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ScienceDirect
Progress in Oceanography 70 (2006) 91–112
Progress in Oceanography
www.elsevier.com/locate/pocean

Gabriel T. Csanady: Understanding the physics of the ocean

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Received 27 January 2006; accepted 26 March 2006
Available online 23 August 2006

Abstract

Gabriel T. Csanady turned 80 in December 2005 and we celebrate it with this special Progress in Oceanography issue. It comprises 20 papers covering some of the many areas that Gabe contributed significantly throughout his professional career. In this introductory paper we briefly review Gabe's career as an engineer, meteorologist and oceanographer, and highlight some of his major contributions to oceanography, both as a scientist as well as an educator. But we also use this opportunity to remember and thank Gabe, and his wife Joyce, for being such good friends and mentors to several generations of oceanographers. The authors of the collection of papers in this volume deserve special thanks for their efforts. We also are pleased to acknowledge the support of Progress in Oceanography's editor, Detlef Quadfasel, and the many anonymous reviewers who generously contributed their time and expertise.

Keywords: Csanady; Oceanographer; Biography; Ocean circulation; Turbulent diffusion; Air-sea interaction

1. Engineer, meteorologist, and physical oceanographer

Gabriel Tibor Csanady started his studies of mechanical engineering at the Budapest Technical University, and completed them at the Technische Hochschule Munich in 1948. His Diplomarbeit (thesis) on gas turbines paved the way for a later monograph on the *Theory of Turbomachines* (McGraw Hill series in Mechanical Engineering, 1964). Work in the power generation industry in Germany and Australia brought him in contact with air pollution problems. Research on such problems led to entry into academia at the University of New South Wales, and to a Ph.D. thesis on atmospheric diffusion (1958). After a brief foray into jet noise research in England and Canada, he joined the faculty of the University of Waterloo as professor and Chairman of the

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0079-6611/$ - see front matter
doi:10.1016/j.pocean.2006.07.002

Mechanical Engineering Department. There he started a vigorous graduate program, putting his students to work on projects relating to air pollution, jet noise and, in an important new direction, water pollution in the Great Lakes.

Work on the Great Lakes was motivated in part by the construction of a large nuclear power plant on Lake Huron, and was carried out with the help of the Great Lakes Institute of the University of Toronto. The University of Toronto established a research station at Baie du Dore on Lake Huron, where Gabe Csanady centered his research activities from 1962 to 1971. His work on atmospheric diffusion and boundary layer meteorology was supplemented by studies of turbulence and diffusion in the Great Lakes, largely in connection with Travelers Research Co., Hartford, Connecticut. Contact with the staff of Travelers gave the stimulus to much of his work, that lead ultimately to the monograph *Turbulent Diffusion in the Environment* (Reidel Publishing Co., 1963). During the studies of effluent dispersal in Lake Huron, Gabe was confronted by the general lack of understanding of the dynamics and kinematics of coastal currents in large lakes. This problem intrigued Gabe and he began developing the conceptual model of the coastal boundary layer, publishing several landmark papers that combined theory and observations of baroclinic coastal jets in the Great Lakes.

Fascination with circulation problems led Gabe to turn his attention to the coastal ocean. Within a year of spending a sabbatical at the Woods Hole Oceanographic Institution, Gabe joined Woods Hole as senior scientist in 1973. In the remarkably productive period following this move, Gabe emerged as perhaps the most influential theoretician in the field of coastal physical oceanography. His papers examined the effects upon coastal circulation of wind, friction, topography, shoreline orientation, density gradients, runoff, and sea level. These studies fundamentally changed the oceanographic community's view of the coastal boundary layer and shelf environments and led to several comprehensive review articles culminating in his monograph on *Circulation in the Coastal Ocean* (Reidel Publishing Co., 1982).

The stimulating environment at WHOI and close contact with Henry Stommel and the other blue water oceanographers there drew Gabe's interest offshore and toward larger scales. A sabbatical at the Jet Propulsion Laboratory advanced this transition and in 1987 Gabe left Woods Hole for the challenge to help build the Center for Coastal Physical Oceanography, a research-graduate study institute at Old Dominion University in Norfolk, Virginia. There he turned his attention to the physics of boundary currents in the ocean and a renewed attention in air–sea interaction. This productive period lasted till 1995, when Gabe retired to devote his time to compiling his latest ideas on ocean-atmosphere interaction in a fourth monograph entitled *Air–Sea Interaction: Laws and Mechanisms* (Cambridge University Press, 2001).

A short CV of Gabe Csanady is presented as Appendix A, while in Appendix B we have reproduced an autobiography he wrote shortly after his retirement. The list of his publications is included as Appendix C.

2. Csanady's lines of research

The constant theme of Gabe Csanady's research is to improve the understanding of the basic physical mechanisms that control fluid behavior, whether in machines, the atmosphere, lakes, or oceans. The span of his publications is exceptionally broad, and has led to significant advances of such diverse topics as coastal circulation, boundary currents, turbulence, water mass formation, and air–sea interaction at many different spatial and temporal scales. His success in advancing such diverse areas is due to his remarkable mathematical aptitude, practical engineering approach, and a keen intuitive physical mind. Gabe's special talent is to grasp the essential physics of a problem and use this to illustrate appropriate fluid mechanics principles with conceptually simple but theoretically sophisticated models. The success of these models is borne out by the fact that they have greatly influenced experimental programs and the development of numerical studies.

An important aspect of Gabe's work has been the educational character of many of his publications. He was particularly successful in linking apparently difficult problems to simple physical concepts, and placing this in the reach of students and researchers. In many publications Gabe reviewed field and experimental results and combined them with his deep physical perception to produce wonderful research and educational masterpieces. Additionally, Gabe's research often had an important interdisciplinary component, fully necessary in nowadays oceanography, collaborating in the preparation of major interdisciplinary programs and writing some key interdisciplinary papers and reviews.

In the following sections, we highlight a few scientific contributions that we believe exemplify Gabe's career. In large part this will be a personal view limited inevitably by our perspectives and understanding of his work. In short, it is a brief collective scientific memoir of our personal and professional interactions with him.

2.1. Turbulent diffusion and mixing

Gabe did an engineering thesis in Germany on gas turbines (1948), and was immediately employed by the German power generation industry to work on pollution problems. In 1949 he moved to Australia where he completed his Ph.D. thesis on atmospheric diffusion (1958). He published several papers on compressors and smoke plumes, and eventually wrote his first monograph on the *Theory of Turbomachines* (1964). Gabe's background and early experience as an engineer has been a positive influence throughout his career. Two examples are his arrested topographic wave theory, where he used the classical temperature diffusion equation to understand the vorticity behavior in the coastal ocean, and his perception of the global atmospheric and oceanic heat transports as heat engines.

Almost simultaneous with his work on turbomachines, Gabe became involved on the study of atmospheric contamination and, soon after, the diffusion of contaminants in lakes. During the 1960s Gabe produced many excellent publications on turbulent diffusion in both water and air, which lead to his 1973 monograph *Turbulent Diffusion in the Environment*. The early works cover an amazing number of topics. These include chimney dispersion, diffusion in stratified and shear flow, laminar and turbulent Ekman layers, coastal eddies, experimental diffusion studies, and heat disposal in lakes.

During the following decades Gabe extended his work on diffusion to deal with other issues such as mixing in the continental shelf of the eastern United States, turbulent transfer of momentum from the atmosphere into the ocean, and diapycnal mixing in intense boundary currents. This task included some wonderful comprehensive descriptions, such as his 1990 paper "Mixing in coastal regions". Gabe's research on diffusion provided him with physical insight and mathematical tools for later research on a very wide variety of other topics. Just to mention a few examples: "The birth and death of a warm core eddy" (1979), "Mass transfer to and from small particles in the sea" (1986), "Physical basis of coastal productivity" (1990), "The role of breaking wavelets in air–sea gas transfer" (1990), "Vortex pair model of Langmuir circulation" (1994), and "The slip law of the free surface" (1997).

2.2. Physical limnology

Gabe's research on circulation dynamics started in the Great Lakes. During the 60s he worked in several institutions in Canada and became very active in this field. His work was publicly recognized in 1976, when he was awarded the Chandler–Misener Award, as the most valuable paper in that year's volume of the Journal of Great Lakes Research. In that paper, "Circulation, diffusion and frontal dynamics in the coastal zone," he summarized ongoing research in the Great Lakes, providing an overview of the first and second order circulation patterns. He also produced several reviews, such as "Hydrodynamics of large lakes" in 1975, and his well-known 1982 book, *Circulation in the Coastal Ocean*, which includes many examples taken from his work on lakes.

Gabe went to Canada in 1961 from Hungary via Germany, Australia and England. He brought with him a freshly-minted Ph.D. (Mechanical Engineering, University of New South Wales), an enquiring mind, and lots of enthusiasm. Gabe started his Canadian sojourn as Professor of Mechanical Engineering at the University of Windsor (across the river from Detroit), moving to the University of Waterloo in 1963, where he became Chairman of the Department of Mechanical Engineering in 1964. He also became an Associate of the Great Lakes Institute of the University of Toronto (1962–1972). The Institute had a field research station on the eastern shore of Lake Huron at Baie de Dore, where graduate students undertook botanical and limnological research. Gabe became its resident (summer) senior scientist and station manager.

During these same 12 years, Ted Munn was with the Air Quality Research Branch of the Meteorological Service of Canada in Toronto. One of the activities of this Branch was the organization of field studies in the vicinity of Douglas Point where the Ontario Hydroelectric Power Commission was constructing a nuclear power station. The objective of the field studies was to define the mesoclimatology of the area, thus providing background data in case of an accident. By chance, the field station at Baie de Dore was located only a few kilometres north of the reactor site, and some members of the mesometeorological field team were billeted there.

While at the University of Windsor, Gabe came to see Ted to get an overview of the ongoing work in turbulent diffusion research across the Canadian landscape. Ted recalls Gabe as a handsome well-mannered fellow, with a slight European accent. At that time, the Meteorological Service was engaged in defending its turf as the sole provider of meteorological services in Canada, and was ignoring the needs of scientists in such diverse fields as agriculture, forestry, hydrology, oceanography, engineering and air pollution. As for Ted, he was promoting the idea that scientists in these related fields should incorporate meteorological considerations into their studies. (By *meteorological* not simply meaning to develop correlations with standard measurements made at the nearest climatological observing station.) So after spending only a couple of hours together, Gabe was persuaded to establish strong contacts with the Meteorological Service of Canada.

It is difficult to recall exactly what topics were mentioned at these initial meetings. Among other things, Gabe and Ted discussed Sir Graham Sutton's classic text, *Micrometeorology*, which at that time was the bible in the field of turbulent diffusion. Sutton had analyzed many diffusion studies undertaken at the Porton Field Station in Southern England, and he had produced an integrated picture of diffusion. But he had ignored wind shear and he had introduced a parameter, *Sutton's n*, to account for the discrepancies. Gabe and Ted almost immediately found common ground – that *Sutton's n* was an improbable fudge factor. They had numerous delightful conversations over this and many other themes, continuing until Gabe left Canada in 1973. In thinking about the discussions over those years, a main recollection is that the three main subjects of conversation ultimately became Gabe's textbooks. Ted was a convenient sounding board for Gabe in those early days, on topics such as the approximations to the Navier-Stokes equations, Taylor's simplifications for short and long travel times, and Richardson's two-particle diffusion equations, for example.

In *Turbulent Diffusion in the Environment*, Gabe elaborated on theoretical and practical aspects of turbulent diffusion. Both Gabe and Ted had chosen this topic for their doctoral dissertations, Gabe at the University of New South Wales, and Ted at the University of Michigan. The two theses were widely different in scope and emphasis but they did have some common understanding of the field. Gabe and Ted also spoke often of air–sea interactions, including the viscous sub-layer separating lakes/oceans from the atmosphere. They agreed that this layer was the most important one in the Earth–Atmosphere system. Amongst other things, they talked about the effects of organic monomolecular films on the fluxes of momentum, heat and water vapour. But it was not until 2001 that Gabe published his book *Air–Sea Interaction: Laws and Mechanisms*.

Gabe and Ted have not crossed paths since Gabe moved to Woods Hole in 1973. That seems like a long time ago, but the memories of those early days flood back with great clarity – with one exception. Was Gabe involved in the following "lark"? Ted does not remember. Graduate students at Baie de Dore routinely released drift bottles to estimate lake circulation patterns. At the end of one particular summer when everyone was packing up, the students decided to take spare drift bottles home with them. They subsequently released these bottles in some of the other downstream Great Lakes, off Nova Scotia, Vancouver Island and Florida, and even into the Mediterranean. You can imagine the consternation when retrieved drift bottles began arriving by mail in Toronto!

2.3. Coastal circulation

It is hard to overstate Gabe's impact on the advancement of the theoretical understanding of coastal circulation. When Gabe began his investigations of dispersion in the Great Lakes, he quickly realized that the lack of theoretical understanding of circulation processes hindered investigations of transport and mixing nearshore. At that time there was burgeoning interest in developing idealizations of circulation processes in the open ocean, but there was a general feeling that the problems nearshore were hopelessly complex, and that few terms in the Navier–Stokes equations could be safely neglected. Undaunted, Gabe began a bold and incisive simplification of these problems, in what became the hallmark of his work. He systematically stripped away all but the most fundamental dynamics to formulate theoretical constructs that illuminated the essence of the dominant processes. Gabe referred to these as "conceptual models", and today they still serve as the basic building blocks of what we now consider the foundation of coastal circulation dynamics.

In the late 1960s, Gabe began a series of investigations of wind-driven coastal circulation, using a barotropic model of the mean circulation in a closed basin subject to steady wind. This early work lead to the concept of the topographic gyre, with downwind flow in the shallows and a return flow in the deep central region of the basin. Shortly thereafter he turned his attention to wind-driven events in a layered fluid. Although limited by the lack of dissipation, his "baroclinic coastal jet" model still provided deep physical insight into both the oscillatory and non-oscillatory response of the coastal region to a transient wind event. Among the enduring contributions of these models were the clear delineations between the alongshore and cross-shore response to strong, or repeated, wind-stress events.

Gabe published a series of important papers during the Woods Hole years that presented theoretical conceptual models dealing with the effects of topography, friction, wind and thermohaline forcing, and forcing by the deep ocean on the coastal circulation. In idealized form, all of these factors were included in a truly remarkable model that Csanady referred to as the arrested topographic wave. The original vertically-averaged model is steady, parameterizes frictional dissipation as a linear function of the velocity, and assumes a bottom sloping linearly offshore. However, it retains alongshore dependence on shoreline, wind forcing, and runoff (coastal mound) forcing, and allows vertically-averaged cross-shore flow.

The arrested topographic wave model is remarkably robust. Despite its many simplifications, the complex flow structures that it predicts in response to wind forcing in the presence of coastline curvature, alongshore pressure gradients imposed from offshore and point sources of coastal runoff, have all been detected in observational data and in primitive-equation three-dimensional numerical circulation outputs. The model was generalized to more complex topography, and has found wide application in closed basins, along open coastlines, and over submarine banks. Perhaps most remarkable about Gabe's model is its simplicity; the vorticity dynamics are a balance between the curl of the net stress (wind stress minus bottom stress) and the vortex stretching associated with cross-isobath flow. Nearly thirty years after its publication, the arrested topographic wave model remains firmly fixed in the collective consciousness of coastal dynamicists.

In 1982 Gabe published the monograph *Circulation in the Coastal Ocean* that extensively reviewed the subject and, necessarily, summarized his own contributions. Later, in 1988, he wrote a very influential paper that, for the first time, clearly elucidated the physical mechanisms that control the transient and steady circulation patterns in the slope region. Nearly a decade later, in 1997, he provided yet another review of shelf circulation, emphasizing the importance of interactions between shelf, slope, and offshore regions.

2.4. Large-scale circulation

Gabe Csanady's research on large-scale circulation arose naturally as he encountered many instances where the coastal ocean is forced by the deep ocean. Early examples include the previously discussed arrested topographic wave, and his 1979 analysis of the pressure field along the eastern coast of North America. In the latter work he also proposed what has become a widely used method to calculate geostrophic currents over the continental slope, when the sea bottom gets shallower than the offshore reference level. During the last 20 years Gabe has made significant contributions in various aspects of large-scale ocean circulation, such as cross-gyre transport, western boundary currents, warm water formation, and equatorial circulation.

In 1980 Henry Stommel and Gabe published a short paper where they related a North Atlantic T-S relationship with heat and freshwater transports, and estimated water transport to the polar ocean to be of the order of 10 Sv. This sparked Gabe's interest on the role of the tropical oceans in the global heat transport. In his 1984 paper "Warm water mass formation", Gabe clarified the important concept of equatorial entrainment of colder subsurface water towards the sea surface, and its subsequent conversion into warm surface water via heat exchange with the atmosphere. This warm water mass formation process is required to close the global heat transport cycle, thus being a process as important as the deep-water formation at high latitudes. In his 1986 paper entitled "Cross-gyre transports", he revisited a classical gyre circulation problem by resolving interior transport of a deep surface into nonvortical and nondivergent components. His analysis revealed that the nonvortical transport component, which is concealed in the classical solutions, is indeed responsible for the observed massive poleward transport of warm surface water in the North Atlantic Ocean.

In a series of papers that followed, particularly the 1987 and 1990 papers published in the Journal of Marine Research, Gabe extended investigations of cross-gyre transport by focusing on the water mass balance in the tropical ocean. The 1987 paper, entitled "What controls the rate of equatorial warm water formation?", showed his deep understanding and insight on the subject. There Gabe identified and parameterized the critical elements of the heat and mass balances in the equatorial ocean, and showed the delicate interplay between wind, upwelling and western boundary transport. In the 1990 follow-up paper Gabe made a significant contribution to our understanding of the retroflection and leakage of the North Brazil Current. The critical point analysis used in that study arose from discussions with Denny Kirwan, Gabe's long time friend and colleague. Under the hypothesis that the observed behavior results from the encountering of water masses with different potential vorticity, he examined the relevance of cross-gyre transport through surface Ekman transport and was able to reproduce the retroflection and leakage of the North Brazil Current.

After the "tropical" period Gabe became involved with several experiments that studied the interaction between the United States eastern continental platform and the Gulf Stream (MASAR and SEEPs), and during the late 80s and the 90s he published several papers on the physics of the Gulf Stream. One beautiful example is his 1989 paper on energy dissipation and upwelling in a western boundary current, where he examined the energy balance between wind input over the whole subtropical gyre and dissipation at the western boundary current. In this paper he proposed the appealing hypothesis, yet to be proved, that interior flow is incorporated into the boundary current through a peristaltic pumping mechanism, where water is effectively transported into the boundary current through the positive correlation of layer thickness and cross-shore velocities. Later on came several papers that supported the idea that the Gulf Stream undergoes intense diapycnal mixing, apparently linked to unstable meanders, and others that examined the flux of potential vorticity from the sea bottom and sea surface into the interior ocean. In these works Gabe became an enthusiastic defender of the isopycnic perspective, in contrast to the more widespread vertical approach, as he argued that epipycnal and diapycnal transfers do correspond to real oceanic processes.

Gabe became very interested in the way boundary currents, specifically the Gulf Stream, transport and redistribute nutrients, both to the continental shelf and to higher latitudes, to sustain large phytoplankton blooms. Gabe and José Pelegrí found that the Gulf Stream gathers and transports into the subpolar gyre large amounts of nutrients, with a well-defined nutrient core centered at some upper-thermocline isopycnal. They found these results so interesting that in 1990 they presented them at the Brookhaven National Laboratory as "The Nutrient Stream, artery of Gaia, the living planet". The reason for this physiological metaphor is the parallelism between this stream and the arteries of a living being, in terms of localized major fluxes of nutrients. The nutrient Gulf Stream is indeed the main artery sustaining primary production in the North Atlantic high latitudes, as shown in the paper by José Pelegrí and collaborators in this issue.

During the last several years before retirement, Gabe went back to examine the energetics of equatorial upwelling and the pathways for water to warm up and reach back the high-latitude regions. Gabe and Sang-ki Lee published two papers in the Journal of Geophysical Research, where they used a simple 2.5 layer model to provide a realistic seasonal cycle of the warm water formation and northward escape processes in the tropical Atlantic Ocean.

Gabe's 2001 book, *Air–Sea Interaction: Laws and Mechanisms*, is a clear example of his scientific style. In this book he integrates small and large-scale ocean and atmosphere forcing from basic thermodynamic concepts. The last chapters explore how both atmosphere and ocean are capable of releasing great amounts of heat through convection from the mixed layer near the air–sea interface. In the atmosphere the continuous release of latent heat in the rising water vapor self-sustains the formation of very high convective clouds. In the ocean, cooling can only take place at the air interface and the thermohaline overturning circulation has to be helped through work done by the surface wind, much like Gabe's 1985 hypothesis on the driving mechanism for oceanic jets.

2.5. Small-scale air–sea interaction

Although Gabe was always interested in boundary layer problems at the sea surface and the consequent transfer of momentum between the ocean and the atmosphere, he did not start research on the coupled atmosphere-ocean problem until the mid 80s. Through several papers, the last few in collaboration with Glen Wheless, he did some very careful analyses on the coupled problem and the implications on air–sea transfer and the growth of waves. In these works it was demonstrated that the different streams of momentum transfer almost entirely unite a few centimeters below the surface, with the slip velocity being affected by the Stokes drift-shear flow interaction. Let us recall how Gabe himself exposed his search for a slip law of the free surface in CCPO Circulation, the Center for Coastal Physical Oceanography's award winning newsletter.

"Momentum flux from the wind to the sea splits above the surface into three streams supporting respectively mean shear stress, pressure drag on waves, and momentum transfer to waves via shear stress variations. Some distance below the surface, the streams unite again into Reynolds flux of momentum (just as they do some distance above the surface). How far below the surface this takes place, and in what other ways waves interact with the turbulent shear flow, affects the near-surface velocity distribution on the water side of the interface... A plausible hypothesis on the velocity distribution under a free surface is that it obeys the law of the wall, best remembered for the logarithmic velocity profile with minor variations due to waves."

Even though Gabe supported this idea he was acutely aware of its major weaknesses, the neglect of Stokes drift. He wrote: "The main argument against the validity of the law of the wall is, however, that waves may well distribute their momentum over a substantial portion of the mixed layer, bypassing the near surface shear flow: some authors speak of the wave-mixed layer. Is this really the case? The mixed layer gains momentum from the waves, as the waves lose it. Deepwater waves lose momentum by two mechanisms: viscous drag on orbital motions and wave breaking, a process akin to boundary layer separation in steep waves sometimes made visible by the foam and bubbles of a spilling breaker. Classical hydrodynamic theory shows that the effects of viscous drag are confined to a thin wave-boundary layer at the surface and, just underneath this layer, the waves exert a mean viscous stress (by maintaining mean shear in addition to the gradient of Stokes drift). Thus, loss of wave momentum due to viscosity, including eddy viscosity action on long waves, appears as Reynolds flux already very close to the surface. That a similar conclusion holds for wave momentum loss in breakers has only become clear recently, from detailed studies of the flow field in breaking waves... A prominent feature of the flow in a breaker is fluid overtaking the wave at the crest. In a wave-following frame, this translates into two stagnation points on the surface where the fluid is at rest relative to the wave, and a closed circulation cell within a roller sitting on top of the wave, separated from the regular wave motion. The weight of the roller presses down on the wave in such a way as to extract momentum from the wave, transferring it to a wake (near surface shear flow) by Reynolds stress. Observations show high Reynolds stress a few centimeters below the surface. The wave-to-wake momentum conversion is thus analogous to viscous drag on waves in that it occurs close to the surface."

Gabe summed up his work on small-scale air–sea interaction in his *Air–Sea Interaction: Laws and Mechanisms* monograph. He treated the transfer of momentum, heat, and gas across the air–sea interface as laws of non-equilibrium thermodynamics, where each property flux is related to some conjugate force, and examined the actual mechanisms (e.g. breaking of waves) that make this transfer possible. In this particularly insightful work he also presented a thorough treatment of mixed-layer thermodynamics and heat budgets at the air–sea interface, for both the atmospheric and oceanic mixed layers.

3. The person

Gabe Csanady turned 80 in December 2005. The authors of the papers in this special issue have known Gabe in many different ways. Some of us had the privilege of working and sharing experiences with him for decades, while others have known him primarily through his clear exposition of the physics of the ocean. Even those of us who had a close personal relationship got to know him better through his papers and monographs. They are scientific and rigorous, and yet have an almost lyrical impact. His writings clearly reflect the intuitive, artistic, and even emotional, facets of science, where creativity and imagination, are many times paired with rigor.

Gabe has used his writing and editorial skills for the benefit of several generations of oceanographers. His book, *Air–Sea Interactions: Laws and Mechanisms*, is a clear example of his intuitive and physical approach to science. As Jim Price recently commented to one of us, this book is a master piece: it goes well into the physical mechanisms with crystal and illuminating clarity. We know Gabe has been lately working on a descriptive comparison of the Gulf and Jet streams. We hope he gets on with it, as it will certainly be wonderful to read!

Gabe's character is a combination of intensity and sensibility, emotion and rigor, independence, gentleness, and enthusiasm for science and life. His special skill for exposing basic mechanisms and ideas, whether scientific or not, is one of his distinctive characteristics. Regardless of the venue, an encounter with Gabe is an intellectual and cultural experience. He has always been a hard act to follow. As students and colleagues, it would be easy to be intimidated or discouraged when faced with his example. But Gabe has a generous and optimistic soul. He expected rigor but never pressed for quick results, and he let students mature at a natural pace. Science, as any artistic skill, has to be slowly mastered. His great gift as an advisor was that he would welcome students time after time with an encouraging air of expectation despite the muddled encounters of the past! His advice and opinions were always valuable even if not immediately understood. To this day, when new understanding comes suddenly, many of us think back on a conversation with Gabe decades before and think "so that's what he meant!"

Gabe married Joyce in 1965. In every way she is his soul mate. Joyce's serene yet strong character has supported Gabe's intellectual activity during the last 40 years. Joyce and Gabe liked to gather people at their place, specially "their" students. They indeed were surrogate parents to several generations of students. Joyce has a sense of humor perhaps even finer than Gabe's. With her it is difficult to know whether she is serious or just joking. Joyce and Gabe's joy for life is clearly reflected in many small things, like their continuous pleasure for dancing. Above all, Joyce and Gabe have been mentors, good persons and gentle friends.

4. Organization of papers in this volume

The 20 papers in this special issue are by an unusually diverse group of scientists who share an admiration of Gabe Csanady, as a researcher, mentor, and as a colleague. It is interesting that Gabe has been active in nearly all the areas covered in this volume. However, it is stressed that these papers reflect just the oceanographic component of the spectrum of Gabe's research interests. As noted above his research has played pivotal roles in other areas of fluid mechanics.

As with Gabe's own research there is no unique way to categorize these contributions. Thus, the editors decided to divide the papers by phenomenological scales as they relate to dynamical processes. Thus, the first section of papers is concerned with small-scale physical processes. Section 2 contains papers on a wide variety of aspects of physical processes in the coastal ocean. The final section has contributions on mesoscale and large-scale processes. It is a testament to Gabe's stature and versatility as a scientist that he has made signal contributions in all of these areas.

Acknowledgement

We thank the Center for Coastal Physical Oceanography, University of Old Dominion, for allowing us to reproduce material that appeared in their quarterly newsletter CCPO Circulation, as well as for providing Figs. 1, 4 and 5.

Appendix A. Gabriel T. Csanady Short CV

Education

- Dipl. Ing. (Mechanical Engineering), Technische Hochschule, Munich, Germany, 1948.
- Ph.D. (Mechanical Engineering, thesis on air pollution), University of New South Wales.

Career

- 1948–1954: Engineering posts in electric power generation industry, Germany and Australia.
- 1954–1960: Lecturer and Senior Lecturer in Mechanical Engineering, University of New South Wales, Sydney, Australia.
- 1960–1961: Senior Research Fellow, College of Aeronautics, Cranfield, England.
- 1961–1963: Associate Professor of Mechanical Engineering, University of Windsor, Ontario, Canada.
- 1963–1973: Professor of Mechanical Engineering, University of Waterloo, Ontario, Canada (Department Chair, 1964–1967).

- 1973–1987 Senior Scientist, Woods Hole Oceanographic University, Woods Hole, Massachusetts, USA.
- 1987–1995: Samuel L. and Fay M. Slover Chair of Oceanography, Old Dominion University, Norfolk, Virginia, USA.
- Since 1995: Professor emeritus, Old Dominion University, Norfolk, Virginia, USA.

Part-Time Associations

- 1962–1972: Associate, Great Lakes Institute, University of Toronto.
- 1965–1968: Visiting Scientist/Consultant, Traveler's Research Center, Hartford, Connecticut, USA.
- 1966: Visiting Professor, Department of Meteorology, University of Wisconsin, Madison, USA.
- 1969: Professor of Meteorology, University of Wisconsin, Madison, USA (on sabbatical leave from Waterloo).
- 1982: Sherman Fairchild Distinguished Scholar, California Institute of Technology, Pasadena, California, USA.
- 1984–1986: Distinguished Visiting Scientist, Jet Propulsion Laboratory, Pasadena, California, USA.

Awards

- 1970: President's Prize, Canadian Meteorology Society.
- 1975: Editor's Award, American Meteorology Society.
- 1977: Chandler–Misener Award, International Association for Great Lakes Research.
- 1991: A.G. Huntsman Award, Bedford Institute of Oceanography.

Professional Societies and Duties

- 1968–1976: Associate Editor, *Journal of Applied Meteorology*.
- 1969–1975: Associate Editor, *Atmospheric Environment*.
- 1972–1982: Associated Editor, *Water, Air and Soil Pollution*.
- 1975–1979: Editor, *Journal of Geophysical Research, Oceans and Atmospheres*.
- 1979–1990: Managing Editor, *Reidel Monographs on Environmental Fluid Mechanics*.
- 1994–2001: Associate Editor, *Journal of Oceanography*.

Publications

- About 150 publications in refereed journals.
- Some 50 publications in proceedings and technical reports.
- Four monographs: *Theory of Turbomachines* (McGraw Hill), *Turbulent Diffusion in the Environment* (Reidel Publishing), *Circulation in the Coastal Ocean* (Reidel Publishing), *Air–Sea Interaction: Laws and Mechanisms* (Cambridge University Press).

Advising and Formation

- Initiated graduate program at University of Waterloo.
- Participated setting up the Center for Coastal Physical Oceanography, a Commonwealth research and educational excellence center at Old Dominion University.
- Advisor of some 20 doctoral thesis to students from many different countries.

Appendix B. Gabriel Csanady's autobiography

Gabe retired from CCPO-ODU in June 1995. CCPO has a Circulation letter that dedicated an issue to Gabe Csanady. In this issue Larry Atkinson, then CCPO's Director, wrote: "I think what most of us learned from Gabe was to stay focused. As you go through your career, from young researcher and teacher, to the stage where administration tempts you, and finally to the stage where you want to finish research started long ago and teach those last graduate students what the years have told you they need to know – stay focused.'' Gabe was asked to write down a short autobiography on his personal memories, which we reproduce below.

''To wax nostalgic on youthful pastimes comes naturally at retirement time – to remembering boating excursions on the Danube or afternoons of hunting in the countryside with Grandfather. One episode I like to tell about happened when I was just 11 years old. Grandfather and I went after foxes up on a hill half covered with vineyards. Very thirsty, we called on a vintner and asked for some water; he did not have any water, but he had plenty of wine, which satisfied the thirst all right. It must also have made me happy because Grandfather and the vintner laughed a lot.

The real world intruded when Russian troops started laying siege to Budapest. We escaped on one of the last trains out before they encircled the city. The spring of 1945 was beautiful. With two other young fellows, we criss-crossed the Bavarian and Austrian Alps, hitch-hiking on army trucks and banging on the drivers' cabins when airplanes came into sight, so that the drivers could jam on their brakes and duck in a roadside ditch. Overnight accommodation was not luxurious. I remember sleeping on a narrow table, belted to another fellow back to back, so we would not fall off. When the war ended, my companions and I were in Innsbruck with one pair of pants between the three of us. When one of us went out, two had to stay home.

The Technische Hochschule in Munich reopened in early 1946, and I enrolled in my second year in mechanical engineering. Student years are always great. Jitterbug was popular, but food supplies were erratic. Once I lived on cheese for a week. I also went *hamstern* in the Swabian countryside for apples (go house to house and offer to buy) to stock up for the winter.

We emigrated to Australia in 1949, sailing from Naples to Sydney. On the Red Sea, the dining room temperature was 138°. We celebrated reaching the Indian Ocean rather too well – that was the only time I ever got seasick. After a few interesting jobs in the migrant camp (PA announcer, interpreter for the camp director, kitchen supervisor) and engineering jobs outside, I got involved in air pollution research. One memorable duty was to sample flue gases from a chimney platform 150 feet above rooftop (and I always hated heights). One of my assistants just sat with his back against the stack, petrified. In compensation, though rather later, the University of New South Wales gave me a Ph.D. for a thesis entitled *Dispersal of dust from industrial stacks*. My first paper, on the same topic, appeared in the Australian Journal of Physics in 1955, and it made me walk on air.

Soon after taking a post at the University of Windsor, Ontario, a colleague from Toronto visited me (Ted Munn, much later, until recently, the editor of Boundary Layer Meteorology). Ted told me about a great field project on the shores of Lake Huron where the government was about to build a large nuclear power station. Ted was carrying out atmospheric dispersal studies at the site. Upon my envious congratulations, he suggested that I do similar studies of effluent dispersal in the Lake, so I started my association with the University of Toronto on limnological research and later to evolve into work on coastal physical oceanography.

The 1960s were my *Sturm und Drang* period. In 1963, I became department chairman in mechanical engineering at the University of Waterloo, ran a research station on Lake Huron for the University of Toronto, and acquired seven Ph.D. students. Waterloo operates year-round, and one of the three semesters is off for faculty. I spent these at the Travelers Research Center in Hartford, CT, on air pollution work, or at the University of Wisconsin, Madison, on lake dynamics studies. The Canadian Meteorological Society awarded me their President's Prize in 1970; the American Meteorological Society their Editor's Award in 1975; the International Association for Great Lakes Research their Chandler–Misener Award in 1977; and the Bedford Institute of Oceanography's A.G. Huntsman Award in 1991 (Fig. 1).

All was not rosy, however. My first marriage blew up in 1965, and it was followed by a distressing period and a bitter divorce. To my great good fortune, this did not last long. A then recently widowed lady neighbor just happened to be the woman heaven intended for me. Joyce has been my love and inspiration for almost thirty years now. She soon helped me over my troubles, a task not made easier by frequent changes of venue. When we moved to Madison for an off semester in 1966, I just happened to be in Japan attending a conference (together with A. D. Kirwan, Jr., Fig. 2). Officials at the airport at Tokyo made difficulties about returning to

Fig. 1. Gabe Csanady at CCPO-ODU in 1992.

Fig. 2. Gabe is in the third row, above the word "layers" and just below Denny Kirwan.

the US with my H1 visa; I almost got stuck there with 30 in my pocket. The Tokyo officials relented in the end and kindly rebooked me to Toronto. When I got to Madison in the middle of the night, I had to call a colleague to find out where we lived.

Joyce also came with three lovely daughters, Pat, Connie, and Susan, with whom we now form a harmonious family, including sons-in-law, my son Andrew, his lady, and grandchildren. On top of this, one role Joyce has always enjoyed was to play surrogate mother to graduate students. For my seven students in Waterloo, we gave a 'seven son's party'. Each was awarded a separate diploma. To name a few, one became Doctor of Safety, remembering that he just missed blowing up the lab with his oil smoke windtunnel studies. Another was honored for his 'brilliant blackboard technique,' conducting his thesis defense with liberal blackboard use in complete darkness.

The last two off semesters (these could be saved up and pushed together) I spent at Woods Hole as a guest investigator in 1972–73. We made wonderful friends there and were fortunate enough to be able to return on a permanent basis after a final semester in Waterloo. With a retired English professor couple, we debated sundry subjects holy and profane. In our gourmet club, we explored dishes of the world. I would not recommend Danish beer soup (tastes like wet bread), ginseng root (effective emetic), or retsina wine (wine and turpentine). We had a vizsla, *Scrooge* (Hungarian hunting dog, like my grandfather had, who could easily have got a Ph.D. at one of the lesser institutions); a horse for Susan in her teen years, *Cricket*; and built a dance hall in the basement for ourselves, keen ballroom dancers.

A nice interlude in our life was Pasadena in 1982, when CalTech honored me with a Sherman Fairchild Distinguished Fellowship. California poppies, date palms, and Palm Spring weekends were wonderful. In Norman Brooks' Environmental Engineering Science Group, where my office was, I learned such tidbits as that the pH of dew in the local park was 2.0. We were also delighted to find a ballroom dance studio in Los Angeles with the most accomplished dance teachers anywhere, people we later saw on TV. The lessons we took there remain among our fondest memories.

So far I have not said anything about our cottage, a thing of beauty on the shores of Lake Huron, which is indeed a joy for ever (Fig. 3). We built it in 1966, just south of the site of the field studies I mentioned. This is a family seat to which we have returned every single summer for family gatherings, barbecues, and uncrowded golf courses. I have a second-story office over the boathouse, which overlooks the lake.

In 1987, William Dunstan, then chairman of the Department of Oceanography at Old Dominion University, was kind enough to hire me for a Slover chair. Joyce and I bought a house in Virginia Beach, VA, and promptly decided we did not like the house's looks, so we had it remodeled while living there. This was as

Fig. 3. The Csanady's cottage by Lake Huron.

messy a project as Joyce ever had the pleasure of enduring with me. We have one photo of the house wrapped in plastic to keep out the rain, which came copiously that winter. Landscaping the grounds, one of my enduring hobbies, was great fun.

The Cape has now claimed us again. We built our dream house in Sandwich and will be leaving you good friends presently. I am happy to have taken part in the effort to launch CCPO (Fig. 4), and I have very much enjoyed having a group of graduate students again, decades after the Waterloo years (Fig. 5). Thanks for the memory."

But Gabe and Joyce could not stay very long in Cape Cod. They were far so much restless to stay in one single place, and the cold winters did not help either. First they moved to a drier place, Arizona, next to a very cultural city, Charlottesville, and last they decided to move back to Ontario, near family. Fig. 6 shows them in their old cottage by Lake Huron, during summer 2003.

Fig. 4. Denny Kirwan and Gabe Csanady at CCPO-ODU in 1992.

Fig. 5. Gabe with former graduate students (from left to right) Gudavalli Vittal, Glen Wheless, Sang-ki Lee, and Ajoy Kumar.

Fig. 6. Gabe and Joyce in their cottage porch.

Appendix C. List of Gabriel Csanady's publications

1955	Csanady, G.T.	Dispersal of dust particles from elevated sources. Aust. J. Phys. 8, 545–550.
1956	Csanady, G.T.	The rise of a hot smoke plume. Aust. J. Appl. Sci. 7, 23–28.
1957	Csanady, G.T.	Dispersal of dust particles from elevated source. II. Limitations of the approximate theory. Aust. J. Phys. 10, 558–564.
	Csanady, G.T.	Deposition of dust particles from industrial stacks. Aust. J. Appl. Sci. 9, 1–8.
	Csanady, G.T.	Flow lines in atmospheric diffusion. Ind. Eng. Chem. 49, 1453.
	Csanady, G.T.	Design parameters for diesel engines. Engineering, April, 459.
1958	Csanady, G.T.	Head correction factors for radial impellers. Engineering.
1960	Csanady, G.T.	An approximate equation for the choke-line of a compressor. J. Aerospace Sci. 27, 637
	Csanady, G.T.	Linkage dynamics via linear dependence. Machine Design, 173–177.
1960	Csanady, G.T.	Effects of flow unsteadiness in turbomachines. J. Aerospace Sci. 27, 879–880.
1961	Csanady, G.T.	Some observations on smoke plumes. Int. J. Air Water Pollut. 4, 47.
	Csanady, G.T.	Radial forces in a pump impeller caused by a volute casing. J. Eng. Power 61-WA-77, 1–4.
1962	Csanady, G.T.	Turbulent diffusion in a stratified fluid. Bull. Amer. Meteorol. Soc. 43, 318.
1962	Csanady, G.T., H.K. Ellenton	Douglas Point project. Ann. Rep., Great Lakes Institute, University of Toronto.
1962	Csanady, G.T., H.K. Ellenton, R.E. Deane	Slicks of Lake Huron. Nature, 196, 1305.
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1964	Csanady, G.T.	Turbulence and diffusion in the Great Lakes. In: Proc. 7th Conference Great Lakes Research, University of Michigan, Ann. Arbor.
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1964	Csanady, G.T., M. Berretta, P. Sullivan, A. Bergs, A.M. Hale	Hydrodynamic studies on Lake Huron at Baie du Dore. University of Waterloo, Water Resources Institute and University of Toronto. Great Lakes Institute Rep., 144 pp.
1965	Csanady, G.T.	The buoyant motion within a hot gas plume in a horizontal wind. J. Fluid Mech. 22, 225–239.
1965	Csanady, G.T.	Windrow studies. University of Toronto, Great Lakes Institute Project Rep. 26, 60–82.
1966	Csanady, G.T.	The effect of mean velocity variations on jet noise. J. Fluid Mech. 26, 183.
1966	Csanady, G.T.	Generalization of the mixing-length argument in turbulent diffusion. J. Atm. Sci. 23, 667–671.
1966	Csanady, G.T.	Accelerated diffusion in the skewed shear flow of lake currents. J. Fluid Mech. 71, 411–420.
1966	Csanady, G.T., G.R. Hilst, N.E. Bowne	Dispersal of foreign matter by the currents and eddies of the Great Lakes. Pub. No. 15, Great Lakes Division, University of Michigan. In: Proc. 9th Conference Great Lakes Research, 283 p.
1966	Carter, H.H., A. Okubo, G.T Csanady	Comments on paper by G.T. Csanady – Accelerated diffusion in skewed shear flow of lake currents. J. Geophys. Res. 71, 5012.
1967	Csanady, G.T.	Large scale diffusion experiments at Douglas Point. In: Proc. 10th Conference Great Lakes Research, International Association of Great Lakes Research.
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1967	Csanady, G.T.	Turbulent diffusion in shear flow at Fort Wayne Indiana. Bull. Amer. Meteorol. Soc. 48, 29.
1967	Csanady, G.T., I.S.F. Jones, B.C. Kenney	Douglas point "saturation run". Great Lake Institute Project Rep. 30, University of Toronto, Toronto, Ontario, Canada, 52 pp.
1967	Scott, J.T., G.T. Csanady	Nearshore currents off Long Island. J. Geophys. Res. 81, 5401–5409.
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1967	Foxworth, J.E., G.M. Barson, G.T. Csanady	Comments on paper by G.T. Csanady – Accelerated diffusion in skewed shear flow of lake currents. J. Geophys. Res. 72, 2683.
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1968	Csanady, G.T.	Observations on a coastal jet in Lake Huron. EOS Trans. Amer. Geophys. Union 49, 701.
1968	Csanady, G.T.	Diffusion in an Ekman layer. Bull. Amer. Meteorol. Soc. 49, 762.
1968	Csanady, G.T., G.R. Hilst, N.E. Browne	Turbulent diffusion from a cross-wind line source in shear flow at Fort Wayne Indiana. Atmos. Environ. 2, 273.
1969	Csanady, G.T.	Diffusion in an Ekman Layer. J. Atm. Sci. 26, 414–426.
1969	Csanady, G.T.	Dosage probabilities and area coverage from instantaneous point sources on ground level. Atmos. Environ. 3, 25–46.
1969	Csanady, G.T.	Dynamics and diffusion in the Great Lakes. University of Waterloo, Waterloo, Ontario, 142 pp.
1969	Csanady, G.T., B. Pade	Windrow observations, Dynamics and diffusion in the Great Lakes. University of Waterloo, Rep. Department Mechanical Engineering, 3–38.
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1970	Csanady, G.T., W.R. Crawford, B. Pade	Thermal plume study. Rep. Environmental Fluid Dynamics. Laboratory, Department Mechanical Engineering, University of Waterloo, Canada.
1971	Csanady, G.T.	Baroclinic boundary currents and long edge-waves in basins with sloping shores. J. Phys. Oceanogr. 1, 92–104.
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1971	Csanady, G.T.	Reply. J. App. Meteorol. 10, 1039.
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1972	Wigley, T.M.L., G. T. Csanady	Ice fog clouds formed by vapour emissions in cold climates such as the Upper Mackenzie Valley. Water Research Institute Project Rep. 2073, University of Waterloo.
1972	Wigley, T.M.L., R.P. Slawson, G.T. Csanady, J.H. Rennie	The behaviour of moisture laden plumes. Water Research Institute Project Rep. 1021, University of Waterloo.
1973	Csanady, G.T.	Big eddies and mixing processes in the great lakes. Washington, D.C., U. S. Environmental Protection Agency, Rep. Office of Research and Development.
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