Zonal Jets

Phenomenology, Genesis, and Physics

In recent decades, great progress has been made in our understanding of zonal jets across many disciplines – atmospheric science, oceanography, planetary science, geophysical fluid dynamics, plasma physics, magnetohydrodynamics, turbulence theory – but communication between researchers from different fields has been weak or non-existent. Even the terminology may be so disparate that researchers working on similar problems do not understand each other. This comprehensive, multidisciplinary volume will break cross-disciplinary barriers and aid the advancement of the subject. It presents a state-of-the-art summary of all relevant branches of the physics of zonal jets, from the leading experts. The phenomena and concepts are introduced at a level accessible to beginning graduate students and researchers from different fields. The book also includes a very extensive bibliography.

BORIS GALPERIN is an associate professor in the College of Marine Science at the University of South Florida, where he has received two Outstanding Research Achievement Awards. He discovered a deep similarity between zonal jets in oceans and on giant planets, conducts laboratory investigations emulating geophysical and planetary flows, and is a co-developer of an analytical theory of anisotropic turbulence that explains observed spectra up to numerical coefficients.

PETER L. READ is a professor in the Department of Physics at the University of Oxford. He is best known for research on laboratory analogues of atmospheric and oceanic circulation, and for studies of the dynamics of almost all Solar System planets (including the Earth). He was a co-investigator on the Cassini and Mars Reconnaissance Orbiter missions. He was awarded the Adrian Gill Prize of the Royal Meteorological Society and the Lewis Fry Richardson Medal of the European Geosciences Union for interdisciplinary contributions to the nonlinear dynamics of rotating fluids and planetary atmospheres.

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ZONAL JETS

Phenomenology, Genesis, and Physics

Edited by

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FOREWORD

The winds in our atmosphere and currents in our oceans are often described in terms of *turbulence*, *vortices*, *waves*, and *jets*. We introduce these concepts and the analysis techniques that go along with them to try to make sense of the complexity of the flows that we observe. The present volume takes the concept of jets as its primary focus, but starting from this perspective it provides a distinctive and timely introduction to current trends in atmospheric and oceanic fluid dynamics, and the dynamics of rotating, stratified flows more generally.

Turbulence is sometimes thought of as the amorphous background, characterized by chaos but also by distinctive spectral shapes and movements of energy between scales. From the perspective of atmospheric and ocean fluid dynamics, a great advance was the realization of the profound differences between two-dimensional and three-dimensional turbulence, with energy cascading to larger rather than smaller scales in the two-dimensional case, resulting in much reduced dissipative flows. The naïve picture that the thinness of the atmosphere and oceans as compared to the radius of the planet underlies the relevance of two-dimensional turbulence for large-scale flows is incorrect. Rather, it is the extent to which the flow is dominated by solid-body rotation when viewed in an inertial reference frame, and the way in which rotation constrains the vertical gradient of the horizontal winds, that is the key – a constraint that was not fully incorporated into our theories of geophysical fluid dynamics until the advent of quasi-geostrophic theory in the late 1940s.

The study of atmospheric *vortices* goes back at least to Aristotle's theory of "whirlwinds" in his *Meteorology* (not the starting point that I recommend to my students). There are vortices in the atmosphere, tropical cyclones, that are so well-defined that we give them names, but the Jovian Great Red Spot takes the prize for longevity and name recognition. Well-defined vortices on scales of tens to hundreds of kilometers are now known to be widespread in the ocean. Vortices can emerge naturally from more turbulent antecedents in the presence of background rotation, and idealized systems have been designed to study the transition between turbulence-dominated and vortex-dominated flows.

But a quick look at the weather map makes it clear that an alternative starting point for describing large-scale atmospheric flows is that of *waves*. These are predominately Rossby waves, owing their existence to ambient vorticity gradients. These vorticity gradients in turn exist due to the fact that the radial component of the vorticity due to solid-body rotation is a function of latitude, increasing monotonically from the south pole to the north pole, and it is this gradient that creates the potential for Rossby waves. This seemingly esoteric consequence of rotation and sphericity colors all of large-scale meteorology and oceanography. Quasi-geostrophic theory again provides the key insights into how Rossby waves can be generated through the process known as baroclinic instability in both atmosphere and oceans. When these waves become sufficiently nonlinear they can generate geostrophic (quasi-two-dimensional) turbulence or roll up into vortices, justifying the term *extratropical cyclones* even though the wavy underpinning of these mid-latitude weather producers are always evident. We sometimes refer to this mix of finite-amplitude Rossby waves and quasi-geostrophic turbulence as the *macroturbulence* of the mid-latitude troposphere.

The same combination of rotation and sphericity creates conditions that allow for the existence of persistent zonal (east–west) jets in planetary atmospheres. Zonal jets are also prominent in the oceans, especially near the equator and in the Southern Ocean. These jets are combinations of forced and internally generated structures. In the atmosphere, radiation creates a north–south temperature gradient in the troposphere that, in combination with rotating and surface friction, creates west-to-east winds in the upper troposphere. These winds are reshaped by the Hadley circulation in the tropics, creating the subtropical jet, and by energy fed back into these zonal flows by the atmosphere's macroturbulence, the dominant process shaping mid-latitude *eddy-driven* jets. The Earth presents a relatively complex setting, with the subtropical jet not always clearly separated from the single eddy-driven mid-latitude jet. But if you have an atmospheric model all you have to do is increase the rotation rate or increase the radius of the planet to create better separation, and, most famously, multiple eddy-driven zonal jets, resulting in banded circulation patterns having more than a superficial resemblance to that observed on Jupiter.

Zonal jets in our terrestrial atmosphere contain about half of the total kinetic energy of the atmospheric flow, and as much as 90% of the available potential energy (the potential energy that can be converted to kinetic energy by rearranging the fluid adiabatically and lowering its center of mass). It is this available potential energy in the jets that is tapped by baroclinic instability, providing the engine driving the atmosphere's macroturbulence, which then feeds back to shape the jets into forms that may have little resemblance to the zonal flows that exist in the absence of these interactions.

Change in the structure and position of jets is a central theme in climate change research. We are confident that the ozone hole in the stratosphere over Antarctica has caused the mid-latitude tropospheric jet in the Southern Hemisphere to shift poleward, and the world's climate models consistently predict that a warming surface will also push the mid-latitude jet poleward in both hemispheres, accompanied by all of the weather patterns that ride on this jet. We need to understand these jet shifts due to human activity far better than we do today.

This ambitious book provides an up-to-date survey of atmospheric and oceanic jets and their interactions with turbulence, waves, and vortices. It introduces the reader to the latest theoretical ideas and, crucially, it brings in data and insights from studies of other planetary atmospheres, especially the gas giants with their beautiful jet structures, and from laboratory experiments, to create a broad overview of jet dynamics that will widen the perspectives of students and active researchers studying the dynamics of the atmosphere, the oceans, other planetary atmospheres, and climate change.

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ACKNOWLEDGMENTS

The origins of this book date back to early in 2011 when one of us (BG) proposed bidding for a study team at the International Space Sciences Institute (ISSI) in Bern, Switzerland. This entailed identifying a suitable problem and assembling a small group of interested scientists who might be prepared to come together for a series of meetings over a period of three years. The theme we came up with focused on the origin of zonal jets, primarily as found in the atmospheres and oceans of the Earth and other planets. This was, we thought, a rich field in which, although there was already a large literature of research on the subject, many problems were outstanding. It was also timely, given recent developments e.g. in satellite oceanography and planetary exploration, as well as in numerical modeling and related theory, especially in relation to eddy-driven phenomena and the anisotropic properties of turbulence in rotating fluids.

In the event, our application was successful and led to the establishing of a core team of around a dozen scientists at various career stages, and an agreement to begin with our first meeting in March 2012. At the same time, Boris floated the idea with Cambridge University Press (CUP) that this team could collaborate to produce an authoritative book on the subject. ISSI encourage their study teams to produce a publication at the end of their project, and so we were pushing at an open door so far as they were concerned. CUP responded enthusiastically, and so our journey began, to end with the production of this book. For this we must acknowledge the support, encouragement, and patience of our editor, Dr Matt Lloyd, for sticking with us and, together with his colleague, Zoe Pruce, for all their help in bringing this project to fruition.

At the outset, the scope of our discussions was restricted to geophysical jets and related studies in laboratory fluid-mechanical experimentation, but from an early stage we entrained the interest of Professor Pat Diamond from the University of California, San Diego. Pat came from the plasma physics community, but had long been intrigued by analogies, both mathematical and physical, between plasma phenomena, such as drift wave turbulence, and Rossby wave turbulence in rotating flows. Thanks to Pat's interest and encouragement, we were persuaded to broaden the scope of the team to explore these analogies in greater depth. Accordingly, the following two meetings of the ISSI team in 2013 and 2014 included participation by a number of (mostly theoretical) scientists from the plasma physics community, during which a host of insights were shared. This meant that all of us were being confronted by some challenging new and unfamiliar ideas, concepts, and terminology, but the synergy rapidly became apparent. So we must acknowledge and express our appreciation of all of the participants throughout the ISSI program for joining in this exercise with such energy and enthusiasm. The success of these meetings owes much to the dedication and hospitality of the staff at ISSI, of whom we would particularly mention Dr Maurizio Falanga and his team, especially Saliba F. Saliba for his assistance in running the IT equipment during our meetings at ISSI. We also thank Jesse Hoemann for his efforts in maintaining the ISSI web pages that were so useful in keeping the study team and (later) the authors informed about the ISSI meetings and the book project.

Having pulled together such a team for the ISSI study, the real work began to build a team of authors to write the individual chapters for the book. While the ISSI participants were already signed up to contribute chapters to the book, it rapidly became apparent that this would still leave gaps in the coverage of certain topics, so we are very grateful to a number of other authors who either volunteered or were recruited to the cause after the end of the ISSI project. From the original core team, our group had expanded to about 60 contributors by the end of this endeavor. Most scientists these days lead very busy lives, keeping up with the literature, writing grant proposals and research papers, and balancing a range of responsibilities such as managing laboratories, teaching, administration, and a host of other activities. So the editors are greatly indebted to all of our colleagues for agreeing to take some precious time out of their busy lives to summarize and review recent major results in their areas of specialization. We are also grateful for their patience and persistence in the face of what must often have seemed to some like incessant nagging (or stalling) from the editors.

Next in line for acknowledgment by all of us – editors, authors, and readers – are the dozens of colleagues who provided independent external reviews for all of the chapters of this book. These people are also among the leading experts in a wide range of topics, and they, too, sacrificed significant time to perform an important community service: making sure that the results and other information in these chapters are accurate, complete, and balanced. Their time and effort have substantially improved this review, and will hopefully have made it a much more useful future resource for students and other researchers new to this field.

Finally, we express our profound gratitude to Dr Roland Young for his invaluable assistance with the final proofreading and the correction and consolidation of the reference list. The accuracy, consistency and completeness of the latter is due in no small measure to his herculean efforts.

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ABBREVIATIONS

ACC	Antarctic Circumpolar Current
ADCP	Acoustic Doppler Current Profiler
ADT	Absolute Dynamic Topography
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AVHRR	Advanced Very High Resolution Radiometer
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
AzC	Azores Current
CCS	California Current System
CCSR	Center for Climate System Research
CE2	Second-order Cumulant Expansion
CHM	Charney–Hasegawa–Mima
CHME	Charney–Hasegawa–Mima equation
CIV	Correlation Imaging Velocimetry
CLS	Collecte Localisation Satellites
COCO	CCSR Ocean COmponent model
CTD	Conductivity, Temperature and Depth
DIA	Direct Interaction Approximation
DIMES	Diapycnal and Isopycnal Mixing Experiment: Southern Ocean
DNS	Direct Numerical Simulation
DSS	Direct Statistical Simulation
DWBC	Deep Western Boundary Current
EBC	Eastern Boundary Current
EDJ	Equatorial Deep Jet
EDQNM	Eddy-Damped Quasi-Normal Markovian
EEJ	Extra-Equatorial Jet
EHM	Extended Hasegawa–Mima
EIC	Equatorial Intermediate Current
EICS	Equatorial Intermediate Current System
EJ	Equatorial Jets
EKE	Eddy Kinetic Energy
ESA	European Space Agency
EOF	Empirical Orthogonal Function
ESA	European Space Agency
EUC	Equatorial UnderCurrent
GCM	General Circulation Model
GFD	Geophysical Fluid Dynamics
GRACE	Gravity Recovery and Climate Experiment
HLCC	Hawaiian Lee CounterCurrent
HW	Hasegawa–Wakatani
ICCs	Intermediate CounterCurrents
ITCZ	InterTropical Convergence Zone
JPL	Jet Propulsion Laboratory
KPP	K-Profile Parameterization
LEIC	Lower Equatorial Intermediate Current
LH	Low-to-High
MDOT	Mean Dynamic Ocean Topography
MDT	Mean Dynamic Topography
MHD	magnetohydrodynamics
mHME	modified Hasegawa–Mima Equation
MI	Modulational Instability
MRS	Miller–Robert–Sommeria
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NEC	North Equatorial Current
NECC	North Equatorial CounterCurrent
NEIC	North Equatorial Intermediate Current
NICC	North Intermediate CounterCurrent
NOAA	National Oceanic and Atmospheric Administration
NSCC	North Subsurface CounterCurrent
ODE	Ordinary Differential Equation
OFES	Ocean Model for the Earth Simulator
OGCM	Ocean General Circulation Model
PDE	Partial Differential Equation
PDF	Probability Density Function
PF	Polar Front
PIV	Particle Image Velocimetry
PNA	Pacific–North American
POP	Parallel Ocean Program
PV	Potential Vorticity
QDIA	Quasi-diagonal Direct Interaction Approximation
QG	Quasi-Geostrophic
QL	Quasi-Linear
QZJ	Quasi-Zonal Jet
RAFOS	SOFAR, spelled backward
ROMS	Regional Ocean Modeling System
S3T	Stochastic Structural Stability Theory
SACCF	Southern ACC Front
SAF	SubAntarctic Front
SCC	Subsurface Countercurrent
SEC	South Equatorial Current
SECC	South Equatorial CounterCurrent
SEIC	South Equatorial Intermediate Current
SICC	South Intermediate CounterCurrent
SL9	Shoemaker–Levy 9
SLA	Sea Level Anomaly
SOFAR	SOund Fixing And Ranging
SOFINE	Southern Ocean Finescale Mixing Experiment
SPCZ	South Pacific Convergence Zone
SSCC	South Subsurface CounterCurrent

SSD	Statistical State Dynamics
SSH	Sea-Surface Height
SST	Sea-Surface Temperature
SVP	Surface Velocity Program
TFM	Test-Field Model
WBC	Western Boundary Current
WJ	Wyrtki Jets
WKB	Wentzel–Kramers–Brillouin
WOCE	World Ocean Circulation Experiment
WT	Wave Turbulence
XBT	eXpendable BathyThermograph
ZELTs	Zonally Elongated Large-scale Transients
ZF	Zonal Flow

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DEDICATIONS: RAYMOND HIDE AND GARETH P. WILLIAMS

During the production of this book our community sadly lost two great scientists who were present at the dawn of geophysical and planetary science and contributed a great deal to shaping the science as we know it today. They were Raymond Hide and Gareth P. Williams. We dedicate this book to their memory.

Raymond Hide

Raymond Hide CBE ScD FRS (1929–2016)

Raymond Hide was born on 17 May 1929 into a working-class family in an impoverished coal-mining village in South Yorkshire. The eldest of three brothers, he had a tough early life. His father committed suicide when he was 12 and his mother left the family shortly afterwards, leaving Raymond and his grandmother to bring up his two younger brothers, earning money by cleaning windows and working in a baker's shop. Despite these hardships (or perhaps because of them?) he turned to academic study (at which he excelled), winning scholarships, first to the Percy Jackson Grammar School near Doncaster and later to read Physics at Manchester University, from which he graduated in 1950 with first class honours.

It was during his time at Manchester that he encountered the Nobel Prize-winning physicist P. M. S. (later Lord) Blackett, which, together with his background from the coal-mining industry, fired his lifelong interest in geophysics. At this time, in the late 1940s, Blackett was exploring a new theory for the generation of the Earth's magnetic field and Raymond became involved in some of Blackett's measurements while at Manchester. Blackett's theory was in competition with the dynamo hypothesis, being promoted at the time by Sir Edward ("Teddy") Bullard, then at Cambridge University. Raymond subsequently went to Cambridge to work for his PhD, initially to investigate a laboratory analogue of fluid motion in the Earth's core in the form of a differentially heated, rotating, cylindrical fluid annulus. Although this experiment was a long way from being able to capture the Earth's geodynamo, its possible link to the dynamics of the atmosphere was only made (according to Raymond's own account) following a chance encounter with Sir Harold Jeffreys, who happened to pass by Raymond's experiment when it was running, peered over his shoulder and remarked "Hmm – looks like the atmosphere!" This opened up a wholly new perspective on these rotating annulus experiments and Raymond's seminal observations of baroclinic waves, quasi-periodic "vacillations", intransitive multiple flow states and hysteretic transitions towards irregular states we now interpret as "deterministic chaos" or "geostrophic turbulence". It is difficult now to overestimate the significance of these discoveries, which predated the much more prominent developments in the theory of dynamical systems and chaos in the 1970s and 1980s by others such as Ed Lorenz, David Ruelle and Floris Takens.

After his PhD, Raymond moved briefly to work with S. Chandrasekhar at the University of Chicago in the USA, where he also met fellow experimentalist Dave Fultz (famous for his "dishpan" baroclinic convection experiments) before spending a period of National Service working in plasma physics at Harwell. Raymond met Ann Licence whilst at Harwell, marrying her in 1957 and beginning a long and devoted partnership that lasted until Ann's death in 2015. He became a lecturer in physics at King's College, University of Durham (now the University of Newcastle upon Tyne) in 1957, but in 1961 he was offered a prestigious faculty position at MIT where he set up a successful laboratory and was promoted to full professor.

This proved to be a very important development, bringing him into close contact with key people in meteorology at the time, such as Ed Lorenz and Jule Charney, who were then developing a whole new way of thinking about the general circulation of the atmosphere and issues such as its predictability. The influence of Hide's and Fultz's experiments on these developments was frequently acknowledged by Lorenz himself. It is now clear that they were crucial in establishing the relevance and physicality of idealised theories of baroclinic instability, such as those of Eric Eady and Jule Charney, to synoptic meteorology. Raymond's time at MIT also brought him into contact with NASA's space programme during the opening phases of the unmanned exploration of other planets and their atmospheres. This stimulated his imagination to propose inventive explanations for features such as Jupiter's Great Red Spot (the first of these based on the concept of a Taylor column over a large mountain) and cloud bands, which remained an object of his interest throughout his life. For the latter, he noted the significance of the length scale $L = (U/\beta)^{1/2}$ some ten years before its more well-known invocation by Peter Rhines (now known as the "Rhines scale"). For the former, it relied on the presence of a solid obstacle blocking the flow, which became untenable on realising that Jupiter has no solid surface; he later came up with other ideas involving sloping convection that are still being discussed.

In 1967 Raymond made the headlines in the UK when he was persuaded by Sir John Mason to return to England to take up a senior scientist position at the Met Office, against the "brain drain" of European talent toward the USA at the time. Mason's reasoning was to invigorate the research culture of the Met Office by recruiting a charismatic intellectual role model who could connect Met Office researchers more effectively with the wider scientific world. With hindsight, this led to one of Raymond's most effective legacies, as a succession of researchers spent part of their early career working in Raymond's research group, alongside university research students and occasional international visitors, before moving on to senior and influential positions elsewhere within the Met Office and beyond. His irrepressible energy and enthusiasm also led him to interact effectively with other, more conventional, areas of meteorological research, playing a role, for example, in John Findlater's discovery in the early 1970s of the Somali low-level jet and identifying it as a western boundary current (similar to the Gulf Stream and Kuroshio in the oceans) in the atmosphere. In other work on the Earth's rotation, an extremely fruitful collaboration he led between the Met Office, ECMWF and JPL was able to link small fluctuations in the length of the day and instantaneous pole of rotation to exchanges of angular momentum between the atmosphere and solid Earth. This showed that astrogeodetic measurements of the Earth's motion could shed important light on the dynamics of the atmosphere and, moreover, that the atmosphere plays an important role in exciting natural oscillations (the "Chandler wobble") in the solid Earth itself.

Raymond moved to Oxford in 1990, briefly to become the Director of the Robert Hooke Institute, a joint collaboration which he helped to set up in the 1980s between Oxford University, the Met Office and NERC's Institute for Oceanographic Studies, while the remainder of his group was assimilated into the university. He retired from the Met Office in 1992 and later moved to London, where he remained active for a while, based at Imperial College. He died peacefully on 5 September 2016 after a long period of illness and is survived by his two daughters, Kathryn and Julia, his son, Steve, and their respective families.

Raymond's research career was the epitome of cross-disciplinary creativity, embracing fundamental fluid mechanics and magnetohydrodynamics, planetary interiors, atmospheres and oceans, climatology and meteorology. His many achievements were recognised by a succession of medals and awards from both national and international learned societies and institutions. He had the unique distinction of having been elected President of both the Royal Meteorological Society (1974–76) and the Royal Astronomical Society (1983–85), as well as of the European Geophysical Society (1982–84). For those of us who had the privilege of working with him, it is a joy to recall and appreciate his energy, creativity, enthusiastic curiosity, wisdom and, in particular, his selfless support, advice and encouragement for generations of younger scientists. He was also a talented harmonica player!

PETER L. READ
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Gareth P. Williams (1939–2014)

Gareth Williams, an atmospheric scientist who focused on the large-scale structure of planetary atmospheres and a fellow of the American Meteorological Society, died on November 5, 2014 at the University Medical Center of Princeton. Gareth was born in a small Welsh-speaking community, Penrhynside, in North Wales in the UK. He once said that he only learned English when he went to school. From an early age he excelled in mathematics and outdoor sports. He loved biking and roaming in the mountains of Wales close to his home. He received a bachelor's degree and a PhD in mathematics at the University of Wales at Bangor. He was recruited by Joseph Smagorinsky to come to the United States and join the General Circulation Laboratory of the US Weather Bureau in Washington, DC (later the Geophysical Fluid Dynamics Laboratory, GFDL, of NOAA in Princeton, NJ). In 1964 Gareth married Janet Harding, whom he had met while she was vacationing near his seaside village; a keen cyclist, he once rode 100 miles to visit her at her home in England. After a honeymoon in Corsica they crossed the Atlantic on the *Queen Mary* for Gareth to take up his position at the Weather Bureau.

In the 1960s the discipline of geophysical fluid dynamics was still in its infancy. There was great interest in the laboratory experiments of Dave Fultz and Raymond Hide, which illustrated the physics of stratification, rotation and horizontal density gradients and the remarkable variety of fluid dynamical behavior that result. Gareth's first major contribution was to build a numerical model of Hide's experiment that could be run on the primitive computers of the day. In addition to understanding these laboratory experiments more thoroughly, the goal was also to see if numerical models could succeed in simulating the parameter dependence of flows that resemble the general circulation of the atmosphere. Gareth's investigations succeeded, providing an invaluable link between laboratory results, numerical models and theory, and lent credibility to early audacious attempts at simulating general circulation.

After the GFDL moved from Washington to Princeton in the fall of 1968, Gareth's interests gradually moved from laboratory experiments to the dynamics of planetary atmospheres. In the early 1970s groundwork was being laid for an ambitious exploration of the planets of our solar system by NASA's Jet Propulsion Laboratory. While the banded patterns on the face of Jupiter were known since Galileo's time, the data available provided little insight as to their origin. The Pioneer probes showed that the visible outer clouds of Jupiter were in motion and showed a regular pattern of circulation, spatially correlated with the light and dark bands known previously. Wide areas of cum sole zonal motion were separated by narrower bands of much faster motion in the opposite direction. This suggested to Williams that the circulation of Jupiter was driven by a type of geostrophic turbulence analogous to that which exists in the Earth's atmosphere, but with very different scales relative to the size of the planet. To support this conjecture Williams used a numerical model of a shallow, two-dimensional flow of uniform density on a spherical surface. The turbulence in this model was generated by random forcing. The flow patterns in

Gareth Williams in 1983. In the background, Mt Snowdon, the highest peak in Wales.

the model, with multiple zonal jets emerging spontaneously, received widespread attention when first published in 1975. Earlier work had emphasized the possibility that the jets visible at the surface were a manifestation of deep convective cells driven by heating in the interior of the planet. Gareth's work highlighted a very different perspective in which the surface flow is driven in a thin shell by the absorption of solar radiation, resulting in dynamics familiar to terrestrial meteorologists, albeit in a very different parameter setting.

Gareth devoted much of his career to pursing this idea, first in a two-dimensional framework, building on the work of Peter Rhines on the interactions between waves and jets in rotating flows, and then in three-dimensional systems in which the imposed random stirring was replaced by naturally occurring instabilities. Although definitive theories of the Jovian atmosphere must await future three-dimensional measurements of Jupiter's atmospheric circulation, Gareth's innovative work on surface-driven theories have left a permanent imprint on the field. Another feature of the Jovian atmosphere, the Great Red Spot, also fascinated Gareth and he continued to energetically pursue the goal of simulating the Jovian jets, the Great Red Spot and other smaller vortices in Jupiter's atmosphere in a single coherent model until his health problems intervened in recent years. While he collaborated with a number of colleagues, Gareth primarily wrote single-authored papers which reflected his distinctive style and a very sharp focus on the problem that fascinated him, a problem best described by the title of a 1982 paper in which he showed how to create a Jovian-like circulation by modifying parameters in a standard terrestrial global atmospheric model: "The Range and Unity of Planetary Circulations."

In the 1970s, when the lab first moved to New Jersey, we had winters with snow on the ground for weeks at a time. Gareth took up cross-country skiing and became an expert. He had the love of music of a true Celt and regularly attended concerts in Princeton with Janet, his wife of 50 years. He leaves behind two sons and three grandchildren.

Isaac Held and Kirk Bryan
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