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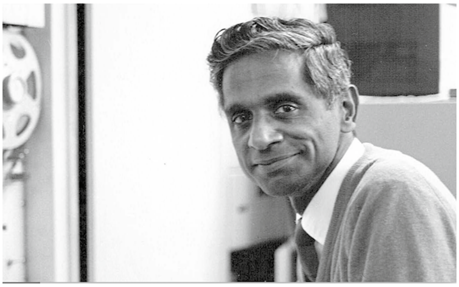
OBITUARY

Jagadish Chandran Kaimal (1930–2021)

John Finnigan[1] · James Wilczak[2]



Jagadish Chandran Kaimal, a prominent atmospheric scientist who made pivotal contributions to the study of turbulence in the Earth's boundary layer, died peacefully of natural causes at his home in Hamilton, New York, on 25 January 2021. He was 90 years old.

Chandran was born in 1930 in Kuala Lumpur, Malaysia (then Malaya). His father was a research botanist at the Rubber Research Institute (RRI) of Malaya. Chandran spent the World War II years with his mother and sister in India at the home of his mother's extended family in Parur, Kerala, while his father remained at RRI. After the war his father returned to India to head India's rubber research and production efforts from 1950 to 1960; he was Chandran's personal and professional model. Chandran earned his B.Sc. in Physics and Mathematics at Banaras Hindu University in 1952 and came to the University of Washington in Seattle in 1954, where in 1961 he received his Ph.D. in Meteorology and Electrical Engineering.

As a graduate student, Chandran became interested in finding ways to measure wind and temperature fluctuations accurately in order to gain better insight into laws governing turbulent flow near the ground. There was then a sense of urgency about this because of the risk of contamination of populated areas from accidents at emerging nuclear facilities and rocket launch sites, coupled with the absence of atmospheric diffusion models to predict the resultant pollutant spread. Attempts to use sonic anemometers to make the measurements of turbulent fluctuations necessary for such models were failing. However, in his

✉ John Finnigan
John.finnigan@csiro.au

1 Research School of Biology, Australian National University, Canberra, Australia

2 NOAA/Physical Sciences Laboratory, Boulder, CO, USA

Ph.D. dissertation, Chandran was able to build and field test a working sonic anemometer–thermometer. Joost Businger was his advisor and mentor in this effort.

In 1961 Chandran joined the Air Force Cambridge Research Laboratory (AFCRL) in Bedford, Massachussets. This laboratory had been actively studying turbulent transport in the boundary layer for nearly a decade. Chandran led the effort to further improve their approach to sonic anemometry, making use of emerging computer technology to acquire, process, and record the data. This enabled him and his colleagues to conduct their landmark Kansas 1968 Experiment, as it provided them with the fast-response (10 Hz) wind and temperature fluctuation measurements they required. They made measurements at three levels on a 100-ft tower [Note that 100 ft is approximately 30.5 m. Ed.] over extremely flat terrain in south-western Kansas (Kaimal and Wyngaard 1990). The results from Kansas '68 were pivotal in testing the fundamental theories of Kolmogorov, Monin, and Obukhov, which had been developed in Russia some decades earlier (Kolmogorov 1941; Monin and Obukhov 1954).

Together with complementary results from similarly flat terrain in Australia (Dyer 1967), the Kansas data led to the development of practical formulae linking turbulent fluxes and mean gradients of momentum and scalars in the surface layer and elevated Monin–Obukhov similarity theory to the central position in boundary-layer meteorology that it has occupied ever since. Another of the key theoretical outcomes of the Kansas '68 experiment was the Kaimal spectral forms, through which Chandran was able to demonstrate fundamental scaling properties of surface-layer turbulence and to link the behaviour of the large, energy-containing turbulent eddies to the inertial subrange theory of Kolmogorov (1941). These spectral forms still provide the benchmark against which turbulence data from landscapes more complex than Kansas are assessed. For his part of this landmark work, in 1969 Chandran was honoured for "Unique and Distinguished Contributions to the Research and Development Program of the United States Air Force".

The next major challenge confronting AFCRL was to extend the understanding of the surface-layer flow structure to the top of the boundary layer—roughly 1500 m on a clear day—where the rising air begins its slow downward return flow. The Minnesota 1973 Experiment accomplished this with wind and temperature sensor probes packaged to hang from the tethering cables of a large barrage balloon. Developed by the United Kingdom Meteorological Office, these packages were launched and operated over the flat plains of north-western Minnesota by Christopher Readings of the UK Meteorological Research Unit. This joint effort provided important information on the evolution and decay of the whole boundary layer as it responded to the semi-diurnal heating of the ground by the sun. Amongst other results it explained why vertical turbulent motions in the surface layer scaled with height above the ground whereas horizontal fluctuations did not, a question posed by the Kansas'68 data.

In 1975, Chandran and three colleagues, Duane Haugen, John Wyngaard, and Jim Newman, moved from AFCRL to Boulder, Colorado, to join the NOAA Wave Propagation Laboratory (WPL). They were able to bring with them their entire inventory of sensors and the Mobile Micrometeorological Observing System. This move accelerated WPL's plans to build an observing facility with a 1000-ft tower to test and intercompare the remote sensors (radars, lidars, and sodars) they were developing to monitor the lower atmosphere. By 1978, the new Boulder Atmospheric Observatory (BAO) was built and ready for operation with eight levels of sonic anemometers and other sensors in continuous operation. From then until the mid 1990s, it was the site of numerous intercomparison experiments and turbulence-structure studies by scientists from many countries. In 1980, the BAO received a Unit Citation for "Outstanding Individual and Collective Contributions in Furthering NOAA's Mission".

Chandran directed the BAO operation until 1982 when he moved to head the Atmospheric Studies Program at WPL. He never lost his interest in sonic anemometry though, and over the years he continued his collaboration with Herbert Zimmerman of Applied Technologies in Longmont, Colorado, which made the instruments deployed at the BAO. Chandran devoted most of his final year at the WPL working with Australian scientist John Finnigan to write a book, Atmospheric Boundary Layer Flows, published by Oxford University Press in 1994—a fitting culmination of three decades of work and more than 70 papers in peer-reviewed journals and conference proceedings.

His colleagues will remember him for his agile and inventive mind but mostly for his warmth and kindness, especially to young scientists. When John Finnigan arrived in Boulder in 1978 to start a post-doctoral fellowship at the Cooperative Institute for Research in Environmental Sciences, Chandran took him under his wing and gave him free rein amongst the cornucopia of data being recorded at the BAO at too fast a rate for the BAO's small scientific team of Chandran and John Gaynor to monitor in detail. The discovery of numerous days when gravity-wave motions modulated the turbulence at the BAO led Chandran to introduce Finnigan to Franco Einaudi and the start of a collaboration that was to produce a stream of papers on wave–turbulence interaction at the BAO.

Similarly, as a graduate student in 1978, Jim Wilczak was fortunate to work with Chandran using data collected at the BAO to help define coherent structures in turbulent flows—an ongoing interest of Chandran's. Later, after Jim's return as a post-doctoral researcher, further work that Chandran strongly supported revealed the important influence that topographically-generated mesoscale flows had on the boundary-layer structure at the BAO. Jim notes that Chandran taught by example, providing a high standard for others to emulate. One particular lesson he learned through Chandran was the importance of communicating research results clearly and concisely, and in particular of the value of carefully crafted publication figures. Each of Chandran's figures was meticulously worked and reworked, going through multiple drafts, blending a mix of art and science to produce lasting, iconic images of boundary-layer science that remain well known to the present.

It was typical of Chandran to lavish the same care and attention on young scientists like Wilczak and Finnigan and many others, as he did on luminaries of turbulence such as Julian Hunt and Akiva Yaglom, whom he attracted to work with him at the BAO. The scientifically fruitful collaborations that resulted magnified his enduring influence on our field.

In 1992, Chandran retired at age 61 and moved to Hamilton, New York, with his wife, Lorraine, to live near their eldest child Padma and her family. He is survived by Lorraine, their children Padma, Narayan, and Maya and their spouses, six grandchildren, and one great-grandchild.

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