

Michael Robin Raupach 1950–2015

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ABSTRACT

For four decades from the mid 1970s, Dr Michael Robin Raupach (Mike) was recognised around the world as a pre-eminent researcher in the fields of micrometeorology and Earth System science. A scientist who combined a fertile imagination with outstanding analytical and mathematical skill, he played a pivotal role in transforming the way we understand and model interactions between those key components of the climate system, the living biosphere, and the atmosphere. Based on the fundamental advances he had made in the understanding of flow and transport of heat, water vapour, momentum and trace gases at plant canopy scales, Mike proceeded to apply this knowledge at regional and then global scales, providing us with some of the essential tools that are now being used to understand anthropogenic climate change. As well as a brilliant scientist, Mike was a much-valued mentor and supporter to colleagues around the world, especially to young scientists with whom he generously shared his help and insights.

Keywords: aeolian transport, atmospheric physics, biogeochemical cycles, carbon-climate feedbacks, climate variability and change, Earth system science, global carbon budget, micrometeorology.

Introduction

Dr Michael Robin Raupach (Mike) was a brilliant scientist, a man of deep integrity, and a talented musician, who found solace and inspiration in equal measure in science and in playing music. Mike was an inspiring and generous leader, mentor and colleague—not just in Australia, but around the world.

A creative yet rigorously analytical scientist, Mike made profound and enduring contributions to atmospheric, climate and Earth Systems science. Throughout his career he published more than one hundred and fifty scientific papers and fifty reports and edited two books. He was a contributing author of the 2007 Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, and was appointed as a CSIRO Fellow in 2010 in recognition of his outstanding and innovative research. As a Fellow of the Australian Academy of Science, the Australian Academy of Technological Sciences and Engineering, and the American Geophysical Union, Mike commanded enormous respect from scientific peers around the world.

Mike was committed to ensuring his work made a difference and was an eloquent, courageous and effective spokesman for his science. He communicated sometimes inconvenient truths, with clarity and purpose to a diverse audience that included politicians, activists, civil society and academics (Fig. 1).

Over the last two decades, Mike became one of Australia's foremost climate scientists—harnessing his intellectual and analytical skills to understand the interactions between climate, the carbon cycle and humans. In 2014, after a thirty-five-year career working at CSIRO, Mike joined the Australian National University as Director of the Climate Change Institute. Motivated by an increasingly strong sense of moral duty to speak out, especially on climate change, this afforded Mike the opportunity to draw on his formidable scientific and communication skills to influence a wider audience, untrammelled by the constraints imposed by CSIRO, in its role as a Statutory Authority within the Australian Government.

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Fig. 1. Mike was a skilled communicator, as well as an outstanding scientist and science leader. Here he is being interviewed by the local media from the Riverina district of New South Wales during the OASIS field campaign.

Early years

Mike was born in Adelaide, the eldest of three children, to Max and Jean Raupach. Alongside his distinguished career as a soil chemist, Max was also a talented artist with a love for music. Jean was a fierce intellect, who excelled in writing, languages and communication. With these influences, it is no surprise that Michael was an outstanding student. His lifelong love of music started with learning piano, and then the guitar under the tutelage of Peter Combe (the well-known children's entertainer), who was an early teacher and influence. Mike also enjoyed singing in church groups and relished opportunities to perform and share his music with others. This continued when he was an adult, sharing most Sunday afternoons with his fellow musician and close friend Michael Williams, playing their own material as well as a repeated playlist.

Joining the boy scouts as a schoolboy helped nurture Mike's developing respect for, and interest in, other people. From an early age he loved trains and boats. Helping his grandfather to build and sail boats at their holiday house at Encounter Bay in South Australia fostered Mike's love of the sea and his weather eye.

Mike's dad, Dr Max Raupach, was a highly respected CSIRO soil scientist working at the Waite Campus in Adelaide. Max was very proud of his son's career, although annoyed that internet searches did not differentiate between the two M. Raupach authors and citations! Obviously having a scientist as a father was an important influence. Indeed, Mike's first job was working in Max's laboratory. A precision weighing balance at home provided valuable insights for Mike, as he experimented with calculating the atomic masses of different elements, learning about measurements and accuracy, and the physical and chemical basis of materials.

Beyond science, though, it was the family's love of arts, music and languages, and their strong ethos of success that

were equally important in shaping the scientist and man that Mike became.

The 1970s were a time of disruption, with Australia's involvement in the Vietnam War being a catalyst for Mike's generation to demand societal change. Mike's awareness of global issues was sparked by these events, which combined with his folk singing, and values of kindness and respect for others, to foster an enduring humanitarian sensibility. As both a source of truth and a 'reality check', Mike realised that science provided a way to navigate these complex social issues as well as providing solutions to the environmental challenges that were emerging around the world.

As an accomplished musician, Mike faced a difficult choice between pursuing an artistic or a scientific career. He realised that earning a living as a musician might compromise the joy he found in music and so, about the time of his Honours degree, Mike chose science. He embarked on a PhD at Flinders University, beginning his successful career in scientific research. But Mike's love of music never faded, and music was an enduring source of internal solace and joy that was essential to the 'hard' science of his chosen vocation. Science and music were equally important throughout Mike's life, providing complementary avenues for his creativity. Music sparked Mike's imagination, helping him to connect ideas in new ways and explore the new insights this inspired.

University and postdoctoral experience

Mike's career had begun at the University of Adelaide, with a BSc Honours degree in mathematical physics that he completed in 1971 before he continued to a PhD at Flinders University, with Professor Peter Schwerdtfeger as his primary supervisor. Presciently, Mike wanted to study global climate change, but was cautioned against researching such a 'speculative theory', and instead was encouraged

to study turbulent exchange processes in plant canopies—reflecting the focus on micrometeorology by Professor Schwerdtfeger’s research group.¹ He eventually did return to climate change science many years later, and the micrometeorological community is a significant beneficiary of this early career detour.

For his PhD on Atmospheric Flux Measurement by Eddy Correlation, which he completed in 1976, Mike built his own measurement and data processing system. In this way, he became one of the early pioneers in the flux measurement technology that is today replicated at hundreds of flux towers in the global network of regional flux towers, including Australia’s OzFlux.² It is no coincidence that, under Mike’s leadership, CSIRO developed an ambitious and comprehensive research program based on an observation network of flux towers.

It was while Mike was studying at Flinders University that he met his soulmate, Hilary Talbot. They married in 1976 and went on to have three children, who were the light of his life. He was immensely proud of them.

CSIRO and the Pye Laboratory

Following his PhD, Mike took up a postdoctoral fellowship at the University of Edinburgh, where he worked with the late Alasdair Thom, an outstanding micrometeorologist whose influence helped shape Mike’s research direction and career. His postdoctoral research on atmospheric turbulence laid the foundation for decades of research that fundamentally changed the paradigm of plant canopy turbulent transport, revolutionised our ability to measure water use and carbon uptake in forests and crops, and led to models that are used in today’s sophisticated weather and climate modelling systems, including Australia’s.

From Edinburgh, Mike returned to Australia to join CSIRO in 1979 as a research scientist in the Division of Environmental Mechanics at the F. C. Pye Laboratory in Canberra that became his intellectual ‘home’ for the bulk of his CSIRO career. Mike epitomised the science ethos of the group at the Pye Laboratory, combining a superb scientific imagination with great mathematical skill that enabled novel and creative ideas to be transformed into solid science. His research exemplified the key pillars of research excellence: experimentation and validation underpinned by a strong theoretical framework.

In his thirty-five years with CSIRO, Mike held many senior positions—from researcher and senior scientist to

mentor, supervisor, and leader. In a trajectory that took him from his PhD research on micrometeorology to the global change issues that always motivated him, Mike made paradigm-changing contributions to environmental physics and Earth System science at scales that ranged from plant canopies to the planet, as described in the following sections.

Flow and transport in plant canopies

Mike’s early research made pivotal contributions to our modern understanding of turbulent flow in plant canopies and the consequent transport of momentum, energy and biologically important scalars such as CO₂ and other trace gases. This has profoundly influenced the scientific disciplines of micrometeorology and boundary layer meteorology and has led to significant advances in our ability to quantify the exchange of these properties, between the land surface and the atmosphere. As the many outcomes described in this paper demonstrate, Mike’s research has helped transform the way the terrestrial biosphere is included in the current generations of weather and climate models, which provide the essential underpinnings of disaster risk and reduction, climate mitigation policies and climate adaptation plans globally. Some significant steps along this journey included:

- In 1979, drawing on field observations, Mike identified and named the *Roughness Sub-Layer*—the atmospheric layer immediately above an aerodynamically rough surface such as a forest or city.³ This concept proved critical in parameterising such surfaces in weather and climate models in a physically realistic way.
- Mike devised and published the results from a series of now-classic wind tunnel experiments⁴ that led to his *localised near-field (LNF) theory*, a physically rigorous, elegant and practical means to quantify scalar transport within, and above, plant canopies. Mike also developed the inverse application of the LNF theory, which enables the sources and sinks of these scalars to be determined from the much easier to measure concentrations.
- Together with Drs John Finnigan and Yves Brunet in the early 1990s, Mike developed a *unified theory of turbulence in plant canopies*, including the ground-breaking discovery and evidence that this flow closely resembles a turbulent mixing layer rather than an atmospheric boundary layer. Not only did this unify many observed features of canopy flow, which could not be reconciled with boundary layer theory, but it also provided a physically based and consistent model to characterise and simulate turbulent

¹It’s worth noting that several other leading micrometeorological researchers were part of this group, including Dr Peter Coppin (pictured in Fig. 2) and Yaping Shao, who both worked in CSIRO’s Pye Laboratory with Mike.

²<http://fluxnet.ornl.gov/> and <https://ozflux.org.au/>. Accessed January 31, 2025.

³Raupach (1979).

⁴Raupach (1987).

flow and transport processes within, and above, plant canopies.⁵

- *Drag properties of aerodynamically rough surfaces:* Mike built on this canopy turbulence research to develop a physically based model of the shear stress (that is, drag) on an aerodynamically rough surface, and to partition this stress between the roughness elements (for example, plants) and the underlying ground.⁶ This model is applicable across a very large range of roughness element densities. It has underpinned strategies for ameliorating the risk of wind-driven soil erosion, dust uplift and sand transport; and associated environmental and economic losses. This physically based model was also the basis for Mike's method⁷ for estimating the surface roughness length. This method has been used in a broad range of applications, including to estimate roughness on regional to continental scales from satellite-based remote sensing.

Atmospheric flow and transport in (real) landscapes

In a natural extension of this research developing a quantitative understanding turbulent flow and transport in plant canopies, Mike went on to advance our knowledge of atmospheric flow in complex terrain, featuring for example, low hills, scattered trees and windbreaks. This research has led to important practical applications, such as designing windbreaks (and trees on farms generally) to optimise environmental outcomes and agricultural production, and demonstrates well Mike's commitment to applying his science to solutions for protecting the environment, locally and globally.

In a research project for the cotton industry to understand why high concentrations of the endosulfan pesticide were being observed in waterways, where there was no obvious runoff from nearby cotton farms. Mike proposed that vapour-phase transport could be a significant transport pathway in addition to the spray drift, dust borne, and water borne routes. Although the industry sector was initially sceptical, subsequent field testing confirmed the hypothesis that endosulfan could move from cotton farms to nearby rivers in its vapour phase, leading to revisions to industry guidelines for use of these pesticides.⁸

This example illustrates well Mike's commitment to applying his research to find solutions for some of Australia's pressing environmental problems. He was equally at home in the most basic and the most applied science, giving lie to the false

dichotomy that so many like to draw between the two. Great scientists are good at all of it.

There were three areas where Mike advanced the theoretical basis, and then proceeded to use this to develop quantitative guidance and solutions, namely: (i) wind erosion processes and impacts; (ii) the effects of tree windbreaks on farm microclimates, and the flow-on consequences for agricultural productivity and land degradation via dryland salinity and wind erosion of soils; and (iii) the effect of hills on winds near the surface and its influence on local climates, hydrology and atmospheric transport.

- *Wind Erosion:* From 1985 to 1995, Mike applied his knowledge of atmospheric turbulence to aeolian research and especially the problem of wind erosion, reflecting his personal interest in environmental issues—in this case, land conservation and, by extension, air quality, agricultural productivity and the cycling of carbon and its interactions with the Earth's climate system. His interest in aeolian processes was probably sparked during the period of successive El Niño events that culminated in record drought conditions in eastern Australia from 1982 to 1983. The resulting dust storm that hit Melbourne on February 8, 1983, brought wind erosion and its impacts to the public's attention.⁹

In 1993, Mike and colleagues provided the basis for subsequent dust research by identifying the sources of wind-blown dust, particularly the previously unappreciated role of saltating heavy particles in mobilising fine soil and clay particles so they can be lofted by the wind. This mechanism was revealed by an elegant wind tunnel experiment, and is crucial to quantifying nutrient losses in the topsoil that is stripped due to wind erosion, as the nutrients are preferentially attached to fine particles.¹⁰

Together with Dr John Leys (NSW Soil Conservation Service and a PhD student at Griffith University under the supervision of Professor Grant McTainsh), Mike developed Australia's aeolian-research wind tunnel, whose excellent fluid dynamic features made it a valuable research tool for applications in land-conservation, as well as research into fundamental wind-erosion processes.¹¹

Mike's critical advances in many aspects of aeolian research underpin much of our contemporary knowledge, numerical modelling, and solutions to wind erosion problems, as comprehensively described by Shao's group in 2015.¹² Mike's work also laid the foundation for understanding the

⁵Raupach and others (1996).

⁶Raupach (1992).

⁷Raupach (1992, 1995). Raupach and Finnigan (1995).

⁸Raupach and others (2001a, 2001b).

⁹Raupach and others (1994).

¹⁰Shao and others (1993, 1996).

¹¹Raupach and Leys (1990).

¹²Shao and others (2015).

effects of wind erosion on other components of the Earth System—such as the cycling of carbon between the land, rivers and oceans.

- **Windbreaks:** Growing concerns throughout the 1990s about the impacts of land degradation on Australia's agriculture and environmental sustainability saw investment by national programs, such as the Rural Industries, and Land and Water Research, Research and Development Corporations—RIRDC and LWRRDC respectively—along with CSIRO, into the fundamental and applied research needed to advance knowledge and develop solutions. An assessment of the potential role that agroforestry could play in Australia's farming regions found that sheltering animals was a major reason for planting trees on farms amongst Australian farming community. While research overseas reported significant increases in crop productivity from windbreak shelter, no equivalent research had been done in Australia, and therefore, the impacts of windbreaks on agricultural productivity in Australia was poorly known.

Mike was already part of a collaboration between CSIRO and HortResearch (New Zealand) investigating the physical effects of windbreaks on airflow, drawing on a long history of windbreaks research by Pye Laboratory colleagues and linked to his wind erosion research.¹³ When approached for his advice on the effects of windbreaks, Mike was therefore very excited at the prospect of building on this work to further advance our understanding of windbreak flows. Importantly, Mike also identified that a collaboration would be needed between environmental physicists, crop modellers and plant physiologists¹⁴ to translate this physical understanding into improving crop yields in Australia. This insight led to the establishment of the National Windbreaks Program in 1993, funded by RIRDC and LWRRDC under the Joint Venture Agroforestry Program; and began a fruitful scientific partnership with CSIRO's Pye Laboratory and crop modellers at APSRU.¹⁵

As part of this national program, Mike and colleagues undertook ground-breaking research that yielded the first experimental data on airflow and scalar transport around multiple and single arrays of porous windbreaks. These data validated and advanced a new model for windbreak flows that included scalar transport; provided the evidence base to quantify both direct (for example, soil losses and plant damage) and indirect (for example, changes in microclimate and water use) effects of wind shelter on plant growth and agricultural productivity; and underpinned guidance on designing and using windbreaks on Australian farms.¹⁶

- Mike's major contribution to the *physics of boundary layer flow over hills* arose from the time he spent on sabbatical at the University of Cambridge in the late 1980s. Based on the asymptotic small-perturbation model of Professor J. C. R. Hunt and colleagues for the structure of turbulent flow over a low hill, Mike and colleagues at the Cambridge Department of Applied Mathematics and Theoretical Physics developed a theory for the effect of a hill on heat and water vapour transfer.¹⁷ The surface energy balance imposes coupled boundary conditions on the two-scalar problem (that is, heat and water vapour). The solution, a linear recombination of the two scalars which separates the boundary conditions, provided a foundation for many later developments by others, including studies of the effect of topography on eddy flux measurements.

Biosphere—atmosphere interactions

Building on the culmination of this early research, Mike made fundamental contributions to understanding the multi-scale interactions between the terrestrial biosphere and the atmosphere: from leaves to plant canopies to regions, across timescales from hours to decades, typically with a focus on the role of real-world heterogeneity.

This research has provided the essential underpinning for measuring and modelling the coupled cycles of energy, water vapour (that is, evapotranspiration), greenhouse gases and other biologically active trace gases with certainty and accuracy. It applies equally to the transport of other important materials such as dust, nutrients and pollutants. In turn, these budgets provide the evidence base for developing and verifying climate policies to reduce net greenhouse gas emissions; decision-support systems, management strategies and policies for managing water resources; environmental sustainability measures; and more recently nature-based solutions to these problems.

- **Averaging and upscaling land surface heterogeneity:** Using scaling principles derived from fluid mechanics, Mike developed and demonstrated physically consistent (as required by thermodynamic constraints and the conservation equations) rules for averaging the heterogeneity in a landscape within the atmospheric boundary layer.¹⁸ Mike developed a theoretical framework that accounts for the dominant length scale of the landscape heterogeneity and demonstrated its validity and applicability using data and analyses from the OASIS field experiments of 1994 and 1995 (that Mike co-led, see also [Figs 1 and 2](#)). This work

¹³Judd and others (1996).

¹⁴Roslyn Prinsley, pers. comm. September 30, 2024

¹⁵Agricultural Production Systems Research Unit—a partnership between CSIRO, University of Queensland and the Queensland State Government, established in 1990.

¹⁶For example, Cleugh (2003).

¹⁷Raupach and others (1992). Raupach and Finnigan (1997).

¹⁸Raupach (1991, 1995). Raupach and Finnigan (1995).

provided the physical basis for methods to scale up surface-atmosphere interactions from leaves to paddocks to regions and beyond.

- *Estimating regional-scale land surface evaporation:* Building on this research, and ideas advanced by researchers overseas (primarily Keith McNaughton and Henk de Bruin), Mike proved that the evapotranspiration in a closed, well-mixed evaporating environment supplied with energy (for example, a well-watered pasture or crop during the daytime) corresponds to the thermodynamic equilibrium rate and is independent of the heterogeneity of the evaporating surfaces. He showed that regional-scale evapotranspiration therefore could be adequately represented by the equilibrium evaporation model (for a closed atmospheric boundary layer) or Priestley–Taylor (in the case of a convectively dominated atmospheric boundary layer).¹⁹
- *Atmospheric boundary layer budget methods* for inferring scalar fluxes: Mike introduced and developed simple methods, based on mass balance principles, for inferring the daytime regional-scale land-air exchanges of heat, water vapour and CO₂ from concentration measurements.²⁰

Quantifying the dynamics of Australia's landscapes

The demand for better weather and climate models in the 1990s led to increased interest in better representation of all aspects of the Earth's climate system, including the land surface, the cycling of energy, water, momentum and CO₂ in terrestrial ecosystems, and their feedbacks with climate across time scales ranging from decades to millennia, and length scales from regional to global. By the time of the IPCC's Third Assessment Report in 2001, the carbon cycle and dynamic vegetation models were being included in physical climate models—marking the early development of Earth System models that combine physical and biogeochemical systems into a single, fully coupled model.

Mike's earlier work on representing plant canopies, topography and spatial heterogeneity, and scalar and momentum transfer processes, was relevant to this challenge of building and improving climate and Earth System models where he made several profound contributions:

- *Consistent biophysical models from leaf to regional scales:* Mike developed a framework for modelling land-atmosphere fluxes that is consistent across scales ranging from leaves to plant canopies to regions, enabling him to develop prototype land surface schemes for use in global

and regional climate and hydrological models. The first of these, BIOSEquil, quantified for the first time, at a fine spatial scale, the long-term average balances of water, carbon, nitrogen and phosphorus for Australia's National Land and Water Audit's Agriculture Assessment.

- *Monitoring the state and trend of the terrestrial water balance of the Australian continent* (the Australia Water Availability Project, AWAP²¹): Building on his earlier foundational work, Mike led the development of this pioneering model—data fusion framework and modelling system, for simulating the past and current state of soil moisture and the water fluxes (rainfall, transpiration, soil evaporation, surface runoff and deep drainage) that contribute to changes in soil moisture across the entire Australian continent at a fine spatial resolution of five km and on a weekly basis in near-real-time.

These fundamental modelling developments from 2005 to 2012 delivered important information for managing Australia's water, carbon and nutrient resources. They were key steps towards Mike's longer-term goal of monitoring and understanding the dynamics of Australian landscape systems, especially in response to climate variability and change (for example, the impacts of climate on water availability that Mike and his team investigated as part of the South Eastern Australian Climate Initiative²²), in order to support adaptive, system-wide management through the feedback that arises from ongoing monitoring.

The outputs from these model-data systems (BIOS, AWAP and WaterDyn, the water balance model developed for AWAP) are still used by governments, university researchers and academics, industry and NGOs. This is a testament to the rigorous and physics-based approach to the modelling, and its significant value and impact in practical applications - hallmark features of Mike's skills and expertise.

- *The first terrestrial carbon budget for Australia:* Mike pioneered the conceptual basis and required parameterisation and data assimilation techniques to implement an innovative model—data fusion framework for quantifying the terrestrial budgets of carbon, water, energy and greenhouse gases. This approach enabled Mike and his team to deliver in 2013 the first biogenic carbon budget for continental Australia, constrained by a range of observations across multiple time and space scales.²³
- *Representing the land surface in climate and Earth System models:* Through Mike's intellectual leadership,

¹⁹Raupach (2000, 2001).

²⁰Denmead and others (1996). Cleugh and others (2004).

²¹Australian Water Availability Project: <https://eo-data.csiro.au/projects/awap/>. Accessed January 31, 2025.

²²South Eastern Australian Climate Initiative, SEACI: <https://www.seaci.org/>. Accessed January 31, 2025.

²³Haverd and others (2013).



Fig.2. Mike Raupach during the OASIS field campaign: (a) in a canola field at the Bowning field site; (b) with Mr Chris Drury, Technical Officer in CSIRO Environmental Mechanics; and (c) in the micro-meteorology data acquisition and processing caravan with Dr Peter Coppin, CSIRO Research Scientist who was a PhD student with Mike at Flinders University (centre), and John Bryan (right hand side)—a Technical Officer in CSIRO Environmental Mechanics. Mike is on the left hand side.

the foundation for Australia's national climate and Earth System model (ACCESS) and its land surface scheme (CABLE) was built.²⁴ Australia has contributed future climate simulations from ACCESS and CABLE to the last two phases of the World Climate Research Programme's Coupled Modelling Intercomparison Project (CMIP5 and CMIP6),²⁵ which provides the modelling data for the IPCC's Assessment Reports. Current CABLE developments, enabled by the NCRIS-funded ACCESS-NRI facility,²⁶ draw on many elements of the pioneering land surface modelling work undertaken by Mike and his team.

Earth System science and the global carbon budget

By the early 2000s, Mike's world-leading research quantifying the role of the land surface in moderating weather and climate led to a long and distinguished series of international roles. Mike served on the steering committees for many influential global fora, 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—the World Climate Research Programme (WCRP), International Human Dimensions Programme on Global Environmental Research (IHDP) 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.²⁷

The flagship project of the ESSP was the Global Carbon Project (GCP)²⁸ and, coinciding with his appointment as Science Leader of CSIRO's Earth Observation Centre (2003–5), Mike became the inaugural co-chair of the GCP (2000–8). Together, these roles both influenced and strengthened Mike's research into the feedbacks and interactions between the carbon and water cycles, climate and human activities. His research gaze lifted from paddocks and plant canopies to regions, continents and the planet; and expanded from purely biophysical analyses of carbon cycle fluxes to studies that measured human contributions to, and ways to mitigate, climate change.

This work at the global scale led to significant advances in our knowledge of carbon–climate–human interactions and was highly influential. For example, in the mid-2000s Mike took on a leading role with an international team who published a series of seminal and influential papers

identifying trends (including the recent acceleration) and regional drivers of CO₂ emissions, especially:

- Analyses²⁹ of the observed multi-decadal increase in the airborne fraction of CO₂ clearly demonstrating that the natural land and ocean CO₂ sinks were failing to keep pace with growing emissions.
- A companion paper,³⁰ focussing on the drivers of fossil fuel emissions, revealed the rapid increases in the carbon intensity of the energy system (that is, the CO₂ emissions per unit of energy generated), and the important role that China was playing in driving these changes. For the first time, fossil fuel emissions were found to be following the most carbon-intense scenarios of the IPCC's 2007 Fourth Assessment. If unchanged, this was a pathway leading to a 4°C rise in global mean temperatures (above pre-industrial temperatures). The analysis, and accompanying graphs showing increased emissions tracking the most carbon-intensive scenarios, issued a clear warning bell to the world: climate negotiations, which had started in the early 1990s (a decade and a half earlier), were having no impact on the emissions trajectories. Even worse, these trajectories were rapidly accelerating and taking the world to the worst-case scenario in terms of global warming.

These two papers were published in the prestigious *Proceedings of the National Academy of Sciences, USA* (PNAS) and had a profound impact around the world, via hundreds of media interviews; commentaries in popular science journals such as *Nature* and *New Scientist*; and through the thousands of citations in published scientific papers over the ensuing decades—including hundreds of papers replicating the team's methods in subsequent studies.

Consequently, Mike became a contributing author of the IPCC Fourth Assessment Report in 2007, in part because of his important research into the global carbon cycle and his leadership of the GCP's annual global carbon budget reports. He was also invited to advise the Garnaut Review of Australia's climate policy in 2008.

Mike and his colleagues in the GCP subsequently explored ways to partition the remaining global carbon budget between regions and nations—something that was regarded as impossible and maybe not even desirable. Across a range of temperature stabilisation targets, Mike developed a robust numerical approach and proposed a number of approaches that took account of ethical considerations, population, emissions per capita, current trends etc.³¹

²⁴Law and others (2012).

²⁵CMIP—Coupled Model Intercomparison Project. Accessed March 19, 2025.

²⁶<https://www.access-nri.org.au/models/model-components/land-model-components/>. Accessed January 31, 2025.

²⁷Steffen (2015).

²⁸<https://www.globalcarbonproject.org/>. Accessed January 31, 2025.

²⁹Canadell and others (2007).

³⁰Raupach and others (2007).

³¹Raupach and others (2014).

Mike's continuing interest in social dynamics increasingly led to research that transcended biophysical science, including shaping and co-editing the first transdisciplinary synthesis of carbon–climate–human interactions.³² In Australia, Mike was invited by the then Chief Scientist, Professor Penny Sackett, to lead the development of a report to the Prime Minister's Science, Engineering and Innovation Council on the importance of taking an integrative approach to managing energy, water and carbon in Australia; and he led the first phase of the Australian Academy of Science's *Australia 2050* project, which explored the implications of Australia's population trajectory for economic, social and ecological sustainability. His published research provided objective ways to determine nations' responsibilities and commitments for mitigating climate change globally.

The ANU Climate Change Institute

In 2014, after his thirty-five-year career with CSIRO, Mike joined the Australian National University (ANU) as Director of its Climate Change Institute. This Institute was initiated by the late Professor Will Steffen (1947–2023), another distinguished pioneer of Earth System science, whose pedigree can also be traced back to CSIRO's Division of Environmental Mechanics at the Pye Laboratory. Motivated by an increasingly strong sense of moral duty to speak out, especially on climate change, this move from CSIRO afforded Mike the opportunity to broaden his influence even more widely, drawing on his formidable scientific and communication skills to speak truth about government actions and policy on climate, untrammelled by the constraints imposed by CSIRO as a Statutory Authority of the Australian government.

Sadly, Mike's time as Director of the Climate Change Institute was cut cruelly short by his death in 2015, but his influence and legacy as one of Australia's predominant Earth System scientists in the period spanning the twentieth and twenty first centuries will endure, both through his technical contributions, the scientists he has mentored, and the path he has blazed in our quest to find solutions to the existential problem of our age.

Concluding remarks

Mike is survived by his wife, Hilary Talbot, and their three children, Alex, Anna, and Tim, the dearly loved individuals around whom his personal life revolved. His scientific legacy we have described at length above, but in conclusion, we need to re-emphasise the degree to which his research

set the standard of excellence not only for his scientific peers but more importantly for the myriad young scientists for whom his work served as a goal to which they should aspire. Mike's lifetime of research continues to profoundly influence the science of Earth's interconnected biosphere–climate system and defines the role that humans must play in sustaining our planet's health.

We also reiterate Mike's exemplary communication skills. These set an example to us all, especially his willingness to listen to what others had to say. He could synthesise complex concepts into clear, unambiguous metaphors and stories which, combined with his steadfast commitment to rigour and analytical ability, made Mike an enormously influential and effective leader who inspired others.

In closing, we make two final observations from the 2017 Australian Academy of Science celebration for Mike.³³ When asked, as Director of ANU's Climate Change Institute, about his views on scientists entering the political debate and expressing views on policy choices, Mike responded: 'To pretend that science, and in particular environmental science, can remain at the side of that debate is simply no longer tenable.' Clearly, the world is poorer for having lost a scientist such as Mike, who could contribute to and lead 'the informed, forthright, and humane discussion that is too often absent at the intersection of science and policy.'³⁴

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Data availability. Any relevant data sets can be found in the references cited and URLs provided as footnotes.

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