# Below the surface: simulating waves in the ocean's interior

> **Internal solitary waves can travel far from their generation site, transporting both mass and momentum over tens of kilometres,before remotely depositing their energy**

Internal waves represent a key mechanism of energy transfer within our oceans and are an important, albeit often unresolved, component in global climate models. However, they have proven to be challenging to observe in the field and difficult to simulate. Together with skilled collaborators, **Professor Peter Diamessis**, from the department of Civil and Environmental Engineering at Cornell University, has developed a model to simulate how a particular highly nonlinear class of these waves, internal solitary waves, propagate into progressively shallower waters and adapt their waveform driving the formation of turbulence inside the wave.

Due to solar heating and salinity effects, the Earth's oceans tend to be stably stratified, comprised of layers of water that increase in density as depth increases. These layers are typically described and visualised with the use of isopycnals, theoretical surfaces joining points of equal density. The condition of stable stratification allows for the formation of internal waves, a very specific type of wave that propagates (travels) along the interface between different oceanic layers. Often referred to as internal tsunamis, internal solitary waves (ISWs) are a distinct class of internal wave with wavelengths on the order of 1km. ISWs are particularly powerful and, as they propagate along the pycnocline (the portion of the water column with the highest density gradient), they can vertically displace isopycnals by, at times, up to 100m. When a wave shoals, i.e., it encounters changes in depth as it propagates towards shallower waters, its wave length and amplitude adjust. Although very particular in their behaviour, ISWs can be generated through a range of mechanisms, primarily through interactions between tidal flow and the underlying bathymetry. For this reason, ISWs are ubiquitous throughout coastal waters and open oceans and can also be found in certain lakes.

As ISWs propagate towards shallower waters, turbulence and vertical mixing develop within the wave interior, facilitating the exchange of oceanic heat and nutrients, with important consequences for biological primary productivity – the measure of how quickly energy is converted to organic substances. Additionally, ISWs can pose potential hazards to offshore drilling operations.

## A FINE BALANCE

One of the most interesting features of ISWs is their ability to travel very long distances whilst maintaining their shape through a delicate balance between nonlinearity and dispersion: nonlinearity forces a wave to steepen whilst dispersion forces a wave to break down into smaller waves. This very particular property allows ISWs to travel far from their generation site, transporting both mass and momentum over tens of kilometres, before remotely depositing their energy. As such, ISWs represent a key mechanism of energy transfer within the oceans and are an important element in global climate models, which are sensitive to their effects. Prof Diamessis is working to increase our understanding of the propagation of ISWs and the turbulence and particulate transport that forms in the wave interior during shoaling so they can be better incorporated into global climate models.

## A COMPUTATIONAL APPROACH

Since completing his post-doc in 2005, Prof Diamessis has (self-admittedly) been obsessed with simulating the evolution of ISWs, turbulence included, over long distances and gentle slopes. Together with his research group at Cornell University, Prof Diamessis has a particular interest in the design of computational models and how these can be applied to simulate stratified flows in the environment, including ISWs.

## THE OBSERVATIONAL AGE

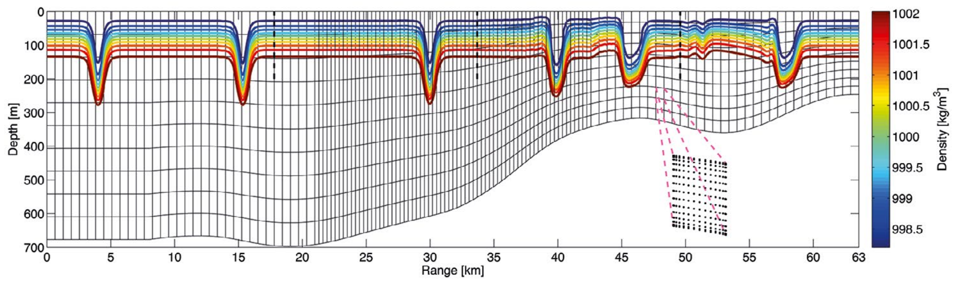
Historically, ISWs have been incredibly challenging to observe. However, recent advancements in aircraft and satellite imaging technology have led to widespread observations of ISWs, indicated by distinct patterns of sea-surface roughness. This increase in observations has triggered a new era of opportunities to study and understand ISWs, as driven through advanced techniques to measure within the water column. These techniques have been employed in a recent series of carefully designed seagoing field campaigns.

## OBSERVING INTERNAL WAVES IN THE SOUTH CHINA SEA

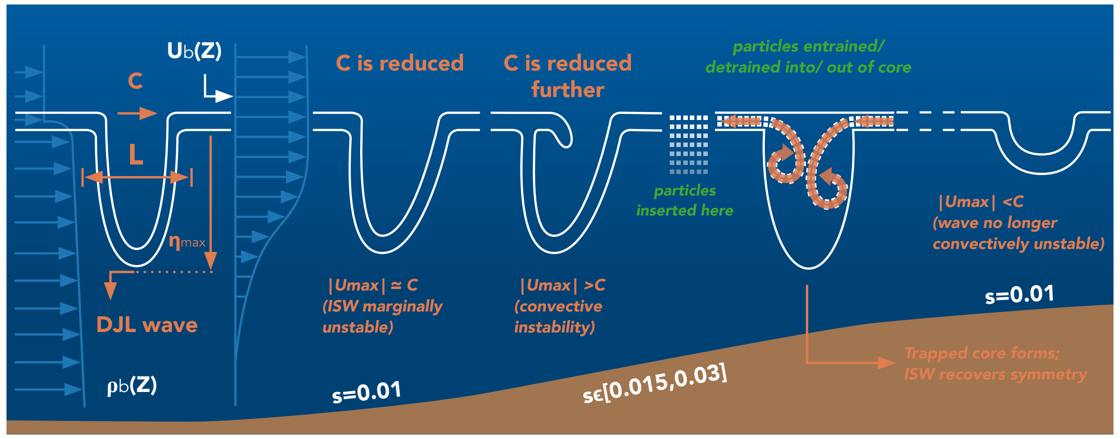
Professor Diamessis' research is highly interdisciplinary and, as such, relies heavily on the input of a number of key collaborators. Dr Ren-Chieh Lien, of the Applied Physics Laboratory of the University of Washington has been instrumental in data collection, spearheading an observational programme monitoring ISWs in the South China Sea (SCS).

As it stands today, the SCS is the generation site of the oceans' most powerful known ISWs. However, extreme flow conditions have presented significant challenges to the observation of these waves, which have only been investigated in detail over the last decade.

Using multiple methods, including Lagrangian floats (autonomous underwater devices that track the trajectories of water parcels), Dr Lien has monitored ISWs and the formation of turbulence within them. These observations have revealed that it is convective instabilities (see Q&A for further details) which are the predominant driver of the formation of turbulence within ISWs in the ▶




Stream-depth transect of the computational domain for the 2-D simulation of an ISW propagating over a slope from a sample 1-D transect along SCS bathymetry at 20° 56' N for a shoaling track extending from 117° 45' to 117°E. Isopycnals are shown in color in a model two-layer stratification with the density gradient within the pycnocline equal to the value observed in the SCS. Snapshots of the propagating large-amplitude ISW are shown at six different locations along the propagation path. Black lines delineate spectral subdomains. Subdomains may be positioned to enable greater resolution of both the ISW-displaced thermocline and the steeper slope region. Bottom right inset shows an exploded view of an example deformed subdomain with its own set of computational grid points. The vertical dashed lines along the top surface represent windows over which sub-simulations of the full ISW shoaling run have been performed.



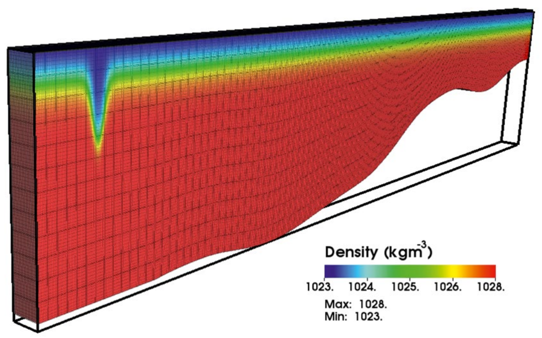

Schematic of the idealised bathymetry used by the proposed numerical simulations showing background density stratification and currents [$\rho_b(z)$ and $U_b(z)$] and the various stages in ISW evolution, as it is "launched" from constant depth (650 m) waters, becomes marginally unstable over a gentle (s=0.01) slope, undergoes convective instability over an intermediate steeper slope, and re-enters a gentler slope region at 375m depth for a total shoaling distance of 35 km. C, $U_{max}$, L and $\eta_{max}$, represent the ISW phase speed, maximum subsurface current within the wave, wavelength and maximum isopycnal displacement induced by the ISW.

SCS. The data also illustrated a particularly interesting property of these ISWs: despite being convectively unstable, they are able to maintain their shape as they propagate. As a result, the ISWs are able to support a 'trapped core' of internal vortices, retaining individual fluid parcels within the wave for up to an hour and transporting them over multiple kilometres. Whilst previously theoretically proven by Professor Kevin Lamb at the University of Waterloo, Dr Lien's programme provided the first observations of trapped core formation. Both Prof Lamb and Dr Lien are important collaborators in the project with an ongoing involvement.

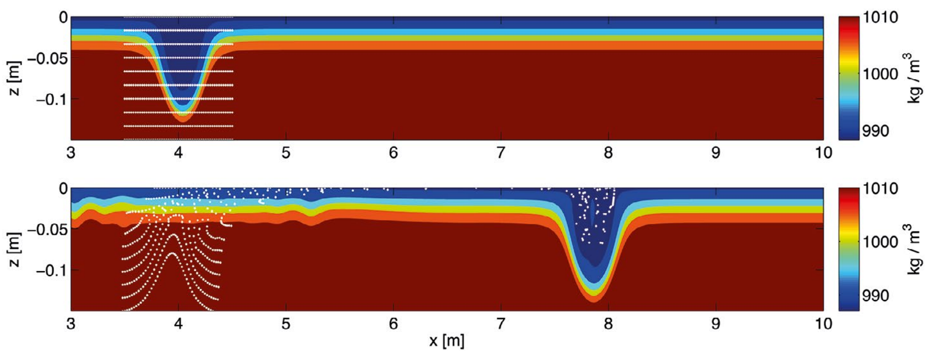
## WHERE THEORY MEETS FIELDWORK

Confusion surrounding mechanisms of ISW generation, propagation and dissipation, stemming from a lack of in situ data, has made it extremely difficult to account for their effects in climate models. Building on the recently obtained observational data in the SCS, Professor Diamessis is currently working on a project that aims to computationally simulate the propagation of ISWs, with the specific aim of capturing the internal turbulence observed by Dr Lien. In order to achieve this, Prof Diamessis and his team are utilising high-order element-based methods, computational methods that are particularly suitable due to their ability to realistically represent wave propagation, complex internal turbulence, detailed bathymetry, and their computational efficiency.

Whilst computational methods are unable to replicate exactly what happens in the field,




Schematic of the computational domain for a 3-D simulation of a shoaling simulation. Black solid lines represent computational subdomains and colored contours indicate density stratification. Shown is the initial wave at the left of the domain. Notice the narrow transverse dimension of the computational domain which allows for capturing 3-D turbulence, as the wave propagation is 2-D and normal to the isobaths lines.




Density contours and particles from a preliminary 2-D simulation, in a virtual laboratory tank, of a high-amplitude ISW which has just undergone convective instability. A particle cloud is injected into the wave core immediately prior to the onset of this instability. A fraction of particles is captured by the recirculating core formed inside the wave that transports them, with some losses due to leakage.

Professor Diamessis and his collaborators have created an idealised model of the natural system that retains its principle features and has inputs based on real observations. With the use of this model, Professor Diamessis aims to investigate and understand how convectively unstable waves affect turbulent fluxes of energy and heat, and the transport of particulates from deep to shallow waters.

## ACHIEVEMENT THROUGH COLLABORATION

In addition to close collaboration with Dr Lien and Prof Lamb, the success of Professor Diamessis' current research has been dependent on a number of other contributors. The state-of-the-art algorithms that are used to track particle motions were built by Professor Gustaaf Jacobs at San Diego State University. Mr Greg Thomsen, a computational scientist, was instrumental in the development of the software that provides the backbone of the simulations. Furthermore, Dr Steve Lantz of the Cornell Centre of Advanced Computing has worked on the management of the very large datasets that are produced by the simulations. The effective storage and dissemination of this data facilitates its use by the wider oceanographic and fluid mechanics research communities, ensuring its impact beyond this project.

## MORE THAN JUST A DROP IN THE OCEAN

The work of Professor Diamessis and his collaborators has made a significant contribution to our knowledge of the formation and behaviour of ISWs. As a result of their work, ISWs can be more accurately represented within global climate models. The collaborative approach of Professor Diamessis proves that a concerted research effort, across disciplines, can result in far-reaching research outcomes with important consequences.



# Q&A

***What are the principle challenges faced when trying to simulate real oceanic phenomena, such as internal solitary waves?***

a) The efficient resolution of the scale separation between the long wave and the finer-scale turbulence therein; b) Capturing a sizable fraction of the broad range of scales within a turbulent burst itself; c) Accounting for non-hydrostatic effects, i.e. strong vertical accelerations, which requires solving a Poisson equation for the pressure, a non-trivial endeavour in terms of computational cost; d) Correctly inserting into the simulation the background current and stratification profiles, filling in any missing information therein, and comparing simulation results to actual oceanic observations.

***What factors will indicate the presence of internal solitary waves when using indirect detection methods such as satellite imagery?***

In remote imagery measurements, ISWs often appear as alternating patterns of quasi-periodic dark and bright bands against a grey background. These bands result from enhanced and reduced radar backscatter with bright and dark bands representing convergent (rough, with potentially fine-scale capillary gravity waves present) and divergent (smooth) zones on the ocean surface. These two zones are intimately connected to along-wave variations of the ISW-induced subsurface current. This canonical surface pattern can be modified by a number of factors including wind speed and direction and the presence of surface films, the latter likely to give rise to surface slicks.

***What are convective instabilities?***

The propagating ISW carries within it a localised subsurface current pattern, whose along-wave velocity is aligned with the wave propagation speed (phase speed). As an ISW encounters shallower waters, its phase speed is reduced. For a sufficiently large wave, this reduction may be so strong that the wave-induced current will exceed the phase speed. The rear of the wave then steepens, as it tries to catch up with the front. The convective instability manifests itself through a spilling of fluid from the rear of the wave into its interior.

***Observations from the South China Sea have shown that it is typically convective instabilities that drive the formation of turbulence in internal solitary waves in this region. Is this unusual? Why might we see convective instabilities, as opposed to shear instabilities in this region?***

Shear instabilities are assumed to be the predominant form of turbulence-generating instability across ISWs of different amplitude. However, their presence in the South China Sea has not been documented in detail, presumably because existing deployments did not use instrumentation customised to capture their finer spatiotemporal scales. Convective instabilities are limited to high amplitude waves, where the pycnocline is depressed to 80% or more of its physically allowable value, and are expected to produce even more vigorous turbulence. Bottom topography and internal tides synergise in a uniquely ideal manner to produce in the South China Sea some of the largest ISWs observed.

***Internal solitary waves with 'trapped cores' can transport fluid parcels over large distances. What are the implications of fluid transport through this mechanism?***

ISWs can drive horizontal shoreward transport, over very long distances, of not just fluid of different heat and mass content but also of nutrients, larvae, plankton, fish and other biota. A wave with a "trapped" core is in fact even more efficient in this regard, as fluid, nutrients and biota captured within the recirculating motions of this core reside within the wave interior for a much longer time and are, consequently, transported over a much longer distance. In some cases, such nutrients and biota, originating from very deep water, can be deposited close to the coast, critically controlling ecosystem balance.

# Detail

## RESEARCH OBJECTIVES

Prof Diamessis' work looks at internal solitary waves that travel within the ocean, sometimes for miles at a time. In particular, he is interested in how these waves change as they encounter changes in the sea depth in shallower waters and, as a result, develop turbulence in the wave interior. With collaborators, he has developed a modelling system to learn more about these waves.

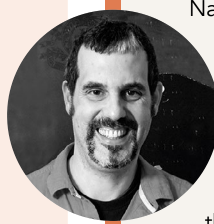
## FUNDING

National Science Foundation (NSF)

## COLLABORATORS

- Dr Ren-Chieh Lien, Applied Physics Laboratory, U. of Washington: Co-Principal Investigator, field oceanographer.
- Prof Kevin Lamb, Dept. of Applied Mathematics, U. of Waterloo, Canada
- Mr Greg Thomsen, Wandering Wakhs Research.
- Dr Steve Lantz, Cornell Center for Advanced Computing.
- Prof Gustaaf Jacobs, Aerospace Eng., San Diego State University.

## BIO



Peter Diamessis is a graduate of the National Technical University of Athens, Greece and University of California, San Diego and has worked as a postdoc at USC. His research focuses on the development of high-order element-based techniques and their application to the study of the interplay between internal waves and turbulence in naturally stratified waters.

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