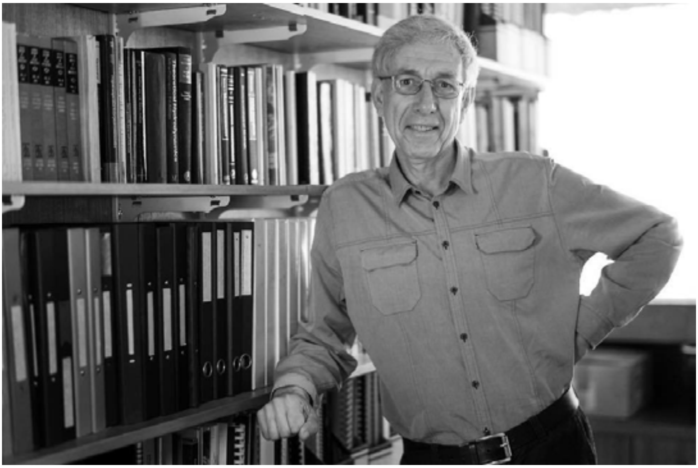
MICHAEL RAUPACH

A celebration of his contribution to science and humanity



"The narrative emerging from Earth System science has enormous potency. We, the scientific community, are pointing to objective realities about the way the Earth works – in climate, oceans, land, fresh water, ecosystems and more – that are changing ways that people think and changing social and political discourses. There is a great deal of pushback, and a profound contest going on. We cannot avoid a central role in this contest."

MONDAY 6 FEBRUARY 2017

THE SHINE DOME, AUSTRALIAN ACADEMY OF SCIENCE

SPEAKERS

HELEN CLEUGH (MC)

JOHN FINNIGAN

CATHY TRUDINGER

VANESSA HAVERD

PEP CANADELL

PENNY SACKETT

AGENDA

6.00PM GUESTS ARRIVE

6.10PM WELCOME (HELEN CLEUGH)

6.15PM JOHN FINNIGAN

6.30PM CATHY TRUDINGER

6.45PM VANESSA HAVERD

7.00PM PEP CANADELL

7.15PM PENNY SACKETT

7.30PM CLOSING REMARKS FROM HELEN CLEUGH AND ALEX RAUPACH

Immediately following the lecture, there will be drinks and canapes available in the Jaeger room. Please stay to join us for a toast to Michael's legacy.

THE LIFE AND SCIENCE OF MICHAEL RAUPACH

Michael Robin Raupach was born in Adelaide, the eldest of three children to Max and Jean Raupach. Max had a distinguished career as a soil chemist, and Jean Nancarrow was a fierce intellect with particular skills in languages and communication. With these influences, Michael was an outstanding student. He had a love of music, at first learning piano, and then as a teenager teaching himself guitar and singing with others in church groups. At school, he chose boy scouts as an alternative to cadets. Their activities were enjoyable and influential in developing his respect and interest in other people. From an early age Michael also had a lifelong love of trains and boats. He helped his grandfather to build and sail boats at their holiday house at Encounter Bay, where his love of the sea and his weather eye probably evolved.

Michael completed a BSc with honours in mathematical physics in 1971 at the University of Adelaide and then a PhD in micrometeorology at Flinders University in 1976. Presciently, he actually wanted to research global climate change but he was cautioned against doing a PhD on such a "speculative theory" and instead was encouraged to study turbulent exchange processes above plant canopies. Michael's research involved building a fast response infrared hygrometer to directly measure eddy fluxes of water vapour in the atmosphere. While he eventually did return to climate change science many years later, the world's micrometeorological community remains a significant beneficiary of this early career detour.

At university Michael was also deeply involved in the folk music scene and in using music in protests such as those against the Vietnam War. For a time, he considered an alternative career in music and, although he chose science, writing songs and playing guitar remained a lifelong passion. At university, he also met his soulmate, Hilary Talbot. They married in 1976 and in time had three children, Tim, Anna and Alex.

After his PhD, Michael was offered a post-doctoral position with Prof. Alasdair Thom at the University of Edinburgh. Alasdair played a key role in shaping Michael as a scientist. It was here that he learned the nuances of careful measurement and, more importantly, careful thought prior to experimentation so that the experiment addressed the issues at hand and yielded data that pushed current understanding into the unknown. Under Alasdair, Michael continued to hone his mathematical and physical sciences skills to provide not only experimental evidence, but also theoretical substance to his data and ideas. Throughout his career, Michael continued Alasdair's legacy of complementing new experimental data with mathematically and physically sound theoretical explanation.

In 1979, Michael returned to Australia to join CSIRO's Division of Environmental Mechanics (DEM), which was located on Black Mountain in Canberra. He remained with CSIRO until 2014. The Division (and then later the Centre of Environmental Mechanics), was organised around the concept of integrated, multi-disciplinary research into the flow of material, energy and information through the soil-plant-air continuum, a prescient concept for the time. Work in DEM was initially directed towards enhancing agricultural productivity and advances made by the group resulted in a large donation by Charles Frederick (Fred) Pye, a grazier and pastoralist, which funded the construction of the Pye Laboratory, a heritage listed building on the CSIRO Black Mountain complex. Here, the young Michael Raupach rubbed shoulders with some of the world's leading environmental scientists, including John Philip, Robin Wooding, Tom Denmead and Frank Bradley.

Over the next two decades, Michael, together with colleagues Brian Legg, John Finnigan, Yves Brunet, Peter Coppin, and others, re-wrote our understanding of the mechanisms governing the exchange of momentum and scalars like water vapour, carbon dioxide and heat between plant canopies and the atmosphere. During this time, Michael spent a great deal of time in the Pye Laboratory wind tunnel, helping push hotwire anemometry to its limits, and developing probes that allowed improved measurement in the highly turbulent flows that develop around plant canopies. Field experiments, especially at Uriarra and Mogo Forests, provided real-world data to complement the work in the wind tunnel.

At the same time, together with Roger Shaw and John Finnigan, Michael was improving the mathematical description of plant canopy flow. Traditional ways of representing the impact of plants on the airflow, using concepts like aerodynamic drag or sources and sinks of scalars, led to anomalous predictions, particularly that turbulence would be suppressed within the canopy airspace. Experimental data in contrast showed that the aerodynamic drag of the foliage strongly increased turbulence levels. The introduction of spatial averaging to the canopy equations not only resolved this anomaly, producing the standard equation set now universally employed to describe turbulent canopy flows, it also pointed to new ways of moving between single leaf and whole-canopy descriptions of the surface energy balance, a direction Michael was to develop fruitfully some years later.

The second benchmark result of Michael's research into the details of canopy turbulence was his resolution of the then baffling phenomenon of *counter-gradient* diffusion in some regions of tall plant canopies. Simultaneous observations of fluxes and concentrations of heat, water vapour and CO_2 at many sites but especially by the PYE Lab team of Denmead and Bradley at Uriarra Forest, showed regions where fluxes of scalars were in the direction of increasing concentration. Although not forbidden by physics, this was a challenge both to common sense and calculation. Using a combination of fundamental theory and a critical wind tunnel experiment, Michael was able to not only explain counter gradient diffusion in a physically satisfying way using Lagrangian physics but his work also provided a practical calculation method that is now incorporated in many applications, including CABLE, the land surface scheme built into Australia's climate model, ACCESS.

The third major advance in the understanding of flows over tall roughness, in which Michael played a key part, came with the publication of the *mixing layer hypothesis* by Raupach, Finnigan and Brunet in 1996. This finally provided an explanation for the origin of the large coherent turbulent eddies that play a ubiquitous role in the dynamics of surface-atmosphere coupling over all but the smoothest natural surfaces. By this time, however, Michael's interests were outgrowing detailed canopy studies as he sought to extend his understanding of turbulent exchange at the local scale to whole landscapes and regions and, eventually, to continental scale. This broadening of perspective led to his leading role in the multi-disciplinary field program, OASIS and to several measurement seasons near Wagga Wagga. During OASIS, CEM staff and collaborators littered the padlocks with every conceivable instrument from soil and plant physiological sensors to flux towers, a tethered balloon and even an aircraft. One of the more unexpected outcomes of this program was the "oh sh*t" profile collected when the tethered balloon escaped its moorings and headed upwards in free abandonment, causing untold consternation for Michael and Helen Cleugh.

Michael also found the time to undertake a great deal of research into wind-driven soil erosion, including key research into the windborne transport of solid particles (see Shao et. al. (2015) A tribute to Michael R. Raupach for contributions to Aeolian fluid dynamics, *Aeolian Research*, 19(A):37-54). In particular, Michael made major contributions to how drag is partitioned near the surface and how this impacts soil erosion, the saltation roughness length and bombardment and threshold friction velocities for particulate flows. He dabbled with bushfire dynamics and flow around buildings and the use of vegetation to modify flow patterns and protect local systems from dust and spray. There was a great piece of wind tunnel work on the effect of forest clearing on the nesting of Abbott's Booby on Christmas Island and an excellent theoretical model of the transport of endosulfan to rivers by vapour, spray and dust.

He also worked with colleagues in the Rural Development Corporations (RIRDC and LWRRDC), and the Joint Venture Agroforestry Program, to help establish the National Windbreaks Program – whose goal was to quantify the effect of tree windbreaks on farm microclimates, crop yields, and land degradation (dryland salinity and wind erosion of soils). While CSIRO's leadership of the research was eventually handed to Helen Cleugh, the approach of marrying theory, experiments, modelling and field measurements epitomises Michael's rigorous approach. And the success of the research program owes a great deal to the role Michael took in its original establishment.

In the mid-1990s, as Michael started to move away from small scale micrometeorology he was forced to confront some niggling inconsistencies that appeared when the spatial averaging concepts, developed with Roger Shaw and John Finnigan, were applied at the whole boundary layer scale. Rather than ignoring these small problems as many had done up to that point, Michael's rigorous analysis led in 2000 to his seminal paper on equilibrium evaporation and to a deeper understanding of boundary layer controls on evaporative processes. This in turn led to the formulation of a surface-atmosphere exchange model for homogeneous but especially for inhomogeneous landscapes. Based on these boundary layer control concepts, Michael, together with John Garratt and John Finnigan, developed a soil-vegetation-atmosphere-transport or SVAT model for heterogeneous landscapes for CSIRO's nascent climate models, significantly more advanced than anything available at the time elsewhere in the world. This work provided also the critical underpinnings for what were to be Michael's next major contributions.

In the late 1990's the development of high-resolution gridded daily meteorology opened the door to modelling of land surface processes for the whole of Australia at the scale of a few kilometres. Under the aegis of the National Land and Water Audit, Michael led the multidisciplinary team that developed the BiosEquil model and the first fine-scale maps of the average landscape balances of water, carbon, nitrogen and phosphorus for Australia, a key component of the NLWRA's Agriculture Assessment. This was followed by the Australian Water Availability Project (www.csiro.au/awap), an automated soil moisture modelling and mapping system which monitors the state and trend of the Australia's soil water balance. As part of AWAP, Michael's WaterDyn model has operated almost uninterrupted since 2007 and continues to ingest daily meteorology, reporting every Wednesday on the state of soil moisture and the components that contribute to it. In numerous model intercomparisons and independent validations AWAP WaterDyn continues to be a top performer. AWAP historical and near real-time model results from 1900 to present have been used in over 150 projects across government, universities, industry, and NGOs. Ten years after its development it is still finding new uses as a scientific, educational, policy, and resource management tool. Michael was at the forefront of theoretical developments in land surface modelling, and although he quickly moved on from AWAP to greater scientific challenges, the longevity of the AWAP system is a testament to the value of practical applications when they are backed up by the solid science that Michael brought to all his endeavours.

By now, his work in quantifying the role of land-surfaces in moderating weather and climate was well known and he started a long and distinguished international career on steering committees beginning with the Biospheric Aspects of the Hydrological Cycle (BAHC) core project of the IGBP (International Geosphere-Biosphere Project).

In 2001, IGBP and its sister global change research programmes – WCRP (World Climate Research Programme), IHDP (International Human Dimensions Programme on Global Environmental Research) and Diversitas (a global programme on biodiversity) joined forces to form the Earth System Science Partnership (ESSP), which aimed to tackle the most challenging, highly interdisciplinary problems that were at the heart of global change.

The flagship project of the ESSP was the Global Carbon Project, and Michael was appointed, from an outstanding field of the world's best biophysical global change scientists, to be one of the three inaugural chairs of the GCP (the others coming from the climate and social science communities). From then on, Michael was set on a mission to "save the world" from climate change, working closely together with Pep Canadell in his role of GCP executive director. Michael's interests grew rapidly from purely biophysical analyses of carbon cycle fluxes to studies that measured human contributions to and ways to mitigate climate change.

Along with colleagues in the Global Carbon Project, Michael described changes in the dynamics of the natural carbon sinks on land and in the oceans, which together remove about half of all anthropogenic CO_2 emissions and, in consequence, slow the progression of human-induced climate change. This work developed into one of the finest integrative pieces of science at which Michael so excelled. He developed the “sink rate”, a diagnostic that relates carbon uptake in oceans and on land with the amount of excess atmospheric CO_2, and an attribution approach to assign changes in the sink rate to underlying causes. He showed that the efficiency of sinks was declining due to the trajectories of extrinsic factors, including the slower-than-exponential growth in CO_2 emissions and volcanic eruptions and, more concerningly, intrinsic feedback responses such as the responses of the land sink to climate change and nonlinear responses to increasing CO_2, mainly in the oceans. His critical contribution was to combine these disparate factors in a single modelling framework.

Michael pioneered research showing how global carbon emissions were tracking the most carbon-intensive scenarios of the Intergovernmental Panel on Climate Change. He also identified how a century old declining trend—an improvement—in the carbon intensity of the global economy ceased as emerging economies took centre stage in the growth of the global economy. This work has led to a whole new body of international research using various formulations of an expanded Kaya Identity to understand the underlying drivers of human carbon emissions and progress towards climate mitigation objectives.

Despite his growing interest in global scale problems, Michael maintained a passion for quantitatively monitoring the state of the Australian environment. He used model-data fusion methods to constrain the land carbon and water cycles. Model-data fusion involves obtaining a mathematically optimal combination of models and observations through parameter estimation and/or data assimilation techniques, with consideration of uncertainties. Michael understood these complex concepts and methods well, and was very good at communicating them clearly to a non-specialist audience. In the early 2010s, Michael and his CSIRO team (Vanessa Haverd, Peter Briggs, Cathy Trudinger, and Pep Canadell) extended his Australian regional land-modelling capability (AWAP) to include the terrestrial carbon cycle, which led to the first comprehensive assessment of the Australian terrestrial carbon budget.

During his last decade of research, Michael was a strong advocate for the scientific community to combine first class and societally relevant research. He examined relationships between emissions and economic development, the contributions of urbanization to the global carbon fluxes, drivers of present and future greenhouse emissions, and ways to explore the responsibilities of nations to address mitigation and their commitments. Michael also led numerous groups in Australia on behalf of the Australian Academy of Science to explore the implications of Australian population trajectory for economic, social and ecological sustainability. One important example was a report to the Prime Minister's Science, Engineering and Innovation Council on the need for an integrative approach to managing energy, water and carbon. His commitment to the relevance of research also led him to become interested in climate change narratives as a way to engage with stakeholders in the climate change debate, from policy makers to the public, who wanted to take part in climate mitigation. One manifestation of this engagement was the leading role Michael played in the Academy of Science booklets 'The Science of Climate Change, Questions and Answers'?

Michael's contributions to national and international committees were highly effective, not only because of his excellence in scientific research and thinking, but also because of his warm and thoughtful demeanour. Michael listened to what others had to say and he treated everyone, scientists, politicians, the public, and children, with respect and humility. He was able to synthesise complex concepts into clear, unambiguous metaphors and stories that took his audience with him on his intellectual journeys and insights. And all through these communications, there remained his steadfast commitment to rigour; to going back to first principles; and to clarity and precision in his spoken and written word. Few can assemble and guide groups of strong-willed individuals like Michael could and he ended up leading some very challenging projects which in turn led to some of his best work.

In early 2014, Michael left CSIRO to head up the Climate Change Institute (CCI) at the ANU, a change in institution but not fundamental direction. The cross-disciplinary CCI engages researchers in any area of the University, all experts in their own fields. Michael saw it as an opportunity not only to continue fundamental climate research, but also to take further the search for a societal ethic for guiding the cohabitation of human societies and a finite, vulnerable natural world.

Although we will never know exactly in which directions Michael may have taken the CCI or which new areas of his own he would have pursued with his characteristic honesty and rigour, one thing is clear: he wished to both broaden and deepen climate change discourse.

Michael was interested in how the objective assessments at the heart of scientific research related to subjective values in society and saw the awareness of how science relates to ethics as critical. And he saw great power in the emerging story of human-environment interactions. He described narratives in evolutionary terms, as ethical DNA, the means by which we communicate our ethics to each other. “Ethics are breathing things, breathing entities, and we communicate and cross fertilise our ethical networks by telling stories about them.”

After taking up the CCI Directorship, Michael was asked about the extent to which he felt scientists should enter political debate and express a view about policy choices. He responded: “To pretend that science, and in particular environmental science, can remain at the side of that debate is simply no longer tenable.”

The world is poorer for having lost Michael so soon as a leading scientist in the informed, forthright, and humane discussion that is too often absent at the intersection of science and policy.

Thank you for attending this lecture in loving memory of Michael Raupach, 30/10/1950-10/02/2015.

This lecture has been recorded. If you would like view the lecture again, it will be uploaded to the Australian Academy of Science YouTube channel:

www.youtube.com/ScienceAcademyAu

This lecture was a joint effort of the Australian Meteorological and Oceanographic Society and the Australian Academy of Science. Special thanks to both organisations, in particular Margi Bohm and Clem Davis.