

The optimal placement of tsunameters in the Tasman Sea

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As part of the Australian Tsunami Warning System project, the Australian Bureau of Meteorology deployed two tsunameters in the Tasman Sea. The locations of these tsunameters were initially chosen through determination of an ‘optimal’ location and placing both buoys near this location. There is some justification for relocating these tsunameters and this work presents an analysis to determine the optimum locations for two tsunameters in this area. This takes into account a number of factors, such as international maritime boundaries, provision of the earliest possible tsunami observation times and the ability to detect the largest tsunami amplitudes. Based on the results of the analysis, two specific locations are recommended for the optimal placement of the tsunameters.

Introduction

An essential element in the provision of tsunami warnings is the ability to detect tsunamis through changes in sea level. This is important because not all earthquakes cause tsunamis, even those occurring along subduction zones, where tsunamigenic earthquakes are most likely to occur. Furthermore, it is not currently possible to determine in real time, from seismic data alone, whether an earthquake has generated a tsunami or not. There are a number of possible instruments that can be used for observing tsunami-generated sea-level variability, such as coastal radars (e.g. Heron et al. 2008) and satellite altimeters (Ablain et al. 2006). The two main techniques used operationally within the Australian region for the detection of tsunamis are coastally based tide gauges and open-ocean-based tsunameters.

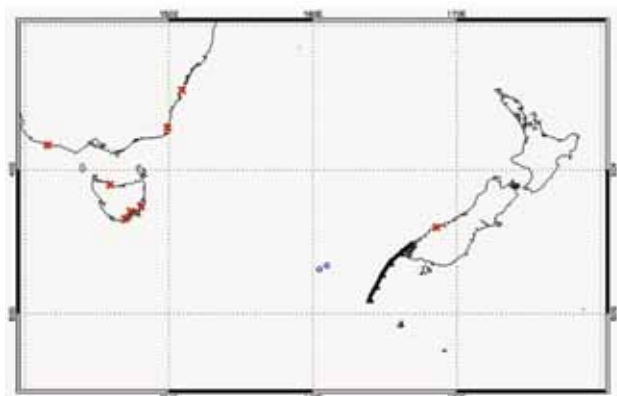
A tsunameter consists of a bottom pressure recorder (BPR) installed on the sea floor, in deep water (typically deeper than 3000 m) which communicates via an acoustic link with a moored surface buoy. The BPR records pressure at fifteen-second intervals which is then converted to a change in sea surface height, with a precision of one millimetre (Meinig et al. 2005).

As part of the Australian Tsunami Warning System project, the Australian Bureau of Meteorology (the Bureau) significantly expanded its sea-level observing network, including a mix of tide gauges and tsunameters. Two

tsunameters were initially deployed in the Tasman Sea. These were placed in order to detect and provide warning guidance for tsunamis caused by earthquakes on the Puysegur subduction zone, located to the southwest of New Zealand (see Fig. 1). Over the past 25 years, there have been six earthquakes in this region with magnitudes over $M_w = 6.0$. These earthquakes occurred in 1988 (M_w 6.7), 1989 (M_w 6.4), 1993 (M_w 7.0), 2000 (M_w 6.1), 2003 (M_w 7.2) and 2009 (M_w 7.8) (Uslu et al. 2011).

For the initial deployment of the tsunameters, both were placed near a single location deemed to be ‘optimal’, with a separation of approximately 70 km (Greenslade 2007). There were a number of reasons for placing them near each other. Firstly, and predominantly, one of the tsunameters was an experimental Easy-To-Deploy Deep-ocean Assessment and

Fig. 1 Location of the Puysegur subduction zone (thick black line), existing tide gauges in the region (red crosses) and initial tsunameter deployments (blue circles).

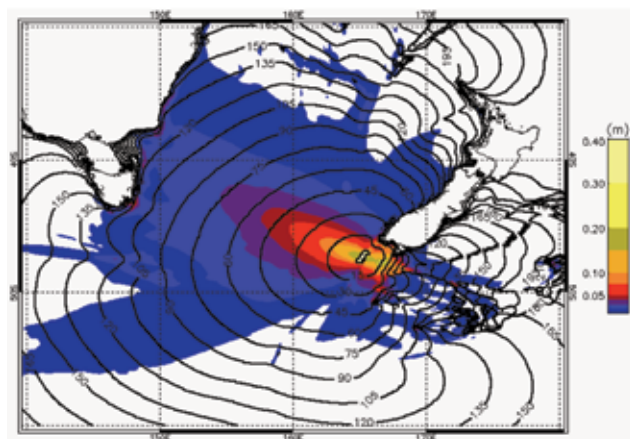


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Reporting of Tsunamis (ETD DART) instrument, and the co-location was undertaken for testing and evaluation purposes in a collaboration with the Pacific Marine Environmental Laboratory (PMEL) of the United States National Oceanic and Atmospheric Administration (NOAA). Secondly, placing the two buoys near each other provides a level of redundancy in case one of the tsunameters is non-functional. Australia is highly vulnerable to tsunamis in this region because there are no options for locating land-based sea-level detection stations directly between the Puysegur subduction zone and the Australian coastline (Warne 2007). A side benefit to placing the tsunameters near each other is that over the long term, the costs for servicing the instruments, such as ship time, are reduced.

Figure 1 shows the locations of the initial tsunameter deployments in addition to the locations of all tide gauge stations in the region that are owned and operated by the Bureau. In practice, a more extensive network is available, consisting of observations from other Australian and international providers. However, these do not all have the same requirements for timeliness of reporting or data return rates as the Bureau's operational network and so in this case, only the data sources that the Bureau owns are shown. It can be seen that there is no land located directly between the Puysegur subduction zone and the southeast of Australia on which a tide gauge station could be located. Of course, given that tsunamis radiate in many directions from the source, the tide gauge on the New Zealand coast seen in Fig. 1 is likely to detect a tsunami emanating from the Puysegur subduction zone before it arrives at the Australian coastline. However, it can be seen from the maximum amplitude maps discussed later (Fig. 2 and Fig. 6) that the tsunami amplitude will be relatively small at this location, and potentially not easily detectable. Furthermore, it is difficult to extract relevant details of the tsunami such as wave period and amplitude from land-based tide gauges due to coastal effects. So while the land-based observations may be useful for confirmation of whether a tsunami has been generated or not, their ability to provide input for tsunami warnings will be limited.

Fig. 2 Maximum amplitude (colours) and arrival times in minutes (contours) from T2 scenario 216a.



The co-location period was completed in early 2011 and a cruise was scheduled to service the tsunameters in April 2011. This provided the opportunity to potentially improve detection based on observations from two more widely spaced sites. This paper describes the method and results for determining the optimal locations for two tsunameters in the Tasman Sea. It should be noted that for both tsunami warning and scientific purposes, more data is always desirable, so ideally, there would be more than two tsunameters in this region. However, the number of deployments here is limited to two, for economic reasons.

Background

There is relatively little in the published literature relating to the optimal siting of tsunameters. The most relevant previous work is that of Spillane et al. (2008), who determined the optimal network design for the tsunameter arrays in the Pacific and Atlantic Oceans using a tsunami scenario database as a tool for array design. Omira et al. (2009) examined the requirements for a tsunami detection network for Portugal and Henson et al. (2006) undertook a similar task for the Caribbean region. While relevant, those studies represent a substantially different situation to the Australian case, due to the close proximity of the tsunamigenic sources to the countries of interest. Groen et al. (2010) considered optimal locations for tsunameters in the Indian Ocean, suggesting that ten sites were needed in order to ensure that the maximum population can be warned. There have also been a number of unpublished reports by the author, making recommendations for specific deployments in the Australian region (e.g. Greenslade 2007).

The main intended function of the tsunameters in the Tasman Sea is to provide real-time observations of sea level that can be used within the Joint Australian Tsunami Warning Centre (JATWC) to confirm whether or not a tsunami has been generated, in order to guide the provision of tsunami warnings. A further function will be to provide sea-level observations that can be used to adjust numerical model forecasts in real time, whether they are pre-computed scenarios, or dynamically generated model forecasts. The development of techniques to perform this is currently underway at the Bureau of Meteorology.

Given the above main functions, optimal placement of tsunameters requires a balance between a number of different requirements. Firstly, in order to maximise the time between detection of a tsunami and its coastal impact, the tsunameter should be placed as close as possible to the potential generation region. However, if a tsunameter is located too close to an earthquake, then the seismic waves can contaminate the sea-level signal, which makes it difficult to extract the required information about the tsunami. Current international practice is to deploy tsunameters no closer than 30 minutes tsunami travel time away from subduction zones. Further requirements are that current tsunameter technology requires the tsunameter to be in deep

water (greater than approximately 3000 m) and furthermore, international maritime boundaries, strong ocean currents and the existence of busy shipping lanes need to be taken into account. Some of these aspects are discussed further in the 'Discussion' section.

Method

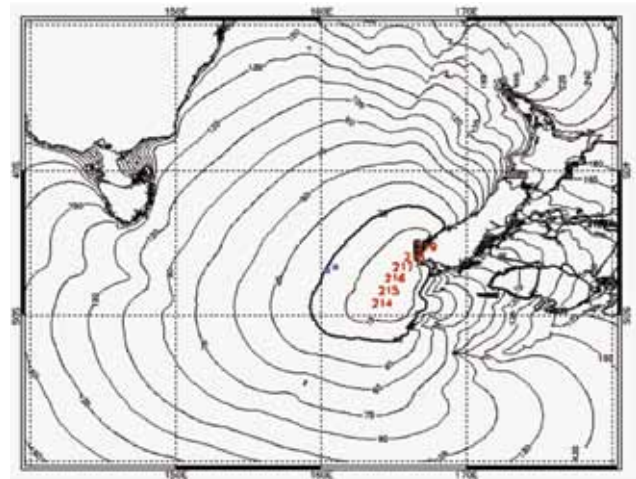
The approach taken here follows that of Spillane et al. (2008) which was also followed in previous tsunameter siting guidance documents prepared for the Bureau by the author. The overall aim is to find the locations that provide the best 'warning characteristics' for the Australian coastline. The word warning is used in a relatively loose sense here, given that an actual tsunami warning requires considerably more effort than just the detection of a tsunami. This is discussed further in the 'Discussion' section. In the present work, the 'warning characteristics' consist of the set of minimum warning times provided by one or more observation locations, where the warning time is defined to be the difference between arrival time of a tsunami at the observation location and arrival time at the coast. Other factors, such as being able to detect maximum amplitudes of the tsunami, are also considered.

Tsunami travel times are derived here from the T2 scenario database (Greenslade et al. 2009; Greenslade et al. 2011). T2 is a database of pre-computed tsunami model runs using the Method Of Splitting Tsunamis model (Titov and Synolakis 1998) representing a comprehensive subset of all tsunamis that could be generated from subduction zone earthquakes and potentially impact on Australia. T2 model output is at four arc minute spatial resolution and two-minute temporal resolution. Travel times can be obtained from any T2 scenario by calculating the time of arrival of the first tsunami crest at every model grid point. The travel time map for one of the T2 scenarios (a magnitude 7.5 event with epicentre at [165.613°E, 47.449°S]) is shown in Fig. 2. This figure also shows contours of the maximum modelled amplitude at every grid point.

The locations of all of the T2 scenarios considered in this work are shown in Fig. 3. These are scenarios 214a to 219a, i.e. tsunamis generated by six magnitude 7.5 earthquakes with ruptures that span the ~600 km subductive stretch of the Puysegur trench shown in Fig. 1. Only magnitude 7.5 events are used here, as this is sufficient to span the entire length of the subduction zone in this region. Incorporating higher magnitude events along the same stretch of the subduction zone is unlikely to have any effect on the results. This is because the warning characteristics are based predominantly on tsunami travel time, and travel time is dependent solely on the depth of the water not on the magnitude of the earthquake.

Figure 3 also shows the travel time 'envelope'. This is determined by calculating arrival times at each model gridpoint for each of the six scenarios and selecting the minimum at each gridpoint. Note that the earliest arrival

Fig. 3 Travel time envelope for the six magnitude 7.5 scenarios along the Puysegur trench. The 30-minute contour is shown in bold. Locations of initial tsunameter deployments are shown as the blue circles.



time at the Australian coast is about two hours. The JATWC is mandated to provide, where possible, at least 90 minutes warning time to the Australian coast for any tsunami event (Bureau of Meteorology 2008). This will make it challenging to find locations for tsunameters that meet the dual requirements of being 30 minutes travel time away from an earthquake but also able to provide sea-level observations in a timely fashion for the 90 minute JATWC warning requirement.

The locations of the two initial tsunameter deployments in this region are again shown in Fig. 3. Note that these locations are just inside the 30 minute travel time envelope. The main reason for this was a desire to meet the 90 minute JATWC warning time requirement, so the requirement to be at least 30 minutes travel time away from the subduction zone was treated with some flexibility. On July 15, 2009, after deployment of these tsunameters, a tsunamigenic earthquake did occur in this region. Both of the tsunameters detected the tsunami but it was found that there was indeed some aliasing of the seismic signal into the sea-level signal. This made it difficult to use the sea-level data for model verification or scenario selection during the event (Uslu et al. 2011). So in the current analysis, the 30-minute travel time requirement is maintained.

The method used here to determine the optimal locations is to inspect all pairs of possible observation locations and find the pair that results in the best warning characteristics. Possible locations in this case are those that are: a) within the general vicinity, and in particular, between 44°S and 48°S; b) in waters of at least 3000 m depth; c) on or outside the 30 minute travel time envelope; and d) in Australian or international waters. This results in 2045 possible locations (and thus 2 089 990 possible pairs) which are shown in Fig. 4. Note that a preliminary assessment was performed in which every 5th model grid point was examined over a larger region, extending to 40°S. This initial coarse resolution

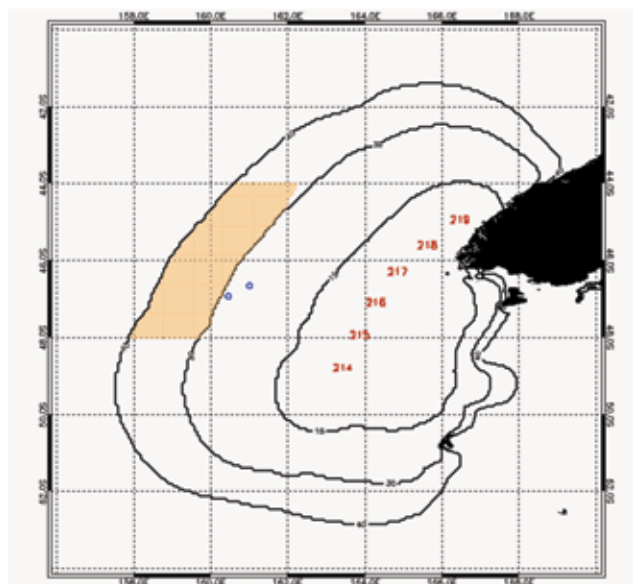
assessment served to provide an indication of potential optimal locations. Further analysis at higher resolution was then performed within the region shown in Fig. 4 in order to refine the placement.

As mentioned earlier, the warning characteristics of a pair of observation sites are the set of minimum warning times provided by those locations to the coastline. More specifically, the warning time for an individual coastal grid point is the shortest warning time provided by either of the observation sites for any of the scenarios. The warning time is simply the difference between the arrival time at the coastal grid point and the arrival time at the observation site, and a coastal grid point is any model grid point that is adjacent to land. A total of 1080 coastal grid points was considered here, along the southeast coast of Australia. The optimal warning characteristics are found by ranking the location pairs according to the number of coastal grid points falling within specific warning time ranges (see Table 1). Priority is given first to minimising the number of coastal grid points with 90 minutes warning or less, then the number of coastal grid points with between 90 and 105 minutes warning, and so on.

Results

Because of the discrete nature of the T2 scenarios, 676 distinct pairs of locations were found to provide identical optimal warning characteristics. These pairs are represented by the black circles in Fig. 5. It can be seen that the optimal locations are distributed into two sets, a northerly set and a southerly set. Note however, that not every one of the southern locations can be paired with every one of the northern locations to produce the optimal warning

Fig. 4 The orange shaded area (which is in fact a large number of small orange circles) shows the possible locations inspected for their warning characteristics.



characteristics. The warning characteristics for the pair of locations indicated by the red circles in Fig. 5, are shown in Fig. 6, bearing in mind that the warning characteristics are identical for all optimal pairs. The colours in Fig. 6 indicate the minimum warning times provided by either location for all of the six scenarios. These warning characteristics are also described by the details in Table 1 (shaded column). Warning characteristics for the existing pair of locations are also listed in Table 1 for comparison. It can be seen that any of the proposed new pairs of locations will provide overall improved warning characteristics when compared to the existing locations.

In order to refine the selection of the specific locations, we consider the warning characteristics of each potential buoy location individually. This will ensure that the warning characteristics are optimised even if only one tsunameter is functional. The ramifications of only one tsunameter being functional are discussed further in the following section.

Fig. 5 Similar to Fig. 3 with black circles showing the locations that contribute to the optimal pairs of locations and red circles showing the recommended pair.

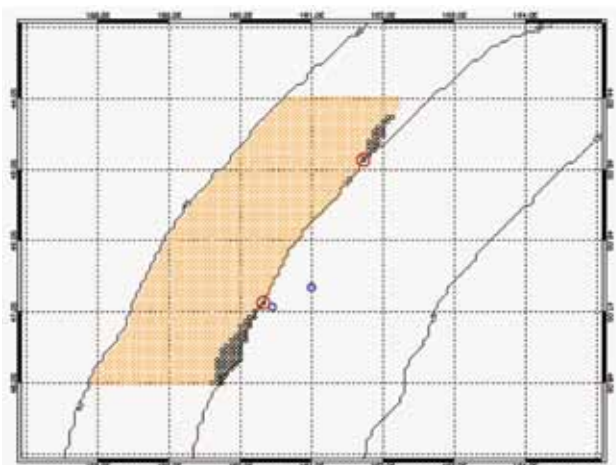


Fig. 6 Warning characteristics for southeast Australia for one of the optimal pairs of locations, shown by the red circles in Fig. 4.

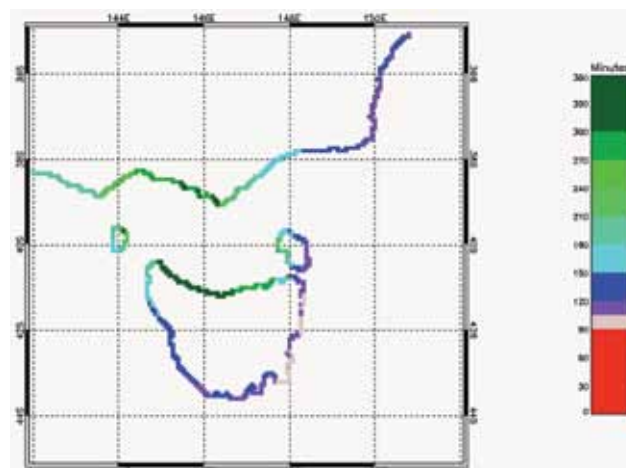


Fig. 7 Maximum amplitude from the six magnitude 7.5 scenarios along the Puysegur trench, with the proposed tsunameter locations designated by the white (or in one case red) circles.

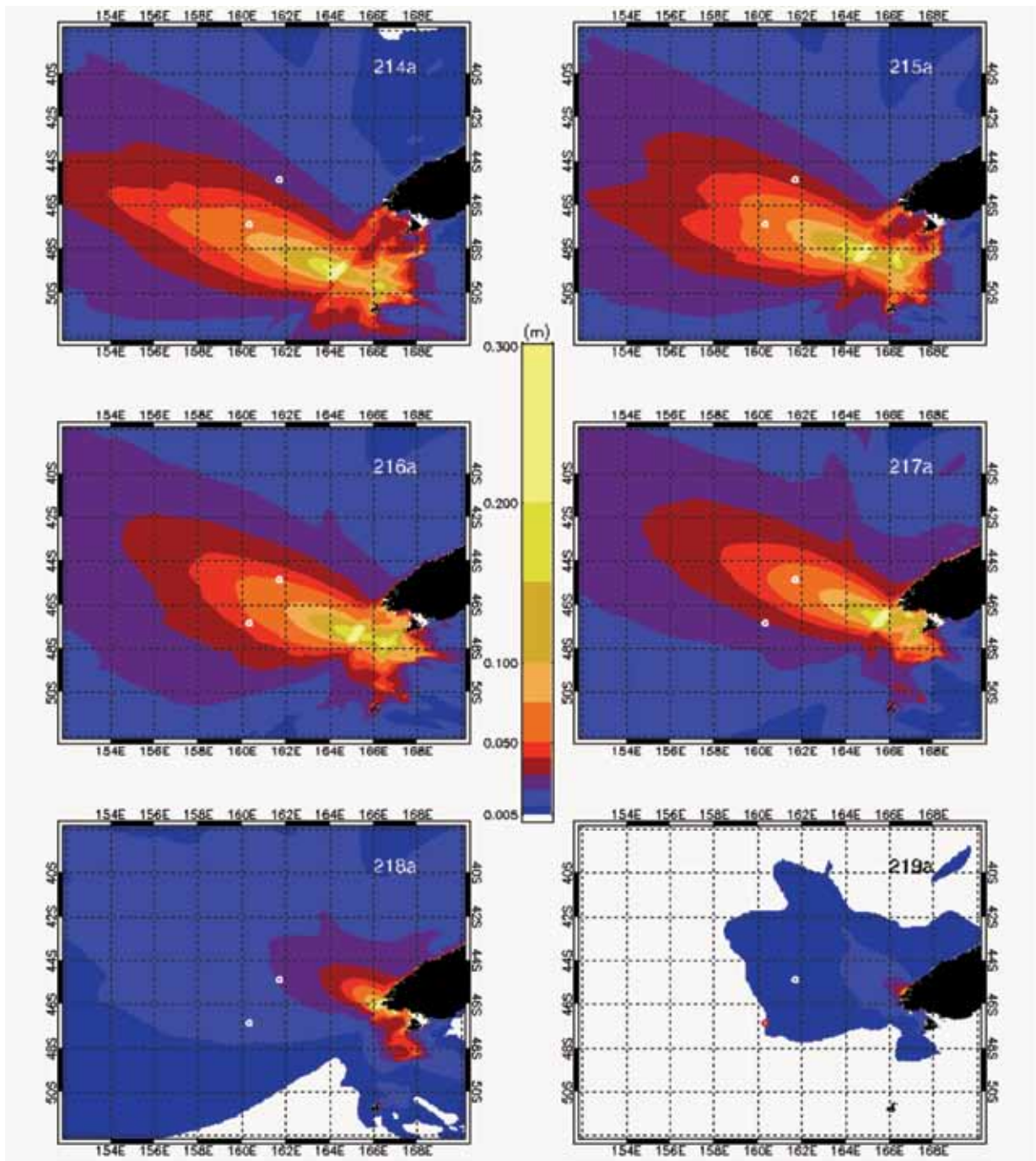


Table 1. Warning characteristics of existing and proposed new locations.

Number of coastal grid points with:	Existing tsunameter locations			New tsunameter locations		
	Both	Northern only	Southern only	Both	Northern only	Southern only
90 minutes warning or less	1	1	2	0	9	2
91 to 105 minutes warning	39	39	46	30	46	59
106 to 120 minutes warning	127	127	132	100	133	131
121 to 150 minutes warning	233	233	227	256	212	219

Most of the individual buoy locations within the optimal pairs shown in Fig. 4 have different warning characteristics. The best individual locations were found from the southern set and the northern set independently. In fact, there are three locations in the southerly set which produce the identical best individual warning characteristics and two locations from the northern set. These five locations are listed in Table 2 and their individual warning characteristics are shown in Table 1. Note that these are the three most northerly locations in the southerly set, and the two most southerly locations in the northerly set. All six possible pairings provided by these five locations are also in the set of 676 best pairs as well, so any of these six pairings can be selected as the optimal locations.

A further assessment of the warning characteristics of the buoy locations can be made by ensuring that the tsunameters are well-placed to detect the largest tsunami amplitudes for any nearby events. This can be easily assessed through inspection of the maximum tsunami amplitudes from the six magnitude 7.5 scenarios. The maximum amplitude maps are shown in Fig. 7. For each of the five possible locations, the mean value of the maximum tsunami amplitude at that location, over all of the six scenarios, was found. These are listed in Table 2. Although the differences are marginal, this does provide some guidance as to which locations are best placed to detect the highest tsunami amplitudes.

Based on all these factors, the recommended locations are therefore 160.33°E, 46.87°S and 161.73°E, 44.87°S. These are indicated by the red circles in Fig. 5 and the white circles in Fig. 7.

Discussion

As noted earlier, it has been necessary to assess the warning characteristics of each individual location, partly to refine the optimal pairs, but also this ensures that the warnings are not significantly degraded in the event that one of the tsunameters is not functional. Table 1 presents the warning characteristics of the individual buoy locations as recommended in the previous section, along with the warning characteristics of the individual existing locations. It can be seen that although the warning characteristics are improved over the existing case when both buoys are

functional, the proposed new locations provide worse warning characteristics (compared to the existing situation) if only one tsunameter is functional. In particular, it can be seen that if only the northern buoy is functional, then there are nine coastal grid points that will receive less than (or equal to) 90 minutes warning for at least one scenario. The actual minimum warning times here are: one grid point with 82 minutes; one with 84 minutes; two with 86 minutes; one with 88 minutes; and four with 90 minutes warning. These grid points are all located in southeastern Tasmania, near (148°E, 43°S).

The question of whether this is tolerable must be considered. If there are likely to be long periods of time when only one tsunameter is functional, then a better option may be to maintain the existing situation in which both tsunameters are placed near the optimal individual location for redundancy. However, when both tsunameters are functional, it could be argued that this is not an effective use of resources because improved warning characteristics can be obtained by locating them separately. Despite the immense challenge of maintaining operational deep ocean buoys, the Bureau has experienced considerable success over the past few years of tsunameter deployments in this region. In fact, the average data return rate of each of the Tasman Sea tsunameters over the time period April 2009 to January 2011 was approximately 95.5 per cent and more importantly, both of the tsunameters were operating for more than 91 per cent of the time. On the assumption that this rate is maintained in the future then the probability of having only one tsunameter (or none) operational on any particular day is less than 0.09. As noted in the introduction, significant tsunami events have occurred in this region less than once every four years. This suggests that the probability of a tsunami occurring on any day is 0.0007. Given that these two events are independent, the probability of there being fewer than two tsunameters operational when a tsunami occurs is $0.09 \times 0.0007 = 0.000063$ or once every 45 years. Discussions with tsunami warning specialists within the Bureau during the course of this work concluded that this is a tolerable risk. Therefore, it is recommended here that the tsunameters are deployed at the proposed separate locations in order to optimise the warning characteristics when both are functional.

It is worth noting that the data return rates quoted above include very short outages such as individual missing data points. These short data dropouts do not affect the warning centre's ability to detect a tsunami, and so the probability of detecting a tsunami is considerably higher than has been assumed here. Therefore the likelihood of having only one tsunameter operational at any time is lower than assumed here and the risk is therefore lower and consequently, even more tolerable.

A further reason for choosing to locate the buoys separately relates to the detection of peak tsunami amplitudes. Examination of Fig. 7 shows that with both tsunameters functioning, for any of the magnitude 7.5 events,

Table 2. Mean tsunami amplitude observed at individual locations.

<i>Southern locations</i>	<i>Mean maximum amplitude (cm)</i>
(160.20°E, 47.00°S)	3.50
(160.27°E, 46.93°S)	3.53
(160.33°E, 46.87°S)	3.56
<i>Northern locations</i>	
(161.73°E, 44.87°S)	3.33
(161.80°E, 44.80°S)	3.27

there will be at least one observation of tsunami amplitude of five centimetres or above, at least for the four most southern T2 scenarios. For scenarios 218a and 219a, this is not the case, but the signal overall is considerably lower for these two scenarios because a portion of the earthquake rupture occurs under land. Note that the existing deployments, with both tsunameters located near the southernmost white circle are not well positioned for detecting maximum amplitudes from events occurring near the northern end of the subduction zone.

There is a more general issue in relation to 'detectability', or rather, non-detection of a potential threat that is worth noting. Based on the current JATWC procedures, the minimum magnitude earthquake on the Puysegur subduction zone that would trigger warnings for southeastern Australia is $M_w = 7.9$. This means that tsunameters in the region need to be able to detect such events in the presence of other sources of variability, such as background ocean sea-level variability or seismic noise. As noted previously, in 2009 there was a $M_w = 7.8$ earthquake in this region when the tsunameters were in their original locations. As demonstrated in Uslu et al. (2011) the resulting tsunami was easily detected by the tsunameters, despite the contamination of the signal by the seismic noise. This shows that any event that might cause a threat to southeastern Australia in this region will be detectable at these locations and so the possible non-detection of a potential threat should not be an issue in this case.

There are some issues related to the method used here that should be acknowledged. One of these relates to the tsunameters' main function of providing timely observations of sea level in order for forecasters to be able to confirm whether or not a tsunami has been generated, as input into warning decisions. As noted previously, the 'warning time' defined in this work does not encompass the total time needed to actually produce and issue a warning. This includes the time taken to detect the earthquake, assess the threat, prepare warnings and perform a number of other required actions. These will obviously increase the total time taken to provide a tsunami warning after an earthquake occurs. However, given that this effect is applied equally to every tsunami event, it will not affect the overall conclusions about optimal locations.

The relevant point is that given the JATWC's aim to provide warnings at least 90 minutes before landfall, it needs to be acknowledged that the observations from these tsunameters will not be useful for these early warnings, but will be limited to the provision of input into an updated threat assessment. This is exacerbated by the fact that it is the arrival time of the first peak of the modelled tsunami that has been used here, despite the fact that in real time, it is not possible to know whether the first crest has occurred until some time after it has passed.

A related issue is that the coastal grid points as defined here (seen in Fig. 6) are derived from the T2 model output, which means they are in water depth of at least 20 m

(Greenslade et al., 2009). In some cases, for example, around large shallow estuaries, this means that they are some distance away from the actual point of coastal impact, which means that the tsunami travel time to the coast will be longer than has been calculated here. Again, this will not have any effect on the selection of the optimal locations because it applies equally to all possible buoy locations. Indeed, the positive aspect of this is that for some coastal sites, it may ameliorate some of the issues noted above that would reduce the available amount of warning time.

There are a number of other factors that need to be considered when finding optimal locations for tsunameters. Regions of strong ocean currents are undesirable due to the pressure they place on the instrument's infrastructure. Spillane et al. (2008) investigated ocean surface current speeds in this particular region and showed that they are not likely to be a problem. Another desirable feature for tsunameter placement is that there are no significant bathymetric features between the tsunameter site and the relevant subduction zone that may cause scattering of the tsunami signal. Spillane et al. (2008) again showed that this is not an issue in this region. A further factor that can affect tsunameter placement is the existence of major shipping lanes. While there are some regular shipping lanes in this region, it is a very low traffic area by world standards (Halpern et al. 2008) and can readily be tolerated here. Intentional and non-intentional damage is also a major issue for deep ocean moorings (Data Buoy Cooperation Panel, 2011). No incidences of vandalism have been reported in this region, although it is acknowledged that the buoys have been deployed for a relatively short time and it can not be assumed that this will not be encountered at some stage in the future.

Summary and conclusion

In summary, the recommended locations for the placement of two tsunameters in the Tasman Sea are 160.33°E , 46.87°S and 161.73°E , 44.87°S . The selection of these locations takes into account a number of factors, such as water depth, international maritime boundaries, the potential for aliasing of seismic waves, provision of the best warning characteristics for the Australian coastline and the ability to detect maximum tsunami amplitudes.

If both tsunameters in these locations are functional, then they will have the ability to detect any tsunami emanating from the Puysegur trench at least 90 minutes before the tsunami arrives at any point on the Australian coast. This is an improvement over the current configuration. If only one of the tsunameters at the proposed locations is functional, then the warning characteristics are slightly worse than in the initial configuration, but as discussed in the previous section, it is suggested that this risk can be tolerated.

One of the main reasons for modifying the existing locations is to move the tsunameters further away from the subduction zone and thus reduce the risk of seismic aliasing

which creates difficulties in using the data. The fact that the proposed locations are within the recommended guidelines for avoiding seismic aliasing, but yet provide improved overall warning characteristics (assuming that they are both functioning) is a very positive result.

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