Research School Of Earth Sciences
(Earth Physics)
Research Activities 2009

Exploding stars, colliding comets, DNA based life on Earth – they all connect in the search for extra-terrestrial life.
Image - JPL-NASA
Earth Physics

Introduction

The Research School of Earth Sciences includes substantial activities in geophysics. The main research themes are Geodynamics, Geodesy, Geophysical Fluid Dynamics, Mathematical Geophysics and Seismology. These span observational, theoretical, laboratory, computational and data oriented studies, all directed towards understanding the structure and physical processes in the earth’s interior, the crust or the earth’s fluid envelope.

In 2009 Professor M. Sambridge was awarded 2009 Prince medal from the Royal astronomical Society of London for achievements in Earth Science. Dr M. Roderick was awarded the Australasian Science Prize by the journal Australasian Science for his work on the Earth’s hydrologic cycle and showing how pan evaporation rates in Australia have decreased over time with global warming. Professor R. Griffiths joined the Australian Research Council College of Experts (Physics, Chemistry, Earth Science panel).

RSES continues to take a major role in the National Cooperative Research Infrastructure Strategy (NCRIS): “Structure and Evolution of the Australian Continent”, which is managed through ‘AuScope’. RSES hosts activities in Earth Imaging through support of portable instrumentation and transects, Geospatial through gravity measurements and testing of portable equipment for satellite laser ranging, and Simulation & Modelling through ’pPlates’ software for tectonic reconstruction. As a linked activity between three AuScope components (Imaging, Geospatial and Access and Interoperability), the Terrawulf II cluster computer at RSES (Centre for Advanced Data Inference) provides capability in geophysical inversion and the computation reduction of observational data. RSES also continues the management of the Warramunga Seismic and Infrasonic Research Station near Tennant Creek in the Northern Territory, as a primary station in the International Monitoring System for the Comprehensive Nuclear–Test-Ban Treaty Organisation.

Research in geodynamics and geodesy has focused on measuring deformation of the Earth from both terrestrial and space-based observations. Estimates of total water storage from the GRACE space gravity mission were compared to terrestrial estimates of surface, soil and ground water in a study of the multi-year drought in the Murray-Darling Basin. The finding that a significant component of water loss had come from groundwater reserves generated considerable media interest. Other results were a demonstration of the non-stationary nature of geophysical signals observed by GRACE, that positive gravity anomalies in Enderby Land (Antarctica) are not related to glacial isostatic adjustment, and improvements in GPS analysis strategies that lead to a better agreement between GPS- and GRACE-based surface deformations than reported in previous studies. Terrestrial gravity measurements have been made using an absolute gravimeter and tidal meters in order to quantify the surface deformations caused by ocean tide loading.

In geophysical fluid dynamics, laboratory experiments have been used to examine the three-dimensional flow in mantle subduction zones, and the interaction of ascending mantle plumes with subduction zones, with a view to explaining the history of volcanism in the Columbia River Basalts, the Lava High Plains and Yellowstone hotspot of the northwest USA. Modelling of the combined chemical and thermal evolution of the Earth’s mantle has been extended to Venus’ mantle to test ideas about the operation of plate tectonics on Venus and whether the ‘basalt barrier’ mechanism can explain the outburst of volcanism that completely resurfaced Venus about 500 Myr ago. Another highlight is an explanation of the energetics of the global meridional overturning circulation of the oceans, which shows that energy supplied to irreversible turbulent mixing from the winds and tides (or other sources) must be in balance with the available potential energy supplied by the surface buoyancy fluxes. Hence the energetics indicate that the rate of overturning is governed by both the buoyancy fluxes and the mixing rate, as previously argued on the basis of dynamical considerations. Numerical solutions from a general circulation model were also found to be different depending on whether it was run in the usual hydrostatic and low-resolution mode, or in non- hydrostatic mode with an extremely high resolution resolving the vertical convective motions. In closely related work aimed at understanding both turbulent mixing and the global circulation, new experiments were carried out to obtain additional information about the nature of mixing in exchange flows over topographic sills. The results indicate that the proportion of energy input that goes into raising the potential energy by mixing is in the range 5–10%, efficiencies much smaller than the 20% often assumed in analyses of global ocean energy balances. Work also continues in high-resolution modelling of flow in the Southern Ocean, designed to determine the dynamics driving the circulation in this region. The latest results give a clearer indication of the likely response of the Southern Ocean to climate change.

In parallel with the gravity satellite research, and the ocean studies, we conduct detailed studies on the hydrologic cycle. Of principal interest here is the development of a theoretical framework that can provide physical understanding of the possible changes in the hydrologic cycle with global warming, at both global and local scales. One highlight this year was the publication of “The Global Water Atlas” (by ANU ePress), which documents model predictions contributed by international climate modelling groups to the 2007 4th Assessment Report of the Intergovernmental Panel on Climate Change. Activities in seismology in 2009 included extensive field-based deployments of seismic instrument arrays, data analysis and theoretical development, for studies of Earth structure from the crust to the core. Much of the activity centred on the WOMBAT experiment, a rolling-array deployment that has been in operation since 1998 and is currently focused on achieving
high resolution imaging of the crust and upper mantle beneath south-eastern Australia, including the Flinders ranges and the Murray Basin. The results show little evidence for the Palaeozoic building blocks of the southeast Australian continent that had been inferred from geological mapping. By utilizing differential PcP-P times from WOMBAT, high resolution imaging of the core-mantle boundary is also possible and current efforts are directed at mapping variations in core-mantle boundary geometry and D’ velocity. New global observations of waves reflected from the Earth’s inner and outer core (PKiKP and PcP waves), originating from earthquakes and nuclear explosions, were used to place bounds on density ratio between the inner and outer cores. Other arrays were deployed in the region around Mt Isa in Queensland and between the Eyre Peninsula in southern Australia and Tennant Creek in northern Australia, in order to examine the transition between the northern and southern Australian cratons. The new Seismic Data Centre (SDC) now provides easy access to all current and past seismic data collected by RSES in a variety of user-friendly formats. Model structures for the inner core were re-examined using our Antarctic permanent stations as well as the temporary SSCUA deployment operated by the RSES during 2002-2005, and provide evidence against a proposed cylindrical structure in the outer core tangent to the inner core in the southern hemisphere.
A portrait of the Bárdarbunga volcano, Iceland, earthquake and insights into the kinematics of the caldera drop

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The Bárdarbunga volcano lies beneath the 500-m-thick Vatnajokull icecap, the largest glacier in Europe. An earthquake with Mw=5.6 occurred beneath the caldera on 29 September, 1996 and produced an unusual radiation that cannot be explained by a shear slip on a planar fault. A peculiarity of this earthquake was that it was the first in a sequence of seismic and magmatic events and that it was followed, not preceded or accompanied, by a major eruption, which ultimately led to a breakout flood from the subglacial caldera lake. It was hypothesized that the observed source mechanisms result from slip on an outward-dipping cone-shaped ring fault beneath the caldera, as a result of a change in pressure in the volcano’s shallow magma chamber. The earthquake was recorded well by the Iceland Hotspot Project seismic experiment.

The absence of a volumetric component in the source mechanism is surprising, however a possible mechanism that can produce an earthquake without a volumetric component involves two offset sources with similar but opposite volume changes. We show that although such a model cannot be ruled out, it is unlikely. We simulated different caldera geometries and rupture scenarios on the walls of a conical surface. These experiments support a super-shear rupture extending unilaterally across one-half perimeter of the caldera or a bilateral rupture extending across full perimeter of the caldera as likely scenarios for the Bárdarbunga earthquake.

If studied in different frequency bands, synthetic seismograms based on a point source approximation fail to simultaneously explain the observed data, and this indicates the presence of finite-source effects. Using a 3D model of the Icelandic crust and upper mantle, we perform a probabilistic finite source inversion. One of the most robust outcomes of this is a well-constrained source duration with approximately equal amount of energy radiated by individual segments. This indicates that the caldera dropped coherently as a single block. We also hypothesise that a smaller subglacial eruption that triggered the caldera collapse occurred and went unnoticed. The caldera drop could have increased the pressure in the magma chamber thus inducing the principal eruption. The major eruption after the earthquake is consistent with the classical model where the ring fault is located above the magma chamber.

Link to the online article:
http://www.bssaonline.org/cgi/content/abstract/99/5/3077

Figure 1. Bardarbunga volcano, Iceland

Figure 2. Map of Iceland showing the Hotspot seismic stations used in the study. The locations of Bardarbunga and Grimsvötn volcanos are also displayed.

Figure 3. Marginal probability distributions for the rupture time on the individual fault segments. The height of a bar in the histograms indicates the probability that the magnitude on a given segment falls into the interval covered by the width of that bar. The circular image in the centre shows the marginal probability densities as gray scale distributions. Each of the 10 subfaults released about 10% of the total elastic energy. The relative magnitudes for the most probable finite source model are shown as gray columns.
South Australian Seismic Arrays
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As part of a wider AUSCOPE project 67 short-period seismometers were deployed across the Gawler and Curnamona Cratons in South Australia. Station spacing was approximately 60 km and covers the area from the Streaky Bay in the east to the New South Wales border in the west. The north-south extent of the array runs from Cameron Corner to Port Lincoln. Stations recorded continuous three component data for a period of 6-8 months. The instruments are capable of recording data from both local and distant earthquakes.

The primary aim of these arrays is to increase data coverage in this part of Australia for seismic imaging. There are few permanent seismographs in the region covered by this array. The area covered is currently of particular interest for the supply of geothermal energy and there are many ongoing industry projects in the area. This area of South Australia is also seismically active and local earthquake data recorded on this array will help improve our ability to locate and characterize these events.

Currently the data are being used for receiver function analysis to locate seismic discontinuities such as the crust-mantle boundary (Moho). This is contributing the the ongoing AusMoho project mapping the Moho beneath the Australian continent (figure 1).

Curnamona Craton seismic stations

Gawler Craton seismic stations

Figure 1. Current AusMoho map. Contours show the depth to the crust-mantle boundary in kilometers. Data points from short-period receiver functions are shown as circles, data points from broadband receiver functions are shown as diamonds and reflection/refraction line data are shown as triangles.
High Resolution Imaging of the Core Mantle Boundary with PcP-P Differential Travel Time Residuals

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Southeastern Australia is favorably positioned relative to much of the Pacific Rim and SE Asian subduction systems for detection of PcP phases from subduction zone earthquakes, which are best recorded between approximately 25-75°. The subduction zones of Indonesia, Papua New Guinea, Tonga/Kermadec, Philippine, Izu-Bonin-Mariana, and Japan are all within 25-75° of SE Australia. As such, any seismic stations deployed in this area have potential for detailed PcP-P travel time studies. Using data from a large rolling seismic array in southeast Australia, we obtain unprecedented high-resolution coverage of the core-mantle boundary in this region.

Surface projections of PcP bounce points are clustered directly beneath the large region spanning central and northern Australia, the Arafura Sea, north of Papua New Guinea, and the Tasman Sea. There is an overall predominance of negative residuals throughout the region, particularly near Sulawesi, western Indonesia, central Australia, and west of New Zealand. In particular, results under the Tasman Sea show a transition from large and negative residuals to moderate and positive residuals, which could be suggestive of remnant subduction signals at the CMB from the Tonga/Kermadec region.

With the remaining analysis using the rest of the >500 short-period stations in SE Australia and >100 stations in Sumatra, we aim to produce high-resolution images of the lower mantle and core-mantle boundary. We will focus on the regions of central Australia and the Timor and Tasman Seas in particular as they have the densest raypath coverage. Using traveltime tomography, waveform coherence, any precursory phase analysis, and amplitude information, we will investigate the trade-off between velocity structure and interface depth at the core-mantle boundary.
Figure 3. Surface projections of PcP-P bounce points. Points are scaled by PcP-P residual, black circles are negative, red triangles are positive. Inverted blue triangles are stations used in the study.
Ambient noise tomography of southeast Australia using WOMBAT seismic data

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Detailed images of Rayleigh wave group velocity are derived from ambient seismic noise recorded by WOMBAT, a large rolling seismic array project in southeast Australia (see Figure 1). Data from 282 stations deployed as part of seven separate array movements are used, with a maximum of 57 stations recording at any one time. Group velocity maps sensitive to shallow crustal structure (Figure 2) reveal the presence of low velocity regions associated with sedimentary basins and the Newer Volcanic Provinces of western Victoria, and high velocities associated with regions of outcropping metamorphic and igneous rocks in the Great Dividing Range. Distinct and well-constrained patches of low velocity within the Murray Basin, a large Tertiary intra-cratonic basin, point to the presence of infra-basins, the existence of which have been confirmed by drilling, but whose spatial extent is poorly understood. In a broader tectonic context, our results show little evidence for the Palaeozoic building blocks of the southeast Australian continent that have been inferred from geological mapping and potential field data. For example, the transition from the Delamerian to the Lachlan Fold Belt is not marked by a change in group velocity, nor is the so-called Tasman Line, which supposedly separates Precambrian western Australia from Phanerozoic eastern Australia. In the latter case, the new results support the contention that the change from an accretionary orogenic terrane in the east to a much older cratonic terrane in the west is likely to be gradual rather than distinct.
High Frequency Po/So and the nature of the oceanic lithosphere

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It has long been recognised that high frequency seismic body waves can travel for substantial distances through the oceanic lithosphere. In the western Pacific such Po and So phases are very common from shallow events in the various subduction zones, and have been recorded at more than 3000 km from their earthquake source. Usually So is stronger and longer duration than Po when recorded on seismometers, but weaker when a hydrophone is used as the sensor. A combination of multiple propagation legs within the lithosphere reinforced by more rapid reflection processes in the water and sediments helps to carry such Po and So energy to long distances. The complex observed waveforms with long tails can be well simulated by numerical models that include heterogeneity in the lithosphere with much large horizontal than vertical extent.

Despite the generally good propagation to stations in the western Pacific where poor propagation is inked to source location in the back arc region, the situation is more complex in the east. The underwater observatory H2O on an old telephone cable between Hawaii and the Mainland USA only records So from events on Hawaii, and even these arrivals are relatively weak compared with Po. A survey of Po/So properties across the Pacific (Fig 1) highlights the differences in propagation characteristics. It appears that the poor transmission of Po and So may be related to the presence of the major transform fault systems in the eastern Pacific that are likely to be linked to changes in lithospheric thickness. These effects are being investigated through detailed analysis of the signals and numerical modelling of the high frequency wavetrains. Oblique incidence on a major step in lithosphere thickness is likely to have a significant effect on the complex wave packets.

Figure 1. Compilation of Po and So propagation characteristics in the Pacific showing the clear propagation of Po and So in the western pacific and the relatively poor propagation in the east where paths traverse major transform faults systems.
Eddy response of the Southern Ocean to climate mode forcing

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The Southern Ocean consists of some of the most dynamically complex ocean currents in the world. Not only does it include the Antarctic Circumpolar Current (ACC), which is among the world’s strongest in terms of transport, but also contains a network of vigorous small-scale eddies. As a transit point for the exchange of water masses between the other major oceans, the Southern Ocean plays a crucial role in the climate of our planet, and these currents can have a significant impact on the state of world oceans.

The consequences of this active eddy field have yet to be fully understood. For example, the ACC transport has been shown to be largely insensitive to wind forcing in high resolution models. Rather, such forcing tends to produce a more vigorous and spatially inhomogeneous eddy field. Modeling work of the GFD group at ANU has shown that this eddy field is sensitive to standard modes of climate variability, specifically the Southern Annular Mode (SAM) and ENSO. In particular, ENSO can have a modulational effect on SAM, either amplifying or suppressing the eddy response in specific regions across the Southern Ocean (Figure 1). Such an inhomogeneous and time-dependent eddy field directly impacts the mixing and large-scale transport of water throughout the Southern Ocean, and can lead to long-term impacts on the world’s oceans.

Figure 1. Wind forcings based on the Southern Annular Mode (SAM) and La Niña are applied over a two year period (below dashed line), producing eddy kinetic energy (EKE) responses with dramatic spatial and temporal variability. Despite a dominant SAM mode, La Niña can enhance (90W, Pacific) or suppress (30E, Atlantic) the SAM response.

Figure 2. This snapshot of the pressure field from numerical modeling reveals an active eddy-rich flow along the fronts of the Antarctic Circumpolar Current. Variations in wind forcing are transferred predominantly to these small-scale structures.
Mixing in flows between ocean basins
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Underwater cascades carrying huge volumes of water are common in the oceans. They occur where water overflows from sea and ocean basins into neighbouring basins over bottom ridges, or through channels and straits. When the overflow water is dense enough, it falls down the slopes to the bottom of the ocean as a turbulent current. The extent to which the cascading water mixes with its new surroundings influences the density stratification in the oceans, and we have previously argued that this mixing also influences the global rate of overturning of the oceans, hence the poleward heat transport.

Overflows, or hydraulically-controlled density-driven exchange flows, have been set up in the Geophysical Fluid Dynamics Laboratory at ANU. The amount of mixing was measured to see whether it depends on sill height, bottom slope, or density difference (figures 1-3). These experiments also serve as a case study of the fundamental nature of turbulent mixing more generally, and may help to improve climate models by allowing us to develop a better description of mixing in the oceans.
The global ocean overturning: what pushes must pull

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What governs the rate at which cold water from the ocean surface sinks at high latitudes, passes through the deep ocean, is reheated and returns to the surface? This is an important question because the overturning circulation redistributes heat and helps to regulate the Earth’s climate.

Oceanographers argue about the relative importance of heat fluxes through the sea surface (heating of the upper ocean at low latitudes and cooling it at high latitudes) and mixing within the ocean. Some ask whether the dominant factor is the “push” from the buoyancy of the dense sinking water at high latitude or the “pull” associated with the downward mixing of heat and buoyancy over much of the area of the oceans.

In a paper in the Journal of Physical Oceanography we have shown how surface buoyancy fluxes generate available potential energy (figure 1). The density of the ocean water can be altered only by irreversible mixing and surface buoyancy fluxes. Hence the energy transports associated with these two processes must balance (in a steady circulation). In other words, both the surface heat fluxes and sources of kinetic energy for turbulent mixing - commonly associated with winds and tides - are simultaneously necessary to maintain the observed ocean overturning circulation. The analysis of energy transformations shows that “pushing” and “pulling” cannot be separated, a point we have previously argued based on models of the forces and momentum balance of the circulation.

As a corollary, aspects of the ocean overturning circulation predicted by general circulation models are strongly influenced by the nature of the model computation. In particular, the circulation (figure 2) is influenced by whether vertical convective motion is parameterized, or whether these motions are fully resolved by using extremely high-resolution computations. Parameterisation of convection and an assumption of hydrostatic flow are commonplace in climate models, but do not correctly describe the energy changes.

These concepts are being further examined in laboratory experiments with overturning forced by salt and freshwater fluxes at the surface. In the experiments turbulent mixing is generated by horizontal bars, which are traversed up and down through the depth of the water, and the flow is allowed to reach an equilibrium state before the density stratification and circulation flow velocities are measured. The results, particularly the dependence on vertical diffusivity owing to mixing, will be compared with theoretical solutions and with the behaviour of ocean general circulation models.
Internal gravity waves and convection
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Coherent propagating waves have been discovered to be a ubiquitous feature in numerical simulations of convection that have been undertaken in RSES to investigate the dynamics of global ocean overturning circulation. These waves have been identified as internal gravity waves, and are normally absent in convective flows because the convection tends to keep the fluid well mixed. In contrast, when the ocean surface is heated at low latitudes and cooled at high latitudes, the associated buoyancy forces drive a circulation that maintains both gravitationally stable density stratification and overturning throughout the flow. This form of circulation is known as “horizontal convection”. Our simulations, supported by evidence from laboratory experiments, show that the sinking leg of the circulation, a turbulent plume, excites a spectrum of internal gravity wave modes, and that these are a source of strong variability throughout the domain (figure 1). Further work is required to assess the importance of this phenomenon in the ocean overturning circulation.

Figure 1. Hovmöller plot of the vertical velocity along a horizontal section towards the bottom of the box in a 2-D numerical simulation of horizontal convection. Time increases downwards; blue represents upwelling motion, green approximately no motion, and red downwelling motion. The region of high latitude sinking is located at the left hand end of the horizontal section, and excites strong wave modes that propagate towards the right hand end of the section (“low latitudes”). The waves appear to be responsible for much of the variability in this flow.
Wind forcing of the Southern Ocean
Do small scales alter wind power input?
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Circulation in the Southern Ocean is driven by strong winds which help to force the world’s strongest ocean current, the Antarctic Circumpolar Current (ACC). Recent satellite measurements have indicated small-scale structure to the wind stress field (see Fig. 1). In this study, we investigated the effect of small-scales in the forcing field upon the large-scale circulation.

We use a high-resolution ocean model of the Southern Ocean region, coupled to a dynamic atmospheric mixed layer to evaluate the performance of two different wind stress parameterisation schemes. The first is the standard quadratic drag law used by most climate models, while the second (more exact) formulation is based on the difference between ocean and atmosphere velocities. The two different schemes give very similar magnitudes of stress, but, somewhat curiously, the latter scheme contributes substantially less energy to the ocean circulation. The differences occur because small scale (10-50 km) turbulent eddies act to reduce energy input.

These results have significant implications for the Antarctic Circumpolar Current. In particular, despite the lower power input to the ocean, the relative velocity scheme has a stronger ACC, because there are less turbulent eddies to dissipate the flow.

Pre-print of Hutchinson et al. (2009; In Press)

Time: 152.02 yrs

Figure 1. An image showing the distribution of wind stress over the Southern Ocean. The large spatial scales show stress due to atmospheric motion (e.g. high and low pressure cells, storms) while the smaller scales show the effects due to oceanic eddies.
Thermal erosion of felsic ground by the laminar flow of a basaltic lava

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Thermal erosion of basaltic ground during the laminar flow of a basaltic lava has been observed on the Big Island of Hawaii, where flows about 1 m deep have been observed to erode 5-15 m into the underlying solidified basalt over several months to create deep lava tubes (Figure 1). These observations were first explained fluid dynamically by Kerr (2001).

In Kerr (2001), the lava was assumed to be identical to the ground it was flowing over. However, in many geological situations, the lava will have a composition that is different to that of the underlying ground. For example, in the Cave Basalt on Mt. St. Helens (Figure 2), the basaltic lava flowed over and eroded a dacitic pyroclastic flow, which led to contamination of the basaltic lava. This geophysically and geochemically interesting problem has been recently investigated by Kerr (2009). My analysis predicts that initially a chill layer is grown and then remelted at the base of the lava flow. A steady thermal erosion velocity is then established, which is limited by the buoyant instability of the melted ground or by the effective freezing temperature of the basaltic lava. When my analysis is applied to the longest lava tube system of the Cave Basalt on Mount St. Helens, it is found that about 100 days of flow is sufficient to produce the observed ground erosion.


Figure 1. A roofed lava tube in Hawaii Volcanoes National Park (photo courtesy of the USGS).

Figure 2. Ape Cave in Mount St. Helens National Volcanic Monument. It is one of the longest lava tubes in the continental United States, with a length of about 4 km.
Model dimension and data uncertainty in non linear inversion: An expanded Bayesian formulation.

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In an inverse problem, it is well known that the data fit is improved as more unknowns are added into the problem. If too many unknowns are introduced the data may become over fit and artifacts introduced into the model.

In contrast to optimization based approaches to inversion (e.g. a least square minimization), the transdimensional approach uses a sampling based (Bayesian) framework and is able to directly adjust the model dimension in order to fit the data to the degree required by the noise. In this case, the both the degree of freedom in the model and the level to which the data is fit is driven by the data itself rather than imposed subjectively. This property is illustrated when applying the reversible jump scheme to a simple 1D non-linear regression problem. Figure 1 shows solution curves obtained with the same data assuming different values of data noise, $\sigma_{\text{est}}$. The true value of the noise is $\sigma_{\text{est}}=10$. When assumed too small ($\sigma_{\text{est}}=4$) we see the classic feature of over fitting the data. The estimated curve green departs from the true curve (gray) as it tries to fit the data to the required accuracy. When it is too large ($\sigma_{\text{est}}=30$) the data are under fit and the model is too smooth. Only when it is correct ($\sigma_{\text{est}}=10$) is the recovered model close to the true solution. This shows the importance of knowing the noise in the data in a Bayesian framework. The trans-dimensional inversion approach is the same in all three cases and we see how it has only introduced the number of unknowns (cells) necessary to fit the data adequately. This is an advance over the alternative which is to impose the number of unknowns beforehand. In absence of information about data noise, it would be impossible to give a preference to any of the three solutions in Figure 1.

An expanded Bayesian formulation can take into account the lack of knowledge we have about data errors. Instead of being fixed, the variance of the measurement errors can become an unknown in the problem also and be determined by the data. This methodology is called "Hierarchical Bayes" and results are shown in Figure 2. Without knowledge about the data noise and the complexity of the true model, the algorithm is able to provide a solution model (top panel in Figure 2) with the correct complexity, and that fits the data to the required level. Furthermore, the expected posterior value for the data noise (bottom panel in Figure 2) is close to the true data noise.

Current applications of this approach are to seismic inversion of receiver functions for 1-D earth models and also to palaeoclimate time series data where little is known about data errors. The hierarchical Bayes formulation gives also promising results when used for seismic tomographic imaging.
Figure 2. Results with hierarchical Bayes. Here, the estimated data noise is not a number to be given by the user but a unknown parameter whose posterior probability distribution is to be determined by the Bayesian inversion. Top : solution model. Middle : Posterior probability distribution on the model complexity (the value of the true synthetic model is 9). Bottom : Posterior probability distribution for data noise (the true value of data error is 10)
TerraWulf II: Many hands make light work of data analysis

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In 2008, RSES launched TerraWulf II the latest in a long line of high powered computing facilities, stretching back more than 30 years. As the name suggests, this is the second of its particular species. The first, built in 2003, capitalised on a worldwide trend of combining off the shelf PC computers to form a highly cost effective (BeoWulf) supercomputer. The second, TerraWulf II (or TII as it is known to users) has 10 times the compute power of TI (~1.5 Teraflops) and occupies one quarter of the room space. Its construction was a joint venture between ANU (through RSES) and AuScope Ltd (The Earth Science infrastructure initiative funded through the Federal Government’s National Collaborative Research Infrastructure Strategy program). TII was designed primarily for use in earth imaging and geospatial applications however scientists are constantly finding new and innovative ways to exploit its power and convenience.

A key difference between modern computational clusters like TII and the 1980s machines at RSES is the focus on parallelism. The increase in processing power of each generation of micro-processors has begun to slow down, however computational gains can still be made by combining multiple processors together to perform complex calculations. Hence the rise of parallel based clusters like TI and TII. The initial uses of parallel computers (more than 10 years ago) were largely in areas involving highly advanced simulations of physical phenomena, e.g. weather prediction, ocean modelling, mantle convection and seismic wavefield simulation through complex media. As a consequence, parallel computing facilities gained a reputation for being highly exotic and only for the specialised user. In recent times, this situation has begun to change, as the power of parallel computing has become accessible to a broader range of scientists, even those without the interest in or need for advanced computational methods. A prime driver is the need to analyse data from large spatial arrays of instruments being used to build earth observing datasets, a task which is often particularly suited to parallelism. TII is increasingly being used for this type of 'loosely coupled' calculation.

An example is the geospatial scientist who has to perform the same processing tasks on many separate subsets of data independently (e.g. one analysis for each day of recorded observations). With a cluster of computers, each independent job is performed simultaneously in parallel meaning that the whole task can be achieved in a fraction of the time that it would normally take with single processor workstations. Another example is in the use of Monte Carlo based data inference (inversion) methods where many independent potential solutions to a problem need to be tested against the data, e.g. seismic models of the Earth interior fitting observed travel times or waveforms. TII has been used for both types of calculation, as well as the more traditional simulation of geophysical phenomena using advanced computational techniques. In its short life it has already racked up over seven hundred thousand cpu-core hours of use across applications ranging from earth imaging, geospatial analysis as well as simulation of geophysical processes from the Earth’s surface to its core. In addition it has been used as a test bed to develop a new generation of data inference tools.

These examples show how cluster-computing facilities like TerraWulf II are becoming an invaluable tool to the geophysicist. Clusters have been proliferating in research institutions, business and industry in recent years and as more applications evolve we can expect demand for such facilities to increase in the future.

http://rses.anu.edu.au/terrawulf/
Figure 1. A Monte Carlo style inversion performed on TII for seismic structure in Australia using ambient noise. (a) Ray path density for 1158 rays in ambient noise dataset of Saygin and Kennett (2009). (b) Shear wave speed model produced by averaging 8000 models generated by the Bayesian Monte Carlo procedure on Terrawulf II, (c) best fit model obtained, (d) number of cells in the model as a function of iteration. Red and blue lines represent results from two of the 200 independent random walks through the model space.
Figure 2. GPS data re-processing of eight years of data performed on TII. On a single CPU it is estimated that this analysis would taken approximately 23 years to complete. (a) Map of GPS site locations used in the analysis. The time series of the height estimate of the site at Alice Springs, NT, (b) from the original analysis (upper right) and (c) the refined analysis (lower right). The weighted root-mean-square of the daily height estimates has been reduced from 5.2 to 3.7 mm.