**Accomplishments / Advancements**

- NTWC
    - SIFTv4 (original started ~2005, so NOT a result of Tohoku)
    - PMEL Brochure: https://nctr.pmel.noaa.gov/Pdf/brochures/sift_Brochure.pdf
    - Tech and tsunami.gov enhancements robustness. Combination of both PTWC and NTWC into tsunami.gov.
    - Seismic and water level network expansion (NOTE: NDBC highlights us in their achievements with 1 minute tide gauge data access on the website)
    - NTWC Twitter: Joined August 2012
    - NTWC Facebook Page created - March 2015
    - SIFT forecasting

    - October 1, 2013, the WCATWC was renamed the National Tsunami Warning Center (NTWC) in recognition of its expanded AOR.
    - NTWC “All Call” technology updated
    - AT-Tsunami Gauge was developed and a station was installed at Ventura CA.
    - Staff list increased to meet demands of the watch and program improvements

- Observations
    - NDBC
        - The engineering improvements made with the integration of newer acoustic electronics systems' hardware. This occurred since the Tohoku Earthquake and Tsunami and allowed NDBC to deploy slack moorings, thus improving mooring reliability and improving DART data availability return.
    - PMEL
        - This may need some word-smithing for your purposes and NDBC please review for accuracy.
            - The Tohoku event was a pivot point for the RDT&E of DART systems, as there is a clear need for warning communities under threat from near-field tsunamis. Over the past ~10 years we have designed, developed and tested new technology that is aimed at measuring the water height in near real-time as the earth is still shaking. This has been accomplished by increasing the pressure sensor sampling rate and employing a filter based on actual near field earthquake and tsunami data from the historical record. The new DART near-field systems have no loss in fidelity of detecting far-field events, present emergency managers new siting options to optimize detection and were tested over several years off the Pacific NW, Alaska and Chile. Many earthquakes have been detected but no tsunamis have occured in locations with DART near-field sensors deployed, so validation is still on-going. There are over 15 DART near-field systems presently deployed

operationally by Chile and New Zealand and are being evaluated by NOAA-NDBC for inclusion into the US array.

- PMEL

  The 2011 Tohoku event was essential in addressing the strengths and areas for needed improvement of a Tsunami Forecast System that had been built in the wake of the 2004 Sumatra event based on wave height observations in deep water (DART buoys) and hydrodynamic numerical models (SIFT) to model propagation and forecast inundation. This assessment helped focus research and development efforts in the following decade to enhance the strengths and minimize the weaknesses.

  **Strengths:**

  - The large magnitude of the event (Mw 9.0) and generated tsunami allowed for a large signal-to-noise ratio at near- and far-field DART stations.
  - DART buoys were optimally deployed in the proximity of the source and in the main beam of tsunami energy, at the time of the event.
  - The accurate DART inversion solution showed a forecast accuracy of maximum wave height of over 75% at more than ~50 tide gauges along US coastlines.

  **Deficiencies:**

  - Initial seismic analysis of the event largely underestimated the earthquake magnitude as Mw7.9 during the first half hour after origin. This could have affected the initial impact estimate for the near-field. Faster and more accurate estimate of earthquake magnitude was necessary, especially for large events.
  - Latency in tsunami arrival at DART buoys and transmission of enough data for inversion, underscored the difficulties in timely forecasting for the near-field coastlines.
  - Latency had to be reduced and computation of inundation numerical models on the coast had to be accelerated.

  **Correction of Deficiencies (over the last decade):**

  - GNSS analysis to generate a geodetic inversion solution to the earthquake and obtain accurate Peak-Ground-Displacement (PGD) earthquake Magnitude (or CMT and Finite Fault solutions if sufficient stations) within the first 5 minutes from origin time (currently in development).

- Development of the DART 4G generation of DART stations (described by C. Meinig) to be deployed closer to the earthquake rupture area and minimize tsunami arrival time and data latency (15 stations already deployed).
- Graphics Processing Units parallelization of numerical models to accelerate propagation and inundation forecast calculations (already implemented and deployed at the TWCs).

- Washington Sea Grant - Carrie Garrison-Laney
    - **Academic research at University of Washington with Washington Sea Grant participation**
        - NSF funded M9 project - an interdisciplinary examination of the effects of a M9 Cascadia earthquake and tsunami.
        - With funding from the M9 project, Washington Sea Grant, Washington Emergency Management Division, Washington Geological Survey, and the City of Bellevue conducted a study of tsunami hazards for the Port of Bellingham.
        - NSF Coastlines and People (CoPe) projects including the *CoPe EAGER Coastal Hazard Planning in Time*, and the *CoPe Cascadia Coastal Hazards Research Coordination Network (RCN)*, both of which have tsunami components.
        - A pending *NSF Coastlines and People Cascadia Research Hub* (proposal submitted in October 2020) will be a 5 year multi institution and agency project across Cascadia that will focus on improving the resilience of coastal communities to coastal hazards, including tsunami.
        - Research collaboration between Washington Sea Grant, UW, and Tohoku University's International Research Institute of Disaster Science (IRIDeS), which was established after the 2011 earthquake and tsunami. This collaboration has resulted in publications, travel of WSG (me) and UW researchers to Japan, and visiting researcher/professor positions.

    - **Washington Sea Grant projects with a tsunami hazard component**
        - Washington's Coastal Hazards Resilience Network.
        - The Washington Coastal Resilience Project

    - **Washington Sea Grant has a liaison** (Carrie Garrison-Laney) with the NOAA Center for Tsunami Research at PMEL in Seattle serves as a bridge between NOAA research and communities and academic institutions and other agencies.

    - **Development/advancement of tsunami modeling capabilities at UW and NCTR**

        - Addition of capabilities to tsunami models, including higher resolution model outputs, improvement to both propagation and inundation models, and current modeling including tidal and river flow influences
        - Modeling of tsunami flow around structures in the built environment
        - Tsunami debris modeling

    - **New tsunami hazard products**
        - New high resolution tsunami inundation maps and animations reflecting a "worst considered case" in reaction to the unexpectedly large 2011 Tohoku tsunami. Prior to 2011, inundation maps used a model based on the 1700 tsunami, with less inundation height and runup. (Washington Geological Survey)
        - New tsunami evacuation models and products (USGS and Washington Geological Survey)

    - **Studies and construction of tsunami evacuation structures**
        - The construction of the tsunami evacuation structure at Ocosta school. The tsunami modeling for this work was done by Randy LeVeque, Loyce Adams, and Frank González at University of Washington, but many others were involved in the design, funding, building, outreach.
        - The funded tsunami evacuation structure at Tokeland (it may already be under construction, Maximilian would know). Modeling for this work also done by Randy LeVeque, Loyce Adams, and Frank González at UW.
        - Others TESs being studied and planned.

    - **Outreach**
        - The Washington Tsunami Roadshow
- CNMI - TJ Manglona
    - Acquisition and installation of mounted warning sirens for first responding vehicles.
    - Installation of Hazard Zone, Evacuation Route & Assembly Area signage throughout the islands of Saipan, Tinian and Rota
    - Public education and outreach activities with school staff & faculty, daycare & healthcare facilities, and local students from schools located along the inundation zones.
    - The production and distribution educational awareness materials for the public.
    - The conducting of a series of tsunami awareness training workshops with fellow government and private partners with topics that included types of warnings, tsunami generation and arrival time frames, flow of warning information and various other tsunami-related topics.
- NCEI - Nicolás Arcos
    - Updated historical tsunami data interface
    - Seamless high-resolution digital elevation model (DEM) tiles allowing update-able DEMs as new data become available

    - Archiving & quality controlling of U.S. Tsunami Program Coastal Water Level Data Inventory, in partnership with NOAA TWCs and CO-OPS
    - Marigram digitization process, in partnership with NCTR
    - Tsunami Event Summary and Water Level Reports
    - Development of Regional Historical Tsunami posters, in partnership with ITIC and CTWP
- American Samoa - Mulivanu Aiumu
    - In 2019 American Samoa held a commemorative service as remembrance for the 10th year anniversary of the 2009 Samoa EQ and Tsunami
    - In the last ten years American Samoa has added indoor sirens in addition to its outdoor sirens (all are offline at this time)
    - American Samoa Tsunami Program has built a solid relationships with the people of American Samoa through its outreach/education programs
    - American Samoa has joined the Tsunami Ready community
    - Inundation Maps
    - Maritime Port Mapping Project (Pago Pago Harbor)
    - Established a Tsunami Working Group (TWG) with memberships from both Territorial and Federal entities
- Washington State - Elyssa Tappero
    - While Washington wasn't directly impacted by the March 11th Japanese tsunami, it provided the impetus for us to launch Project Safe Haven. This collaborative project developed the Tsunami Vertical Evacuation Structure Manual and lead to the building of the first VES in North America – Ocosta Elementary in Westport, WA. Since then, our program has supported successful VES funding initiatives in Ocean Shores, Westport, Aberdeen, and for the Shoalwater Bay Indian Tribe. We are also in the final stages of completing a VES needs assessment for the outer coast which identifies high-risk communities who need VES and recommends potential locations, capacities, etc.
    - We completed deterministic tsunami modeling for all 3,000+ miles of at-risk coastline and have published tsunami inundation, current velocity, and pedestrian evacuation walk time maps for most of the outer coast (inner coast mapping in progress), along with inundation and current velocity simulations. Our simulation videos have been viewed a combined 313,000+ times and are widely shared by the media and other partners. These videos are key visuals for the public and are one of our most popular products.
    - We installed 41 state-of-the-art All Hazards Alert Broadcast tsunami sirens in high-risk areas along the outer and inner coasts thanks to NTHMP and state funding, with plans to install another 29 sirens in spring 2021 to officially complete the statewide AHAB network with a total of 121 sirens. This furthers community readiness and supports tsunami warning dissemination requirements for the TsunamiReady program.
    - Along with coordinating and attending many other outreach events, we developed the Tsunami Roadshow, a targeted tsunami hazard/preparedness public education event series which brings the WA tsunami team and other guest

speakers to some of the most densely populated and at-risk communities in Washington for 8 community presentations in a 4-day period. The Tsunami Roadshow, which garners hundreds of attendees and significant media attention each year, has toured the outer coast for 5 years and in 2020 came to the entire state as the first ever Tsunami Roadshow Webinar and the follow-up webinar "So You're Expecting: A Tsunami".

    - We developed targeted trainings, outreach materials, resources, and guidance documents for stakeholders and partners such as the media, the maritime community, the hospitality industry, schools, and vulnerable populations. Some of these products include the NTHMP newsletter *TsuInfo Alert*, a Tsunami Maritime Response and Mitigation Strategy for the Port of Bellingham with site-specific modeling and mapping, a Media Guidebook for Natural Hazards in Washington, recorded webinars, social media graphics, and yearly tsunami ad campaigns aligned with the Great Washington ShakeOut which have reached more than 1 million people.

- NOS CO-OPS - Paul Fanelli
    - Modernization of our 1-minute water level website https://tidesandcurrents.noaa.gov/tsunami/ displaying high frequency water level measurements from coastal water level stations maintained by NOS and a handful maintained by NTWC.
    - Over the past decade, we have made several improvements including:
        - More modernized plotting
        - Integration of NTWC tsunami stations at:
            - Ventura, CA
            - Akutan, AK
            - Amchitka, AK
            - Shemya, AK
            - Chignik, AK
            - Craig, AK
            - Old Harbor, AK
        - Clearly denoting stations on the map where 1-minute water level observations are unavailable (due to transmission / station issues)

      These improvements were aimed at providing better service delivery of these critical coastal observations to external users (including NWS) during tsunami events.

    - Internally, we are also now including NTWC and PTWC on maintenance emails for tsunami capable stations in order to keep them up to date on station outages and GOES platform ID changes.

- East Coast
    - James Kirby
        - Tohoku related science projects

- \item Kirby, J. T., Shi, F., Tehranirad, B., Harris, J. C. and Grilli, S. T., 2013, ``Dispersive tsunami waves in the ocean: model equations and sensitivity to dispersion and Coriolis effects'', {\em Ocean Modelling}, {\bf 62}, 39-55, doi:10.1016/j.ocemod.2012.11.009.
- \item Grilli, S. T., Harris, J. C., Tajalibakhsh, T., Masterlark, T. L., Kyriakopoulus, C., Kirby, J. T. and Shi, F., 2013, ``Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source'', {\em Pure and Applied Geophysics}, {\bf 170}, 1333-1359, doi:10.1007/s00024-012-0528-y.
- \item Tappin, D. R., Grilli, S. T., Harris, J. C., Geller, R. J., Masterlark, T., Kirby, J. T., Shi, F. and Ma, G., Thingbaijam, K. K. S. and Mai, P. M., 2014, ``Did a submarine landslide contribute to the 2011 Tohoku tsunami?'', {\em Marine Geology}, {\bf 357}, 344-361, doi:10.1016/j.margeo.2014.09.043.
- \item Abdolali, A. and Kirby, J. T., 2017, ``Role of compressibility on tsunami propagation'', {\em Journal of Geophysical Research: Oceans}, {\bf 122}, 9780-9794, doi:10.1002/2017JC013054.
- \item Tehranirad, B., Kirby, J. T. and Shi, F., 2021, ``A model for tsunami-induced morphology adjustment'', {\em Pure and Applied Geophysics}, in press, doi:10.1007/s00024-020-02614-w. (uses response to Tohoku in Crescent City CA harbor as verification test).

- **Advancements/accomplishments of NTHMP East Coast (EC) modeling team related to the 2011 Tohoku tsunami (S. Grilli and J. Kirby)**
  - Starting on the day of the event, as part of an ongoing NSF project on megathrust events that should have focused only on the 2004 Indian Ocean Tsunamis, the EC modeling team performed new and unique modeling of the Tohoku event, aimed at better understanding its tsunami generation and coastal impact, first in the near-field in Japan, and later in the far-field.
    - Grilli et al. (2013) developed a novel finite element model with geodetic data assimilation of the megathrust event, that predicted better than any other earlier model the coseismic tsunami generation and coastal impact. This work showed that the largest 40+ m runups along the 80km long Sanriku coast could not be explained by the earthquake alone and that another source of wave generation was needed. In view of the numerous landslide scars on the seafloor, they conjecture a large tsunamigenic submarine mass failure (SMF) was triggered by the earthquake. They used FUNWAVE in the modeling, which is main model used for the NTHMP tsunami propagation work.
    - Tappin et al. (2014) identified and parameterized a large SMF in the Japan Trench and dynamically modeled the dual source coseismic-SMF tsunami generation, by specifying the space and time varying bottom deformation in the 3D model NHWAVE and coupled it with FUNWAVE to perform high-resolution near-field

simulations. They showed that the dual source results explained all the runup and inundation observations to date better than any other model. This methodology is currently applied to the modeling of landslide tsunamis in the EC NTHMP work.

- Kirby et al. (2013) studied the far-field impact of the tsunami and compared results to DART buoys measurements. To do so, they developed and validated a new version of FUNWAVE in spherical coordinates, including dispersive and Coriolis effects. They showed that dispersive effects significantly affected far-field results (up to 60% differences), unlike earlier common beliefs that large coseismic tsunamis can be modeled with non-dispersive models. They also showed, Coriolis effects were much smaller than dispersive effects in the far-field. This version of FUNWAVE is used in the EC NTHMP work to propagate tsunamis over the large-scale Atlantic grids.
- 2013: For the second anniversary of the Tohoku event (in early March 2013), the main Japanese TV channel (NHK) came to Grilli's lab at URI, for filming and interview related to the above work identifying an underwater landslide as responsible for the large runups in Sanriku. They made it a 5 min long prime time segment in Japanese (https://www.dropbox.com/s/8jvpn72dfi6j325/nhkTsunami.mp4?dl=0) and also a shorter version on the NHK World channel. In this long version, Prof. Imamura (the leading Japanese tsunami scientist) is seen in his lab commenting on our work and my Japanese colleagues said he was very praising.
- Abdolali et al. (2017) used the Tohoku event to validate a new model simulating and quantifying water compressibility effects. They showed, this allowed better simulating tsunami phases (i.e., arrival times) in the far-field compared to Kirby et al. (2013).
- Tehranirad et al. (2021) used the erosion caused by this event in Crescent City CA harbor as verification test for a new model including realtime erosion during tsunami impact. This model is now being used in EC NTHMP work for high-resolution hazard maps.

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- FEMA - Mike Mahoney / Amanda Siok
    - Most recent update of FEMA/NOAA *Guidelines for Design of Structures for Vertical Evacuation from Tsunamis* (FEMA P-646). This most recent update incorporated information and findings from the Tohoku earthquake and tsunami. The document can be found at: https://www.fema.gov/sites/default/files/2020-08/fema_earthquakes_guidelines-for-design-of-structures-for-vertical-evacuation-from-tsunamis-fema-p-646.pdf.
    - Washington - Amanda Siok
        - Washington (Total FEMA Funding Obligated for Tsunami Mitigation: $6,869,349.50)
        - -Grays Harbor County, City of Ocean Shores Tsunami Vertical Evacuation Shelter- Federal Share Obligated $3,592,141.50 (PDM)
        - -Grays Harbor County, Stevens Elementary Tsunami Vertical Evacuation Shelter- Federal Share Obligated-Pending (PDM)
        - -Pacific County, Long Beach Safe Haven Program- Tsunami Vertical Evacuation Berm- Federal Share Obligated $362,020 (HMGP- DR-4056-0020)
        - -Pacific County, Fire Protection District #1- Preliminary Studies and Design work for Vertical Evacuation Structure- Federal Share Obligated $90,000 (HMGP- DR-4249-0008)
        - -Pacific County, Tokeland Vertical Evacuation Tower- Federal Share Obligated $2,825,188 (PDM)
    - Oregon - Amanda Siok
        - Oregon (Total FEMA Funding Obligated for Tsunami Mitigation: $2,537,233)
        - -Curry County, Port of Brookings Harbor- Floating Dock Reinforcement Mitigation for Tsunami- Federal Share Obligated: $123,500 (HMGP- DR-1764-0002)
        - -Lincoln Co, Newport Tsunami Safe Haven Hill Retrofit, Hardening and Access Improvements- Federal Share Obligated: $680,478 (HMGP- DR-1764-0002)
        - -Lincoln County, Seal Rock Water District- Water and Sanitary Sewer System Protective Measures- Federal Share Obligated: $571,667 (HMGP-DR-4055-0013)
        - -Tillamook County, Bay City Water and Sewer Protective Measures- Federal Share Obligated $1,161,588 (HMGP)

- USGS tsunami research accomplishments - Stephanie Ross
    - Pedestrian evacuation modeling techniques were developed by the USGS and turned into a publicly available GIS tool which is now in use by several state NTHMP members and incorporated into the FEMA HAZUS software
    - Pedestrian evacuation modeling related to tsunami threats was completed by the USGS for the entire California, Oregon, and Washington coasts, all of American Samoa, one Hawaii county, and several communities in Alaska
    - Policy-related geospatial modeling was completed to support for vertical-evacuation planning in Washington, post-event recovery planning in Alaska and Washington, and evacuation procedures and land-use planning efforts in California
    - Estimates of tsunami-hazard exposure has been documented in USGS report for all coastal communities in California, Oregon, Washington, and Hawaii, in terms of the number and type of residents, employees, critical facilities, and infrastructure that are in state-developed tsunami-hazard zones.
    - Developed the SAFRR (Science Application for Risk Reduction) Tsunami Scenario, an in-depth study of potential impacts to California, and especially to the Ports of Los Angeles and Long Beach, from a modeled tsunami generated by a M9.1 earthquake off the Alaska Peninsula
    - Organized the Powell Center Working Group on Tsunami Sources to increase coordination between U.S. states, territories, and federal agencies on developing the tsunami sources used for mitigation efforts.
    - Developed framework and methodology for including non-seismic tsunami sources (meteorological and submarine landslide), as well as extreme seismic sources, into probabilistic tsunami hazard analysis (PTHA).
    - Along with international colleagues *Rabinovich, Tanioka, and Fritz", USGS' Eric Geist edited three volumes of "Global Tsunami Science" published by Springer that highlights state-of-the-art tsunami research.
    - Completed tsunami hazard assessments for the Nuclear regulatory Commission.\
    - Continued the investigation of tsunami deposits on Anegada, BVI, a benchmark for Caribbean tsunami deposits.
    - Using the Haiti tsunami to propose tsunami generation by dynamic triggering of early aftershocks.
    - Completed comprehensive paleotsunami deposit studies in California and Hawaii. The California study found additional evidence for Cascadia tsunamis in northern California and for historical tsunamis, but little evidence of paleotsuanamis. The Hawaii study found evidence of a widespread tsunami striking the islands between 1250 and 1450 CE. Independent studies in the Aleutian Islands found evidence of a large earthquake and tsunami at about the same time suggesting that tsunami could have been the source for the extensive coastal flooding in the Hawaiian Islands.
    - Developed forward, inverse, and hybrid tsunami sediment transport modeling to reconstruct the size of paleotsunamis.

    - In the past decade, the USGS has carried out paleotsunami research at 10 remote sites along the Alaska-Aleutian subduction zone. The findings of this research, published in 7 peer-reviewed articles (see attachment), have advanced understanding of megathrust locking, rupture and tsunami hazards in Alaska.

- Oregon - Jon Allen
    - Successfully implemented a routable road networking capability to allow for on the fly web access to evacuation routes and travel speed information for egress out of the inundation zone in four Oregon communities (ongoing);
    - Completed countywide risk (Hazus) assessments for the northern half of the Oregon coast (ongoing);
    - Increased saturation of tsunami signage (blue thermoplastic lines/posted tsunami signs; entering- and leaving tsunami signage along US Highway 101);
    - Completed evacuation modeling of ~90% of coastal communities (ongoing);
    - Completed evacuation brochures for every coastal community (2013)
    - Completed statewide modeling of tsunami inundation zones (2012);

**Tohoku 10 yr Commemorative Activities**

The NTHMP and others in the tsunami community are organizing various activities to commemorate the 2011 Tohoku, Japan earthquake and tsunami.

- Redwoods Coast Tsunami Work Group
    - The Redwood Coast Tsunami Work Group, including NWS WFO Eureka and NTWC, will be creating a ten-year remembrance web page to commemorate the upcoming milestone. We plan to have links to other sites and efforts that relate to the earthquake, the tsunami and ongoing recovery and resilience efforts.
- Washington Sea Grant - Carrie Garrison-Laney
    - To commemorate the 10th Anniversary of the Tohoku earthquake and tsunami I will be writing an article for the March issue of Washington Sea Grant's *Sea Star* newsletter. I haven't written it yet, but it will likely focus on the research, mitigation, and outreach work in Washington that has been "inspired" by the Tohoku earthquake and tsunami.
- NCEI - Nicolás Arcos
    - Short summary of 2011 Japan event (Note: will go live *10 March*): https://www.ncei.noaa.gov/news/day-2011-japan-earthquake-and-tsunami
    - NCEI social media will push the above story via NCEI's Facebook, Instagram, and Twitter on *11 March*.
- Washington State - Elyssa Tappero
    - TsuInfo article featuring a review of non-scientific literature on the topic (fiction, nonfiction, poetry, etc)
    - A longer version of this article on our Military Department blog (https://mil.wa.gov/news)