# Quantifying, Predicting and Exploiting Environmental and Acoustic Fields and Uncertainties

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## LONG-TERM GOALS

The overall goal is to *better understand, model, forecast and exploit environmental and acoustic fields and uncertainties for efficient sonar operations and to research, integrate and demonstrate end-to-end prediction and DA systems to do so.*

## OBJECTIVES

Our specific objectives for the main four years of the DRI are to:

- Carry out scientific computations and process/sensitivity studies to better understand dynamics, predictabilities and uncertainties in the East China Sea (ECS) and the continental shelf and slope northeast of Taiwan, especially the Cold Dome and its interactions with the meandering Kuroshio, Taiwan Strait currents, atmospheric forcing, barotropic tides, and internal tides and waves.
- Further research and implement multiply nested and coupled environmental and acoustic models.
- Develop uncertainty estimation schemes using ESSE ensembles and new prognostic equations.
- Assimilate ocean physics, acoustic and seabed data; and, utilize data-model misfits to improve the corresponding models.
- Carry out Observation System Simulation Experiments to estimate some observation system properties and use adaptive sampling schemes to optimize the placement of sensor systems for the reduction of uncertainty and best exploitation of the environment.
- Research smaller-scale non-hydrostatic modeling and link our regional modeling effort to larger-scale modeling, including the use of acoustic measurements in deep waters.
- Participate to real-time exercises, issue data-driven forecasts and recommendations to exploit uncertainties, and so develop end-to-end real-time multi-model systems.
- Collaborate with the DRI-QPE team.

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## APPROACH

The regional ocean dynamics and modeling focus is the continental shelf and slope northeast of Taiwan, and especially the Cold Dome, its dynamics, variabilities and uncertainties, as well as impacts of this environment on low-frequency (100 to 1000Hz) acoustic propagation. The dynamics in this region is under the influence of a large number of processes that can occur simultaneously, very energetically and on multiple scales. These processes and associated features include:

- the Kuroshio, a western boundary current interacting with complex topography and influenced by larger-scale Pacific variability;
- ocean responses to atmospheric forcing including Typhoons;
- mesoscale and sub-mesoscale variability, such as the Kuroshio's meanders and eddies, formation of semi-permanent features (Cold Dome) and sub-mesoscale eddies, filaments and thin layers;
- Taiwan Strait shelf jets and currents and their effects on Kuroshio intrusions;
- and, finally, surface and internal tides, internal waves and solitons.

These rich dynamics and processes constitute the larger oceanography context of our effort. They lead to significant uncertainties in and around the Cold Dome region.

The methods and schemes developed for the DRI are generic, but are driven by the above dynamics. The technical research includes: new scientific computations and sensitivity studies; predictability quantification using ESSE; multiply nested high-resolution ocean and acoustic modeling; uncertainty estimation using new prognostic equations and ESSE ensembles; coupled data assimilation and model improvements; observation system simulations and adaptive sampling to exploit uncertainties; and, end-to-end multi-model systems. The uncertainty research builds on the efforts of the UNcertainty and Interdisciplinary Transfers through the End-to-End System (UNITES) Team which contributed to understanding, characterizing and quantifying uncertainty in the ocean environment and assessing its impact on sonar system performance in the littoral. Novel uncertainty work in this new project includes research towards prognostic uncertainty equations, real-time uncertainty estimation and real-time uncertainty exploitation, in each case for acoustic-oceanographic fields.

## WORK COMPLETED

**IOP09 Ocean Modeling and Forecasting**: A large number of simulations were run in the 6 months prior to the real-time QPE-IOP to prepare the bathymetry, atmospheric and tidal forcing and data filtering schemes, and to tune numerical and physical parameters. To support the 18 Aug – 10 Sep real-time exercise, 10 simulations, on average, were run each day to further optimize model parameters as well as initialization and assimilation methodologies. These simulations included both short runs to assimilate the most recent data and reanalysis runs that spanned the entire exercise to date. The initial and boundary fields were created using OR2/OR3 initialization surveys, SeaGlider data, SSH and SST analyses, and a background constructed from high resolution August WOA-05 climatology with deep Summer WOA-05 climatology profiles. The simulations were forced with a combination of COAMPS (wind stress) and NOGAPS (net heat flux, E-P) atmospheric fields along with barotropic tides (Logutov and Lermusiaux, 2008) fitted to both our topography and the Egbert global model. Temperature/salinity data from SeaGliders and SeaSoar as well as SST analyses from OceanWatch were assimilated into these simulations. Skill was evaluated by daily comparisons with all data types.

**Uncertainty Forecasting, Adaptive Sampling and Exploitation:** In addition to standard forecast products (temperature, salinity, velocity), uncertainty forecasts (in the form of ensemble standard deviations of temperature, salinity and velocity) were provided on selected days. These uncertainties were constructed using the ESSE approach. The ESSE ensembles consisted of 20 to 50 simulations with perturbed initial conditions and an additive error model in the form of a simple white noise forcing added in the upper 500m to temperature and salinity. Uncertainty estimates were provided before and after data assimilation to show the impacts on uncertainties of data collected at sea. Suggestions on Seasoar sampling plans were provided daily based on these uncertainty fields (e.g. see Fig. 3b). Similar plans were also provided for the OMAS acoustic runs.

A new method for efficient forecasting of uncertainties governed by stochastic partial differential equations has been developed (Sapsis and Lermusiaux, 2009). The method is based on dynamically orthogonal field equations which are derived from within the original stochastic partial differential equations. Examples are provided for stochastic flows within a cavity and around a cylinder.

**IOP09 Acoustic Modeling and Forecasting:** Prior to the real-time work, new schemes for computing the acoustic variability in time, space and frequency were developed. New parallel codes were written so as to efficiently distribute the corresponding runs on a computer cluster. During IOP09 proper, three different types of acoustic products were provided on a routine basis. Two of those products (acoustics climate map forecasts and Nx2D canyon acoustics forecasts) were generated by us:

- *Acoustics climate map modeling:* These forecasts showed the acoustic variability estimated using our predicted ocean estimates over the QPE Acoustic Area /OMAS Area. The purpose was to provide insight into optimal placement of acoustic and oceanography sensors, as a function of our acoustic variability predictions. The acoustic modeling covered a 56x33 km rectangle area with a 31x31 grid resolution, using the parabolic equation Range-dependent Acoustic Model (RAM). Specifically, a source is placed at each grid point and sound is propagated to 15 km distance in N=8 different directions (at $45^o$ intervals). The overall result is an "*Acoustic Climate Estimate*", i.e. in the present case, an N-by-2D transmission loss (TL) that is a function of (latitude, longitude, bearing, depth, range) at each grid point.

- *Nx2d Canyon Acoustic modeling:* Several Nx2D canyon acoustic forecasts coupled with our ocean modeling were run in real-time. These runs aimed to characterize the variability and to estimate the optimum receiver location. An Nx2D acoustic transmission loss field is computed over the pre-designed OMAS track along the canyon direction. Figure 6 shows examples of these Nx2D acoustic transmission loss field at two different times (6 hours difference).

The third product was produced by Dr. Y.T. Lin of WHOI who closely collaborated with us. His work predicted the 3-D canyon acoustic effect on sound propagation and also the temporal variability of the sound field due to our ocean forecast variability. We disseminated his work via our IOP09 web site.

**IOP09 Real-time Web Support and Product Dissemination:** A web page was created and utilized for operational support and product dissemination during IOP09. Available on the web (http://mseas.mit.edu/Sea_exercises/QPE_IOP09/index_iop2009.html ) were: real-time analyses and forecasts; real-time descriptions of the ocean and acoustic dynamics and findings; estimates of forecast uncertainty; information on preparation and plans; and other links. In addition to the complete web page for each daily product release, a smaller summary page was created for at-sea participants to achieve rapid download and reduce network bandwidth needs.

**IOP09 Data Analysis:** CTD casts have been acquired from their original sources and processed for two cruises during IOP09. These data come from the Ocean Researcher 3 (50 casts, 13-16 August 2009) and the Ocean Researcher 2 (40 casts, 13-16 August 2009). Also used were the CTD-like profiles collected by the SeaSoar operated from the Ocean Researcher 1. There are over 1000 SeaSoar profiles from the nine SeaSoar surveys conducted between August 25 and September 10. Also collected during IOP09 were CTD-like profiles collected by UW-APL SeaGliders SG165, SG166 and SG167. These three platforms provided over 400 profiles from August 17 to September 10.

**Atmospheric forcing:** Surface atmospheric fluxes were acquired from FNMOC via the Metcast system, for the time period, 7 August – 14 September 2009. Currently utilized products are COAMPS at 0.2$^o$ resolution and NOGAPS at 1.0$^o$ resolution. COAMPS products at 5km and 15km horizontal resolution will be utilized in hindcasts. The wind forcings from the COAMPS domains at different resolutions (5, 15 and 45km) were fused together to generate the forcing files for MSEAS.

**Analysis of Moored ADCP data in the Taiwan Strait:** ADCP data from 4 moorings across the Strait of Taiwan, provided to us by Dr. Sen Jan, Institute of Hydrological and Oceanic Sciences, NCU, were analyzed to extract the barotropic and the baroclinic tidal signals from the data and study the observed relationships among barotropic and baroclinic signals. Quality control, filtering, averaging, harmonic analyses, and visualization techniques were applied.

**Tidal modeling:** New tidal boundary conditions were implemented**.** The barotropic tides were simulated using both the inverse barotropic tidal model and the generic MSEAS modeling system to support the activities of QPE teams. Internal tide generation around the Peng-Hu Islands and the northern tip of Taiwan (the QPE domain) has been analyzed.

**Ocean-Acoustics Dynamics for the Pilot Study**: We utilize coupled oceanographic (4D)-acoustic (Nx2D) full field simulations to explain and quantify the mean and variability of mid-frequency sound transmission losses observed during the QPE 2008 Pilot experiment northeast of Taiwan (Lermusiaux and Xu, 2009). The coupled model estimates are for the first time compared to the acoustic observations available. We also study the sensitivity of the TL estimation to the uncertainties in geo-acoustic parameters, bathymetry, sediment layer thicknesses and background sound speed variability including both tidal effects and initial transports in the Taiwan Strait. The transmission loss data and its variability with respect to positions and bearing angles are compared with our coupled oceanographic-acoustic modeling results. The uncertainties in the TL estimates due to various factors are also modeled and studied.

## RESULTS

**IOP09 Ocean Modeling and Forecasting:** The ¼$^o$ WOA-05 August climatology was found to not support a Kuroshio structure strong enough for modeling. Instead, SSH analyses from OceanWatch which melded AVISO altimetry with a Niiler Climatology were used to invert for the total velocity, using as weak-constrain the geostrophic shear and an extension in the vertical with a Gaussian decay scale equal to the minimum of 300m or ¾ H (the local topographic depth). These velocities (and surface elevations) were then added to geostrophic estimates from in situ data and climatology.

A computational result was the sensitivity of the tracer fields to the free surface. Specifically, the primitive equation model was coded to proportionately spread the changes in the free surface throughout all depths in the water column. However the momentum and tracer equations were derived assuming constant (in time) control volumes. In regions where the tidal excursion was relatively large compared to the total depth, this discrepancy leads to large, growing, biases in the tracers (Figure 1). Recoding the PE model to include the time dependency of the control volumes (these terms appear in the local time rates of change of both the tracer and momentum equations) removed this bias.

A semi-persistent feature of the forecasts was the "cold dome" in temperature off of northern Taiwan (Figure 2). This feature was present in the initial fields, showed general decay through Aug 28, strengthened through Sep 5 then had a further decay. Eddies of "cold dome" waters were estimated to spin-off to the north-northeast about every 2 days. In addition to the long term variability, the "cold dome" was strongly modulated by tidal effects, e.g. showing internal tide pattern mostly parallel to the shelfbreak and long filaments entrained by the Kuroshio. Figure 2 shows the variability in the temperature at 50m over a 12 hour period from 12Z Sep 9 through 0Z Sep 10, 2009. Forecast skill evaluations included daily comparisons with the UW glider, Seasoar and satellite data (see Fig. 3a). Other examples are in http://mseas.mit.edu/Sea_exercises/QPE_IOP09/Adapt_Samp/index_adapt.html.

**Uncertainty Forecasting, Adaptive Sampling and Exploitation:** To illustrate forecast uncertainties, Figure 2 shows ESSE standard deviations of temperature at 50m for the same 12 hours. The forecast was about one half degree Celsius uncertainty, which is relatively high for this Cold Dome feature.

The error scheme employed ignored the effects of uncertainties in the tidal forcing. Figure 4 shows the ensemble standard deviation of the total velocity averaged over the upper 750m. On the shelf, where barotopic tides dominate, the velocity uncertainties (0-5 cm/s) are clearly much smaller than in deeper regions (15-40 cm/s). Uncertainties in fact decayed because of common deterministic tides. In the future, we plan to add uncertainties to the amplitudes and phases of our tidal constituents.

Examples of seasoar sampling guidance include a plan for Sep 7 issued on Sep 6. The goal was to reduce Cold Dome uncertainties by extending the original tracks to the west either along the original 130m isobath or along an L-shape plan that would also sample the NM Canyon region (see Fig. 3b). Examples of OMAS sampling guidance include, for the same days: to run an acoustic track with a non-zero east-west projection so as to increase the likelihood of crossing the forecast weakening Cold Dome or to run two acoustic tracks, one in the Cold Dome and one outside of it. Other examples are provided in http://mseas.mit.edu/Sea_exercises/QPE_IOP09/Adapt_Samp/index_adapt.html.

Our new method for forecasting uncertainties governed by stochastic partial differential equations (Sapsis and Lermusiaux, 2009) is very promising. The dynamically orthogonal field equations are derived from within the original equations by assuming that the rate of change of the error subspace is orthogonal to itself. The two examples run, a stochastic flows within a cavity and another around a cylinder. Results indicate that the approach is cheaper and more accurate than a direct Monte-Carlo scheme. Future work focuses on varying the subspace size in time and on data assimilation.

**IOP09 Acoustic Modeling and Forecasting:**

- *Acoustics climate map modeling:* The acoustics forecasts results are illustrated by Figure 5, which shows general acoustic variability for 11 Sep. 2009 for a source at 60m depth at 900Hz in the

IOP09 area of interest. Pictured are mean transmission loss (TL) and the standard deviation of TL over depth and bearing angles. Those forecasts were provided daily during the experiment. They indicate the effect of internal tides on the shelf (see STD in depth of the TL) and of the steep bathymetry on the bearing dependence (se the STD in bearing of the TL).

- *Nx2d Canyon Acoustic Modeling:* The area shown in Figure 6 is a 10 km wide by 15 km long box. At each source location, N-by-2D simulations are set up with a 900 Hz source at 100 m depth. The runs are for a total of 15 km range and for 180 directions (every 2 degree bearing angles in the whole circle). The N-by-2D TL is then projected to this horizontal map and certain depth by averaging it over 61 ± 10 m. In order to show the TL variations clearly, cylindrical spreading loss compensation is applied here. Note the TL dynamical range here is 15 dB.

**IOP09 Real-time Web Support and Product Dissemination:** Nowcast and forecast products with dynamics and uncertainty descriptions and adaptive sampling recommendations were provided for physical (T, S, velocity) and acoustical (sound speed and transmission loss) variables for the period 18 August - 10 September 2009. Products were produced for a large (regional) area and a zoom of the operational area of interest. Model output, in NetCDF format, was included with each product. See: http://mseas.mit.edu/Sea_exercises/QPE_IOP09/index_iop2009.html.

**IOP09 data analysis:** The various sets of synoptic data have been found to be in good agreement. One SeaGlider had a known conductivity cell problem. From this platform only temperature information was utilized. The mixed layer depth is found to vary greatly in time and space, ranging from a depth of a few meters to over 50m, indicative of sub-mesoscales, internal tides and waves, and the differing ocean regiones from which the data was collected.

**Atmospheric Forcing:** Ocean simulations were forced with a combination of COAMPS (wind stress) and NOGAPS (heat-flux, E-P) atmospheric forcing. The winds were found to be generally light during August and stronger in September. The passage of typhoon Morakot is well-captured in both the COAMPS and NOGAPS products on August 7-8, but we were not available prior to that date. Additional COAMPS and NOGAPS are being acquired to better define the passage of the storm. A methodology was developed for the fusion of atmospheric forcing fields by solving the diffusion equations with the boundary conditions provided by the data fields.

**Analysis of Moored ADCP data in the Taiwan Strait:** The baroclinic signal in the velocity measurements (from Dr. Jen San, NTU) was found to be comparable or exceeding the barotropic signal in the Strait of Taiwan. Figure 7a shows the internal tide vertical structure in the Strait of Taiwan. Simulations indicate that the predominant internal tide generation sites are located at the northern tip of Taiwan and in the canyons around the Peng-Hu Islands. The tidal signal by far dominates the rest of the dynamics (Fig. 7b) and takes the form of tidal waves propagating through the Strait of Taiwan from North to South, with distinct similarities to a Kelvin wave. The data stressed the importance of capturing internal tides and the barotropic-to-baroclinic conversions in the domain around Taiwan. Figure 7c, showing the observed depth-averaged currents through the period of 08/99 - 12/99, demonstrates the asymmetric structure of current caused by the geometry and bottom topography of the domain.

**Tidal modeling:** Tidal fields in the free-surface model of MSEAS (which supports barotropic-to-baroclinic conversions) and the inverse barotropic tidal model (no barotropic-to-baroclinic conversions) were compared and found to be in reasonable agreement (Figure 8), with the differences presumably coming from the barotropic-to-baroclinic conversions. Tidal forecasts obtained using our barotropic tidal model were utilized to support the planning of the at-sea activities. Comprehensive description of tidal properties and the forecasts of tidal currents were provided to Tim Duda and the at-sea team through the web site http://mseas.mit.edu/Sea_exercises/QPE_IOP09/Tides/index_tides.html and through personal communication. Example provided tidal velocities are shown in Figure 9.

**Ocean-Acoustics Dynamics for the Pilot Study:** During the QPE Pilot, a striking difference between acoustic transmission data collected on the shelf and shelf break in the north-eastern Taiwan (Figure 10a) was observed. On the shelf, the acoustic transmission from a moving sound source along a circular track showed little TL variation with respect to bearing angles. The largest variation there was increased loss along propagation directions parallel to the 125m isobath but with amplitudes less than 5 dB. However, on the shelf break, the data for the same type of circular tracks showed no transmission when the moving source was in the deeper waters. From our coupled oceanographic (4D)-acoustic (Nx2D) numerical simulations (Figure 10b), we found that there was about 20 dB higher transmission loss in Event A when the sound source was in the deep water region on the shelf break. We show that the dramatic TL change around the circle over the shelf break is due to the complex bathymetry: when the sound source moved over the steep shelf break region with upper slope transmission, the sound propagated down at depth and the TL increased (most sound energy is trapped into the bottom). In fact, the up-slope TL was much higher than that in the reverse direction with down-slope propagation.

The variability of the TL due to tidal effects was examined. Figure 11 shows the sound speed as function of time from 0000 Sep. 8 to 0000 Sep. 9, 2008 at three hour intervals. Shown are sound speed variations at a depth of 60 m on the shelf and shelf break caused by internal tides. The variation of TL during Event A (on the shelf) and B (on the shelf break) at different times (at 3 hour intervals) is shown in Figure 12 for Sep. 8th, 2008. The nine different times are the 3-hour intervals from 0000 to 2400, which covered the time frame of Event A and B. The striking result is the one-to-one relation between the TL and internal tide fields, with the same periodicities. Tides caused more coherent vertical motions of the water column on the shelf than over the shelf break. In addition, we show stronger variations in TL with respect to bearing angles in Event A than in Event B. The variations of TL in different directions are found inversely proportional to the local water depth, particular in the case of Event A.

## IMPACT/APPLICATIONS

Better understanding, quantification and exploitation of environmental and acoustic fields and uncertainties for efficient sonar operations. Better integrate, demonstrate and utilize end-to-end prediction and DA systems.

## TRANSITIONS

Multiple approaches, results and data were transferred to members of the DRI, including Taiwanese colleagues. Prior to the IOP09, results from our reanalysis of Pilot08 were used to provide guidance for positioning moorings to Ren-Chieh Lien (APL). During the IOP09 experiment, specially formatted zooms of the forecast products were provided to Kevin Heaney (OASIS) for use in adaptive sampling.

**RELATED PROJECTS**

This effort is linked to AWACS (N00014-07-1-0501) and PLUS research.

**PUBLICATIONS**

Lin, Y.-T., A.E. Newhall, T.F. Duda, P.F. J. Lermusiaux and P.J. Haley, Jr., 2009. Statistical Merging of Data Sources to Estimate Full Water-Column Sound Speed in the New Jersey Shallow Water 2006 Experiment, IEEE Transactions, Journal of Oceanic Engineering. [Submitted, refereed]

Logutov, O.G., 2008. A multigrid methodology for assimilation of measurements into regional tidal models, Ocean Dynamics, 58, 441-460, doi:10.1007/s10236-008-0163-4 [Published, refereed]

Logutov, O.G. and P.F.J. Lermusiaux, 2008. Inverse Barotropic Tidal Estimation for Regional Ocean Applications, Ocean Modelling, 25, 17-34. doi:10.1016/j.ocemod.2008.06.004 [Published, refereed]

Sapsis, T.P. and P.F.J. Lermusiaux, 2009. Dynamically orthogonal field equations for continuous stochastic dynamical systems, Physica D, doi:10.1016/j.physd.2009.09.017. [In press, refereed]

**FIGURES**

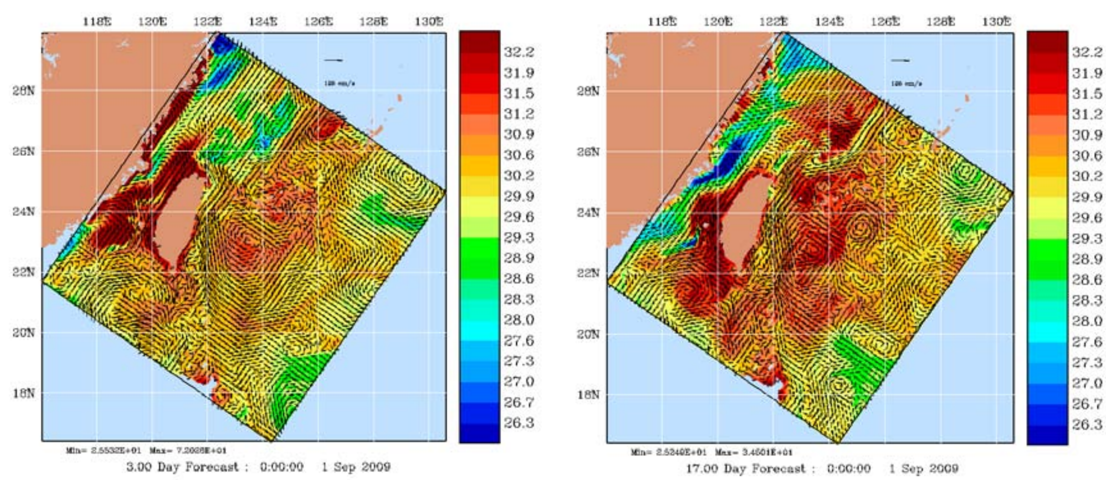



***Figure 1. This figure shows the surface temperature on Sep 01, 2009 from two different simulations. In the left panel is shown a simulation which does not properly account for the effects that the time dependency of the vertical spacing in the model grid have on the local rates of change. Note that the maximum temperature reaches a value of $70^o$ C. In the right panel, the simulation properly accounts for this time dependency of the vertical grid spacing (in the local time rates of change of both the tracer and momentum equations). Here the temperature maximum is a more reasonable $34^o$ C.***

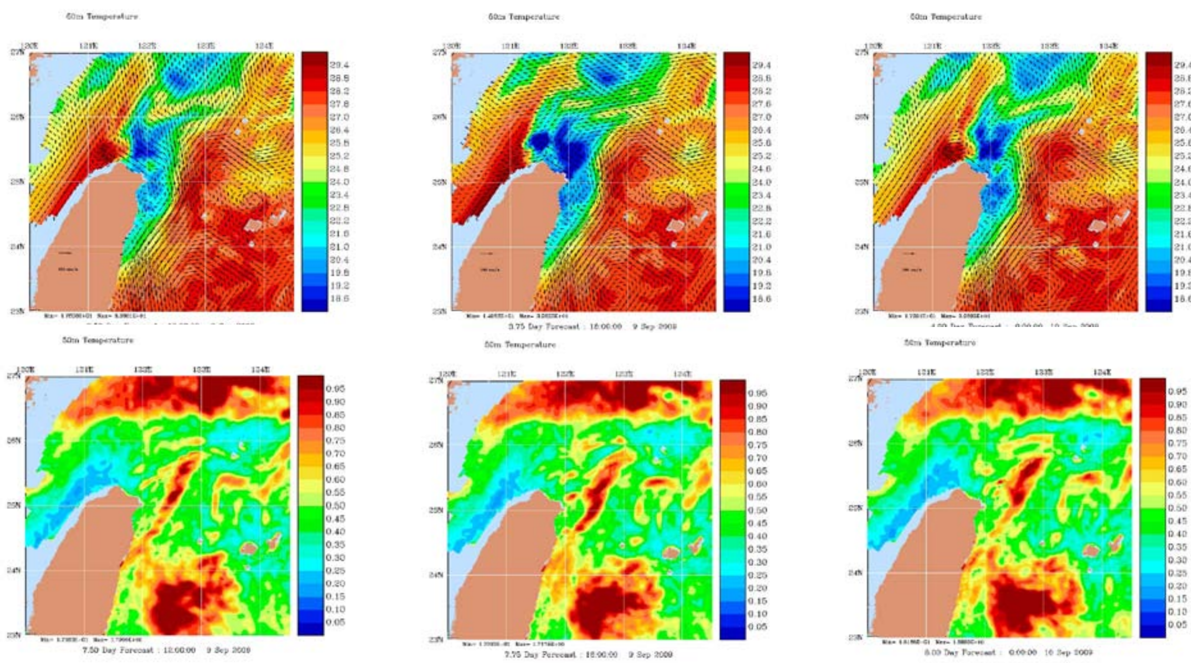


***Figure 2. Top row, 50m temperature fields off northern Taiwan from 12Z on Sep 9 to 0Z on Sep 10. Bottom row ensemble standard deviation of temperature at 50m off northern Taiwan for the same period.***

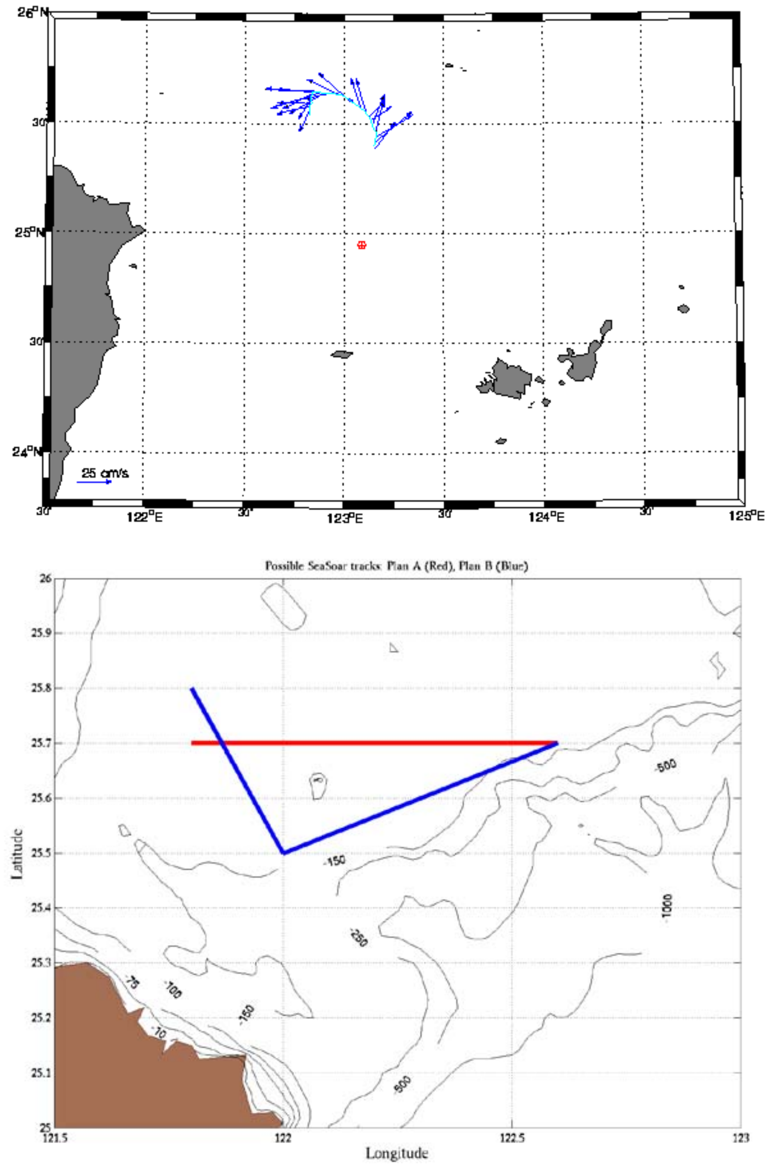



***Figure 3. a) Velocity vectors from UW-APL SeaGlider SG167 collected 3-5 Sep. 2009. Properties of this observed velocity pattern were well forecast in real-time by our MSEAS products. b) Proposed SeaSoar sampling tracks issued 6 Sep. 2009 for 7 Sep. with the goal of reducing Cold Dome forecast uncertainties.***

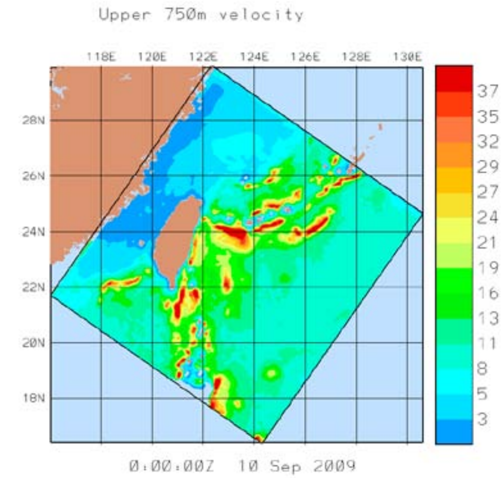



***Figure 4. Ensemble standard deviation of velocity averaged over upper 750m.***

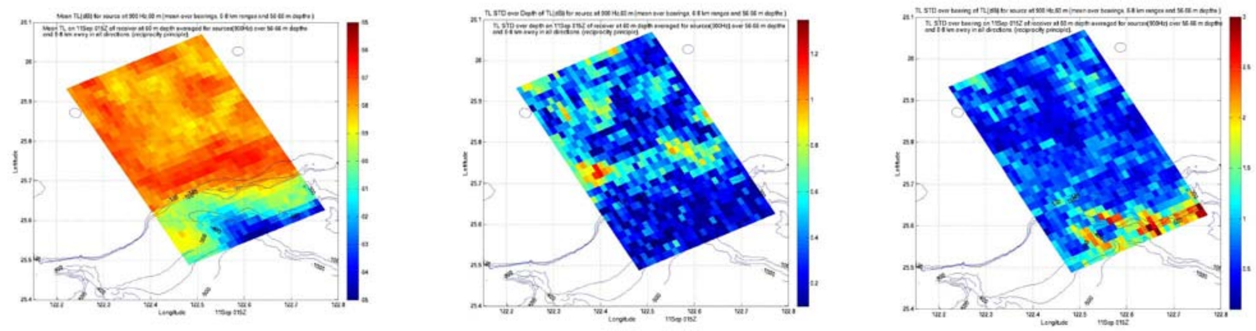


***Figure 5. Acoustic climatology maps for 11 Sep. 2009: (left) Mean TL, (center) TL STD over depth, (right) TL STD over bearing.***

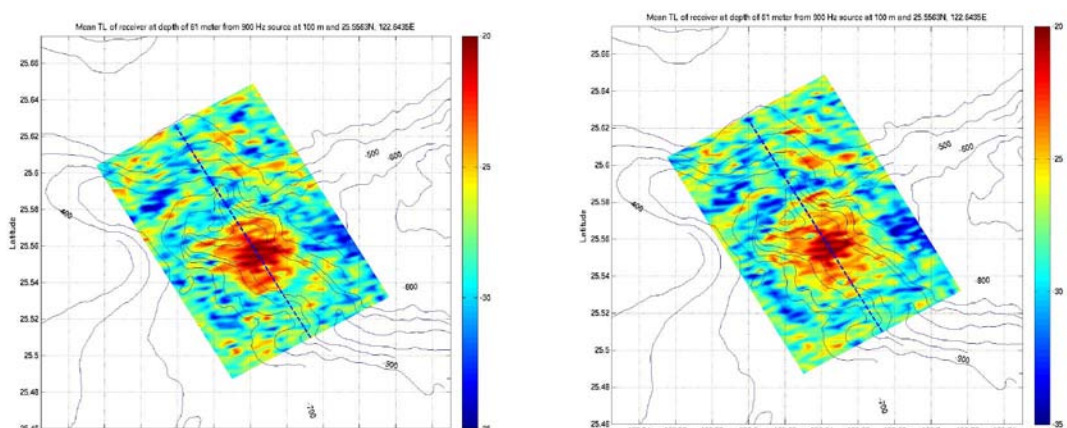


***Figure 6. Mean TL forecast field at depth of 61 m for an OMAS 900 Hz source and depth 100 m. Left and right panels are TL fields for two different times: Sep. 08 15Z, 2009, and Sep. 08 21 Z, 2009. These two plots shows the TL field snapshots when the OMAS source moves from the starting point (SHRU location, 25.6264 N, 122.5986 E), which is the center of upper boundary, to the location of 25.5563 N, 122.6435 E. The blue dash line indicates the OMAS track, which is 150 degrees from due north to the south-east.***

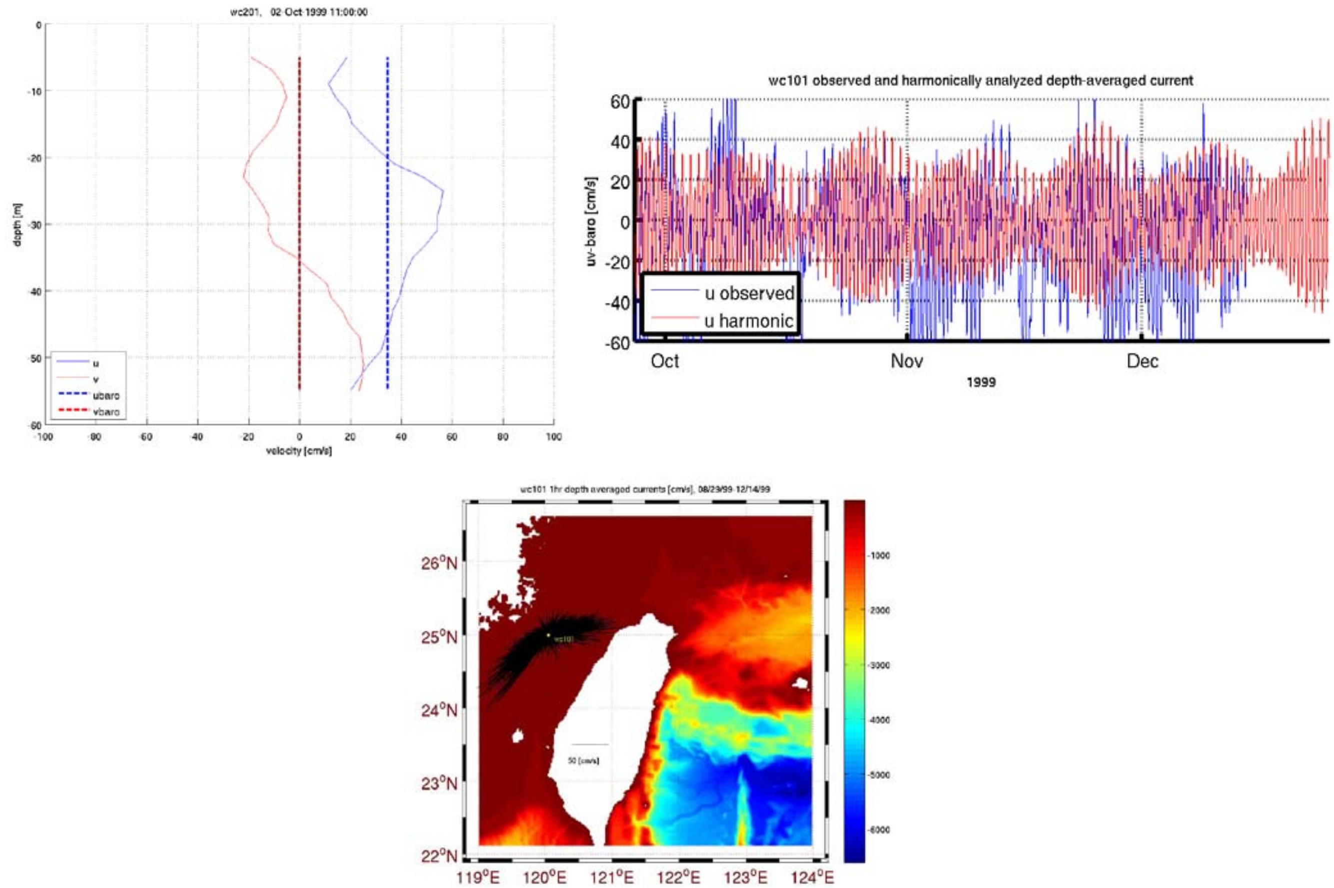



***Figure 7. Mooring WC1-01 in the Strait of Taiwan at 25-00.020'N, 120-02.681'E. (left) Typical velocity profile illustrating the baroclinic structure of tidal waves propagating through the Strait of Taiwan. (right) observed versus harmonically analyzed depth-averaged currents, (bottom) observed depth-averaged currents.***

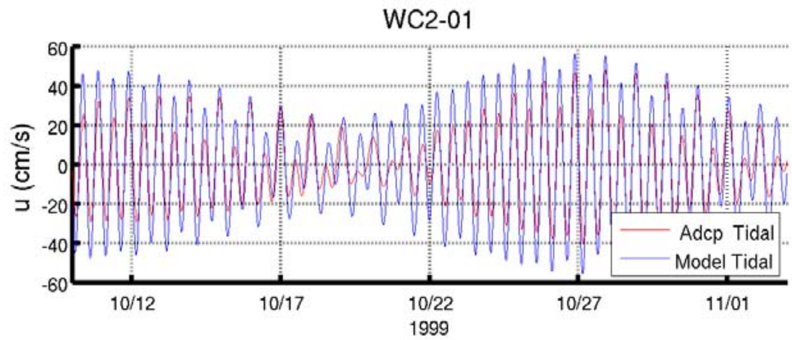



***Figure 8(a): mooring WC2-01 at 24-49.811'N, 119-47.930'E. ADCP tidal velocities (blue) versus barotropic model (Logutov and Lermusiaux 2008) tidal velocities (red).***

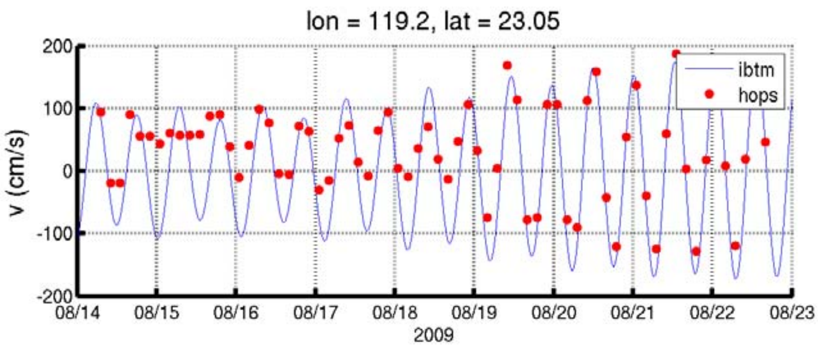



***Figure 8(b): Tidal velocities near Peng-Hu Islands (lon = 119.2; lat = 23.05). Blue - forward barotropic tidal model, Red - HOPS depth averaged velocities.***

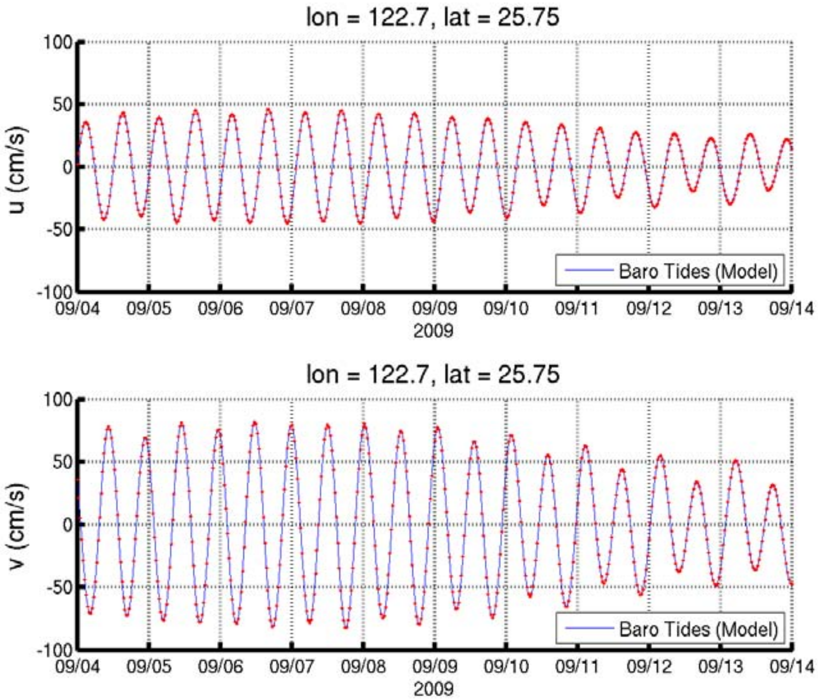
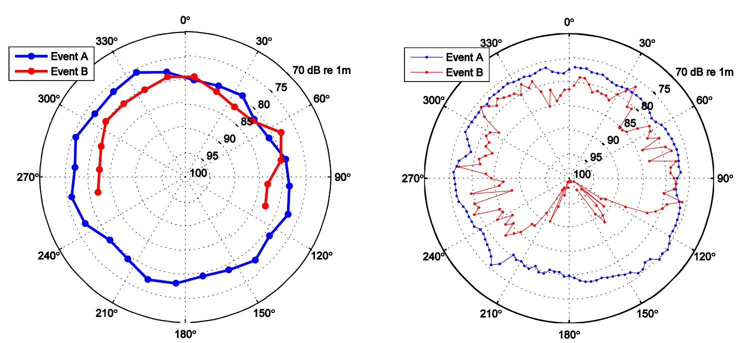



***Figure 9. Predicted tidal currents in the area of at-sea operations provided to Tim Duda for the purposes of planning of mooring deployment (lon = 122.7, lat = 25.75).***




a) b)

***Figure 10 a). Measured mean TL of Events A (blue, on the shelf) and B (red, on the shelf break). b). Mean TL estimation of Events A (blue) at 1200Z September 8, 2008, and B (red) at 1500Z September 9, 2008.***

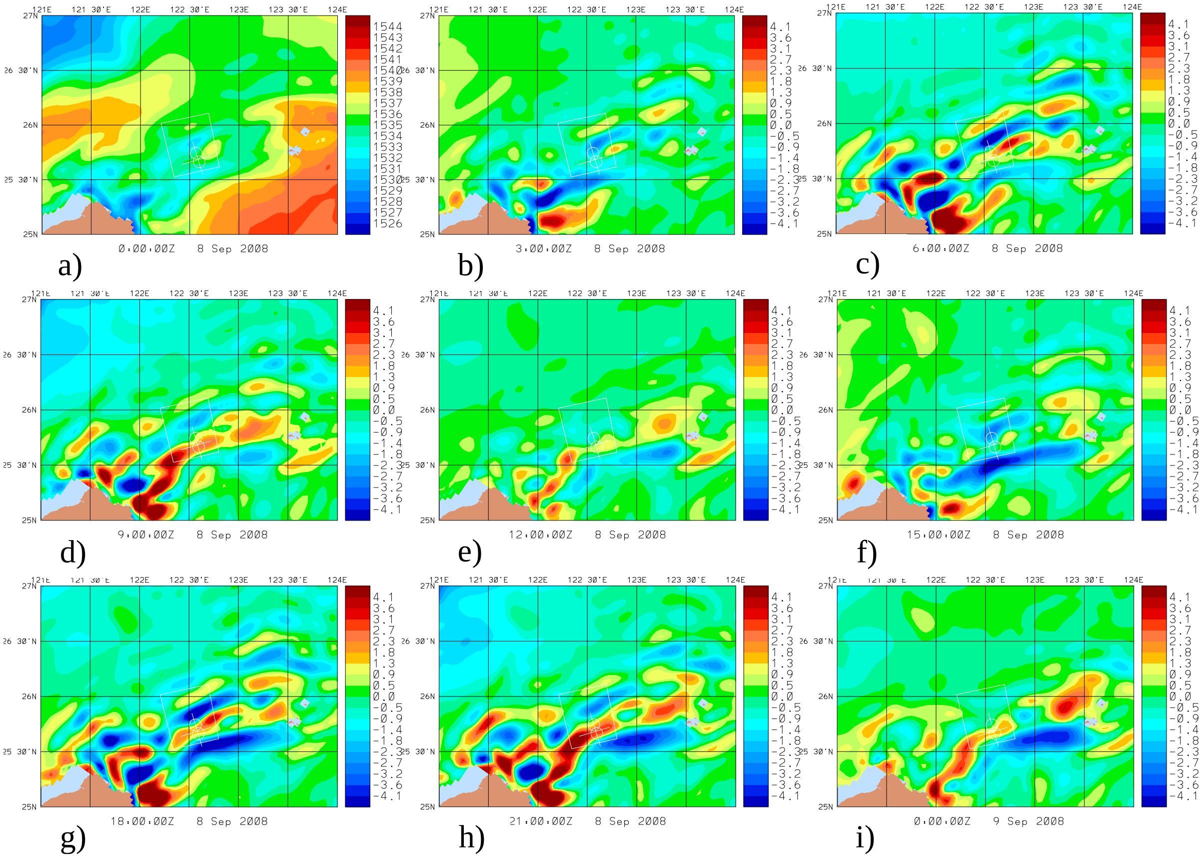



***Figure 11. Sound speed section in horizontal plane at depth of 60 meter. a-i correspond to time from 0000Z Sep 8 to 0000Z Sep 9, 2008 at three hour intervals. From panel b to panel i, we show only the sound speed difference from sound speed (panel a) at 0000Z Sep 8, 2008***

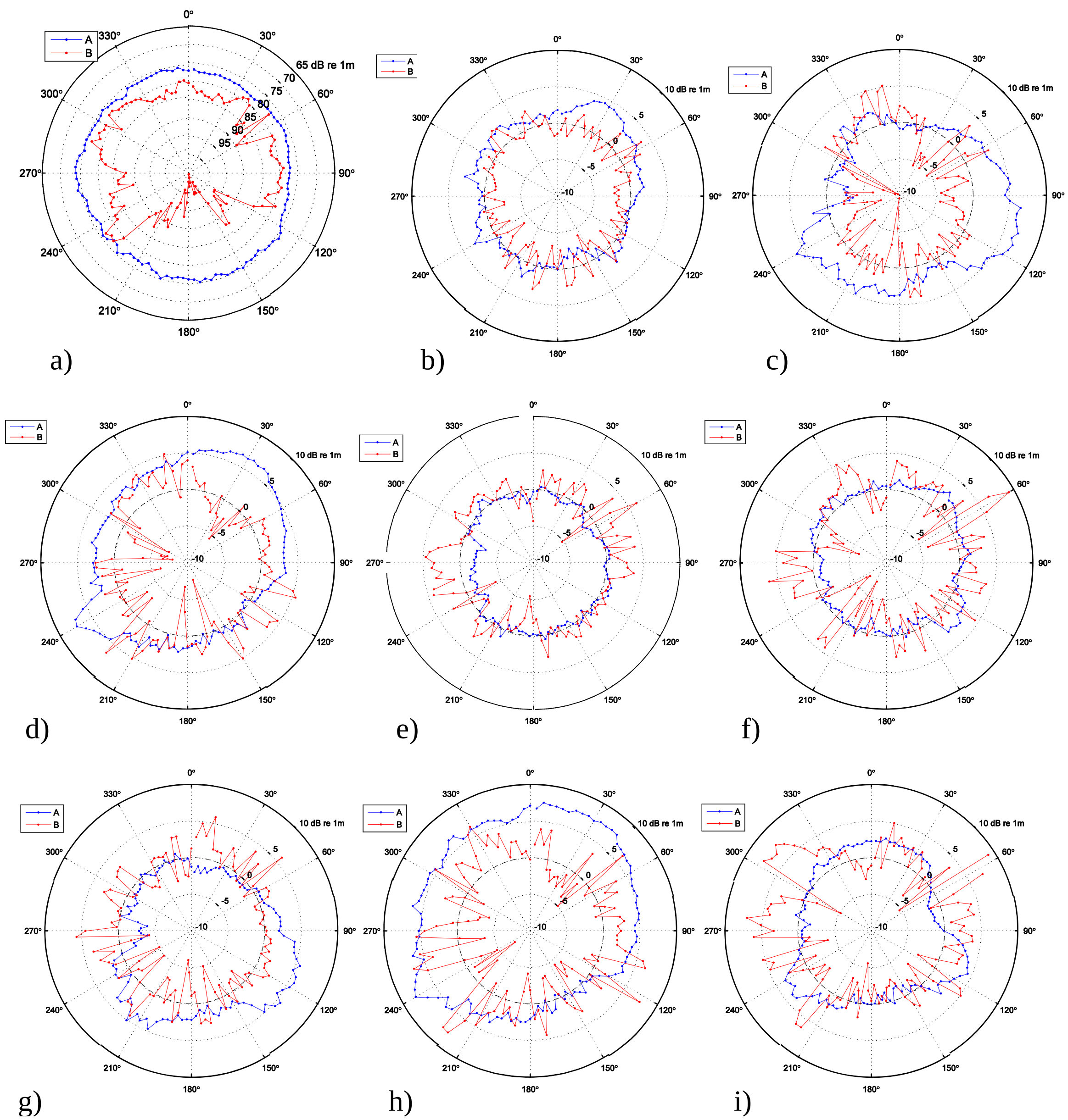



***Figure 12. TL estimation of Event A (Blue) and B (Red) at different times. The nine different times are 0000Z to 2400Z on Sep. 8, 2008 at 3 hour intervals. From panel b to panel i, we only show the TL difference from TL (panel a) at 0000Z Sep 8, 2008; note the TL range is from -10 dB to 10 dB***