Ship-based Tsunami Detection and GPS Meteorology

An opportunity to improve hazard mitigation through public-private collaboration

James Foster, Todd Ericksen, Steven Businger, Jon Avery, Vanessa Almanza
University of Hawaii

Motivation

Recent tsunamis are responsible for the loss of 100's of thousands of lives and 100's of billions of dollars in damage and economic losses. Evacuating coastal zones can cost 10's of millions of dollars.

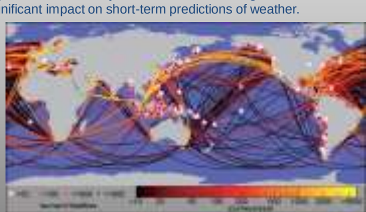
Atmospheric rivers are the dominant cause of flooding and play key roles in drought in US West Coast watersheds. Flood costs are estimated at ~$1B/year. Water supply benefits are estimated as ~$10B/year.

Q: How can we cost-effectively acquire spatially dense observations of tsunamis and improve short-term forecasts for land-falling meteorological hazards?

A: Use the vast existing infrastructure provided by ships!

Ship-based tsunami detection and meteorology network

Ship tracks provide excellent coverage of tsunami source regions. We have demonstrated that geodetic GPS on ships can detect open ocean tsunamis. Ship tracks are at their most dense along coast-lines: exactly where GPS-meteorological estimates of IPW could provide the most significant impact on short-term predictions of weather.



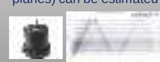
There are ~15,000 large container ships active. Instrumenting just 10% (similar to the Voluntary Observing Ship program uptake) would give ~1000 new tsunami and IPW detection systems at sea at any given time.

Current Tsunami Detection Systems

Seismic

Advantages:

- Extremely rapid detection and location estimation of large earthquakes
- Fault plane (conjugate planes) can be estimated



Disadvantages:

- For very large/slow slip events ground motion may be under-predicted
- Uncertain estimation of energy transferred into water column

Tide Gauges

Advantages:

- Direct measurement of runup

Disadvantages:

- Limited to land sites – sparse and uneven coverage
- Runup strongly dependent on complex interplay between tsunami source and local bathymetry
- May be destroyed by tsunami, limiting information recovered

DART system

Advantages:

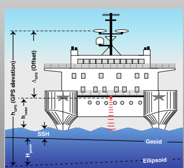
- Accurate point measurements of ocean depth perturbations

Disadvantages:

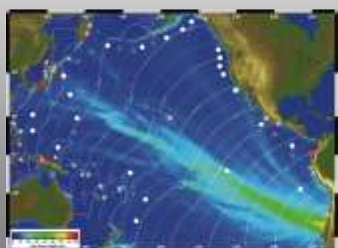
- Expense limits the number that can be deployed and maintained (25-30% offline at any given time)
- Network based on current best-estimate of hazard… may not be accurate
- Local bathymetry may perturb signal

Example of tsunami detection from a ship: Maule EQ tsunami, Feb 2010

The R/V Kilo Moana was underway from Hawaii to Guam when the tsunami from the Maule earthquake passed the ship. The predicted amplitude of the wave was ~10 cm.



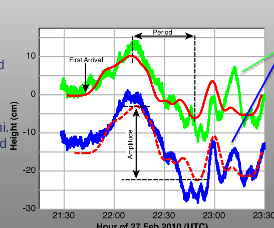
University of Hawaii Research Vessel *Kilo Moana* is equipped with twin dual-frequency GPS systems



Sea surface height perturbations

Post-processing of the GPS data revealed sea-surface perturbations very similar to the predictions from numerical models of the tsunami. This was further explored by cross-correlation with a "matched-filter" formed from the first 60-min of the predicted wave field.

By perturbing (rescaling the period and amplitude) the initial model prediction to find a best fitting version, a new model can be used to measure primary characteristics of the tsunami. These estimates can be used to nudge forecasts, or re-ingested by the model to update its prediction.



Elevation perturbations for the Kilo Moana's two antennas

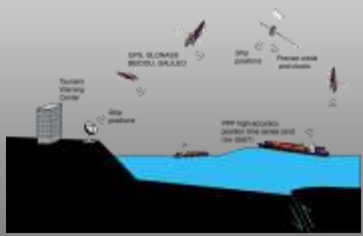
Pacific Tsunami Warning Center RIFT model predictions for *Kilo Moana's* position

Ship-based tsunami detection network concept

GNSS signals + high-accuracy satellite orbits and clock solutions transmitted to ships allows for Precise Point Position solution.

Position time-series transmitted to land analysis center.

Trimble RTX service has demonstrated ~8 cm RMS vertical positioning on land.



AMS Washington Forum
2-4 May 2017

Pilot Network

A 10-ship pilot network was built by the University of Hawaii, collaborating with Matson, Maersk, and the World Ocean Council, with funding from NOAA

GPS:	Trimble NetR9 receiver w/ RTX positioning service & GLONASS enabled
Satellite Comms:	miniVSAT + 2GB/month (pooled) data plan
Data Flow:	Corrections streamed to GPS receiver via internet. Position solutions streamed to UH

Matson Ships	
Total Round Trip	14 days
Port calls	3.5 days
Underway	10.5 days

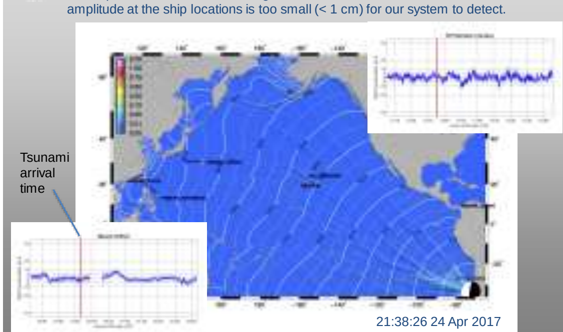
Maersk Ships	
Total Round Trip	~63 days
Port calls	11 days
Underway	52 days

AMS Washington Forum
2-4 May 2017

M6.9 Valparaiso Earthquake

Model predictions for the tsunami generated indicate that the maximum amplitude at the ship locations is too small (< 1 cm) for our system to detect.

Tsunami arrival time



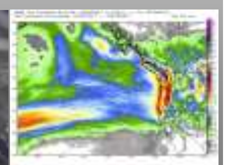
21:38:26 24 Apr 2017

AMS Washington Forum
2-4 May 2017

Improving meteorological hazard prediction and mitigation

Problem: Many of the extreme weather events that impact our communities form over the oceans. Although satellites provide excellent global coverage, observations may be contaminated by clouds, and by the land at coastlines, reducing the quality of data. Limited temporal resolution also limits the quantity of data available in this zone. This impacts the short-term predictions crucial for effective mitigation.

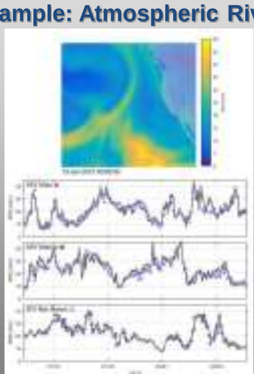
Solution: Ship tracks are at their most dense along coast-lines.



AMS Washington Forum
2-4 May 2017

Example: Atmospheric Rivers

Atmospheric rivers transport huge quantities of water vapor from the tropics to the higher latitudes (fluxes an order of magnitude greater than Mississippi River). These features can generate devastating flooding during land-fall, and have been implicated in the reduction in ice cover over the Arctic ocean.



ERA-Interim Reanalysis, with ship tracks

IPW estimated from data collected on Matson cargo ships Manoa & Maui with ERA-I estimates

GPS IPW from R/V Ron Brown CalWater2015 campaign with sonde measurements

AMS Washington Forum
2-4 May 2017

Summary

- **6 ships were live at the time of the 24 Apr 2014 Valparaiso event. A similar number were available for the 2015 Illapel event.**
- **The tsunami model predicted max amplitudes at ship locations from events to date were <2 cm, well below our anticipated detection threshold.**
- **Performance is in line with our expectations of the system**
- **IPW estimates from cargo vessels show great promise for providing high spatial and temporal resolution observations of atmospheric rivers**

AMS Washington Forum
2-4 May 2017

Going Big… What is needed to scale up to a network with 1000+ ships?

More cost-effective equipment package, with more optimal installation locations (on top of mast)

On-board processing to reduce bandwidth while estimating IPW and other products (e.g. TEC for space weather)

Reduced communications costs

Active partnerships between commercial shipping companies and government/academic/international agencies

Thank You.

ADDITIONAL MATERIAL

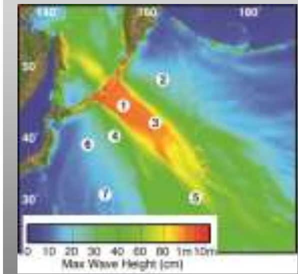
Meteorological Death & Destruction

System Components

- Ships: GPS with PPP-AR for accurate positions, and satellite communications for data streams

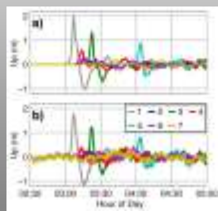
Tsunami Warning Center: real-time/rapid tsunami modeling capability (e.g. RIFT), to provide predictions for sea-surface perturbations at ship's postion to update model

Tsunami Detection Simulation



Simulation of an M8.8 Kamchatka earthquake

Ships in the near-field, or along the main energy "beam" of a major tsunami would detect it without the need for the matched filter approach



Matson