Energy Budget of Nonlinear Internal Waves near Dongsha

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LONG-TERM GOALS

Our long-term scientific goal is to understand the mechanisms by which mixing occurs in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is our particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. In this study, our broad focus is on the energy sources of nonlinear internal waves (NLIWs) in a complex environment of strong internal tides and abrupt topography (continental shelf and slope). We expect a rapid evolution of internal tides and NLIWs, and aim to understand their dynamics, energy cascade, and role in mixing.

OBJECTIVES

The primary objectives of this project are 1) to identify the generation site and understand the generation mechanism of NLIWs, 2) to understand the evolution of NLIWs interacting with abrupt topography, 3) to quantify the energy budget and energy cascade from internal tides to NLIWs, and 4) to quantify the seasonal variation of the energy of NLIWs near Dongsha Plateau in the northern South China Sea (SCS). Our particular interest is to understand the energy cascade from barotropic tides, internal tides, and NLIWs to turbulence mixing in the northern SCS, and to understand the evolution of NLIWs interacting with the shoaling continental slope.

APPROACH

Our approach is to take direct observations of NLIWs near Dongsha Island where NLIWs are often captured in satellite images. Primary platforms include an ADV Lagrangian Float, an array of bottom mounted ADCP moorings, and shipboard EK500, marine radar, ADCP, and CTD. Our main goals are to quantify the energy budget and evolution of NLIWs across the rapidly shoaling continental slope and the gentle plateau near Dongsha Island and to quantify the seasonal variation of the NLIW characteristics.

WORK COMPLETED

We have completed three components of this observational experiment: (1) pilot observations in 2005, (2) extended observations in 2006–2007, and (3) intensive observations in 2007.

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Pilot Observations (April 2005)

In April 2005 we conducted a two-week observational experiment near Dongsha. Large-amplitude NLIWs, greater than 150 m, and strong turbulence mixing were observed by the Lagrangian float and shipboard sensors including ADCP, CTD, EK500, and X-band marine radar. Combined remote sensing and in-situ measurements provided detailed properties of large-amplitude NLIWs.

Extended ADCP Observations (June 2006–May 2007)

An array of three ADCP moorings was deployed along the prevailing path of NLIWs near Dongsha in June 2006. Three ADCPs were serviced once and recovered in May 2007. Two of three moorings took velocity measurements for about 11 months. These long-term observations of NLIWs allow us to (1) quantify the seasonal variation of NLIW energy, (2) map the geographical distribution, (3) better understand the dynamics of NLIW evolution over the shoaling topography, and (4) assess the model prediction skill of NLIWs.

Intensive Observations (April–May 2007)

We participated in the multi-ship intensive observation experiment near Dongsha in April–May 2007. Another bottom-mounted ADCP mooring was deployed on the Dongsha plateau to help acousticians understand effects of NLIWs on acoustic propagation. Our main goals were to understand the interaction of internal waves, including internal tides and NLIWs, with the rapidly shoaling continental slope, and to quantify the energy budget of internal waves near Dongsha. Our primary instruments included Scripps Institution’s fast CTD profiler, and shipboard ADCP, CTD, EK500, and marine radar. During the cruise, two McLane moored profilers were deployed, one on the continental slope and the other on the Dongsha Plateau (Fig. 2).

In 2007–2008 we began processing CTD and ADCP data collected during the intensive observations in April–May 2007, and processing ADCP data taken in the extended mooring observations on the slope of Dongsha Plateau, June 2006–May 2007. Our main focus in 2008 was to develop schemes to compute (1) the total kinetic energy of NLIWs, (2) the propagation speed and direction of NLIWs, and (3) the potential energy of NLIWs using moored ADCP data.

The average wave speed between moorings may be estimated by the difference of arrival times of NLIWs on moorings across the Dongsha Plateau. The extrapolation of the wave speed to individual mooring site could be seriously inaccurate because NLIWs reduce propagation speed dramatically over the shoaling slope across three moorings. Therefore, it is necessary to develop independent schemes to estimate propagation velocity, using ADCP measurements at individual mooring sites to compute the NLIW energy flux at mooring sites.

In 2008–2009 we have continued our analysis to (1) estimate propagation speed and direction of NLIWs using ADCP measurements at individual mooring sites, (2) describe trapped core properties on the slope, (3) quantify the intra-annual variations of internal tides and NLIWs, and (4) quantify pressure perturbations induced by NLIWs.

RESULTS

Estimation of Propagation Speed and Direction using Single ADCP Mooring Measurements

We developed a set of equations to estimate the propagation speed C and propagation direction θ using measurements obtained from a single ADCP mooring, *i.e.*,

$$\theta = \tan^{-1}\frac{v - V(z-\eta)}{u - U(z-\eta)},$$

$$C = \frac{\partial_t u'}{\partial_z w} = \frac{\partial_t (u\cos\theta + v\sin\theta)}{\partial_z w},$$

$$\eta = \int dt \frac{w}{1 - U'(z-\eta)/C}$$

where u, v, and w are zonal, meridional, and vertical velocity components, U and V background zonal and meridional velocity components, and η the vertical displacement. U' is the background velocity at the NLIW propagation direction, and u' is the total velocity at the propagation direction. Estimates of C, θ, and η are solved by the iteration method.

Note that ADCP mooring measurements are subject to the effect of ADCP acoustic beam spreading (Scotti et al., 2005). When NLIWs pass the mooring, they may cause strong motion at the ADCP and a rapid change of its heading. If the change of ADCP heading is small, the beam spreading effect can be corrected following Scotti et al. (2005). We are in the process of comparing our estimates of NLIW propagation speed and direction using this method with the estimates using arrival times across successive moorings.

Properties of Trapped Core NLIW

The evolution of one large-amplitude NLIW propagating westward onto the shoaling continental slope in the South China Sea (SCS) was observed. As the NLIW shoaled, its speed dropped from 2 m s–1 to 1.2 m s–1 as it propagated ~30 km over 5 hrs. A sub-surface trapped core formed, in which the particle velocity exceeded the propagation speed of the NLIW (Fig. 3). The trapped core consisted of two counter-rotating vortices, with a maximum magnitude of vorticity of ~0.05 s–1 and a mean of ~0.015 s–1. The upper-front vortex had the opposite sign of vorticity from the primary vorticity induced by the NLIW without the trapped core. The lower-back vortex had the same sign of vorticity as the primary vorticity induced by the NLIW without the trapped core. The reduced shear squared was positive, i.e., Ri < ¼, within the trapped core suggesting the presence of shear instability. Vertical overturning of ~50 m occurred within the trapped core suggesting strong turbulence kinetic energy dissipation. Unlike the conventional concept of the trapped core being an isolated recirculation water body, as it traveled with the NLIW the observed trapped core evolved continuously, entraining and mixing water on its path. To maintain its size, the trapped core must release water mass. During our observations of the evolution of the trapped core, a smaller wave developed behind the original NLIW. We propose that this fission process is part of the evolution of the trapped core.

Before the formation of the trapped core in the deep water, the aspect ratio of the observed NLIW agreed well with the prediction of the fully nonlinear DJL internal solitary wave model, although the prediction over-estimated the wave speed. After the formation of the trapped core, the observed NLIW departed from the DJL solutions, as expected due to the unsteady and dissipative nature. The mass transport by the trapped core is estimated to be O(1–10) Sv. Our observations suggest that the trapped core formation within NLIWs on the shoaling continental slope is important in modulating the energy and mass budgets in the SCS.

Pressure Perturbations Induced by NLIWs

Large-amplitude depression solitary internal waves are observed on the continental slope of the South China Sea. The waves produce strong pressure perturbations, as large as 40 cm, near the bottom, ~600-m depth. One example is shown in Figure 4. Using bottom-mounted moored ADCP measurements, it is shown that the temporal variation of the observed pressure perturbations is predicted well by the Bernoulli balance, though it underestimates the magnitude (Fig. 5). The discrepancy is presumably due to the diabatic process effects, which are not included in the Bernoulli balance, and due to the fact that the streamline at the depth of near-bottom ADCP measurements is not horizontal as assumed. The non-hydrostatic component of pressure perturbations has an opposite sign at the trough as that observed and the same sign at the front and rear ends of solitary internal waves. We conclude that solitary internal waves can be measured directly from a bottom-mounted pressure sensor. Given the propagation speed of solitary internal waves and the stratification profile, the kinematic properties of solitary internal waves may be inferred from the observed pressure perturbations they induce.

IMPACT/APPLICATION

Our analysis concludes that NLIWs evolve rapidly across the upper flank of the continental slope and the Dongsha Plateau via complicated processes, e.g., the formation of trapped cores, and the development of wave trains. These processes are responsible for the strong dissipation of NLIWs in the SCS. Our analysis of combined remote sensing and in-situ measurements yields a model to predict NLIW properties applicable to satellite observations. The newly developed scheme to estimate NLIW wave speed and direction is useful for quantifying wave properties, including energy flux, using a single bottom-mounted ADCP. Further long-term observations of NLIWs in the vicinity of Dongsha Plateau are under way and will provide a better prediction of NLIWs in the SCS.

RELATED PROJECTS

Study of Kuroshio Intrusion and Transport Using Moorings, HPIES and EM-APEX Floats (N00014-08-1-0558) as a part of QPE DRI: The primary objectives of this observational program are 1) to quantify and to understand the dynamics of the Kuroshio intrusion and its migration into the southern East China Sea (SECS), 2) to identify the generation mechanisms of the Cold Dome often found on the SECS, 3) to quantify the internal tidal energy flux and budgets on the SECS and study the effects of the Kuroshio front on the internal tidal energy flux, 4) to quantify NLIWs and provide statistical properties of NLIWs on the SECS , and 5) to provide our results to acoustic investigators to assess the uncertainty in acoustic predictions. Results of the NLIWI DRI will provide a better understanding of the dynamics of NLIWs that have strong effects on acoustic propagation and sonar performance.

Process Study of Oceanic Responses to Typhoons using Arrays of EM-APEX Floats and Moorings (N00014-08-1-0560) as a part of ITOP DRI: We study the dynamics of the oceanic response to and recovery from tropical cyclones in the western Pacific using long-term mooring observations and an array of EM-APEX floats. Pacific typhoons may cause cold pools on the continental shelf of the East China Sea.

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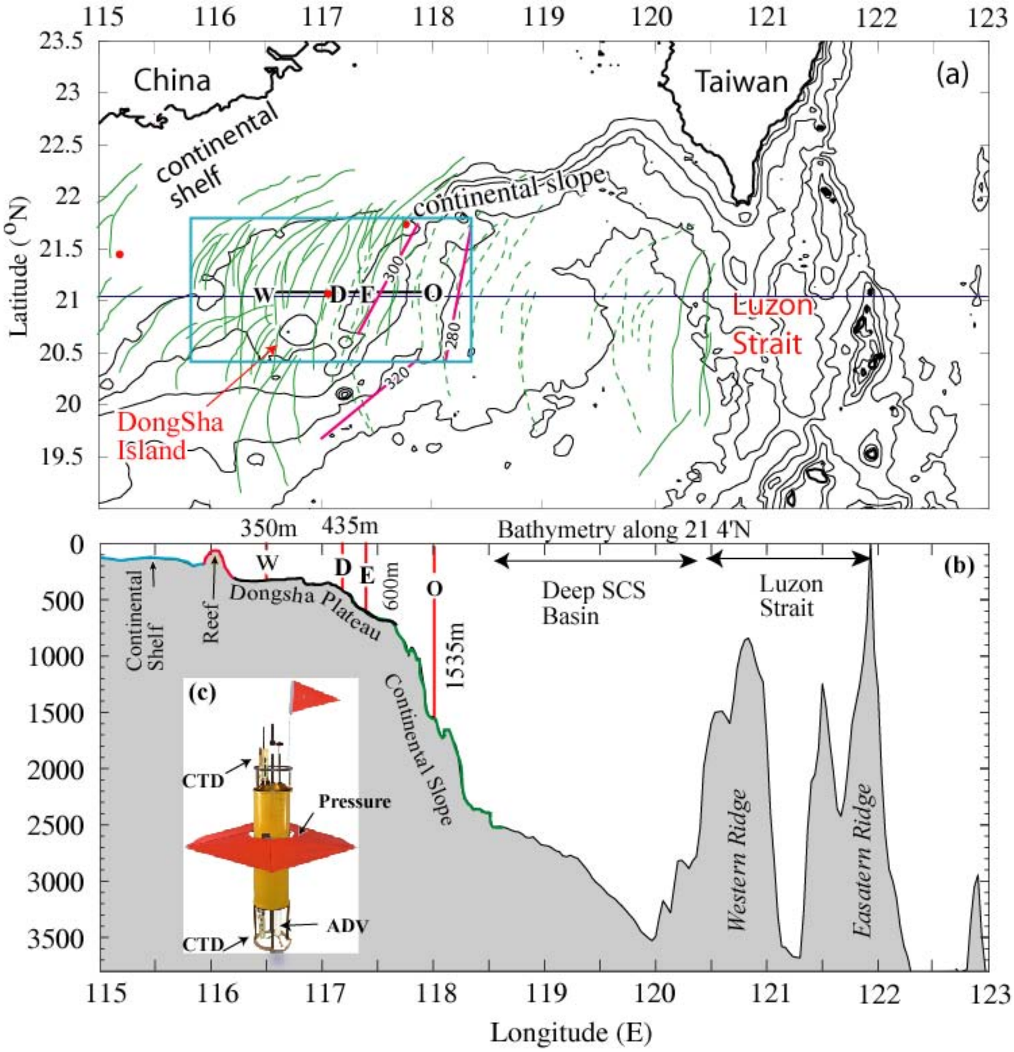

Figure 1. (a) Map of the northern South China Sea, and (b) bottom bathymetry along 21°4'N. In (a) green curves represent surface signatures of NLIWs identified in satellite images (Zhao et al., 2004), dashed for single-depression waves and solid for multiple wave packets. The blue box delineates the area where multiple wave packets are mostly found. Four primary stations in our April–May 2005 cruise are labeled as O, E, D and W. Shipboard and float measurements were taken along O-E-D-W. Three magenta curves illustrate isobaric orientations on the continental slope. In panel (b) two submarine ridges in the Luzon Strait are labeled. They are responsible for generating strong internal tides. Depths at four primary stations are also labeled. The inset (c) shows the Lagrangian float and sensors equipped on the float.

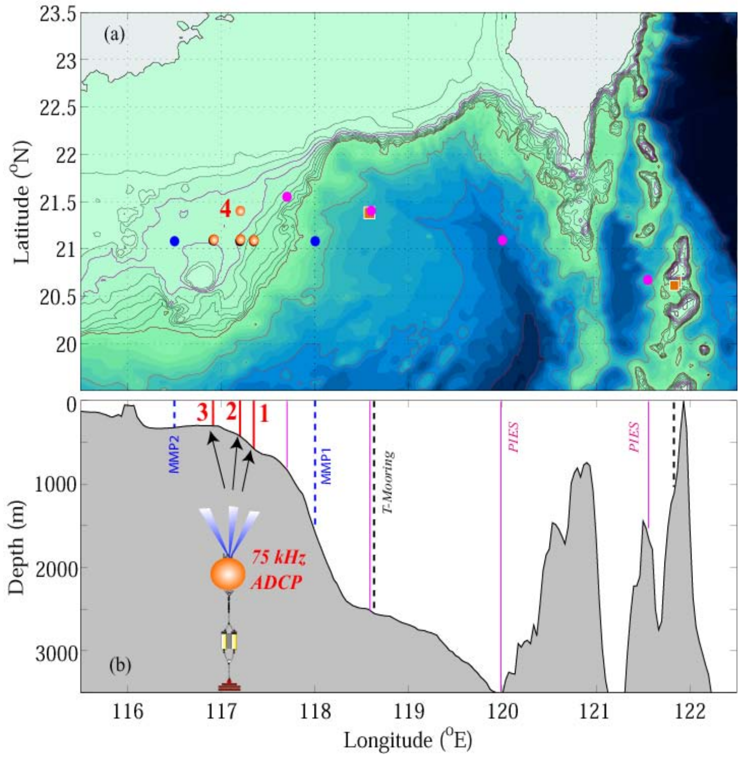

Figure 2. (a) Map of South China Sea and (b) bathymetry along 21°N. Four yellow bullets and red lines mark the locations of moored ADCPs. The configuration of the bottom mounted 75-kHz ADCP is shown in (b). Two blue dots (vertical blue dashed lines), magenta dots (vertical magenta lines), and brown squares (vertical black dashed lines) mark the positions of McLane moored profilers (Alford), PIES (Farmer), and temperature moorings (Tang and Ramp), respectively. Labels 1–4 represent the moored ADCPs.

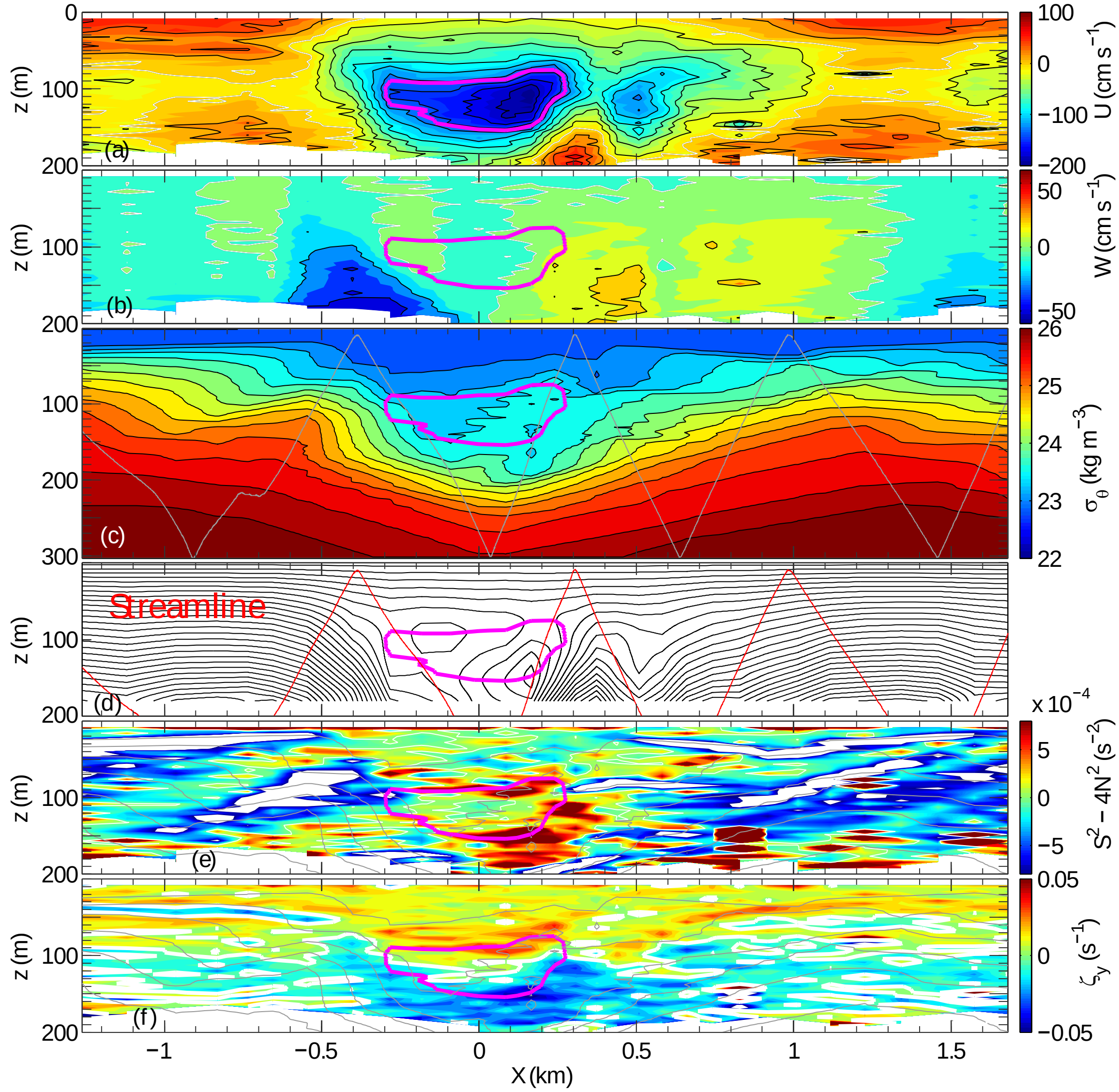

Figure 3. (a) Contour of zonal velocity, (b) contour of vertical velocity measurements obtained from shipboard ADCP, (c) contour of density measurements obtained from yoyo shipboard CTD, (d) streamlines computed from the vertical integration of zonal velocity, (e) reduced shear squared, S^2 - $4N^2$, and (f) relative vorticity . Magenta curves in (a)-(f)) are contour lines of velocity of the propagation speed of the NLIW. The grey and red zigzag lines in (c) and (d) represent the position of CTD profiles. Grey curves in (e) and (f) are isopycnal surfaces.

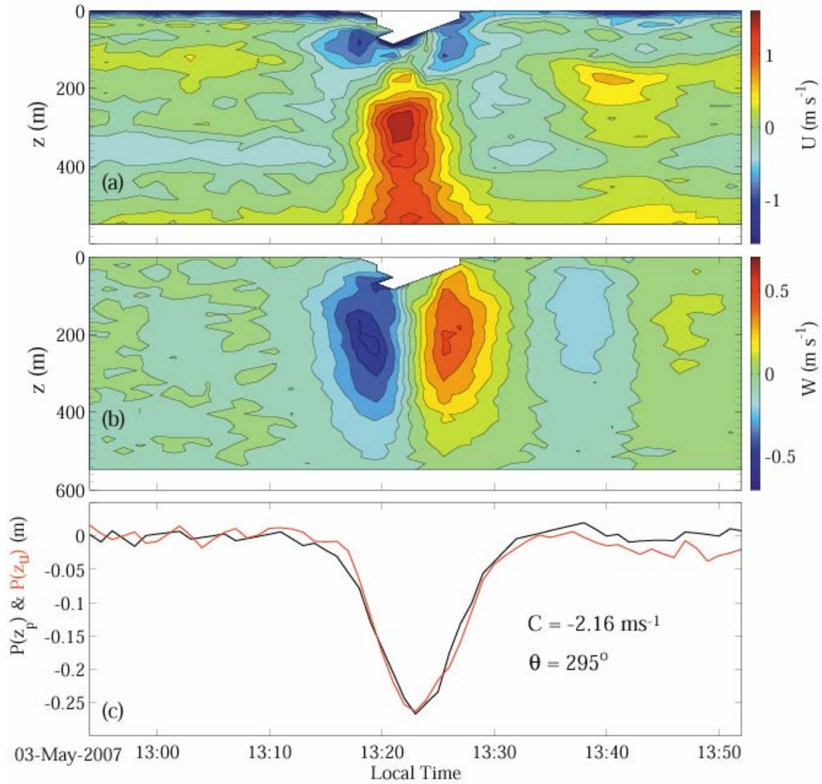

Figure 4. Example of velocity and pressure perturbations of one solitary internal wave observed on May 2, 2007. The panels (a) and (b) represent the contour of horizontal velocity in the wave propagation direction, and the contour of vertical velocity observed from the bottom-mounted ADCP. The panel (c) shows pressure perturbation measured from the near-bottom high-precision pressure sensor (black curve), and the pressure perturbation estimated using the deepest ADCP measurements assuming the Bernoulli balance (red curve).

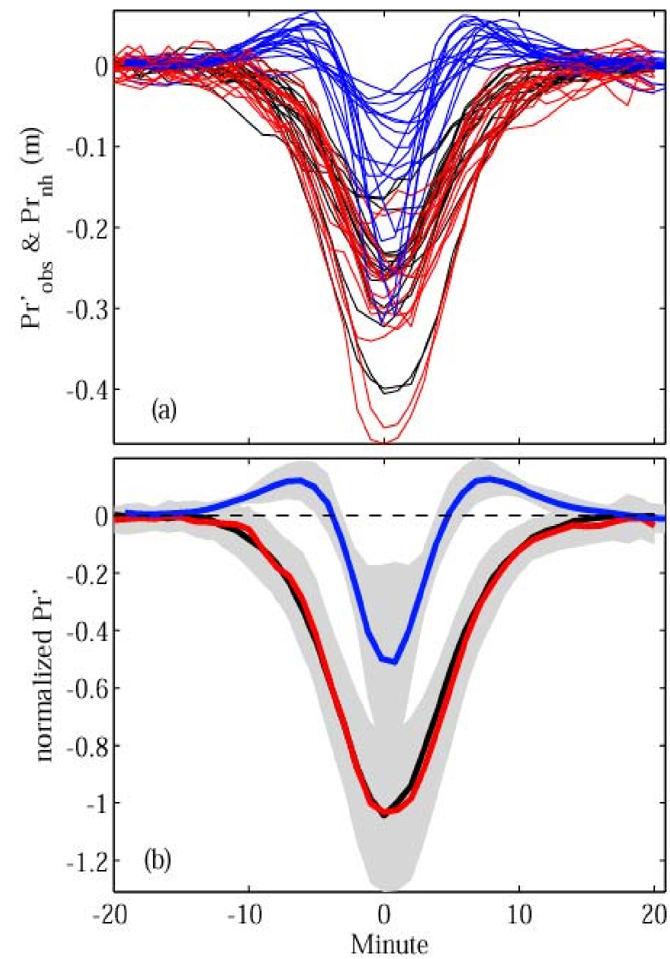

Figure 5. (a) Temporal structure of observed pressure perturbations of 14 NLIW events (red), estimates of pressure perturbation computed using Bernoulli balance (black), and estimates of pressure perturbation due to non-hydrostatic effect (blue), and (b) their normalized form scaled by the top 1/10 of observed pressure perturbation of individual event. The shadings indicate one standard deviation. In (b), the black curve is 140% of pressure perturbation estimated using Bernoulli balance.