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A Tribute to Melvin E. Stern

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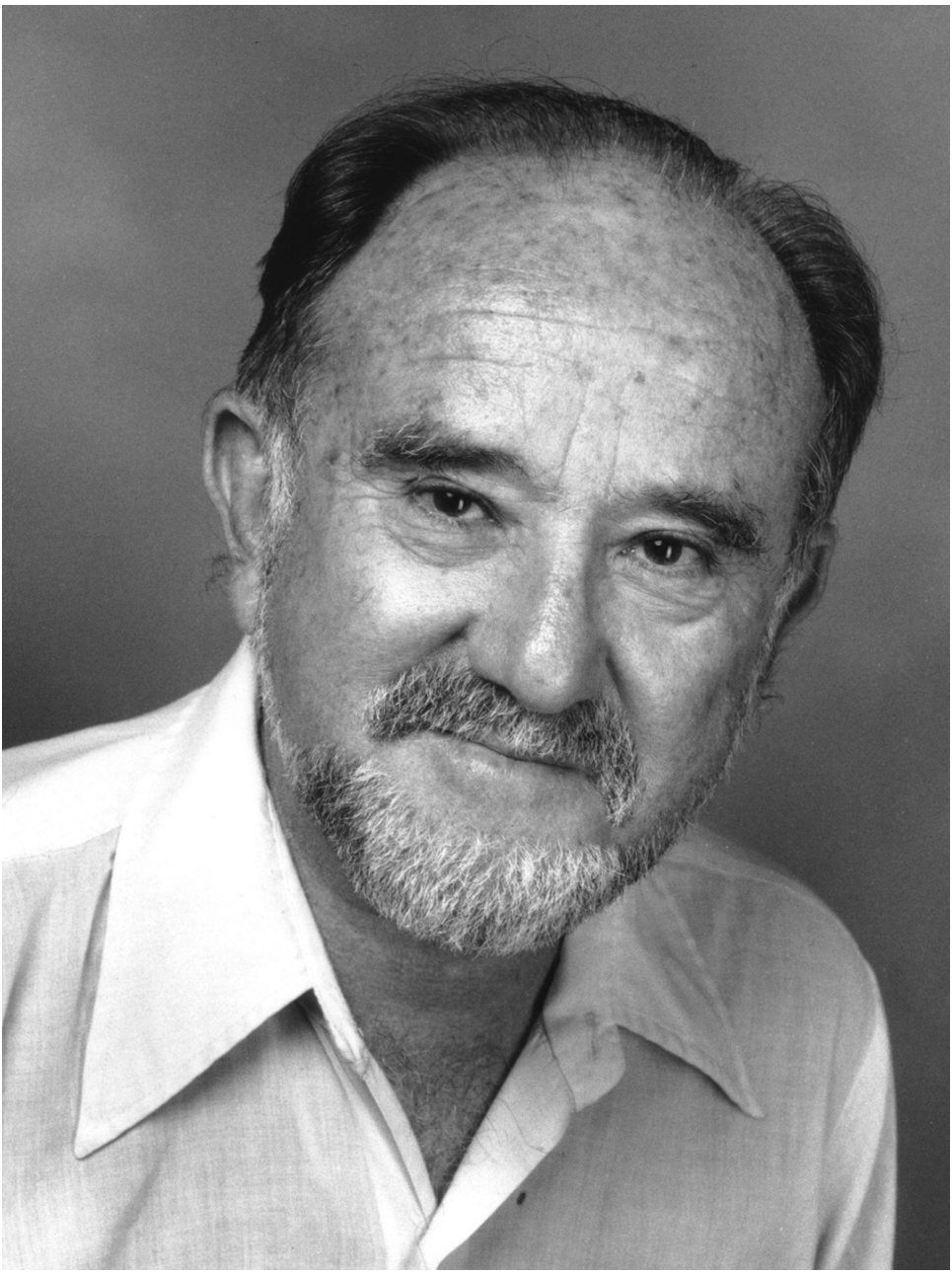

Melvin E. Stern
1929–2010

Journal of MARINE RESEARCH

Volume 69, Numbers 4-6

A Tribute to Melvin E. Stern (1929–2010)

by George Veronis[1]

Melvin Stern was a brilliant theoretician who introduced a number of innovative ideas in oceanography. These include his (a) penetrating introduction of double diffusive processes, (b) introduction of MODONS, the important, small scale, coherent features in the ocean, (c) incisive studies of rotating hydraulics, (d) investigation into bores, jumps and boundary flows, (e) analyses of the role of vortices in ocean dynamics, and (f) frequent contributions to instabilities in the ocean. He tended to think very intuitively, not unlike Henry Stommel. When he introduced a new idea, he accompanied it with a very thorough analysis. Generally speaking, he communicated most effectively in one-on-one situations, particularly with his graduate students. In these situations he was a wonderful and positive critic. His ideas, particularly his work on salt fingers, permeated the field and led to extensive developments of topics that today are fundamental elements on which our understanding of oceanic processes is built.

Melvin was born around the beginning of the Great Depression and he grew up in New York City at a time of hardship for most Americans, his family included. He had to work after school and during summers to help his family make ends meet and he continued that "extracurricular" activity while in college. He was always a very bright student and he resented the time that these menial tasks took away from his educational development. Working as a delivery boy for a local butcher and then as a printer made him appreciate the academic life in which he could spend his time thinking and working intellectually. Early in his career at the Woods Hole Oceanographic Institution (WHOI) he, Willem Malkus, Henry Stommel and I had a discussion about why we carried on research on esoteric topics.

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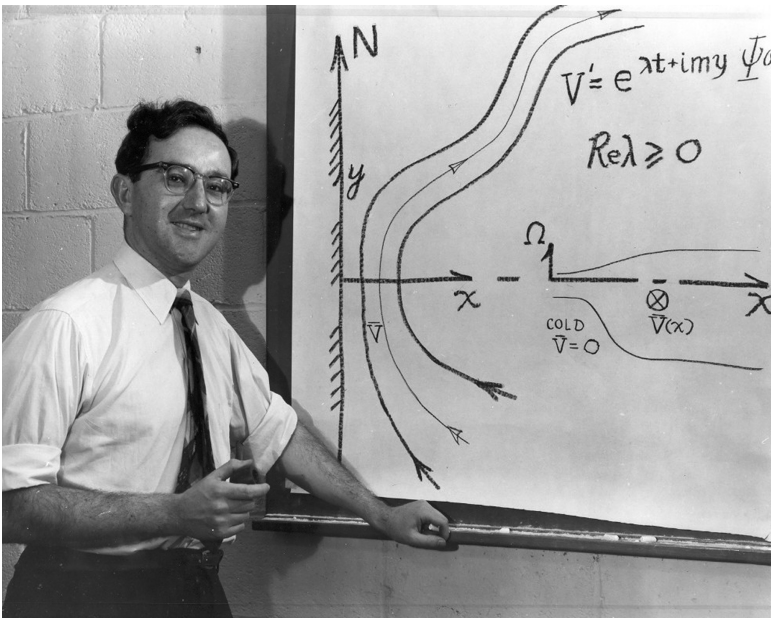
Melvin expressed his delight in being able to do what he most wanted to do and be paid for it. He said that it was the first job he had ever had that totally satisfied him.

Melvin's professional career can be divided into three stages, an early period of development mostly at the Woods Hole Oceanographic Institution (WHOI), his middle years at the University of Rhode Island (URI) and, finally, the years after his appointment in 1987 at Florida State University (FSU).

He had such an early aptitude for mathematics that his grade school teacher encouraged him to apply for entry to Stuyvesant High School, famous for its strong academic program, and he was successful in passing the entry exam. After high school he obtained a bachelor's degree in electrical engineering at The Cooper Union School of Engineering in 1950, which was tuition-free. He then enrolled at the Illinois Institute of Technology from which he was awarded an M.S. degree in physics in 1951. It was there that he met Joanne Malkus, who had a great influence on the direction of his career. She was impressed by Melvin's abilities and urged him to consider applying for a position at WHOI, where she and her husband, Willem, had recently joined the staff. Melvin did so and was hired to work on issues in oceanic physics. The US was involved in the Korean War at that time and was drafting eligible men for service. In order to avoid active military service, Melvin joined the Air Force as a first lieutenant and was assigned to the Geophysics Research Directorate (GRD) in Cambridge, MA. For all practical purposes he was pursuing a PhD at the Massachusetts Institute of Technology (MIT) as part of his military training.

While he was at WHOI, he coauthored an article (Malkus and Stern, 1952), on determining ocean transports by electromagnetic effects. Later (Longuet-Higgins *et al.*, 1954) he worked on a paper on electric fields induced by ocean currents and waves. These were his only publications involving electric fields and ocean currents but they were among the earliest contributions to that subject. He also published two articles (Malkus and Stern, 1953; Stern and Malkus, 1953) on flow of a stable atmosphere over a heated island, and shortly after that he wrote a related paper (Stern, 1954) on mean atmospheric perturbations produced by differential heating, a topic related to his doctoral dissertation. The early collaborations before his PhD, all with such gifted scientists, are indications of his remarkable intellect and ambition.

Melvin returned to WHOI in 1957 but he published nothing from 1954 to 1959. He was always somewhat of a loner, especially so during his early years, but he was not inactive. In 1956 a biweekly seminar was established between MIT (Charney, Phillips, Lorentz, Howard, Greenspan *et al*.) and WHOI (Stommel, Fuglister, Malkus, Von Arx, Faller, Veronis *et al*.) in which the visiting group would provide the lecturer. Melvin attended the ones at MIT when he was at GRD and continued to take part after he moved to WHOI. He spent a good deal of time studying some of the monographs of senior scientists and absorbing recent developments without publishing anything until sometime later, but he took active part in the discussions. In those days and often later in his career, when he wanted to ask a question or make a point he would ramble on for five or ten minutes, at the end of which time he would say "Isn't that so?" Even so, what he said was always pertinent to the topic under discussion.



Melvin Stern, ca 1962.

In 1960 he published a long study (Stern, 1960a) on the instability of Ekman layers. I think that this paper summarizes the results of his four or five-year study of how the introduction of rotation affects established theories in nonrotating fluids. That article must rank as the most difficult to comprehend of all of his publications. Even after all of the familiarity with rotating flows gained over the years, looking back at that article to understand his analysis is a serious challenge. I feel that it is important to understand how difficult his presentations were at the beginning of his career so that one can appreciate how far he had to come to be able to make his work understandable. Even the form of the presentation is peculiar with a very detailed Abstract (twice as long as the Introduction) that blends aspects of the results in the preliminary discussion before the problem is even defined. The analysis in the main body of the paper is made difficult by a cluttered notation. Melvin knew exactly what he wanted to include in the article but he didn't know how to say it so that others could understand. In the last section of his article he reports spin down experiments that he himself carried out together with the theory ("not included herein") for the experiments. He concluded that section with the statement that his theory agreed with his experimental results. My feeling is that one has to take his word for it.

Stommel *et al.* (1956) published a short note on an experiment, in which they immersed a vertical pipe into a gravitationally stable fluid, stably stratified by heat but unstably stratified by salt, and filled the pipe with fresh, cold water from the bottom. The temperature in the pipe equilibrated by horizontal diffusion with the ambient temperature but the salinity

remained the same. Consequently, the surrounding water was denser than the water in the column so the water in the pipe rose and continued to rise as long as the ambient conditions were maintained. They called this a perpetual salt fountain and considered it simply as an oceanographic curiosity, although Hank Stommel and Louis Howard took part in a cruise to the Sargasso Sea in an unsuccessful attempt to try to observe this effect in nature.

Four years later in his first major publication after rejoining the staff at WHOI, Melvin (1960b) showed that the presence of the pipe was unnecessary. A fluid stabilized gravitationally as described would be unstable to cells with horizontal wavelength of a cm or so with up-(down)going cells surrounded by down-(up)going cells so that the stabilizing temperature (T) would be short circuited by *horizontal* diffusion – i.e., upgoing cells gain heat laterally from downgoing ones and become warmer and downgoing ones give up their stabilizing heat laterally to upgoing ones so that the vertical stabilizing temperature gradient in each cell is obliterated. The unstable salt (S) stratification is only mildly affected by horizontal diffusion because of the small diffusivity of salt. The horizontal scale of 1 cm for the heat/salt system is the most effective one in that it leads to maximum growth rate for the instability. Melvin gave this phenomenon the name salt fingers. It was the first example[2] of the process of double diffusion in the scientific literature and it is remarkable that it was essentially Melvin's first major independent research publication. Although there were others at WHOI working on problems of thermal convection at the time, there was no other research, there or elsewhere, on what became known as double diffusion.

It is interesting that Melvin treated the problem of a horizontal layer of fluid between two plates, essentially the Benard convection setup but heated and salted from above. In this case the instability takes the form of cells with a horizontal wavelength the same as that for Benard convection. But salt fingers have a horizontal wavelength that is much smaller than the vertical. Melvin showed that the wavelength of the fastest growing cells leads to vertically long slender features (taking advantage of the effect of horizontal diffusion). Those features are the signature of salt fingers. It is characteristic of his thinking that he more or less knew the answer before he did the analysis. It turns out to be much more straightforward, particularly in a lab experiment, to consider a two-layer system, warm salty over cold fresh (although it is more common to use fluids stratified by two solutes with different diffusivities, such as salt and sugar, to avoid the heat loss to the environment that is present in the heat/salt system). Perturbations at the interface immediately select the horizontal scale of salt fingers with salty fingers moving down, interlaced with fresh fingers moving up. Most theoretical studies of properties of arrays of salt fingers started out with domains that are vertically uniform.

In an article published two years later (Stern, 1962a) he studied the effects of rotation and stratification on the shear flow in a jet in the upper layer of a two-layer ocean with the lower layer quiescent. The linear stability problem in this reduced gravity system is similar

2. It was later discovered that W.S. Jevons (1857) had conducted a successful salt finger experiment in an attempt to understand cirrus clouds, but he did not understand the cause of the phenomenon.

to that of shear flow in a nonrotating system but the effect of rotation is present in the potential vorticity and its gradient. When Melvin applied Rayleigh's instability criterion to the quasigeostrophic (small Rossby number) analysis, he found that the jet is stable when the thickness of the upper layer is below a certain value and unstable otherwise. He speculated that the result may be valid for larger Rossby numbers in which case it could apply to the Gulf Stream system in the ocean beyond Cape Hatteras and therefore serve as a constraint on the depth of the Gulf Stream in the open ocean.

In his paper, Melvin acknowledges input from Jule Charney, who suggested the connection between the results in CC Lin's monograph on instability theory and the result in an earlier version of Melvin's paper. The two then collaborated in an extension of Melvin's theory (Charney and Stern, 1962) to a reconsideration of baroclinic instability by including horizontal shear in the classical baroclininc instability problem. They developed a systematic derivation of the quasigeostrophic potential vorticity equation and proved that for zonal flows in the atmosphere and the ocean bounded by isentropic surfaces, the potential vorticity gradient had to vanish somewhere within the flow for instability to occur. They suggested that their results might be pertinent to the breakdown of the polar-night jet. The theorem has been extended and applied widely by many meteorologists and oceanographers over the years. It is one of the most important of Melvin's contributions.

After his seminal article on salt fingers Melvin turned to other topics, often connected to research by others in his immediate environment and often far afield from oceanography. Folks who have known him for the past several decades are familiar with his many contributions to oceanography but not with his work on these other topics, which he pursued while familiarizing himself with oceanographic issues. For example, he wrote a short article (Stern, 1962b) on the relative stability of solutions in nonlinear convective studies, a topic first raised by Malkus and Veronis (1958). He also looked into the joint instability of rotating magnetic fields that are separately stable (Stern, 1963) a topic previously studied by Chandrasekhar. For oceanographers, a more familiar related issue is the joint instability of fluids with uniform shear and with stable stratification, each of which is stable individually, but unstable when both are present. And he delved into an analysis related to statistical mechanics (Stern, 1968) where he proposed a minimum free energy principle to be applied to the study of turbulence. These publications on such widely separated topics provide additional evidence of Melvin's profound intellect.

Among the scientific staff at WHOI there was considerable unhappiness with the directorship of Paul Fye and many people left to work at other institutions. Melvin was among them and in 1964 he accepted a Professorship of Oceanography at the University of Rhode Island.

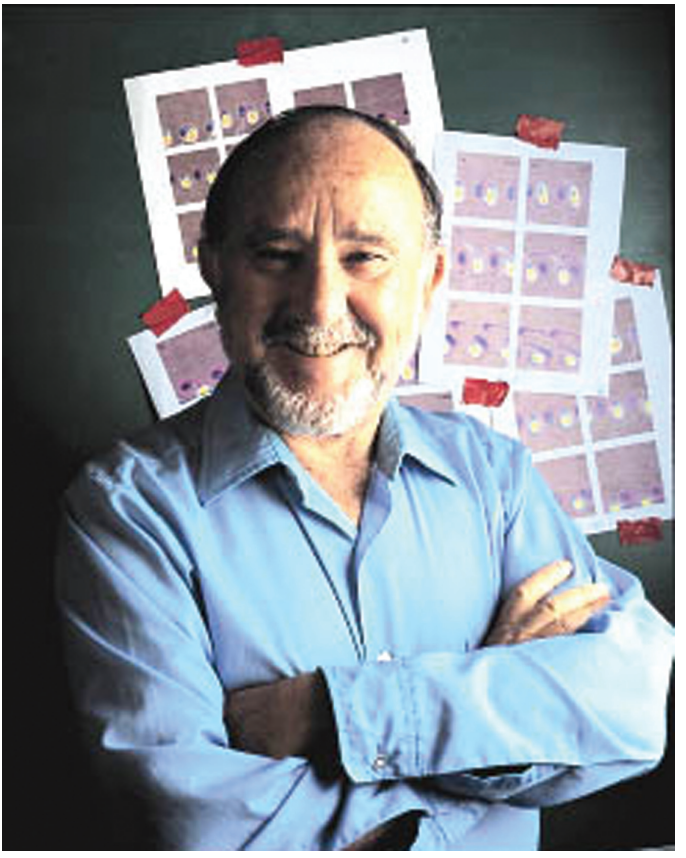
It wasn't long before double diffusion beckoned and Melvin took up his pen again in the late 1960s to expand his study of phenomena in that arena. Stern (1967) extended the setup to include horizontal gradients of T and S, in particular, the case where the two gradients compensate each other so that there is no horizontal gradient of density. The neatest setup for this phenomenon was presented a decade later in a lab experiment by

Ruddick and Turner (1979), where initially they had a stably stratified fluid with salt on one side and density-compensating temperature on the other so there was no horizontal gradient of density. When the vertical barrier separating the two fluid halves was removed, tongues of fluid from each side intruded into the other. Since the lower boundary of the salty tongue was warmer than the cold fresh fluid below, salt fingers formed and rained down on the cold fluid making the latter sink. The loss of salt made the intrusive salty fluid lighter so it rose. The result was interlacing horizontal intrusions that redistributed the T and S properties of the fluid. Applying this process to adjacent water masses in the ocean, Melvin proposed it as a mechanism to enhance lateral mixing of properties in the ocean.

The purely vertical salt finger mechanism transfers salt and heat downward. Melvin figured that the accumulation of salt below the finger layer would create a layer of dense fluid that could cause gravitational overturning in the underlying fluid. Similarly, the accumulation of fresh fluid above would cause an overturning with the overlying salty fluid so that a staircase of fingers and mixed layers would ensue. He and Stewart Turner (1969) verified that in a laboratory experiment. The vertical distribution of salt finger layers bounded above and below by unstratified (mixed) fluid (a staircase structure) has been observed in the upper kilometer of many subtropical regions of the oceans. In the CSALT region northeast of Venezuala (Schmitt *et al.*, 1987) these stratified layers have been observed more or less unchanged over the past 5 decades. They extend over a horizontal distance of 1000 km or more so that the effect of laminar salt fingers with a horizontal scale of a cm or so has a direct influence on phenomena with horizontal scales eight orders of magnitude larger.

At about the same time Stern (1969) studied the stability of a vertical array of salt fingers and found that an internal gravity wave can make the array unstable. He called this phenomenon a collective instability. In subsequent articles on double diffusion he managed to derive gross features on flux ratios and other properties in salt-finger setups by use of integral relationships and accompanying inequalities but additional dynamical behavior eluded him, largely because of his avoidance of numerical integration. For more than a decade he stayed away from the topic while he explored other issues of oceanic dynamics.

During this period and throughout his career Melvin took part in the Geophysical Fluid Dynamics (GFD) summer program at WHOI. He had embraced the philosophy of GFD, i.e., constructing abstract models of phenomena of importance in geophysical fluids, and he found the members of the GFD program at WHOI to be congenial and accepting. He directed the program several times, even though he was not oriented toward administration. The members of the steering committee at the GFD program normally advise a fellow during the summer and Melvin was a most willing mentor. He would often advise a fellow on an experimental project, frequently with Jack Whitehead as cosponsor to help with technical issues. He also interacted with the visiting staff and struck close working relationships with some of the more active participants, such as Peter Killworth, Herbert Huppert and Stewart Turner. During the many summers when he attended the program he could be seen walking the streets of East Falmouth with his jaws clamped on a pipe in his mouth as he mulled over and thought deeply about some particular problem.



Melvin Stern, 1998, Professor, Florida State University.

In 1987 he accepted an appointment as professor of oceanography at Florida State University, a position that he particularly relished because he felt that the many theoreticians at FSU appreciated his approach more than did the staff at URI, which had a more exclusive focus on observational activity. In 2000 he was named the Ekman Professor of Oceanography at FSU. His cv reflects his greater comfort at FSU at which he remained without making forays to other institutions, something that he did frequently at URI. And it was at FSU where he attracted Timour Radko and Julian Simeonov as graduate students, both of whom were proficient with numerical techniques with which they helped him open up new vistas of exploration of double diffusive processes. With their help he was able to extend the study of salt-finger phenomena from two to three dimensions and to relax the dependence on a vertically infinite basic state. Toward the end of his life he, together with Radko, was able to extend his progress toward understanding the physics of double diffusion and its application to oceanographic phenomena on levels that went far beyond anything that he had accomplished previously.

Interspersed among those explorations, particularly during the hiatus mentioned earlier, was an elegant analysis of finite amplitude motions in the oceans. Over many years observational oceanographers had generally agreed that the deep ocean was quiescent except for slow motions of the order of mm/sec or less. But in the late 1950s John Swallow made a major discovery when he lowered a neutrally buoyant float to depths of 1 km or more. Attached to the float was a pinger, and by listening to it with sensitive earphones, he found that the float moved with velocities of tens of cms per second in relatively random directions; in other words, the deep ocean had motions that were much more intense than previously thought. So the idea of a quiet ocean at depth was quickly abandoned and both theoreticians and observers turned their attention to efforts to obtain a better understanding of deep oceanic motions. In 1970 Henry Stommel proposed an observational study with an array of instruments at closely spaced intervals at depth just as meteorologists have for studying weather. The resulting effort, the Mid-Ocean Dynamics Experiment, which was supported by the National Science Foundation (NSF) and the Office of Naval Research (ONR) and was referred to as MODE (Rossby, 1978). The observations showed that the deep ocean does, indeed, have eddies, cyclones and anticyclones, just as the atmosphere does. After the fact it was obvious that the deep ocean would have substantial motions just in response to the transient winds and associated pressure fluctuations at the surface. But there was no dynamical theory to explain how free oceanic eddies (closed, self-contained, structures) could exist on a spherical earth or the beta-plane because an isolated feature would be torn apart as a Rossby wave. A few years earlier Nick Fofonoff had produced a steady barotropic model with a circulation consisting of a westward current feeding a "Gulf Stream" on the western side. The motion was independent of a driving force but it required solid boundaries on the eastern and western sides, so it did not explain how free eddy motions could occur.

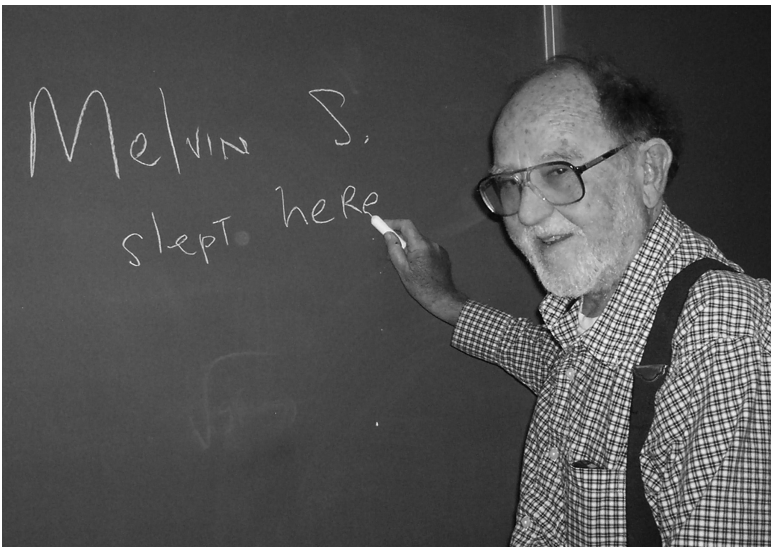
To obtain an isolated eddy, Melvin began by first pointing out that a free, symmetric vortex, which can exist on the f-plane, cannot exist on the β-plane because the Coriolis force is not symmetric due to the β effect. In general, conservation of potential vorticity (PV) is used to analyze motions on the β-plane and the usual procedure for a barotropic model is to expand PV in powers of the streamfunction. The lowest-order linear solution is transient and leads to Rossby waves, which propagate westward, i.e., they are not self-contained features. So Melvin got around the two difficulties by dropping both the transient term and the requirement for symmetry. He set PV proportional to the streamfunction, ψ, and as part of his procedure he had to include a boundary condition for the eddy itself to insure that the eddy was self-contained, i.e., that it was isolated from the surrounding sea. On a circle surrounding the center of the eddy he set $\psi = 0$ and also allowed the vorticity to be discontinuous across the boundary by setting the region outside the circle to be quiescent. He made use of the Bernoulli equation on the circle and the entire model was the simplest one that he could construct for an isolated eddy. The result was not a single vortex but a dipole with anticyclonic vorticity on the equatorward side and cyclonic on the polar side. Another, less detailed, way to understand the model is to realize that the variation in the planetary vorticity, which precluded a monopole, is balanced by the variation of vorticity

of the dipole. The β-effect leads to westward propagation in Fofonoff's model. In Melvin's solution the tendency for the westward flow is balanced by the mutual influence of the two eddies where each tends to drive the other eastward. He showed that the mean square vorticity (enstrophy) of the eddy is independent of the proportionality constant and, using a variational principal, he showed that the value of the enstrophy that he had derived is the smallest area-averaged value possible. He named the feature a modon, (Stern, 1975) a neat reference to the eddies observed in MODE. I remember his Santa-like ho-ho as he introduced the word modon for the rest of us at the GFD program. It was his gift to us. The simple modon has been used by him and others as a building block for both a sea of eddies and other isolated features observed in the ocean and the atmosphere.

Another area that attracted Melvin is the hydraulic control of flows over sills and ridges (Stern 1972, 1974). There are many locations in the oceans where water flows from one basin to another. The exchange of water between the Mediterranean and the Atlantic is a familiar phenomenon, with surface water flowing into the Mediterranean and deep water flowing out. There are deep flows from the Arctic into the Atlantic compensated by surface flows in the opposite direction, though not in the same location. Thus, the hydraulic control that is familiar for a weir is made complicated by both geometry and rotation. The simple control for flow over a weir is that the fluid speed is equal to the speed of a gravity wave, $(gh)^{1/2}$, where h is the minimum depth of the fluid over the weir. Melvin's analysis showed that the speed of the flow must be that of the gravity wave somewhere in the domain, even with rotation and varying bathymetry, a seemingly simple result for a complicated system.

This led to a theory for a free jet flowing along a boundary in a rotating fluid with the same limiting velocity. It was accompanied by accurate experiments carried out by Jack Whitehead with Melvin looking on and making suggestions. This was one of several instances in Melvin's explorations where it was necessary (and possible!) for accurate experiments to accompany the theory for verification. He was not a proficient experimenter himself, but he was very much interested in seeing that the experiments were carried out and he contributed both enthusiasm and cogent suggestions to help bring them to fruition. Melvin's theory was accompanied by experiments in several more studies of flows involving vorticity, jets, eddies and/or flows along boundaries. In Stern (1980) and Stern and Whitehead (1990) he studied the instability of a buoyant jet along a boundary (a fresh water coastal current over denser water) and showed how the flow becomes unstable with swirling vortices penetrating offshore. That study of fronts and bores preceded a substantial production of articles in which he used contour dynamics to study a variety of phenomena such as formation of eddies from currents, eddy formation from the Gulf Stream being an example, departure of a current from a bend in the coastline, and other interesting features associated with jets, either along a coast or freely flowing.

Melvin had four graduate students at URI: J. Demenekow, N. Paldor, C. Shen and S. Ramp, and four at FSU: Q Du, J. Bidlot, T Radko and J Simeonov. His graduate students found him to be very fair but also very demanding. He imposed his own standards on his



Melvin Stern, Farewell party, 13 December, 2007, Oceanography Department, Florida State University.

graduate students. In the last decade of his life he interacted extensively with Radko and Simeonov after they received their PhDs.

He became a Fellow of the American Academy of Arts and Sciences in 1977 and a Fellow of the American Geophysical Union in 1995. He received the first Henry Stommel Research Award from the American Meteorological Society in 1995 and was elected to the National Academy of Sciences in 1998.

Melvin's friends and colleagues were attracted to him because of his inspiring mind, his sense of fairness and honesty, and his serious approach to science. Standing at the blackboard with him discussing a perplexing issue often resulted in a satisfying resolution of the problem. Having someone as eager and willing to help the way Melvin did is something that one does not encounter often. We will all miss this man of extraordinary and generous gifts.

Acknowledgments. I am indebted to Joseph Pedlosky, who wrote a memoir about Melvin for the National Academy of Sciences and allowed me to use some of his material.

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Biographical Notes

Melvin E. Stern

Curriculum Vitae

Date of Birth:	22 January, 1929
Place of Birth:	New York, New York
Education:	
1950	The Cooper Union School of Engineering, B.E.E.
1951	Illinois Institute of Technology (Physics), M.S.
1956	Massachusetts Institute of Technology (Meteorology), Ph.D.

Professional Experience:

1951–52	Woods Hole Oceanographic Institution
1952–57	1/Lt. U.S.A.F. stationed at M.I.T. as Geophysics Research Directorate
1957	Woods Hole Oceanographic Institution, Physicist
1962	Director of summer program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution
1964–87	University of Rhode Island, Professor of Oceanography
1975–76	Visiting Professor, M.I.T. Department of Meteorology and Oceanography
1978–79	Visiting Professor, Max Planck Institute for Meteorology and Oceanography
1979	Director of summer program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution
1980	Visiting Professor, University of Gothenburg, Sweden (2 months)
1983	Director of summer program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution
1985	Visiting Professor, Institut de Mechanique de Grenoble (3 months)
1986	Director of summer program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution
1986	Distinguished Visiting Scientist Jet Propulsion Lab (1 month)
1987–2006	Florida State University, Professor of Oceanography
1989	Director of Summer Program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution

Honors and Awards:

2003	Fellow American Meteorological Society
2000	Ekman Professor of Oceanography, Florida State University
1998	Member, National Academy of Sciences
1996	Distinguished Research Professor, Florida State University
1995	Fellow American Geophysical Union
1995	The Henry Stommel Medal, American Meteorological Society, First Recipient
1977	Fellow, American Academy of Arts and Sciences
1970–71	John Simon Guggenheim Fellow

Bibliography

Melvin E. Stern

List of Publications

1. Malkus, W. and M. E. Stern, 1952: Determination of ocean transports by electromagnetic effects. *J. Mar. Res.*, **11**(2), 97–105.
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