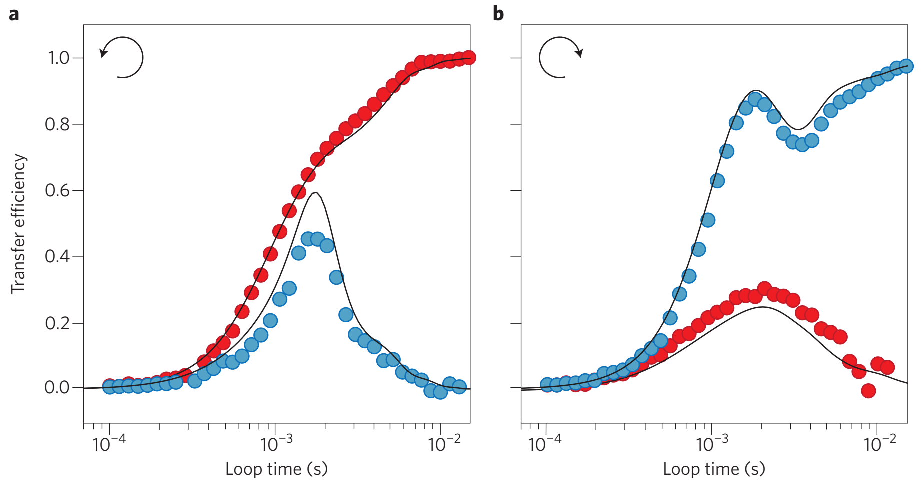

Figure 2 | The transfer efficiency as a function of loop time. **a**,**b**, The measured transfer efficiency of the two different states (labelled red and blue) ends at different values depending on the direction the exceptional point is encircled. For the anticlockwise direction it is the red state (**a**) and for the clockwise direction it is the blue state (**b**) that is driven and attains maximal efficiency after sufficient loop time while the efficiency of the partner state vanishes. The solid lines represent numerical results. Reproduced from ref. 2, NPG.

words, the non-adiabatic terms lead to chiral behaviour. Jörg Doppler and colleagues confirm this using two coupled waveguides[1]. And Haitan Xu and co-workers report the same finding in an optomechanical system[2].

Such experiments are extremely challenging. Firstly, as the system is open it interacts with the environment. There is loss (by absorptive material or radiation) and gain (by laser pumping), which must be delicately balanced. Only then will the position of the exceptional point remain stationary in the parameter space. And most importantly, only then will non-adiabatic effects appear (Fig. 1). Secondly, the encircling must be done dynamically, thus requiring a continuous time-dependent change of the parameters. Moreover, the speed of the encircling must also be controlled. This is actually implemented by imposing an appropriate slow change of the boundary parameters along the propagation direction.

The reports of Doppler *et al.* and Xu *et al.* confirm the non-adiabatic and asymmetric nature of encircling exceptional points. These experimental approaches are not limited to electromagnetic waves, but are also applicable to acoustic and other matter waves. The results could be used for quantum control and switching protocols and further studies could explore the behaviour of thermal and quantum fluctuations in the vicinity of an exceptional point, thus opening intriguing directions for further research. ❐

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PHYSICS OF WAVES

Warning from the deep

Insights from the emerging field of branched flow are directing us towards a way of anticipating the effects of tsunamis. A framework linking bathymetric fluctuations to wave physics marks a promising step forward.

Eric Heller

There's no doubt about it: work published earlier this year in *Nature Physics* by Henri Degueldre and colleagues[1] has the potential to save lives. Recent long-distance tsunami wave events have reminded us of their destructive power. Even tsunami waves travelling at hundreds of miles per hour can go undetected mid-ocean on a ship. Yet the energy these waves carry is huge, and travelling over an uneven ocean floor causes local branches of higher energy to form in the wave. When these branches collect near the shore, they slow down. And like traffic braking bumper to bumper on the freeway, when the wave energy finally collects onshore, it does so with devastating results.

The dramatic slowing down near the shore happens more gently in the mid-ocean as the wave passes over highs and lows of ocean depth. Rather incredibly, tsunami waves are so extended that they consider the Pacific Ocean shallow, and refract according to the shape of the bottom. Branches of concentrated high energy form. Where will these branches hammer onshore? This is what Degueldre *et al.*[1] sought to understand, by developing a framework for analysing how fluctuations in the profile of the ocean floor impact the characteristics of tsunamis.

Without knowing where the arriving energy will be especially high, tsunami warnings are made repeatedly out of general caution; with the result being that such warnings may soon go unheeded. But what if the warning said: "Unusual and dangerous seas with strong currents expected near shallows and shoreline in extreme northern California starting in 75 minutes" — and then it actually occurred, as predicted, with lives saved.

Crescent City in far northern California is estimated to have received more damage from the 1964 earthquake in Anchorage, Alaska, on a block-by-block basis, than did Anchorage itself, because local ocean-floor contour conditions near Crescent City are known to amplify tsunamis. After the 2011 earthquake in Sendai, Japan, five people in Crescent City were swept out to sea and

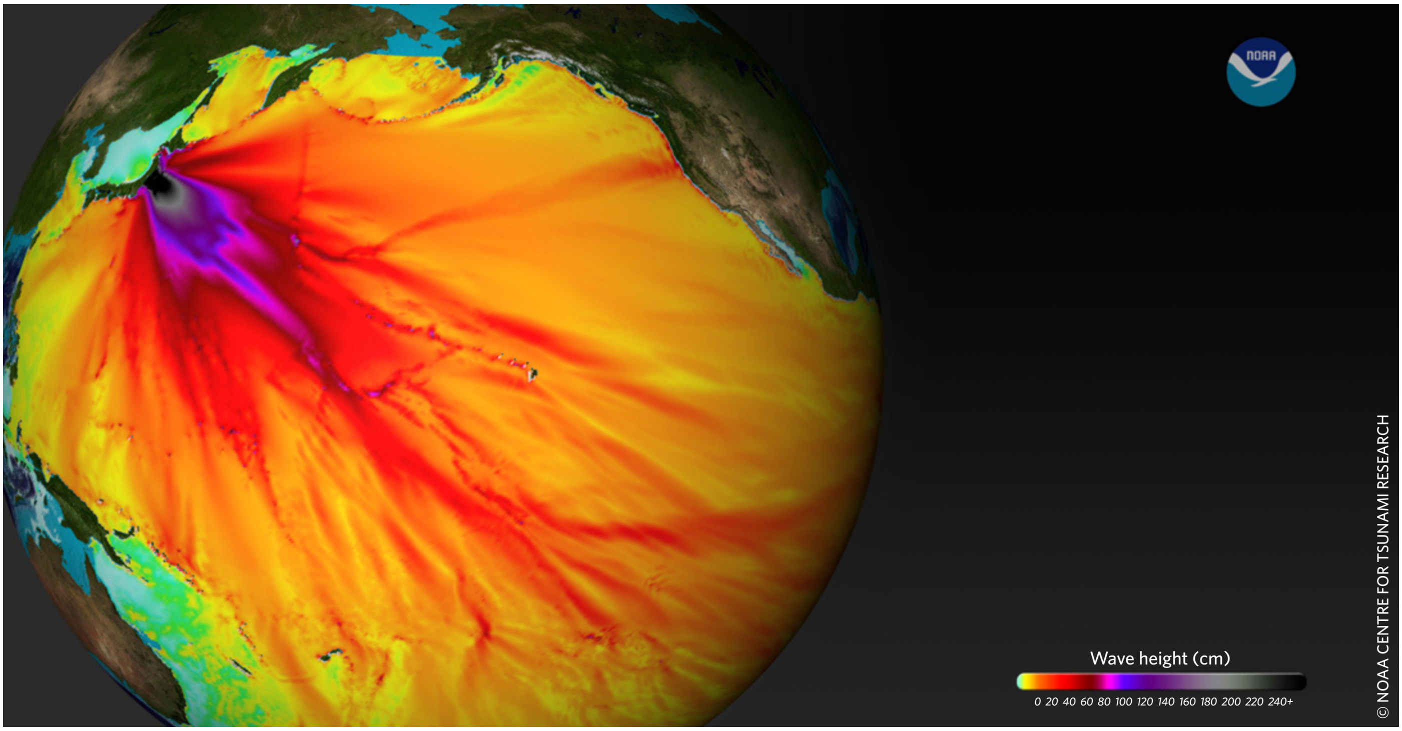

Figure 1 | Branched flow seen in a National Oceanic and Atmospheric Administration wave energy map produced after the 2011 Sendai earthquake in Japan. Note the strong branch heading for Crescent City in northern California.

one killed. It wasn't just the ocean-floor contours right around Crescent City that did it, according to the *post facto* National Oceanic and Atmospheric Administration wave energy estimate. Oddly, a branch of high wave energy headed straight for Crescent City all the way from the mid-Pacific (Fig. 1).

A fast developing field called 'branched flow' links phenomena as diverse as tsunamis[1], freak waves[2], laboratory microwaves[3], electron waves[4], and sound[5] and light[6] waves in many different contexts. Cosmic microwaves from pulsars passing through interstellar clouds also form part of this set, although here the possibility of branched flow has apparently not yet been considered. Until recently, these fields were thought not to be connected, and some are only now finding themselves to be part of this new discipline.

Two papers caused nucleation of the branched-flow field, and the realization of how ubiquitous it is. The first considered long-distance wave propagation of sound in the ocean, passing through random refracting thermal fluctuations that lead to unexpected long-range branching behaviour[5]. The second differed by many orders of magnitude in scale, but described the same phenomenon: the propagation of electrons in a two-dimensional electron gas in a semiconductor, as imaged by a tiny scanning charged tip[4]. The electrons in the two-dimensional electron gas were weakly but randomly deflected by positively charged donor atoms embedded in a nearby parallel layer. The spectacular branches that were observed were completely unexpected — but would have been predicted by branched flow, had it already been a field.

Even though branched flow is ultimately closely related to classical chaos and its wave implications, the sensitivity of the branches to small changes in the random potential had not been sufficiently studied. Degueldre *et al.*[1] were the first to work out the effect of estimated bathymetry errors and implications for the energy flow in the world's oceans after a major event. Their results were surprising — especially for anyone living on an ocean shore.

The likelihood is that with better bathymetry and fast computers, a major event could be accurately predicted via detection of large concentrations of energy far from the source well before their arrival. The data cannot be 'pre-computed' for all likely earthquake source zones. The shape and length of the fracture zone, the simultaneity of its fracture and energy variations along the rift (which seismic data travelling very fast through the Earth's crust can reveal) all need to be taken into account. And even local tides and currents may make differences in the arrival of tsunami energy far away. But Degueldre *et al.*[1] showed that all this data is not enough without better bathymetry.

A major effort should be mounted to realize fast and accurate tsunami wave propagation predictions. The effort has some parallels with asteroid detection and deflection: both can be devastatingly large events that are 100% certain to happen given a sufficiently long time span. Deflection of asteroids and comets is possible, but it requires time, together with good computers and trajectory data. The case has long been made for asteroids and efforts are ramping up. We need to exploit our technology to make predictions and minimize dangers for tsunamis as well. ☐

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