Idealised numerical model of the Southern Ocean overturning, at 1/16th degree resolution.
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 2010 Prof. B. Kennett was awarded the 2011 Flinders Medal, the highest award in the Physical Sciences, from the Australian Academy of Science. Prof. M. Sambridge was elected a Fellow of the American Geophysical Union. Prof. Griffiths was elected an inaugural Fellow of the Australasian Fluid Mechanics Society and also delivered a plenary lecture to the American Physical Society. Prof. P. Cummins was awarded the Stillwell Award by the Geological Society of Australia. Dr. G. Davies was honoured upon his retirement with a special session at the Fall meeting of the American Geophysical Union. Dr. H. Tkalcic was awarded a JSPS Fellowship from the Japanese Government. Dr. G. Hughes was awarded a Future Fellowship for research in ocean dynamics and solar energy systems. During the year it was announced that Earth Physics will host the ANU node of the new ARC Centre of Excellence in Climate System Science, with Drs M. Roderick and A. Hogg as Chief investigators and Profs. R. Griffiths and G. Farqhuar (Research School of Biology) as Associate Investigators.

RSES Earth Physics 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 with absolute and relative gravity measurements being made at several sites across Australia, and the investigations of crustal deformation continued through the analysis of GPS observations and space gravity analysis. The Terrawulf II cluster computer at RSES 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. This year saw the awarding of a second phase of AuScope activities through the Federal Governments Education Infrastructure Fund (2011-2014).

Seismology fieldwork in 2010 was undertaken primarily in New South Wales and Queensland. The WOMBAT transportable array experiment in southeast Australia, which began in 1998, now comprises 12 separate subarrays of between 20 and 70 instruments each deployed for periods of between 6-12 months. In 2010, the 53 station EAL2 array was deployed in central NSW, bringing the total number of WOMBAT station locations to over 550, making it one of the largest experiments of its type in the world. These passive arrays mainly detect signal from large distant earthquakes that take place in regions such as Indonesia, Fiji, New Zealand. This information can be used to image the structure of the crust and upper mantle using a variety of methods including seismic tomography, receiver functions and shear wave splitting. The background noise (or Earth's hum) can also be used to image the crust in high detail. Recent results from Tasmania show that the transition between the Eastern and Western Terranes is marked by a very distinct region of low Rayleigh wave group and phase velocity, which appears to correlate with elevated crustal heat flow and conductivity. On the mainland, teleseismic tomography results show evidence of the signatures of Palaeozoic orogenic events, as well as more recent tectonic activity associated with the break-up of Gondwana and the opening of the Tasman Sea.

In the Mt. Isa region of Queensland, two 25 instrument short period arrays have been sequentially deployed as part of AuScope Earth Imaging. These arrays are designed to complement recent seismic reflection transect work undertaken in northern Queensland, and will help unravel the complex tectonic history of the Mt. Isa Inlier and surrounding regions.

Data recorded by a temporary seismograph deployment was used to infer constraints on the state of crustal stress in the Flinders Ranges, one of the most intense concentrations of intraplate seismicity in the world. Earthquake first motion measurements show that the direction of principal stress is consistent with the E-W shortening inferred from geological observations of fault movement.
Research into tsunami generation by megathrust earthquakes has highlighted the potential threat to Tonga's capital, Nuku'alofa, which lies on a low-lying peninsula facing the Tonga Trench and is home to 35,000 people, (~1/3 of Tonga's population). It was shown that the challenge of modeling tsunami propagation over the shallow reef platform offshore Nuku'alofa can be met using high-precision bathymetry models derived from multispectral remote sensing data. In contrast to previous results, tsunami simulation using the new high-precision model shows that earthquakes commensurate with historical events along the Tonga Trench pose a serious threat to Nuku'alofa's population.

In the area of deep earth studies a new model of inner core consisting of a conglomerate of anisotropic domains has been proposed to reconcile travel time and normal modes data. Work has continued on an automated real time regional seismic moment tensor inversion using full 3D structural models of the Australasian region. A collaboration with the ANU’s Research School of Information Sciences and Engineering has led to new java software IRFFM2 for interactive simultaneous modelling of receiver functions and surface wave dispersion. In the area of data processing and archiving, the new Seismic Data Centre (SDC), which facilitates user-friendly access to all current and past seismic data collected by RSES via a Java-based GUI and Seismomap Tool has now reached the final stage of development. About three-quarter of all digital data from past experiments has now been converted into continuous miniseed format accompanied by metadata files.

In Geophysical Fluid Dynamics research has continued to tackle the dynamics of the Southern Ocean and of the global overturning circulation of the oceans. The forces balances and energy budget of the Antarctic Circumpolar Current have been examined using high resolution eddy-resolving computations. These studies have indicated that surface buoyancy forcing (heating/cooling at the ocean surface) play a greater role on the ACC than previously thought. Further experimental investigations of overturning circulation driven by surface buoyancy forcing have been carried out. Also completed are studies of the role of topographic sills between ocean basins and marginal seas in determining the density of abyssal ocean waters, and of the behaviour of circulation forced by a ‘see-saw’ oscillation of surface heat fluxes between hemispheres, and continuing a study of the adjustment of overturning circulation to changes in surface buoyancy forcing. An experimental investigation of the combined roles of mechanical mixing (due to energy from sources such as tides, winds or biological activity) and surface buoyancy forcing was commenced.

In Mathematical Geophysics research has been directed to the study of nonlinear inverse problems and development of new ensemble based approaches for seismic imaging. In lithosphere dynamics attention has focused on the dynamics of the Indian plate over the past 10 Myrs. Recent reconstructions of the ocean-floor spreading allow identifying a peculiar counter-clockwise rotation of the Indian plate, resulting from accelerated convergence across the eastern India/Eurasia margin as opposed to the western end. Global models of mantle/lithosphere dynamics have been employed to link this plate motion change to the dynamic evolution of the Himalayan topography.

Numerical models of mantle/lithosphere dynamics have been employed to explore the possibility that global plate tectonics carries a signature of the amount of heat transferred at the core-mantle boundary (CMB). Efforts have also been undertaken to explore the effect of lateral variations of mechanical coupling along the Andean convergent margin on the evolution of the trench morphology.

Geodynamics research has focused on using temporal gravity changes from the GRACE mission, with progress made in the development of in-house software to account for gravitational variations independent of the hydrological cycle and glacial isostatic adjustment. These effects include ocean and atmospheric tides, planetary gravitational effects, satellite attitude control and manoeuvres and atmospheric pressure effects. In a study of comparisons between GRACE-derived hydrological changes and soil moisture models across the Great Artesian Basin they showed both strong agreement suggesting that the models are accurate and that the dominant geophysical process sensed by GRACE is related to soil moisture variations.

The ongoing investigations into errors in GPS analysis have shown that some of the periodic variations remaining in GPS time series are related to the mismodelling of the solar radiation pressure forces acting on satellites. Work is continuing in collaboration with colleagues at MIT to improve the existing models and reduce the spurious signals.
A new study in conjunction with Ecole Normale Superieure Cachan (Paris) derived a relation between Love loading number ratios and a spherical harmonic field that can be used to approximate the present-day response of the Earth to melting events that occurred over 10,000 years ago. This relation is independent of both the rheological model for the Earth and the ice history model used. The gravity gPhones purchased in 2009 were deployed at Tennant Creek, Jabiru and Katherine and have operated normally for the required 6 month period.
The Moho is a seismological boundary that represents the base of the Earth’s crust. We present a new Moho map of Australia estimated from the compilation of seismic receiver functions, tomography, seismic reflection and refraction profiles. This map represents the current status of the AusMoho project, which ultimately aims to image the Australia continental crust with a 50 km resolution.

The current Moho map includes over 5000 km of deep seismic reflection profiles and 400 data points from permanent seismic stations, 3-component broadband and short period stations deployed over the last 15 years and large-scale refraction profiles conducted in the last 35 years. Seismic data coverage of the Australian continent has greatly increased over the last 10 years, doubling the number of data points that were available for previous maps.

The new Moho map provides information about the present day large scale crustal structures that define the geological provinces of Australia and will supply much needed constraints for use in tomographic imaging of the Earth below. The most striking feature of the new Moho depth map is the short wavelength transition from the thickest Proterozoic crust (>50 km) in central Australia to the thin crust (~30 km) of Phanerozoic eastern Australia.

Figure 1. Moho depth data points from reflection and refraction data and receiver functions. The depths are averaged over 50 x 50 km blocks and a surface is fitted through. Where there is no data within a 250 km radius the surface has not been plotted. Data points are colour coded using the same depth scale as the plotted surface to highlight any differences. The regions of thickest crust are found in the North Australia and Central Australia. The Moho extends to a depth of > 55 km depth where the Central Australia is sandwiched between the North and South Australia. This is a region of Mesoproterozoic suturing and is characterized by crustal scale thrust faulting (Korsch et al 1998). A region of thicker Phanerozoic crust, in southeastern Australia coincides with the Lachlan Fold Belt.
Benford’s law of first digits: a universal phenomenon

Malcolm Sambridge¹, Hrvoje Tkalcic¹ and Andrew Jackson²

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Institut fur Geophysik, ETH Zurich, CH-8092 Zurich, Switzerland

More than 100 years ago it was predicted that the distribution of first digits of real world observations would not be uniform, but instead follow a trend where measurements with lower first digit (1,2,...) occur more frequently than those with higher first digits (...8,9). This idea was first described by an astronomer, Simon Newcomb in 1881. Newcomb noticed that the pages of logarithm tables were more thumbed for low digits than higher ones. He argued that this was because scientists had more need to look up logs of real numbers with smaller first digit than larger. He produced a mathematical formula predicting the distribution of first digits. The result has long been regarded as a mere mathematical curiosity and largely ignored across the sciences. It was rediscovered in 1938 by an engineer called Benford. Despite a waning of interest the latter name is now associated with the first digit law.

Our new study shows that Benford’s first digit rule is a natural phenomenon which is likely to hold universally. We test 15 sets of modern observations drawn from the fields of Physics, Astronomy, Geophysics, Chemistry, Engineering and Mathematics, and show that Benford’s law holds for them all. The data sets used in our study consist of more than 750,000 values which vary over 19 orders of magnitude and differ in origin, type and physical dimension. These include the rotation frequencies of pulsars; green-house gas emissions, the masses of exoplanets; as well as numbers of infectious diseases reported to the World Health Organization.

Figure 1 shows predictions of the occurrence frequency of first digits according to Benford’s Law together with digit distributions of three of our data sets. A particular focus of our study has been Earth Science observations and here we have shown that the first digit rule applies to the strength as well as timing of reversals of the Earth’s geomagnetic field, seismic tomographic models of the Earth’s elastic properties and the depth distribution of Earthquakes.

Our results suggest that Benford’s Law is a universal feature for data sets with sufficient dynamic range raising the question of how it might be exploited. Use in a forensic mode, e.g. to detect fraud or rounding errors, is possible by simply looking for departures in the frequencies of individual digits. There have been previous applications of this type to detect fraud in financial data. A more intriguing question is whether it can be used to detect signals in contrast to background noise, e.g. in time series data such as seismic signals.

Figure 2 shows an example of how seismic energy from an earthquake follows Benford’s law which means that earthquakes can be automatically detected from just the first digit distribution of displacement counts on a seismometer. Our study led to the first ever detection of an anomalous seismic disturbance (assumed to be a small local Canberra earthquake) using first digit information alone.

We have also managed to extend the mathematical description of Benford’s law to account for situations where the range of observables is arbitrary. As awareness of this novel phenomenon grows across the natural sciences we expect new applications will appear, one possibility is in checking the realism of computer simulations of complex physical processes, such as in the climate or oceans. If the natural processes are known to possess the first digit property then any computer simulation of that phenomenon should do also. Another is in the detection of rounding errors or other anomalous signals in data. We hope this work will encourage others to look at their digits more closely.
Figure 2. Lower panel. Seismogram of the Sumatra-Andaman earthquake recorded at seismic station NNA in Peru. The onset of seismic waves is marked at time $t_2$. Shading shows the 200-second sliding time-window in position $t_1$ to $t_2$. The earthquake signal enters the moving time-window at $t_1$. Central panel. Goodness of fit to Benford's law (as defined in the text) as a function of time. Upper panel. Dynamic range as a function of time. b) Distribution of first digits for the 20-minute period before time $t_2$ (left panel) and after time $t_2$ (right panel) versus those predicted by Benford's law (blue diamonds).
Earthquake location and source determination using coda waves

David John Robinson\textsuperscript{1,2}, Malcolm Sambridge\textsuperscript{1} and Roel Snieder\textsuperscript{3}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Risk Research Group, Geospatial and Earth Monitoring Division, Geoscience Australia, GPO Box 378, Canberra ACT 2601
\textsuperscript{3} Department of Geophysics and Center for Wave Phenomena, Colorado School of Mines, Golden CO 80401-1887, USA

The majority of existing seismological techniques ignore high frequency coda that result from scattering and focus on early onset body waves to model earthquake location and source properties. A recent technique known as coda wave interferometry utilises the cross correlation of coda waves to constrain changes in source properties between earthquake pairs.

Our work focuses on extending coda wave interferometry by designing mathematical frameworks and practical algorithms which enable the use of coda in studying the properties of earthquake clusters. We have demonstrated how to construct a probability density function (PDF) for the location of a cluster of earthquakes using either coda waves by themselves, or in combination with early onset body waves. This joint PDF is studied using direct search, ensemble inference and optimisation under a range of conditions for earthquakes in Western Australia and California. Combining coda and travel times leads to the best solution in most cases.

We have shown however, that coda waves significantly enhance location constraints when the uncertainty associated with travel times exceeds half the event separation. Furthermore, coda waves are demonstrated to provide valuable information in poor recording situations with few stations and can be used with as little as one station. In contrast, travel time techniques require multiple stations and good azimuthal coverage. This feature of coda waves to succeed with limited data is its greatest strength, lending itself to use in intraplate regions where station density is sparse.
Figure 2. Sequence of images illustrating the similarity of locations obtained for a cluster of earthquakes (black) using coda wave interferometry with a reducing number of stations. Open circles illustrate scattered nature of locations for neighbouring events when absolute travel times are used.
Crustal Stress in the Flinders Ranges, South Australia

Stress inversion using earthquake first motion data

Phil R. Cummins\textsuperscript{1,2}, Natalie Balfour\textsuperscript{3} and David Love\textsuperscript{4}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Geoscience Australia, Canberra, ACT 2607, Australia
\textsuperscript{3} School of Earth and Ocean Sciences, University of Victoria, Victoria, BC V8W 3V6, Canada
\textsuperscript{4} Primary industries and Resources South Australia, Adelaide, SA 5001, Australia

Compared with other stable continental regions, Australia has a relatively complex crustal stress field which is thought to result from orogenic forces acting at the boundaries of the Australian and Indian Plates. At the same time, with very few well-recorded large earthquakes, Australia's stress field is poorly constrained. The Flinders Ranges in south-central Australia is one of the few places in Australia where there is clear and abundant evidence of neotectonic deformation, and it is one of the most intense concentrations of intraplate seismicity in the world. This makes it an ideal location to study active intraplate deformation.

We used data recorded by a temporary seismograph deployment conducted in 2003-2005, to infer constraints on the state of crustal stress in the Flinders Ranges. Earthquake first-motion measurements were inverted for constraints on the direction of principal stress and the stress regime. These data also allowed us to estimate 65 focal mechanisms that are consistent with our preferred solution for the stress, which corresponds to an oblique thrust regime with $S_{\text{Hmax}}$ oriented roughly east-west. This contrasts with the pure thrust and pure strike slip regimes suggested by earlier studies. We found that, although the data from shallow earthquake’s reflect velocity and/or stress heterogeneity, our new estimate of stress is more consistent with the E-W shortening inferred from geological observations of fault movement than previous estimates. This study also demonstrates the effectiveness of temporary, concentrated seismograph deployments in constraining the stress field in intraplate environments.
Figure 2. The Flinders Ranges study area in South Australia (see box in Fig. 1), with (left) indicating the location of temporary seismographic stations whose data were used in this study, along with topography and the surface expression of faults thought to have been active since the Quaternary. (center) indicates focal mechanisms for the 65 earthquakes used in the stress inversion of this study, which best match the data subject to the constraint that they are consistent with our preferred solution to the stress orientation shown in Fig. 3. (Grey circles indicate epicenters for the approximately 500 earthquakes recorded during 2003-2005). (right) shows historical focal mechanisms and first motion data plotted at the earthquake epicenter, while to its left/below is plotted the best-fitting focal mechanism that takes into account potential errors in the first motion data, and to the right/above is plotted the best-fitting mechanism that is consistent with our preferred solution to the stress orientation.
The Threat from Tsunamis Generated on the Tonga Trench

Use of Satellite-derived Bathymetry for Inundation Modeling

Phil Cummins1,3, Herve Damlamian2 and Stephen Sagar3

1 Research School of Earth Sciences, Australian National University, Canberra ACT 0200, Australia
2 Pacific Applied Geosciences Commission (SOPAC), Sopac Secretariat, Suva, Fiji Islands
3 Geoscience Australia, Canberra, ACT 2601, Australia

In this study we have investigated the use of nearshore bathymetry models estimated using multispectral remote sensing data for tsunami inundation modeling. The technique used here was a per-pixel, physics-based approach (SAMBUCA) used with Quickbird imagery. Tsunami inundation results using this approach were compared with a previous model obtained via an empirical approach with Landsat data. The main difference in these methods is that the SAMBUCA/Quickbird approach produces models with much finer (2.4 m) horizontal resolution, whereas the empirical/Landsat approach has a 30 m horizontal resolution. In addition, the SAMBUCA/Quickbird approach appears to applicable to greater water depths than the empirical/Landsat one (about 20 m vs. 5 m, respectively).

We compared numerical models of tsunami inundation in Tonga’s capital, Nuku’alofa, using the two different bathymetry models. The scenario used was a tsunami generated from a hypothetical magnitude 8.25 earthquake commensurate with historical activity elsewhere along the Tonga Trench. Such an earthquake has yet to occur so near to Tongatapu, so in terms of earthquake location this is a worst case scenario. There was a stark contrast between the results: the modeling using the coarse, empirical/Landsat shallow bathymetry predicted inundation only of a narrow coastal strip along Nuku’alofa’s shoreline, while the modeling using the fine, SAMBUCA/Quickbird shallow bathymetry predicted that most of Nuku’alofa would be inundated.

These results show that data of 30 m horizontal resolution is insufficient for modeling tsunami shoaling on coral reef platforms such as those surrounding many Pacific islands. It seems more likely to us that data having resolution closer to that obtained using the SAMBUCA/QuickBird approach (i.e., 2.4 m) is required, but further studies are needed to establish the required resolution with precision. The results also tentatively suggest that the SAMBUCA/QuickBird approach provides data of sufficient accuracy that can be used where better data (such as LiDAR) are not available, but this is likely to be true only in shallow water of exceptional clarity. Fortunately, this situation exists offshore many Pacific island communities.

Although the inundation modeling results presented here for a plausible maximum earthquake size on the Tonga Trench suggests that such an event presents a substantial threat to Nuku’alofa, these results should be interpreted with caution, since only poor topography data were available for the study. In particular, these results are not of sufficient accuracy to form the basis of an evacuation plan. However, since Nuku’alofa is home to 35,000 people, roughly 1/3 of Tonga’s population, it would make sense to consider better inundation modelling that can support evacuation planning. We are in the process of collecting better topography data so that this modeling can be repeated, in order to better assess the threat and help disaster managers develop an evacuation plan.
Figure 2. Tsunami inundation modelling results for a magnitude 8.25 scenario earthquake on the Tonga Trench, compared using two different bathymetry models: (left) a previous model obtained using an empirical method with 30 m Landsat data, and; (right) a new model obtained using a physics-based approach (SAMBUCA) with 2.4 m QuickBird data.
Imaging Turkey’s Crust

Hunting for the Moho

E. Vanacore¹, E. Saygin¹, T. Taymaz² and Y. Cubuk²

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Department of Geophysical Engineering, Istanbul Technical University, Istanbul, Turkey

Earthquake signals at detected teleseismic distances, approximately 300 to 900 kilometers away from the physical recorder, provide a valuable resource to image the Mohorovicic discontinuity (the Moho), which denotes the boundary between the Earth’s crust and mantle. The Moho is characterized by a large jump in seismic velocity that causes teleseismic P-waves to generate P to S converted waves; the time difference between these seismic phases is indicative of the thickness of the crust. To highlight this conversion and its associated reverberations, we use receiver functions in our analysis.

Turkey is currently instrumented with over 250 3-component broadband stations from both temporary and permanent deployments (Figure 1). To date, we have conducted a preliminary analysis of event data between 2008 and 2009. The calculated receiver functions are analyzed with both H-k and depth stacking techniques. The former allows the Vp/Vs ratio to vary whereas the latter employs a set 1-D velocity model to determine the depth of the Moho (Figure 2). The weighted results of both these methods have been used to generate a preliminary Moho map of Turkey (Figure 3). The calculated Moho depths are to the first order consistent with the tectonic structure of Turkey. The thin lithosphere in the southwest is associated with regional extension, and a “sharp” transition near 37°E between deeper 40+ km Moho depths to shallower Moho depths may delineate the Arabian block. Mapping Turkey’s Moho is and will continue to be a useful tool in understanding the ongoing geological processes of the region as more data is analyzed and more details of the complex Moho structure become apparent within the study region.
Figure 2. Example of results of the receiver function analysis for the station ALT (39.06°N, 30.12°E) located in western Turkey. (a) Distribution map of the 44 teleseismic events used in the receiver function analysis. (b) The average receiver function generated by the radial and vertical components for station ALT linearly stacked in the time domain with a 95% confidence interval. The converted and reverberated phases are labeled. (c) The H-κ stacking results for the receiver functions; hot colors denote the likely Moho depth and Vp/Vs ratio combination. The white lines denote the automatic pick of Moho depth and a Vp/Vs ratio. (d) The stacked receiver function after time to depth conversion based on the IASP91 model. The square dot indicates the observed Moho depth.
Figure 3. Preliminary Moho depth map of Turkey for the current receiver function data set; warmer colors indicate shallower Moho depths. The used stations are indicated by the triangles and the black lines delineate the major faults.
The Ambient Noise Tomography of Turkey

Erdinc Saygin¹, Brian L.N. Kennett¹, Tuncay Taymaz² and Elizabeth Vanacore¹

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Department of Geophysical Engineering, Istanbul Technical University, Istanbul, Turkey

The ambient seismic noise correlations is an important tool to understand Earth’s internal structure. In this study, we use 5 months of continuous data from the 2 major seismic broadband networks of Turkey (TU, KO) for extracting the interstation Green’s functions from the ambient seismic noise (figure 1). The vertical and horizontal components of the stations are used to extract the Rayleigh and Love wave type Green’s functions. The other available data from temporary deployments are also included to improve the ray path coverage. The group velocity dispersion of the Green's functions is estimated by applying narrow band filters consecutively over a period range of 1 s to 40 s. The measurements are then inverted with nonlinear tomographic inversion schema to create the Rayleigh and Love maps for different periods. The images presented in figure 2 show the complex geological structure of the region, and matches with some of features shown in figure 1b.

In the centre, the Kirsehir Block is marked with increased velocities. Western Turkey has low velocities for the shallow depths with possibly linked to the elevated heat gradient in the region. The transition from Anatolian block to Arabian plate is marked with high velocities (Rayleigh 3-20 s).
Figure 2. Ambient seismic noise tomography images for Rayleigh and Love waves.
Crustal Structure of Australia from Ambient Seismic Noise Tomography

Erdinc Saygin and Brian L.N. Kennett

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The cross-correlation of the ambient seismic noise field recorded at two different seismic stations gives a surface wave type Green's function between the two. The surface wave type Green's function has dispersive characteristics which carries information from different depths of the Earth over a range of periods.

In this study, we use all of the available broadband data from temporary and permanent stations in Australia to extract the Green's functions from the ambient seismic noise field. Then we create a number of tomographic maps from the inversion of the group velocity dispersion of Rayleigh and Love waves (figure 1). As a final step, we merge the results by inverting each point for estimating the 1-D shear wave velocity structure with a nonlinear direct search algorithm.

The tomographic images in figure 1 show complex patterns of seismic velocities for the shallower depths (3-10 s) for both classes of the wave tomography. The thick sedimentary basins of the regions i.e. Canning, Eromanga are well imaged with lowered velocities. The Archaean Cratons in Western Australia show consistently high velocities in compared to other parts of the continent. The rapid change in group velocities from Canning Basin to the Kimberley region corresponds to the terrane change.

In figure 2, the inverted shear wave velocity model from dispersion curves are given for the seismic station TL07 located in central Australia.

Figure 1. Combined images of Rayleigh and Love waves from ambient seismic noise tomography.

Figure 2. Shear wave velocity structure of station TL07 obtained from the inversion of ambient seismic noise tomography.
Is the Earth's Inner Core a Conglomerate of Anisotropic Domains?

Hrvoje Tkalčić

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Cylindrical anisotropy in Earth’s inner core has been invoked to account for travel times of PKP core-sensitive seismic waves, such as from the South Sandwich Islands (SSI) earthquakes observed in Alaska (Figure 1), which depart from predictions. Newly collected travel-time residuals from seismic waves from the SSI region that sample only Earth's mantle (PcP and P waves; see inset of Figure 1) have a comparable range to the PKP differential travel-time residuals, yet they are insensitive to core structure. This observation suggests that mantle structure affects PKP travel time residuals more than previously acknowledged and challenges the existing conceptual framework of a uniform inner core anisotropy. The inner core could be a conglomerate of anisotropic domains (Figure 2), and the PKP travel times are most likely influenced by the geometry of inner core sampling and inhomogeneous mantle structure. Spatial and temporal variations of the geomagnetic field and the lowermost mantle heterogeneity via the outer core can contribute to the complex structure of the inner core. Columnar convection and convective heat flux in the outer core result in heat transfer variations, which influences the inner core growth and crystal alignment. Thus, only for certain geometries of sampling, the accumulated travel time anomaly will be strong enough to be detected at the surface. Contrary, if elastic anisotropy in the inner core is weak or cancels out in the domains sampled by body waves, then some very anomalous travel times with respect to spherically symmetric models of Earth for those ray paths are likely to be a result of inhomogeneous or anisotropic structure outside the inner core, such is probably the case for the SSI earthquakes. The inner core as a conglomerate of anisotropic domains reconciles observed complexities in travel times while preserving a net inner core anisotropy that is required by observations of Earth’s free oscillations (Figure 2).

Link to the online article:
http://www.agu.org/journals/gl/gl1014/2010GL043841/

Figure 1. Map of locations of the SSI earthquakes used in this and in the previous study of PKP travel times (stars). Reflection points of PcP waves at the core-mantle boundary are projected to the surface (ellipses) in different colors corresponding to the observed PcP-P differential travel-time residuals. Piercing points of PKPdf and PKPbc waves in the IC are projected to the surface (small and large diamonds) with the corresponding PKPdf-PKPbc differential travel-time residuals using the same color scheme. Travel-time residuals are relative to the model ak135 by Kennett et al. [1995]. PKP and PcP ray-paths projected to the surface are shown in white and black lines. GSN stations PLCA and TRQA are highlighted. Yellow lines indicate a corridor in which some of the largest departures from theoretical predictions in PKPdf-PKPbc and PcP-P travel times are observed. A schematic representation of Earth’s cross-section and ray-paths of seismic phases PKP, PcP and P waves used in the study is shown in the inset.

Figure 2. A schematic representation of three distinct anisotropic domains in the IC where the strength and orientation of fast crystallographic axes are shown as straight lines. Two different PKPdf ray paths are shown sampling different domains. A represents a semi-constant...
anisotropy domain with a predominant alignment of fast anisotropic axes; B is a transitional domain with a mixed orientation of fast anisotropic axes, and C is an isotropic or a weakly anisotropic domain. The arrow in the middle represents the net direction of the fast axis of anisotropy.
Monsoon speeds up Indian plate motion

Giampiero Iaffaldano¹, Laurent Husson² and Hans-Peter Bunge³

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Geoscience Rennes, University of Rennes, France
³ Geophysics Section, LMU Munich, Germany

Short-term plate motion variations, occurring over few Myrs, represent a powerful probe into the nature of forces acting along lithospheric plate boundaries, as mantle-related buoyancies evolve on longer time-scales. New reconstructions of the ocean-floor spreading record reveal an increasing number of such variations, but the dynamic mechanisms producing them are still unclear. In this study we show quantitatively that climate changes may impact the short-term evolution of plate motions. Specifically, we link the observed counter-clockwise rotation of the Indian plate since ~10 Ma to increased erosion and reduced elevation along the eastern Himalayas, due to temporal variations in monsoon intensity. By assimilating observations into empirical relations for the competing contributions of erosion and mountain building, we estimate the first-order decrease in elevation along the eastern Himalayas since initial strengthening of the monsoon (Figure 1). Furthermore, we show with global geodynamic models of the coupled mantle/lithosphere system that the inferred reduction in elevation is consistent with the Indian plate motion record over the same period of time (Figure 2), and that lowered gravitational potential energy in the eastern Himalayas following stronger erosion is a key factor to foster plate convergence in this region. Our study implicates lateral variations in plate coupling and their temporal changes as an efficient source to induce an uncommon form of plate motion where the Euler pole falls within its associated plate.

Figure 1. Present-day and past Himalayan elevation as observed and predicted from 2D analytic models. We model relief as the algebraic sum of time- and space-dependent contributions from mountain building and erosion rates, integrated since time of continental collision ~50 Ma. Grey thin line is the observed elevation at the present-day. Thick grey line is the observed elevation after short wavelengths have been filtered out to preserve wavelengths longer that 1000 km. Solid black is the prediction of our model at the present-day. We compare it against the observed elevation, filtered for wavelength shorter than 1000 km (thick grey). Based on the good agreement, we trust our model in its prediction of elevation at 13 Ma (dashed black), when the monsoon had reached its first peak. We infer that prior to monsoon intensification, elevation in eastern Himalayas was significantly different from the one at present-day, featuring an average relief as high as 4 km. At the same time, central and western Himalayas are predicted to be very similar to the present-day.
Figure 2. Indian plate-motion change following erosion of eastern Himalayas due to intensified monsoon. Impact of erosion in eastern Himalayas on Indian plate motion is estimated as the difference between the velocity fields computed before and after simulated intensification of the monsoon. We predict a velocity change induced on India as high as 8 mm/yr (black arrows), directed normal to the eastern IN/EU margin. An almost equal increase is predicted for the trench-parallel component along the western margin. Numerical result
compares well with our reconstruction of India/Eurasia kinematics (see Fig. 3-5). Importantly, predicted change of Indian plate motion is well described by an Euler pole located within Indian plate itself (black dot). Oceans are in white, continents in grey. Plate boundaries are in black, plate names as in Fig. 8.
Transdimensional Inversion of Receiver Functions with the Hierarchical Bayes Algorithm

Thomas Bodin, Malcolm Sambridge and Hrvoje Tkalcic
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Receiver functions (Fig 1) are time series that are sensitive to the structure underneath a seismic station. These waveforms can be inverted for a 1D Shear wave velocity model of the crust and uppermost mantle beneath the receiver. In this type of inversion, the number of layers defining the velocity model, the level of smoothing and the required level of data fit are usually arbitrarily determined by the user prior to the inversion. These quantities are often manually "tuned" by means of subjective trial-and-error procedures, and this represents a recurring problem.

We address these issues by proposing a novel and alternative inversion strategy. Different methodologies recently developed in the area of Bayesian statistics (i.e. transdimensional Markov chains, hierarchical models) are combined to produce an inversion algorithm, which treats the tunable quantities as unknowns to be constrained directly by the data. In this way the number of layers as well as the presumed magnitude and correlation of data noise are variable and treated as unknowns in the problem.

In such a transdimensional approach, the level of data uncertainty directly determines the model complexity needed to satisfy the data. The level of data noise effectively quantifies the usable information present in the data (a very noisy dataset does not contain much retrievable information), and thus it naturally controls the quantity of information that consequently should be present in the model (i.e. the number of model parameters). Here, an Hierarchical Bayes formulation of the problem enables us to estimate the level of data noise while at the same time controlling model complexity in an automated fashion.

The method developed is an ensemble inference approach, where many potential solutions are generated with variable numbers of layers (Fig 2a). This large ensemble of models is distributed according to a probability density function that represents the full state of knowledge we have about seismic structure. At each depth, local information about the velocity model is represented by a complete probability distribution (density map in Fig 2b). It is tantamount to picking a depth and asking the ensemble solution what velocity constraint is given by the data. This density plot is used as a way to visualise the ensemble solution, and it is particularly useful to picture the constraint we have on the Shear wave velocity model. Then, the probability of Shear wave velocity at each depth can be used to construct a solution 1D model. In Figure 2a is plotted the “mean model” (red line) which follows the mean of the distribution with depth.

If one is interested in assessing the number and position of seismic discontinuities beneath the seismic station, it is possible to examine the ensemble solution from a different point of view and to plot the probability distribution on the location of interfaces. Figure 2c shows an histogram of interfaces depth in the ensemble of models. For each depth, this function represents the probability of having a discontinuity, given the data. This provides useful information on the location of transitions, which can be unclear in other plots.
Figure 1. A noisy receiver function. Here, there is no information available about the data uncertainty, and hence it is difficult to separate the signal from the noise.

Figure 2. Results given by the transdimensional inversion. A) The models in black have variable number of layers and they represent the complete solution of the inverse problem. The model in Red is the average over the ensemble of models. B) Density plot showing the probability density for the Shear wave velocity at each depth. C) Probability distribution for the position of transitions.
Seismic multi-pathing in complex media

Nick Rawlinson and Malcolm Sambridge

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

As seismic waves propagate through the Earth, they focus and defocus in response to variations in the physical and material properties of rocks. Even in relatively simple media, wavefronts can distort to such an extent that they eventually self-intersect, which results in more than one energy packet arriving at a receiver. This phenomenon is commonly referred to as multi-pathing, and is distinct from the arrival of multiple phases due to reflections and refractions in stratified media, and scattering. In order to numerically simulate the propagation of seismic waves in the presence of realistic Earth structure, one can solve the full elastic wave equation, but this is extremely time consuming, even on modern computers. A much simpler, but in many cases extremely effective, approach is to invoke the so-called "high frequency" assumption, where it is assumed that the wavelength of the seismic wave is much smaller than the dominant scale-length of the underlying heterogeneity. Under this assumption, principles from geometric optics can be used to track evolving wavefronts via their characteristics, commonly referred to as rays. These rays represent the propagation path of energy between a source and receiver, and in many cases can be computed very rapidly (e.g. by repeated application of Snell's Law). An alternative approach is to directly solve the so-called eikonal equation, which describes the evolution of wavefronts. These eikonal solvers are very efficient and robust, and can rapidly compute the traveltime field (traveltimes from some source to a grid of points that spans the medium) of very complex media. Both wavefronts and raypaths can be readily extracted from the traveltime field. However, one limitation of eikonal solvers is that they only find the first arrival, and provide no information on multi-pathing.

We develop a novel approach for locating multi-paths in complex media which harnesses the speed and efficiency of eikonal solvers. In its simplest form, our method involves computing traveltime fields for the both the source (forward field) and receiver (reciprocal field). By summing the two fields together, it is possible to identify stationary curves, which correspond to segments of later-arriving rays. Complete rays can readily be found by beginning at some point along the stationary curve, and following the traveltimes gradient back to the source and receiver through the forward and reciprocal fields respectively. In theory, this approach can be extended to locate all later arrivals. Tests in complex 2-D media show that the new method is rapid, robust and highly accurate.
Figure 1. Example showing how the forward and reciprocal traveltime fields can be summed to extract "raylets", which are stationary curves that represent segments of complete raypaths.
Passive seismic imaging of the southern Tasmanides

Nick Rawlinson\textsuperscript{1}, Elizabeth Vanacore\textsuperscript{1}, Brian Kennett\textsuperscript{1}, Stewart Fishwick\textsuperscript{2} and Dick Glen\textsuperscript{3}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Department of Geology, University of Leicester, Leicester LE1 7RH, UK
\textsuperscript{3} Geological Survey of New South Wales, Department of Industry and Investment, PO Box 344 Hunter Regional Mail Centre NSW 2310, Australia

The Tasman Orogen or Tasmanides of eastern Australia largely consists of a series of accretional orogens that formed outboard of the Pacific margin of eastern Gondwana from the Middle Cambrian through to the Middle Triassic. Occupying approximately one-third of present day Australia, the Tasmanides incorporate five orogenic belts, including the Delamerian and Lachlan orogens in the south, the Thomson and North Queensland orogens in the north, and the New England Orogen in the east. The Delamerian Orogen, which incorporates the Adelaide Fold Belt in South Australia, extends southward from the mainland into Tasmania, where it is often referred to as the Tyennan Orogen. It comprises Precambrian and Early Cambrian rock sequences that were subject to contractional orogenesis along the eastern margin of Gondwana between about 514 Ma and 490 Ma. This was followed in the Late Cambrian by the formation of the Lachlan Orogen to the east, which continued through to the Early Carboniferous.

In order to study this fascinating region of Australia, a series of passive array deployments have taken place in Tasmania, Victoria, South Australia and New South Wales over the last twelve years which has resulted in over 550 station locations spaced between 15-50 km apart. The collective array is referred to as WOMBAT, and the large volumes of passive data that have been recorded provide a unique opportunity to image a large region of the Australian continent at high resolution. Teleseismic tomography using relative arrival times from seven of the sub-arrays has been carried out to image the mantle lithosphere beneath most of Victoria, southern New South Wales, and eastern South Australia.

The results from the teleseismic tomography show a marked variation in the strike of dominant P-wave velocity anomalies with depth. Immediately beneath the crust, dominant variations in velocity tend to strike east-west, and share little resemblance to Palaeozoic boundaries inferred in the shallow crust from surface geology and potential field data. A broad region of elevated wavespeed beneath central Victoria may represent the signature of under-plated igneous rocks associated with detachment faulting during the break-up of Australia and Antarctica. A distinct low velocity anomaly to the south of this feature appears to correlate well with the Quaternary Newer Volcanic Provinces. Towards the base of the mantle lithosphere, the dominant structural trend becomes north south, and five distinct velocity zones become apparent. Of particular note is a transition from higher wavespeed in the west to lower wavespeed in the east beneath the Stawell Zone, implying that the Proterozoic lithosphere of the Delamerian Orogen protrudes eastward beneath the Western subprovince of the Lachlan Orogen. This transition zone extends from southern Victoria into central New South Wales (the northward limit of the arrays), and is one of the dominant features of the model. Further east, there is a transition from lower to higher wavespeeds in the vicinity of the boundary between the Western and Central subprovinces of the Lachlan Orogen, which has several plausible explanations, including the existence of a Proterozoic continental fragment beneath the Wagga-Omeo Zone.
Figure 2. Map showing the locations of all WOMBAT stations. The thick red line encircles only those arrays that were used in this study.
Varying mechanical coupling along the Andean margin: implications for trench curvature.

Giampiero Iaffaldano¹, Erika Di Giuseppe², Fabio Corbi³, Francesca Funiciello³, Claudio Faccenna³ and Hans-Peter Bunge⁴

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Laboratoire FAST, CNRS/UPMC/Université Paris Sud, France
³ Dipartimento di Scienze della Terra, Università Roma 3 – Italy
⁴ Geophysics Section, LMU Munich, Germany

The Andean system, where the Nazca plate plunges beneath continental South America, is often regarded as the archetype of convergent margins where spatial and temporal correlations between the trench curvature, shortening, and uplift stand out from the geologic record. These links however remain debated. There is distinctive evidence that the degree of mechanical coupling between converging plates, i.e. the amount of resistive force mutually transmitted in the direction opposite to their motions, may significantly vary along the Andean margin at present-day. In this study we employ laboratory models of subduction to investigate quantitatively the role of the lateral variations of the mechanical coupling between converging plates in controlling the evolution of trench curvature. The analogue of a two-layer Newtonian lithosphere/upper mantle system is established in a silicone putty/glucose syrup tank-model. We perform two models where we monitor the temporal evolution of the trench. In the first one, the central portion of the margin is more strongly coupled compared to the rest, where a lubricant paste has the effect of reducing plate coupling (Figure 1). In the second model we instead maintain plate coupling at a uniform low level along the entire interface by leaving a channel of glucose syrup between the overriding and the subducting plates (Figure 2). We find that the ability of the experimental overriding plate to slide above the subducting one is significantly inhibited by strong mechanical coupling. This inference applies in particular to the central Andean margin, where the overriding plate shortens more than elsewhere along the margin, and the trench remains stationary as opposed to the advancing northern and southern limbs. Consequently, the margin evolves into the peculiar shape observed along the Andes in the present-day.

Figure 1. Laboratory model 1. Panels A-D are snapshots of trench evolution; elapsed time from model start is in the
upper-right corner. The subducting plate undergoes the overriding one from left to right. The upper half of each panel is a picture of the plates, where 2 x 2 cm squares are outlined to detect deformation. The lower half is a laser-scanned image of plate relief (offset from the beginning of the model) acquired at the same moment: red represents bulging upwards, blue is bulging downwards. Note that the model plates are manually attached to the pistons, therefore the peripheral regions naturally bulge upwards or downwards, and are thus detected as anomalous. Panel E shows the evolution of half-trench through time, as detected through the laser-scanned images. Red on white is the portion of trench with no lubricant paste, hence featuring high coupling. Blue on gray is one of the lateral edges with lubricant paste, thus featuring average coupling.
Figure 2. Laboratory model 2: analog subduction featuring uniformly low mechanical coupling along the plate interface, obtained with lubricating syrup (panels A-D). Images are equivalent to the ones in Figure 1.
Tears or thinning?

Subduction structures in the Pacific plate beneath the Japanese Islands

B.L.N. Kennett¹ and T. Furumura²

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Earthquake Research Institute, University of Tokyo, Tokyo, Japan

The nature of a subduction zone at depth is affected by the evolution of its tectonic system, and the geometry of the trench line can change over time due to slab roll-back or the arrival of a distinctive feature with the incoming oceanic lithosphere. The configuration of the plate has to accommodate such changes with buckling, thinning or the formation of tears depending on the rate of influx to the trench.

Tomographic imaging is commonly used to recognise the presence of such tears through marked reductions in wavespeed anomalies in localised zones. A good example is provided by Pacific Plate subduction beneath the Japanese Islands. A horizontal tear in the plate below 300 km depth can be recognised at the southern end of the Izu-Bonin arc associated with the change in slab morphology to the much steeper Mariana arc. Beneath southern Honshu a break in the fast wavespeeds associated with the Pacific plate has been described as a tear based on evidence of converted phases from the edge of the zone and tensional focal mechanisms for seismic events in the tear zone.

In the north, close to the Hokkaido bend in the subduction zone, the reduction in the shear wavespeed anomaly is just as dramatic, so that a slab tear might be inferred. A test of the nature of the slab can be made by using high frequency waves trapped within the subduction zone that are guided by elongate wavespeed variations along the length of the slab. Such waves can travel to the surface from even the deepest earthquakes, but the conditions for trapping energy are quite subtle and can be readily disrupted. In the zone of apparent tear such guided waves propagate but with a reduced high frequency content. This behaviour requires continuity of slab material and indicates a thinning of the subduction zone. The thinned slab has less wavespeed contrast within the affected cells and so appears in the tomographic images as a weakened anomaly.

The various modes of slab deformation represent different ways in which the subducted material accommodates the strains imposed by the evolution of the geometry of the subduction scenario. Not all significant reductions in wavespeed anomalies represent tears and thus it is important that such interpretations be checked against the characteristics of wave propagation through the zone.
Figure 2. Propagation paths for guided waves superimposed on the tomographic image at 400 km that shows a distinct gap between the fast wavespeed structures associated with the subduction zones beneath Honshu and the Kurile chain. Seismograms from the four marked events A-D observed at stations on the east coast of Japan show clear guided waves indicating continuity of the slab despite the weak signature in the tomographic images. The dashed paths have less high frequency content and suggest thinning of the subduction zone to accommodate the change in geometry from Honshu to the Kuriles.
A Synthesis of Local, Teleseismic, and Ambient Noise Data for High-Resolution Models of Seismic Structure in Western and Southeast Australia.

Mallory Young, Hrvoje Tkalcic and Nick Rawlinson
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The use of ambient seismic noise has become an increasingly popular method of imaging the Earth's crust with high resolution. For example, variations in group and phase velocity in the Tasmanian and Western Australian lithosphere were mapped through the cross-correlation of ambient seismic noise recorded by temporary array deployments. Additional constraints from receiver functions improve the depth resolution and sensitivity to velocity gradients and allow a joint inversion for shear velocities.

The southeast Australia dataset comes from the WOMBAT rolling seismic array project in Tasmania, which in the last decade has seen over 500 stations deployed. The group and phase velocity maps for this area clearly discriminate between regions of hard rock and sediment and indicate temperature differences. One of the prominent features of the maps is a pronounced low velocity zone that coincides with the Tasman conductivity anomaly, a region of elevated conductivity and heat flow, which may reflect the presence of a lithospheric boundary.

These methods were also applied to the 20 CAPRAL stations in Western Australia. Significant improvement in fit between synthetic and regional earthquake waveforms is evident after the shear velocity models of the crust replace those of current earth reference models. Moreover, reliable crustal maps are crucial to the accurate full waveform inversion of regional earthquake source parameters and enable a better understanding of the rupture process.

Figure 1. Shown here are the variations in phase velocity (km/s) in eastern Tasmania for a period of 4 seconds as determined from ambient seismic noise.

Figure 2. The CAPRAL stations in Western Australia are shown on the left. On the right, you can see the excellent agreement between synthetic and recorded vertical waveforms from a local magnitude 5.3 earthquake. The inverted focal mechanism solution is shown as well.
Balancing the Southern Ocean
Marshall L. Ward and Andrew McC. Hogg

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Intense eastward winds blow perpetually over the waters around Antarctica, injecting a continuous stream of energy and momentum into the Southern Ocean. This leads to the formation of the Antarctic Circumpolar Current, a massive current responsible for the exchange of water between the world’s oceans and a crucial component of the Earth’s climate. But what determines the eventual circulation? What prevents this current from accelerating endlessly? What balances the surface winds from above?

The answers to these questions depend on subtle interactions between the largest and smallest features of the circulation. The Geophysical Fluid Dynamics group at ANU has been using high-resolution numerical models to simulate the currents of the Southern Ocean. Our calculations show that the winds are largely counterbalanced by the undersea mountains and ridges, which push back against the winds as the current struggles to flow over them. But it is actually the mesoscale eddies, local swirls of ocean currents many times smaller than the ocean, that regulate the flow and determine its equilibrium state.

The currents flowing over the bottom ridges are inherently unstable, and faster currents tend to undulate and create more mesoscale eddies. These eddies emulate the effect of the topography below, pushing back against the current and countering the surface winds. As the winds continue to accelerate the current, the current produces more and more mesoscale eddies, until this pushback completely balances the surface wind forcing.

The details of these eddies are crucial to determining the eventual transport of the Antarctic Circumpolar Current, and our simulations demonstrate that even the smallest scales of the ocean can be responsible for the regulation of the climate in the ocean, highlighting the immense challenges ahead as we continue to improve our understanding of the global climate.
What drives the Antarctic Circumpolar Current?

Wind vs thermal forcing

Andrew McC. Hogg

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The Antarctic Circumpolar Current (ACC) is the world's strongest ocean current, connecting the three major ocean basins. The ACC is usually considered to be forced by strong westerly winds over the Southern Ocean. However, a comprehensive theoretical prediction of the volume of water transported (around Antarctica) by the ACC as a function of wind stress remains elusive.

In this study, simulations of an idealised, but eddy-resolving, channel model of the ACC are used to investigate the sensitivity of ACC transport to both wind stress and surface buoyancy forcing (heating/cooling). Sample temperature field form the simulations are shown in Fig. 1. The surprising result is that, even without any wind stress, a realistic ACC can be driven by surface heating/cooling alone. When wind stress is varied (Fig. 2) the kinetic energy of the entire system increases, but transport around Antarctica is slightly reduced. On the other hand, transport is strongly influenced by change in the surface buoyancy forcing.

The results are consistent with theoretical predictions of the "eddy-saturated limit", where transport is independent of wind stress. In this parameter regime, surface heating/cooling is the primary control over ACC transport.

Figure 1. (a) Temperature in a north-south transect through the domain; (b) Plan view of temperature (colour) and streamfunction (lines) of a snapshot of the flow, illustrating the resolved eddies.

Figure 2. Kinetic energy response to (a) changes in wind stress; (b) changes in surface buoyancy forcing. Transport response to (c) changes in wind stress; (d) changes in surface buoyancy forcing.
Response of Southern Ocean overturning to future climate change

Adele K. Morrison, Andrew McC. Hogg and Marshall L. Ward

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The world’s oceans have absorbed around one third of the total anthropogenic CO₂ emissions to date, with the Southern Ocean responsible for ~40% of the global oceanic anthropogenic carbon sink. The overturning circulation, through ventilation of upwelled deep water masses and subsequent formation of intermediate waters in the Southern Ocean, makes the region a dominant player in the exchange of air-sea CO₂ fluxes. Dense upwelled waters, rich in natural dissolved inorganic carbon, result in a significant outgassing band around Antarctica which nearly balances the Southern Ocean anthropogenic sink further north. Any future change in the strength of the overturning circulation has the potential to upset the balance between the outgassing and subduction of carbon, leading to feedbacks on the system.

Currently, the dynamics of the overturning are poorly understood and coarse resolution models fail to simulate the turbulent mesoscale eddy field, which plays a significant role in determining the magnitude and response of the overturning. We use idealised, but high resolution, eddy-resolving models of the Southern Ocean to investigate the sensitivity of the meridional overturning circulation to changes in surface wind stress and heat fluxes. We have found that the overturning is likely to increase under future warming and freshening of the southern hemisphere mid-latitudes. Enhanced westerly winds are also likely to increase the overturning, though the presence of eddies will partially compensate for the wind-driven changes.
The energetics of ocean circulation: the link between surface buoyancy forcing and the global rate of mechanical mixing

Ross W. Griffiths, Graham O. Hughes, Kial D. Stewart and Andrew McC. Hogg

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The density of the ocean water can be altered by surface buoyancy fluxes (which tend to produce density differences) and irreversible mixing (which tends to eliminate differences). Hence the energy conversions associated with these two processes must balance when globally integrated (in a steady circulation). Thus we have argued in previous years that both the surface buoyancy (heat and freshwater) fluxes and sources of kinetic energy for turbulent mixing are simultaneously necessary to maintain the observed ocean overturning circulation. These factors have not been widely recognized: the turbulent mixing rate in the oceans is often viewed as independent of surface heat fluxes.

We are examining these concepts further in laboratory experiments with large-scale overturning forced by salt and freshwater fluxes at the surface (in place of heating and cooling) and in which mechanical stirring is imposed. The stirring is generated by horizontal bars, which are gently oscillated while being traversed up and down through the depth of the water column. The stirring causes a vertical mixing rate that can be accurately calibrated and parameterized in terms of an ‘eddy diffusivity’. The rate of mixing of density depends on both the diffusivity and the vertical density gradient. Greater mixing rates gives rise to a greater rate of large-scale overturning. The results can be compared with theoretical solutions and with the behaviour of ocean general circulation models.

Professor Griffiths delivered a plenary lecture on this topic at the APS-DFD conference, Longbeach California, in November.

A simple demonstration of the concepts of available potential energy produced by surface buoyancy forcing, and irreversible mixing, as illustrated in figure 2, can readily be set-up and would be useful for fluid mechanics teaching.
The effects of marginal seas on ocean density
Kial D. Stewart, Ross W. Griffiths and Graham O. Hughes

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Heating and cooling along one horizontal boundary of a fluid leads to an overturning circulation known as “horizontal convection”. Numerical modelling and laboratory experiments with horizontal convection are helpful in understanding the role of surface buoyancy fluxes in the oceans. For instance, the meridional variation of sea surface buoyancy fluxes leads to a poleward transport of heat and to localized sinking plumes at the polar extremities of the oceans. The plumes form the Deep and Bottom Waters that fill the abyssal ocean.

The majority of abyssal waters are formed by outflows from marginal seas or semi-enclosed basins, where submarine topography strongly influences transport. However, the role topography plays in the global meridional overturning circulation (MOC) is largely unknown.

In 2010 we have built on our previous studies of convective overturning circulation and examined the effects of a topographic sill, which defines a simple marginal sea, or smaller basin, at one end of a simple rectangular basin. Laboratory experiments (figure 1) and computer modeling show the presence of the marginal sea influences the global density structure when the sill depth is less than twice the oceanic thermocline depth. In these cases the dense water overflowing the sill interacts directly with the surrounding thermocline water, bringing the properties of the overflow (and thus, deep) water closer to those of the warm surface water. This result is the opposite of the effect expected on the basis that the sill tends to restrict exchange and increase the density of the sill overflow.

Application of the results to the North Atlantic circulation predicts that the Greenland-Scotland Ridge is shallow enough to lead to a significant reduction of the density of North Atlantic Deep Water. This conclusion is consistent with an analysis of North Atlantic water mass properties (figure 2).
Rayleigh-Taylor instability of an inclined buoyant viscous cylinder

Ross Kerr\textsuperscript{1}, John Lister\textsuperscript{2}, Nick Russell\textsuperscript{2} and Andrew Crosby\textsuperscript{2}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Institute of Theoretical Geophysics, Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge CB3 0WA, United Kingdom

The Rayleigh–Taylor instability is most familiar as the gravitational instability of horizontal layers of fluids of differing densities when the lighter fluid underlies the heavier. The Rayleigh–Taylor mechanism also applies to linear, rather than planar, buoyant regions and has variously been invoked to explain regularly spaced volcanism above linear regions of buoyant melt production, such as mid-ocean ridges and island arcs. Applications to flow in the Earth’s mantle have also motivated studies of the shape and stability of a very viscous buoyant plume as it rises through a background shear flow that progressively tilts it further and further from vertical.

In the last two years, we have examined the Rayleigh–Taylor instability of an inclined non-diffusing cylinder of one very viscous fluid rising through another, using a combination of linear stability analysis, numerical simulations and laboratory experiments (Lister, Kerr, Russell & Crosby 2010). The stability analysis represents linear eigenmodes of a given axial wavenumber as a Fourier series in the azimuthal direction, allowing use of separable solutions to the Stokes equations in cylindrical polar coordinates. As the angle of inclination increases, the maximum growth rate decreases and the upward propagation rate of disturbances increases; all disturbances propagate without growth if the cylinder is sufficiently close to vertical, estimated as 70°. The results from the linear stability analysis agree with both numerical calculations (for a viscosity ratio of 1) and experimental observations (Figure 1). A point-force numerical method is used to calculate the development of instability into a chain of individual plumes via a complex three-dimensional flow. Towed-source experiments show that nonlinear interactions between neighbouring plumes are important for inclinations greater than 20°, and that disturbances can propagate out of the system without significant growth for inclinations greater than 40°.

The effects of isolated catchments on calculations of GIA

Anthony Purcell and Kurt Lambeck
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Given a model of the ice-loading history through the last glacial cycle, the CALSEA package developed by the ANU Earth Physics groups makes it possible to calculate the corresponding change in sea level, surface deformation, and gravity through time. The accuracy of these calculations depends not only on having a detailed ice sheet history but also on correctly incorporating the corresponding change in water depth across the Earth's surface. Previously, the water-loading calculations have been very limited in their handling of water catchments that are isolated from the ocean basins. Given the scale and complexity of the problem, water-level in these separate catchments has been assumed to rise and fall in time with the water-level in the ocean basins.

We have developed a new methodology whereby the CALSEA program will identify isolated catchments and, at the user's direction, allow the water-level within them to vary independently of ocean-water level. The water-loading effects of these isolated lakes can be included in the calculations of sea-level change, surface deformation or gravity. The user can also suppress water-loading effects in areas where such isolated catchments are water free (such as the Dead Sea and Death Valley). The loading effects of these isolated catchments can be significant, contributing as over 20 m of vertical uplift since the Last Glacial Maximum (22,000 years ago). This increased functionality will allow more precise calculations of sea-level change, and more detailed reconstructions of the major ice sheets and associated peri-glacial lakes.

Figure 1. Plot showing paleotopography for Northern Europe during the Last Glacial Maximum, including the effects of the ice sheet damming the north-flowing river systems. The contours show the difference in sea-level produced by the inclusion of the loading effects due to the quite substantial peri-glacial lakes. The contour interval is 2.5 m.
A technique for estimating GIA effects from observations of the Earth’s gravity field

Anthony Purcell, Amaury Dehecq, Paul Tregoning, Kurt Lambeck, EK Potter and S McClusky

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The ongoing response of the Earth to the exchange of mass between the oceans and ice sheets during the last glacial cycle are collectively referred to as glacial isostatic adjustment (GIA). The resulting surface deformation and perturbation to gravity can be detected by satellite-based observing techniques such as the Gravity Recovery and Climate Experiment (GRACE) and the Global Positioning System (GPS). Before these geodetic data can be used to estimate present day mass changes, it is necessary to calculate the corresponding GIA signal and remove it from the observations. If the ice history is well-understood, calculating the effects of GIA is straightforward. However, in some previously glaciated regions, neither the ice history nor the Earth’s response are sufficiently well-understood to permit a reliable reconstruction. In the absence of evidence constraining the ice history, changes in the gravity field observed by GRACE may be used to characterise the GIA signal. This reconstructed GIA signal can then be used to determine the corresponding vertical uplift due to GIA. These GIA effects can then be removed from the uplift observed at GPS sites to leave the signal due to modern processes. For such a technique to be practically useful, the relationship between the gravitational perturbation and vertical deformation should not be dependant on either the Earth’s response function or the ice history.

We explored the validity of representing the effects of GIA using synthetically derived response parameters and developed a new technique for determining the ratio between changes in gravity and surface deformation. With this technique, one no longer needs to know accurately either the Earth’s response or the ice load history. We can replace the ratio of the present-day response functions with a simple, linear expression that is independent of both Earth and ice histories, provided that the changes in the ice load have been static for at least 10,000 years. With this result, given an observed change in the Earth’s gravity field we can derive the corresponding surface deformation with greater accuracy than has previously been possible.
The gravity component of the AuScope project has purchased an FG5 absolute gravimeter, 3 gPhone portable earth tide gravimeters and completed the refurbishment of the Reynolds Dome at Mount Stromlo for use as a gravity instrument testing and intercomparison facility.

During 2010 absolute gravity observation were completed at existing gravity stations at Mount Stromlo CSO, Mount Stromlo Seismic vault and the Townsville AIMS facility. A standard maintenance service was completed on the FG5 gravimeter by the instrument manufacturer and a post maintenance test measurement at Mount Stromlo confirmed that the FG5 is performing to specification with an improvement in the operation of some sub-systems. This service took longer than anticipated with the instrument being unavailable for use for 3.5 months. Absolute gravity measurements using the FG5 gravimeter on the four new fundamental gravity piers in the refurbished Reynolds dome are planned to commence early in 2011.

The prime purpose of the FG5 absolute gravity measurements is to provide independent confirmation of the vertical deformation rates of the continent. Repeat absolute gravity measurements are being made at a network of existing and newly selected geometric measurement technique sites (e.g. SLR and GPS) across the Australian continent. Also, the FG5 is being used for calibrating and testing the relative gravimeters including the Mount Stromlo SG, and for other geodynamics projects requiring high precision absolute gravity.

Gravity measurements with the gPhone gravimeters has continued at Jabiru, Katherine and Tennant Creek during 2010. These gravimeters are performing well with interruptions to data acquisitions being due to failures of the controlling laptop computers. All three gPhone gravimeters are planned for deployment to new sites early in 2011.

The gPhone relative tidal gravimeter data are being used to model the actual ocean load tide around Australia. Sites in the north and north-west of Australia are being measured first to enable an assessment of the density of network sites required across the continent and to confirm the proposed analysis strategy for comparison of the gravity derived ocean load tides with models being used in GNSS data analysis.

AuScope geospatial gravity programme

G. Luton1, H. McQueen1 and N. Dando2

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
2 Geoscience Australia

The gravity component of the AuScope project has purchased an FG5 absolute gravimeter, 3 gPhone portable earth tide gravimeters and completed the refurbishment of the Reynolds Dome at Mount Stromlo for use as a gravity instrument testing and intercomparison facility.

During 2010 absolute gravity observation were completed at existing gravity stations at Mount Stromlo CSO, Mount Stromlo Seismic vault and the Townsville AIMS facility. A standard maintenance service was completed on the FG5 gravimeter by the instrument manufacturer and a post maintenance test measurement at Mount Stromlo confirmed that the FG5 is performing to specification with an improvement in the operation of some sub-systems. This service took longer than anticipated with the instrument being unavailable for use for 3.5 months. Absolute gravity measurements using the FG5 gravimeter on the four new fundamental gravity piers in the refurbished Reynolds dome are planned to commence early in 2011.

The prime purpose of the FG5 absolute gravity measurements is to provide independent confirmation of the vertical deformation rates of the continent. Repeat absolute gravity measurements are being made at a network of existing and newly selected geometric measurement technique sites (e.g. SLR and GPS) across the Australian continent. Also, the FG5 is being used for calibrating and testing the relative gravimeters including the Mount Stromlo SG, and for other geodynamics projects requiring high precision absolute gravity.

Gravity measurements with the gPhone gravimeters has continued at Jabiru, Katherine and Tennant Creek during 2010. These gravimeters are performing well with interruptions to data acquisitions being due to failures of the controlling laptop computers. All three gPhone gravimeters are planned for deployment to new sites early in 2011.

The gPhone relative tidal gravimeter data are being used to model the actual ocean load tide around Australia. Sites in the north and north-west of Australia are being measured first to enable an assessment of the density of network sites required across the continent and to confirm the proposed analysis strategy for comparison of the gravity derived ocean load tides with models being used in GNSS data analysis.

AuScope geospatial gravity programme

G. Luton1, H. McQueen1 and N. Dando2

1 Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
2 Geoscience Australia
Southeastern Australia is favorably positioned relative to much of the Pacific Rim and SE Asian subduction systems for recording of $PcP$ phases from subduction zone earthquakes.

$PcP$ seismic phases bounce off the core-mantle boundary (CMB) and are valuable for investigating this complex region in the earth, especially when they are compared to $P$ phases that travel nearly the same path except for close to the CMB. In this way, anomalous differences between $PcP$ and $P$ can be attributed to differences at the CMB. Differential $PcP$-$P$ phases are best recorded between approximately 25-75 deg, which is precisely the distance of SE Australia relative to the subduction zones of Indonesia, Papua New Guinea, Tonga/Kermadec, Philippine, Izu-Bonin-Mariana, and Japan. As such, any seismic stations deployed in this area have potential for accurate $PcP$-$P$ travel time studies.
New High-Resolution Seismic Attenuation Imaging of Australian Lithosphere with the WOMBAT Array

Pozgay, S.H. and Rawlinson, N.

Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

Since 2001, Australia’s WOMBAT array has been leap-frogging across the continent (see Fig. 2). Each subarray within WOMBAT consists of 30-72 short-period seismometers with solid-state recorders deployed for 6-12 months. Station spacing is 15-50 km, resulting in high-resolution coverage at the continent scale. To date, over 500 short-period stations have been deployed in SE Australia. Furthermore, the lack of anthropogenic noise for most stations, and the presence of low attenuation in parts of the upper mantle, enable good signal-to-noise ratio and make the dataset ripe for detailed seismic investigations beyond that of travel time tomography.

We extend prior travel time tomography studies to utilize amplitude data for analysis of the attenuation structure of the lithosphere and upper mantle (Fig. 1). We modify the adaptive stacking code of Rawlinson & Kennett [2004] to include frequency-dependent differential $dt^*$ attenuation measurements. Initial analysis of teleseismic $P$ waves recorded using only a preliminary dataset of 100 stations shows good structural coherency with travel time tomography. Further high-resolution studies will provide a comprehensive picture of the attenuation structure of the Australian lithosphere and will enable direct comparison and integrative interpretation between observed velocity and attenuation anomalies.
Tasmania). The earliest deployment was LF98 in 1998 (light pink triangles) and the gray circles (EAL2) are currently recording. Data from the SETA deployment shown here are highlighted with the pink circle.
Hydrological deformation of the Earth

Paul Tregoning¹, Christopher Watson², Guillaume Ramillien³, Herb McQueen¹ and Jason Zhang¹

¹ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
² Centre for Spatial Information Systems, University of Tasmania
³ CNRS, Toulouse, France

Variations of water storage at different times of the hydrological cycle mean that the amount of water pressing down on the continents of the Earth varies. This causes changes in the deformation of the surface of the Earth that can reach up to 15 mm in the vertical. Such deformations can be detected in time series of site coordinates estimated by GPS, while the change in total water load can be estimated from the GRACE space gravity mission.

In this study, we used the hydrological loads derived from the French solutions of GRACE spherical harmonic monthly gravity fields to calculate the elastic deformation that would occur at the surface of the Earth. We then compared these deformations with those estimated from GPS coordinates on a global network. The agreement in height is at times spectacular, especially considering that these two space geodetic techniques are completely independent and are sampling different geophysical effects.

However, the variations in the horizontal coordinates is less convincing when the deformation signals are < 2 mm, suggesting that either the analysis of one of the two techniques is in error or that the broad-scale GRACE computations and the discrete GPS sites are not sampling the same hydrological loading effects.

Work is continuing to improve the GPS analysis, in particular to mitigate the presence of spurious harmonic signals in the site coordinates that are known to relate to orbital errors.

The research was published [Tregoning et al., 2009] in Geophysical Research Letters and is available at: http://rses.anu.edu.au/geodynamics/tregoning/38.pdf
Improving GPS analysis strategies
Paul Tregoning\textsuperscript{1} and Christopher Watson\textsuperscript{2}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Centre for Spatial Information Systems, University of Tasmania

The Global Positioning System (GPS) can be used to detect earthquake deformation (including the buildup of strain prior to earthquakes), uplift and subsidence of continents, tectonic drift etc. Naturally, the higher the accuracy of the analysis, the greater the likelihood of detecting accurately these geophysical signals.

In this study, we focused on assessing the accuracy of different approaches to estimating the delay of the signals transmitted by the GPS satellites as they pass through the atmosphere, and the accuracy of different approaches to modelling atmospheric pressure loading deformation (the movement of the surface of the Earth as a result of changes in atmospheric pressure). We derived new estimates of atmospheric pressure loading that properly accounted for the weather-related loading (up to 15 mm deformation) and daily and semi-daily atmospheric tides (up to 1.5 mm amplitude).

We found that modelling the atmospheric tidal deformation reduced spurious periodic signals in site coordinate estimates and that modelling the atmospheric delays using information from global numerical weather models significantly improved the accuracy of the site coordinate estimates, in particular in the vertical component. However, our best analysis still contains periodic signals at harmonics of frequencies related to the satellite orbital dynamics. Research is continuing to understand and mitigate the causes of these errors.

The research was published \cite{Tregoning and Watson, 2009} in the Journal of Geophysical Research (solid Earth) and can be found at the link below.
Figure 3. Time series showing differences in the up component between solutions using (left) different a priori tropospheric delays, (middle) different mathematical relations of tropospheric delay in the vertical to any elevation angle, and (right) the combined effect for (a) Bahrain, (b) Alaska, (c) NyAllesund, and (d) Northern Russia.
Monitoring groundwater variations in the Murray-Darling basin using space gravity measurements

Paul Tregoning\textsuperscript{1}, Marc Leblanc\textsuperscript{2}, Guillaume Ramillien\textsuperscript{3}, Sarah Tweed\textsuperscript{2} and Adam Fakes\textsuperscript{4}

\textsuperscript{1} Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Hydrological Sciences Research Unit, James Cook University, Cairns
\textsuperscript{3} CNRS, Toulouse, France
\textsuperscript{4} CSIRO Sustainable Ecosystems, James Cook University, Cairns

Data from the Gravity Recovery and Climate Experiment (GRACE) have been used in conjunction with borehole groundwater depth measurements, soil moisture models and surface water storage estimates to show that, of the 200 cubic kilometres of water lost in the Murray-Darling Basin since 2002 (equivalent to 400 Sydney Harbours), the majority has come from a loss of groundwater resources. The results were published in Water Resources Research (Leblanc et al., 2009), where monthly estimates of changes in the Earth's gravity field were used to calculate the change in total water resources in the basin.

The twin GRACE satellites were launched in 2002 and detect small changes in the Earth's gravity field. The satellites are in a tandem orbit (one following the other) 450 km above the Earth's surface and are separated by \(~\text{200 km}\). The distance between the satellites is measured with a K-band radar system and changes in the distance yield information on the time-varying nature of the gravity field.

Geophysical processes that can cause the Earth's gravity field to change include annual exchanges of water between oceans and continents, melting of polar ice sheets and mountain glaciers, droughts and floods, ongoing adjustment of the Earth's crust as a result of melting of ice sheets thousands of years ago, and even earthquakes.

The paper by Leblanc et al (2009) is available at the following link.

Information on the GRACE satellite mission can be found at
http://podaac.jpl.nasa.gov/grace
Slow slip subduction events in Mexico detected by GPS

M. Vergnolle, A. Walpersdorf, N. Cotte¹, V. Kostoglodov, J. A. Santiago², P. Tregoning³ and S. I. Franco¹

¹ Laboratoire de Géophysique Interne et Tectonophysique, CNRS, Observatoire de Grenoble, Université Joseph Fourier, Grenoble, France
² Instituto de Geofisica, Universidad Nacional Autónoma de México, Mexico City, Mexico.
³ Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

The world’s largest observed Slow Slip Events (SSE) occurred in 2001–2002 and 2006 in the Guerrero subduction zone, Mexico. Using an improved GPS processing that accounts for time-varying atmospheric phenomena as well as oceanic, atmospheric and hydrologic loading corrections, the 11 year GPS position time series in Guerrero show a noise reduction of ~50% with respect to previous studies. Thanks to the improved position time series and, in particular, the simultaneous analysis of the three-dimensional GPS observations, we can provide new information about SSEs in the studied area. First, we detect seven nonperiodic anomalous displacements with subcentimeter amplitude, but no quasi-annual anomalies as proposed previously. The displacements seem to occur simultaneously with the observed peaks of non-volcanic tremor activity in the area. Second, we refine the characteristics of the two major SSEs in terms of timing, duration, and cumulative displacements, and highlight the complex surface spatiotemporal evolution of the displacements during these SSEs. In particular, we observe a clear initiation phase for the 2006 SSE as well as ending phases for both large SSEs. The ending phase shows a strong deceleration of the anomalous displacements with respect to the main displacement phase already observed, for the 2001–2002 and 2006 SSEs. The duration of the SSEs increases by 30–40% including the initiation and ending phases. For the 2006 SSE, the main displacement phase also shows spatiotemporal complexity. Our results demonstrate the need for improved three-dimensional GPS processing technique in order to undertake detailed studies of SSEs.

PDF
Figure 2. 3D time evolution of the displacement at each analyzed station from June 2005 to December 2007 representative of the 2006 SSE (see text for explanation, section 5.1). (left) Monthly cumulative displacement (in cm) with respect to the north and east components. (right) Monthly cumulative displacement (in cm) with respect to the north and vertical components.