PTWC Enhanced Products
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Tsunami Travel Time Computation
PTWC Real-time Forecast Model

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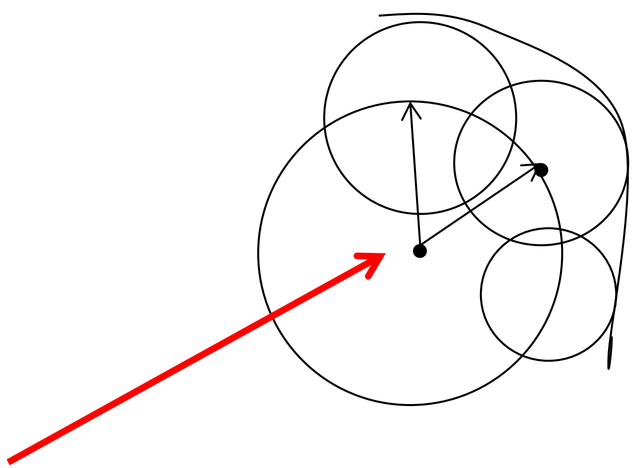
1. Tsunami arrival/travel time computation

Wave speed $c = \sqrt{gh}$ **where h is water depth and *g* is gravitational acceleration**

Huygens Principle:

Every point on the wave front of a point source is also a point source.



New wave front

Point source (or epicenter of the earthquake)

Calculating ETAs

- **Epicenter of the earthquake (EQ) is assumed to be the location of the initial point source. If the epicenter of the earthquake is on land, the nearest ocean point is assumed to be the initial point source.**

- **The estimated tsunami arrival times (ETA) listed in PTWC's bulletins are computed in real-time using the GEOWARE TTT (tsunami travel time) software http://www.geoware-online.com/tsunami.html) with the GEBCO 30-arc-second bathymetry data (http://www.gebco.net). For speed of computation, a lower resolution might be used (such as 5 or 10 arc-minute grid).**

Reference: Wessel, P. (2009), Analysis of observed and predicted tsunami travel times for the Pacific and Indian Oceans, Pure and Applied Geophysics, vol 166, 301-324, doi:10.1007/s00024-008-0437-2.

Limitations of tsunami travel computation

- **Tsunami is not generated by a point source**
- **Main energy propagation path might not be the shortest possible path, assumed in TTT method.**
- **This usually results in tsunami arrival times <u>earlier than the observed in the far field</u>, and <u>later in the near field</u>.**

The GEOWARE TTT software is capable of computing ETAs based on finite source but it is not yet implemented at PTWC.

Sensitivity of ETAs to size of sources

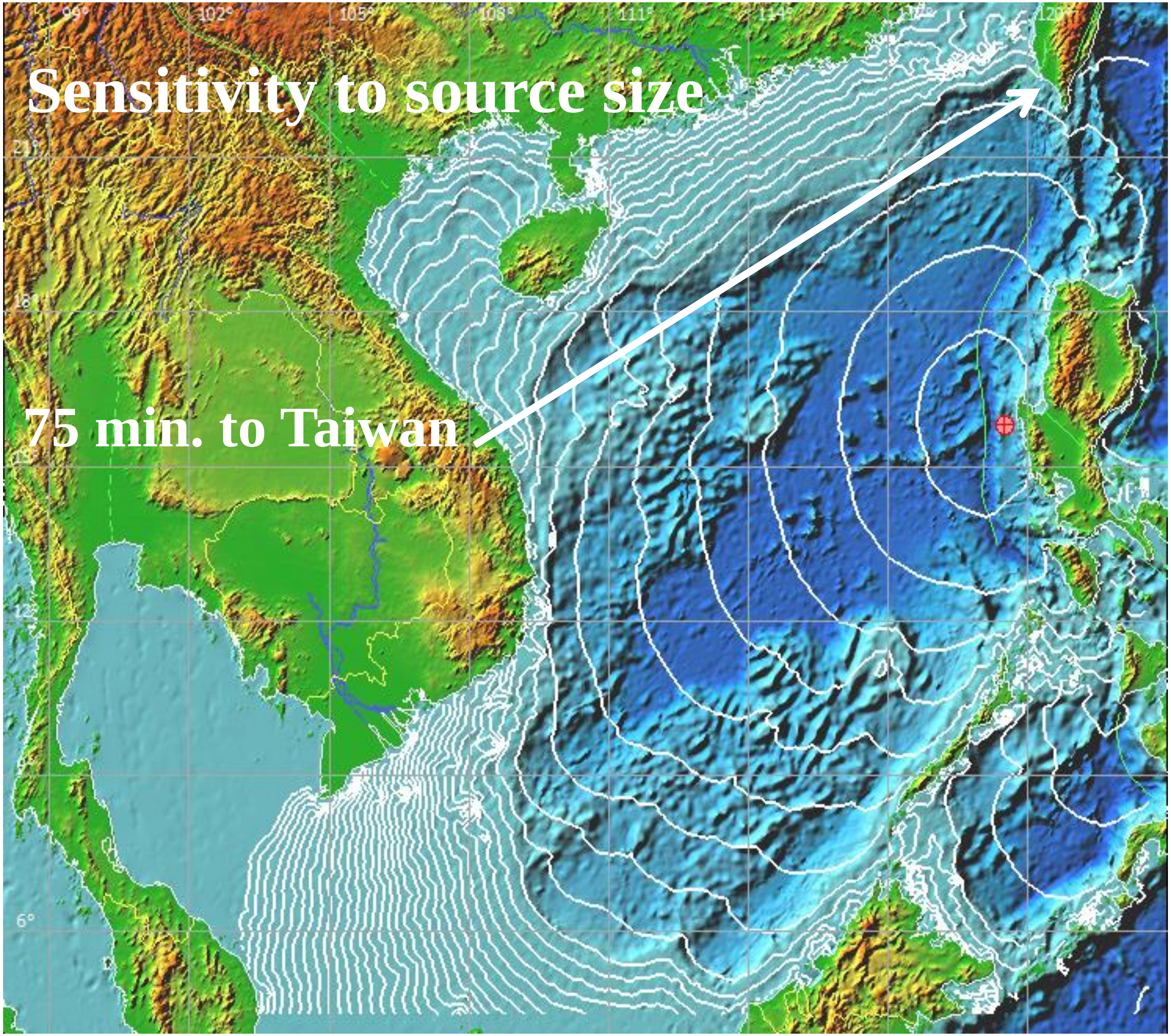
- **We next discuss the sensitivity of ETAs to the fault size of earthquakes, using the tsunami travel time computation software of Dr. Viacheslav K. Gusiakov**

  (http://tsun.sscc.ru/WinITDB.htm).

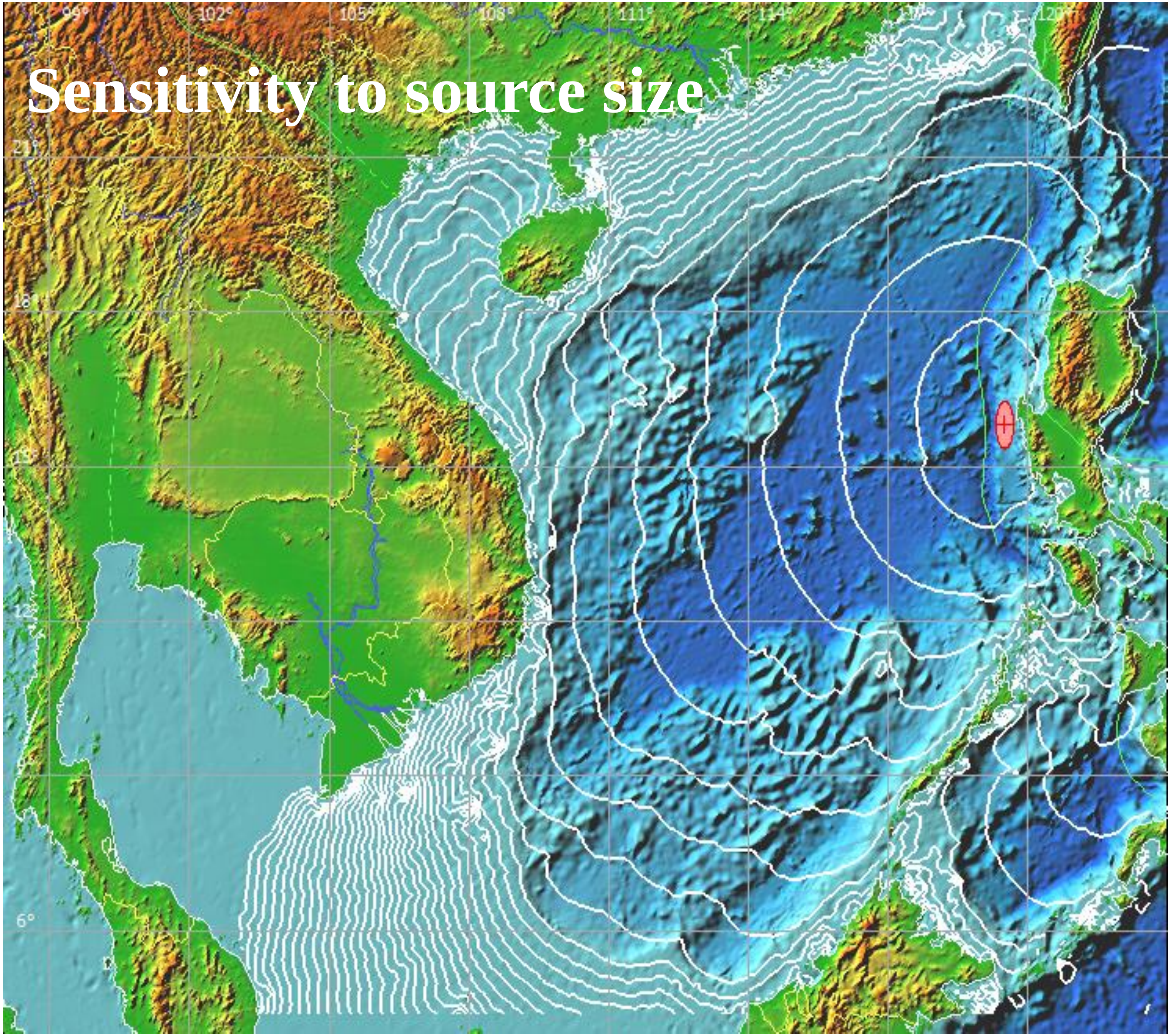
- **For a hypothetical earthquake in the Luzon trench, the ETAs decrease as the size of the source increases (note the changes of ETA contours near Taiwan).**

  The size of source increases from 20 km x 20 km (approximately a point source) to 20 km x 225 km (225 km is about the fault length of a magnitude 8.2 earthquake).

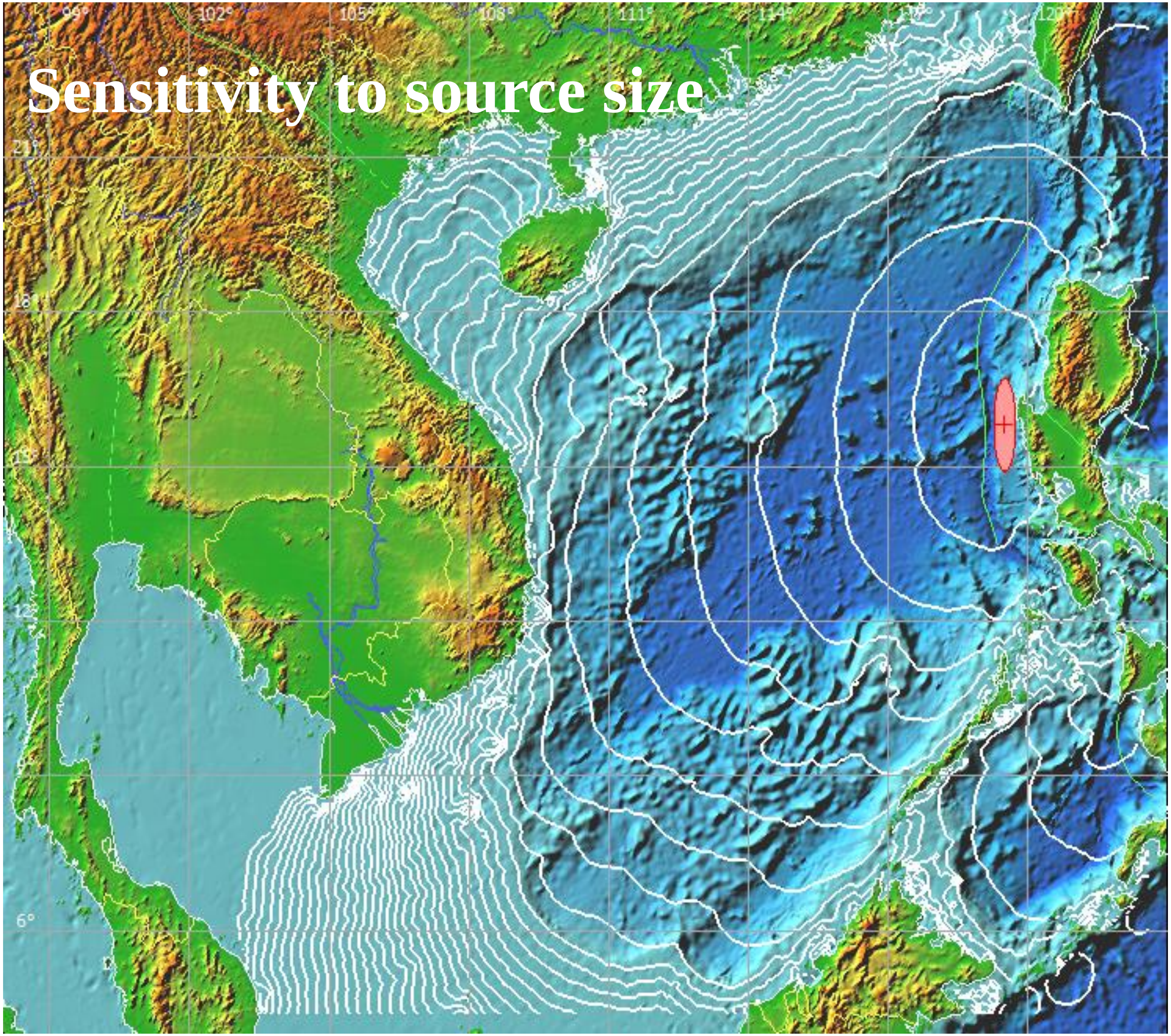
Tsunami Travel Times: 20 x 20 km Source and 15-min Isochrons



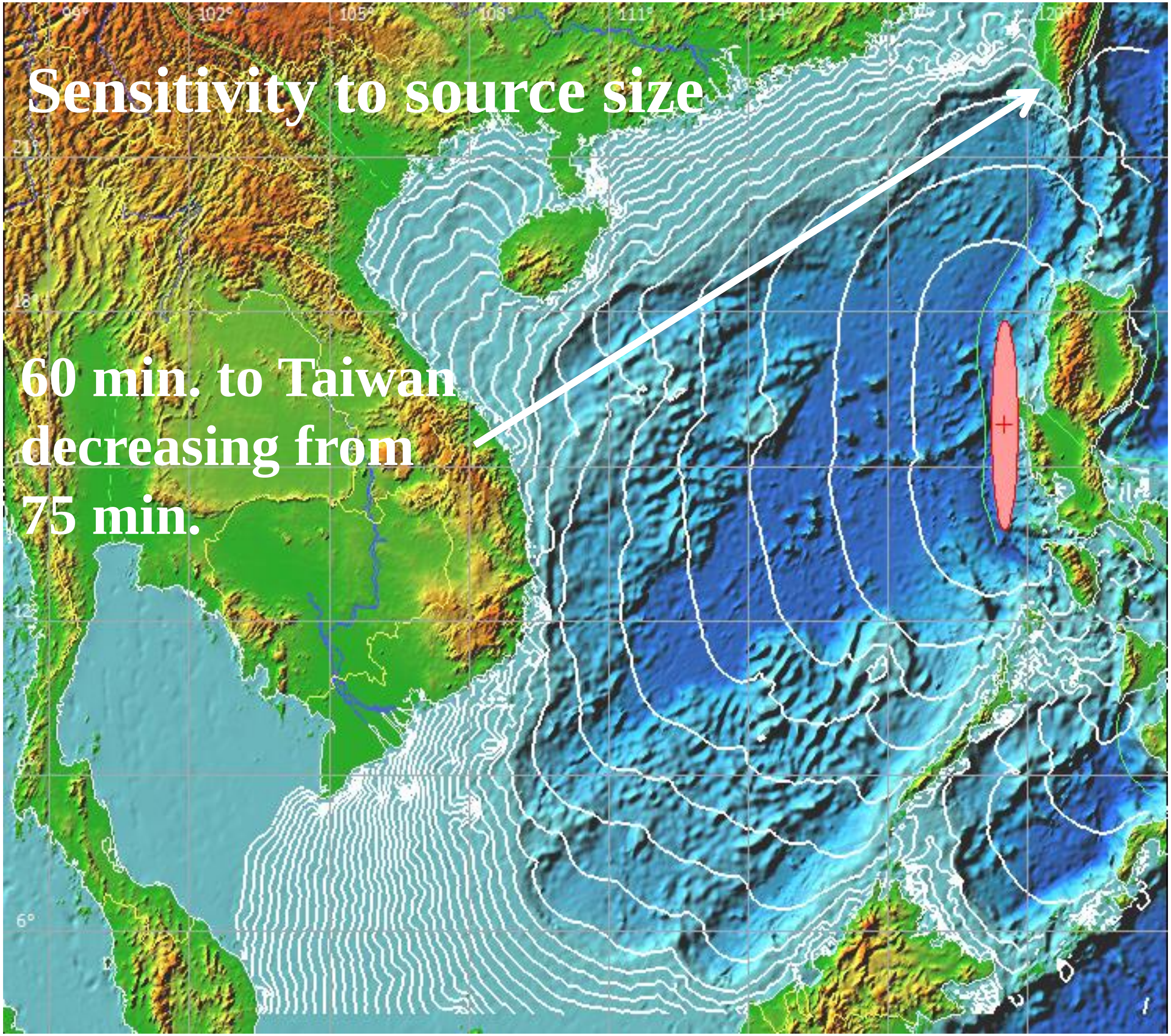
Tsunami Travel Times: 20 x 50 km Source and 15-min Isochrons



Tsunami Travel Times: 25 x 100 km Source and 15-min Isochrons



Tsunami Travel Times: 30 x 225 km Source and 15-min Isochrons



2. Description of the PTWC RIFT Model

- RIFT stands for "Real-time Inundation Forecasting for Tsunamis" or "Rapid Inclusive Forecasting for Tsunamis". The latter is probably a more appropriate name since it is a propagation model and currently there is no inundation component in the model.
- The RIFT model is run completely in real-time using real-time earthquake parameters.
- Physics: Linear shallow water equations
  Numerics: Arakawa C-grid in space and leap-frog in time.
- Bathymetry: GEBCO 30-arc-sec. grid, typically 4-arc-min resolution is used for basin-wide forecast or for a large EQ (mag > 7.8). Resolution as high as 30-arc-sec can be used for smaller earthquakes for regional domains.

Why is there a need for real-time forecasting?

- The pre-computed database approach cannot exhaust all possible earthquakes (locations and focal mechanisms). Many recent earthquakes have not been thrust faults, as are typically assumed in databases.
- Smaller earthquakes are not well represented by the current database models used at PTWC (usually the unit sources are too large for smaller earthquakes)
- It is labor and resource intensive to create and maintain a large database, especially for a global domain (the current database models at PTWC are only for specific basins. Sumatra 2004 tsunami, for example, is a global-reach tsunami).
- If model physics are changed (e.g., improved or modified), the entire database needs to be recomputed

Non-thrust Earthquakes causing tsunamis

Many large earthquakes (including ones that caused destructive tsunamis) are not of shallow thrusts. Here is a list of large non-thrust earthquakes since 2006:

- Kuril 2007, M8.1, normal
- Samoa 2009, M8.0, normal
- Sumatra 2012, M8.6, Strike-slip
- Philippines 2012, M7.6, Normal
- Okhotsk 2013, M8.3, Normal
- Scotia Sea 2013, M7.7, Strike-slip
- Aleutians 2014, M7.9 Normal/Strike-slip

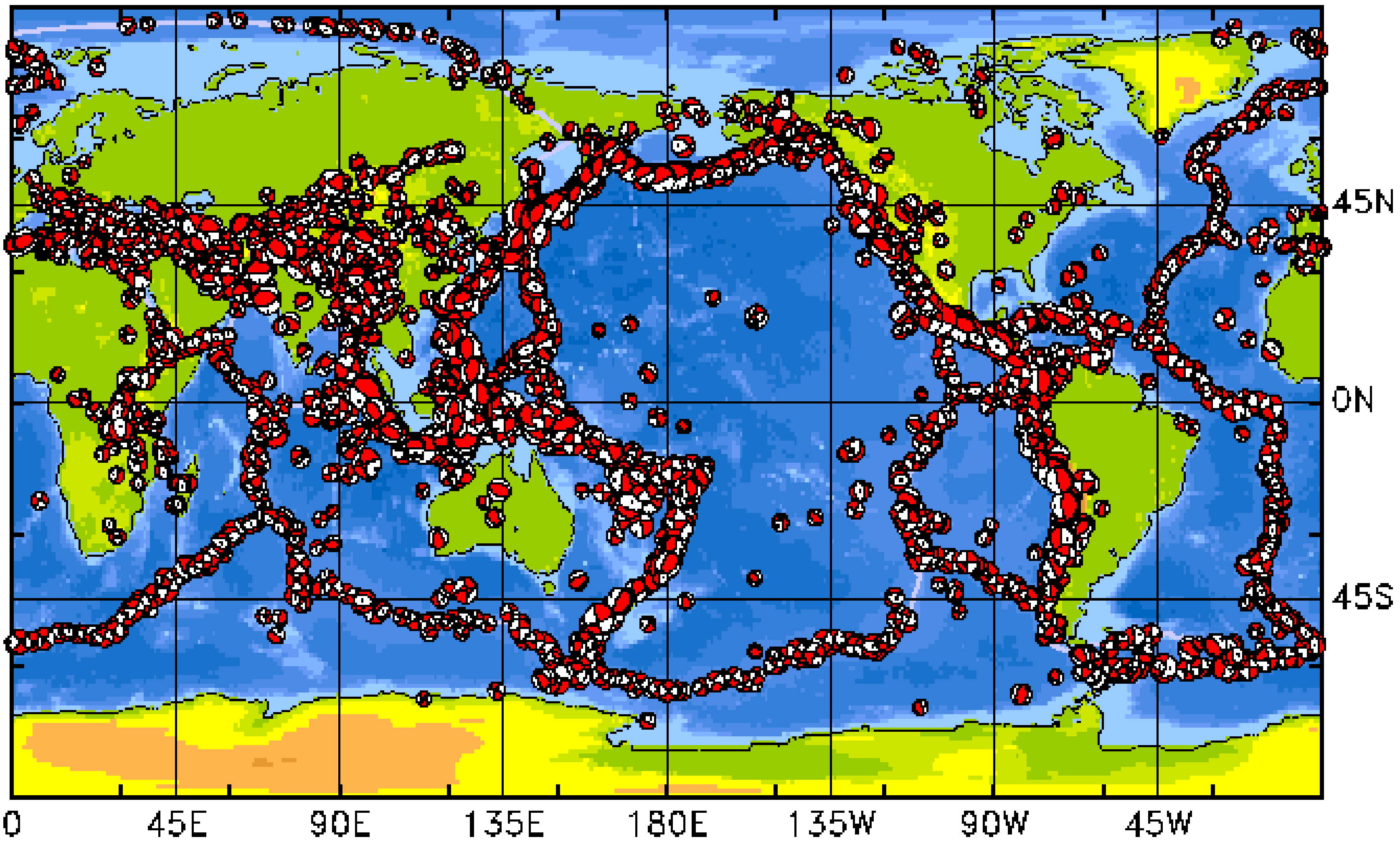
The RIFT Model domain

- **Automated model domain based on tsunami travel time**
- **For a large earthquake, the model domain includes regions within five hours of tsunami arrival time.**
- **For smaller earthquakes (magnitude < 7.7), resolution and domain size are magnitude dependent. For a magnitude 6.6 earthquake, for example, 30-arc-sec. will be used. The model execution times for these runs are ~10 seconds wall-clock time.**
- **There about 40 Pre-defined ocean basins and marginal seas, including the global ocean. For the Pacific basin at 4-arc-min. resolution, 36-hour integration takes about seven minutes.**
- **The operator can also enter domain parameters and integration length manually or select the domain graphically using the mouse.**

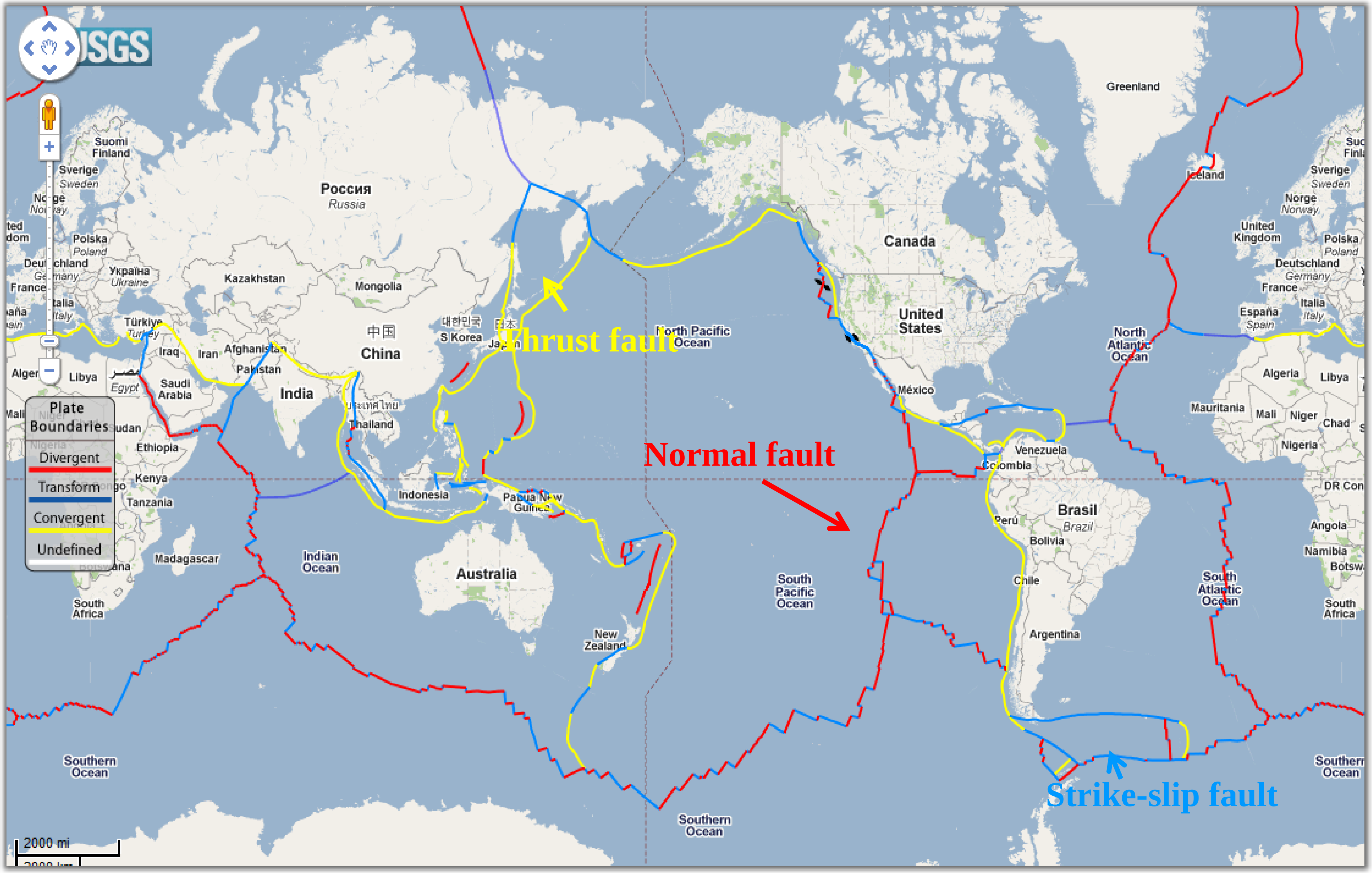
Default focal mechanisms:

- Historical centroid moment tensors (~40,000 CMT solutions since 1976).
- Default focal mechanism based on EQ epicenter proximity to the type of fault line (USGS)
- Real-time focal mechanisms:
  - W-phase Centroid Moment Tensors
  - Global Centroid Moment Tensors (when available)
  - Other Centroid Moment Tensor solutions (when available
- Seafloor deformation:
  Okada (1985) static dislocation model

Focal mechanisms:
Global (formerly Harvard) CMT catalog
Map as of Dec. 2008
Credit: http://www.globalcmt.org/



Default focal mechanisms based on earthquake's proximity to the type of plate boundaries (credit: USGS)



Green's Law Coastal Forecast (Green, 1837)

$$A_c = A_o\left(\frac{H_o}{H_c}\right)^{\frac{1}{4}}$$

- **Ho: water depth of an offshore point**
  Hc: water depth of a coastal point (assumed to be at 1 m).
  Ao: offshore wave amplitude = 0.5*(max-min) or half of the waveheight
  Ac: Green's law coastal wave amplitude

- **Offshore point: closest model grid point in deep water. The offshore water depth is chosen such that the waves with 10-min. period can be resolved by the model grid (eight grid points within one wavelength).**

- **For example,**
  - At 4-arc-min. resolution, Ho = 1000 m
  - At 30-arc-sec resolution, Ho = 16 m

- **If an offshore point is not found within a 300 km radius from a coastal point, there will be no forecast at that point. This essentially excludes wide continental shelves at 4-arc-min. resolution. Higher resolution is needed to have a Green's law forecast in those regions.**

Underlying Assumptions of the Green's Law

- The coastline is linear and exposed to the open ocean. Therefore, it is assumed that tsunami waves near the coast behave like one-dimensional plane waves.

- There is no significant wave reflection and there is no turbulence dissipation. In the real world, dissipation is important in shallow water. The seafloor composition has an influence on tsunami runup (e.g., coral reefs tends to dampen the tsunami runup).

- The bathymetry is assumed to be slow varying compared to the wavelength of the tsunamis. Thus, for locations with steep bathymetry (such as small islands and atolls), the Green's Law forecast tends to overestimate the wave amplitudes, everything else being equal.

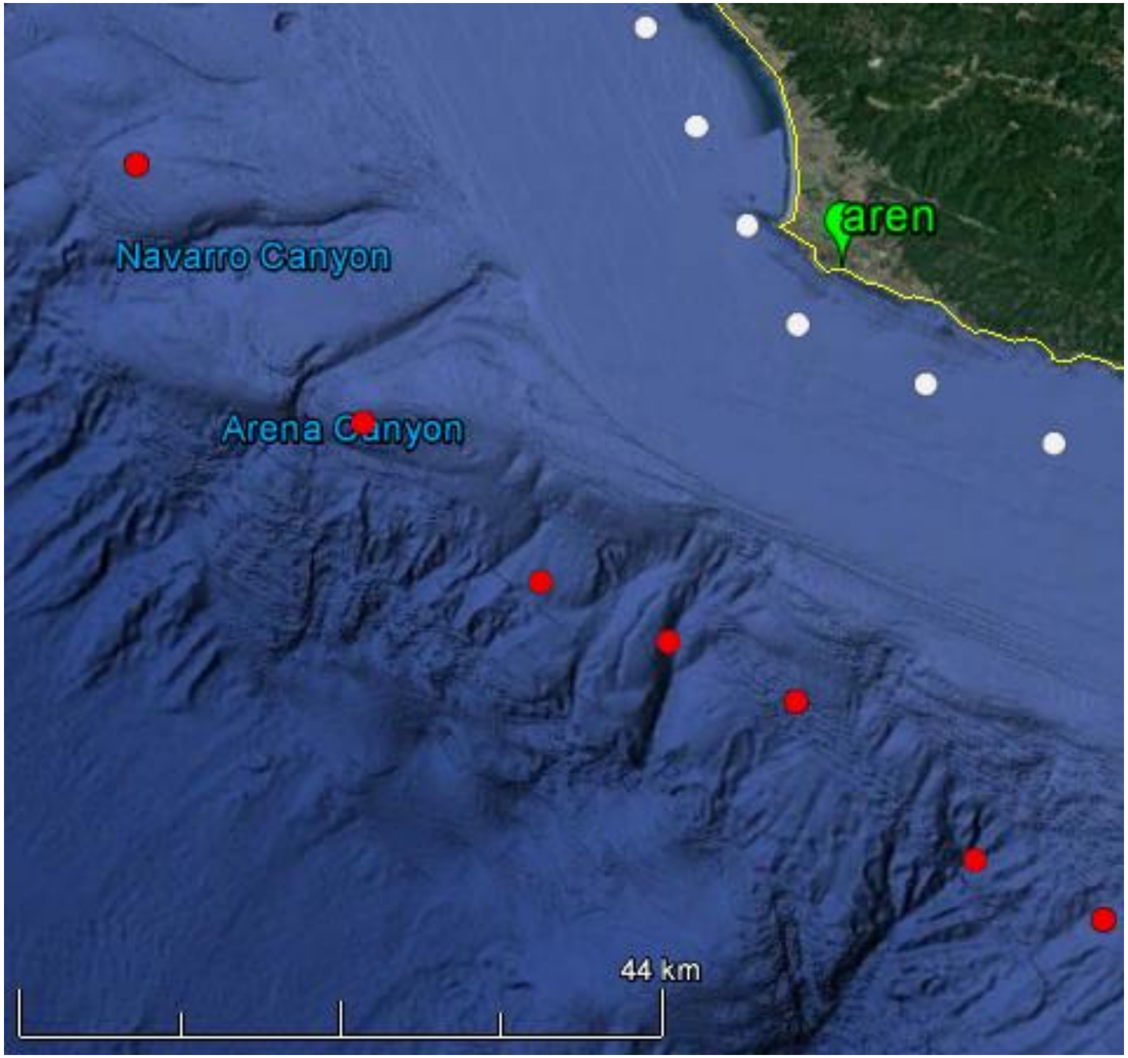
Caveats of the Green's law:

- Meant for coastal points exposed to the open ocean. In other words, forecast for coastlines with complex geometry (Fjords, estuaries, river mouths, etc.) can be easily in error. The results for these regions if shown should be interpreted as forecast for the part of the coast that is more exposed to open ocean.

- It is a stretch to compare Green's law forecast with observations at hidden tide stations (e.g., too far from open ocean, usually over predict) and at tide stations in resonant harbors (usually under predict). In fact, the model at 4-arc-min. resolution cannot resolve the tide gauge location.

- For small islands and regions with steep bathymetry, it tends to over-predict. The true wave amplitude might lie between the Green's law amplitude (upper bound) and the resolved amplitude at the nearest model ocean/offshore point (lower bound), without the Green's law being applied (see Section 4 Error Analysis).

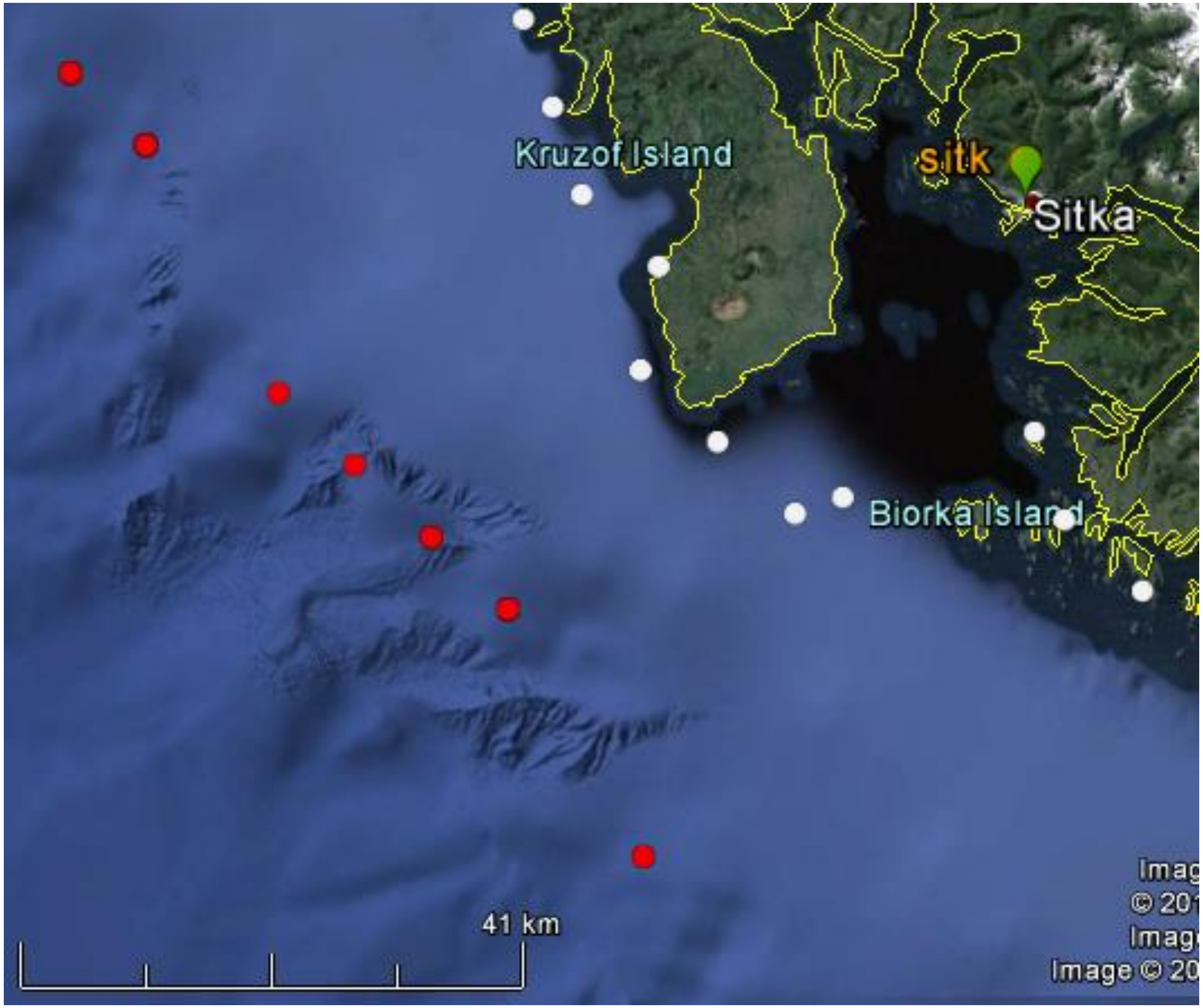
At 4-arc-min. resolution, the RIFT model does not really know where exactly the tide stations are located. However, comparisons with tide stations that are more exposed to the open ocean can be helpful in assessing the quality of forecast (e.g. for the tide station in Arena Cove, California)



White dots are model coastal wet points and red dots are offshore points, (depths of which are used in the Green's Law computation)

Note that more than one coastal point might share the same closest offshore point, thus having the same forecast. In other words, the distribution of coastal wave amplitude might be more uniform than in reality.

Comparison of Green's law coastal forecast with tide stations that are hidden or too far from the open ocean is not meaningful, as is shown below (white dots are model coastal points, red dots are offshore points used in the Green's law).



Note the Sitka tide station is many kilometers away from the model coastal wet points (white dots).

Forecast at the model coastal wet points should be interpreted as forecast for the adjacent coastline exposed to the open ocean, not necessarily at the tide station location.

Another example of hidden tide station. This tide station (in Kwajalein Atoll) is inside the lagoon, not exposed to the open ocean. Comparison of observation at this station with Green's law (meant for the open ocean side) would not be very meaningful.

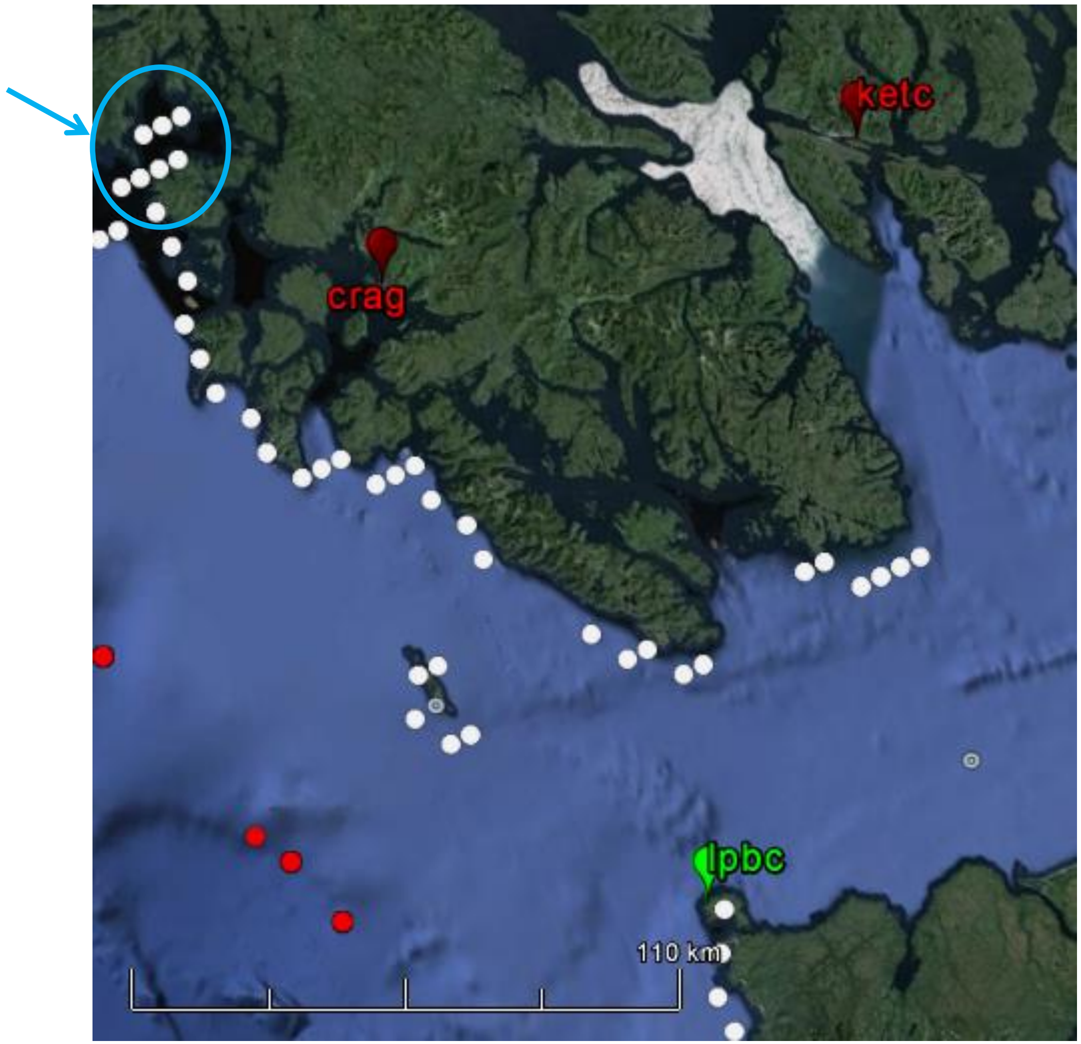
Green's law forecast tends to overestimate for tide stations on Atolls or on islands with fringing/barrier reefs with steep bathymetry (e.g., Wake Island is such a location).

RIFT's offshore wave amplitude (without Green's law applied) or twice the offshore wave amplitude, tends to agree better with tide station observations at these locations. Twice the offshore wave amplitude is equivalent to runup on a vertical wall, assuming the ocean bottom is flat from the offshore point to the coast. Note the offshore point here is the closest model ocean point to the coast/tide station, not necessarily the offshore point used in the Green's law computation, which has to be at a water depth of 1000 m or deeper for a 4-arc-min. resolution.

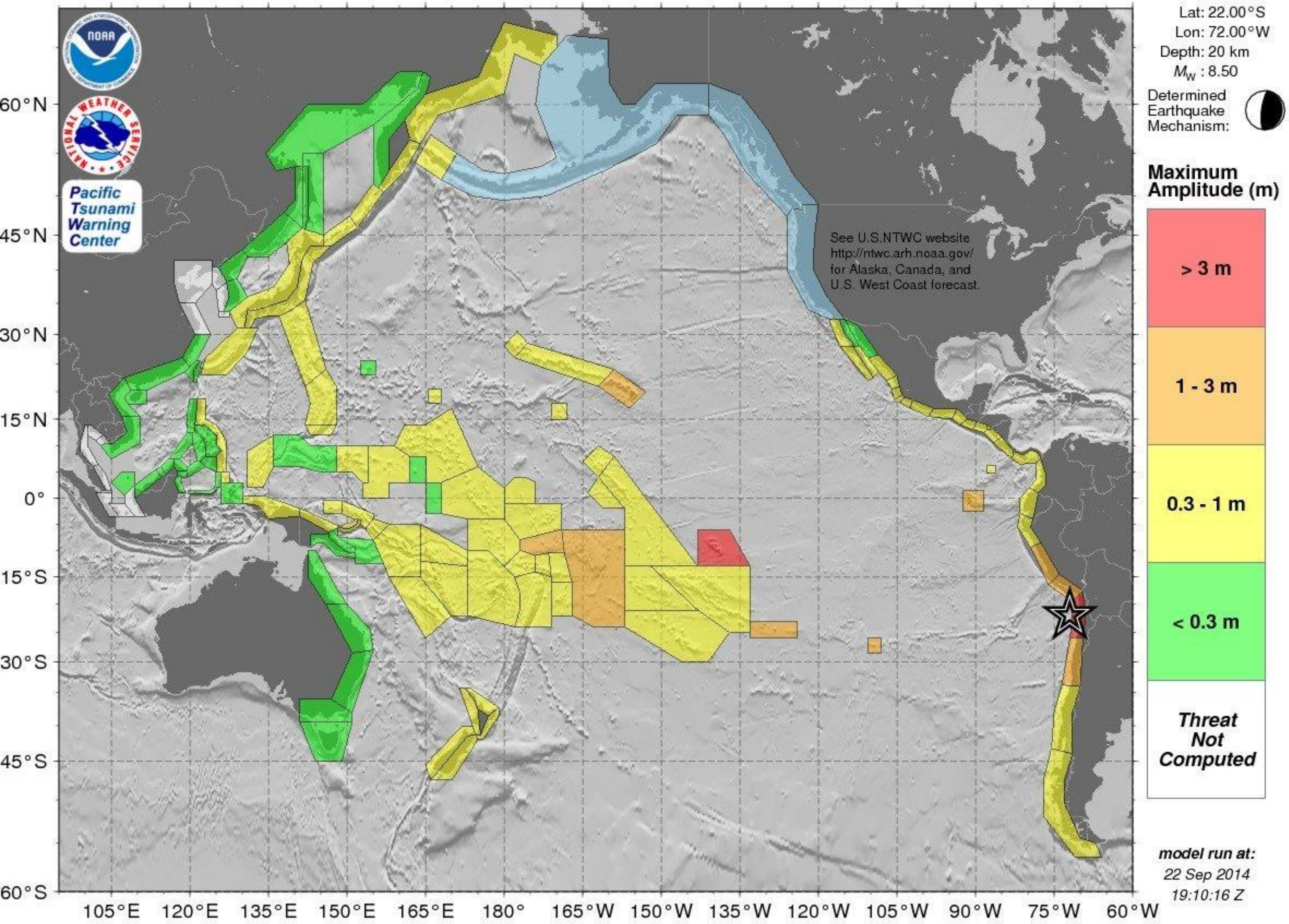
Green's law coastal forecast cannot be applied to locations too far from the open ocean. There will be no forecast for tide stations/coastal points that are too far from the open ocean (e.g., crag and ketc as shown below).

Also note that the forecast inside the circle on the left is not meaningful (i.e., these points are too isolated/hidden from the open ocean). Forecast at these locations should be discarded.

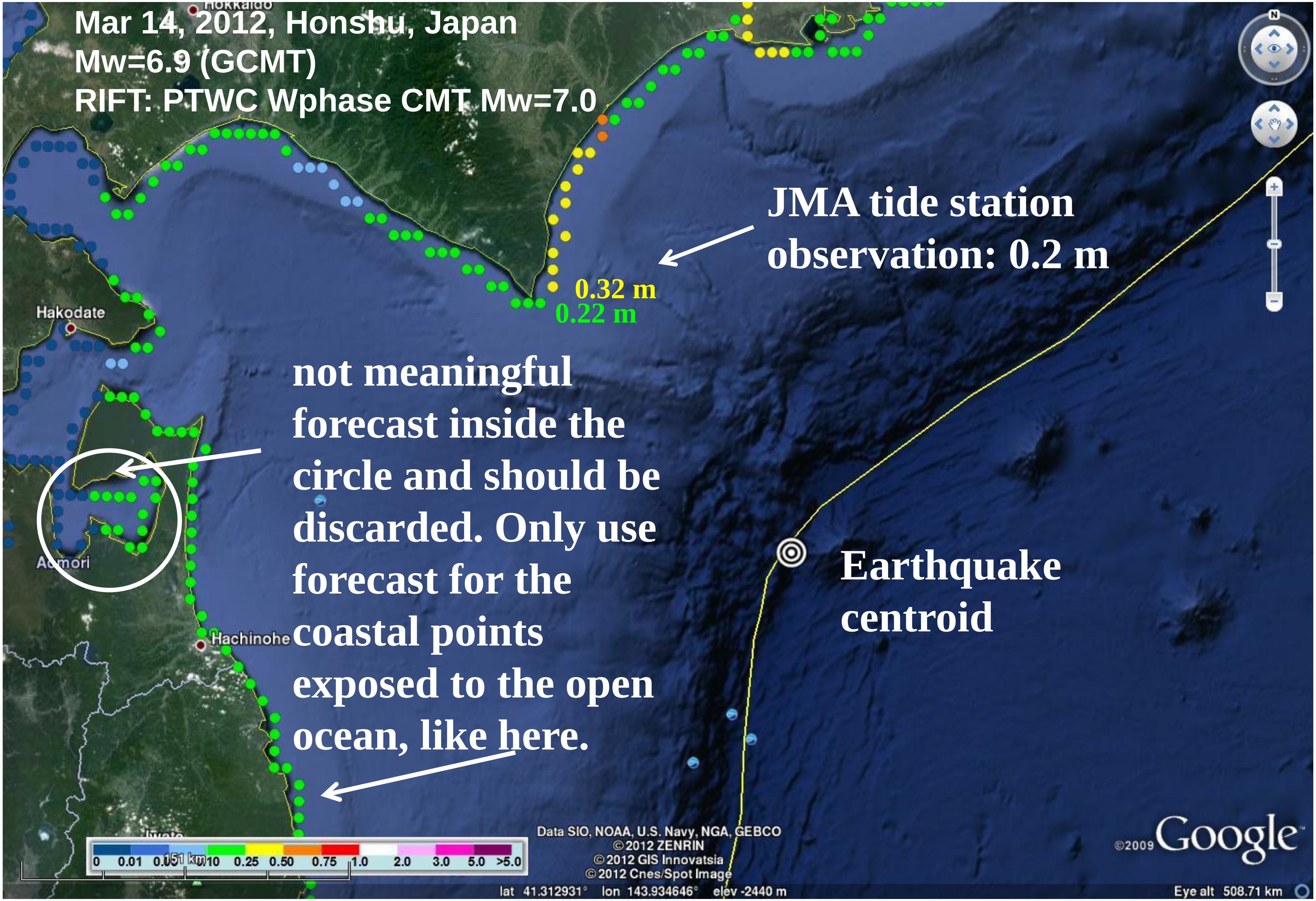
Note however, that the polygon/threat map of PTWC's enhanced product is constructed from the maximum coastal forecast inside each polygon — (usually large enough to include coastlines that are more exposed to the open ocean). Therefore, the "spurious" forecast as shown in the circle has no consequence for the threat map (see next slide).



The color of each polygon is based on the maximum Green's law wave amplitude inside the polygon. There might be hundreds of coastal points inside some polygons, covering more than 1000 km of coastline. A single point having an amplitude exceeding a threshold determines the color of the polygon, even if the rest of the coastal points inside the polygon have wave amplitudes below the threshold.

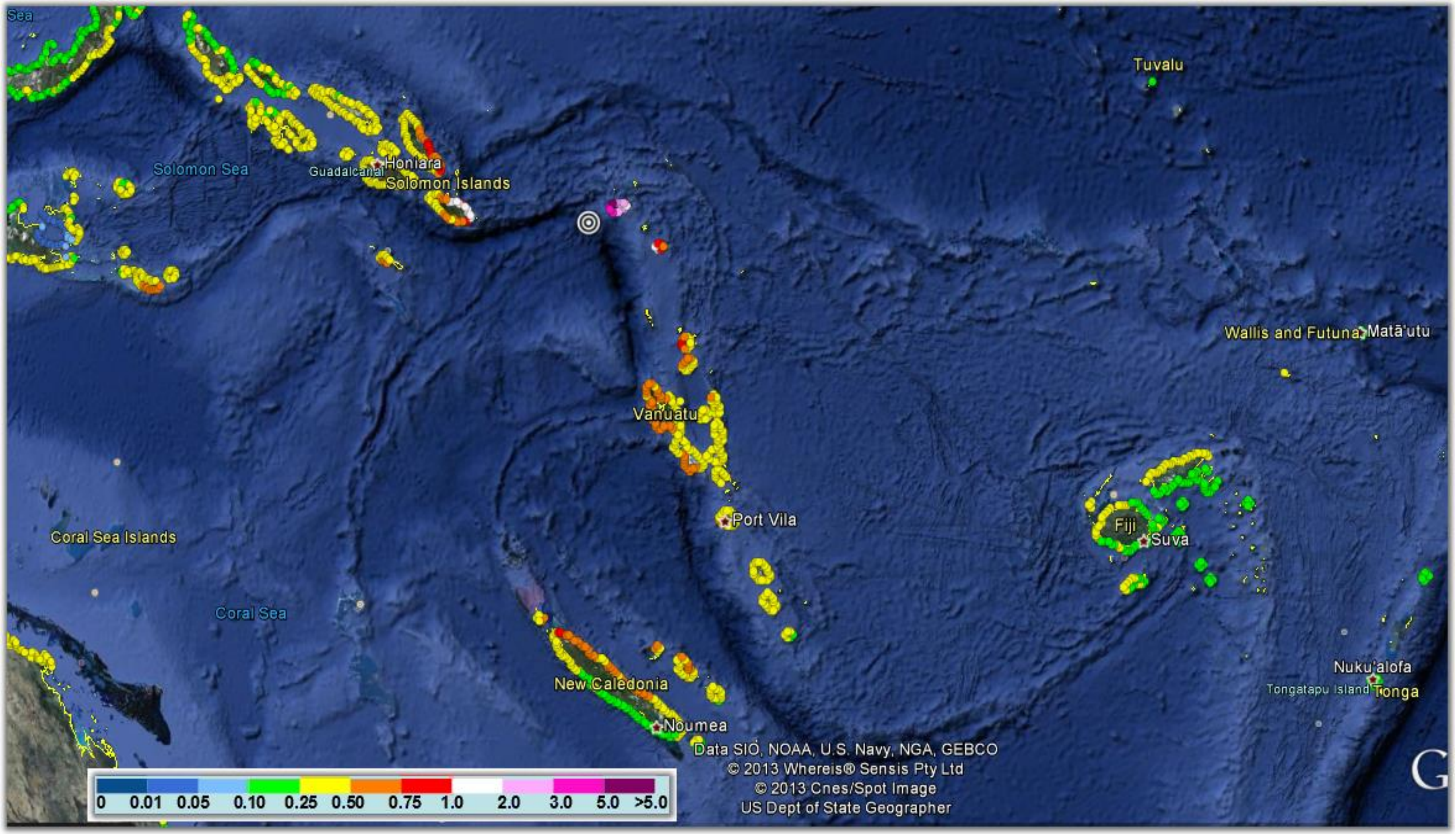


Example of a real event. Coastal forecast for a small earthquake



Feb. 6, 2013 Solomon Island Tsunami (Mw=8.0)

PTWC earthquake magnitude and travel time based warning criteria placed many coastal regions under warning/watch during the event. RIFT's Green's law results obtained during the event (shown below, coastal_amp.kmz) only indicated a local/regional land threat (amplitude > 1 m).



3. Sensitivity and Uncertainty of RIFT Model Results

- There are many uncertainties in the RIFT forecast due to uncertainties in earthquake magnitude, location, depth, and focal mechanism. Any of these uncertainties can easily result in a factor of two or more difference in forecast.

- For very large earthquakes, the uniform slip assumption on a rectangular fault might be unrealistic, resulting in erroneous propagation forecast and thus erroneous coastal forecast. Detailed distribution of slips, which might be unknown during the event can be important, especially for the near field.

- The Green's law coastal forecast is crude. Even if the propagation forecast is correct, the coastal forecast might still be in error, especially for regions of complex bathymetry (e.g., the tendency to under-predict for resonant harbors and over-predict for coastlines hidden from the open ocean).

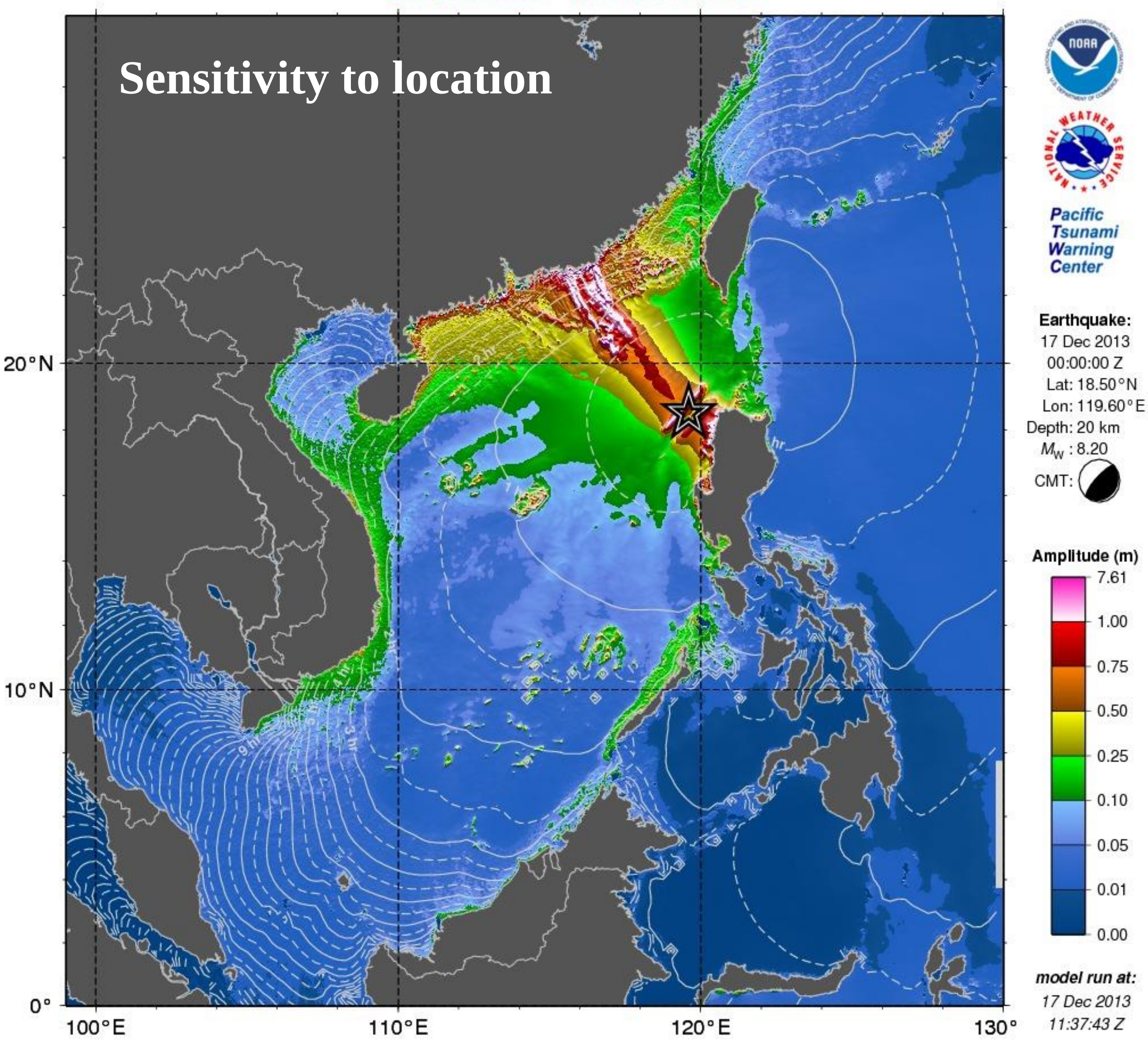
Sensitivities of RIFT model solution to earthquake location, magnitude, depth, using hypothetical Luzon trench scenarios

- **Sensitivity to location --** Time is essence for tsunami warning operations. The gain in speed can result in errors in earthquake parameters. **The initial location can be easily off by 50 km, resulting in different tsunami forecast.**

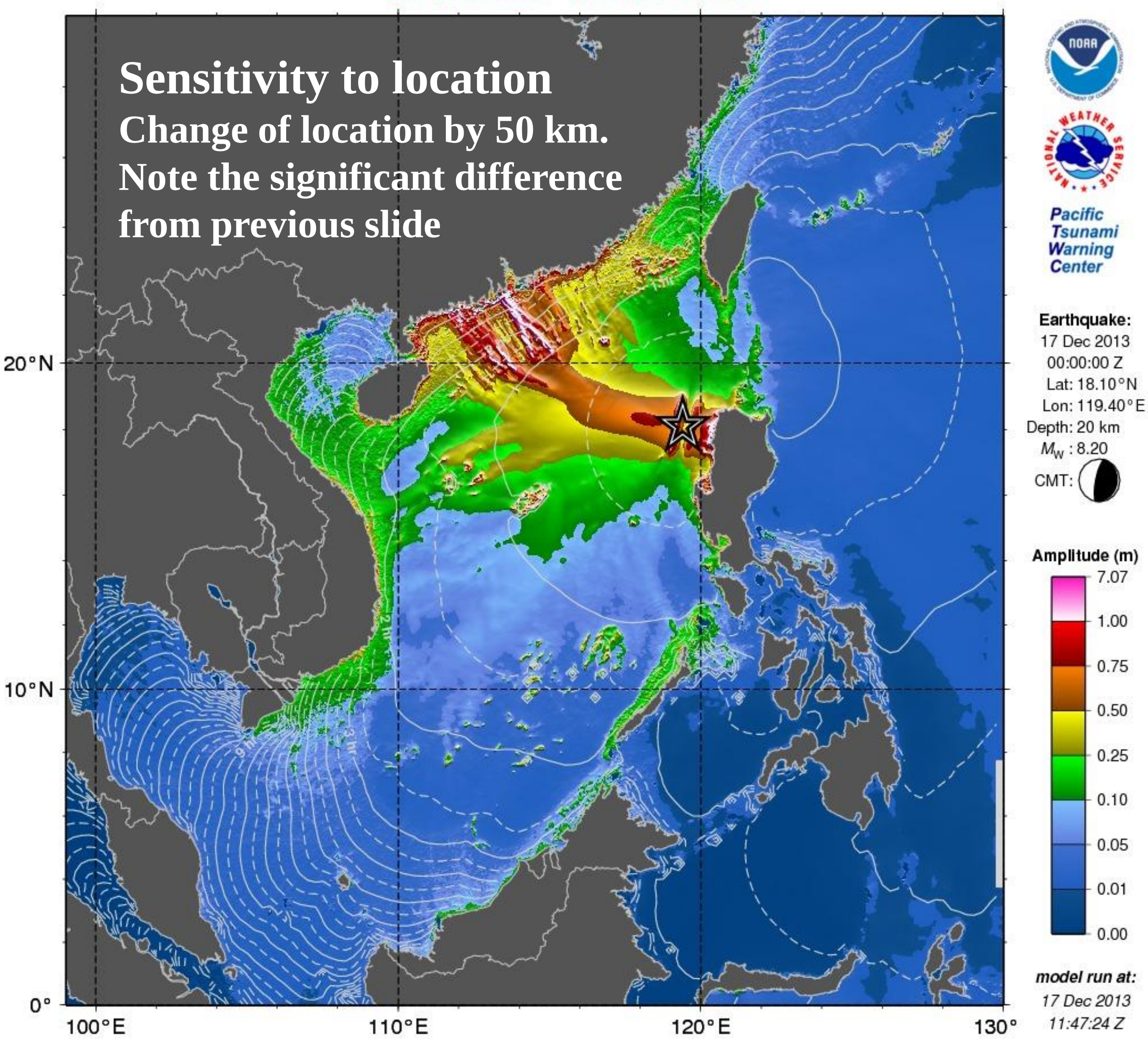
- **Sensitivity to earthquake depth --** **The smaller the earthquake magnitude, the more sensitive the model result is to earthquake depth.** For example, a hypocentral depth of 50 km is a 'deep' event for a magnitude 6.5 earthquake but it is not a deep event for a magnitude 8.5 earthquake.

- **Sensitivity to earthquake magnitude --** For tsunami warning operations, the initial earthquake magnitude can be easily off by 0.2. **A 0.2 difference in earthquake magnitude generally means a factor of two change in tsunami wave amplitude.**

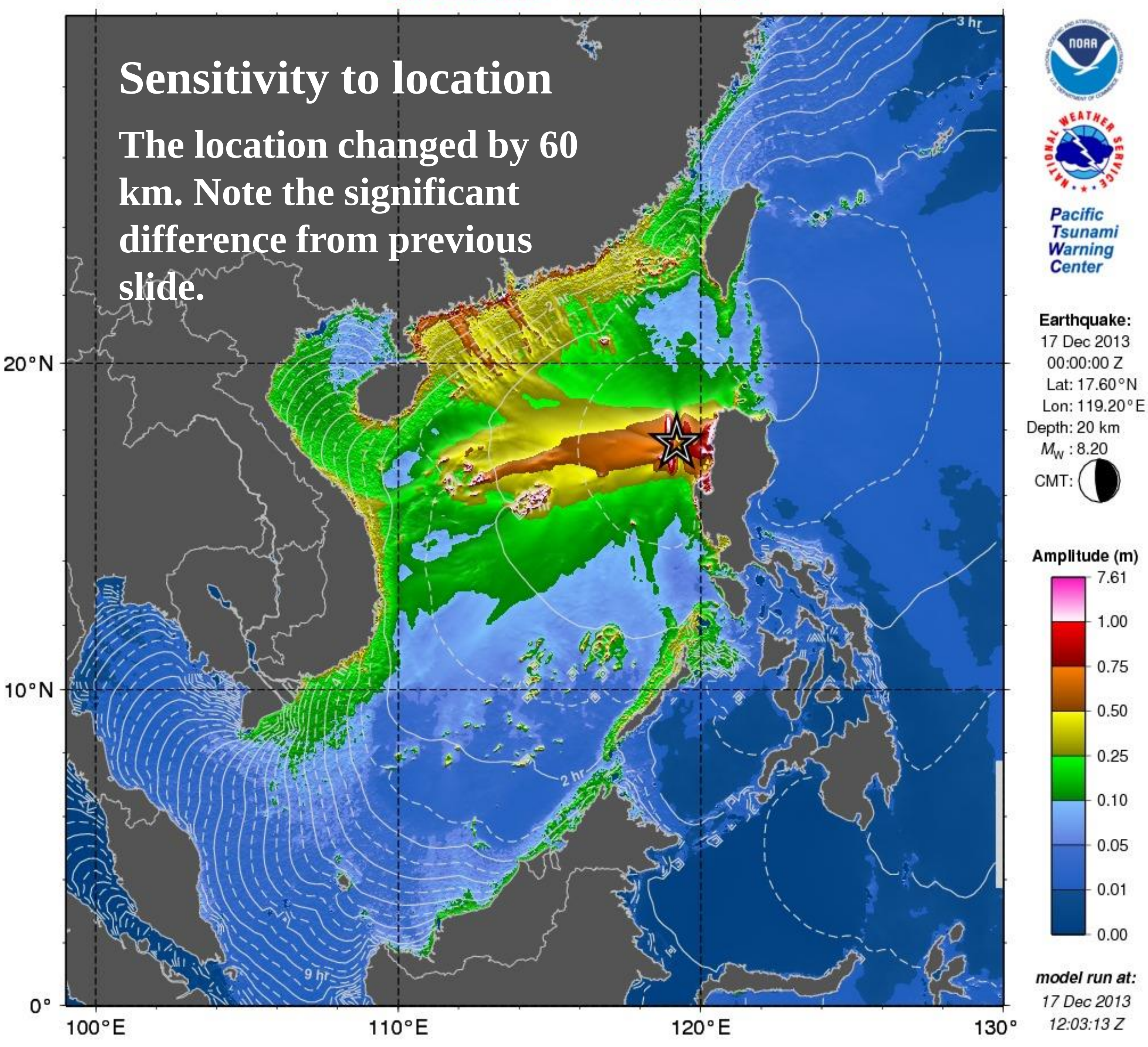
Maximum Deep-Ocean Tsunami Amplitude from Mw 8.2 Earthquake



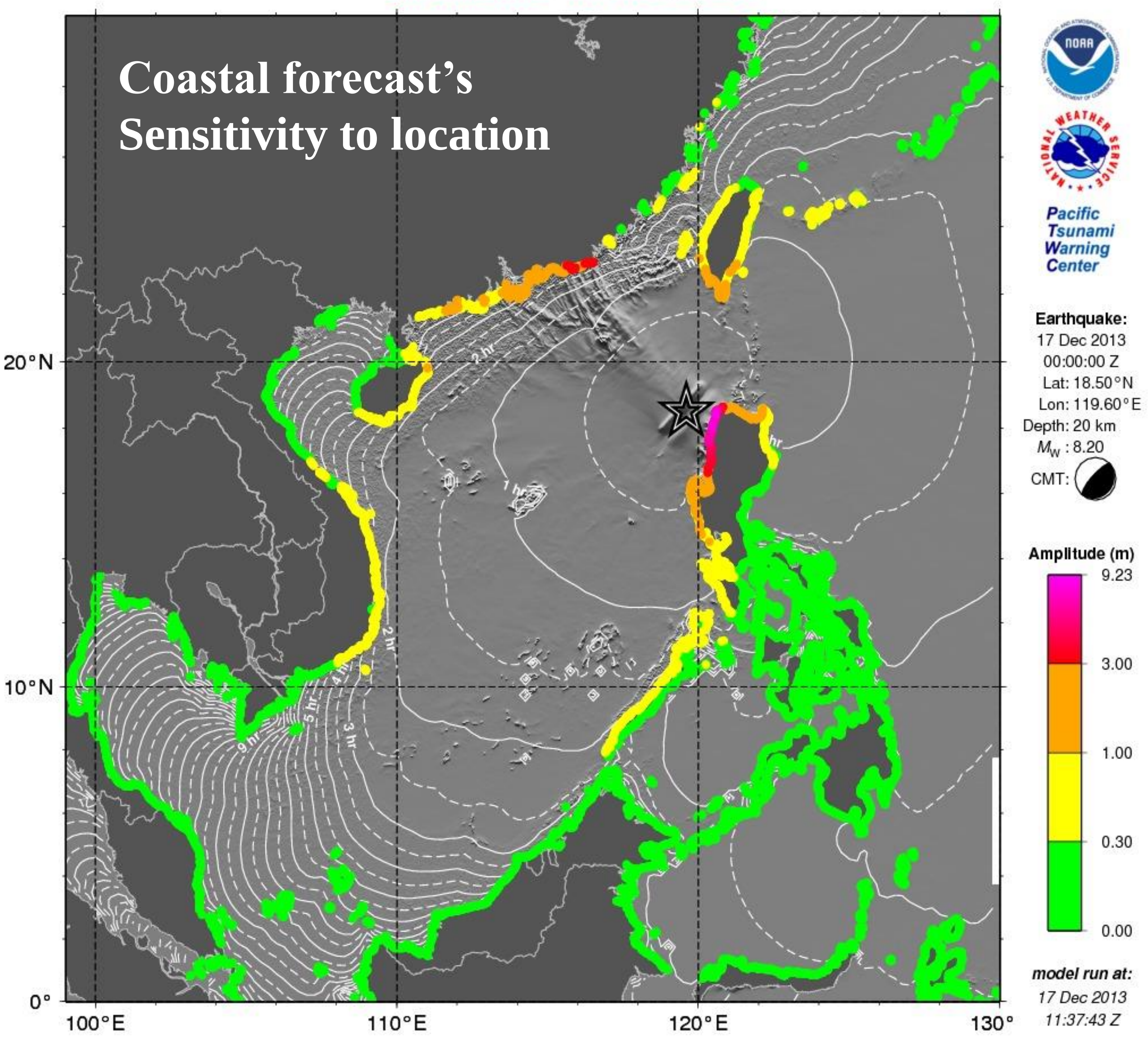
Maximum Deep-Ocean Tsunami Amplitude from Mw 8.2 Earthquake



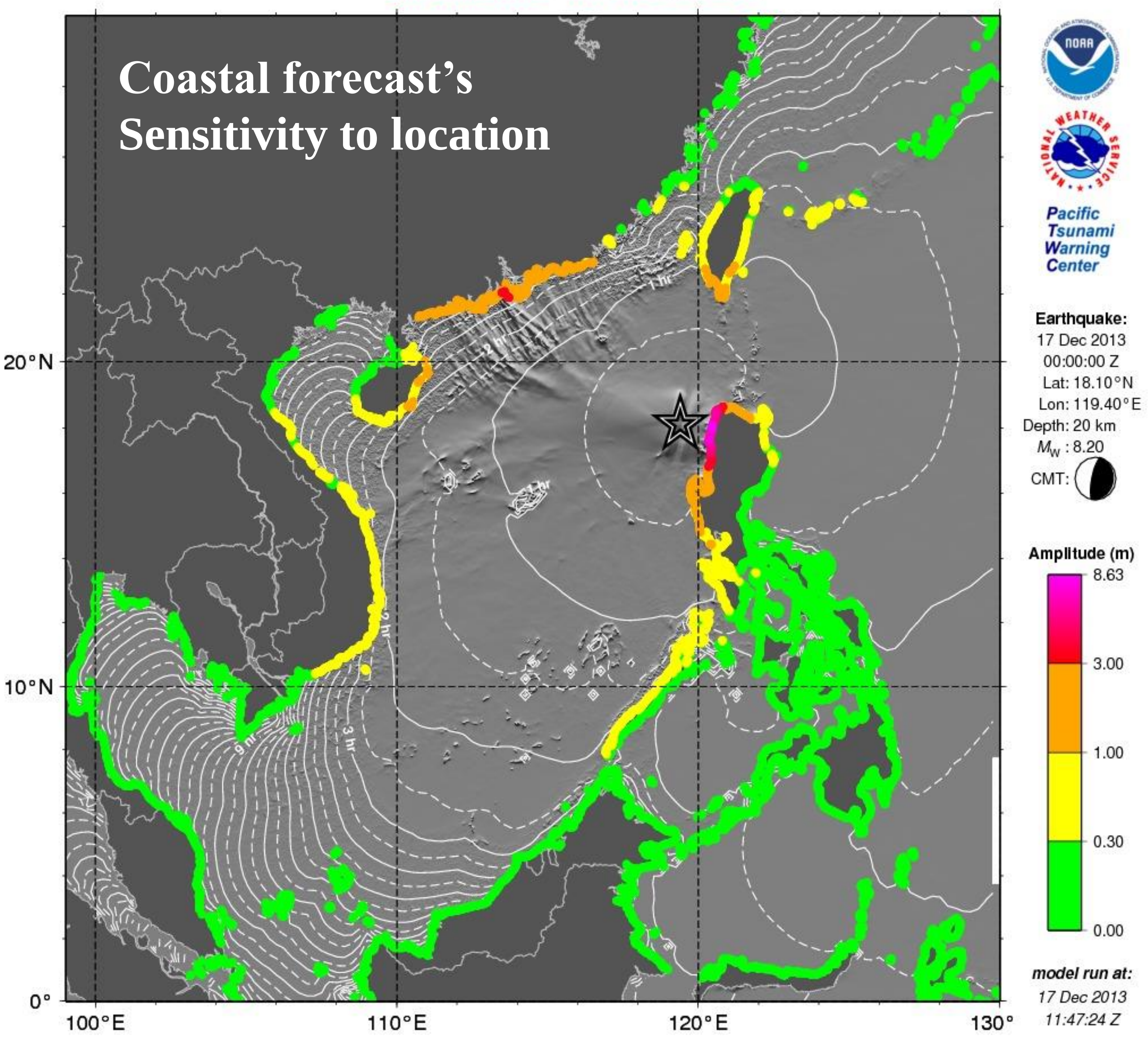
Maximum Deep-Ocean Tsunami Amplitude from Mw 8.2 Earthquake



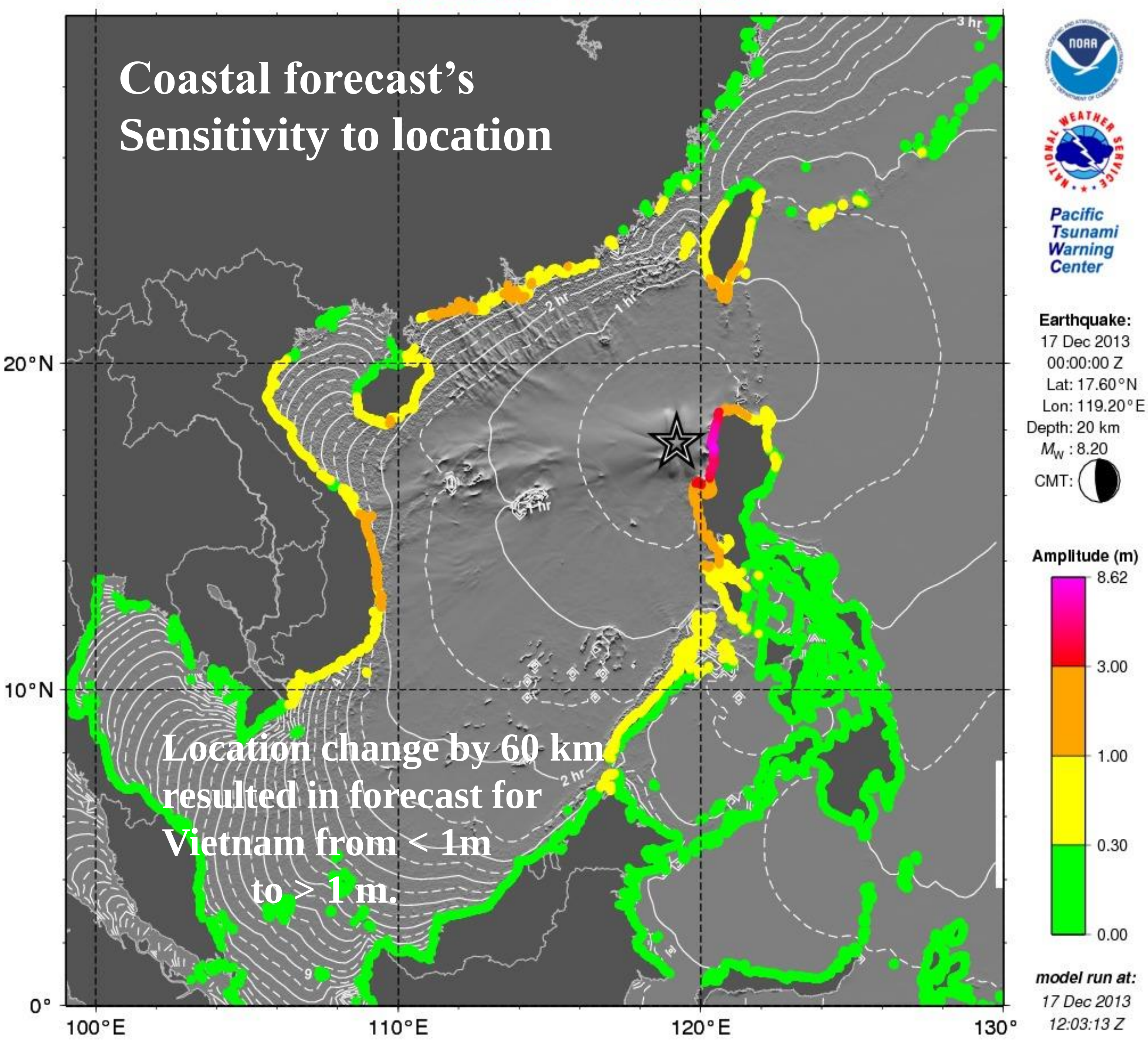
Maximum Coastal Tsunami Amplitude from Mw 8.2 Earthquake



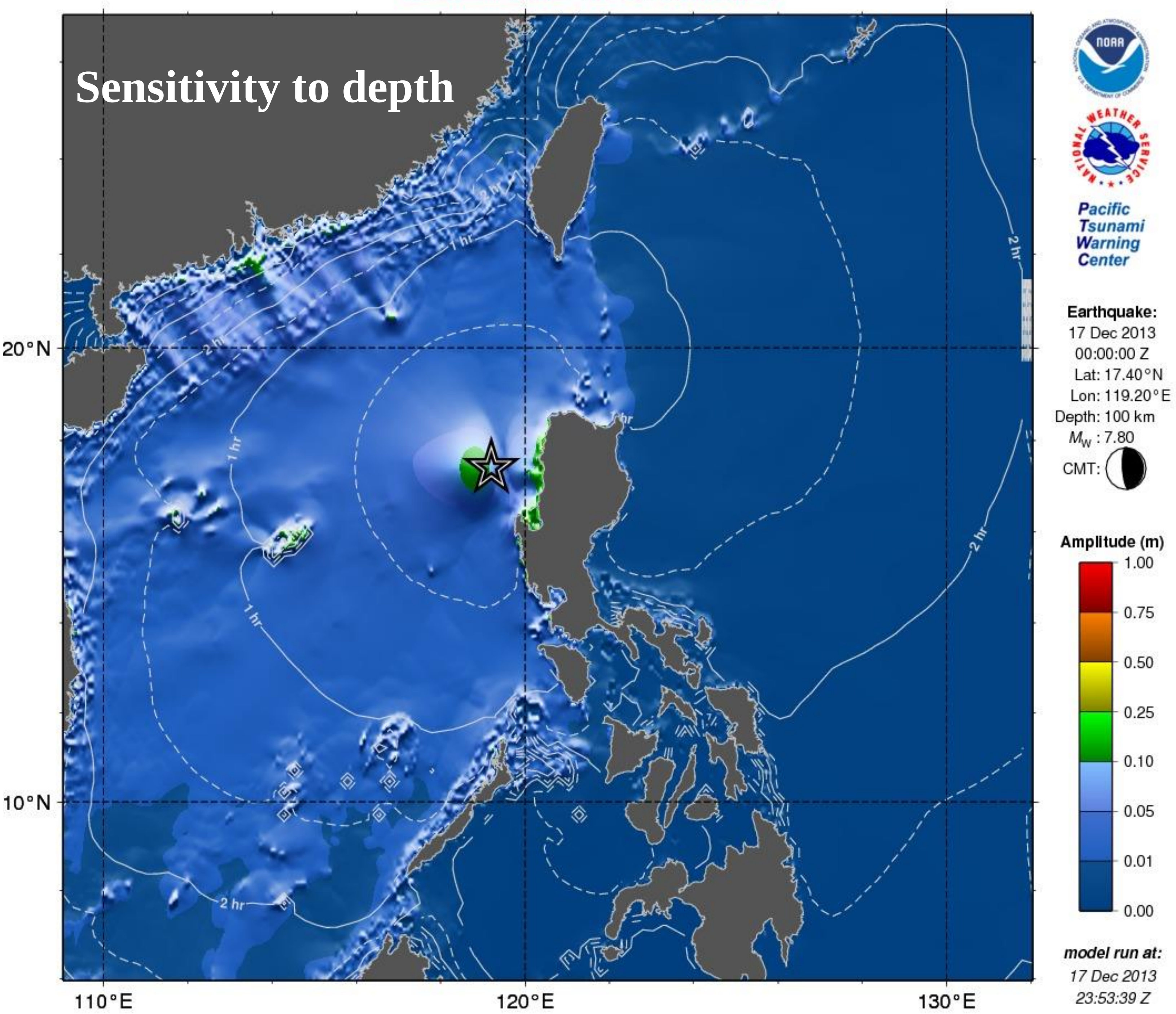
Maximum Coastal Tsunami Amplitude from Mw 8.2 Earthquake



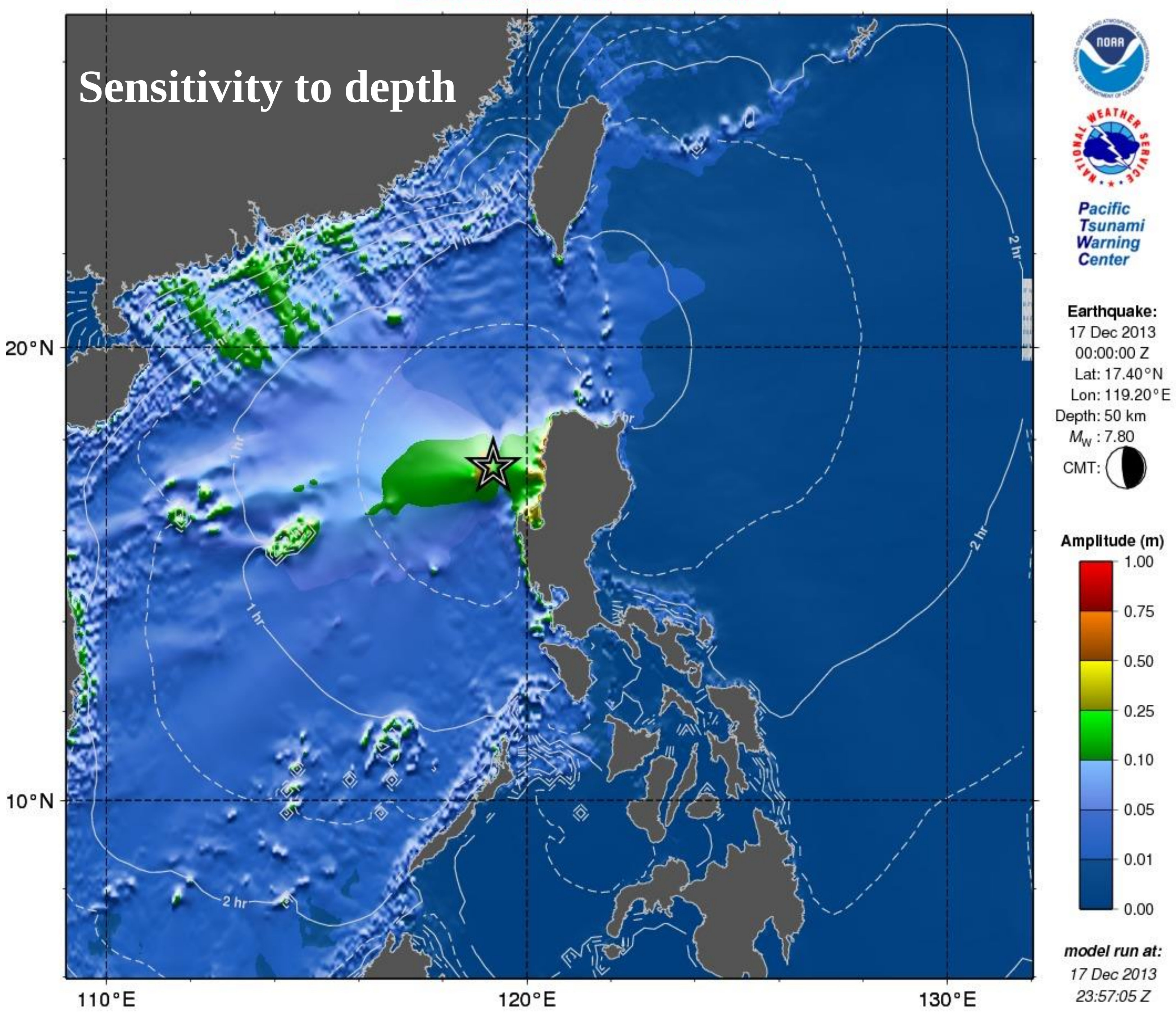
Maximum Coastal Tsunami Amplitude from Mw 8.2 Earthquake



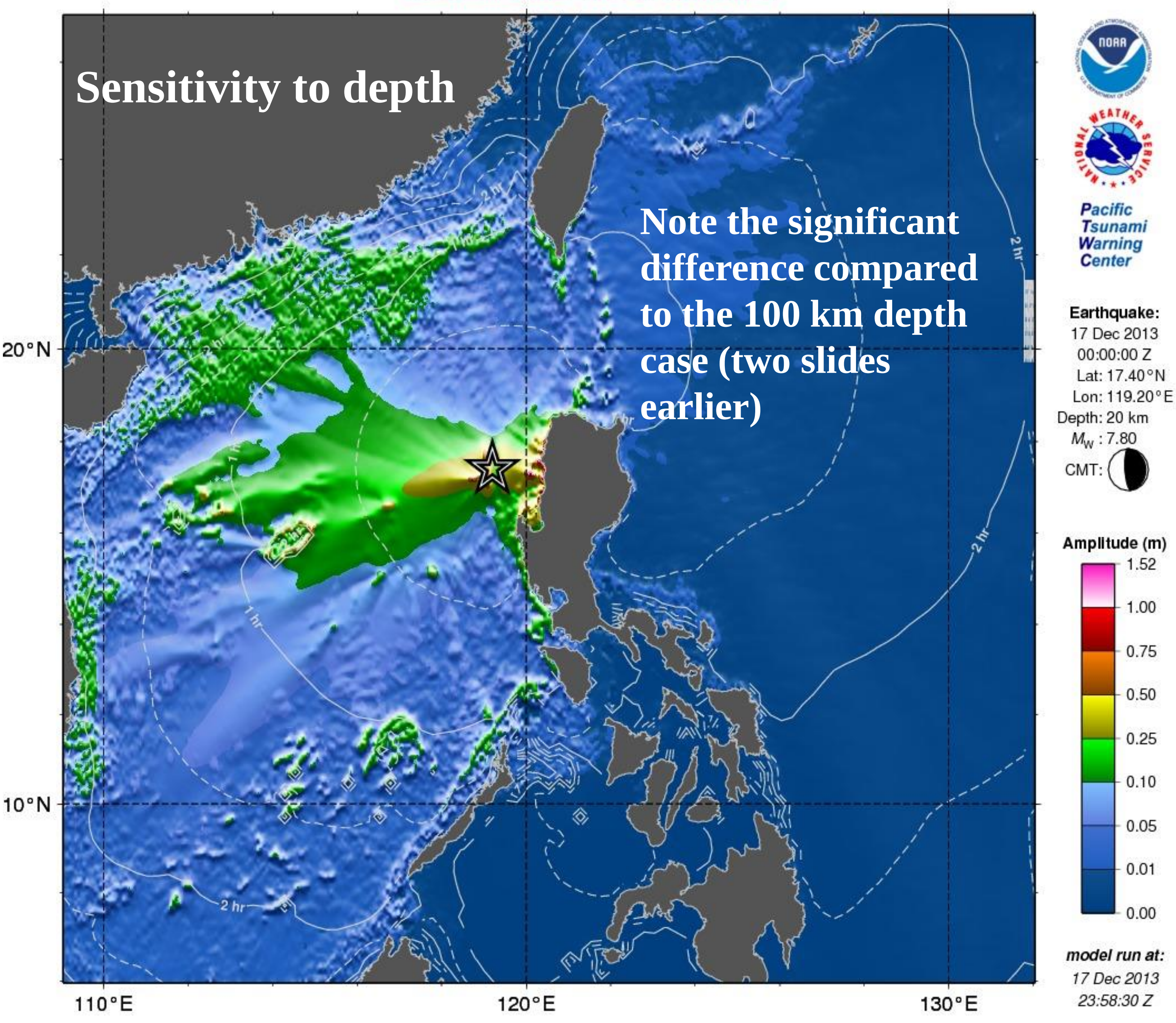
Maximum Deep-Ocean Tsunami Amplitude Mw 7.8 Earthquake at 100 km depth



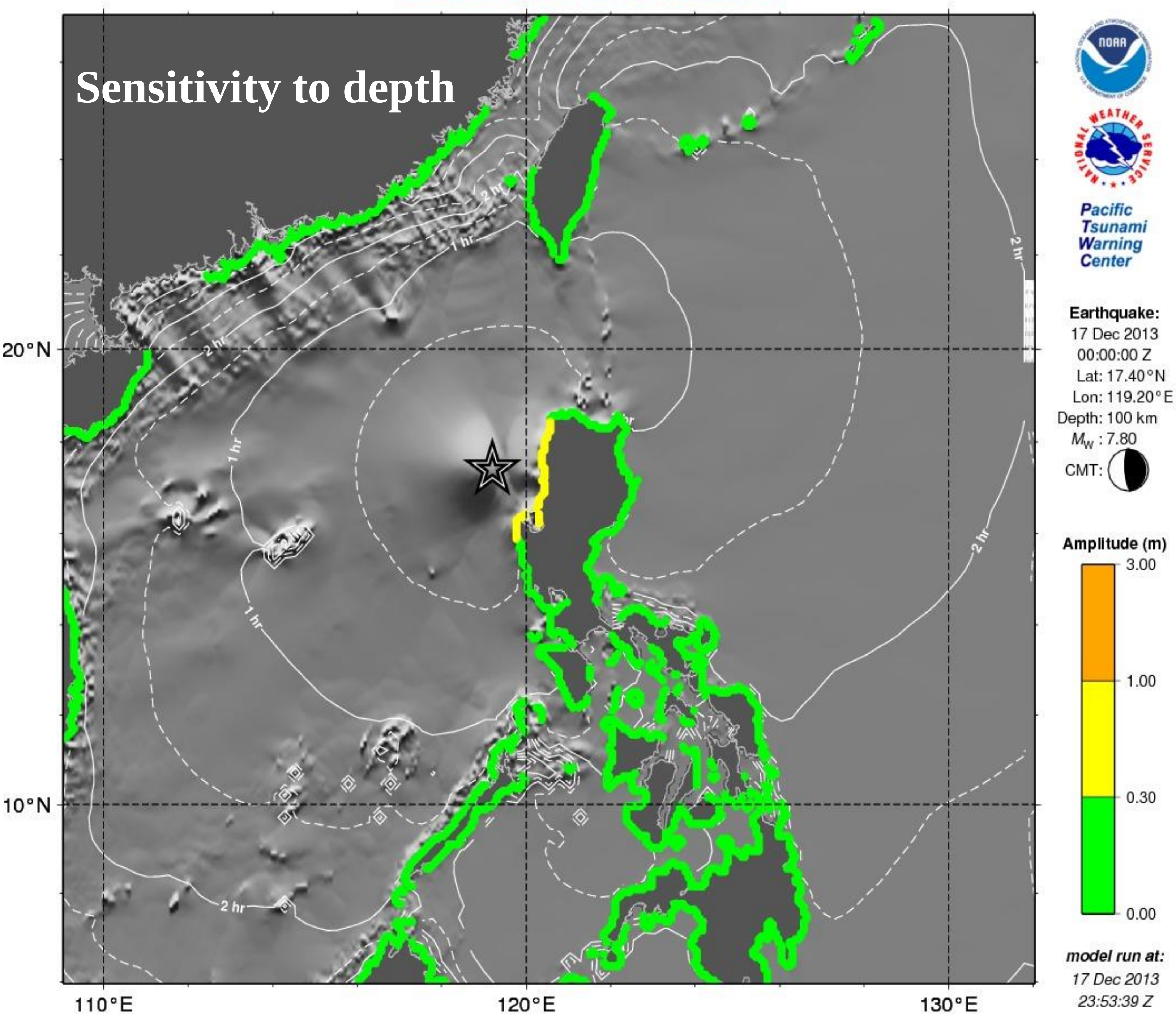
Maximum Deep-Ocean Tsunami Amplitude Mw 7.8 Earthquake at 50 km depth



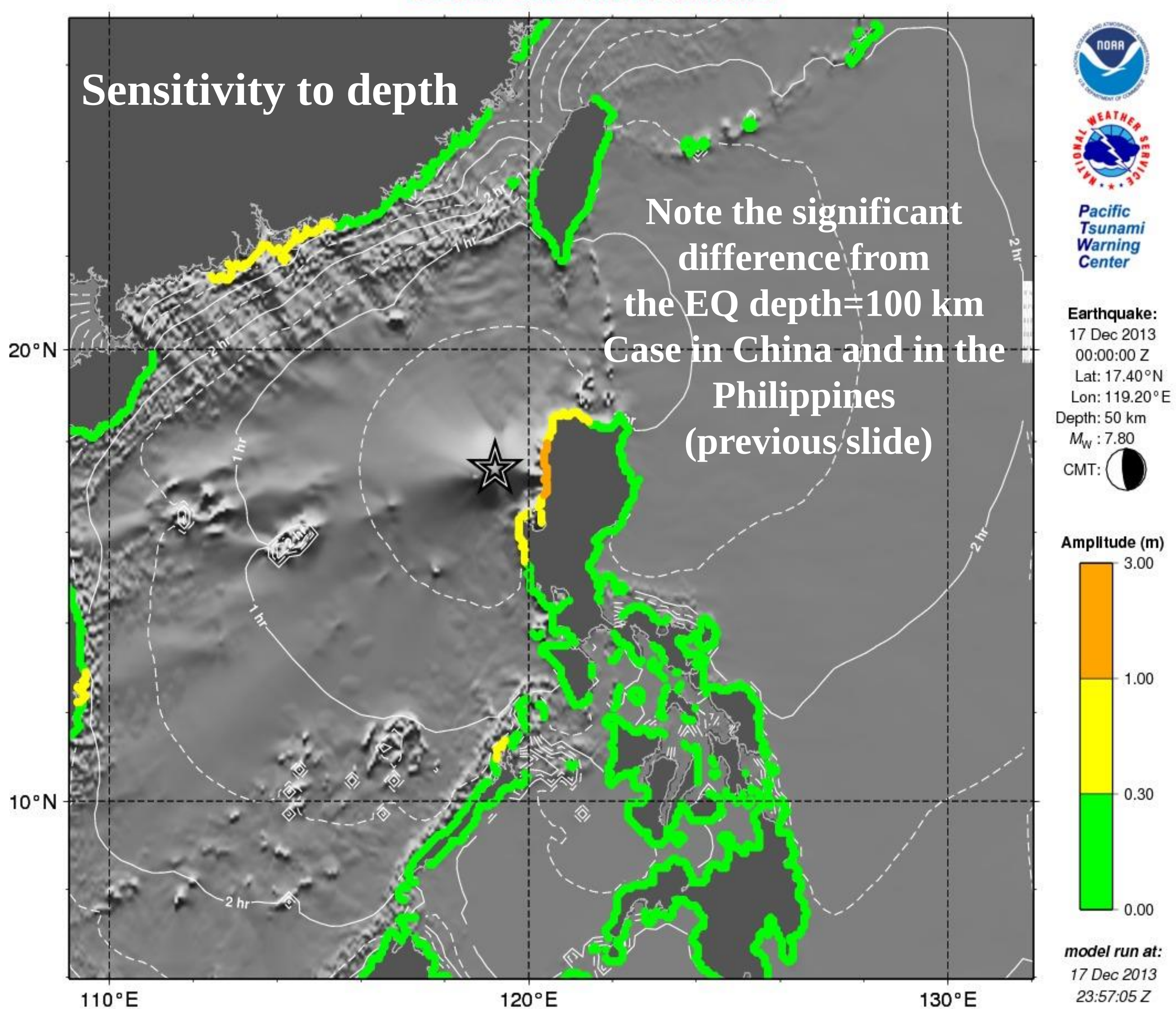
Maximum Deep-Ocean Tsunami Amplitude Mw 7.8 Earthquake at 20 km depth



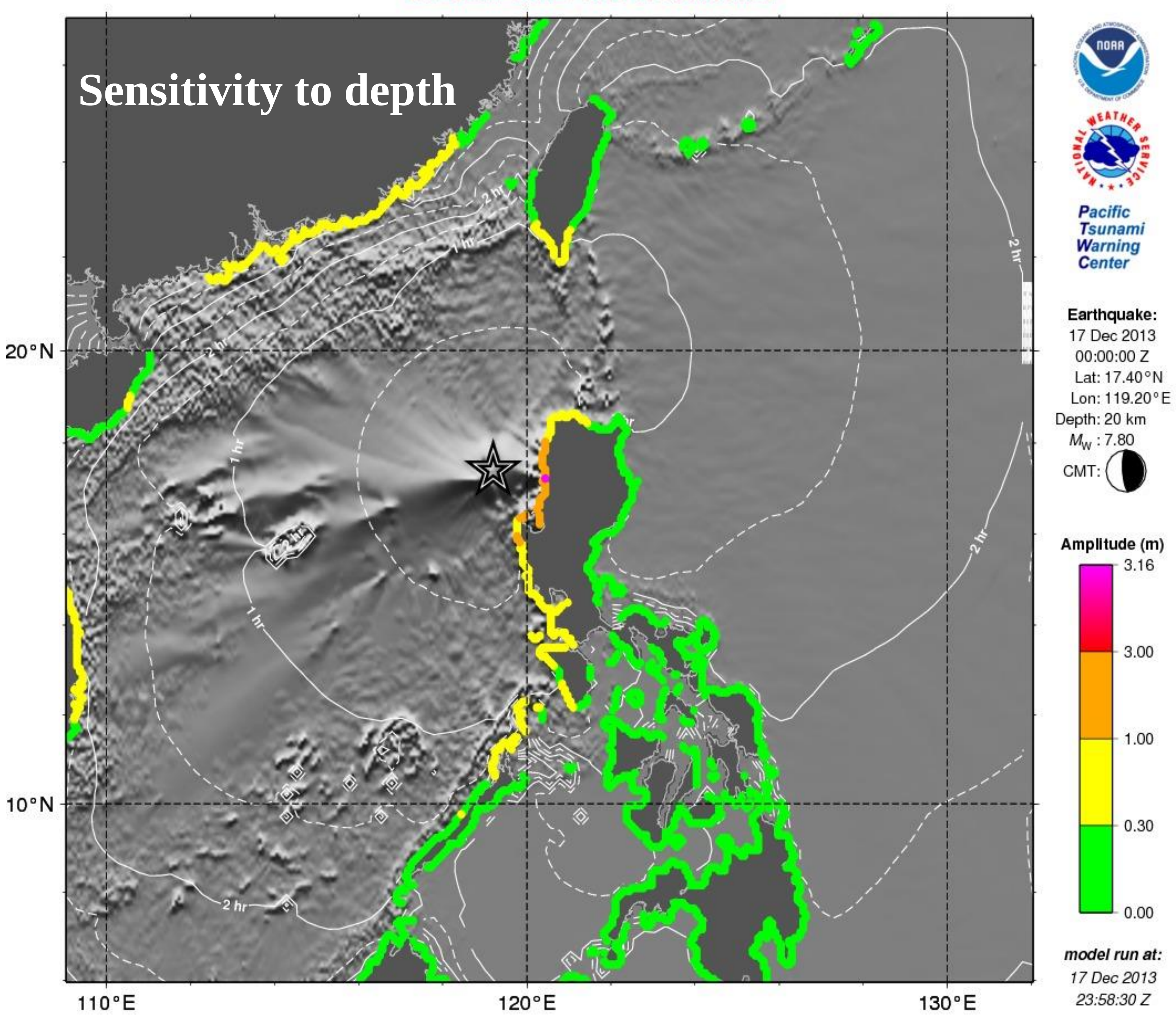
Maximum Coastal Tsunami Amplitude Mw 7.8 Earthquake at 100 km depth



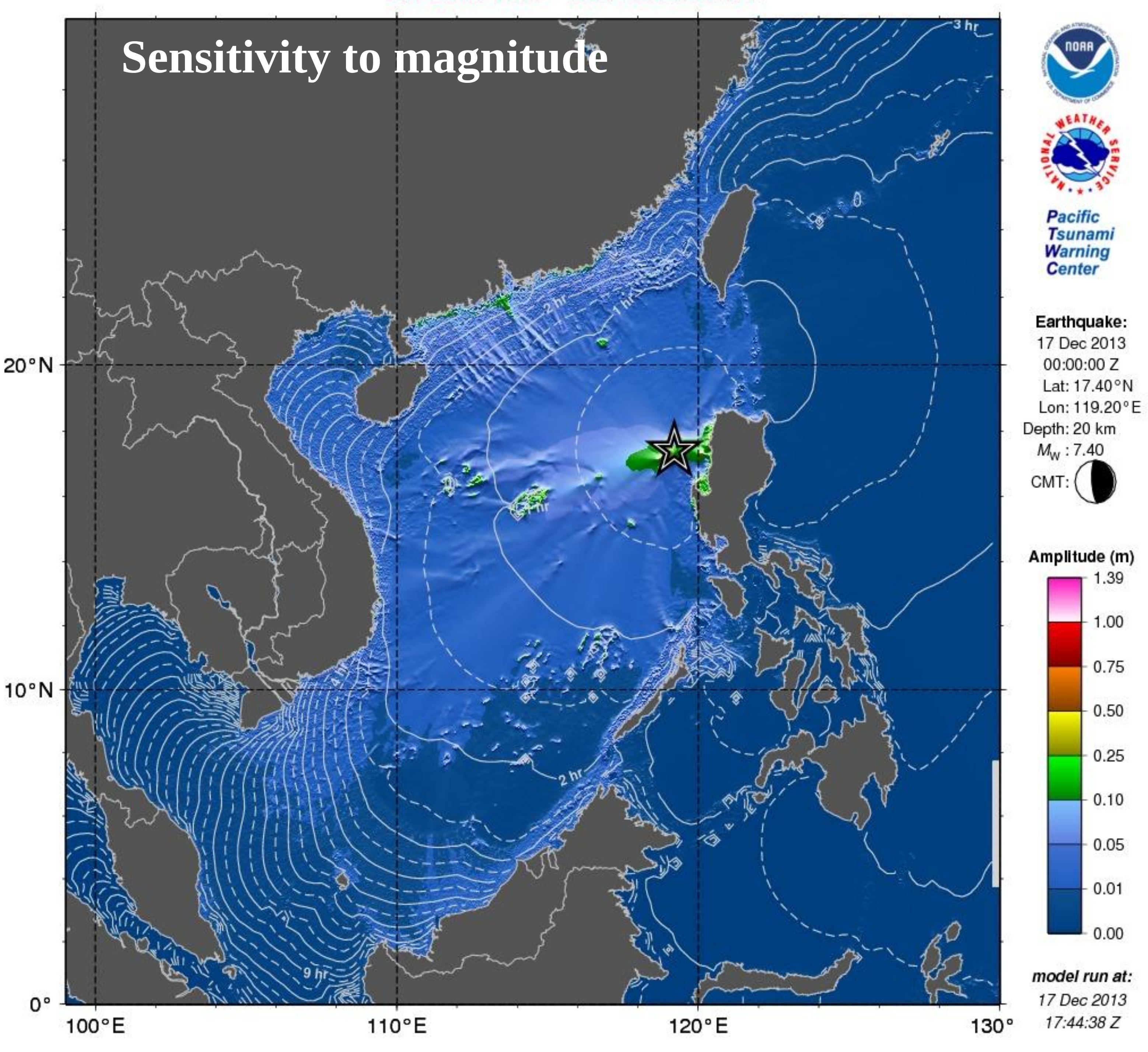
Maximum Coastal Tsunami Amplitude Mw 7.8 Earthquake at 50 km depth



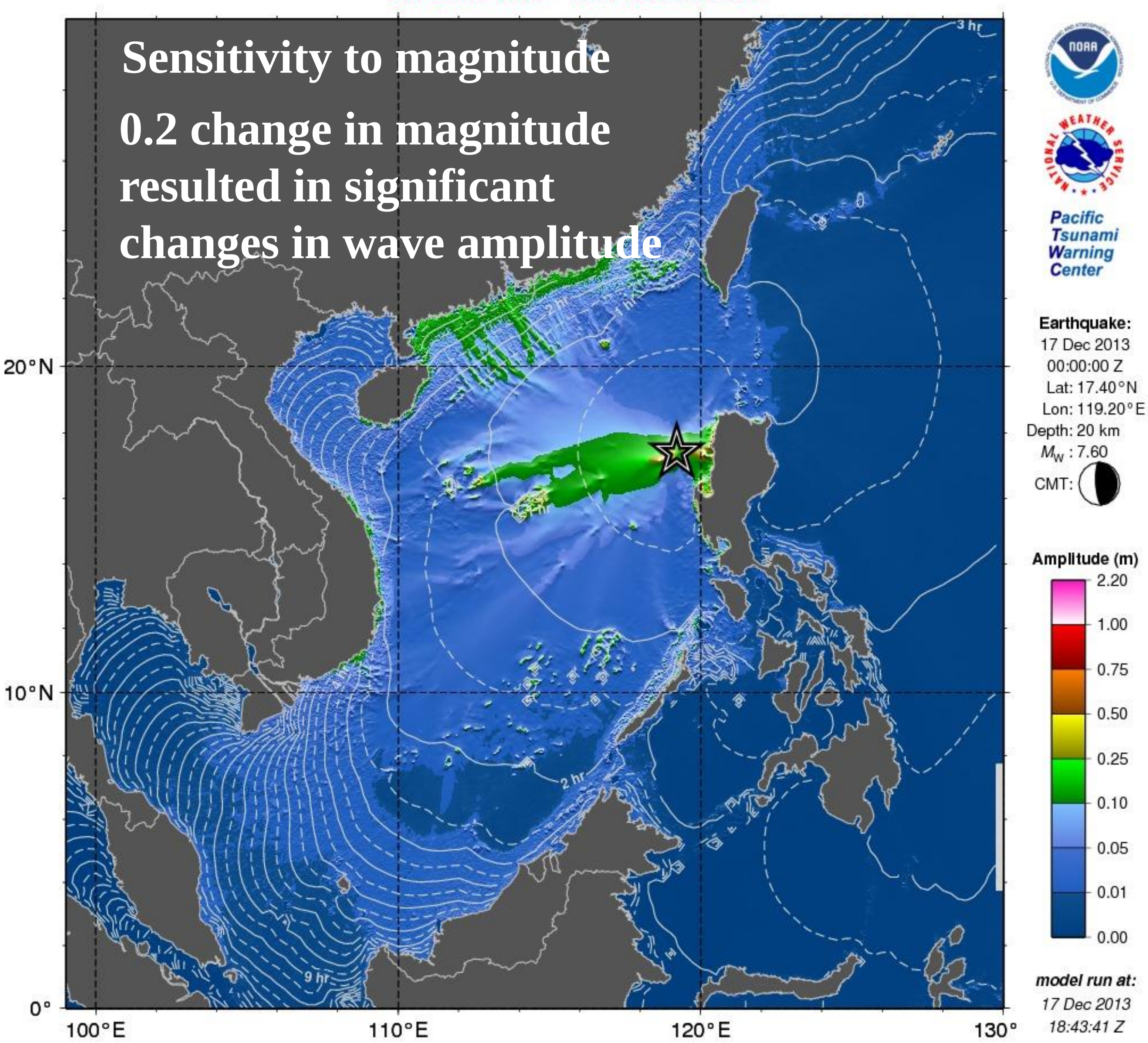
Maximum Coastal Tsunami Amplitude Mw 7.8 Earthquake at 20 km depth



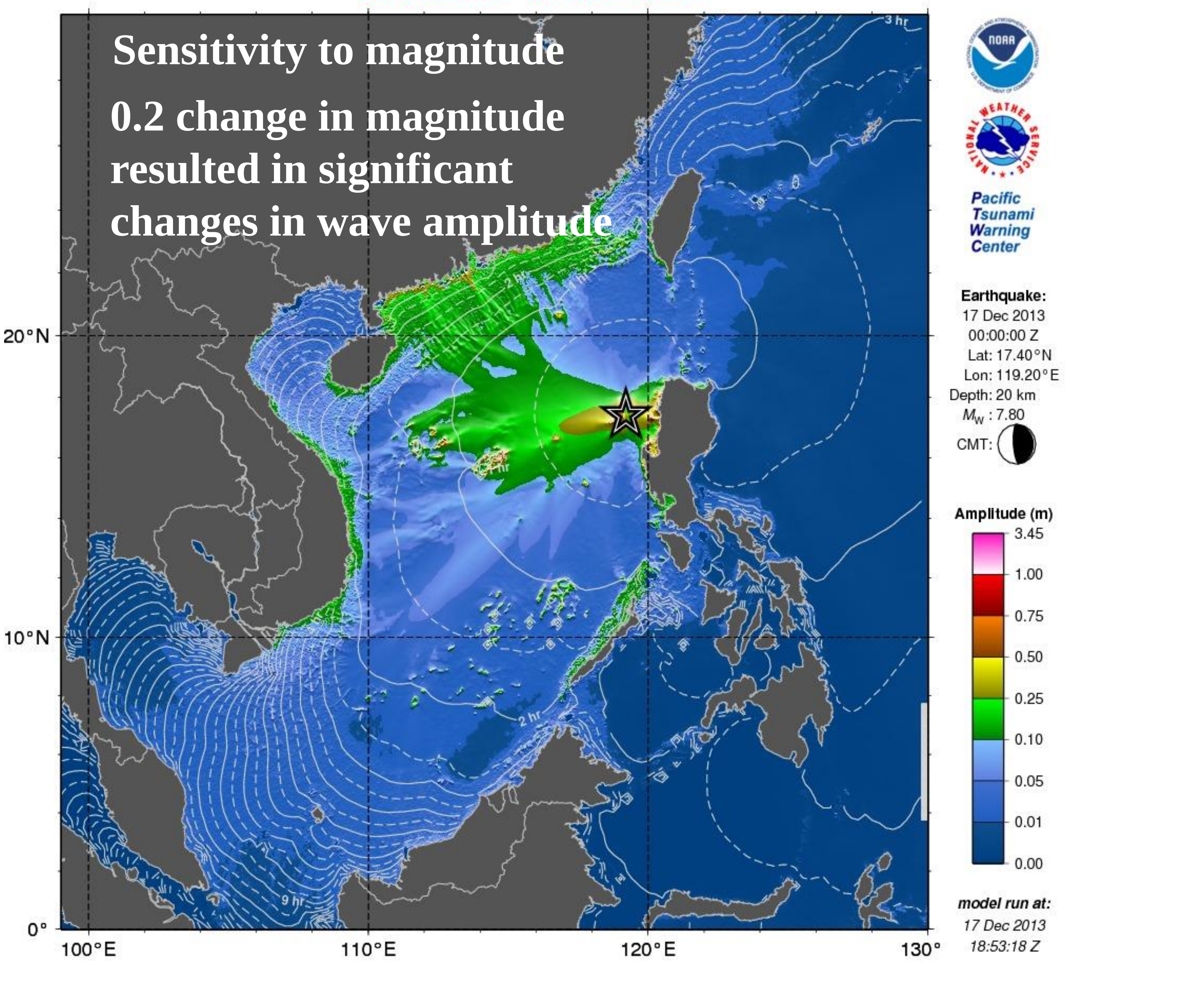
Maximum Deep-Ocean Tsunami Amplitude from Mw 7.4 Earthquake



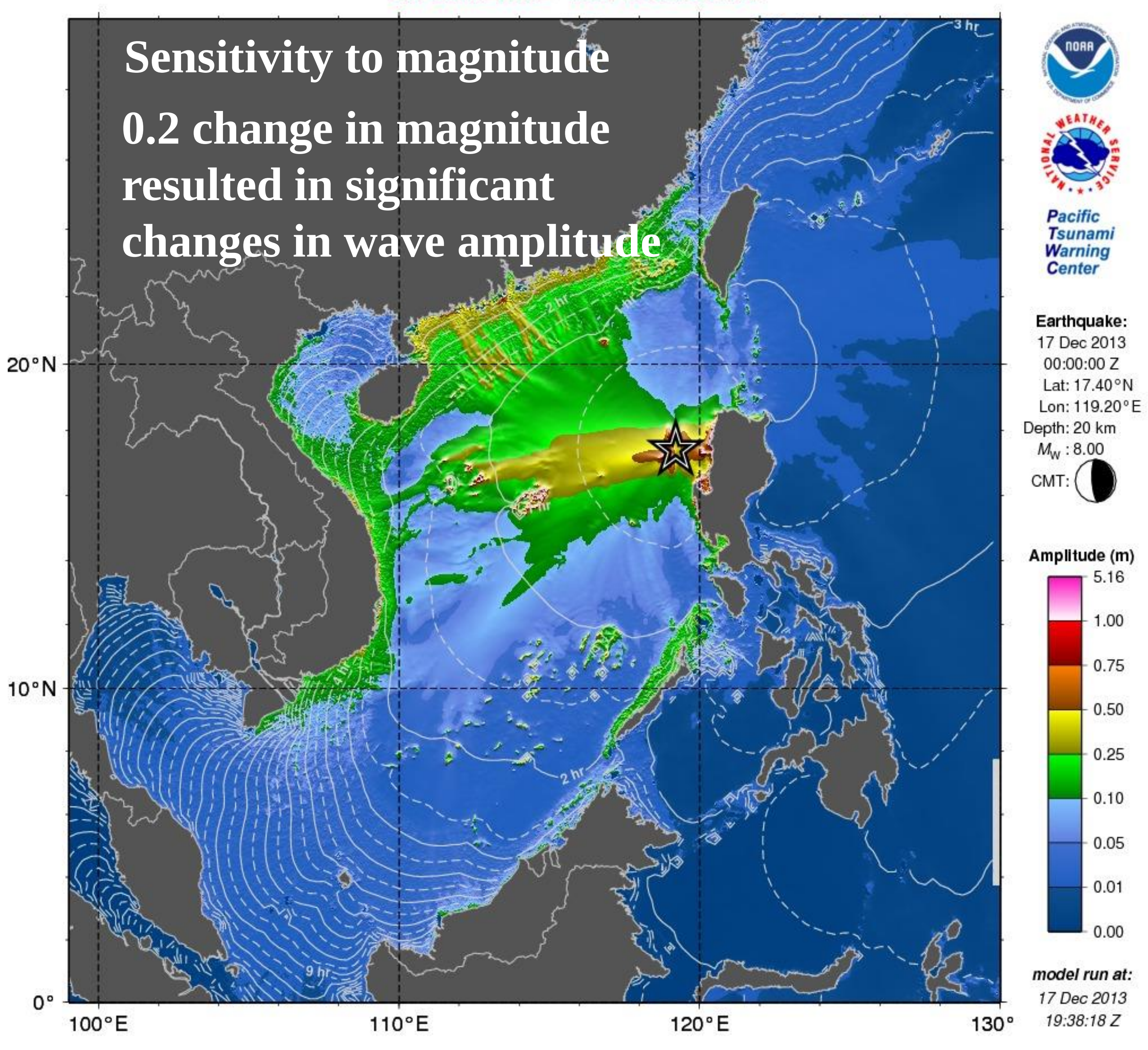
Maximum Deep-Ocean Tsunami Amplitude from Mw 7.6 Earthquake



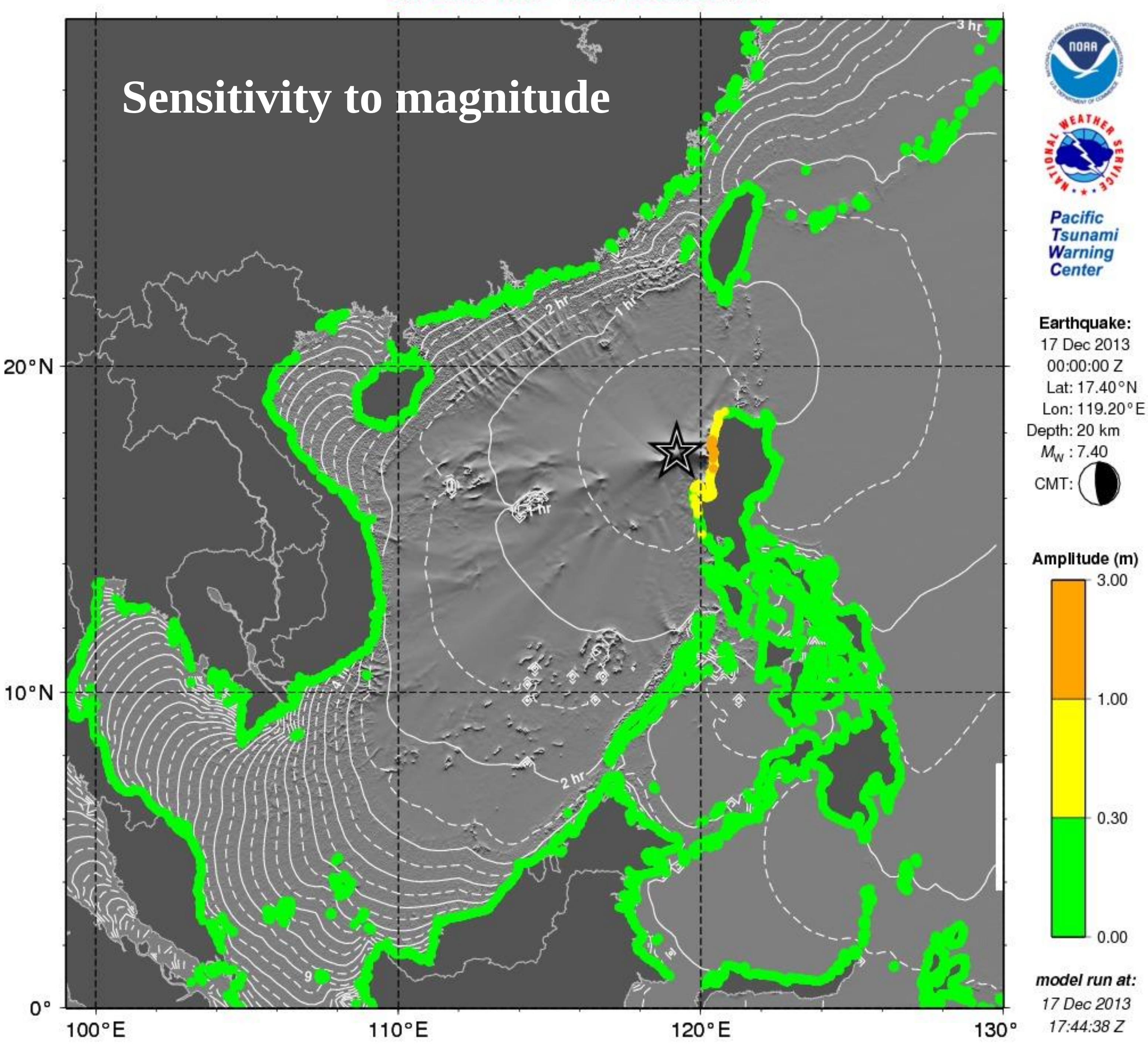
Maximum Deep-Ocean Tsunami Amplitude from Mw 7.8 Earthquake



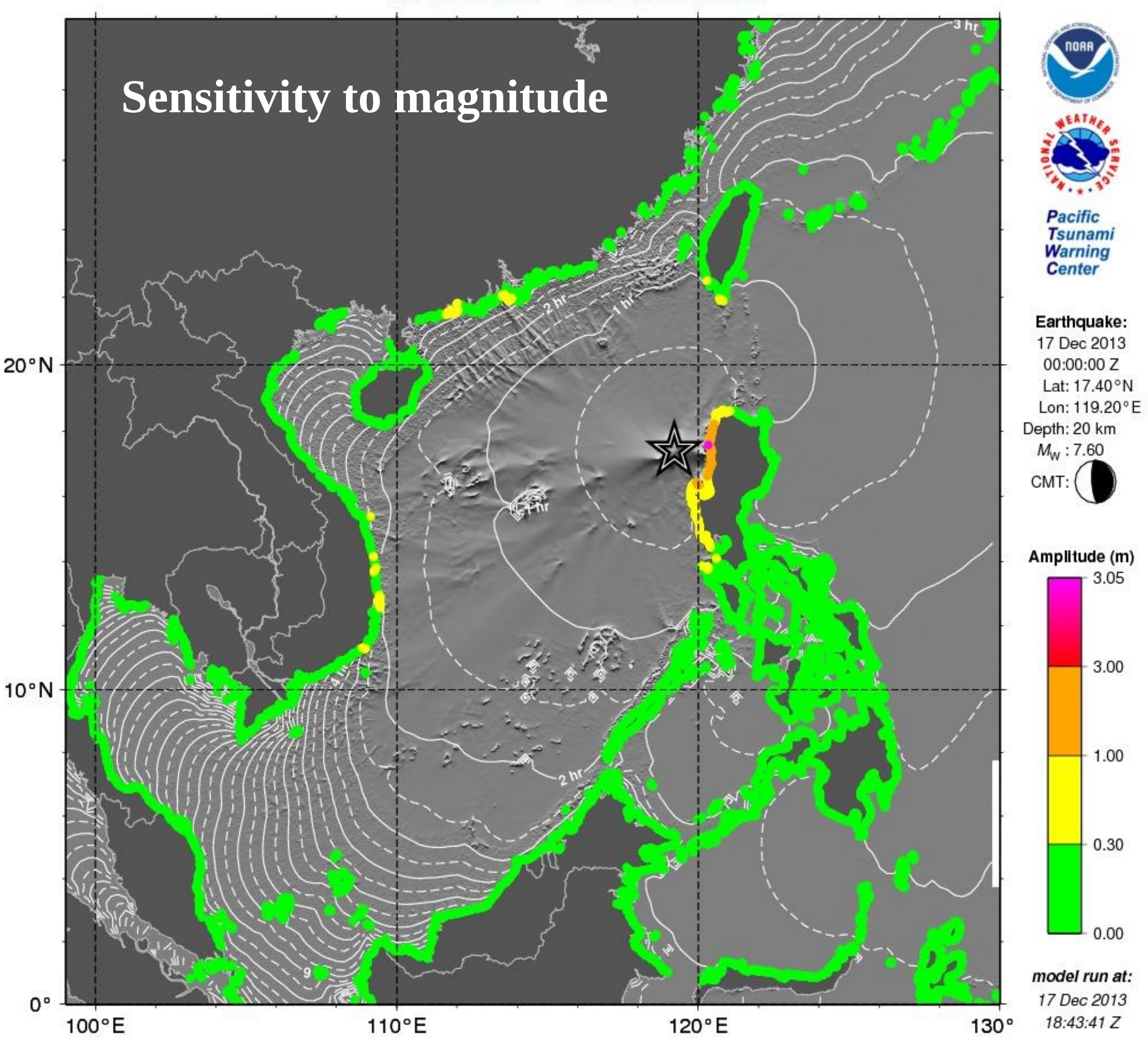
Maximum Deep-Ocean Tsunami Amplitude from Mw 8.0 Earthquake



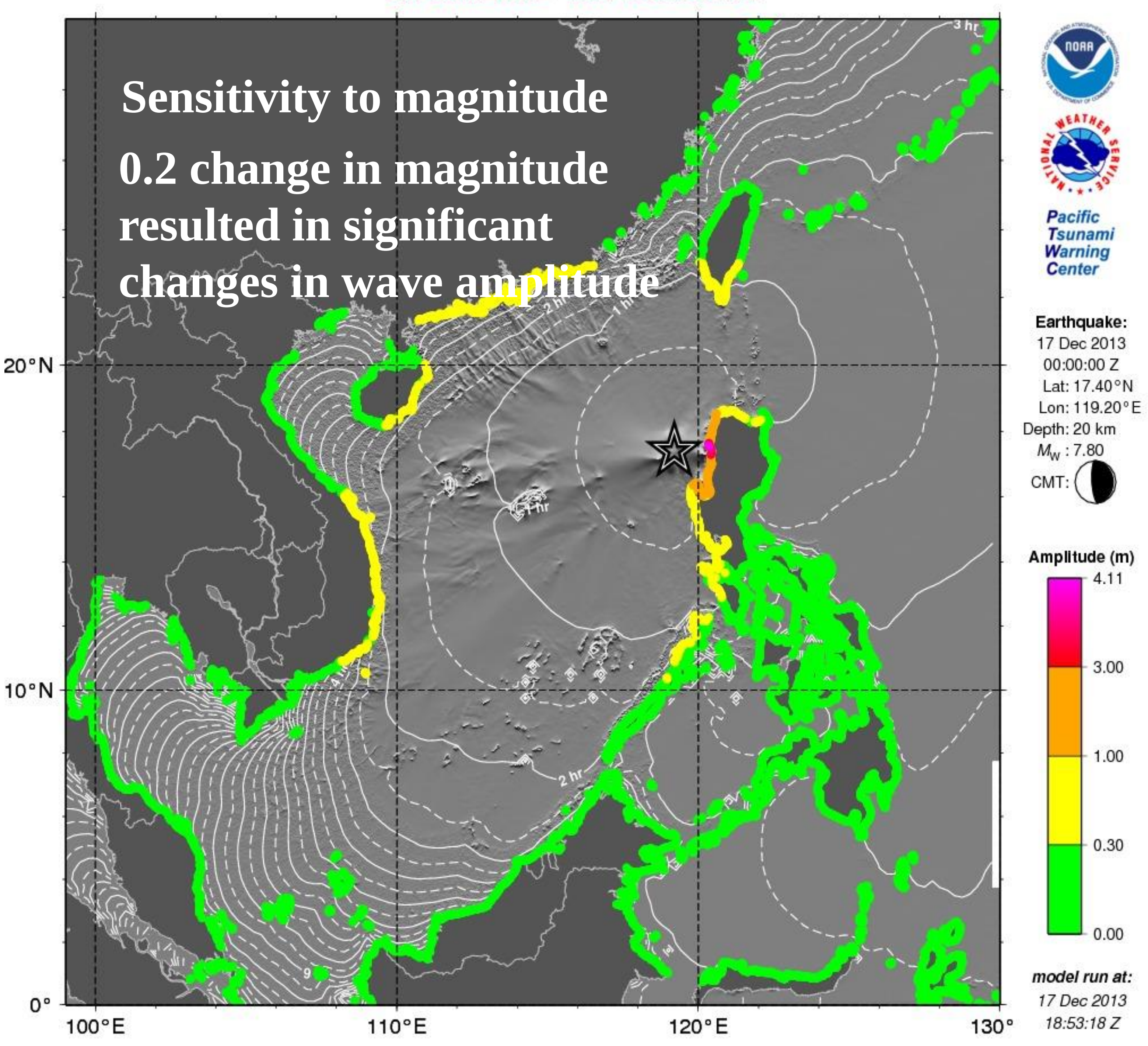
Maximum Coastal Tsunami Amplitude from Mw 7.4 Earthquake



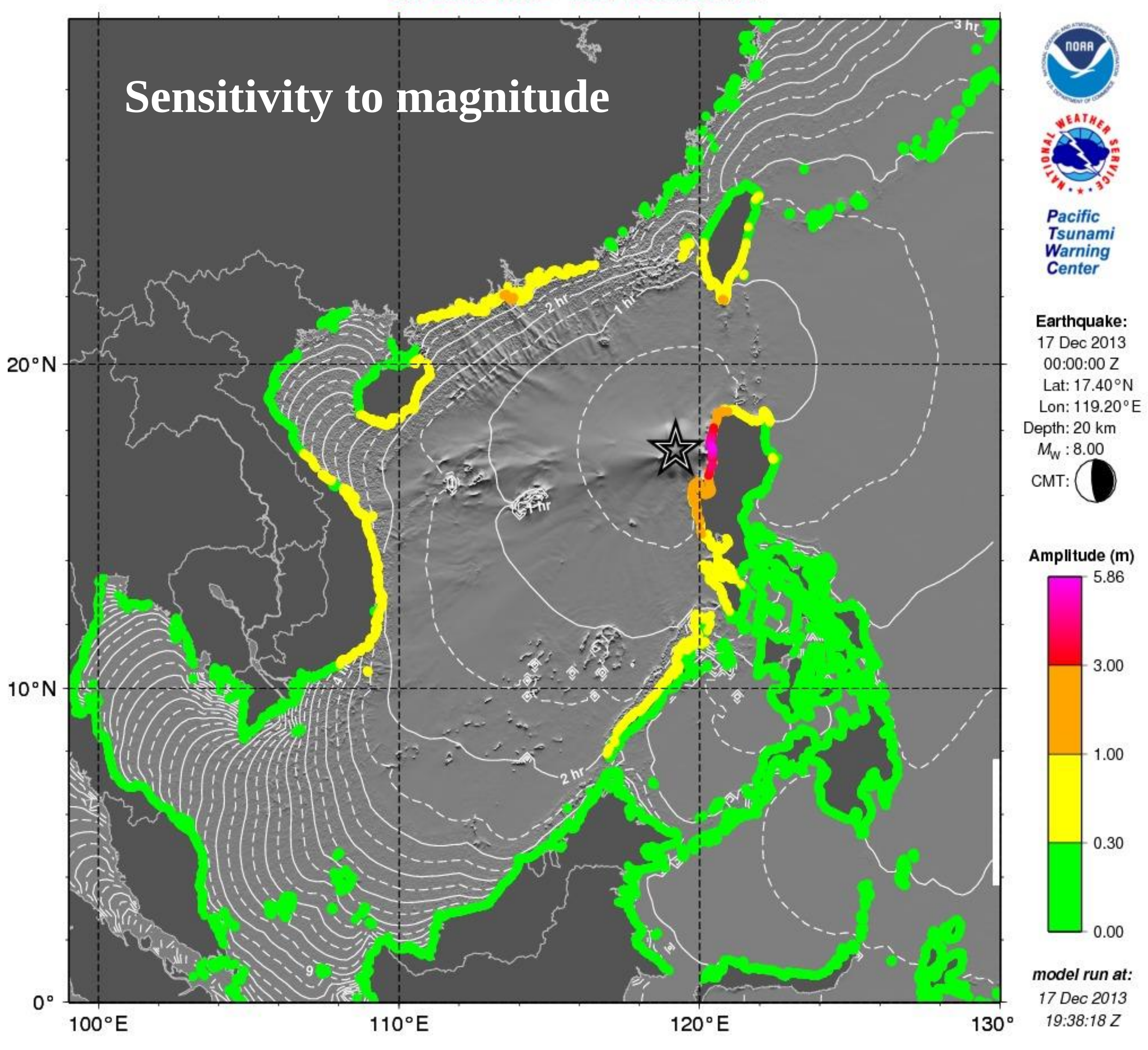
Maximum Coastal Tsunami Amplitude from Mw 7.6 Earthquake



Maximum Coastal Tsunami Amplitude from Mw 7.8 Earthquake



Maximum Coastal Tsunami Amplitude from Mw 8.0 Earthquake



Sensitivity to Focal Mechanism

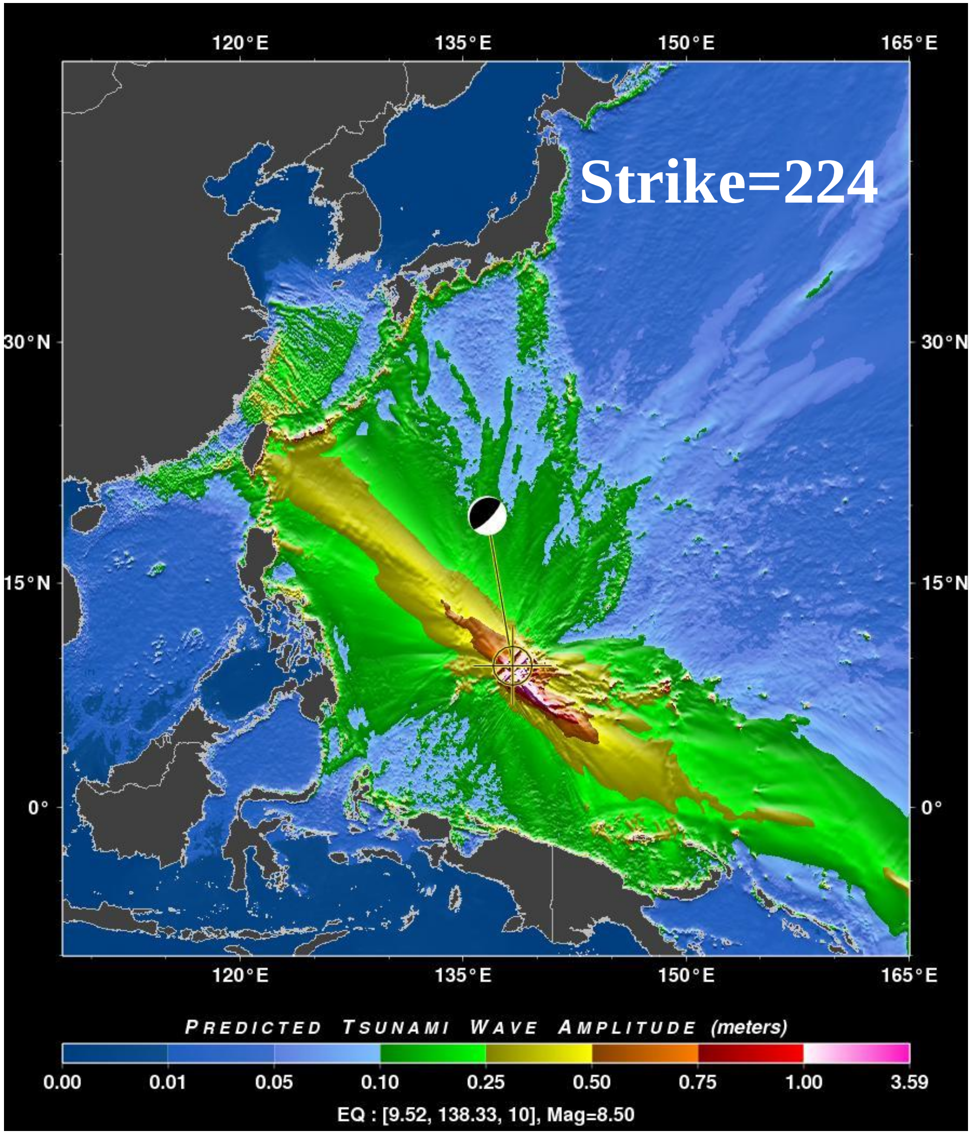
- Model result is also sensitive to focal mechanism
- Here is an example of an earthquake scenario in the Yap trench. Two hypothetical earthquakes have exactly the same location and magnitude, except the strikes of the faults differ by 20 degrees (or 6% of a full circle), but have very different results:
- Yap Trench scenario:

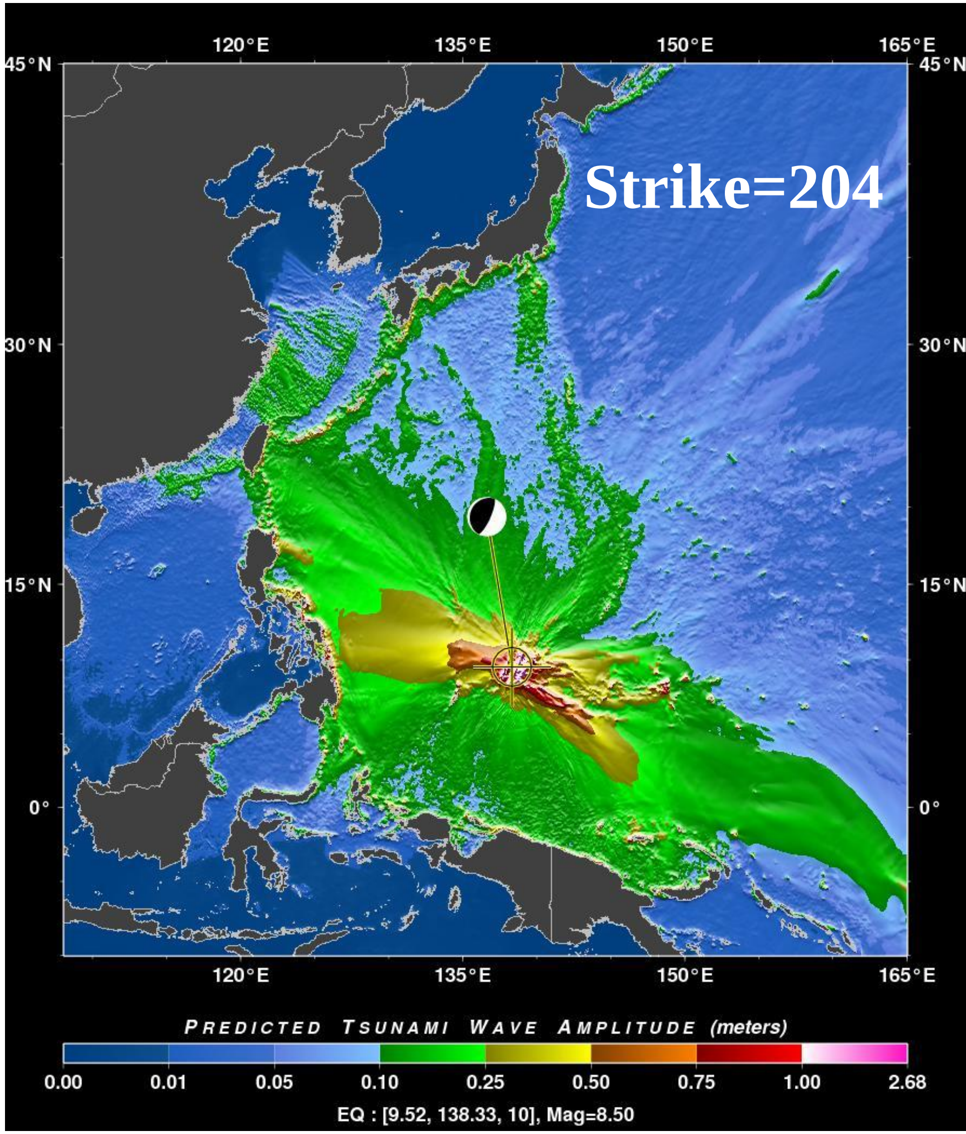
  M8.5, 19.2N, 137.4E, Depth=10 km

  strike1=224, dip=15, rake=90

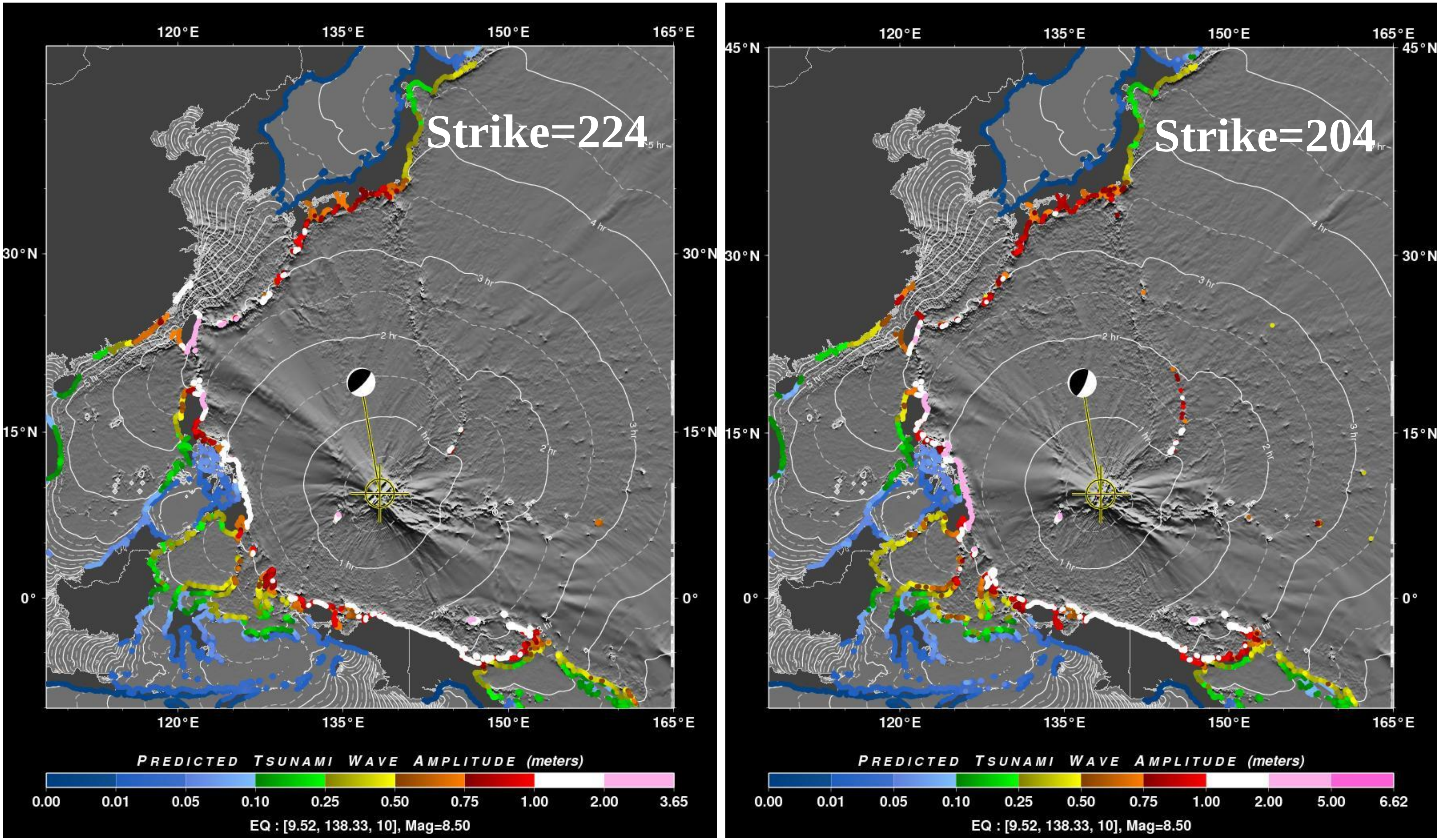
  strike2=204, dip=15, rake=90

A change of 20 degrees in the strike angle changed the energy beam direction from being towards Taiwan to towards the Philippines





And resulted in more than a factor of two change in wave amplitudes in Taiwan and the Philippines.

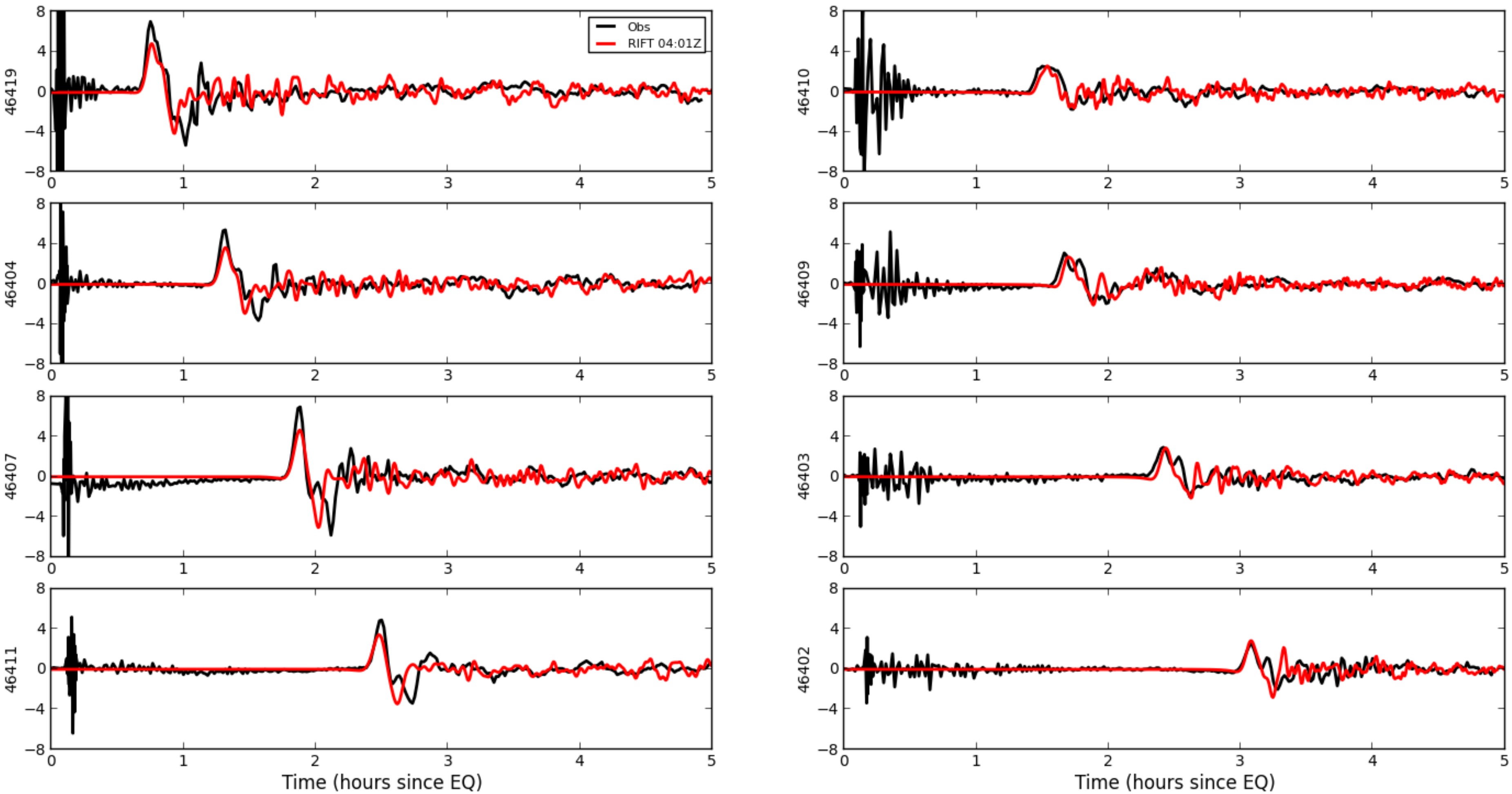


4. Comparison of RIFT results with recent events

- **In this section, we compare RIFT results with observations at tide stations of eight recent events that generated basin-crossing tsunamis in the Pacific (event, followed by forcing used):**
  - Kuril M8.3, Nov. 15, 2006
  - Kuril M8.1, Jan. 13, 2007
  - Samoa M8.0, Sep. 29, 2009
  - Chile M8.8, Feb. 27, 2010
  - Tohoku M9.0, Mar. 11, 2011
  - Haida Gwaii, M7.7, Oct. 28, 2012
  - Solomon Islands, M8.0, Feb. 6, 2013, M8.0
  - Northern Chile M8.2, Apr. 1, 2014
- **RIFT runs were made post-event using the current model executable, forced with W-phase CMTs or Global CMTs (when W-phase CMT was not available).**

In general, the RIFT model agrees better with DARTs than with tide station observations. For example, below is a comparison of RIFT real-time forecast during the event with DARTs for the 2012 Haida Gwaii tsunami.

Comparison with DARTs, RIFT model forced with USGS WCMT 03:28Z



Error Analysis

Here we focus on comparing RIFT model with observations at tide stations. We look at the following two metrics:

Mean Error Err = Average % error = 100*mean($|A_{mod} - A_{obs}| / A_{obs}$)

where A_{mod} and A_{obs} are model and observed wave amplitudes, respectively, defined as the average of maximum zero-to-peak and zero-to-trough amplitudes (i.e., half of the waveheight). Err measures the overall error, averaging over all tide stations for each event.

Mean Ratio R = Mean (A_{mod} / A_{obs})

R is the mean ratio of model wave amplitude over observed wave amplitude. It measures the systematic bias of the model forecast.

R > 1 means model systematically overestimating
R < 1 means model systematically underestimating

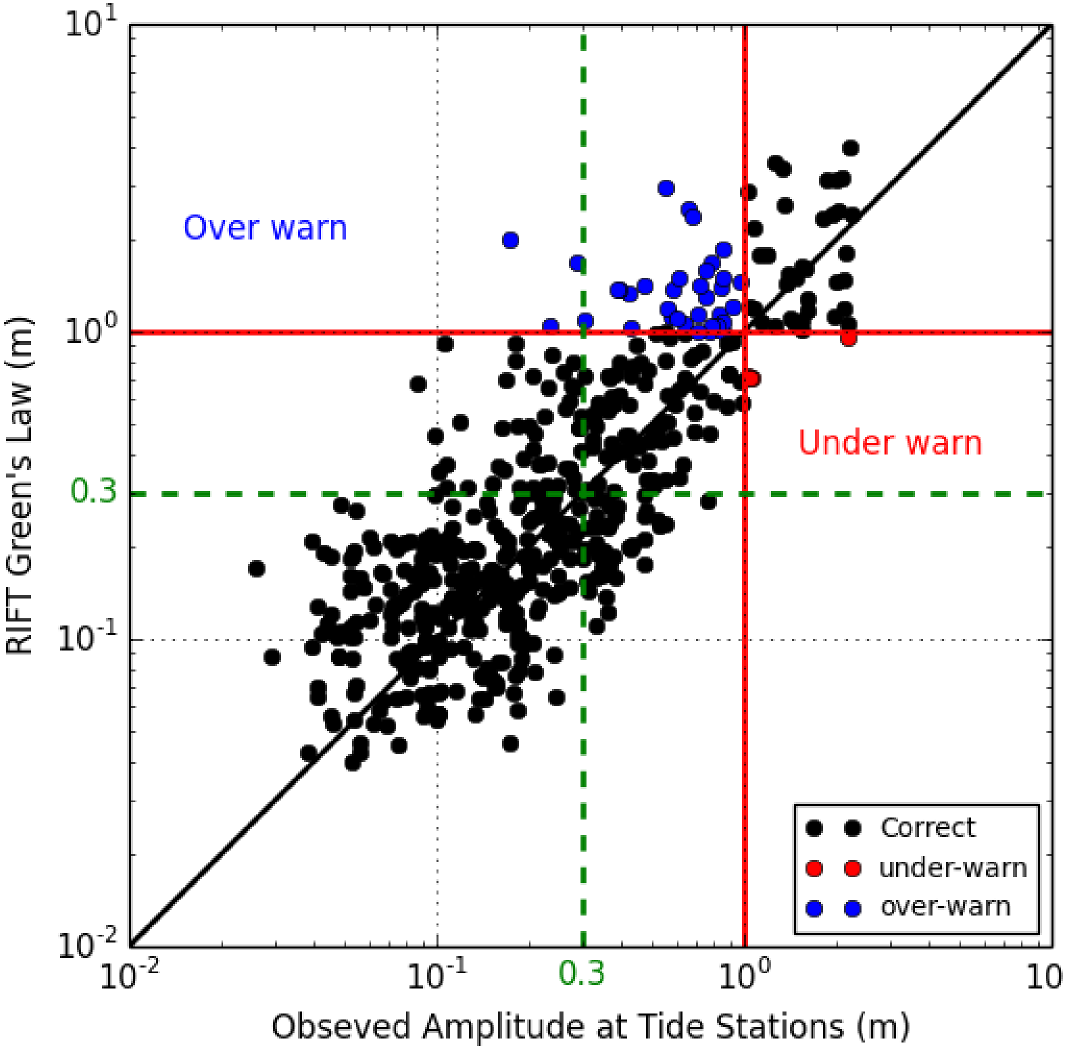
A real-time model is deemed useful if the forecast is within a factor of two of the observations on average. In terms of the above metrics, it means Err < 100% and R within range [0.5, 2.0].
We refer this criterion as a tsunami forecast model requirement.

- As we discussed earlier, RIFT’s Green’s law forecast is meant for coastlines that are more linear and are exposed to the open ocean. Comparison with tide stations that are well-hidden from the open ocean is not very meaningful. Therefore, comparing RIFTs Green’s law forecast with tide stations that are more exposed to the open ocean is most logical. We will compare RIFT with “open ocean” tide stations and then with all tide stations separately (but excluding tide stations that are too hidden or too far from the open ocean for the comparison to make sense. Examples of such tide stations were given in earlier slides).

- Error analysis was done for each event. The RIFT model was forced with Global CMTs or USGS CMTs (Kuril 2006, Kuril 2007, Samoa 2009) or W-phase CMTs (remaining events). The RIFT results satisfy the “factor-of-two” requirement (see previous slide) for all eight events tested. Here we will only show slides of composite error results. In other words, we will look at errors after combining all observation data of all events into a single ensemble (more than 500 data points).

Composite comparison of RIFT's Green's law with tide station observations from eight basin crossing tsunamis.

All tide stations, including hidden tide stations (atolls/reefs, small islands but excluding stations that Green's law obviously would not apply, e.g., Craig tide station in Alaska. Tide stations with 6-min. sampling intervals were also excluded because 6-min. is too coarse to resolve the tsunami).



Mean Error = 71%
Mean Mod/Obs Ratio=1.5

The mean ratio of 1.5 means there is a systematic upward bias from the model, because the inclusion of "hidden" tide stations.

Still, the model results are within a factor of two of the observations on average, despite significant scatter at individual locations, especially at lower amplitudes.

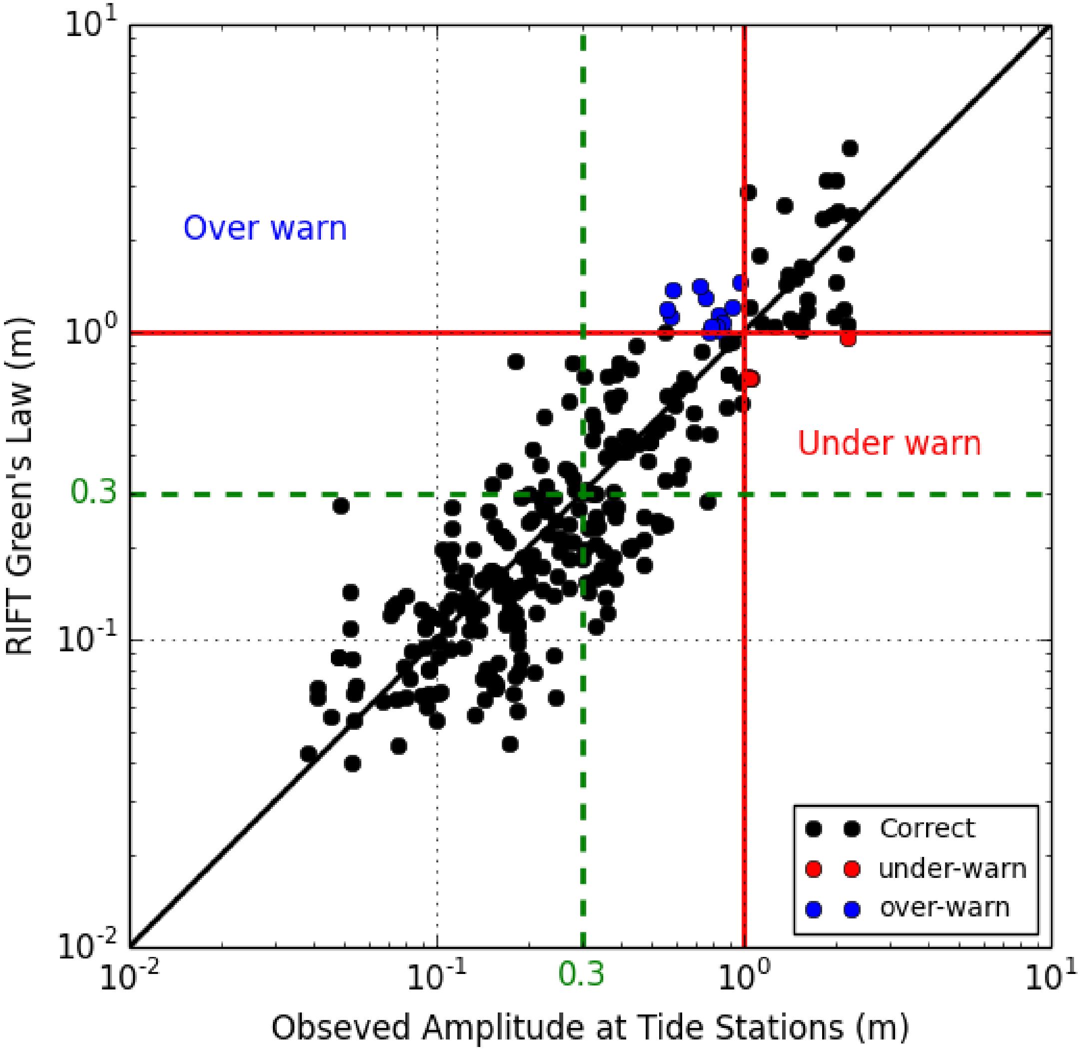
Using 1-m as warning threshold, the model:
under-warns: 1% of total
over-warns: 7% of total
is correct: 92% of total

On the upward bias of the Green's law

When all tide stations are included, it is understandable why the model has a systematic upward bias. Because the Green's law forecast is really meant for the open coast. So when compared with "hidden" tide stations, it tends to over-estimate. To a lesser extent, the upward bias is also due to the fact that the model maximum is computed at every time-step (a few seconds) whereas the observation has sampling intervals of 1 to 3 min. (stations with a 6-min. sampling interval were not included in the analysis). In summary, the upward bias of the Green's law forecast is expected, when compared with all tide stations. If there were no upward bias (mean Mod/Obs ratio=1), the forecast would be wrong for the open coast, i.e., underestimating the true threat faced by the open coast. Therefore, the error analysis including hidden tide stations is misleading. We next look errors at "open ocean" tide stations.

Composite comparison of RIFT's Green's law with tide station observations from eight basin crossing tsunamis.

"Open ocean" tide stations: excluding tide stations on atolls, islands with barrier or fringing reefs, small islands, and tide stations in well protected harbors or are too far from the open ocean.



Mean Error = 41%
Mean Mod/Obs Ratio=1.1

This means the model result is well within a factor of two of the observations on average.

Note that upward bias is greatly reduced when only "open ocean" tide stations are included in the error analysis, which is a more meaningful assessment of the efficacy of the Green's law.

Using 1-m as warning threshold: the model :

under warns: 1% of total
over warns: 5% of total
is correct: 94% of total

Threat levels in PTWC's enhanced product:

Amp < 0.3 m	:	No threat
Amp > 0.3 but < 1.0 m	:	Marine threat
Amp >= 1 but < 3 m	:	Land threat
Amp >= 3 m	:	Major land threat

We next discuss the model performance in this context, using "open ocean" tide stations, which are meaningful in assessing the efficacy of the Green's law results. The statistics for the threat levels above are summarized in the table on the next slide. For tsunami warning operations, an ideal model would be a model that never underestimates and overestimates the threat. Unfortunately, RIFT is not such a model as far as the above levels of threats are concerned.

Note that there were no tide station records from data available to us showing wave amplitudes of more than 3 m (some tide near field tide gauges were destroyed or damaged/clipped). So there is no assessment for the Major-land-threat category. Comprehensive runup data is needed to carry out such a assessment.

Observations	NoThreat < 0.3 m % (mobs,mmod)	MarineThreat 0.3 - 1.0 m % (mobs,mmod)	LandThreat > 1.0 m % (mobs,mmod)
Model NoThreat	91 (0.1,0.1)	35 (0.4,0.2)	0 (0.0,0.0)
Model MarineThreat	9 (0.2,0.4)	51 (0.5,0.6)	12 (1.3,0.8)
Model LandThreat	0 (0.0,0.0)	14 (0.8,1.2)	79 (1.6,1.6)
Model MajorLandThreat	0 (0.0,0.0)	0 (0.0,0.0)	9 (2.0,3.4)

The numbers inside the parentheses are mean values of observations (mobs) and model results (mmod) for the same set of tide stations that are binned according to the observational values: < 0.3, 0.3-1.0, and > 1.0 meters. Red, green, and blue numbers are percentages of model underestimating, being correct, and overestimating, respectively, for the same set of observation points.

When the observation showed no-threat (<0.3 m), the model showed no-threat for 91% of those points. Both observations and model results have the same mean value 0.1 m. At 9% of the no-threat observation points, the model showed marine threat. Note however, the mean value for those model points is 0.4 m, closer to the no-threat level of 0.3 m.

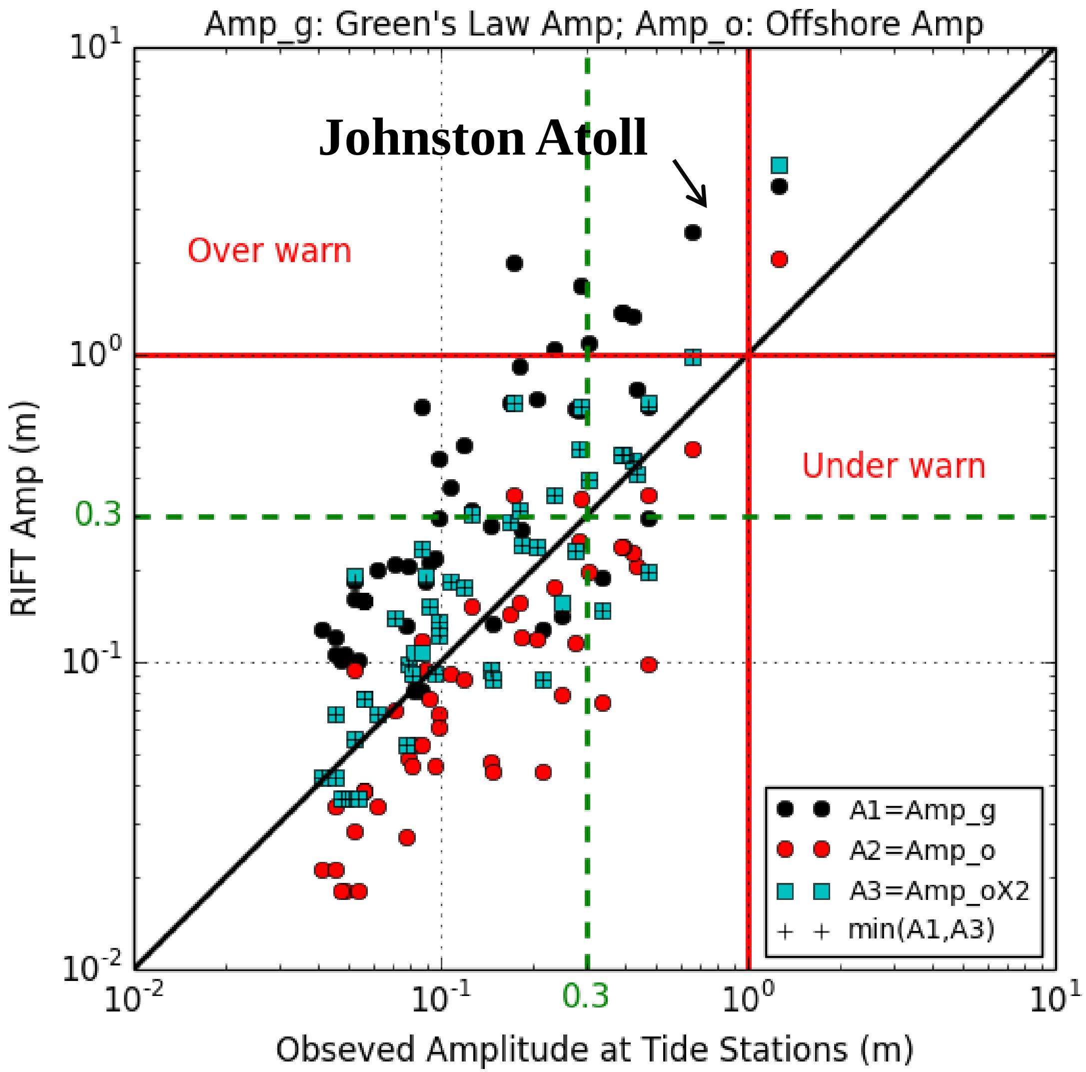
For the observational points that showed marine-threat (0.3 to 1 m), 35% of the corresponding model points showed no threat. Although this is a large percentage, the mean observation value 0.4 m is close to the no-threat threshold of 0.3 m. About 14% of the model points showed land-threat. Note that the mean observation value 0.8 m (compared to the model mean value 1.2 m), is also closer to the land-threat threshold of 1.0 m, than to the lower boundary 0.3 m of marine -threat.

For the observational points that showed land threat (amp > 1 m), 12% of the corresponding points showed only marine-threat. This is undesriable. Still, the mean model value of 0.8 m is close to the land threat level 1m.

- **Comparing RIFT's Green's law with tide stations that are hidden can be misleading. For example, for the Tohoku 2011 tsunami, the RIFT model wave amplitude at Midway Islands is 3.6 m (major land threat), but the observed wave amplitude at the tide station is only ~1.3 m (zero to peak of ~1.5 m, land threat). In other words the error is ~180%. Based on over-wash observations , the actual maximum runup at Midway Islands was probably closer to 3 m. Inundation model results showed maximum run-up of closer to 5 m (from the real-time inundation model of the SIFT database model used at PTWC, developed by NOAA's Pacific Marine Environmental Laboratory).**

- **For the same event, the observed wave amplitude was 1.3 m at Kawaihae, Hawaii Island, and the model result was 3.3 m (154% error). Field survey showed at least a 2-m runup around the harbor. About 60 km south of the tide station, a 5-m runup was observed (USGS). So the 3.3-m model result reflected the general threat to this region, despite the large difference from the observation at the tide station. In other words, forecast at the tide station should be interpreted as for the open coast near by, not necessarily exactly at the tide station. The model at 4-arc-min. resolution, does not really know exactly where the tide station is.**

Composite comparison of RIFT's Green's law with tide stations on atolls and islands with fringing/barrier reefs from eight basin-crossing tsunamis.



A1=Amp_g: Green's law amp
A2=Amp_o: Offshore amp
A3=2*Amp_o: 2 X Offshore amp
A4= Min(A1, A3)

Green's law (A1 in figure, black):
- **Mean Error = 200%**
- **Mean Mod/Obs Ratio=2.9**

Offshore (A2 in figure, red):
- **Mean Error = 43%**
- **Mean Mod/Obs Ratio=0.7**

Offshore X 2 (A3 in figure, cyan):
- **Mean Error = 59%**
- **Mean Mod/Obs Ratio=1.4**

A4= Min(A1, A3) (+ sign):
- **Mean Error = 57%**
- **Mean Mod/Obs Ratio=1.4**

NOTE: A3 (blue cyan squares) and A4 (+ signs) are mostly similar.

Discussion of RIFT comparison with Tide Stations - Atolls and Islands

- For tide stations on atolls and islands with fringing reefs with steep bathymetry, offshore forecast gives the smallest average error 43% (see A2, previous slide). However, mean mod/obs ratio of 0.7 indicates a systematic underestimating bias, which is undesirable for tsunami warning purposes.

- Two times the offshore amplitude is equivalent to a wave runup on a vertical wall (it is an approximation for atolls and islands with steep bathymetry). It is reasonable to expect the Green's law wave amplitude will be the upper bound (assuming a gentle slope). Therefore the following seems logical as forecast for atolls and islands with fringing/barrier reefs:

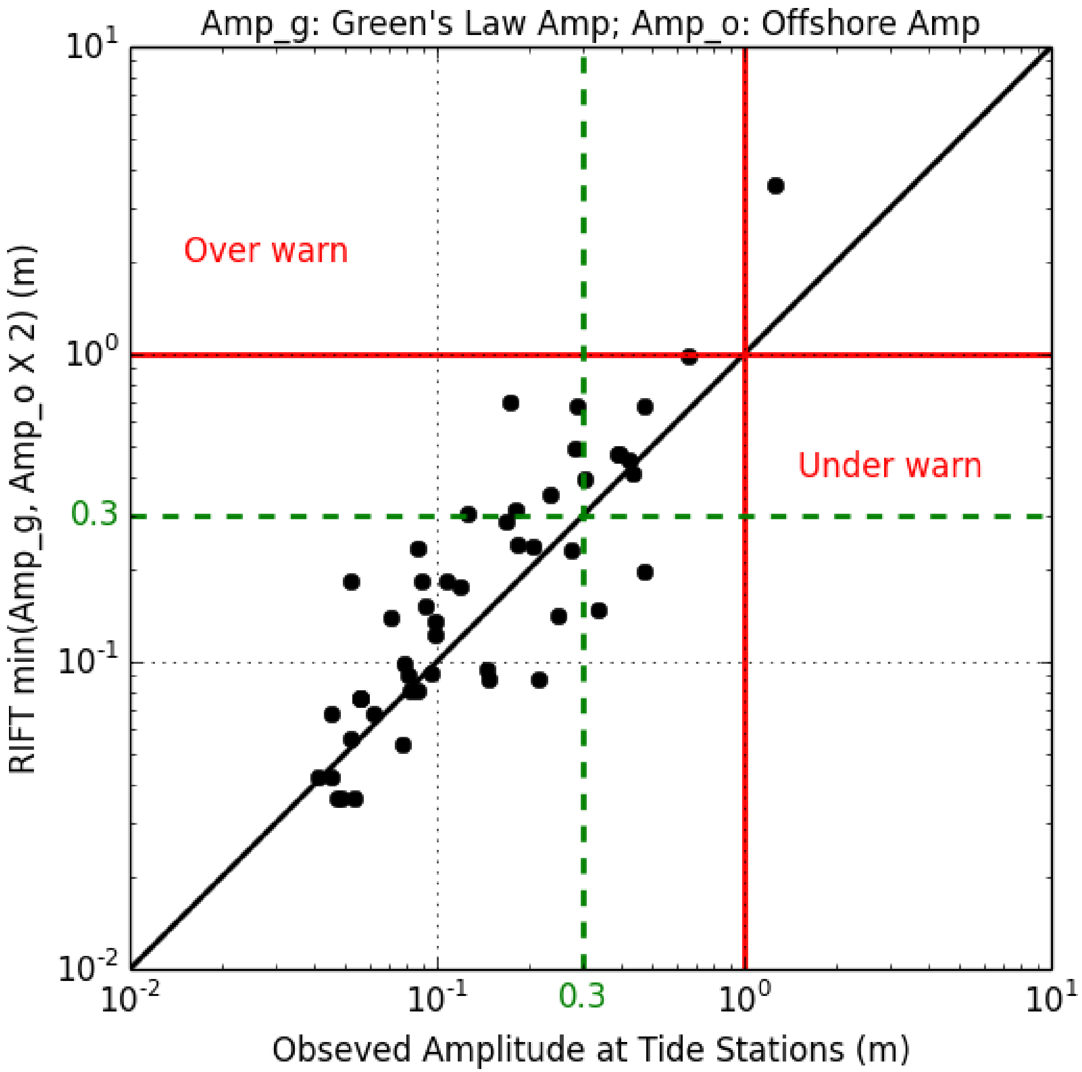
  Amp = min (Amp_g, 2*Amp_o)

  where Amp_g is Green's law amplitude, Amp_o is offshore wave amplitude (from the closest model grid point to the tide station, without Green's law applied).

- The comparison of this formula with tide station observations is shown as symbol '+' in the previous slide, and is shown again alone for clarity in the next slide (now using circles).

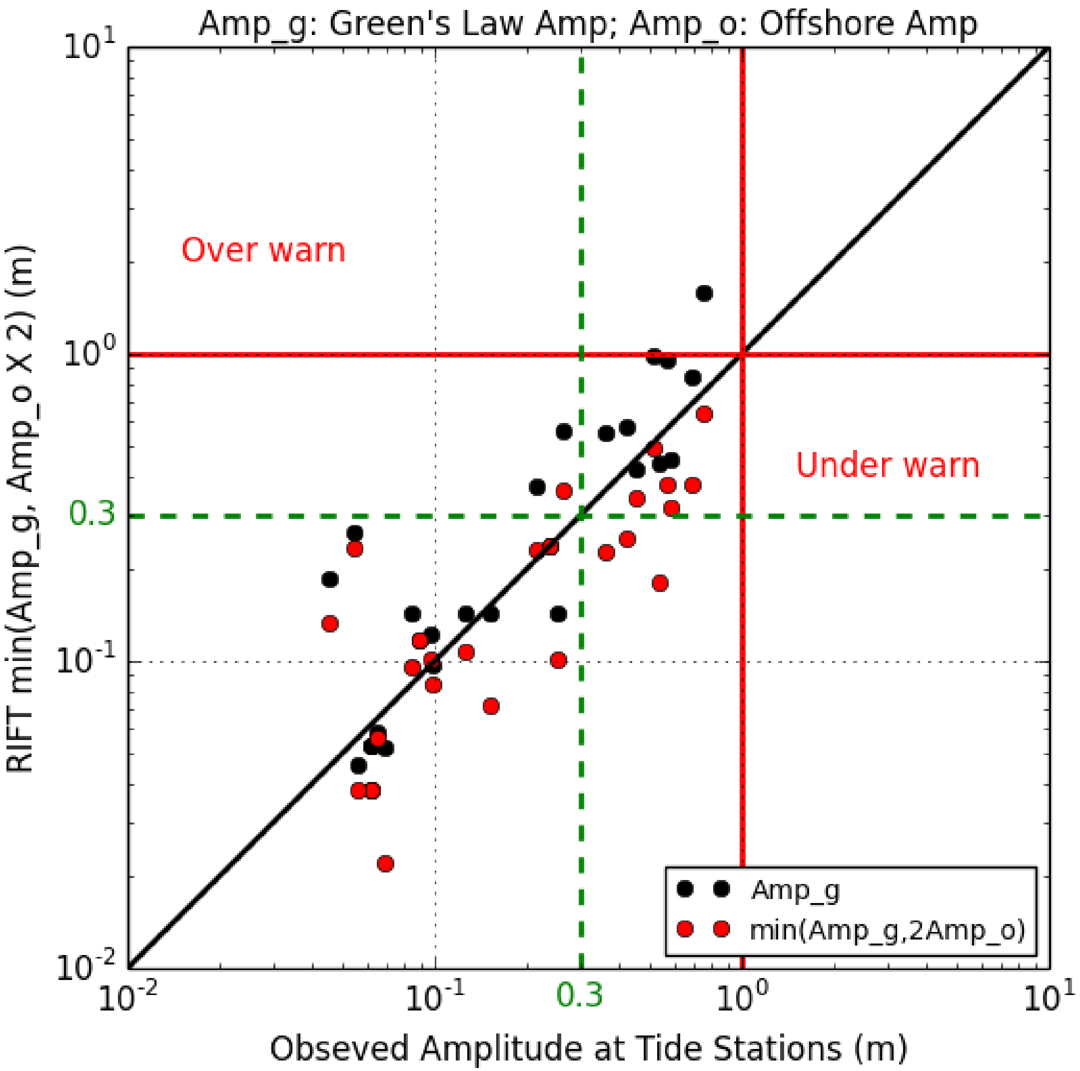
Amp_af = min (Amp_g, 2*Amp_o) is a better predictor of the wave amplitude at atolls and islands with fringing reefs
“af” in Amp_af stands for atolls and reefs

Mean Error = 57%, Mean Mod/Obs Ratio=1.4
There is still an systematic upward/overestimating bias, but the error is much smaller compared with Green’s law forecast error of 200%



Although the offshore forecast without Green’s law (A2 or red dots—two slides earlier) showed the smallest mean error of 43%. Clearly, it might not be suitable for warning purposes, because of the systematic underestimating bias. Amp_af defined above is better in assessing the tsunami threat, although it has systematic upward/overestimating bias. To be conservative, the Green’s law amplitude might be better in some situations, despite the large errors compared to observations at tide stations.

Composite comparison of RIFT's Green's law with tide station observations on small islands without fringing reefs from eight basin crossing tsunamis.



Green's law Amp_g, black dots:
Mean Error = 63%
Mean Mod/Obs Ratio=1.5

Min(Amp_g, 2Amp_o), red dots:
Mean Error = 49 %
Mean Mod/Obs Ratio=1.0

Although Min(Amp_g, 2Amp_o) gives a smaller mean error than the Green's law amplitude, there are many points it underestimates. It might be better to use Green's law estimate to be conservative for small islands without fringing reefs in general.

Summary Statement

1. **Although real-time computation of tsunami travel time (TTT) and the RIFT model is feasible for any earthquake location and any focal mechanism, these methods have their limitations.**

2. **The Green's law coastal forecast is meant for an open/linear coast. It is not capable of making a forecast for hidden locations. Therefore, forecasts at well-hidden locations should be discarded or the results should be interpreted as forecast for the nearby open coast. A good algorithm is yet to be implemented by the PTWS to prevent the "spurious" forecast from being shown. However, this has no bearing for the polygon maps.**

3. **Green's law coastal forecast is an order of magnitude forecast (general level of threat) and is not suitable for evacuation mapping.**

Summary Statement

4. **Although RIFT model forecast was generally within a factor of two of the observations on average at tide stations that are more exposed to the open ocean (for eight recent basin-crossing tsunamis) when central moment tensor solution was used as the source, it is prudent to assume RIFT forecast can be easily off by a factor of two on average (a forecast of 1 m could easily be 0.5 m or 2 m in reality). If the earthquake magnitude, location, and focal mechanism are in error, the errors can be even larger. For individual locations, the errors can have a much larger range of scatter.**

5. **For atolls or regions with fringing/barrier reefs and steep bathymetry, the minimum of Green's law amplitude and twice the offshore amplitude (from the closest model ocean point without the Green's law applied) agrees better with observations at tide stations. Whether this will always be true requires further study.**

Summary Statement

6. For small islands without fringing/barrier reefs, although the minimum of the Green's law and twice the offshore amplitude (from the closest model ocean point without the Green's law being applied) has a smaller mean error than the Green's law estimate, it is prudent to use the Green's law forecast as guidance because it has an upward bias to avoid under-estimating the tsunami threat for some locations.

7. For locations that historically tend to show resonance and tsunami amplifications (e.g., Crescent City, California and Kahului Bay, Hawaii), the Green's law might underestimates the threat substantially.

8. The RIFT forecast does not take into account the possibility of landslide generated tsunamis.

PTWC Enhanced Products
September 2014

Tsunami Travel Time Computation
PTWC Real-time Forecast Model

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