TTIDE: The Tasman Tidal Dissipation Experiment
CLIVAR PSMI Webinar February 14 2017

Mixing
The Deep Sea

Field phase: January-March 2015
Issue for today:

Climate modelers need realistic parameterizations for diffusivities of scalars & momentum. Any parameterization must be relevant at climatological scales and be able to respond to changing climatological conditions.

The physical phenomena involved in establishing these diffusivities in the deep sea are only now being identified. Achieving a global parameterization from a very limited series of local process experiments is the present challenge.

Roughly 1-2 TW is required to maintain a diffusivity consistent with the overturning circulation of the present ocean. Is this energy provided as the end result of a cascade through processes included in a climate model or through a separate (semi-) parallel cascade?
Pacific Semi Diurnal Baroclinic Tidal Beams

H. Simmons
Preliminary TTide Simulations
Harper Simmons & Dmitry Braznikov (UAF), Sam Kelly (U Minn Duluth)

GOLD global model
Simulation

Harper Simmons
Anticipated Shoaling and Mixing on the Deep Slope
Anticipated Shoaling and Mixing on the Slope

J. Klymak

MIT GCM
TTIDE Experiment Format

Satellite Observations
Zhao & Alford
Altimetry

Numerical Studies
Klymak
MIT GCM
Idealized & Realistic

Simmons & Braznikov
GOLD & ROMS
Global to Regional

Glider Surveys
Johnston- Rudnick
Tidal Focus
Robertson, Rainville
Mesoscale Focus

2013-2015

Robertson, Rainville
Experiment Format:

TTIDE: R.V. Revelle

**Leg I:** Alford, MacKinnon, Nash, et. al.
- a) McLane, T-chain moorings, ADCPs
- b) L-ADCP, microstructure surveys

**Leg II:** Pinkel, Lucas, Jones, et. al.
- Fast-CTD surveys

**Leg III:** Alford, Nash, et.al.
- a) L-ADCP, microstructure surveys
- b) Mooring recovery

January-March 2015
TBEAM: R.V. Falkor
Waterhouse, Kelly, et. al.
Offshore mooring and L-ADCP surveys to quantify the incident flux offshore

TSHELF: R.V. Revelle
Jones, Lucas, Schlosser, et al.
On-shelf moorings to quantify upper-ocean consequences of deep ocean processes
Northern Slope

Less incident energy but near-critical slope is efficient at dissipating it. Expect high-mode conversion, bottom bores,…

Southern Slope

Center of the “main” incident beam. Very supercritical. Local dissipation physics includes along-shore corrugations, possibly down-going high-mode beam.

Reflection Antenna

Designed to do plane-wave fits to incident and reflected waves.

T-Beam

T-Shelf
FIG. 2. Glider tracks for (a) Spray 55 and (b) Spray 56 are shown with color indicating time. Increasingly dark dots along the track denote increasing spring-neap phase, which is expressed in terms of days. In both cases, a wide range of phases is seen in the areas with greatest sampling. In Figure 2b, Spray 56 profiles for 2 weeks over the slope near 42.4°S (green to yellow colors).

FIG. 1. To illustrate the geometry of the internal tides (a) incident upon and (b) reflected from a coastal wall (dashed line), the instantaneous cross-slope velocity component of an idealized mode-1 Poincaré wave with a constant 150-km wavelength is shown superimposed on a map of Tasmania. The incident and reflected wave direction are shown (black arrows). The wall (dashed line along a bearing of 18°) is aligned with the steepest section of the slope. The incident and reflected waves combine to produce a standing wave in (c). The inset in Figure 1a shows the area under consideration (red box) in subsequent figures with AUS, TAS, and NZ denoting Australia, Tasmania, and New Zealand. Topography is contoured at 1000-m intervals. The East Tasman Plateau (ETP) is the broad rise offshore, which includes a steep pinnacle, the Cascade Seamount (CS).
To-do list!

• reprocess LADCP tow-yo data to figure out a way to make up and down casts match. No idea why they are so far off? Is it compass error? Perhaps we reprocess some of the full depth casts (using only the bottom half of the water column) to assess what changes when part of the data are omitted.

• reprocess RBR T/P data to obtain Thorpe scales from it, and add to the big CTD structure.

Zero-order

We think we have observed all of the phenomena we expected, and our challenge will be to continue to generalize these! Specifically, there are internal semidiurnal and diurnal tides of $O(30 \text{ cm/s})$ peak-peak, very strong eddies ($> 0.8 \text{ m/s}$; even stronger than observed in the pilot glider missions, and $\sim 50-100 \text{ m}$ overturns and steep bores in places, particularly near-critical slopes and in what appear to be breaking lee waves near a deep bump.

Figure 4: Overview map of the northern region. McLane “flux” moorings in red, T-chain mooring blue, CTD time-series stations in green, tow-yos in magenta, Falkor in orange.

Figure 5: Overview map of the southern region. McLane “flux” moorings in red, T-chain mooring blue, CTD time-series stations in green, tow-yos in magenta, Falkor in orange.
Figure 2: (left) Revelle’s deck full of TTIDE mooring gear. (right) The TTIDE CTD with 150-KHz downlooker and Sea Batteries (orange).

Figure 3: Overview map of the northern region. McLane “flux” moorings in red, T-chain moorings in blue, CTD time-series stations in green, to-yos in magenta, Falkor in orange.

Zero-order

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Leg I Moorings

3 A moorings
- 1 TBEAM mooring (an extra A mooring)
- 6 "long term" T moorings
- 8 "long term" M moorings
- 1 T and 1 M "short term" moorings
(deployed and recovered within 2 weeks)

- 12 McLanes
- 23 ADCPs
- 15 Aanderaa current meters
- 210 Thermistors
- 10 CTDs
- 4 Chipods
• T3: Near-critical slope T-chain
• M1: Deep flux McLane mooring; should see beams scattered onshore from bump.
• M2: 1600-m flux McLane mooring; should see beams scattered onshore from bump.
• M3: 1000-m mooring; recovered; did not profile due to flooded sphere.

• T4: Flux mooring with Nicole Jones' gear at 500-m isobath

Figure 3: Data from mooring T2.

3.1.2 Near-critical region

• N4 (Figure ??): at critical slope.
• N5 (Figure ??): big strain and displacement signals, high-mode velocity several hundred m above bottom.
• N6 (Figure ??): 24-hour station. South of other stations, critical slope. Strong westward mean flow 0.5 m/s, diurnal inequality in IT. Strong mixing event near beginning, weaker one 12 hours later. Harper did his modal analysis at this station.

NT3, NT4: These long non-tidally-resolving East-West tow-yo sections (Tows NT3 and NT4) that go by this critical slope region show lots of tantalizing features, such as apparent propagating 'beams of high strain near but not necessarily attached to the bottom, instances of steepened isopycnals, and various wave-like motions higher in the water column (which are no doubt aliasing time and space variability into their apparent wavelength/period).

Temperature Chain: 3.5 day record

Nash
3.1.2 Near-critical region

- **N4**: at critical slope.
- **N5**: big strain and displacement signals, high-mode velocity several hundred m above bottom.
- **N6**: 24-hour station. south of other stations, critical slope. Strong westward mean flow 0.5 m/s, diurnal inequality in IT. Strong mixing event near beginning, weaker one 12 hours later. Harper did his modal analysis at this station.

**Towyos**

NT3, NT4: These long non-tidally-resolving East-West tow-yo sections (Tows NT3 and NT4) that go by this critical slope region show lots of tantalizing features, such as apparent propagating ‘beams of high strain near but not necessarily attached to the bottom, instances of steepened isopycnals, and various wave-like motions higher in the water column (which are no doubt aliasing time and space variability into their apparent wavelength/period).
Figure 15: Tow-yo 6 on the critical part of the slope at the middle region.
TTIDE Leg II

Fast CTD Tow-Yos & Stations

T-Shelf Moored Arrays
Site 7
On Top of Klymak Rise

12 Hours
Site 6 (transect) crossing 2
1450–2000 m profiling over Klymak Rise: Upcasts red. Feb 12–14 UTC 2015
Caution: Not a numerical simulation

Fast CTD Repeated -Track Run over Klymak Rise

Data interpolated to 54 stations in longitude, Fit to $D_2, D_4, D_6$ frequencies
Radiated density variance D2, D4, D6 Harmonics

East longitude

Depth m
Caution: Based on only five cycles of the D2 Tide
TTIDE Summary

A \( \sim0.5-1.5 \text{ GW} \) \( M_2 \) tidal beam is propagating from the Macquarie Ridge northwestward across the Tasman Sea.

The beam appears robust relative to lateral refraction by the energetic mesoscale.

A large fraction (60-90\%) of the incident flux is reflected from the Tasman Slope, particularly in the south.

The coherent mix of incident, reflected, and locally generated tides produces a complicated internal standing wave pattern in the western Tasman Sea.
Issues:

Mid-water vs sea-floor mixing rates

Up-slope bores vs forward-reflected waves

Forward and back-scattering to higher modes

Local generation vs distant source influence

Diurnal energy & trapped shelf modes

Standing wave patterns due to high $M_2$ reflectivity

~10 km-scale features matter a lot for organizing the mixing. The micro-bathymetry of the deep ocean is important.

Thanks to all TTIDE volunteers and our Tasmanian hosts!!
TTIDE INITIALLY PLANNED AND PROPOSED IN 2008-9
HEIGHT OF ECONOMIC “DOWNTURN”
PROGRAM ACCEPTED IN 2011-12
PERIOD OF MAX FINANCIAL IMPACT TO NSF

BAREBONES PROGRAM FUNDED
MODELING AND GLIDER RECON INDICATES COMPLEXITY OF SITE

PILOT CRUISE CANCELLED ON ECONOMIC GROUNDS
MAIN FIELD PROGRAM DELAYED 1 YEAR BY SHIP AVAILABILITY
(TRANSITING THE REVELLE FROM ASIA TO THE SOUTHERN OCEAN IS VERY EXPENSIVE)

NSF TTIDE FUNDS ARE COMMITTED & DISBURSED TO VARIOUS PLAYERS, BUT LANGUISH FOR 12
MONTHS, MID-PROGRAM

BURN RATE OF RESEARCH-TEAM SALARIES DIALED BACK BUT NOT ZEROED

TTIDE TURNS TO SCHMIDT OCEAN INSTITUTE FOR FALKOR SUPPORT FOR TBEAM
NSF FUNDS WATERHOUSE & KELLY TO EXECUTE TBEAM

JANUARY MARCH 2015 FIELD PROGRAM
ENABLED BY A MASSIVE INJECTION OF SEAGOING VOLUNTEERS, FROM AUSTRALIAN
UNDERGRADS TO THE CURRENT HEAD OF CLIVAR.
FIELD TEAMS DEPLOY / RECOVER MASSIVE MOORING ARRAY WITH NEAR FLAWLESS EXECUTION

RELIABILITY OF MCLANE PROFILERS IN SOUTHERN OCEAN TROUBLING,
LADCP PROFILING VERY DIFFICULT IN ROARING FORTIES

INSTRUMENTS ARE “BACK IN THE LAB” WITHIN 3 MONTHS OF FORMAL PROGRAM END

TTIDE CONTINUES, INFORMALLY DATA ANALYSIS MEETING IN SD JANUARY 2017
EOS : On the Cover
Melting glacier water meanders to the ocean, where it *plummets* toward the seafloor. Internal ocean waves mix warm surface water with cold deep water, maintaining the oceans in a steady state.

“force” “thrust” “drive” “probe” or *forget it!*
High-latitude climate forcing and tidal mixing by the 18.6-year lunar nodal cycle and low-frequency recruitment trends in Pacific halibut (Hippoglossus stenolepis)

Kenneth S. Parker, Thomas C. Royer, and Richard B. Deriso

Abstract: Upper ocean temperatures in the northern North Pacific Ocean have increased by more than 2°C in the last 50 years, and have declined since 1980. These changes indicate that 18.6-year lunar nodal cycle and low-frequency recruitment trends in Pacific halibut (Hippoglossus stenolepis) have been influenced by changes in the upper ocean climate. The changes in the recruitment trends are consistent with changes in the upper ocean climate, and may be related to changes in the upper ocean temperature and salinity, which are affected by changes in the upper ocean circulation.

Geophysical Research Letters

Possible explanation linking 18.6-year period nodal tidal cycle with bi-decadal variations of ocean and climate in the North Pacific

Ichiro Yasuda, Satoshi Doi, and Hiroyuki Taguchi

Abstract:

[1] Bi-decadal climate variability is dominant over the North Pacific on inter-decadal timescales, however the mechanisms have not been fully understood. We have found that the bi-decadal variations in the North Pacific climate and intermediate water properties are positively correlated to the 18.6-year period modulation of diurnal tide. In the period of strong diurnal tide, oceanic induced gravitational mixing creates surface salinity and density gradients in the upper layer. The internal waves, which are modulated by the diurnal tide, can interact with the oceanic stratification, and associated heat transports by about 0.2 PW. These could also explain the warmer SST in the Kamchatka Oyashio Extension region, where positive feedbacks with Alaskan low right amplitude the bi-decadal variations. The 18.6-year tidal cycle therefore could play a role as a basin forcing for the bi-decadal ocean and climate variations.

Decadal Climate Variability: Is There a Tidal Connection?

Richard D. Ray

NASA Goddard Space Flight Center, Greenbelt, Maryland

(Manuscript received 14 June 2006, in final form 8 November 2006)

Abstract:

A possible connection between oceanic tides and climate variability arises from modulations in tidally induced vertical mixing. The idea is reexamined here with emphasis on near-decadal time scales. Seasonal extreme tides caused by unusually favorable alignments of the moon and sun are not likely to influence decadal climate, since these tides are of short duration and, in fact, are barely larger than the typical spring tide near lunar perigee. The argument by Rood and Whorl in favor of extreme tides is further handicapped by an insufficiently precise catalog of extreme tides. A more plausible connection between tides and near-decadal climate is through “harmonic heating” of nearby tidal spectral lines. The 18.6-yr modulation of diurnal tides is the most likely to be detectable. Possible evidence for this is reviewed. Some of the most promising candidates rely on temperature data in the vicinity of the North Pacific Ocean where diurnal tides are large, but definitive detection is hindered by the shortness of the time series. Paleoclimate temperature data deduced from tree rings are suggestive, but one of the best examples shows a phase reversal, which is evidence against a tidal connection.
TTIDE Summary

During January / March 2015, arrays of McLane profilers, ADCPs, and thermistor chains were deployed.

1) Southern Line: more reflective

2) Northern Line: more dissipative

3) Offshore Triangle: the “Reflection Array”

4) Offshore T-BEAM Incoming Flux mooring

5) On-shelf T-SHELF array

LADCP and Fast-CTD profiling from the R.V. Revelle.

LADCP survey of the incident beam from the RV Falkor
BLOG

https://scripps.ucsd.edu/projects/ttide/

https://scripps.ucsd.edu/projects/ttide/category/video/
FIG. 2. Glider tracks for (a) Spray 55 and (b) Spray 56 are shown with color indicating time. Increasingly dark dots along the track denote increasing spring-neap phase, which is expressed in terms of days. In both cases, a wide range of phases is seen in the areas with greatest sampling. In Figure 2b, Spray 56 profiles for 2 weeks over the slope near 42.4°S (green to yellow colors).
Fig. 3. Data from Spray 56 are shown with visible $D_1$ and $D_2$ oscillations and longer duration mesoscale variations in depth-varying (a) $\theta$, (b) $S$, (c) $u$, and (d) $v$ and also in (e) depth-mean $u$ and $v$. $\sigma_\theta$ is contoured at 0.1 kg m$^{-3}$ intervals (gray lines). A weakly-stratified surface layer extends to 200–300 m (Figures 3a–b).
Standing internal tides in the Tasman Sea observed by gliders

T. M. Shaun Johnston* and Daniel L. Rudnick

Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California

Samuel M. Kelly
Large Lakes Observatory and Department of Physics, University of Minnesota, Duluth, Minnesota

ABSTRACT

Large Lakes Observatory and Department of Physics, University of Minnesota, Duluth, Minnesota

Fig. 1. To illustrate the geometry of the internal tides (a) incident upon and (b) reflected from a coastal wall (dashed line), the instantaneous cross-slope velocity component of an idealized mode-1 Poincaré wave with a constant 150-km wavelength is shown superimposed on a map of Tasmania. The incident and reflected wave direction are shown (black arrows). The wall (dashed line along a bearing of 18°) is aligned with the steepest section of the slope. The incident and reflected waves combine to produce a standing wave in (c). The inset in Figure 1a shows the area under consideration (red box) in subsequent figures with AUS, TAS, and NZ denoting Australia, Tasmania, and New Zealand. Topography is contoured at 1000-m intervals. The East Tasman Plateau (ETP) is the broad rise offshore, which includes a steep pinnacle, the Cascade Seamount (CS).

Spatial surveys covering within 150 km of the slope by two autonomous underwater gliders with maximum range of kilometers across ocean basins (Ray and Mitchum 1996, 1997; Simmons et al. 2004; Zhao and Alford 2009). For the latter situation, a particularly good geomorphology is contoured at 1000-m intervals. The East Tasman Plateau (ETP) is the broad rise offshore, which includes a steep pinnacle, the Cascade Seamount (CS).

Long wavelength (i.e., vertical mode 1) internal tides are generated at tall, steep, submarine ridges (Holloway et al. 2003; Bühler and Holmes-Cerfon 2011; Mathur et al. 2014), or shoaling on the continental slope (Nash 2015). For the latter situation, a particularly good geomorphology is contoured at 1000-m intervals. The East Tasman Plateau (ETP) is the broad rise offshore, which includes a steep pinnacle, the Cascade Seamount (CS).

Figures 16 J OURNAL OF P HYSICAL O CEANOGRAPHY

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ABSTRACT

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Leg II Site Summary

Northern Region Extended
Shoaling tides at 1625 m depth on the Tasman Slope
Site 7

On Top of Klymak Rise
Preliminary results from T-Beam

R/V Falkor Cruise 17 Jan – 13 Feb

- LADCP-CTD stations: F1-F9
- Shipboard survey lines: C1-C2, C2-C4, T5-Offshore
- XBT stations: X1-X4

“Energy flux” transect lines: C1-C5 and C6-C7.

Sea surface height from altimetry from 31 Jan 2015

Waterhouse Kelly Rainville
a) Original CTD set up: CTD 911, 2 ADCPs, 2 sea batteries, 4 χ-pods, 8 bottles

b) Modified CTD set up (no batteries)

c) Small CTD package: equipped with radiometer, fluorescence, backscatter and oxygen sensors, and two χ-pods
LADCP station F3

- Better temporal coverage
- Larger pressure perturbations
- Large energy flux
Semidiurnal mode-1 energy fluxes

- Fluxes are based on two fitting methods
- Fluxes at A1 will fill in the picture
- Still optimizing fits to minimize uncertainty
TTIDE Ship & Mooring Program

Legs I & III
Matthew Alford
Jen Mackinnon
Jonathan Nash
Harper Simmons

Leg II
Rob Pinkel
Drew Lucas
Nicole Jones
Robin Robertson
FCTD Drop Rate

FCTD Sea-floor Detection
T-Shelf:

Funded by Australian Research Council and UWA to study *sediment resuspension processes associated with the internal wave field.*

Broader goal was to quantify energy/mass/momentum fluxes over the shelf, relate to various forcing.

Initial hypothesis was that the remotely incident internal tide would be a major player.

Approach: mooring array for leg-II, 24 hour shipboard CTD yo-yo
T-shelf moorings

**Shelf-break (175m depth):**
Bottom frame with upward looking 300 and 1200 kHz ADCPs, ADV, optical backscatter. Adjacent mooring w/ upward looking 150 kHz ADCP, 5-20m separated T and C/T sensors, near bottom intensified sampling.

**Outer-shelf (115m depth):**
Upward looking 300 kHz ADCP, OBS, ADV plus motion package 10 MAB, T and C/T with 5 m separation until 45 MAB, 10 m sep. until 100m.

**Mid-shelf (100m depth):**
Upward looking 300 kHz ADCP, OBS, T and C/T with 2.5-5 m separation until 45 MAB, 10 m sep. until 100m.
Shelf-break mooring (prelim analysis T. Schlosser)
WW outer-shelf mooring

Temperature (°C)

Chlorophyll F (RFU)

Log_{10} Turbidity (RFU)

Dissolved oxygen concentration (mL/L)

Days from February 7th 2015
WW outer-shelf mooring  (Thanks to Jonathan for $\chi$ processing)
T-shelf: Summary and next steps.

- Extensive 16d shelf record of physical and sediment dynamics.
- Excellent data recovery, including perhaps the longest continuous records of microstructure over the shelf.
- Subinertial flow dominated by poleward transport at and above the pycnocline.
- Important contribution of near-inertial, K1, and, less so, the M2 tide. Apparent in both barotropic and baroclinic currents.
- Very energetic and complicated internal wave field at frequencies higher than M2.

Next steps:

These data will form the basis of dissertation of Tamara Schlosser (UWA), co-advised by Jones and Lucas.

Analysis of mixing from $\chi$, in particular building intuition into near-surface turbulent processes.

The sediment story… is there one?
TTIDE Modeling: Jody Klymak

- Surface Tide generation
- Low-mode propagation
- Reflection
- Wave-wave interactions -> basin turbulence
- Local turbulence
- Propagation

(a) Time = 4 tidal periods
(b) Time = 12 tidal periods

Depth (m): 0, 1000, 2000, 3000, 4000
Depth (m): 0, 1000, 2000, 3000, 4000

X (km): 0, 500, 1000, 1500
U (m s\(^{-1}\)): -0.2, 0.0, 0.2
ROMS Simulations of the Tasman Sea

$t_0 = \text{Jan 1 2015}, \, dx = 0.03125^\circ \, (\sim 2.5\, \text{km}), \, M2+S2+O1+K1$

HYCOM initial condition and sponges, MERRA fluxes + tides

Dmitry Brazhnikov
John Pender
Kate Hedstrom
Harper Simmons
Sea surface relative vorticity ($\zeta/f_{40}$)