Remote Sensing of Submerged Oceanic Turbulence and Fossil Turbulence

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ABSTRACT

Microstructure and internal-wave measurements from vertical and horizontal profilers near a Honolulu municipal wastewater outfall are compared to sea-surface brightness anomalies from optical and synthetic-aperture-radar space satellite images. Optical anomalies with unexpected quasimonochromatic wavelengths $\lambda$ were detected September 2, 2002. Anomaly areas covered 70 km$^2$ in SW and SE lobes extending 10 km and 5 km from the diffuser. Studies in 2003 and 2004 increased the range of optical detection to 20 km in areas covering 200 km$^2$. Radar anomalies covered 800 km$^2$ and extended 45 km. The remote detection mechanism indicated by these remarkable observations involves wave-turbulent interactions between advected outfall fossil turbulence patches and $\lambda = 30$–220 m internal-soliton-wave-like (ISW) packets. We speculate these small ISWs originate as near-vertically propagating fossil turbulence waves (FTWs) from intermittent bottom turbulence events. FTWs mix the water column, create ISWs and supply secondary turbulent-kinetic-energy by tilting fossil turbulence patches. Thus, energy, mixing, and information are transmitted near-vertically by both primary and secondary fossil turbulence patches in ISW patterns of surface smoothing, as detected from space. Nonlinear vertical-amplification and vertically-beamed internal wave processes are similar to those of astrophysical masers but more efficient. Off shore advection of the outfall fossil turbulence patches required to produce the anomaly lobes varies widely and unpredictably, and depends on fresh water run off from the island.

Keywords: 4568 Turbulence, diffusion, and mixing processes, 4524 Fine structure and microstructure, 4546 Nearshore processes, 6061 Remote sensing.
Introduction

Three international oceanographic experiments RASP (Remote Anthropogenic Sensing Program) were carried out in August-September, 2002, 2003, and 2004, involving several ships, space satellites, helicopters, and a variety of environmental sensors, Keeler, Bondur, Gibson (2005), hereafter KBG. The objective of the experiments has been to evaluate and monitor space satellite methods to remotely detect submerged turbulence and fossil turbulence from the Sand Island wastewater outfall in Mamala Bay, Honolulu, Hawaii. Synoptic mean and microstructure measurements were employed to explore possible physical mechanisms. Unexpected small-scale narrow-band internal gravity waves with $\lambda = 130 \pm 100$ m indicated by the optical space images were also detected by towed microstructure sensors, surface wave buoys and thermistor strings. In this paper we emphasize outfall microstructure patterns associated with optical imagery of sea surface glint brightness from sun synchronous satellites Ikonos and Quickbird, but include comparisons with synthetic aperture radar (SAR) images and the internal and surface wave measurements. Energy and intermittency constraints beyond the scope of the present paper are discussed in Gibson, Bondur, Keeler, Leung (2005 manuscript in progress, hereafter GBKL) and elsewhere.

Approximately 3-4 m$^3$ s$^{-1}$ of relatively low density $\rho_w$, low salinity S, treated wastewater is pumped 2.4 km offshore from Sand Island through a 1.98 m pipe and discharged by 283 horizontal jets from both sides and the end of a 1,040 m long diffuser section at bottom depths 68 to 71 meters. Buoyant oily surfactants are completely removed by the treatment process. No evidence was found of ambient surfactants on the sea surface or any effects on the present results by surfactants (except for a localized oil spill from the ship anchorage September 14, 2003).

Trapping of the wastewater depends on its strong initial dilution with dense bottom water by the diffuser jets. If the bottom water volume B to waste-water volume W initial dilution ratio $B/W \approx (\rho_b - \rho_w)/(\rho_b - \rho_s)$, the jets rise and merge to form a buoyant turbulent plume with density $\rho_p$ intermediate between the densities of the surface $\rho_s$ and bottom $\rho_b$ receiving waters. The wastewater plume typically rises to a trapping depth $z_T \sim 50$ m slightly below the seasonal pycnocline depth where the plume density $\rho_p$ matches the ambient density $\rho(z_T)$, the plume becomes neutrally buoyant, and its turbulence fossilizes. How does information about the submerged fossil turbulence reach the sea surface?

A submerged-turbulence remote detection mechanism termed beamed-zombie-turbulence-maser-action (BZTMA) is indicated by the RASP data, as discussed in Leung and Gibson (2004), KBG and GBKL. Aspects of the model are new to oceanography, unaccepted, or controversial, so BZTMA must be viewed as a partially tested working hypothesis with RASP a work in progress. In particular, BZTMA employs an inertial-vortex force definition of turbulence that requires a turbulence cascade from small scales to large in all cases and excludes irrotational and buoyancy dominated flows commonly treated as turbulence by oceanographic studies. This definition of turbulence and its turbulent cascade direction are crucial to the BZTMA model, but are contrary to common oceanographic practice, Gibson (1999). Both turbulence aspects apply to studies of
atmospheric and oceanic vertical transport processes, and to radial transport in self-gravitational systems of astrophysics. The fossil turbulence concept of Gibson (1980 etc.) requires this narrow definition of turbulence. The RASP results cannot be understood without fossil turbulence and fossil turbulence wave vertical transport processes.

Buoyancy dominated motions produced by turbulence are classified in fossil turbulence theory as fossil-vorticity-turbulence-waves (FVTWs), which is a unique form of non-propagating internal wave with frequency $\omega = N$ and a universal energy spectral form $k^2\phi = \alpha_N N^2 k^{-1}$, where the universal constant $\alpha_N \approx 0.65$ was derived from Kolmogorov’s universal turbulence theory with buoyancy, Gibson (1986). As friction causes decreases of $\omega < N$ and $h < \lambda$, these waves couple to the stratified fluid and transmit energy, information, and momentum near-vertically as nonlinear fossil-turbulence-waves (FTWs). FTWs are similar to Linden-Sutherland laboratory internal gravity waves except LSWs have smaller amplitudes and are nearly linear, KBG.

Many current oceanographic studies speculate that either fossil turbulence does not exist in the ocean or that it is unimportant. From the RASP evidence, oceanic fossil turbulence and secondary zombie turbulence patches not only exist but participate as crucial dynamical factors at every stage and layer of ocean mixing and throughout the internal wave cascade from barotropic tidal wave scales to microstructure mixing scales. BZTMA mixing employs an interaction of turbulence, fossil turbulence, FTWs and ZTWs that dominates all others in transmitting heat, mass, momentum, chemical species and information vertically in the atmosphere and ocean. Efficient conversion of the horizontal kinetic energy of tides and currents by turbulence and fossil turbulence to vertically beamed internal gravity waves is the beamed stratified (secondary, zombie) turbulence maser action (BSTMA) that permits the vertical transport.

The RASP experiment is unique in oceanography in that the Sand Island outfall provides a continuous source of powerful submerged turbulence and large microstructure patches with Reynolds numbers at fossilization orders of magnitude larger than ambient. The hydrodynamic states of more than 20K microstructure patches have been tested in RASP using hydrodynamic phase diagrams, leaving no doubt that fossil turbulence exists in the ocean and that the largest fossil turbulence patches in Mamala Bay originate at the Sand Island outfall and are highly persistent compared to the short lives of their previous completely turbulent original state. The speculation of oceanographic studies that stratified ocean turbulence patches somehow originate at their largest scales, collapse, and vanish without a trace, is no longer tenable from the RASP studies.

**Background**

The overturning turbulence of the rising waste water plume rapidly fossilizes at trapping depth $z_T$ as buoyancy forces match inertial-vortex turbulence forces, converting all the outfall turbulent kinetic energy to potential and kinetic energy of the bobbing, saturated-internal-wave motions of fossil vorticity turbulence waves (FVTWs). FVTWs cannot be turbulence by definition because they are created when buoyancy forces prevent overturning of the largest turbulent eddies. Bobbing motions of FVTWs with
frequency $\omega$ near the ambient stratification frequency $N$ cannot radiate. As friction reduces the frequency $\omega < N$ of these motions we infer from fossil turbulence theory that nonlinear, breaking, FTWs are radiated near vertically with amplitudes $h$ comparable to their wavelengths $\lambda_{\text{FTW}} = L_{R_0} = \left(\frac{\varepsilon_0}{N^3}\right)^{1/2}$, where $L_{R_0}$ is the Ozmidov scale at fossilization and $N$ is the ambient stratification frequency. Such internal waves are unstable for $h/\lambda \geq 1/8\sqrt{\pi} = 0.0705$, Sutherland (2001). The vertical penetration distance $(Z/\lambda)_{\text{FTW}}$ of FTWs should increase with the Reynolds number $Re_0/Re_F = \varepsilon_0/\varepsilon_F$ of the turbulence events that cause them, where $\varepsilon_F = 30\nu N^2$ and $\nu$ is the kinematic viscosity. Laboratory experiments show small $(Z/\lambda)_{\text{FTW}}$ values near 1, Dohan and Sutherland (2003). Vertical passage of FTWs through density layers triggers momentum transport by small scale mixing and imprints the layers with horizontal ISWs reflecting the FTW wavelength, as discussed in the following section. Field studies of FTWs have not been reported in the oceanographic literature.

Figure 1a (top) shows outlines of optical spectral quasimonochromatic brightness anomaly (SQA) areas detected during the RASP experiments, Bondur (2005b). The shapes and close proximity of the anomaly areas to the diffuser section of the effluent pipe strongly supports the hypothesis that the Sand Island outfall causes the anomalies. The 10 km and 5 km SW and SE anomaly regions from September 2, 2002, cover 70 km$^2$ in advection directions determined by parachute drogues. The single SQA lobe area in Fig. 1a (top) from September 13, 2003, extends more than 20 km to the SW and covers 200 km$^2$, and the corresponding SAR outfall anomaly extends to 45 km and covers more than 800 km$^2$, Fig. 4 (bottom). Anomaly areas in Fig. 1a (top) from 2004 are truncated to the west by limits of the optical satellite images.

Physical processes, hydrodynamic-phase-diagrams, microstructure evidence, Gregg (1977ab), of multiple secondary-turbulence events from a deep, mid-ocean, secondary-fossil-turbulence region (multiple stacked zombie turbulence patches), and derived universal constants of the secondary turbulence events preserved are given in Gibson (1987). An important semi-empirical result indicated by this, and the present study (see Fig. 8 following), is that the location, Cox numbers and $Re_0/Re_F$ values of powerful turbulent source events are approximately preserved as they are transmitted vertically by breaking FTWs. Fossilization of stratified turbulence can be considered a maser action that directs stratified turbulent kinetic energy and information vertically in a narrow range of space-time frequency. At large oceanic Reynolds numbers these unstable fossil and secondary-fossil (zombie) turbulence internal waves break to produce interior oceanic vertical mixing. Atmospheric observations often show evidence of narrow-band spatial frequency non-linear waves such as herringbone clouds and high altitude clear air turbulence above topography.

The BZTMA mechanism is enhanced if fossil turbulence patches are locally larger in size or more numerous than in ambient areas. Fig. 1a (bottom) shows an ERS-1 SAR image of tidally generated internal solitary waves (ISWs) produced at the New York Bight continental shelf and enhanced over the Hudson Canyon, Apel (2002). It is often speculated that linear surface straining directly induced by ISWs is responsible for their
surface signatures in optical and radar images. However, linear strain rates $\gamma = V/\lambda$ for ISWs of speed $V$ and wavelength $\lambda$ are much smaller than strain rates $\gamma \approx \left( N^{-1} \frac{Re_0}{Re_F} \right)_{\text{Bottom Events}}$ of BZTMA powered by bottom and secondary turbulence events, where $Re_0/Re_F$ is the Reynolds number ratio between the beginning and completion of fossilization of a stratified turbulence event with ambient stratification $N$.

Transmission of ISW images to the sea surface and enhancement of such images over topography can be explained by the BZTMA mechanism. BZTMA is powered by turbulence patches that radiate most of their turbulent kinetic energy at fossilization vertically as large amplitude breaking internal waves (FTWs). Large-scale fossil density turbulence patches from such breaking are persistent, and serve as sites for secondary turbulence internal wave radiation, and possibly formation of vertical IW radiation channels termed BZTMA mixing chimneys, discussed below and in GBKL. We propose an alternative speculation that images of the ISWs and images of fronts crossing over Hudson Canyon, Fig. 1a (bottom), are enhanced in intensity by ZTWs from secondary-turbulence-events formed on the more numerous fossil turbulence patches generated by bottom-topography-turbulence-generated-vertical-nonlinear-internal-waves (bottom-FTWs). We speculate that breaking fossil turbulence waves and breaking secondary fossil turbulence waves strongly smooth the sea surface above Hudson Canyon and reveal its presence, and enhance surface manifestations of any other source of submerged stratified turbulence such as ISWs and fronts. SQA maps in the region are unavailable.

Figure 1b (top), Bondur (2005b), shows an SQA map (a) for Quickbird, September 3, 2004, compared to internal wave measurements from thermistor strings inside the anomaly area (d) and near shore (e). Four resolved narrow-band 43-160 m internal waves measured by thermistor string TS-5, ~1 km south of the diffuser in ~300 m deep water, can be identified with four of the five surface brightness anomaly wavelengths in (b). The 43-160 m SQAs are not found in background area (c) and appear much attenuated in the near-shore TS-2 thermistor measurements in ~60 m deep water of (e). Fig. 1b (bottom) shows a schematic of the complex experiments, measurement section paths, and the satellites, ships, and sensors employed in RASP 2004, Bondur (2005b).

How is it possible for multiple, small-scale, narrow-band, randomly oriented soliton-like, internal waves to exist on the thermocline? How does their signature appear in the sea surface brightness anomaly regions associated with the Sand Island outfall, as shown in Figs. 1a (top) and 1b (top)? The narrow-band 30-220 m internal waves appear to be a previously unknown form of internal-solitary-wave (ISW) that is independent of tides and with much smaller scales than tidal coastal lee wave ISW packets discussed in the literature, Apel (2002), Bogucki, et al. (2005), Bogucki et al. (1997), Maxworthy (1979), Moum et al. (2003), Moum and Smyth (2005). These papers address 200-500 m (and larger) wavelength ISWs, which are often bore-like features that ride on shallow pycnoclines and have surface manifestations (slicks, sulosys, siomes) easily detectable by SAR or by eye. How is it possible for deep ocean features such as seamounts and ISWs they generate to be detected by SAR and by astronauts? Speculations about the usually assumed linear convergences and surfactants seem improbable and are generally not

Answers to these questions not generally considered in the ISW literature are provided by theoretical, numerical and laboratory studies of turbulence in contact with stably stratified fluids, Linden (1975), Sutherland and Linden (1998), Sutherland (2001), Dohan and Sutherland (2003), Sutherland, Flynn and Dohan (2004), Flynn and Sutherland (2004), and Aguilar et al. (2005). These studies show near vertical angle (~45°) radiation of narrow spatial-frequency-band internal waves, termed Linden-Sutherland waves (LSWs) in KBG, from stratified turbulence regions. Large amplitude non-linear versions of LSWs apparently penetrate far above their sources to produce herringbone clouds, sinusoidally bumpy airplane rides, and narrow frequency band OH sky brightness patterns in the stratosphere.

Pinkel et al. (2002) note that acoustic scattering strength is strongly increased above deep-water tidal solitons, and that the effect persists for some hours. They refer to the fossil salinity turbulence remnants that cause the enhanced scattering as an acoustic dye. The enhanced vertical mixing and strong surface wave damping, reported by Pinkel et al. (2002) over the passing solitons, give clear evidence of the BZTMA mechanism for remote sensing of submerged turbulence.

The studies of Linden, Sutherland and colleagues are closely related to the analysis of oceanic microstructure by Gibson (1987) who proposed that the Caldwell (1983) paradox “Ocean turbulence: big bangs or continuous creation?” can best be resolved by a merged, sequential, vertical, cascade process termed “… big bangs and continuous creation”. This process is indicated by microstructure measurements in the deep ocean, Gregg (1977ab). In the Gibson (1987) scenario, fossil density turbulence patches extract energy from ambient internal waves to produce secondary and higher order turbulence events with approximately the same Cox number. Therefore the same normalized Reynolds number at fossilization \( \text{Re}_0/\text{Re}_F = \varepsilon_0/\varepsilon_F = \varepsilon_0/30\nu N^2 \) is achieved by the secondary events, reversing the \(-1/3\) direction of decay of a fossilizing patch on a hydrodynamic phase diagram to a \(+1/3\) trajectory for secondary turbulence, as shown in KBG (see Fig. 11).

In Gibson (1987), a 32 m thick microstructure region (TASADAY 11 MSR 20) at 878-910 m depths from Gregg (1977ab) is interpreted as one primary turbulence event that has triggered five or more secondary turbulence events (see Fig. 8 [bottom]). Each secondary turbulence event fossilizes and re-radiates large-amplitude near-vertical LSWs. Leung and Gibson (2004) and KBG have called these zombie-turbulence-waves (ZTWs) to indicate their secondary nature. Zombie turbulence was invented by Professor Hide Yamazaki to describe velocities produced in computer simulations of initially frozen fossil density turbulence after gravity is turned on. Zebra-turbulence-wave (ZTW) is another possible terminology (from an anonymous referee), especially for ISW triggered secondary waves. “Zebra” captures the quasimonochromatic nature of the IW tilting of fossil patches that gives energy for ZTWs but restricts the vertically beamed maser action energy source to ISWs. This would leave out shearing from fronts and other energy sources for the parasitic secondary turbulence events on fossil density turbulence patch interfaces that bring them back to life (as zombies).
The BZTMA vertical radiation of information about submerged turbulence by a sequence of vertically oriented, secondary-turbulence-events, with re-radiation in the vertical by ZTWs that preserve wavelength information about their energy source, is closely analogous to the nonlinear physical processes of beamed masers in astrophysics. In a beamed maser (or in a laser pointer), a molecule like OH⁻ (water missing a proton) is pumped to a metastable quantum energy state by an energy source; for example, powerful radiation heating by a nearby star in an astrophysical maser. Photons with the frequency of the metastable quantum state trigger a cascade of re-radiation at the particular frequency (wavelength) in the line of sight to the star, amplified in strength by many orders of magnitude (up to $10^6$) above the star black body radiation level. Because this secondary radiation can also pump molecules from ground state to the metastable state, the source energy may also form nonlinear cascades to give maser beams. For stratified turbulence, fossil turbulence patches are pumped to metastable zombie turbulence states by ambient tilting, and radiate the energy near vertically as a maser action.

Figure 1c (top) schematically illustrates the process as it has emerged as a working hypothesis in the RASP program. Surface smoothing observed with enhanced mixing over the outfall diffuser without continuous vertical turbulence proves that FTWs produced by submerged stratified turbulence smooth the sea surface, as shown in the photograph. GPS drogue paths prove that outfall fossil turbulence patches are advected into the brightness anomaly regions illustrated in Fig. 1a (top) and Fig. 1b (top) to provide enhanced amplification of ZTWs. Hydrodynamic phase diagrams for large patches in anomaly regions prove the observed patches originated at the outfall, and demonstrate their hydrodynamic states are fossilized or have experienced secondary turbulence (zombie turbulence) enhancement, GBKL.

Fig. 1c (bottom) shows SAR images of a seamount at 3 km depths on the mid-Atlantic ridge south of the Azores with 3.5 km wavelength lee internal solitary waves at less than 3 km depths that have not and cannot be explained by considering surfactants and induced linear convergences. The first astronauts claiming they could see such bottom topographical features and large internal waves in the deep ocean were not believed. Linear straining at the sea surface from such deep slow waves is trivial at the small wave-lengths of sun glitter. However, such images can be easily understood using the BZTMA vertical information transport mechanism, which produces turbulence at the sea surface in recognizable patterns of the bottom topography and ISW sources.

Figure 1d(a) shows a comparison of the BZTMA model of vertical internal wave beaming to the non-linear amplification of narrow-frequency-band radiation along lines of sight by astrophysical masers. In masers the wavelength amplified along lines of sight is determined by quantum mechanics. For FTWs and ZTWs the wavelength amplified is determined by stratified fluid mechanics and is directed vertically.

ISWs are produced either by FTWs at $L_{ro}$ scales or by lee waves at larger $V/N$ scales, where $V$ is an advection velocity larger than vertical turbulence velocities and $N$ is a stratification frequency produced by vertical mixing at the obstruction. Thus $N$ will be somewhat larger than ambient values and the mixed region will relax by radiation of ISWs. Figure 1d is KBG (Fig. 3) modified in Fig. 1d(bcd) to include lee wave ISWs. Lee ISWs are large-wavelength small-amplitude internal gravity waves described by the
“non-turbulent” wave portion of the Sutherland (2001) stability diagram (bottom left). To produce surface manifestations, even small amplitude lee ISWs with $h/L < 1/8\sqrt{\pi}$ must have sufficiently large Reynolds number to generate FTWs at scales smaller than $V/N$. FTWs and ZTWs initially have $h/L \sim 1$, or 14 times larger than the maximum stable value $1/8\sqrt{\pi}$.

Evidence that FTWs are produced at $L_{R_o}$ scales as expected from fossil turbulence theory is at present indirect, since dissipation rates in laboratory experiments are difficult to measure. Figure 1e clearly supports the approximation $\lambda = L_{R_o}$ from lock-release intrusions over stratified layers by Flynn and Sutherland (2004) using synthetic Schlieren methods to measure the wavelength and fossil turbulence theory to infer $L_{R_o}$ from the height of the intrusion.

The cascade of turbulence from Kolmogorov to Ozmidov scales is driven by nonlinear inertial-vortex force term of the Navier Stokes equation $\vec{v} \times \vec{\omega}$. Hence turbulence is defined as flows dominated by $\vec{v} \times \vec{\omega}$, Gibson (1999). Figure 1f(a) shows how $\vec{v} \times \vec{\omega}$ dominates the turbulence cascade from small scales to large by forcing mergers of adjacent eddies with the same spin. This is the physical basis of the universally similar Kolmogorov turbulence cascade. Figure 1f(b) shows the growth of stratified turbulence to form fossil turbulence and fossil turbulence waves on bottom topography. Figure 1f(c) shows curved radiation trajectories of the unstable FTWs as they lose energy by breaking. The more powerful waves may reach the surface but most will be trapped on stratified layers (dashed lines) and propagate horizontally as ISWs with wavelength $\lambda = L_{R_o}$.

The internal wave maser actions of oceanic BZTMA are much more efficient than those of quantum mechanical masers. Most of the turbulent kinetic energy for the high Reynolds number events pumping BZTMA internal waves is beamed vertically. The nonlinear beaming in mixing chimneys is also beamed vertically. Only a small fraction of the energy required to pump molecules to metastable states in astrophysical masers is converted to narrow-band maser frequency radiation, and the nonlinear maser beaming is in random directions, Fig. 1d(a).

Further discussion of field, laboratory, and numerical simulations of mechanisms for remote detections of submerged turbulence is given in the final discussion section of this paper, following presentation of the RASP 2002 observations. Details of microstructure and satellite observations from RASP 2003 and 2004, discussion of available energy sources, and evidence of intermittent ZTW beaming in vertical mixing chimneys are beyond the scope of the present paper and are provided by GBKL.

**Satellite images and brightness anomaly patterns RASP 2002**

Figure 2 shows the IKONOS-2 Mamala Bay image from which the September 2, 2002, spectral anomaly detection of submerged outfall turbulence was computed. Two-dimensional Fourier transforms of the sea surface brightness are shown for 2 km squares representing “Background” and “Outfall” influenced sea surface brightness. Anomalously bright spectral points shown in Fig. 2 “Outfall image b” correspond to SQA
Fourier elements (double dots represented by a double arrow) with wavelengths of 105 m oriented EW that are present but much weaker in Fig. 2 “Background image a”.

The NW surface swell is not aligned with these anomalous spectral components even though it has a similar wavelength. The 105 m wavelength is larger than any fossil outfall turbulence patch detected and larger than the depth of the outfall. These observations imply that an EW oriented internal wave created elsewhere with \( \lambda \approx 105 \text{m} \) exists or has existed on the pycnocline, such as those reported in Fig. 1b (d), Bondur (2005b). These ISWs could be pycnocline trapped waves from vertical (FTW) internal wave packets from a bottom boundary layer turbulence source to the east or west, as shown in Fig. 1c (top), Fig. 1d (b left), and Fig. 1fc, or could be small lee wave solitons as shown in Fig. 1c (bottom) or Fig. 1d (b right).

Levine and Boyd (2005) report patch heights up to 250 m (see their fig. 14) correlated with the tides on the slope at 1453 m depth on Kaena ridge northwest of Oahu. The background stratification frequency was \( N = 1.9 \times 10^{-3} \text{ rad s}^{-1} \), giving \( \varepsilon_0 = 4 \times 10^{-4} \text{ m}^2 \text{ s}^{-3} \) for the bottom turbulence event. Such powerful events from tides and topography on steep Oahu slopes are good candidates for FTW-induced ISWs, giving the 200-220 m anomaly wavelengths detected in the most extensive RASP sea surface brightness anomaly maps.

Grey stripes from the SW with 1000 m separations, shown by arrows in Fig. 2, are similar to the 500 m tidal lee ISWs of Moum et al. (2003), and are interpreted as lee wave ISWs that smooth the surface waves by radiated FTWs from fossil turbulence zones of the tidal lee waves (see Fig. 17). The grey stripes in Fig. 2b are more pronounced in the region of the SW lobes of Fig. 1b (top) and Fig. 3a, consistent with information of their presence being moved to the sea surface by outfall fossils near the pycnocline depth by the outfall-enhanced BZTMA mechanism. Further RASP studies will explore possible sources of SQA internal waves. Information about tidal forcing, microstructure, hydrography, and ambient conditions at large scales near Oahu in September, 2002, are given by Alford et al. (2005).

Microstructure advected in this direction is likely to be 5-15 hours old with origin below the trapping depth, from the available drogue track information (see Fig. 16) and from ADCP progressive vector diagrams. Moderate intensity fragments 70, 72 and 73 to the SW were at \( \sim 10 \text{ km} \), indicating a microstructure age of over a day or at least 260 N\(^{-1}\). Strong and weak fragments 83 and 85 and the lack of any anomaly fragments on the east end of the diffuser reflect the northwest drift of surface layers that advect embedded fossil turbulence waves before they reach the surface.
The glove shaped form of Fig. 3a has been reproduced frequently, as shown in Fig. 1a (top), and can be attributed to fresh-water-induced off-shore drift of the outfall fossil turbulence patches, as shown by the GPS equipped parachute drogue tracks collected in RASP 2003 in Fig. 3b (see also Fig. 6). Continuous fresh water streams to the ocean from Oahu are to the NW of the outfall (Pearl Harbor) and NE (Ala Wai canal).

Figure 4a (top) shows spectral anomaly regions for the largest anomaly region detected in all of the RASP experiments so far, from 9/13/2003, extending 20 km to the SW and covering an area of ~200 km$^2$. The green oval in fragment 14 marks the location of a BZTMA mixing chimney (see Fig. 4b), and the dashed white line marks the location of a mixing front detected by both vertical and horizontal microstructure profiling along an EW section (also discussed in GBKL, but shown in formation by the SAR image Fig. 4 (bottom) from 9/11/2003). Many large anomaly wavelengths > 100 m (frags. 16, 24 Fig. 4a [top]) are observed at >3 km from the outfall, compared to 30-100 m anomalies in Fig. 1b (top) and Fig. 5 at distances <3 km. The flood of outfall fossils from the rainwater induced offshore advection produced the 40 km RADARSAT anomaly shown in Fig. 4a (bottom) the day after the rains, and the 20 km spectral anomaly pattern of Fig. 4a (top) two days later. Powerful outfall triggered BZTMA vertical information transfer and mixing on 9/11/2003 reveal bottom topography features to the SE of Diamond Head, and several strong mixing fronts in Mamala Bay south of the outfall and Waikiki. The random orientations of the spectral anomaly elements (double arrows and dots Fig. 4a [top]) shows that they are not surface manifestations of ISWs radiated by and therefore pointing toward the outfall source.

Figure 4b shows summary evidence of BZTMA mixing chimneys and ISWs from vertical and horizontal profiling 7 km south of the outfall on 9/14/2003, GBKL. BZTMA mixing chimneys (red ovals) are indicated by strong temperature gradient regions (top left) and a 900 m packet of 100 m wavelength ISWs (right center) detected by the catamaran-MSS tow body (bottom right) in the western chimney (segment 47), matching the wavelength of a spectral anomaly detected nearby (segment 24). The mixing patches below the diffuser density depth are labeled “outfall zombies because $L_{T_{\text{max}}}$ = 10-20 m > $L_{T_{\text{outfall}}}$ ~ 6 m. Presumably the growth in $L_{T_{\text{max}}}$ is caused by secondary turbulent mixing triggered by vertically propagating ISWs tilting outfall fossil turbulence patches advected SW as a bottom plume by offshore bottom currents, since large patches with $L_{T_{\text{max}}}$ > 10 m are found below the outfall density depth.

Figure 5 shows a small region of spectral anomalies, detected 9/2/2003. The smaller size anomaly region (compared to other anomaly regions in Fig. 6 top) is attributed to the lack of comparably large offshore flow rates. Surface fragments with the strongest spectral anomalies were close to the outfall and indicated relatively small ISW wavelengths of only 32 and 53 meters. Similar results from RASP 2004 were observed, showing small off shore flows, small spectral anomaly regions, and small anomaly wavelengths (30-160 m), to be reported elsewhere.

Figure 6 (top) shows areas of spectral anomalies compared to drogue tracks and tidal cycles a few days previous to the large anomaly region, Fig. 4 (top), and the small anomaly region, Fig. 5. The large anomaly (dashed line) extends 20 km to the SW of the
outfall, and is attributed to strong anti-estuarine off-shore advection of outfall fossil turbulence patches induced by rainfall and BZTMA vertical mixing, as indicated by the drogue tracks of 9/11/2003 (Fig. 6 bottom panel). Weaker off-shore flows (Fig. 6 middle panel) preceded the small anomaly region of 9/2/2003 (Fig. 6 top dashed black line).

**Vertical microstructure profiles**

Figure 7a shows vertical profiling stations and times near the outfall pipe after the 9/2/2002 Ikonos-2 satellite over flight at noon. Winds were steady at 10-14 knots from the East, with a slight North component reflected by the ship drift between the double stations. Three modified Sea & Sun Technology MSS instruments (MicroStructure Measurement System, MSS) were used to horizontally and vertically profile the mean conductivity, temperature and depth as well as the microstructure parameters temperature-gradient, velocity-shear, micro-conductivity, turbidity and fluorscence, Wolk et al. (2004), Fig. 1b (bottom left). Factory calibrations were confirmed by field intercomparisons. The basic MSS instrument and the method of vertical deployment are described by Prandke and Stips (1998). A similar profiler and the turbidity and fluorescence sensor used in the modified MSS is discussed by Wolk et al. (2002). The MSS sonde is dropped over the side of the drifting ship and the neutrally buoyant sensor cable is paid out and carefully kept slack by an operator controlled winch as the weighted sensor package descends at a constant velocity of 0.7 m s\(^{-1}\). Signals are recorded and monitored in the ship laboratory. GPS navigation permits precise positioning of profiling stations in Fig. 7a (top).

The HAPA, Fig. 1b (upper left) is a shallow draft water taxi. Drifting ship-bottom-boundary-layer turbulence had no influence on microstructure signals below 1-2 m where the shallowest profiles began, Fig. 7a, and would be easily noticed. Inter-calibrations of MSS instruments were carried out using two systems launched simultaneously on opposite sides of the ship from two winches. The profiles showed no ship influence and no significant systematic deviations between sensors. Simultaneous vertical and horizontal profile inter-comparisons were also performed to confirm factory calibrations and to test homogeneity of the microstructure.

Our study represents the first detailed microstructure description of the hydrodynamic behavior and performance of an oceanic municipal outfall. The continuous source of strong, stratified, oceanic turbulence provided by the outfall gives a rare opportunity to make sufficient repetitive oceanic sampling to achieve statistical convergence of stratified turbulence parameters as they evolve, and the possibility for repeated future tests for reproducibility. The Thorpe overturning scale \(L_T\) profiles of Fig. 7a (bottom) show clear evidence of fossil-turbulence-wave (FTW) mixing patches above both the outfall turbulence and the wastewater trapping depth \(z_T\) (dashed line). Increased mixing rates above the trapping depth near the outfall (confirmed by the towed MSS measurements at 37 m depth, Fig. 16) compared to ambient rates are attributed to outfall enhanced BZTMA vertical radiation and mixing. This interpretation is supported by anomaly patch 83 of Fig. 3 (a) NW of the diffuser pipe end. Evidence of FTW and ZTW near-surface breaking is shown by vertical microstructure profiles at the outfall and from
horizontal profiling above the buoyancy trapped wastewater, where larger overturning scales and larger dissipation rates are found near the surface (Fig. 7b) and over the trapped wastewater plume (Fig. 16) than in ambient profiles.

Figure 7b compares the near surface viscous dissipation rates for profiles G4060001 and G4060002 near the end of the diffuser in the direction of the ship drift to ambient profiles G4070001 and G4070002 west of the diffuser and G4030001 and G4030002 to the east. An increase to $\varepsilon = 10^{-5}$ m$^2$ s$^{-3}$ from ambient $\varepsilon = 10^{-7}$ m$^2$ s$^{-3}$ viscous dissipation rate levels by two orders of magnitude is indicated for the upper 10 meters of the water column (arrows). Because there is no continuous vertical turbulent mixing, horizontal shears, wind variation or alternative explanation, the observed effect is attributed to powerful outfall fossil-turbulence-wave and zombie-turbulence-wave breaking at the 10 m deep wind mixing pycnocline. Dissipation rates $\varepsilon$ above the outfall are significantly smaller in the depth range 10-20 m than values away from the outfall, as shown in Fig. 7b. Vertical FTWs and ZTWs breaking over the outfall have smoothed the ambient vertical density layers below 10 m that are sites for larger levels of ambient turbulence formation at 10-20 m depths in the profiles away from the outfall. The same $\varepsilon$ profile pattern was observed on average in RASP 2004 by repeated MSS profiles at comparison stations M1 and M2 with maximum versus minimum SQA outfall anomaly signatures, respectively. Temperature dissipation rates $\chi$ are increased by outfall FTW and ZTW mixing compared to ambient levels (see Fig. 16 below).

Figure 7c shows averages from RASP 2004 of >200 profiles of buoyancy frequency and viscous dissipation rates from station M1 in a strong-anomaly position ~2 km SW of the outfall compared to those at station M2 ~9 km ESE at the same 350 m depth outside all anomaly regions. Patterns were found that may be understood from the BZTMA model, similar to those of Fig. 7b. Because $N^2$ at the thermocline (bottom left) for M1 exceeds that for M2 suggests increased mixing from below in anomaly regions by ISW activated outfall patches radiating breaking ZTWs toward the surface.

The M1 dissipation rate at the thermocline exceeded that for M2, even though the 95% M2 wind speed range (7.7-8.2) m/s was significantly larger than the M1 range (5.8-7.2) m/s. The M1 surface dissipation rates matched those at M2, but were smaller above and below the thermocline, consistent with ZTW mixing above and below and in agreement with the pattern shown below the mixed layer base at 12 m in Fig. 7b. Thick bottom boundary layers indicated fossilized turbulence events with $\varepsilon_0 = 9.5 \times 10^{-4}$ m$^2$ s$^{-3}$ at M1 and $\varepsilon_0 = 6.0 \times 10^{-3}$ m$^2$ s$^{-3}$ at M2. Such powerful events could account for the 30-250 m wavelength ISWs implied by RASP surface brightness anomaly maps, and are the subject of future RASP studies.

Observations of surface smoothing, strong dissipation rates, and large overturns over the buoyancy trapped outfall from the ship and photographs such as that in Fig. 1c (top) prove that breaking near-vertical internal waves from submerged stratified turbulence must be capable of smoothing the sea surface, and only fossil and zombie turbulence patches can radiate large-amplitude, near-vertical, breaking internal waves. Where does all this dissipated and surface smoothing power come from? Extrapolating the measured $\varepsilon$ levels of Fig. 7b to the large spectral anomaly surface areas of Fig. 1a
(top) proves it cannot come from the 50 kw of pumping power required to inject low salinity Sand Island wastewater from the diffuser into denser seawater at 70 m depths. If $\varepsilon = 10^{-5} \text{ m}^2 \text{s}^{-3}$, as shown in Fig. 7b, is representative of the FTW and ZTW power vertically radiated and dissipated at the surface, then about 5 kw, or 10% of the 50 kw pumping power, is dissipated by breaking FTWs and ZTWs in a 50 m wide strip 10 m deep along the km length of the diffuser for a $5 \times 10^{-2} \text{ km}^2$ surface area. This is 100 kW km$^{-2}$. Larger anomaly areas require larger power sources.

Thus the 200 km$^2$ area of the Fig. 4 (top) 9/13/2003 anomaly region, extrapolating the Fig. 7b results, requires 20 megawatts of surface smoothing power to permit the remote detection of submerged turbulence for this RASP experiment. This is far more than available from the outfall itself. The BZTMA mechanism provides a means of extracting the large power levels we see are required for the satellite detections of submerged outfall fossil turbulence from ambient soliton-like internal waves in RASP spectral anomaly maps, Fig. 1a (top).

Bogucki et al. (1997) estimate that 73% of coastal internal wave energy is carried by ISWs, which they show are effective at coastal bottom re-suspension and mixing. What fraction of this energy is extracted from the ISWs and beamed vertically by the BZTMA mechanism? What fraction of the turbulent kinetic energy created by tides and currents on the ocean bottom finds it way to the surface by vertical maser-action beaming of FTWs and ZTWs?

Figure 8 (top) shows mean and microstructure profiles from station G4060001 located about 50 m to the west of the end of the diffuser pipe, reflecting the ship drift due to the surface currents and wind in this direction. Clearly the waste field has also been advected by the current and horizontal diffusion as shown by the low salinity and high turbidity regions between 42 and 50 meters, which we interpret as the wastewater trapping depth.

Below the trapping depth both turbidity and temperature dissipation levels are above ambient values but less that trapping depth values. Viscous dissipation rates reach a maximum near $10^{-5} \text{ m}^2 \text{s}^{-3}$ near the sea surface from indicated fossil turbulence wave breaking in patches F and G, one or two orders of magnitude above the ambient levels from wind mixing, as shown by profile G4020001 and Fig. 7b.

To detect anomalous levels of mixing due to breaking fossil turbulence waves caused by the submerged fossil turbulence field, an MSS instrument was towed 5-10 m above the waste-water trapping depth. The results are presented in the following (see Fig. 16). They support present interpretations from vertical profiling that enhanced mixing levels exist above the advected waste field due to FTWs and ZTWs breaking as they propagate near-vertically through the stratified water column on their way to the surface.

Figure 8 (bottom) shows the Gibson (1987, figs. 4 and 6) analysis of BZTMA physical processes and the most active microstructure region presented by Gregg (1977ab) from profiles 900 m deep in the north Pacific. From the Gibson (1987) analysis, the step structures in temperature with large temperature dissipation rates but negligible Thorpe overturning scales above patch D, Fig. 8 (top) are fossils of a secondary turbulence event that has radiated its ZTW energy near vertically to the
surface. Cox numbers of secondary turbulence events approach Cox numbers of the primary event at beginning of fossilization, Gibson (1987, eq. 20). This analysis justifies the semi-empirical +1/3 slope of zombie turbulence recovery on hydrodynamic phase diagrams presented by KBG, and in Figs. 12, 13 and 14 below, opposite to the -1/3 slope for fossil turbulence decay, Gibson (1986).

Figure 9 shows mean and microstructure profiles from a station about 3 km south of the diffuser on the western edge of the SE brightness anomaly lobe. The largest Thorpe overturn scale patch L is at approximately the diffuser depth of 70 m (HPD locations of the patches in this profile are shown in Fig. 12). Temperature fluctuations within patch L are smaller than ambient levels and a very large $Re_{0}/Re_{F}$ value ~10$^5$ is found by +1/3 slope extrapolation. This reflects zombie turbulence processes where turbulence is generated on the patch boundaries by ambient internal waves that complete the interior mixing and increase the patch size and Thorpe overturn scale (as shown in Fig. 11 below). Patches IJK below the sea surface, and patches MNOP near the sea surface in such a spectral anomaly region are likely candidates for mixing patches produced by zombie turbulence waves radiating near vertically by patches like L and IJK, pumped energy extracted from the ambient internal wave field vertically by maser action.

Figure 10 illustrates the effect of choosing different vertical separation distances $\Delta Z_{ave}$ for the computation of the effective ambient buoyancy forces available to damp turbulence in a growing turbulence patch. $N^2$ is shown in Fig. 10 for patch D of Fig. 8 (top), computed as a function of $\Delta Z_{ave}$ from the rearranged Thorpe density profile. The patch size $L_p$ and the maximum Thorpe overturning scale $L_{T_{max}}$ are shown for comparison. A range of constant $N^2$ was found for $\Delta Z_{ave}$ between $L_{T_{max}}$ and 2$L_{T_{max}}$. The maximum Thorpe overturning scale of about 6 m for outfall fossil turbulence patches shown in Fig. 10 is typical for the RASP 2002, 2003 and 2004 experiments. Unambiguous identification of individual fossil turbulence or active turbulence patches sometimes requires care, Galbraith and Kelley (1996), Prandke and Stipps (1992). For high resolution instruments like the MSS rather than a CTD, multiple zero crossings of the vertical temperature gradient between patches is generally found to be the most computationally efficient and physically robust method for isolating patches (Prandke, personal communication).

Figure 11 (top) shows the evolution of an actively turbulent patch at the beginning of its fossilization, with critical Froude number and length scale $L_{R_0}$, to an active-fossil hydrodynamic state (stages 1,2,3), followed by re-activation by ambient tilting to form a zombie turbulence patch (stages 3,4,5), Gibson (1987). The geometry of the fossil and zombie (top) and the dissipation rate of its turbulence are reflected on the hydrodynamic phase diagram (bottom) introduced by Gibson (1986), where $Fr/ Fr_0 = (\varepsilon/\varepsilon_0)^{1/3}$ and $Re_{F} = \varepsilon/\varepsilon_F$. Strong FTW radiation occurs after stage 1 and decreases as mechanical energy is lost from the patch by friction. The trajectory on a hydrodynamic phase diagram is a straight line with slope near -1/3.

Tilting of the strong density gradients at top and bottom of the fossil (stage 3) by ambient internal waves results in vorticity production at a rate $\nabla \rho \times \nabla p / \rho^2$, where $\rho$ is
the density and \( p \) is the pressure, because the pressure gradient \( \nabla p \) is always vertical and down. Turbulence will be produced if the tilting persists (red lines) and the fossil turbulence patch (stage 3) will be re-activated to fossil-zombie (stage 4) and fully zombie (stage 5) hydrodynamic states, along a straight line with slope near \(+1/3\), taking the patch to regions of the HPD indicating false, larger, \( \text{Re}_0/\text{Re}_F \) values than existed in the original patch. ZTWs are radiated near-vertically as the secondary turbulence fossilizes. From Gibson (1987) the secondary turbulence events, and breaking ZTW wave events, should have approximately the same \( \text{Re}_0/\text{Re}_F \) values as the original patch at stage 1.

**Hydrodynamic phase diagrams**

Figure 12 shows the microstructure patches A-G of Figs. 8 (top) from station G4060001 50 m NW of the diffuser-pipe-end classified according to their hydrodynamic states on a hydrodynamic phase diagram (HPD) compared to ambient near surface conditions sampled 200-600 m east of the diffuser (triangle H) and patches I-J from profile G4010001 in the SE anomaly lobe region about 3 km south, Fig. 9. As shown in Fig. 10, to properly compute \( N \) for each patch it is important to select a vertical separation distance \( \Delta Z_{\text{ave}} \) larger than the largest Thorpe displacement \( L_{T_{\text{max}}} \) by a sufficient amount so that \( N_{\text{ave}} \) for the patch will represent the ambient stratification that opposed the inertial-vortex forces \( \vec{v} \times \vec{\omega} \) of the growing eddies of the active turbulence in the patch before its fossilization.

Sensitivity to the vertical averaging scale \( \Delta Z_{\text{ave}} = L_{T_{\text{max}}} + 2\Delta z \) is shown in Fig. 12 by computing each hydrodynamic state for both \( \Delta z = 0.1 \) m (dark circles) and 0.5 \( L_{T_{\text{max}}} \) (red squares) to bracket the range of reasonable values, as indicated by Fig. 10. Not much change results for these two choices except for the largest \( L_{T_{\text{max}}} \) patches such as D and L. The interpretation of these patches is the same for both \( \Delta z \) values. Patch L from Fig. 9 is an outfall turbulence fossil from its depth and from the extrapolated value of \( \text{Re}_0/\text{Re}_F = 30,000 \). Patch D is a zombie turbulence patch judging from its depth, its location NW of the end of the outfall diffuser, and from its extrapolated \( \text{Re}_0/\text{Re}_F = 100,000 \) that exceeds expected values from the outfall or any other source. Patch N from Fig. 9 at 3 km from the diffuser is a fossilized outfall zombie turbulence patch near the sea surface, with \( \text{Re}_0/\text{Re}_F = 30,000 \) as expected for secondary turbulence patches produced by ZTW radiation from dominant outfall turbulence patches which have \( \text{Re}_0/\text{Re}_F = 30,000 \) values, Gibson (1987).

A comparison is made in Fig. 12 to the Dillon (1982) claimed correlation \( L_{R_{\text{rms}}} \approx L_{T_{\text{rms}}} \) between root-mean-square Ozmidov and Thorpe overturning scales. The correlation is based on a common oceanographic assumption that microstructure patches in the stratified ocean are never fossilized but are always in a state of continuous turbulent equilibrium, Caldwell (1983), Dillon (1982, 1984), Gregg (1987). Thus, from \( L_{R_{\text{rms}}} \approx L_{T_{\text{rms}}} \) the average viscous dissipation rate \( \varepsilon \) for an oceanic region or layer is estimated by averaging Thorpe overturning scales for patches within assuming they are representative; for example, Galbraith and Kelly (1996), Alford et al. (2005), Rudnick et al. (2005), Baumert et al. (2005). However, all tests of the Dillon correlation show wide
scatter orders of magnitude larger than measurement uncertainties. Dissipation rates $\varepsilon$ estimated assuming the Dillon correlation are not representative of the mean as assumed.

No correlation of $L_T$ and $L_R$ is indicated by the RASP data for more than 20K individual HPD patches, contrary to the concept that fossil turbulence does not exist. An important property of stratified turbulence is that the largest most powerful turbulent events that dominate average mixing rates and vertical diffusion rates are also the most intermittent in space and time and most difficult to sample, Baker and Gibson (1987). Most of the mixing and vertical diffusion in the ocean occurs in large fossilized microstructure patches that persist thousands of times longer than their original patches in actively turbulent states. Most of the time dissipation rates $\varepsilon$ in the dominant patches are many orders of magnitude less than their mean or maximum values.

To avoid under-sampling errors, microstructure data sets should be evaluated for adequacy using HPDs to detect the dominant turbulence events in the region. In extremely intermittent layers and regions of the ocean, undersampling errors can be quantitative, qualitative, and vast due to intermittency effects, Gibson (1983, 1987, 1991abc, 1999). HPD classifications of microstructure patches, as described for Fig. 12, permit the detection of the dominant turbulent events in a region of the ocean by extrapolation along the -1/3 locus of fossilization and +1/3 locus for zombie turbulence formation (Fig. 11) to estimate the power of the original turbulence event, as measured by the ratio $\varepsilon_0/\varepsilon_F = Re_0/Re_F$, and to permit maximum likelihood estimates of mean values using stratified turbulence statistical estimators and fossil turbulence theory, Baker and Gibson (1987), Gibson (1986, 1987).

As indicated in Fig. 12, patches A, B, and C below the trapping depth of the wastewater plume have relatively small values of $Re_0/Re_F$ near 3000, only ~3 times larger than ambient turbulent patches and 10 times smaller than $Re_0/Re_F \approx 30,000$ of outfall fossil turbulence at the trapping depth. Because the fossilization time $t_{\text{fossilization}} \leq N^{-1}$, a single microstructure profile is unlikely to capture any of the dominant turbulence events in their original fully turbulent states, even when the profile is at the source of the events as for the near-outfall profile of Fig. 8 (top). Patch D is identified as a zombie-turbulence patch because the extrapolated $Re_0/Re_F \approx 100,000$ is larger than 30,000 determined from thousands of microstructure patches and three years of RASP experiments in Fig. 14 as the $Re_0/Re_F$ value for dominant outfall turbulence patches. The strong mixing region above patch D was identified as secondary (zombie) fossil turbulence in the previous discussion of Fig. 8 (top) and Fig. 8 (bottom).

Figure 13 shows a collection of all the HPD points for the trapping depth interval 40-60 m Aug. 28-29, 2002, classified according to their separation from the diffuser pipe. Those close to the diffuser pipe position (< 100 m - green squares) include two patches in the fully turbulent quadrant and but no active patches along the decay line extrapolating to maximum $Re_0/Re_F$ values about 30,000. Therefore it appears from Fig. 13 that the dominant turbulent mixing patches at trapping depths have been under sampled. All such patches at near distances ~600 m (red circles) are strongly fossilized except for one actively turbulent patch with $Re_0/Re_F < 100$. Far patches beyond 3 km at 40-60 m depths all have $Re_0/Re_F$ values less than $10^3$, which we take to be the ambient maximum for this
depth. More samples are required to detect fully turbulent, or even fossilized, outfall turbulence patches; that is, those patches reflecting \( \text{Re}_0/\text{Re}_F \) values of 30,000 (star) estimated to be characteristic of the outfall diffuser wastewater at trapping depths from RASP 2002 data. Because such active outfall turbulence patches were not detected until following years, the outfall turbulence trapping and fossilization processes are under sampled by the Aug. 28-29, 2002, data set. Microstructure patches were identified by the method of zero crossings, Prandke and Stipps (1992), where several adjacent zero vertical temperature gradients are required as the criterion to separate patches.

Figure 14 shows 2618 HPD points for microstructure patches detected in various locations during the RASP 2003 experiments. In the region of the outfall with many anomalies, a few patches were found with a 1/3 slope extrapolation pointing to \( \text{Re}_0/\text{Re}_F \) of 30,000 for the most powerful outfall patches at the trapping depth just below the pycnocline (red triangles, upper left). Only three patches were detected in their completely actively turbulent state. Clear evidence of zombie (secondary, zebra) fossil turbulence formation is show by patches indicating false large values of their initial normalized Reynolds number \( \text{Re}_0/\text{Re}_F \sim 10^5 \).

Calculations from RASP 2004 from 20K HPD patches to greater depths (extending to the bottom) reveal a few patches with \( \text{Re}_0/\text{Re}_F \) values up to \( 10^6 \) by the 1/3 slope extrapolation method. None were in their actively turbulent state. Such powerful events are difficult to sample directly because of their extreme intermittency. At fossilization such events can produce the 220 m wavelength ISWs detected in RASP by the FTW wave mechanism (\( \epsilon_0 = 10^{-2} \text{ m}^2\text{s}^{-3} \), \( N = 5 \times 10^{-3} \text{ s}^{-1} \), \( L_{R_0} = 282 \text{ m} \)). These ISWs may also be lee waves. It is a question for future research to determine how the soliton-like waves responsible for the numerous RASP detections of submerged outfall fossil turbulence are produced, whether as lee waves or by FTWs or both. More measurements of these ISWs are needed. From their random directions and large energy required for detectability at 20 km distances, it seems unlikely that the waves originate at the outfall.

**Horizontal microstructure profiles**

A double winged catamaran tow body was constructed to decouple vertical ship motions from the horizontally towed sensors. The MSS sensor package is housed in the port hull, as shown in Figure 15. A tow cable passes through the forward wing and a pulley to the 20 kg aluminum hydrodynamic depressor. The depressor keeps the tow cable nearly vertical near its end so the fish can fly above it. This method of decoupling is compared to other techniques in Nasmyth (1980).

The pulley transmits horizontal forces. Vertical forces are transmitted by two slack tethers yoked to attachment points in line with the pulley on the wing above and below. The tethers serve as hydroelastic springs that gently transmit vertical ship forces under way, and permit retrieval. The forward wing resists vertical motions. The aft wing resists pitch and the tail fins resist yaw. Tow speeds were typically 2 m s\(^{-1} \), and ranged between 0.5 and 3 m s\(^{-1} \). The platform mass was 10 kg for ease of handling. Signals from the MSS instrument were transmitted to the ship for recording and monitoring in the
ship laboratory by a signal cable attached by plastic tie wraps to the stainless steel upper tether and tow cable during deployment.

Figure 16 shows ten meter averaged temperature mixing rates along a zigzag towpath over the diffuser at 37 m depth to place the MSS sensors just above the wastewater trapping depth of 42-50 meters. Evidence of enhanced mixing above the waste field by breaking FTWs and ZTWs is shown in the horizontal profile of Fig. 16. Near surface advection of the waste field to the NW was apparent from the ship drift during vertical profiling, as shown by the black arrow at the end of the diffuser, and by vertical microstructure stations G4060001 and G4060002 of Figs. 7ab and 8. The west component of ship drift reflects steady 10-14 knot winds from the east, and the north component possibly compensates for off shore SE advection shown by the 30 m and 50 m drogue path (red arrow).

The strongest mixing at the 35 m tow depth of Fig. 16 is to the NW of the outfall diffuser pipe, which may reflect a NW advection by currents of FTWs and ZTWs as they propagate toward the surface. Regions of enhanced mixing in Fig. 16 are in the same SW and SE lobed pattern of the spectral anomaly fragments 84 and 85 to the SW, fragment 2 to the SE, and fragment 83 and 85 to the NW from the spectral anomaly map area numbers of Fig. 3.

**Discussion of results**

Hydrodynamic phase diagrams in Figs. 12, 13 and 14 for thousands of microstructure patches measured at all locations in Mamala Bay show clear evidence of fossil turbulence patch formation after the inertial-vortex-force driven turbulence cascade in the stratified fluid from small scales to large. Vertical and horizontal profiling and HPD evidence show vorticity and energy are absorbed from measured ambient solitary-like internal wave motions by the zombie turbulence mechanism, Fig. 11, giving efficient vertically beamed zombie turbulence maser action radiation of energy and information to the surface and the observed surface brightness anomalies of Figs. 1b (top), 2, 3, 4 (top), and 5.

Does evidence exist of FTWs elsewhere in the ocean? Dropsonde profiling of Thorpe overturning scales were carried out over the Romanche Fracture Zone (RFZ), one of the channels for the powerful flow of Antarctic bottom water through the Mid-Atlantic Ridge with regions of very rough bottom topography. Polzin et al. (1997) and Ferron et al. (1998) report RFZ measurements of large $\varepsilon$ and $L_T$ values all the way to the bottom at depths more than 5 km. Largest $L_T$ values detected in the water column were vertically correlated with the most powerful regions of topographically generated turbulence, and up to 1-2 km above. Are these mixing regions created by FTWs radiated near-vertically from the measured topographic turbulence regions of the RFZ? Do the patches show evidence of secondary turbulence events, as shown by Gibson (1987), Fig. 8 (bottom)? SAR images such as that of Fig. 1c (bottom) showing evidence of bottom topography FTWs in the North Atlantic do not yet seem to be available from the South Atlantic.

Vertical sampling of oceanic microstructure gives a high signal to noise ratio but is subject to under sampling errors from extreme intermittency in space and time of the
oceanic turbulent mixing process. The deep dark mixing paradox of the > 2 km deep main thermocline is the probable result of such under sampling errors, Gibson (1991c). Vertical eddy diffusivities indicated by the smoothed vertical temperature gradient are least $10^{-4} \text{m}^2\text{s}^{-1}$, Munk (1966), Munk and Wunsch (1998), compared to inferred values from vertical microstructure sampling 30 times smaller, ignoring evidence that the dominant patches were strongly fossilized, Gibson (1987). The deep dark mixing paradox is resolved by recognizing that turbulent mixing in the thermocline below 2 km is extremely intermittent, with viscous dissipation rate $\epsilon$ and temperature mixing rate $\chi$ well described by intermittent lognormal probability density functions, Baker and Gibson (1987).

Intermittency factors $I_\epsilon$ and $I_\chi$ are variances of the natural logarithms of these dissipation rates, and the mean to mode ratio of a lognormal random variable $\exp(3I/2)$ is a good measure of the undersampling error because sparse samples such as dropsonde measurements of $\epsilon$ and $\chi$ are measures of the mode whereas the mean $\epsilon$ and $\chi$ are measures of the vertical diffusivity and may be larger than the mode by factors of $\exp(3I/2)$. Because $I_\epsilon$ and $I_\chi$ increase from 3 to 7 as latitude decreases from mid-latitudes toward zero at the equator where the range of turbulence mixing is maximum, the undersampling error increases from about a factor of 90 to a factor of 36,000. Neglecting fossil turbulence evidence and the effects of intermittency may cause not only quantitative but qualitative undersampling errors, where regions with maximum average dissipation rates, mixing and vertical diffusion could be identified as regions with minima in these important turbulent quantities.

Evidence indicates that the largest outfall fossil turbulence mixing patches that dominate the RASP 2002 remote detection process were under sampled. Fig. 12 provides HPD points for the Sept. 2, 2002, satellite over flight, and Fig. 13 provides HPD points from profiles taken Aug. 28-29, 2002, at the 40-60 m trapping depth range, and at distances close, near and far from the diffuser. Neither of these HPD plots revealed patches with $\text{Re}/\text{Re}_F$ near 30,000 as required by the 1/3 slope extrapolated $\text{Re}_0/\text{Re}_F = 30,000$ values observed. Adequate sampling of the outfall microstructure requires that HPD patches must be detected in the active-turbulence quadrant, with $\text{Re}/\text{Re}_F$ values as large as the largest extrapolated $\text{Re}_0/\text{Re}_F$ values inferred in these categories from the fossilized patches. If the outfall diffuser produces the dominant turbulence events of Mamala Bay only close active turbulence patches with $\text{Re}/\text{Re}_F$ near 30,000 should be found. Thousands of patches in the RASP 2003 results were required to satisfy this constraint, as shown in Fig. 14.

At the outfall trapping depth, inertial-vortex-forces $\vec{v} \times \vec{\omega}$ of turbulence as it cascades to larger scales are damped at the Ozmidov scale at beginning of fossilization $L_{\text{Oz}} \equiv (\epsilon_0/N^3)^{1/2}$ by buoyancy forces of the ambient stratification $N = \left[ -g(\partial \rho/\partial z)/\rho \right]^{1/2}$, where $\vec{v}$ is velocity, $\vec{\omega}$ is vorticity, $g$ is gravity, $\epsilon$ is the viscous dissipation rate and $z$ is up. Damping turbulence by stable stratification produces a unique class of internal waves termed fossil-vorticity-turbulence (FVT) that is also a class of fossil turbulence, Gibson (1980), Gibson (1999), Leung and Gibson (2004), Gibson (2004). FVT internal waves
are saturated and retain most the kinetic energy of the turbulence at scales near $L_{R_0}$, Gibson (1986, 1987). They bob at the local stratification frequency $N$ but do not propagate and do not overturn. Overturning microstructure for various hydrophysical fields (temperature, salinity, density, vorticity) produced by turbulence become fossil turbulence first at the largest scales $L_{R_0}$ and then at smaller scales as $L_R$ decreases toward the scale of complete fossilization $L_{RF} = (30N)^{1/2}$, where $\varepsilon_F = 30N^2$ is the dissipation rate at complete fossilization.

HPD evidence of Figs. 12, 13 and 14 is overwhelming that fossil turbulence patches do not collapse as often assumed, but retain information about their largest previous dissipation rate $\varepsilon_0$ in the maximum Thorpe overturning scale from the relation $L_{T_{\text{max}}} = 0.6L_{R_0}$, Gibson (1987). This faulty assumption that stratified turbulence patches collapse and vanish without a trace is the physical basis of the Dillon correlation $0.8(L_T)_\text{rms} = (LR)_\text{ave}$, Dillon (1982), and Caldwell (1983). The Dillon correlation is not a reliable estimator of $\varepsilon_\text{ave}$, from errors arising from the extreme intermittency of $\varepsilon$ in important oceanic regions, as discussed, and is not evidence that fossil turbulence does not exist as Dillon (1982, 1984), Caldwell (1983), and Gregg (1987) suggest.

FVT wave motions are reduced by friction and then couple to the ambient stratification and radiate fossil-turbulence-waves (FTWs) nearly vertically (40°-50°) in a narrow wavenumber range $\lambda_{FTW} \approx L_{R_0}$. Small amplitude internal waves are reflected by stratified layers and shear layers but large amplitude FTWs produce turbulent patches as they tunnel through weakly stratified regions, Sutherland and Yewchuk (2004), with some fraction of their energy captured on bounding strongly stratified layers to produce secondary turbulence, as well as horizontally-propagating narrow-frequency-band $L_{R_0}$ scale ISWs.

KBG propose that $\lambda_{FTW} \approx L_{R_0}$ for FTWs explains the narrow spatial-frequency band signature of internal waves radiated by turbulence in contact with a stably stratified fluid as observed in the laboratory, Dohan and Sutherland (2003), Sutherland and Linden (1998), Sutherland et al. (1999), and Aguilar et al. (2005). KBGL term such internal waves Linden-Sutherland waves (LSWs), Fig. 1d (d).

FTWs are large amplitude LSWs that can only be produced by turbulence as it fossilizes. Small amplitude LSWs can be produced without turbulence in the laboratory by a moving sinusoidal boundary, Aguilar et al. (2005). Figure 1c (top) is a schematic representation of the RASP experiments and remote detection by the beamed zombie turbulence maser action (BZTMA) mechanism where outfall fossils produce ZTWs by extracting energy and wavelength information from quasimonochromatic ISWs.

Because FTWs have relatively large amplitudes near the breaking limit, they can easily be triggered to break by variations of shear and stratification in the water column, Sutherland (2001). If the source of FTWs is bottom topography with variable currents and tides, the FTW wave radiation can beam along paths of previous radiation to form mixing chimneys, analogous to the amplified radiation beams formed in astrophysical masers, Alcock and Ross (1985ab, 1986). Fossil turbulence patches from previous FTW radiation can extract vorticity and turbulent kinetic energy from subsequent FTWs along
a beaming channel to produce larger, reactivated fossil turbulent patches (zombie turbulence) in BZTMA mixing chimneys.

Evidence of BZTMA mixing chimneys from RASP 2003 is shown in Fig. 4b, as discussed in GBKL. This nonlinear beaming further complicates the vertical sampling process. How can average dissipation rates and vertical transport rates be reliably estimated over topography in the deep ocean or at equatorial latitudes by the Dillon correlation without testing for intermittency effects from fossil turbulence theory and HPD sampling; for example, in the HOME collaboration, Rudnick et al. (2005), and in the CARTUM Project, Baumert et al. (2005)?

Figure 17 shows internal waves and surface slicks propagating toward shore on shallow pycnoclines, as described by LaFond (1962) and Moum et al. (2003). The San Diego wave packets (bottom) occur intermittently about 10% of the time and are correlated with tides, suggesting their source is either lee waves or topographic-tidal-current turbulent events as shown in Fig. 1c(b, c). Wavelengths are 200-300 m (San Diego) and 500 m (Oregon). Levine and Boyd (2005) show 250 m overturns exist on deep slopes. Slick formation occurs at the trailing edge of the advancing waves from the San Diego time-lapse photography and isotherm follower methods, coinciding with the likely location of large fossil turbulence patches and near-vertical radiation of FTWs (red dashed arrows) from the Moum et al. (2003) observations of turbulence along the waves.

Diamessis et al. (2005) have shown by numerical simulation that internal waves are radiated at 45° from a fossilized turbulence wake of a sphere at the scale of the wake, which supports our assumption that \( \lambda_{FTW} = L_{R_0} = L_{T_{max}} \), where \( L_{T_{max}} \) is the maximum Thorpe overturn scale for the patch, Figure 18. Internal gravity waves radiated by a turbulent lock-release intrusion by Flynn and Sutherland (2004) shown in Fig. 1e indicate the same \( \lambda_{FTW} = L_{R_0} = L_{T_{max}} \) relationship and radiation angle.

Figure 19 compares a surface brightness spectral anomaly detected from space with a directional surface wave spectrum measured near the diffuser by a directional wave buoy, Bondur et al. (2005). The image was from the QuickBird satellite, Sept. 3, 2004. The wave buoy was a drifting Datawell directional waverider. The anomaly was at 204° with wavelength 68 m, as shown in Fig. 19. A spectral peak in this direction was detected in the surface wave spectrum. This suggests that internal waves shown by thermistor strings to have the same wavelength as optical brightness anomalies, Fig. 1a(top), also may have the same direction and extend to the sea surface. These are preliminary results, and will be reported fully elsewhere.

**Future work**

Many aspects of the RASP remote detections of submerged turbulence from the Sand Island outfall require further study. The BZTMA mixing chimney model explains the available data, but has many unfamiliar and only partially tested features. Many more profiles and hydrodynamic phase diagrams of microstructure patches near the diffuser are needed to demonstrate the behavior and statistics of outfall fossil turbulence patches, fossil turbulence waves, zombie turbulence patches and zombie turbulence waves. Drifters released in the outfall vicinity must be tracked for longer times and over much
wider ranges to further test the BZTMA hypothesis that outfall fossil turbulence patches extract internal wave energy and radiate it to the sea surface in detectable patterns.

Internal waves and surface waves matching the optical surface brightness spectral anomalies and their directions have been detected and presented here in preliminary form, but what and where are their sources? Are the measurements reproducible? It has been speculated that 30-250 m bottom boundary layer turbulent events are likely candidates, but this must be confirmed by field measurements. Horizontal profiling of microstructure to detect mixing patterns is important to compensate for the vertical orientation and intermittency of the transport mechanisms. Laboratory and numerical studies of stratified turbulence and internal gravity waves should include measured or computed dissipation rates to permit better comparisons of wavelengths and Ozmidov scales.

Synthetic aperture radar (SAR) anomalies from submerged turbulence shown in Figs. 1abc(bottom) and Fig. 4a(bottom) from RASP 2003 are presumably the result of direct FTW radiation enhanced by ZTWs. Much more information is needed.

**Conclusions**

Surface manifestations of submerged turbulence and fossil turbulence from the Sand Island Honolulu wastewater outfall have been repeatedly detected in RASP 2002, 2003, and 2004 from optical satellite images by the Bondur and Savin (1995) spectral anomaly method, as shown in Figure 1a (top). The anomaly regions vary widely in size and shape, and extend distances from 5-20 km from the wastewater diffuser depending on how far fossil turbulence patches produced by the outfall have been advected and how long they persist. From measured advection speeds of the wastewater and the extent of the anomalies, persistence times of outfall fossil turbulence patches > 200 $N^{-1}$. SAR outfall anomalies in Fig. 4a (bottom) extending beyond 40 km suggest outfall fossil turbulence patch persistence times exceed 1000 $N^{-1}$.

The wavelengths of the surface-brightness-spectral-anomalies (SQAs) indicate unexpected small-scale soliton-like internal waves (ISWs) exist on the pycnocline. One set of such ISWs measured by thermistor strings in RASP 2004 is shown in Fig. 1b (d). The soliton wavelengths match the $\lambda = 43-160$ m SQA wavelengths identically, as shown in Fig. 1b (c). A directional surface wave buoy spectrum is presented in Fig. 19 that matches a satellite surface brightness spectral anomaly in both wavelength and direction. Directions of the spectral anomalies not toward the diffuser in Figs. 1b (top), 2, 3, 4 (top), and 5, and energy requirements, contradict the possibility that ISW waves are caused by the outfall. The SQA internal waves may be lee waves as usually assumed for ISWs, Miles (1968), they may reflect a resonant feedback scales between the waves and the turbulence, Sutherland and Linden (1998), or they may result from FTWs radiated from powerful bottom turbulence with $\lambda \approx \lambda_{FTW}$. The wavelength of FTW-ISWs should be the Ozmidov scale at the beginning of fossilization $\lambda_{FTW} = L_{R_0} = \left(\frac{\varepsilon_0}{N^3}\right)^{1/2}$ as shown in Figs. 1e, 1f, 11 and 18.

Fossil-turbulence-waves (FTWs) are radiated by fossilized turbulence events near-vertically, since fossilization occurs at the ambient stratification frequency $N$. 
Microstructure studies at the outfall suggest at least 10% of the outfall turbulent kinetic energy is radiated vertically by FTWs. The direction of internal waves radiated from secondary turbulence events is also vertical and presumably equally efficient. Such ZTWs are produced when fossil turbulence patches extract energy from ISWs, Figs. 1c (top), 1d(bc), 1f(c). Extraction of quasimonochromatic energy with beaming in a preferred direction (vertical for internal waves from stratified turbulence) is a maser action process. The mechanism proposed for the remote detection of RASP outfall turbulence involves at least two maser action stages, and has been termed beamed-zombie-turbulence-maser-action. Vertical beaming of turbulent kinetic energy by FTWs from bottom turbulence events at fossilization is an efficient maser-action process pumped by bottom turbulence, and is suggested as the mechanism of remote detection of ISWs and bottom topography by SAR in RASP and elsewhere and by astronauts, Fig. 1c (bottom) and Fig. 1b (bottom).

The BZTMA mechanism described by KBG is extended in Fig. 1d (bcd) to include tidal lee ISWs detected by SAR radars, Fig. 1a (bottom) and Fig. 1c (bottom). From fossil turbulence theory and deep ocean observations, Gibson (1987), information about submerged ISWs can be moved to the sea surface for detection by fossil-turbulence-waves (FTWs) and secondary zombie-turbulence-waves (ZTWs), Fig. 8 (bottom). Hydrodynamic phase diagrams, Fig. 11, 12, 13 and 14, permit detection and quantification of the process from \( \times 10^4 \) microstructure HPD patches analyzed in the RASP experiments. Thousands of HPD samples were required to detect the dominant outfall actively turbulent patches with \( \Re/\Re_F = \varepsilon/\varepsilon_F = \varepsilon_0/\varepsilon_F = \Re_0/\Re_F = 30,000 \); that is, in their actively turbulent state, as shown in Fig. 14 by points emphasized by red triangles.

Outfall enhanced ISWs at the 1000 m scales are interpreted as tidal lee waves as shown in Fig. 2 from the Sept. 2, 2002, Ikonos image. Smaller scale ISWs are interpreted as FTWs from bottom turbulence events trapped on the pycnocline, Fig. 1f(c). The indicated trapping depth for the waste-field on the Sept. 2, 2002, Ikonos satellite over flight was 42-50 m from vertical MSS profiles in Fig. 7a and Fig. 8 (top). Comparison of HPD plots in Figs. 12, 13, 14 for patches in Figs. 7a, Fig. 8 (top), and Fig. 9 profiles shows that turbulence produced by the wastewater discharge grows in vertical scale as the buoyant plume rises and fossilizes below the trapping depth.

Drogues released at the trapping depth confirm the directions of the surface brightness anomaly maps of Fig. 1b (top), 2, 3, 4 (top), and 5 in SW and SE lobes extending more than 20 km from the diffuser and covering 200 km\(^2\). The detection effectiveness depends on offshore advection, Fig. 3 b, and Fig. 6. Strong dissipation rates measured near the surface close to the diffuser are larger than ambient surface dissipation rates, Fig. 7b, which supports the conclusion that these \( \varepsilon = 10^2 \varepsilon_{\text{ambient}} \) rates represent surface breaking of near vertically propagating fossil and zombie turbulence waves. The photograph of Fig. 1c (top) confirms this interpretation. Detailed energetic considerations are discussed in GBKL. A significant decrease in \( \varepsilon \) was detected below surface values compared to ambient in Fig. 7b and is attributed to FTW and ZTW waves.

Horizontal tows of the MSS at depths above the waste field trapping depth confirm the hypothesis that outfall enhanced mixing should occur above the trapped
wastewater depth and in the directions of outfall advection in areas of spectral anomalies, Fig. 3 a), Bondur and Filatov (2003). The enhanced mixing is attributed to radiation from outfall fossils extracting energy from soliton-like waves below the 50 m deep pycnocline.

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Figures

Figure 1a. (top) Spectral quasimonochromatic anomaly (SQA) regions (\(\lambda\) wavelengths 30-250 m) detected from optical satellite images during the remote anthropogenic sensing program RASP 2002, 2003, 2004, Bondur (2005b). The anomaly regions reflect surface smoothing enhancement from outfall fossil turbulence patches by the BZTMA mechanism, KBG. (bottom) A radar image shows that surface manifestations of ISWs and several fronts are enhanced over Hudson Canyon. This suggests enhancement of surface smoothing by the same BZTMA mechanism, where the supply of many large fossil turbulence patches over the canyon is produced by breaking FTWs radiated vertically from the enhanced bottom topography turbulence.
Figure 1b. Sea surface brightness anomaly map for Sept. 4, 2004, QuickBird image and internal wave spectra from thermistor strings TS-5 and TS-2. Wavelengths $\lambda$ of the anomalies match wavelengths $\Lambda$ of the internal waves at TS-5’s position just south of the diffuser and at TS-2 nearer shore (top). The complex array of ships, satellites, microstructure detectors, platforms, and section paths used in RASP 2004 is shown (bottom), Bondur (2005b).
Figure 1c. Schematic of RASP experiments and the BZTMA detection mechanism. A photograph (top) from the ship (HAPA) positioned over the west end of the diffuser pipe shows evidence of surface smoothing ~50 m to the NW by fossil turbulence waves with no evidence of continuous vertical turbulent mixing (no discoloration, smell, or continuous microstructure in vertical profiles). Lee wave ISW solitons with $\lambda >$ depth are an alternative source of narrow-band forcing at the pycnocline. BZTMA (bottom) is needed to explain how SAR and optical images of lee wave ISW packets and mid-Atlantic seamounts can be detected by radar and astronauts.
Figure 1d. Beamed-zombie-turbulence-maser-action (BZTMA) model for remote detection of submerged turbulence, modified from KBG to include large-$\lambda$ tidal lee ISWs where bottom boundary layer $V/N > L_{R_0}^{-}$. Quantum mechanics determines the frequency of the electromagnetic waves amplified along lines of sight in astrophysical masers. Fluid mechanics determines the frequency of ISWs, beamed vertically in BZTMA. Non-linear beaming in astrophysical masers occurs in random directions. Non-linear beaming in BZTMA occurs vertically in mixing chimneys, GBKL.
Figure 1e. Internal gravity waves produced by lock-release of an intrusion, Flynn and Sutherland (2004). Active turbulence forms at the head of the intrusion from Kolmogorov scales $5L_K < L_R$ to Ozmidov scales at beginning of fossilization $L_{R_0}$.

The fossil turbulence wavelength $\lambda$ shown in the upper diagram closely matches $L_{R_0}$ inferred from the maximum vertical size of the intrusion. The amplitude $h > 8\sqrt{\pi}\lambda$ is initially in the unstable FTW range of the stability diagram of Fig.1dd. The angle of FTW radiation $45^\circ$ is detected by the synthetic Schlieren method in the bottom diagram. The fluid initially has constant density above $z = 0$ and uniform stratification below.
a. The turbulence cascade is from small scales to large

![Diagram of turbulence cascade](image1)

- Inertial-vortex forces drive the turbulence cascade from small to large scales.
- Eddies with the same spin merge, while those with opposite spin diverge.

b. Turbulence powers vertical internal wave maser action

![Diagram of internal waves](image2)

- Turbulence powers growing internal waves that fossilize at the Ozmidov scale $L_{R_0}$ and radiate FTWs.
- FTWs are efficient because most of the turbulent kinetic energy is beamed vertically as FTWs.

In b. the unstable BBL-FTWs trigger mixing and momentum transport that creates linear $\lambda = L_{R_0}$ internal waves (FTW-ISWs) on density layers (dashed lines) that propagate horizontally.

c. FTWs form small scale ISWs reflecting bottom $L_{R_0}$ values

![Diagram of FTWs and ISWs](image3)

- FTWs reflect off density layers, creating small-scale ISWs.

Figure 1f. Turbulence cascades from small scales to large driven by inertial-vortex forces $\vec{v} \times \vec{\omega}$ shown by dashed arrows in a. At all scales adjacent eddies with the same spin (left) induce $\vec{v} \times \vec{\omega}$ forces that cause such eddies to merge. Adjacent eddies with opposite spin (right) induce $\vec{v} \times \vec{\omega}$ forces that cause such eddies to diverge and expand the turbulent region. In b. stratified flow over an obstruction produces growing turbulence that fossilizes at the Ozmidov scale $L_{R_0}$ and radiates FTWs. This is an efficient maser action because most of the turbulent kinetic energy is beamed vertically as FTWs. In c. the unstable BBL-FTWs trigger mixing and momentum transport that creates linear $\lambda = L_{R_0}$ internal waves (FTW-ISWs) on density layers (dashed lines) that propagate horizontally.
Figure 2. Optical image of Mamala Bay sea surface glint from Ikonos-2 satellite at noon Sept. 2, 2002. Analysis from 2 km square patches a. Background and b. Outfall shows anomalously bright Fourier elements just south of the diffuser oriented EW with 105 m wavelengths (double arrow). Grey areas just south of the diffuser indicate large wavelength tidal lee ISWs with surface manifestations enhanced by outfall fossils and the BZTMA mechanism.
Figure 3. Spatial distribution (a) of anomalous spectral brightness caused by submerged outfall turbulence in 1 km areas from the 9/2/2002 Ikonos space image of Fig. 2, Bondur and Filatov (2003). Drogues set at the outfall trapping depth drifted into region 2 to the SE, opposite to the NW ship drift (see Fig. 16). The SW and SE anomaly lobes reflect the advection of outfall fossil turbulence patches as shown in (b) by a collection of GPS equipped parachute drogue tracks, where the weighted parachutes of the drifters were inserted at 30 and 50 m, near the trapping depth.
Figure 4a. (top) Spectral anomaly regions detected 9/13/2003, GBKL. The surface brightness spectral anomaly region extends 20 km to the SW of the outfall, and is attributed to strong offshore advection induced by rains on 9/10/2003. (bottom) The RADARSAT SAR outfall mixing anomaly of 9/11/2003 extends over 40 km to the south, leaving the mixing front (dashed line top) detected 9/13/2003 by vertical and horizontal microstructure sections. Bottom topography features to the SE of Diamond Head are revealed by the outfall enhanced vertical transport of information to the sea surface.
Figure 4b. Spectral anomaly regions (bottom left) detected 9/14/2003, compared to vertical and horizontal microstructure profiles 7 km south of the outfall, GBKL.
Figure 5. Spectral anomaly regions detected 9/2/2003. The anomaly region extends only 8.6 km to the SW of the outfall. The small extent is consistent with indications of relatively weak offshore advection (see the following Fig. 6 middle panel). The small wavelengths (32 m and 53 m) suggest these ISWs are likely produced by bottom FTWs at Ozmidov scales rather than lee wave depression ISWs at V/N scales.
Figure 6. Areas of spectral anomalies (top panel) reported by V. Bondur at UCSD workshop Mar. 9-11, 2005 (Bondur 2005a), compared to drogue tracks and tidal cycles a few days previous for the largest anomaly region 9/13/2003 and for the smallest anomaly region 9/2/2003. The large single lobe anomaly (yellow dashed line top, Fig. 4) extends 20 km to the SW of the outfall, and is attributed to off-shore advection of outfall fossil turbulence patches induced by rainfall 9/10/2003, as indicated by the GPS drogue tracks of 9/11/2003 at bottom. Weaker off-shore flows (middle panel) preceded the small anomaly region of 9/2/2003 (dashed black line top panel, Fig. 5). Tidal curves are shown with drifter periods in magenta.
Figure 7a. Vertical profiling station locations in Mamala Bay Sept. 2, 2002, soon after the IKONOS satellite overflight. Profile G4060001 (shown in Figs. 8 and 12) is about 50 m to the NW of the end of the diffuser pipe reflecting the direction of the ship drift. Profile G4030002 about 600 m east of the diffuser sampled the weaker ambient patch H in the 5-10 m depth wind mixed surface layer compared with patches F and G, which show larger Re₀/Reₕ values attributed to direct fossil turbulence wave breaking. Weak brightness anomaly fragment 81 (Fig. 3) NW of the diffuser pipe suggests that indirect BZTMA fossil wave breaking patterns contribute to the surface smoothing.
Figure 7b. Near surface dissipation rates $\varepsilon$ are increased by outfall fossil turbulence wave (FTW) breaking near the end of the diffuser by two orders of magnitude above ambient values east and west of the outfall. Station locations and times are shown in Fig. 7a (top). No surface smoothing (as in Fig. 1c top) was observed. Below 12 m depths ambient $\varepsilon$ exceeds outfall $\varepsilon$, presumably because outfall FTW and ZTW breaking has previously smoothed the sharpest ambient mean vertical gradients (as in Fig. 7c bottom right) where ambient turbulence events occur.
Figure 7c. Comparisons of stratification frequencies (bottom left) and dissipation rates (bottom right) at anomaly region M1 (blue) 2 km S of the outfall with non-anomaly region M2 (red) 9 km to the ESE of M1 with the same 350 m depth, averaged over ~200 MSS profiles taken to the bottom at each station during RASP 2004. Mean temperature and salinity profiles are shown (upper left). Wind speeds at M1 were 5.8-7.2 m/s, significantly lower than 7.7-8.2 m/s at M2. Profiles of $N^2$ and $\varepsilon$ reflect BZTMA vertical mixing and fossil BBL turbulence events.
Figure 8. (top) MSS dropsonde profiles at station G4060001 50 m NW of the diffuser pipe end. The buoyancy trapped wastewater plume at 42-51 m is identified by cool, low salinity, turbid water with large temperature gradients. The MSS tow path (Fig. 16) at 36 m depth samples temperature mixing triggered by FTWs radiated vertically from the waste-field. Thorpe overturn scales $L_T$ (Thorpe, 1977) of the microstructure patches increase as the buoyancy driven turbulence rises and cascades to larger scales. The largest $L_T$ values are at the trapping depth in patch D. Large $L_T$ values are also found in the 3-10 m depth range in patches F and G, where fossil turbulence waves break at the base of the wind mixed layer. The strong temperature microstructure region above patch D shows secondary turbulence event fossils have radiated energy vertically as ZTWs, (bottom left) as explained by Gibson (1987, fig. 4). A similar region is the most active microstructure found in the deep main thermocline (bottom right) by Gregg (1977ab), which indicates several secondary fossil turbulence events have formed on a primary fossil turbulence patch, Gibson (1987, fig. 6).
Figure 9. MSS dropsonde profiles at station G4010001 about 3 km south of the diffuser. The diffuser depth is shown by a dashed line. Patch L appears to be a 10 m $L_{T_{\text{max}}}$ fossil turbulence patch produced by the wastewater injection at 68-70 m and deeper than its trapping depth by about 20 m by the offshore advection. Its location near the base of the seasonal pycnocline and the spectral anomalies in fragments 14, 15 and 25 suggest that zombie turbulence radiation is reflected by surface patches M, N and O and deeper patches J and I below 200 m. HPD values for the patches shown in Fig. 12 suggest patch K also is an outfall fossil turbulence patch, with $Re_0/Re_T \sim 10,000$. 
Figure 10. Stratification frequency $N^2_{ave}$ computed as a function of vertical depth differences $\Delta Z_{ave}$ for patch D shown in Fig. 8 just below the wastewater trapping depth. A range of constant $N^2_{ave}$ is found for $\Delta Z_{ave} \sim 6$-10 m, larger than the maximum Thorpe scale $L_{T_{max}}$ and smaller than 125% of the patch size $L_p$.
Figure 11. The physical mechanism of zombie turbulence patch formation from a fully turbulent microstructure patch at beginning of fossilization at scale $L_{R_0}$ and its trajectory on a hydrodynamic phase diagram. Both the fossilization trajectory 1-2-3 and the zombie formation trajectory 3-4-5 should follow slightly less than 1/3 slope paths on the log-log plot, Gibson (1987). Thus, fossilized patches tend to underestimate true $Re_0/Re_F$ values, and zombie turbulence patches can indicate large $Re_0/Re_F$ values that never existed. Red lines indicate vorticity and turbulence formation from tilting of the fossilized patch by ambient internal waves and shears.
Figure 12. HPD points A-G are shown for the G4060001 droopsonde profiles of Fig. 8 about 50 m NW of the end of the diffuser. N is averaged over vertical scales 0.1 m larger (black circles) and 0.5 L_{Tmax} larger (red squares) than the patches. The Thorpe overturn scales increase from A to D as the buoyant turbulence of the plume cascades from small scales to large and then fossilizes. Patch D appears to be in the zombie category, with Re_0/Re_F ~ 10^5. Dimmed patches I-P are from the station G4010001 profile of Fig. 9 in the SE surface brightness anomaly lobe of Fig. 3. Patches K and L extrapolate to large Re_0/Re_F ~ 10^4 values, indicating they are outfall fossils produced by the wastewater discharge.
Figure 13. Hydrodynamic phase diagram for 40-60 m depth range microstructure points, close (< 100 m, 6 profiles, squares), near (~600 m, 6 profiles, circles) and far (~3 km, 3 profiles, triangles) from the diffuser pipe (Aug. 28-29, 2002). The dashed line with slope +1/3 shows the locus expected for decaying outfall fossil turbulence patches and their re-activated “zombie” descendants, with Re₀/Re₇ ≈ 25,000 (star). Patches close and near the diffuser pipe have large extrapolated Re₀/Re₇ values > 10⁴, larger than far patches with Re₀/Re₇ < 10³. More close patches had large Re₀/Re₇ values and were actively turbulent than near patches. Neither close nor near categories showed active patches with Re₀/Re₇ > 10⁴, indicating that the dominant mixing process has been under sampled at both locations. Similarly the far category had no active patches with Re₀/Re₇ > 10³ and is therefore badly undersampled.
Figure 14. Hydrodynamic phase diagrams of 2618 patches from vertical profiles of RASP 2003. Only a few (9) patches observed near the outfall in anomaly regions indicate a hydrodynamic state of active (3) or nearly active (6) turbulence (red triangle points upper left). This shows that stratified turbulence rapidly fossilizes, which increases the probability of undersampling this intermittent hydrodynamic state. Ambient regions (lower left) have few outfall and zombie turbulence patches.
Figure 15. Catamaran-MSS tow body. The tow cable passes though a pulley in the wing to a depressor that keeps the cable near vertical. Slack tethers from the depressor below and the tow cable above are yoked to attachment points on the forward wing aligned with the pulley. The MSS microstructure system is mounted in the port catamaran hull with an electrical cable to the ship. Attending the fish on the HAPA deck are Pak Tao Leung, Hartmut Prandke, and Fabian Wolk.
Figure 16. Circle sizes and colors indicate 10-m average temperature mixing rates along the 37 m depth tow path Sept. 2, 2002, 10 meters above the average trapping depth (Keeler et al. 2005). Regions of enhanced temperature mixing match areas of quasimonochromatic spectral anomaly detection of the outfall from the Ikonos-2 image, Bondur and Filatov (2003), in Fig. 3 a.
Figure 17. Examples of surface slicks and internal waves propagating toward shore on shallow thermoclines. The location of most slicks and isotherm depressions at the trailing edge of wave crests, determined by LaFond (1962) July 12, 1958, in San Diego by time lapse photography and isotherm followers, coincides with the likely locations of fossil turbulence and fossil turbulence waves (red dashed arrows). Slicks and isotherm depressions observed by Moum et al. (2003) off the Oregon coast show evidence of similar vertical FTW radiation and mixing.
Figure 18. Numerical simulation of a stratified turbulent sphere wake at Re = 10^4 by Diamessis et al. (2005) showing z-y contours of vorticity. Estimating the maximum Thorpe overturn scale and Ozmidov scale at fossilization from the simulated size of the wake, the fossil turbulence internal waves are shown radiating from the wake at 45° with wavelength $\lambda \approx L_{R_0}$. 
Figure 19. Surface wave buoy and surface brightness anomaly spectra from Sept. 3, 2004 measurements. The QuickBird surface brightness image is shown in a with its anomaly map in b. The circled spots at $(\lambda, \theta) = (68 \text{ m}, 204^\circ)$ match the surface wave spectral peak shown in e. Bottom topography (Fig. 4) 15-20 km SW of the outfall is a possible source of the detected waves by the mechanism shown in Fig. 1f(c).