

Flux Measurements from an Ice-Tethered Profiler: First Look

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Abstract—A current sensor has been added to the Ice-Tethered Profiler to measure mean currents as a function of depth as well as temperature and conductivity. In addition, for periods with the profiler parked at the top of the mooring, turbulent fluxes of momentum, heat flux, and salinity flux have been measured in the under-ice boundary layer in the Arctic Ocean. In order to rotate the measured profiler relative velocities into earth coordinates, a three-axis accelerometer, a three-axis angle-rate gyro, and a three-axis magnetometer were added. This paper will give a first look at the under-ice turbulent flux measurements.

Ice-tethered profiler number 35 was built, deployed in the Arctic on October 8, 2009, and recovered in early fall of 2010. Of 1357 profiles recorded over six months, 335 were stationary profiles for measuring under-ice turbulent fluxes. Of these 335 stationary profiles, six had excessive dropout and were not processed. The other 329 stationary profiles were processed for turbulent fluxes.

The turbulent Reynolds stress magnitude was compared to a drag law stress and the correlation coefficient was 66%. Comparing magnitudes gave a drag coefficient of 0.01, high but not unreasonable for the rough underside of the ice and during a period of ice formation with its associated brine production and negative buoyancy flux in the boundary layer. The turbulent heat flux was compared to the time-rate-of-change of temperature at 5.7m depth and gave a correlation coefficient of 33%. The turbulent salinity flux was compared to the time-rate-of-change of salinity at 5.7m and gave a correlation coefficient of 54%.

I. INTRODUCTION

The Ice-Tethered Profiler (ITP) was developed at the Woods Hole Oceanographic Institution to measure profiles of water properties under the Arctic icepack [1], [2], [3]. Long-term measurements over the upper water column that can resolve the intrusions, internal wave mixing by shear instability and breaking, and turbulent mixing resulting from such events are needed to constrain these estimates and to predict important processes that will affect the climate through Arctic melting. The ITP crawls up and down a mooring hanging under the Arctic ice measuring pressure, temperature, and salinity. At the end of a profile, this data is sent up an inductive modem to a surface buoy and the surface buoy then telemeters this information along with surface GPS positions back to shore by an Iridium modem. This project added a current sensor to the ITP to measure mean currents versus depth and to try to measure turbulent fluxes of momentum,

heat, and salinity in the under-ice boundary layer [4]. This paper gives a first look at these flux measurements.

A modified Modular Acoustic Velocity Sensor (MAVS) was added to the top endcap of the ITP [5]. In order to translate the profiler relative current measurements into earth coordinates, the attitude of the profiler needs to be measured. A three-axis accelerometer, a three-axis magnetic flux sensor, and a three-axis angle rate gyro were added. The pitch and roll are estimated with a complementary filtered sum of low-pass filtered inverse tangent of horizontal and vertical acceleration, and a high-pass-filtered integrated angle-rate from the gyro. Pitch and roll are used to rotate the magnetometer measurements into an intermediate computational horizontal reference frame. The inverse tangent of the horizontal components of magnetic flux is low-pass filtered and summed with a high-pass filtered angle rate from the gyro. A noise budget in estimating tilt and heading showed that using different cutoff frequencies in the complementary filters was appropriate. The cutoff frequency of the pitch and roll complementary filters was 14s while the cutoff frequency of the heading calculation was 200s. Near the magnetic pole, the magnetic lines of flux are nearly vertical and calculating the heading becomes ill-conditioned.

It is not possible to calculate turbulent fluxes of momentum, heat, or salt during moving profiles because of their vertical variability (much of the profile will be below the pycnocline) and there is inadequate averaging time.

II. DEPLOYMENT

Ice-Tethered Profiler #35 was deployed under the Arctic ice in October 2009 with a satellite link to return data from profiles, Fig. 1. Profiles were executed between 5m below the surface (3m below the ice bottom) and 760m below the surface twice a day and from 5m below the surface to 150m below the surface twice a day. In addition to vertical profiles, the ITP was programmed to take stationary 43m 40s measurements to estimate flux twice a day with an 8 hour and 16 hour interval between flux observations. Because of a programming error, only the first two profiles were telemetered to shore. The first 1,357 profiles were internally recorded, were recovered with the profiler in October 2010,

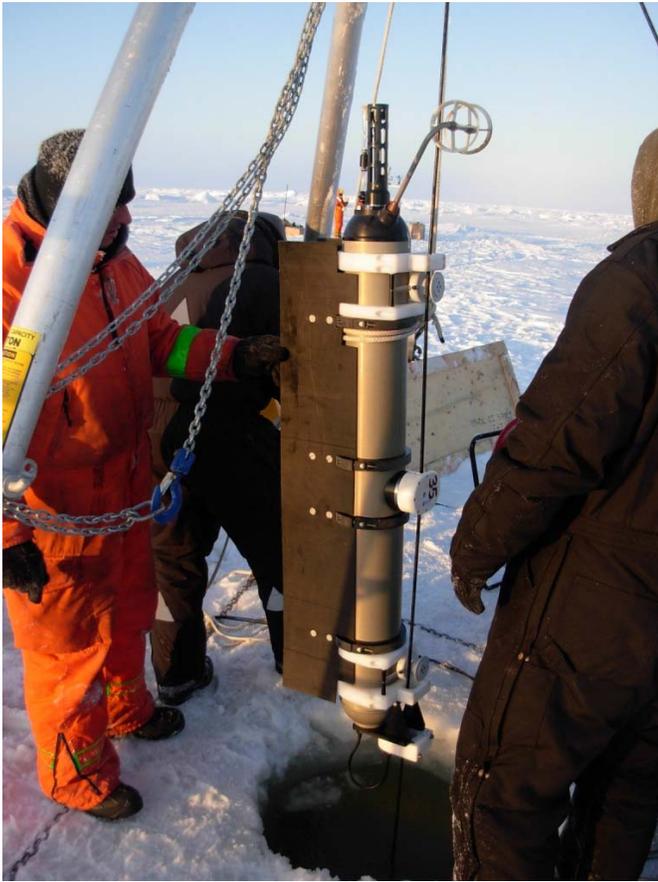


Fig. 1. Deployment of the first ITPV is shown. A tripod was used to support the wire tether and profiler during deployment. The MAVS acoustic current sensor is the bent tube with circular rings extending up and to the right of the ITPV top end cap in this image. The Black plastic tail fins extend from the beam of each side of the vehicle aft, orient the vehicle into the flow, and minimize wagging of heading from vortex shedding off the bluff body.

and these data became available for further analysis. The 1,357 profiles were taken over the first six months of the deployment. An address limit of the profiler controller limits the maximum number of internally recordable files, which would not have limited the number of files had profiles been telemetered back to shore. The profiler was configured to obtain a clean measurement of velocity, conductivity, and temperature on its upward 50-minute profile from 750m to the surface or 9-minute profile from 150m to the surface. The descending profile is slightly noisier due to the wake of the profiler smearing the CTD measurements in time and space. Differentiated pressure from the CTD was available to subtract the nominal 25cm/s vertical crawling speed of the profiler from the vertical component of velocity calculated from the MAVS vector flow measurement. During the stationary flux profiles, the ITP is hanging beneath the ice and senses principally the under-ice boundary layer, which at peak current periods may include an inertial sub-layer with a thickness as great as 3-5m. In these cases, the estimate of Reynolds stress should relate to turbulent transport of heat and

salt to the surface ice as well as momentum, and thus contribute to under-ice melting or at least heat transport from the interior water to the surface. Of the 1,357 profiles, 1,028 were moving profiles and 335 were stationary flux profiles. Six of the flux profiles had excessive dropout and were ignored. The flux processing presented here is from the 329 stationary profiles.

A typical descending profile is shown in Fig. 2. The CTD and Acoustic Current Meter (ACM) are turned on for two minutes before the profile and after. The ACM sensor measures water velocity along four acoustic axes. These four paths over-determine the three-axis water velocity. The measured relative water velocity along the four acoustic paths is transformed into the three orthogonal ITP coordinates of blue forward, green to port, and red up. The profiler is stiffer than water and becomes more buoyant with depth. The profiler is powered by a brush DC motor powered directly by the battery, so as the profiler descends, the buoyancy increases and the profiling speed slows a little. Profiling generates velocity noise, whose high frequency portion gets aliased [6]. The sensor support tube sheds vortices at a scale and frequency that are not resolved by the 2 Hz sample rate and nominal 10cm sample volume of the MAVS. The 1.27cm diameter support structure sheds vortices at the 25cm/s profiling speed of 3.9 Hz, a frequency aliased by the 2 Hz sampling.

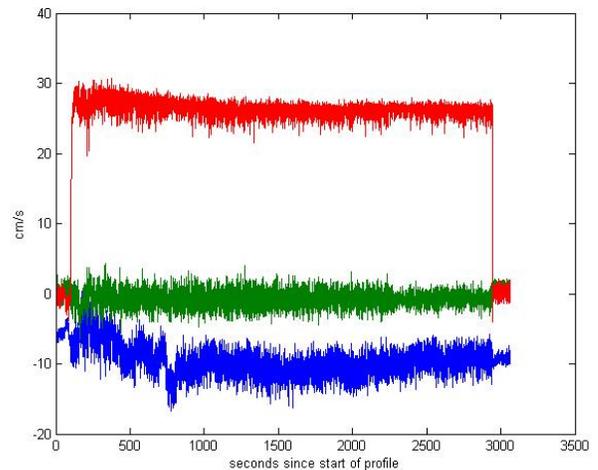


Fig. 2. Typical profile measured velocities in ITP coordinates, blue forward, green to port, and red up.

Fig. 3 shows the measured relative velocity data rotated into Earth coordinates after subtracting the profiler vertical velocity. In this plot, blue is velocity East, green is velocity North, and red is velocity Up.

The CTD data for the same moving profile are shown in Fig. 4. The top graph is the pressure in decibars, the middle graph is temperature in degrees Celsius, and the bottom graph is conductivity in mmho/cm. This water density profile

computed from the temperature, conductivity, and pressure, shows a stable water column.

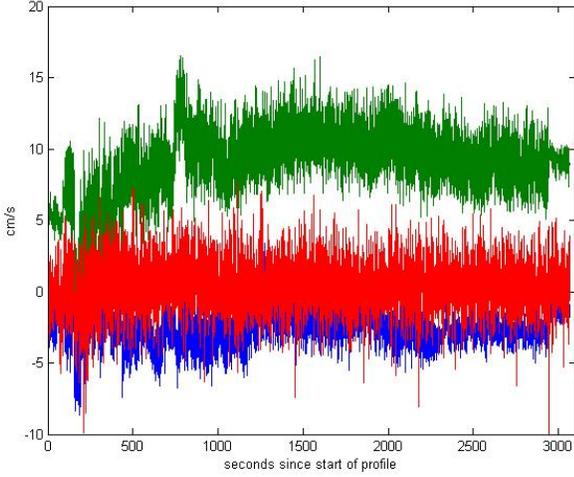


Fig. 3. Velocities from the profile of Fig. 2 rotated into East, North and Up after subtracting the vertical motion of the profiler.

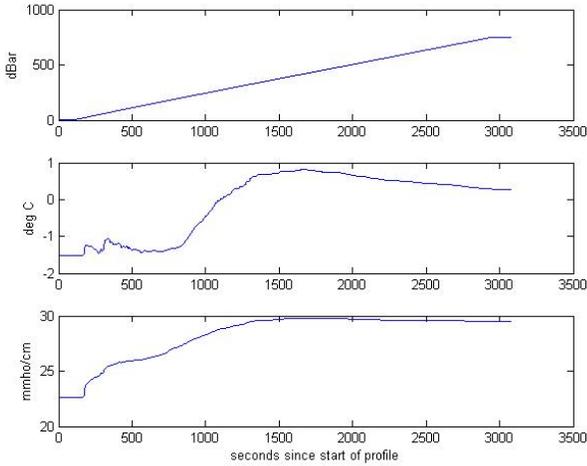


Fig. 4. Measured pressure, temperature, and conductivity from the same profile.

The turn-on time of the CTD and MAVS was not the same and the difference varied. To estimate the turn-on time lag of the sensors, the processing for the moving profiles computes the cross-correlation between MAVS vertical velocity and the time-rate-of-change of pressure interpolated into the sample frequency of the MAVS. The peak of the cross-correlation estimates the actual lag between the CTD turn-on and the MAVS turn-on. In processing the stationary flux profiles, the cross-correlation technique does not produce a useable lag so for these profiles the most common lag of the moving profiles was assumed. The files use mostly linearized processing of attitude but use a nonlinear rotation of measured magnetic fluxes into a horizontal intermediate computational reference frame.

III. FLUX ESTIMATES

There is a need to ground-truth flux measurements, but this is often difficult to do. In this paper, the calculated Reynolds stress is compared to a drag-law stress, the calculated heat flux is compared to the time-rate-of-change of temperature, and the calculated salinity flux is compared to the time-rate-of-change of salinity. The vertical Reynolds stress is given by

$$\tau_{zx} = -\overline{\rho u' w'} \quad (1)$$

and is often called the covariance stress. In this equation, τ_{zx} is the vertical flux of x directed momentum, ρ is the density, u' is the time varying portion of the x-axis velocity, w' is the time varying portion of vertical velocity, and the overbar is a time average. A second estimate of shear stress on a boundary is the drag-law stress

$$\tau = \rho C_d \overline{U}^2 \quad (2)$$

In the drag-law stress, τ is the shear stress on a boundary, ρ is the water density, C_d is the coefficient of drag, and U is the mean velocity at some distance from the surface. The drag-law stress is easier to measure needing only a mean velocity and converges much faster than the covariance stress. A typical drag coefficient, for a neutral boundary layer, one meter above a sand bottom is 0.003. The turbulent vertical flux of heat is given by

$$\rho c_p \overline{w' T'} \quad (3)$$

In this equation, ρ is the water density, c_p is heat capacity of water, w' is the fluctuating portion of vertical velocity, T' is the fluctuating portion of the temperature and the overbar is a time average. The vertical turbulent salinity flux is

$$\overline{w' s'} \quad (4)$$

In the salinity flux estimate, w' is the fluctuating portion of vertical velocity, s' is the fluctuating portion of salinity, and the overbar is a time average.

The heat and salinity flux estimates will be compared to the time-rate-of-change of the top measured temperature and salinity. The time-rate-of-change of the top measured temperature and salinity was from differencing the top temperature or salinity from the previous moving profile and the subsequent moving profile and dividing by the time difference. If we model the water column above the shallow depth of the flux (stationary) profiles as a well-mixed control volume with no heat or salinity transfer other than the turbulent flux at the control volume's bottom, then the time-rate-of-change of heat or salinity of this volume should equal the turbulent flux from below the control volume. This would happen if the heat and salinity transfer to the ice were zero and

all heat and salinity changes resulted from horizontal intrusions of different water masses below the control volume. The depth of the stationary profiles was about 5.7m and the ice sheet was 2.6m thick when the ITP-V was deployed so this depth below the ice should have started at 2.9m. If the only heat and salinity transfer to this control volume is from beneath, then the volume and thickness of this water mass above the stationary profiles should be calculable by equating the fluxes with the time-rate-of-change of this water mass.

While not directly a measured flux, the velocity autospectra from one stationary profile is shown in Fig. 5. The magnitude of turbulent velocity fluctuations and the size of the eddies

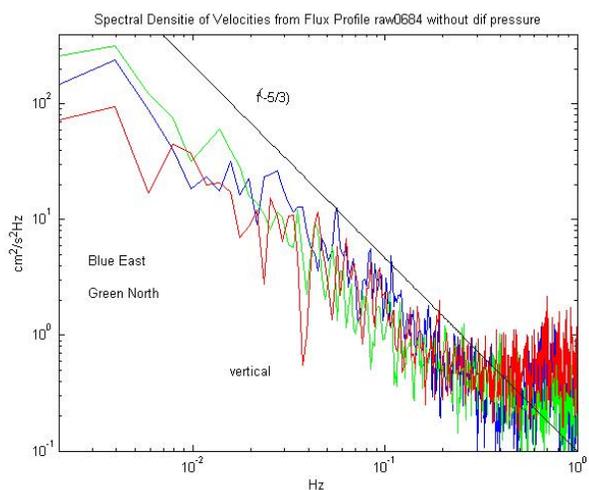


Fig. 5. Power Spectral Densities of Earth Referenced Velocities after Processing for a stationary profile.

increase the turbulent diffusivities for heat and salinity as well as momentum. In this plot, the blue line is the spectra of East velocity, the green line is the North velocity, and the red line is the velocity Up. These spectra were computed without subtracting the dp/dt term; when the spectra are computed from the velocity subtracting the dp/dt term, there is more noise in the vertical velocity spectrum at higher frequencies. These spectra profiles are compared to the minus five-thirds spectra expected in the inertial subrange.

The vertical fluxes of momentum, temperature, and practical salinity were computed for the flux profiles. In this paper, the turbulent momentum flux is compared to the drag-law stress, and the heat and salinity fluxes are compared to the time-rate-of-change of the top measurements of temperature and salinity of the previous and subsequent moving profiles. Preliminary flux observations over the first six months of observations have yielded Reynolds stress values as great as 2.2 dynes/cm^2 . The Reynolds stress and a drag-law stress are compared in Fig. 6. The stresses compared well with a drag coefficient of 0.0102, which is rather large for the distance from the wall of about 3 meters. The correlation coefficient of

0.66 suggests that momentum flux is being measured. The covariance stress is noisier than covariance stress estimates the author measured with a Benthic Acoustic Stress Sensor tripod over a smooth bottom with sensors from one to three meters above bottom [7]. The bottom of the ice may be rough and much of the stress at this depth may be form drag from under-ice pressure ridges. The profiles were from the fall and winter when one would expect ice formation and its associated brine production. Brine is heavier than water and sinks creating a destabilizing, negative buoyancy flux which will increase the momentum diffusivity and drag coefficient.

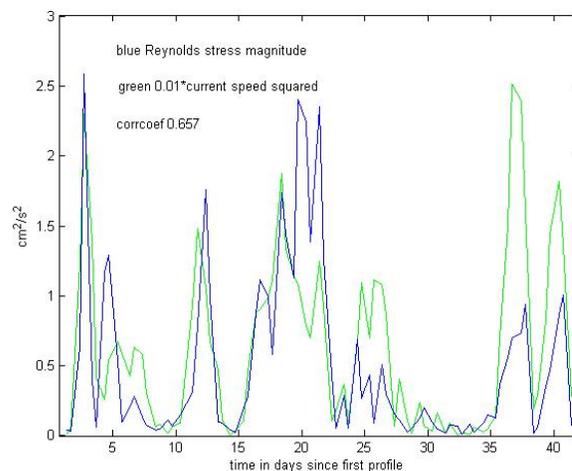


Fig. 6. Magnitude of Reynolds Stress and $0.01 * \text{Current Speed Squared}$.

The vertical heat fluxes of the flux profiles were calculated and compared to 462 (cm) [the best fit] times the time-rate-of-change of the shallowest temperatures of the previous profile and the profile succeeding the flux profile (Fig. 7). While the correlation coefficient of 0.33 is not large, it does suggest that the turbulent heat flux is being measured. There may be (and probably is) heat transfer at the top of the water column. The mean vertical turbulent heat flux was $+ 2.6 * 10^{-5} \text{ } ^\circ\text{Ccm/s}$ consistent with heat loss from the top of the water column in the Arctic fall and winter. The 462 (cm) estimate of control volume thickness is larger than the initial distance under the ice of 3.1m.

Vertical turbulent flux of practical salinity was calculated and compared to 222 (cm) times the time-rate-of-change of the shallowest salinity of the profiles before and after the flux profile and is shown in Fig. 8. The correlation coefficient of 0.54 suggests that the measured turbulent salinity flux was real. The authors do not know why the salinity flux compares better to a 222cm layer above the ITP while the temperature flux compares better to a 462cm layer above, but they are comparable to the 3.1m depth beneath the ice where the profiler started. The mean salinity flux was $- 5.98 * 10^{-5} \text{ PSUcm/s}$ (downward) consistent with brine forming (from ocean water freezing) and sinking during the Arctic fall and winter. While these comparisons do not establish error bars on the flux measurements, they do suggest that the

measurements are at least partly, real. One would expect heat and salinity flux from the under ice-water interface.

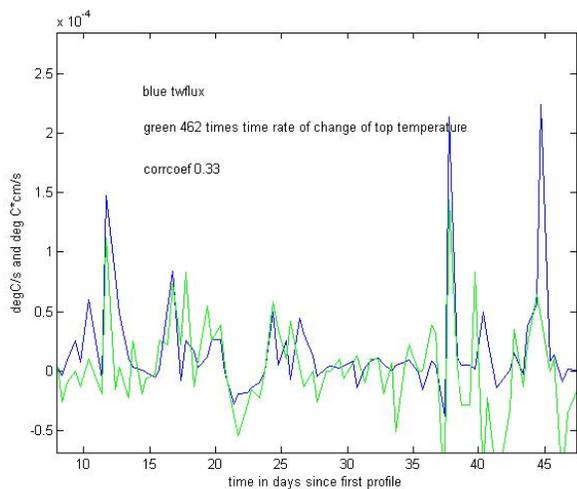


Fig. 7. Vertical Heat Flux and 462 times the time-rate-of-change of the shallowest temperatures of the adjacent profiles.

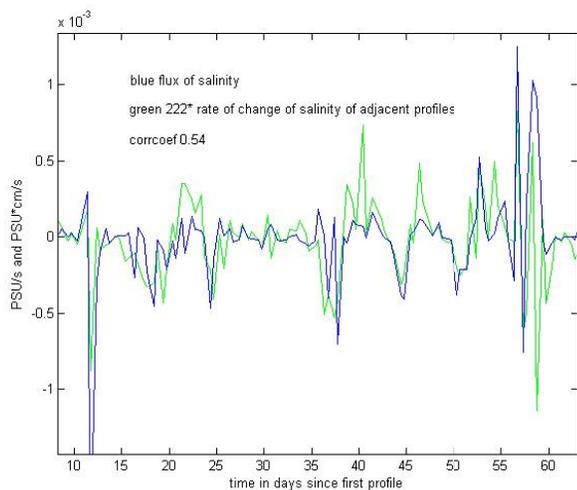


Fig. 8. Vertical Flux of Practical Salinity and 222 times the time-rate-of-change of the shallowest salinity of the adjacent profiles.

In order to estimate how fast the turbulent flux estimates converge for one flux profile, Reynolds stress means were calculated for smaller segments of the period (Fig. 9). In the figure, the blue line is the average for the whole 43m 40s period, the green lines are averages for each half of the record, the red lines are averages for the record chopped into five segments, and the cyan lines are averages of the record cut into ten segments. Heathershaw and Simpson [8] show that surprisingly long averaging times are needed for turbulent flux means to converge. Turbulent momentum transfer is very intermittent in space and time. By the Reynolds analogy, the turbulent heat and salt fluxes need as long an averaging time. The flux profile means are 43m 40s long and it looks like this

long an estimate is needed to get a statistically significant mean.

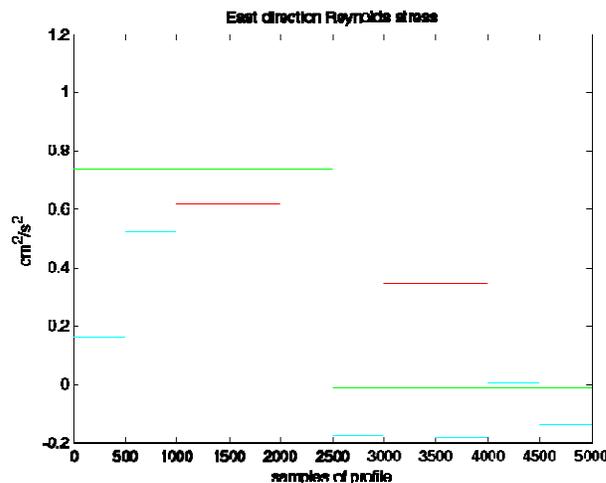


Fig. 9. Convergence of the turbulent flux mean. The blue line is the 5,000 sample mean, the green lines are two 2,500 sample means, the red lines are 1,000 sample means while the cyan lines are 500 sample means.

IV. SUMMARY

A current sensor was added to the Ice-Tethered Profiler and the first such profiler has been deployed in the Arctic Ocean and recovered. This paper has compared the measured Reynolds stress to a drag-law stress, compared the measured heat and salinity fluxes to the time-rate-of-change of temperature and salinity and the results look promising. The authors believe the ITPV is measuring turbulent momentum, heat, and salinity fluxes under the Arctic ice for prolonged periods.

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