

A Personal View of the ONR High Latitude Upper Ocean Physics Programs

Introduction

In the post WWII era, the Office of Naval Research High Latitude Dynamics (formerly the Arctic Code) program sponsored a wide variety of upper ocean research as part of a continuing series of ice station experiments. By using drifting ice as a rotating laboratory (the Coriolis force is important) without the complicating effect of surface gravity waves, our research community investigated how rotation impacts the turbulent boundary layer and upper pycnocline. In this article, I use four examples to illustrate how ice station experiments substantially advanced knowledge of Ekman dynamics, turbulent (Reynolds) stress behavior, fluxes of scalar properties in the ocean boundary layer, and Rossby adjustment.

My introduction to polar regions came with the first nighttime C130 Hercules landing on sea ice at the Arctic Ice Dynamics Joint Experiment (AIDJEX) Pilot Study station in March, 1972. I was standing on the flight deck (FAA restrictions were less stringent in those days) as we came down onto a frozen-lead runway lit with smudge pots, and it is the only time I have ever experienced a landing where I could not tell when the wheels actually touched down. My memory of the remainder of that first night is the roar of the C130 turbines as flight after flight landed,* and we were rousted out to lend a hand offloading. Still, despite the sleep deprivation and aching muscles of the first few days (a common feature of some twenty-odd camps since), I had a chance to observe a completely new environment, where the air was so cold it stopped your nostrils, sunlight so intense it made your eyes ache, and the “terrain” of pres-

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* By modern standards, the AIDJEX Pilot Study drift station was huge. Conceived and organized under the leadership of N. Untersteiner as a pilot for the year-long 1975–1976 AIDJEX study, it was supplied by 18 C130 and numerous smaller aircraft flights. Its peak occupancy exceeded 80 scientists and support personnel (Heiberg and Bjornert 1972).

sure ridges and sastrugi ice dunes made it easy to imagine you had seven-league boots. Aside from the airplane loads of stuff we brought with us, the color spectrum consisted only of gradations from white to blue. I was hooked.

As a neophyte graduate student under Prof. J. Dungan Smith, I learned a lot in the following weeks. Smith was an exacting but inspiring advisor, who fortunately paid little attention to the conventional wisdom that it was impossible to directly measure turbulent fluxes in the ocean. As few had before, he understood the potential of the drifting ice platform as a superb laboratory for studying rotating turbulent boundary layers (where the Coriolis force is important), and he designed a remarkable experiment that was probably the first and most complete study of its kind. It became the focus of my thesis, and in retrospect I was indeed fortunate to have been associated with such a project.

For me, Smith’s approach to science fit well with an attitude that many scientists, at least in the Arctic community, identified with the Office of Naval Research. It seemed that, more so than the other agencies, ONR was willing to stretch to accommodate a researcher with novel, often untried ideas, if the program managers had faith that something useful might come of it. Smith’s 1972 AIDJEX project was a good example: in the face of a community skeptical to begin with that turbulent flux could ever be measured in the ocean, he proposed an audacious ocean boundary layer experiment with 75 optically sensed current meters suspended in triads on inverted masts at various depths up to 54 m below the ice, all sampled 20 times per second and interfaced to one of the first commercially available minicomputers (in fact, the first ever to appear at an ice camp). These arrays would for the first time provide simultaneous measurements of turbulent (Reynolds) stress and velocity spectra through an entire planetary boundary layer.



The author and Prof. J. D. Smith (red vest) deploying a Smith-rotor current meter triad in a large hydrohole during the AIDJEX 1972 Pilot Study north of Barrow, Alaska.

The triads measured three-dimensional currents (u , v , w) at numerous levels to 54 m depth and provided the first simultaneous measurements of Reynolds stress at multiple levels through an entire planetary boundary layer.

Mountaineers and climbers put great store by *first ascents*, i.e., the first documented climb of a particular peak or climbing route. Science has a similar ethic. In my opinion, a disproportionate number of “firsts” in the subdiscipline of upper ocean physics can be traced to farsighted support from ONR High Latitude Dynamics (including its Arctic Code predecessors). In what follows, I have chosen four examples where understanding of outstanding problems in upper ocean (boundary layer) physics has been advanced by ice station experiments sponsored or cosponsored by ONR-High Latitude Dynamics. This list is by no means exhaustive and is meant much more as a personal

reminiscence than as a complete survey. I have taken the liberty of injecting some personal anecdotes and descriptions in hopes of capturing at least a hint of the unique flavor of polar research. In my experience, ice camps are very much collaborative ventures, where the scientists expect (and are expected) to help clear runways, build shelters, drill holes, mine for fresh water, etc. Thus, the names on the title page of any particular scientific article usually represent a much larger pyramid of both scientific and logistic support.

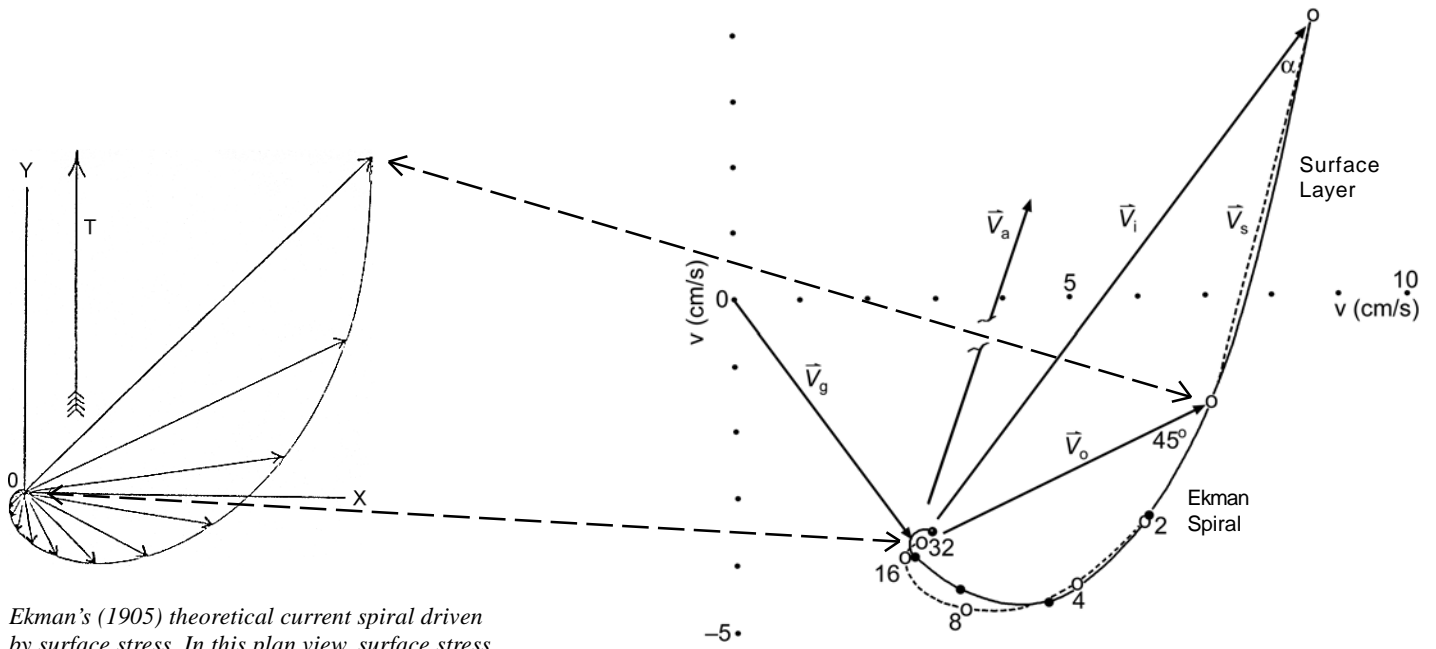
Upper Ocean Physics from Ice Camps

Ekman Spirals and Eddy Viscosity

At the risk of overworking a hackneyed phrase, the holy grail of planetary boundary layer physics in the first half of the 20th century was documentation of Ekman’s spiral. In a remarkable paper published in 1905, V.W. Ekman, inspired by Nansen’s observations during the Arctic drift of the *Fram* in 1893–1896, had predicted that ocean currents forced by wind at the surface would trace an elegantly simple spiral with increasing depth, with the somewhat startling result that at some level in the boundary layer (the Ekman depth) the velocity would be in the opposite direction from the surface wind stress, and that the integrated velocity (volume transport) would be at right angles to the surface stress. He showed that for this to happen over a reasonable depth (tens of meters), there must be an “eddy viscosity” that behaved like kinematic molecular viscosity but several orders of magnitude greater.

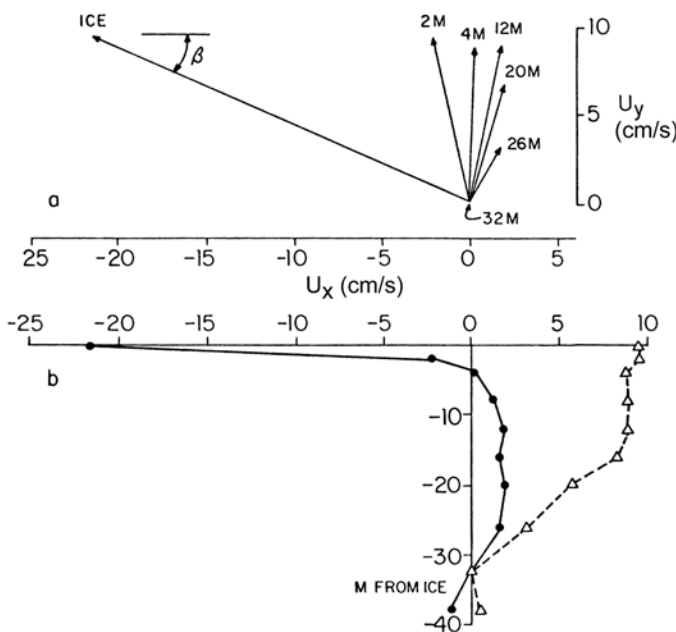
Over time, there was much inferential evidence that Ekman dynamics held for both the atmosphere and the ocean, yet an unequivocal example of an Ekman spiral in the ocean did not appear until Ken Hunkins (1966) published data from Ice Station Charley. Hunkins made use of the concept of a *surface layer*, which accounted for much of the shear in the upper meter or two of the water column, without much diminishing the stress.* In other words, the Ekman layer, through which eddy viscosity was relatively constant with depth, began a short distance into the boundary layer, not right at the interface. Ekman (1905) suggested with remarkable insight that eddy viscosity should vary as the

* In the neutral surface layer, eddy viscosity varies as distance from the surface. For the atmosphere, the surface layer is typically 50–100 m thick, but it is smaller in the ocean by a factor of about 30, approximately the square root of the density ratio of water to air.



Ekman's (1905) theoretical current spiral driven by surface stress. In this plan view, surface stress is indicated by the "T" arrow and current velocities by the connected arrows, which spiral downward with increasing depth from the surface. The surface (largest) vector is 45° to the right of surface stress.

Hunkins's (1966) vector average of nine current profiles (indicated at several depths by filled circles) taken over a two-month period at Drift Station Alpha during the IGY compared with a theoretical Ekman spiral for eddy viscosity equal to 23.8 cm²/s (open circles). Note that a region of high shear (V_y) separates the ice from the upper limit of the spiral in Hunkins's construction, with the assumption that turbulent stress varies little over this distance. The whole boundary layer is advected with respect to the ocean floor with velocity V_g . V_a is wind velocity, V_i is ice velocity relative to V_g , and V_o is Ekman surface velocity relative to V_g .



square of the wind speed, i.e., that it was depth independent but would change substantially with time depending on stress at the surface. Despite this, Hunkins's relatively small value for eddy viscosity based on rather weak mean currents became the de facto standard for oceanographers for some time, apparently for lack of other information. We now know that eddy viscosity (and scalar eddy diffusivity) routinely exceeds Hunkins's value by an order of magnitude in the well-mixed ocean boundary layer and that in essence Ekman was right in his assessment of its dependence on surface stress (McPhee and Morison 2001).

A facet of Ekman's theory of particular importance to ocean modelers and theoreticians is that,

Plan view and profile rendition of an approximate Ekman spiral (plus surface layer) in 5-hour average currents measured on 12 April 1972 at the AIDJEX Pilot Study camp. Velocities are shown relative to the measured velocity at 32 m, where the U_x component (solid circles) is aligned with the negative direction of stress at the interface and the U_y (triangles) component is 90° clockwise. Adapted from MCPhee (1986).

regardless of the vertical structure or magnitude of eddy viscosity, the steady-state volume transport in the boundary layer is at right angles to surface stress and proportional to its magnitude. This was illustrated convincingly by measurements made with Smith's apparatus during a storm at the AIDJEX Pilot Study in 1972. Despite the large U_x component at the surface, its integral from the surface to the base of the mixed layer is nearly zero, corroborating the current reversal predicted by Ekman.

Reynolds Stress

Surface gravity waves make measuring turbulent stress in the open ocean notoriously difficult, because orbital velocities and measurement platform motion must be separated from the relatively small fluctuations that contribute to the covariance among the various velocity components that make up the Reynolds stress tensor (from which both the horizontal shear stress and the turbulent kinetic energy are derived). Consequently, the most successful approach for studying open ocean turbulence is to measure turbulence at the smallest scales (microstructure), then in essence work backwards by a series of assumptions through the turbulent kinetic energy cascade to get at the turbulent kinetic energy (TKE), Reynolds stress, and eddy viscosity that characterize the large-scale flow (Gregg 1987, Shay and Gregg 1986).

A sea ice cover effectively quells short-period waves, and in most situations the ice provides a very stable platform moving at the maximum velocity in the boundary layer. Once the logistic hurdle of operating in polar regions is overcome, drifting ice thus represents an almost ideal laboratory for studying ocean boundary layer physics in the absence of surface waves.

By analogy with atmospheric surface layer methods, Untersteiner and Badgley (1965) used mean profiles of current velocity measured under Ice Station ARLIS II to estimate stress at the ice/ocean interface and the hydraulic roughness of

the ice underside. A different method based on integrating the velocity component perpendicular to stress was adapted by Hunkins (1975) for estimating stress from mean currents.

The first direct evaluation of the Reynolds stress tensor through the entire ocean boundary layer awaited development of Smith's small ducted rotor current meter arrays and their capability of measuring three-dimensional currents. The results showed striking similarity between ocean boundary layer measurements under pack ice and numerical results from the rapidly developing field of atmospheric PBL modeling (McPhee and Smith 1976), suggesting that atmospheric models had direct applicability to the ocean boundary layer, provided scaling was done properly.

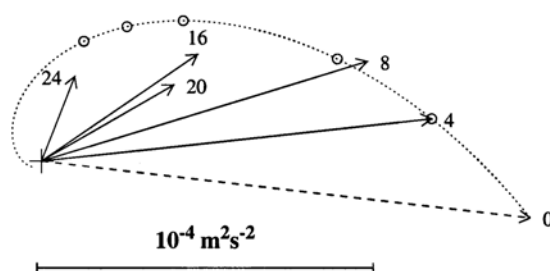
Numerous ice station experiments since Smith's pioneering work during AIDJEX have confirmed the basic behavior of turbulent stress in the under-ice ocean boundary layer. A sometimes overlooked aspect of Ekman's theory is that it predicts a spiral in turbulent stress as well as velocity.

Turbulent Scalar Fluxes in the Ocean

Although Smith's AIDJEX Pilot Study project had demonstrated the feasibility of measuring the covariance of three-dimensional current components in the under-ice ocean boundary layer, the system was not yet capable of addressing directly the important issue of turbulent heat and salt flux. Combined, the scalar fluxes determine buoyancy flux, an important element in the turbulent kinetic energy balance whenever vertical density gradients are encountered in the ocean boundary layer. It is the interplay between buoyancy flux and stress that determines, for example, how deep relatively fresh water from basal melting will penetrate, or how fast heat and salt will be entrained into the mixed layer from the underlying pycnocline. It provides an important constraint on the ice energy balance.

At the time of the AIDJEX experiments in the 1970s, high-resolution profiling conductivity-temperature-depth (CTD) instruments were still in their infancy. Interestingly enough, the genesis of the modern standard for CTD instruments, manufactured by Sea-Bird Electronics, Inc. (SBE), owes much to projects sponsored by ONR-High Latitude Dynamics. According to its founder Art Pederson, the first SBE CTD was built in 1982 for Jamie Morison, who had been a fellow graduate student with me under J.D. Smith. The new instrument implemented a novel period-counting scheme to the Wien-bridge circuitry and unique

Spiral-like structure in Reynolds stress observed at five depths at Ice Station Weddell (1992) during a storm. The numbers refer to the depth in meters from the ice underside. The dashed curve is a simple complex exponential, following the similarity model described by MCPhee and Martinson (1994). Rotation is counterclockwise in the southern hemisphere.



ducted conductivity cell that Pederson had developed earlier in working with the SPURV vehicle at the University of Washington Applied Physics Laboratory. Morison incorporated the new CTD into a profiling instrument that included velocity measurements (again based on a Smith-rotor triad) that he used during several High Latitude Dynamics projects during the 1980s.

For me Pederson's timing was impeccable. I spent the 1982-83 academic year in the High Latitude Dynamics-sponsored Arctic Chair at the Naval Postgraduate School in Monterey, during which I was immersed in planning for the upcoming series of Marginal Ice Zone Experiment (MIZEX) projects in the Greenland Sea as deputy to chief scientist Ola Johannessen, whom I succeeded in the Arctic Chair. I realized that if Smith's current measuring system could be combined with the SBE sensors, we would be able to measure a critical aspect of ice/ocean interaction in the MIZ, namely turbulent heat flux in the ocean, something that had not been done before anywhere. With encouragement from G. Leonard Johnson, High Latitude Dynamics program manager at the time,

I approached Art Pederson with the concept of incorporating output data from Smith's current meters (which by that time had switched from an optical pickup to a Hall-effect magnetic sensor) into the SBE period-counting scheme. Not one to back down from an electronic challenge, Art devised a special version of the SBE CTD he dubbed the SBE 1135, which handled a total of seven instrument clusters, each with five channels: three low-frequency velocity signals plus higher-frequency temperature and conductivity data, with the cables from each cluster plugged directly into the backplane of the 1135 deck unit. The instrument was assembled in Art's garage on Mercer Island, and it worked flawlessly the first time I plugged it in. Some years later Art and Ken Lawson adapted the scheme to a system with a somewhat more conventional combination of pressure case connected by sea cable to a standard deck unit. This allowed a mast with several clusters to be lowered as a unit deep into the upper ocean.

The capability for measuring ocean heat flux during MIZEX did in fact turn out to be quite

A five-component turbulence instrument cluster (u, v, w, temperature, and conductivity) ready for deployment during the 1984 MIZEX project in the Greenland Sea. The cable connects directly to the backplane of the SBE 1135 special CTD deck unit. In the background is Morison's Northern Light enclosure housing the winch for his SBE-based profiling system.





LeadEx just-on-time delivery to the temporary camp deployed at the edge of a lead.

important for understanding ice–ocean interaction. By measuring both turbulent heat flux and Reynolds stress as well as the elevation of temperature above its freezing point (a function of salinity), we were able to establish a functional relationship for heat flux in terms of relatively easily measured variables that has withstood the test of time remarkably well.

The MIZEX heat flux measurements demonstrated for the first time that scalar fluxes of heat and salt at the ice–ocean interface were controlled by molecular processes in thin layers near the interface. While at the Naval Postgraduate School, I had begun a collaboration with George Mellor, who was visiting from Princeton at the time and from whom I learned much about boundary layer modeling. We had worked on details of the boundary condition at the ice–ocean interface, including a modification in which the effective “roughness lengths” for heat and salt were much smaller than the momentum roughness length, thus slowing the melt rate considerably from what had been previously thought (Mellor et al. 1986). Even so, during the last week of the MIZEX drift of the M/V *Polar Queen*, our multiyear floe unexpectedly survived with relatively modest basal ablation in water more than a degree above freezing, when according to our model it should have melted

clean away. By incorporating laboratory results on heat and mass transfer over rough surfaces that explicitly included the laminar sublayers (Yaglom and Kader 1974), we were able to greatly improve the scalar boundary condition representation in numerical sea ice/upper ocean models (McPhee et al. 1987, MCPhee 1987, Mellor and Kantha 1989).

When ice melts rapidly, fresh water introduced at the surface has a strongly stabilizing effect on ocean boundary layer turbulence. The new technology applied during MIZEX substantially increased our observational understanding of this process, confirming both second-moment turbulence model parameterizations (Mellor and Yamada 1982) and a relatively simple similarity approach to scaling turbulence in statically stable, or neutrally stable, planetary boundary layers (McPhee 1981). The other remaining important case—when rapid freezing created statically unstable conditions—provided much of the scientific rationale for the 1992 Lead Experiment. In this truly ambitious undertaking, a complete ice station was transported by helicopters to the edges of newly opened leads, with instruments deployed in just a few hours. Seeing my helo hut lift off for the first time, carrying nearly all of the essential (and expensive) equipment, gave me a decidedly “Wizard-of-Oz” feeling, with new meaning to one of Roger Andersen’s pet ice-camp pronouncements: “We’re not in Kansas anymore.” In keeping with Mother Nature’s proclivity for playing games with scientists, LeadEx was plagued by a shortage of leads near the main staging station (following ice camps like AIDJEX Big Bear, where unwanted leads had forced data interruptions and hasty relocations or abandonment); yet when she did relent and open Lead 3 about 20 km south of the main station, the conditions were almost perfect: a steady north breeze blew our station located on the north edge of a 1-km-wide lead south, so that we were seeing the full fetch of open water and thin ice in our oceanographic measurements.

LeadEx provided a critical test for one further improvement to the turbulence instrument cluster (TIC) concept: the addition of a fast-response microstructure conductivity instrument. The standard Sea-Bird conductivity instrument uses a ducted design to increase accuracy, but the restriction impacts to some extent the response to turbulent fluctuations. As far as I know, LeadEx was the first time the total buoyancy flux was measured directly in the ocean boundary layer. The results confirmed the importance of buoyancy production in the TKE balance for the statically



Temporary LeadEx camp deployed at the north edge of Lead 3, about 20 km south of the main station. The newly opened lead was about 1 km wide, with the ice pack drifting south (toward the left) in response to a northerly breeze.

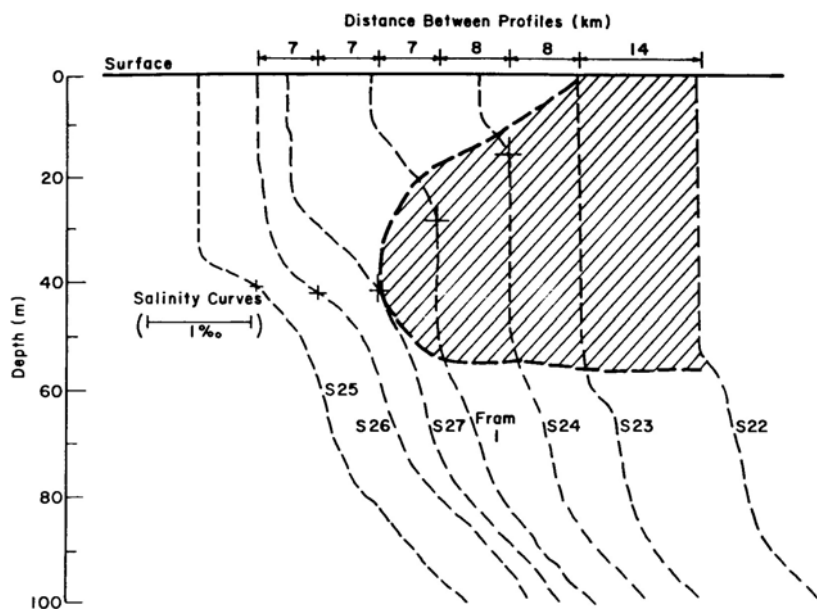
unstable case with rapid freezing, in addition to providing concrete data on turbulence scales in forced and free convective boundary layers, which were roughly ten times as large as for a neutrally buoyant ocean boundary layer with similar surface stress (McPhee and Stanton 1996). There was an unexpectedly strong diurnal signal in turbulent heat flux, with as much as 12% of the total incoming solar energy being mixed downward by turbulence at midday, despite rapid freezing in the lead and a 5- to 10-cm-thick ice cover. There was close correspondence between heat flux measured by the thermal dissipation technique from Tim Stanton's microstructure profiler and the direct TIC flux measurements, as well as comparable measures of TKE dissipation by the two instrument systems. Such comparisons in the ocean are rare, limited mainly to the under-ice boundary layer.

Another unique aspect of LeadEx was using an autonomous conductivity temperature vehicle (ACTV) developed at University of Washington Applied Physics Laboratory by Jamie Morison to observe the horizontal variability associated with

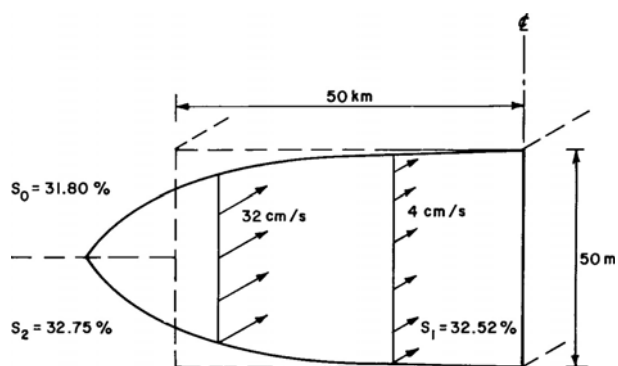
fetch across (and distance from) convecting leads. The ACTV was nearly neutrally buoyant and relatively small, so Morison was able to show that it provided a good estimate of vertical velocity, hence independent estimates of the turbulent heat and salinity flux. Comparisons with the fixed-mast TIC measurements at the edge of the lead provided important calibration and tie-point data (Morison and MCPhee 1998). Similar instrumentation and analysis of data from the SHEBA summer investigated the complementary stably stratified lead situation (Hayes and Morison 2002, Hayes 2003).

Geostrophic Adjustment

One of the great rewards of polar research for me has been the opportunity to work with many extraordinary people. A fine example is Alan Gill, whom I first encountered during the AIDJEX years when he was working as a science technician and all-around Arctic expert for Lamont-Doherty Geological Observatory (LDGO). With a real dedication to his scientific work, he was a legendary figure to a lot of us young Arctic researchers, having



Salinity profiles centered at ice station FRAM I showing an intrusive layer of water with a salinity of 32.5 psu (shaded). Pluses mark a salinity of 32.52 psu. Samples were made by helicopter in a line perpendicular to a current jet observed in a layer 20–50 m deep at the manned station.



Beginning (dashed) and end (solid) structure in the idealized collapse of a lens of intermediate-density fluid with an initial thickness of 50 m and a halfwidth of 50 km, between layers in a rotating, inviscid fluid. Instead of continuing to spread between the upper and lower layers, the intermediate density layer reaches an equilibrium with a jet as shown and a nose about two Rossby radii in extent. Salinity values were chosen to match the observations, yielding an internal Rossby radius of 12 km.

Alan Gill going for the perfect level wind on the portable winch used for helicopter CTD surveying during Fram I in the eastern Arctic in 1979. He made it on at least one occasion.

been a member of the three-man British Transarctic Expedition that trekked by dog sled across the Pole from Barrow to Svalbard in 1968-1969 (thankfully, we did not have to address him as Sir Alan, as Wally Hebert gained the only knighthood from that adventure). Alan and I worked together at Fram I (1979) on a collaborative project with LDGO (K. Hunkins) to gather CTD data by helicopter (we helped time pass in the -35° temperatures at the



edges of steaming leads by carrying on intense level-wind competitions on our portable winch). I figured out early on that if I wanted to get along in the polar environment, I should copy just about everything Alan did, including, on Fram I, literally following in his footsteps over questionable ice during our helo CTD surveys. Nevertheless, I went through to my armpits twice, exactly where he had walked.

I can attest to at least one occasion when Alan's dedication paid off in a big way. Fram I was a particularly hardworking camp with a very international flavor, where we often gathered in the mess hall late at night for conversation and socializing. In the wee hours of one morning, Alan glanced at his watch and started to excuse himself from the gathering to do the standard profiling current meter run. Despite some suggestion that it might not hurt to miss one station, he persevered, and a while later he asked me to look at the profile he had just taken. It showed an anomalous current jet in the upper part of the pycnocline unlike anything we had seen before. We arranged to commandeer the helicopter for the next day, then used it to run a densely spaced CTD survey centered on the station, perpendicular to the direction of the isolated jet Alan had noticed in the profile. Upon later analysis, the results showed that Fram I had drifted across a very nice example of Rossby adjustment in the ocean. The classic problem of how a layer of intermediate density adjusts in a

rotating environment (Rossby 1938) is a staple in nearly every geophysical fluid dynamics textbook (e.g., Stern 1972). The measured current was considerably smaller than the idealized potential vorticity end state, but this would be expected since the fluid was not really inviscid and the feature, which extended north-south for as far as we could measure by helicopter, appeared to be migrating slowly westward.*

Closing Comments

I owe much to ONR High Latitude Dynamics. A whole succession of program managers (Ron MacGregor, Leonard Johnson, Tom Curtin, Mike van Woert, Dennis Conlon) nurtured my career as a scientist early on and then provided me with the support, both financial and moral, to pursue what I thought were interesting and important problems that could be tackled from drifting sea ice. In effect, they provided me and my colleagues with a superb ocean laboratory. I believe that collectively we have built both observational and theoretical bases for understanding ocean boundary layers that have advanced the field substantively. It seems to me that much of the success our nation experienced in fostering the explosive growth in scientific understanding in the postwar period came from a fundamental commitment to basic research: “Go find out how things work; we’ll worry about applications later.” ONR High Latitude embodied that attitude very well and, in my estimation, has much to show for it.

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* The front also drove home the need for caution in interpreting large changes in upper ocean properties. Mixed layer salinity changed by about 0.7 psu (31.8 to 32.5 psu) across a frontal zone about 25 km across measured on one day. This is roughly equivalent to the entire seasonal change in mixed layer salinity measured during summer at the AIDJEX stations in 1975.

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