in Fig. H1. To add coverage of this historically active region, there has been some discussion of relocating the long-deployed "Equatorial" DART®.

Two further additions to the original figure reflect the actions of Australia:

- a DART® has been deployed in the Tasman Sea in recognition of the threat posed to Tasmania and the southeastern mainland of Australia by a subduction zone to the south of New Zealand.
- another DART® in the Coral Sea is believed to be planned to provide warning to northeastern Australia.

While the first of these has little bearing on the U.S. array, the second duplicates much of the role intended for the DART® designated 9-1 in the figure. This issue is discussed below and leads to a suggestion that this instrument might be more effectively employed off South America.

Discussion

As in previous reports the task of DART® site selection is to find locations that satisfy instrument constraints:

- depths in the range 1500–6000 m to seafloor-to-surface acoustic communication,

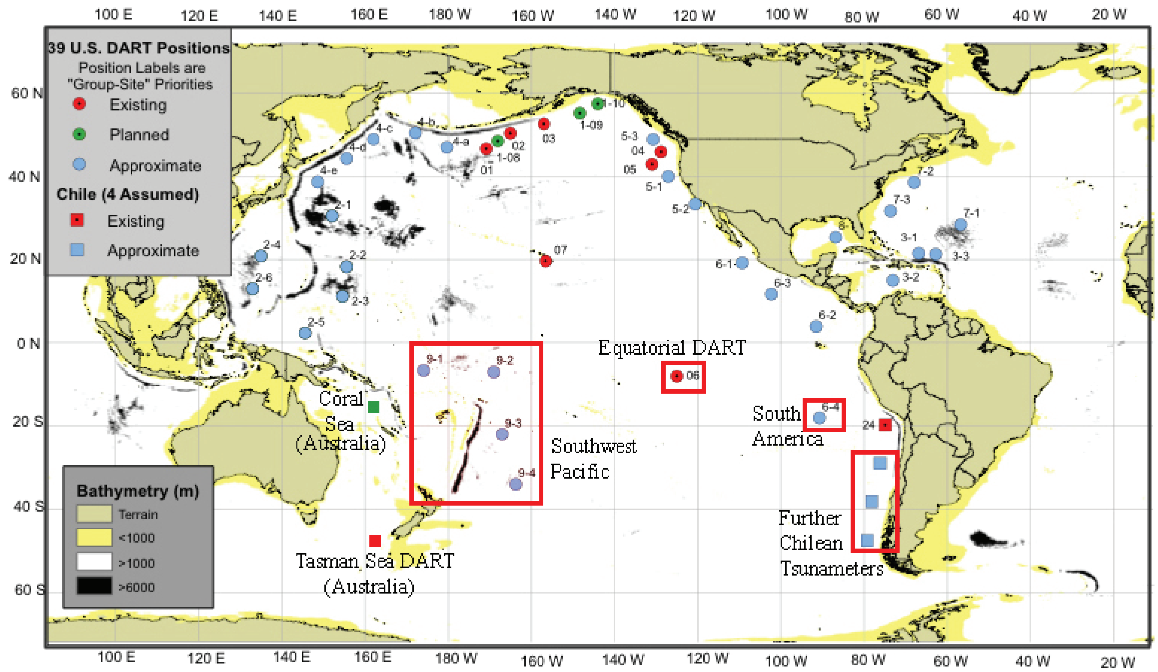

Figure H1: Finalizing the initial deployment of the U.S. DART® Array.

- relatively smooth and level local bathymetry both for the bottom unit and for the anchoring of the surface unit,
- absence of strong topographic features between the DART® and the tsunami sources it is intended to monitor, to avoid scattering,
- lie within international or U.S. EEZ waters to facilitate deployment and service cruise planning without lengthy advance notification requirements,
- avoid areas with seafloor infrastructure, strong currents, intense fishing activity, or a history of vandalism.

In addition a suitable location should be:

- far enough from likely sources to reduce the contamination of the tsunami signal with seismic noise,
- close enough to provide adequate warning time to threatened shores,
- in a location that, in cooperation with other array elements, provides comprehensive coverage and perhaps some duplication/backup for likely tsunami sources.

Constraints in the first set can be addressed through bathymetric, EEZ, and marine navigation datasets. The second set is investigated using the NCTR propagation database which, outside the near-shore zone, allows the prediction of the timing and amplitude of tsunami wave trains from likely sources.

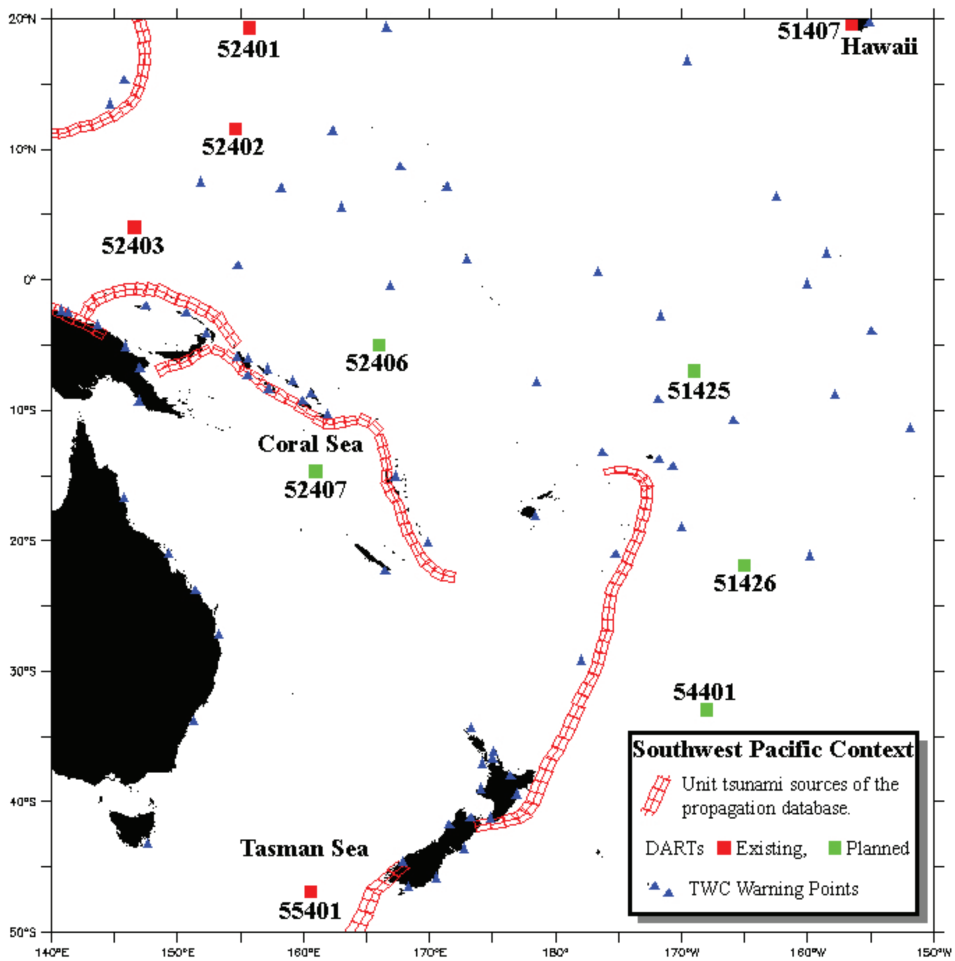

Figure H2: SW Pacific DART® array planning.

Southwestern Pacific—DART® 52406

In Fig. H1 four DART®s were shown to be allocated to this region, which is shown in greater detail in Fig. H2. The three DART®s to the east (51425, 51426, and 54401) are intended to cover the line of potential tsunami sources stretching from Tonga in the north, via the Kermadec region, and terminating at New Zealand's North Island. The remaining DART® (52406) of the group was intended to cover a further source line extending from New Guinea via the Solomon and New Hebrides Islands to Vanuatu. Figure H2 illustrates these sources, as represented in NCTR's propagation database, the island and mainland Warning Points considered by the TWC's, existing DART®s (red) and those subject to planning (green). Among the latter is the Coral Sea DART® 55012 (originally designated 52407), to be deployed by Australia in the vicinity of 14°20′S, 161°E.

A fact not recognized earlier in the planning was the extent to which the island chains between New Guinea and Vanuatu attenuate the passage of tsunami energy northward into the Pacific. In Fig. H3 the maximum tsunami amplitude, over the set of unit sources shown, is contoured. The

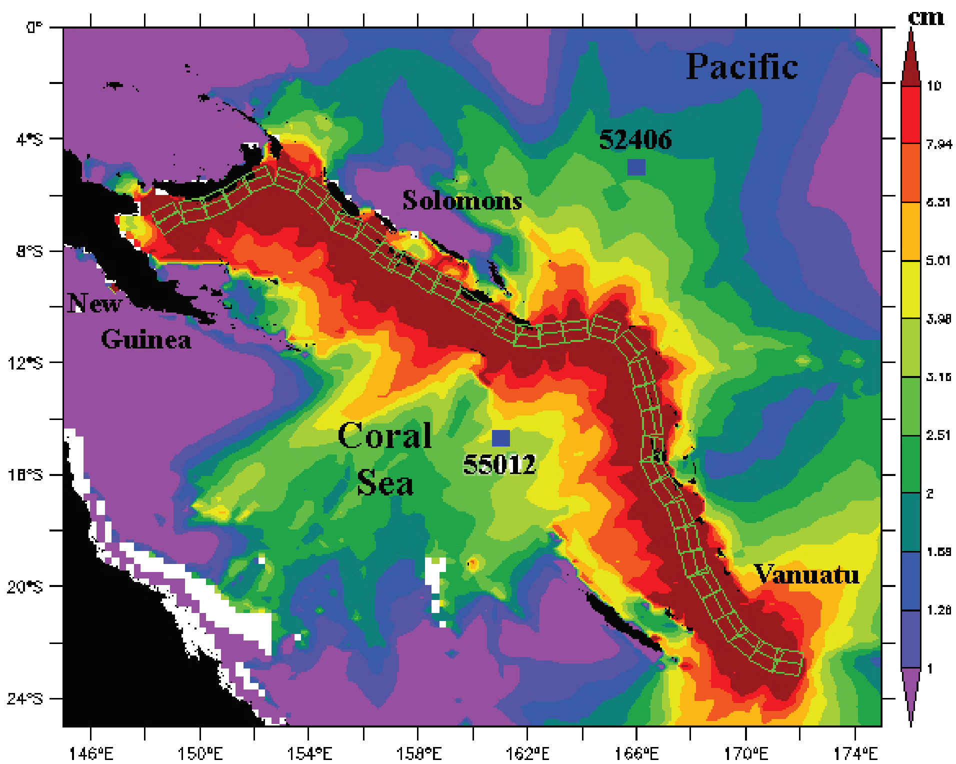

Figure H3: Maximum amplitude from any unit source (M_w = 7.5) of the set shown.

source line lies south and west of the islands and only through a few passages can significant energy penetrate into the Pacific. As a consequence, a Coral Sea DART® is far better at detecting waves emanating from the New Guinea to Vanuatu source subset. For a limited number of these sources 52406 would receive the first wave earlier than at 55012 but, except for major events, the amplitude may not be easily detectable. There are severe limits on the location of 52406 due to the merging EEZ territories (see Fig. H4) of the island nations of the region. However, even if this constraint were removed, it is not likely that a single DART® north of the islands could do more than provide a poor backup to a Coral Sea DART®. However, should it be decided to deploy 52406, the location indicated does lie in international waters in proximity to a TAO buoy (see below), and has reasonable bathymetry.

Note that neither 52406 nor 55012 is well positioned to monitor the ends of the source set shown in Fig. H3. However, while the New Guinea end poses mainly a local threat, those near Vanuatu could, in the case of a substantial event, direct energy toward Hawaii. In the discussion below, there is the possibility that DART® 51425 might be able to detect such energy with sufficient lead time to be of value to Hawaii.

Southwestern Pacific—DART®s 51425, 51426, and 54401

Of the eastern DART®s in the SW Pacific group, only 51425 is substantially constrained by EEZ considerations. In Fig. H4, the EEZ limits of American Samoa and other U.S. interests are shown in red; those of other nations are shown in blue. International waters are un-hatched and are preferred in order to facilitate deployment and service cruises. Buoys of the TAO array are drawn and there are logistical efficiencies in placing a DART® about 120 miles from a TAO buoy, thus allowing overnight steaming between sites. For DART®s 51426 and 54401 the transit to Tahiti, which lies to the east and is a likely staging area for cruises, is a consideration.

The 30- and 60-min minimum travel time envelopes are also drawn in Fig. H4. A location close to the 30-min envelope is generally a good choice where the DART® array is dense. In other circumstances a location closer to the 60-min envelope allows a DART® to cover a greater length of subduction zone. The initial choices for the three sites, indicated in Fig. H4, were based on such considerations, as well as bathymetry and tsunami beam geometry. Unlike 51425, likely sites for 51426 and 54401 lie in international waters permitting greater flexibility.

The original site suggested for 51425/9-2 in the area of international water north of American Samoa (Fig. H4) arose at a time when a closer location for 9-1/52406 in the sliver of international water closer to the dateline was envisioned. With 9-1 much further to the west, or dropped entirely, a site such as 9.5°S, 176°15′W deserves reconsideration. As seen in Fig. H5, such a site is in fact preferable. To the north of American Samoa a DART® would be in the lee of those islands and subject to greater attenuation and scattering than at 9.5°S, 176°15′W. In addition, the latter site is in the path of waves transiting from Vanuatu toward Hawaii. Vanuatu sources are those for which a Coral Sea DART® performs poorest and, while the amplitude and timing of waves from smaller events may not help much with early warning cancellation, the lead time of over 4.5 hours to Hawaii possible with detection at 9.5°S, 176°15′W is for larger events a valuable bonus. The bathymetry at this recommended location 51425 site is acceptable.

Returning to the sites east of the Tonga Trench, we require a pair of locations that monitor those sources whose beam patterns are directed primarily in the eastward direction. In Fig. H4, we see that between 22°S and 40°S and east of 174°W, the choice is only constrained by bathymetry and timing. By locating 51426 at 22.95°S, 168.1°W and 54401 at 33°S, 173°W then together with 51425 all of the sources in Fig. H5, with the exception of those adjacent to New Zealand's North Island, should be detected within 65 min. Waves generated at the southernmost sources have travel times to 54401 that are as much as 2 hours but, given their proximity to land, initial estimates of their threat will likely come from shore locations such as Gisborne or Napier.

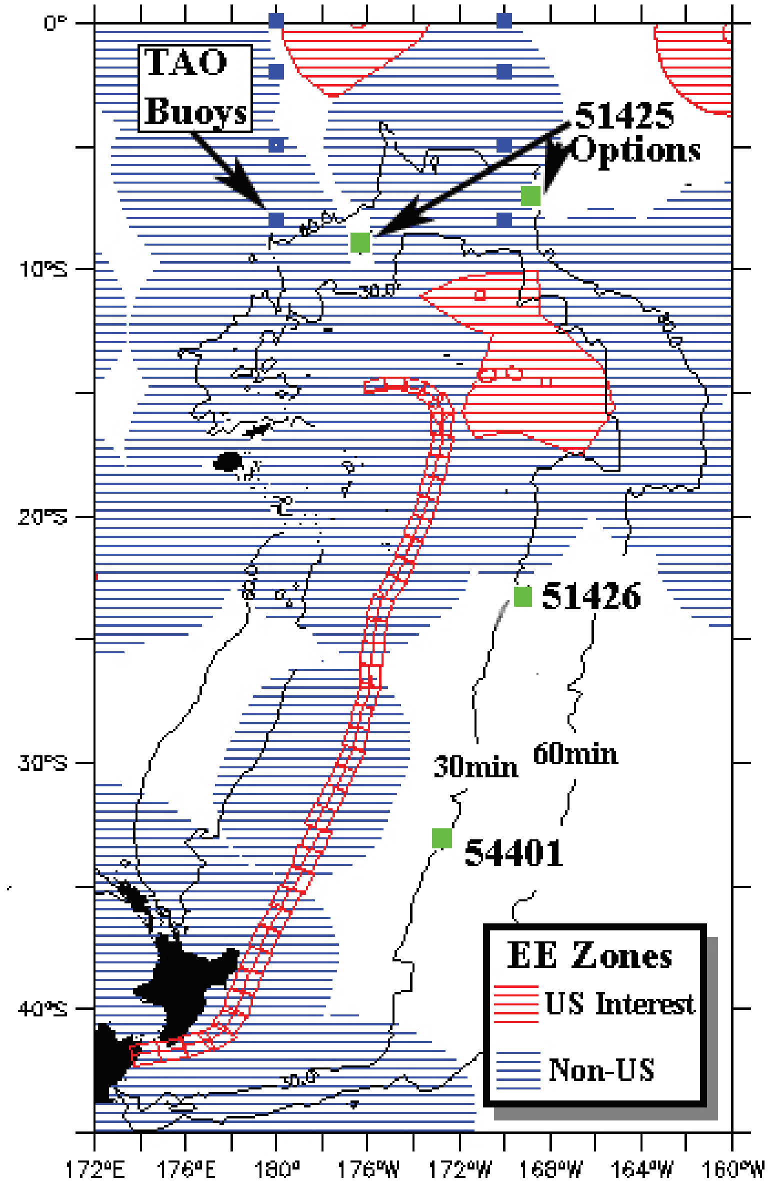

Figure H4: Some factors to consider in Southwest Pacific DART® siting.

Assessing the Array

Assuming that three U.S. DART®s are deployed in the Southwest Pacific, as described above, and that the Coral Sea DART® becomes a reality, it is instructive to view the overall effectiveness of the array to date. This is done in Fig. H6, where at each source location a color-coded symbol is drawn representing the earliest time at which it would be detected if all of the DART®s shown are operational. The undeployed South American DART® and the Equatorial DART® are excluded from the calculation since they, and potentially the fourth southwest Pacific DART®, are candidates for relocation.

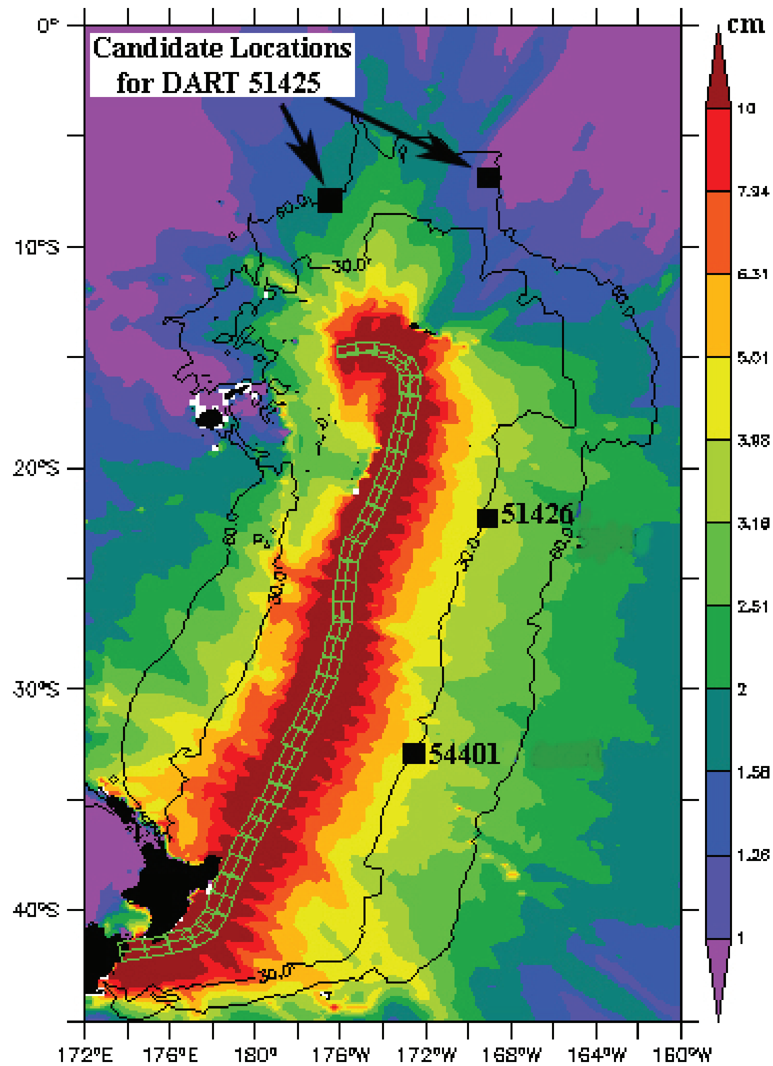

Figure H5: Moving 51425 toward the West.

The majority of sources, with the exception of those off Colombia-Ecuador and southern Chile, are detected within 2 hours. Excluding the South American deficiencies, where detection times (first wave arrival at the closest DART®) can be as high as 6 hours, the source regions with detection times of 2 hours or more lie off New Zealand's South Island, southern Japan, Vanuatu, and New Guinea's Bird's Head. For New Zealand and Japan these near-shore sources are likely to be detected by shore stations. The Vanuatu sources should be seen at 51425 while close to 5 hours remain before impact at Hawaii. Perhaps at greater risk, from late-detected Vanuatu sources, is the North Cape of New Zealand, to which sea floor structures may channel and focus energy. It would, however, likely take a dedicated tsunameter in the northern Tasman Sea to cover this threat.

Absent from the propagation database at this time is a comprehensive set of sources in the East Indies. There is a source line, not shown here, west of the Philippines and energy from the most northerly of these could leak into

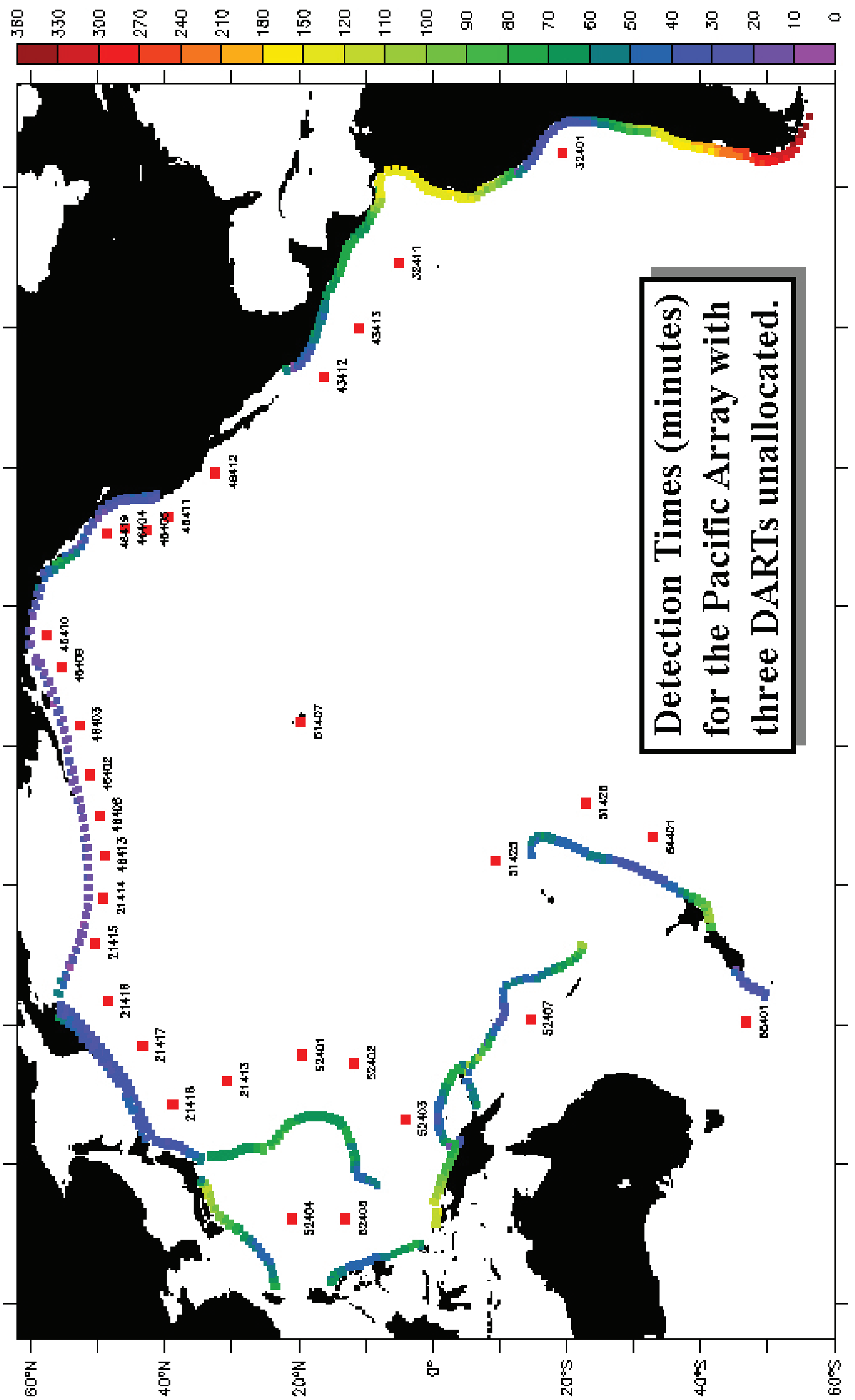

Figure H6: Detection times for the Pacific array with three DART®s unallocated.

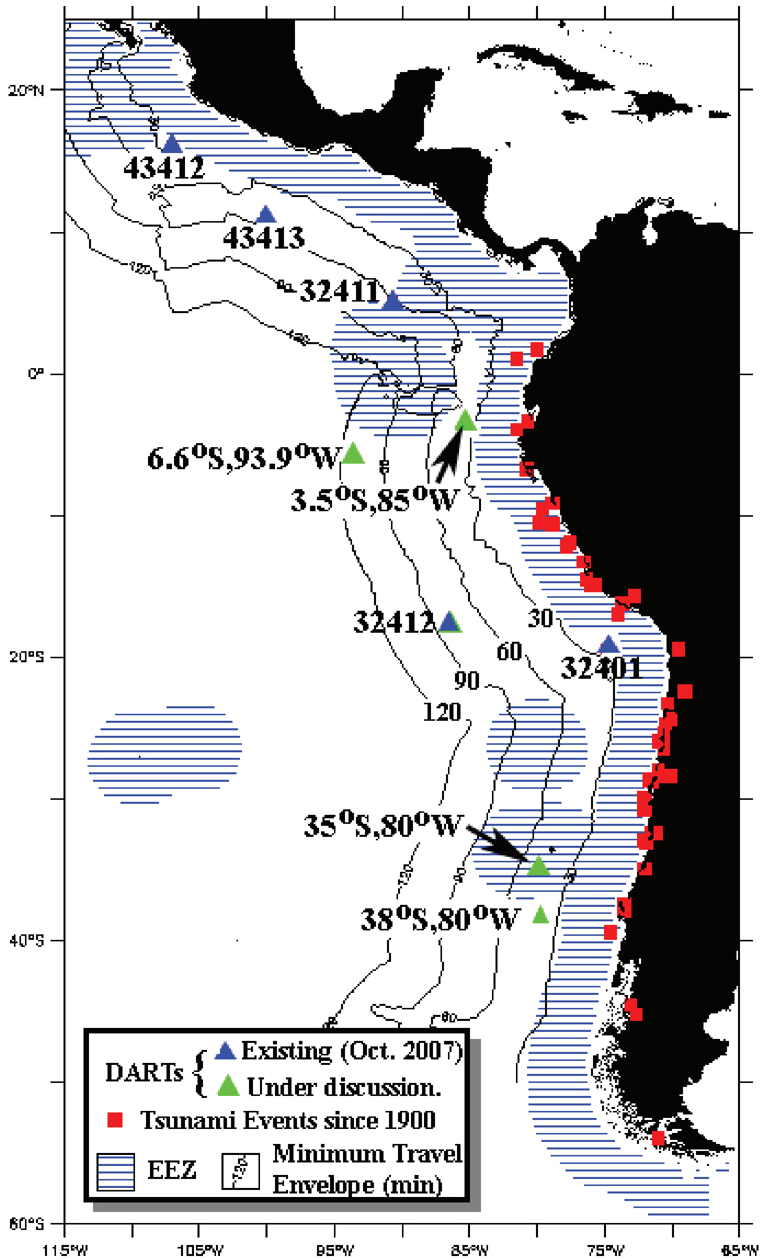

Figure H7: South American DART®s.

the Pacific south of Taiwan. A similar situation may exist for the northern Molucca Sea, though this region has not been modeled. There are, however, ongoing discussions with the Indonesians, who wish to place a DART®-ETD there. If these plans came to fruition, it is possible that earlier detection of Bird's Head and East Philippines events might be a by-product.

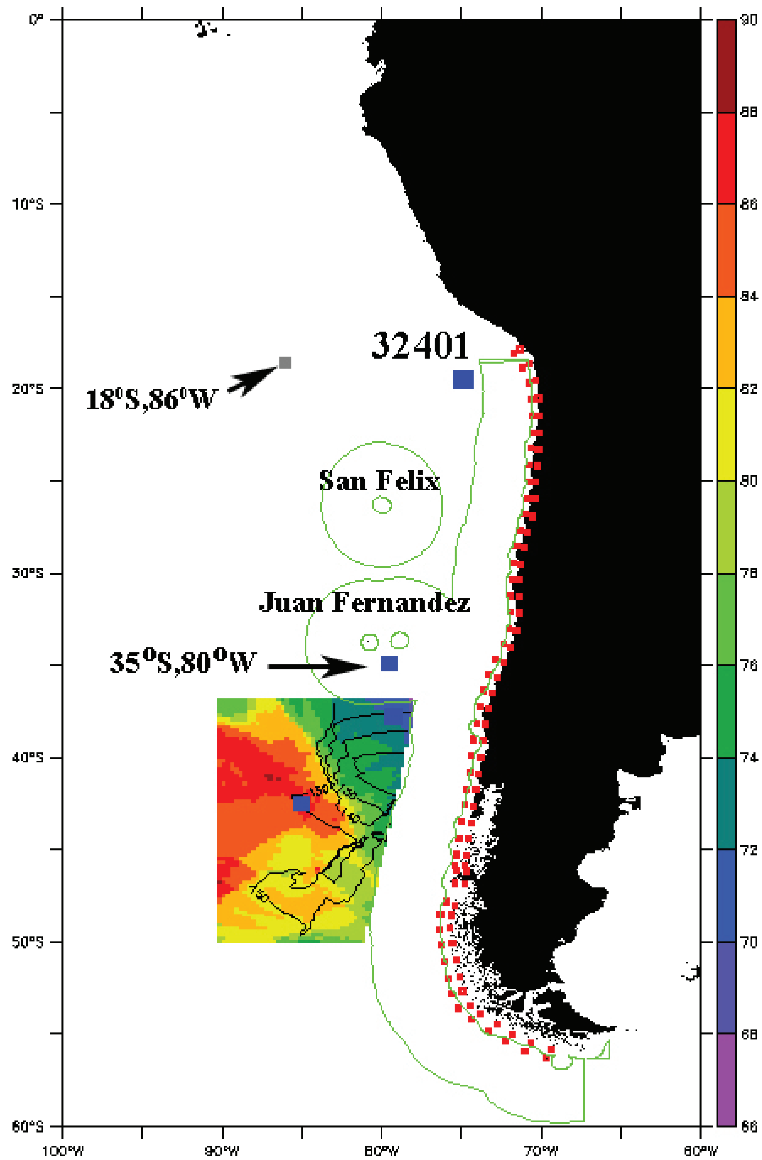

Figure H8: Siting considerations for a DART® off southern Chile.

Expanding the South American Array

Clearly South America, with its tsunamigenic history, is a region most deserving of extra instrumentation. Figure H7 illustrates the situation, with the existing DART®s, the previously proposed addition 32412, and two other sites (6.6°S, 93.9°W and 35°S, 80°W) that have arisen in earlier discussion. The EEZ boundaries are indicated together with South American events since 1900 for which tsunamis were reported.

The southern site falls within the EEZ region surrounding the Juan Fernandez Islands and will need to be nudged either south or north. The site at 6.6°S was mooted earlier as a potential place to relocate the Equatorial

DART®. Considerations of vandalism, and logistical efficiencies associated with the TAO line at 95°W, lead to a suggestion that, in light of the Peruvian event of August 2007, it is too far west. The recommended site for 32412 will also be re-examined in the discussion that follows.

Although the historic events indicated in Fig. H7 are concentrated mainly to the north of 35°S, the propagation database considers sources as far as 55°S.

Figure H8 was generated in an attempt to quantify the joint arrival time and amplitudes of the first wave peak from the 92 sources shown in red. A source is said to be "detected" by either 32401 or a location in the color-coded region southwest of Juan Fernandez if its amplitude exceeds 0.5 cm. Color contours indicate the number of sources detected as a function of DART® placement. The contour lines represent the worst-case detection time (in minutes). The results seem to indicate that a location near 42°S, 85°W might be a reasonable choice, but the seafloor in the vicinity is remarkably rugged, with multiple fracture zones. A compromise might be to locate the DART® somewhat to the north, perhaps near 38°S, 80°W, though this would leave several sources to the south inadequately detected.

Conclusion

In the Southwest Pacific the three sites north and east of Tonga are recommended. A site is also shown for the final DART® initially allocated to this region. However, in light of the discussion above based on the superior performance of a Coral Sea site in achieving the purpose of 9-1/52406, it is recommended that this fourth DART® be reallocated to South America.

Off South America there seems to be a consensus that the "Equatorial DART®," 51406, be moved once the southwestern DART®s are in place. If this is the only extra DART® available it should be placed off Central/Southern Chile near 38°S, 80°W. If an extra DART® from the southwest Pacific becomes available, a DART® near 3.5°S, 85°W would provide improved coverage of the Columbia-Ecuador-Northern Peru region.

Note added during the preparation of this report:

The issue of relocation of DART®s 42406 and 51406 is discussed further in Appendix I. DART® was in fact deployed, and the present plan is to relocate the Equatorial DART® to a site south of Juan Fernandez Island where it can improve coverage of Chilean sources.

Appendix I. Addendum To "The U.S. DART® Array: Recommendations for the Remaining Stages"

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(Originally circulated on 9 November 2007)

Discussion

During the DART-TWC Teleconference of 7 November 2007 the siting of the SW Pacific DART®s was discussed. While the desirability of reallocating one of these instruments to the eastern Pacific was agreed, the existence of a milestone to have the full array deployed in the current fiscal year and the upcoming deployment cruise to the south west Pacific in January 2007 pushed the decision toward the retention of the DART® previously designated 9-1. The group agreed with the siting recommendations for the remaining three instruments in the region in the Draft Report (see Appendix H).

In light of this decision a tentative site in the vicinity of 5°S, 166°E was agreed, with NCTR tasked to optimize a location in that vicinity. A factor influencing the siting decision is the deployment by the Australians of a tsunameter in the Coral Sea. Diana Greenslade, visiting NCTR from the Australian Bureau of Meteorology, confirmed that this will occur but at a slightly less optimal location than that initially selected. The new location, selected to lie within the Australian EEZ, was incorporated in the analysis that follows. It has essentially the same properties as the former site.

The salient features of the recommendation for the 9-1 site are summarized in Fig. I1. Color-coded is the bathymetry in the depth range (1500–6000 m) suited to the DART® system. The overlaid cross-hatching delineates the Exclusive Economic Zones of other nations; un-hatched regions are those best suited logistically to deployment and servicing. Unit sources from the NCTR propagation database are shown as red rectangles and the first wave amplitude and timing from these is a prime factor in site selection. The inset in the upper left contrasts the amplitude (red, in centimeters) expected for a DART® deployed at the optimum U.S. DART® site, north of the island chain, and the Australian Coral Sea site (blue). The (revised) Coral Sea site does far better at detecting sources near Vanuatu (C) and provides lower but quite uniform response to sources to the north and west (A). The U.S. DART® site, though less uniform in its response, does receive a better signal for sources in the north and west of the New Guinea-Vanuatu line that

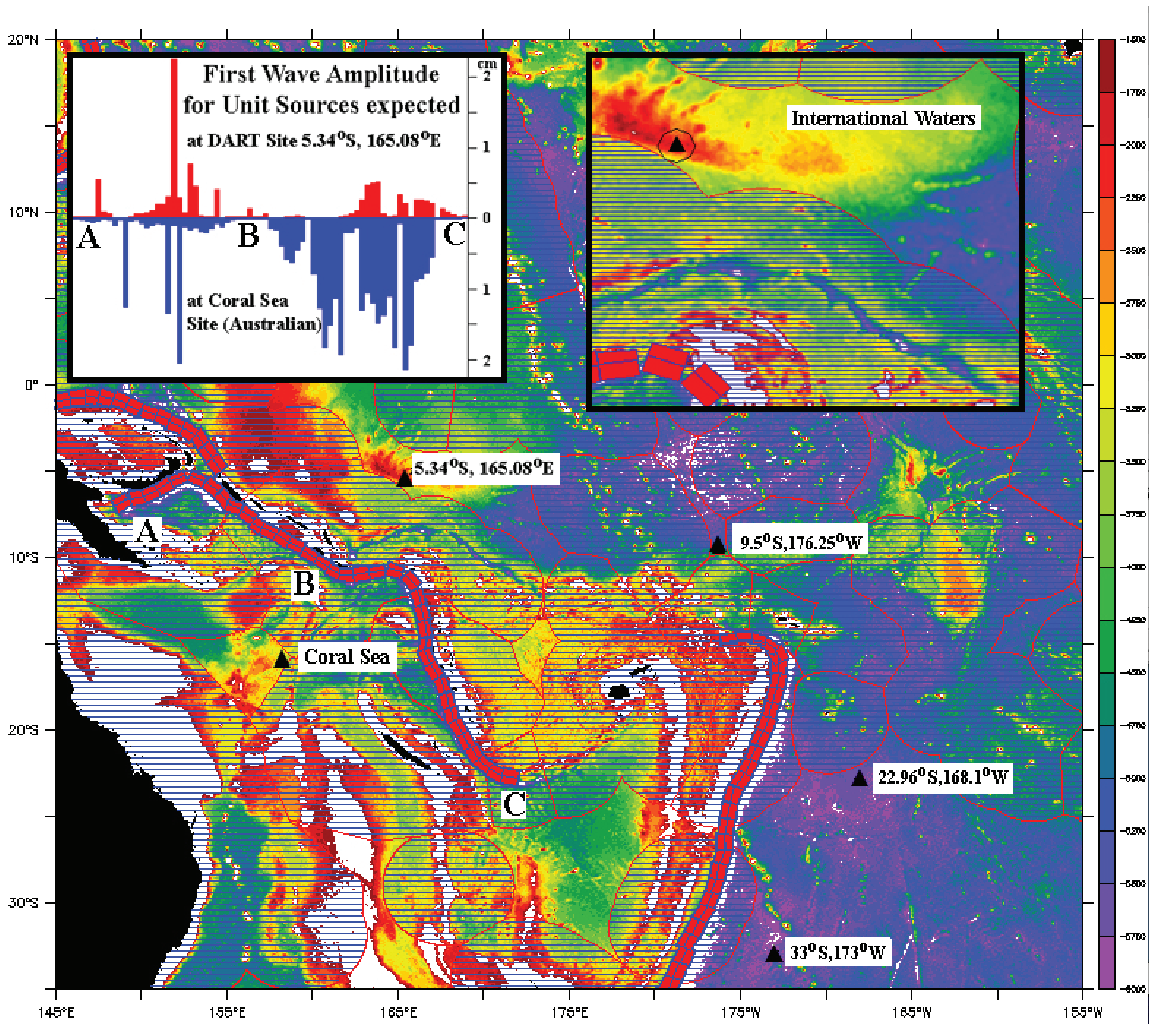

Figure I1: Revised site recommendations for the Southwest Pacific DART® Group.

direct substantial energy into the Pacific. To that extent the U.S. DART® does complement the Coral Sea site, though for the overall capability of a 32-element Pacific array, an eastern Pacific site for the final instrument would be more effective. Note that near A and C, and at B (near Guadalcanal), neither DART® site is very effective.

The recommended site is indicated in the upper right inset panel. While the originally suggested site at 5°S, 166°E has only a slightly less favorable response, the recommended site at 5.34°S, 165.08°E is on the source side of the topographic feature shown. The feature does not rise close enough to the surface to cause major scattering in light of Hal Mofjeld's study of this effect (Mofjeld *et al.*, 2001). A 25-nm circle is drawn around the site and, within that, the response is generally similar; it is hoped that a sufficiently flat bottom can be found there. The recommended site is at about 30 min travel time from the closest source and close to the TAO line at 165°E. Though the range of available sites to the south is constrained by the EEZ,

Table I1: Revised site recommendations for the Southwest Pacific DART® Group.

DART® Designation	Latitude	Longitude	Approximate Depth (m)*
9-1	5.34°S	165.08°E	1904
9-2	9.50°S	176.25°W	4843
9-3	22.96°S	168.10°W	5637
9-4	33.00°S	173.00°W	5677

*From Smith and Sandwell (1997)

consideration of seismic noise would suggest that sites in that direction would be less favorable in any case.

Recommendation

As a result of this analysis the siting recommendation for the Southwest Pacific has been revised as detailed in Table I1 and Fig. I1.

Reference

Mofjeld, H.O., V.V Titov, F.I. González, and J.C. Newman (2001): Tsunami scattering provinces in the Pacific Ocean. *Geophys. Res. Lett., 28*(2), 335–337.

Smith, W.H.F., and D.T. Sandwell (1997): Global seafloor topography from satellite altimetry and ship depth soundings. *Science, 277*, 1957–1962.