

SUCA: An engine for repetitive autonomous profiling near the ocean surface

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Abstract

The SUCA (Submerging Controller Addition) is a robust engine for repeated profiling (yo-yoing) in near-surface waters. It connects to a number of existing oceanic sampling packages and enables many hundreds of profiles to be made over the upper 10 m or so of the ocean or lake in a relatively short period. The workings of the unit are described along with an estimate of power requirements and the wind-limited maximum depth. An advantage of the SUCA is that it enables the entire sampling package to be positively buoyant. The engine has proven to be a simple and robust device that is flexible enough to work with a range of sampling packages in a variety of locations including long-swell Southern Ocean conditions and choppy coastal waters.

Quantifying variability in the upper few meters of the ocean is of primary importance for understanding momentum and mass transfer between the ocean and atmosphere (Agrawal et al. 1992; Gemmrich and Farmer 2004; Stevens and Smith 2004). Near-surface variability is not confined to dissipative scales. Horizontal transects of near-surface temperature show substantial variability at wavelengths of 10 to 1000 m (e.g., Wijesekera et al. 2001; Bowman et al. 1973). It is likely that other biogeochemically important properties will vary on similar scales. Accurate determination of these properties has a substantial influence on estimation of biogeochemical processes such as gas-exchange and vertical mixing of phytoplankton (e.g., Ward et al. 2004a; MacIntyre et al. 2001; Law et al. 2003).

The usual approach to providing near-surface vertical profiles of microscale properties is through the use of some form of timed-release ballast from an otherwise positively buoyant profiler with the sensor-end facing upwards (Carter and Imberger 1986; Soloviev et al. 1988; Anis and Moum

1995). This is labor intensive and not particularly suited to recording many tens of profiles in as short a time as possible. Additionally, the approach necessitates profiling near to the support vessel, which is typically generating substantial flow distortion and a turbulent wake. Near-surface biogeochemical properties are typically sampled from a ship paying only moderate attention to flow distortion by the vessel and no attention to variability.

Multi-parameter profilers are becoming more readily available (e.g., Wolk et al. 2002; Ward et al. 2004b) that can measure many of the properties relevant to turbulence estimation (shear, thermal, and salinity variance) and biogeochemical processes (chlorophyll, light, transmissivity). What is required is a way of remotely and repeatedly profiling a sensor package upwards with as little time between profiles as possible. One approach is for a remote profiler to automatically modify its own buoyancy repeatedly. An example of this is the SOLO float (Davis et al. 2001) used in the ARGO drifter program (Turton 2003). These autonomous floats cycle up and down through several thousand meters of water. However, by their very nature, they have a slow dynamic response and are very finely tuned in terms of buoyancy. The repeat-profiler SkinDeP also uses the SOLO vehicle and is normally negatively buoyant but employs the SOLO gas-filled collar to give a periodic switch to positive buoyancy (Ward et al. 2004b).

There are benefits to working with a package that is always positively buoyant, not the least of which is some potential of recovery in the event of a surface tether or power failure. This article describes an engine for driving the repeated profiling of

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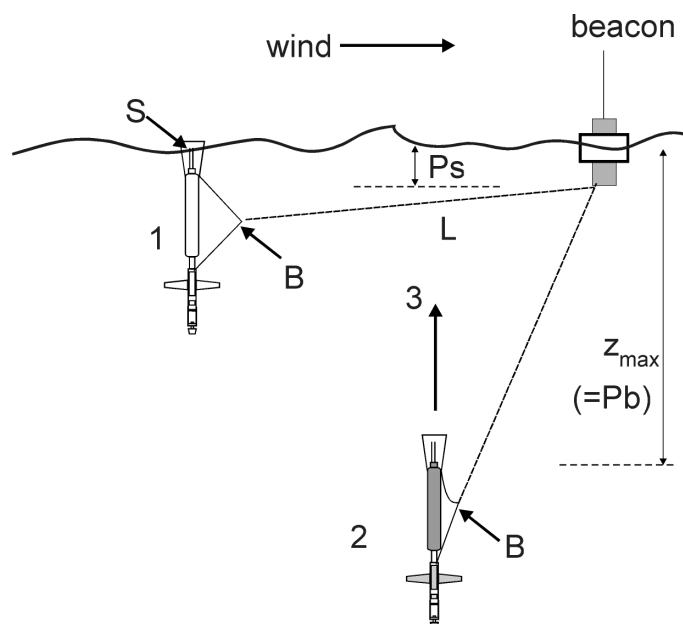


Fig. 1. Deployment configuration showing drifter beacon and tether to profile package. An initially floating SUCA/sensor package (1) with upwards facing sensors, S, is attached via the bridle, B, to the locator beacon by a line of length, L. When the SUCA thruster turns on, the package moves downward as shown by (2). The thruster switches off when the pressure sensor exceeds bottom pressure P_b . The package then rises to the surface due to its positive buoyancy enabling a profile to be sampled. When the pressure sensor determines that the top of the package is closer than P_s to the surface, it restarts the profiling sequence.

a positively buoyant package tethered to a surface very high frequency (VHF) beacon (Fig. 1). The basic design criterion for the engine was that it needed to be able to perform more than 50 profiles of at least 5 to 20 m maximum depth in a continual fashion. Consequently, the usage is not aimed at long-term deployments in the fashion of the SOLO float, but rather for rapidly repeated profiles (more frequent than SkinDeEP) for determination of near-surface variability. For a 20 m profile at 0.5 m s^{-1} , this would require the 50 profiles to be obtained over a period of around an hour.

A second criterion was for the engine to be standalone with its own pressure sensor so that it could be attached to a variety of passive profilers. We have used the device with three sampling packages: SCAMP (Precision Measurement Engineering), VECTOR (Nortek), and TRAMP (a custom profiler based on aspects of SkinDeEP). These packages range from 60 to 150 cm in length. A final issue is the requirement that the tether line be slack during ascent so that there is no motion contamination during the profile.

Because the engine is essentially a standalone programmable thruster and battery pack (Fig. 2), it was named SUCA (SUBmersion Controller Addition). The following sections describe the basic aspects of the SUCA design and electronics as well as a guide to the programmable operating sequence. Solutions to a number of troubleshooting issues are explained.

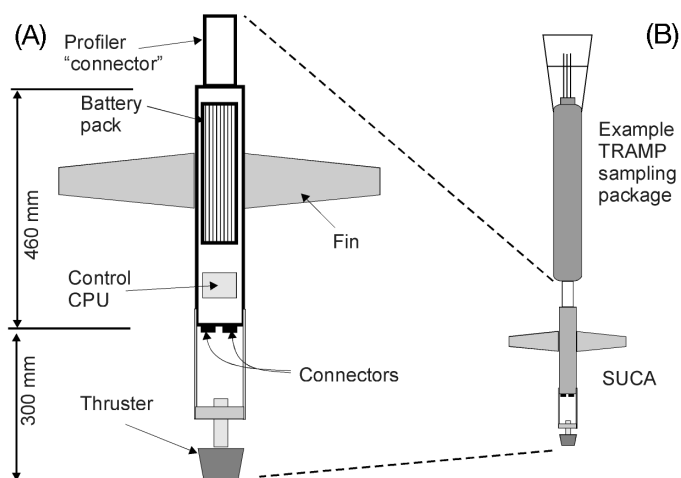


Fig. 2. (A) Cutaway of the SUCA layout and (B) SUCA (bottom) connected with example TRAMP sampling package (top).

Finally, guidance for operation in the ocean environment is provided based on first-order modeling of the dynamic behavior of the unit in situ and the effect of tethering.

Materials and procedures

Typical sampling packages with which the SUCA works provide a few tens of grams of positive buoyancy, although this can be adjusted through the addition of buoyancy or ballast. There is a clear advantage for having reasonable positive buoyancy and a low center of mass because this keeps the profiler aligned vertically.

The SUCA controller and batteries were mounted in an anodized aluminum housing that was 100 mm in diameter, had 6 mm wall thickness, and was 460 mm in length. One end of the housing has a welded-on end-cap made from 10 mm thick aluminum plate. The other end has a 40 mm thick removable end-cap made from the engineering plastic Delrin, sealed with two O rings, and secured to the housing with two over-center clamps. This end-cap has three underwater connectors and a plug for gas-venting during battery recharge. One connector, a 6-pin Impulse LSG-6-BCL, supplies power and control signals to the thruster. Another connector, a 4-pin Impulse IESQ4MF-BC, has 2 pins that are shorted to turn on power and 2 pins used to detect when immersion occurs. This is accomplished by applying a voltage across the pins and sensing the drop in voltage caused by the conductivity of water. The remaining connector, a 6 pin Impulse LPMBH-6-MP, is used for communications to an external computer and for battery charging.

An internal chassis is made from three 10 mm diameter rods and 7 mm thick Delrin bulkheads. The chassis supports a battery pack and two purpose-designed printed circuit boards: one with voltage regulators and power control components and the other with an amplifier, analogue to digital convert-

ers, and a STAMP microcomputer. The thruster itself (150 mm in diameter and 250 mm long) is mounted on a small frame at the base of the housing (Fig. 2) extending 300 mm beyond the end of the housing, making the entire unit around 900 mm long including the connector section (Fig. 2). The housing is rated to 70 m depth. The downward thrust is provided by a single Tecnadyne Model 250 thruster, which can provide up to 50 N of thrust. The thruster requires 48 VDC at 5.9A. This was supplied by a battery pack measuring 220 mm long by 84 mm diameter and containing 40 Nickel-Metal Hydride 4/3A batteries providing a total energy of 690 kJ. This is sufficient to run the thruster at full power for 30 min. These batteries can be recharged in about 3 h with a 60 V power supply. A Data Instruments Model AB pressure sensor monitored the depth.

The control signal voltage (0 to 5 V) for the thruster is provided by a STAMP microcomputer that was chosen because of its low power consumption and ease of programming. Other microcomputers could be used but purpose-designed printed circuit boards and software program would still be required. The STAMP runs a Pico-Basic program with a sequence that automatically recalibrates the pressure sensor for local atmospheric pressure, detects immersion, and then starts the profile cycle, which contains the following loop events: (1) powering up the thruster, (2) checking for pressure exceeding maximum depth and switching off thruster power, (3) checking for return to near-surface, and finally, (4) a wait-period followed by a return to powering up the thruster (1). There is an additional safety cutout that turns the engine off if it runs continuously for an unusually long time (typically set to 90 s).

The program is initiated by first connecting the SUCA communication port to a serial terminal and then inserting a shorting plug into a "start-up" underwater connector. At this point, the STAMP automatically runs a routine to query the user for sampling parameters. At the end of this sequence, the program runs the motor for a second as confirmation. The communications are then disconnected, and the unit is ready to be deployed. Because the SUCA is designed to work with a variety of sensor packages and, additionally, memory capacity on most sensor packages is not usually a constraint, there is no provision for communication between SUCA and the sampling package. Consequently, profiles must be separated in post-processing.

A disadvantage of using a single thruster operating in one rotational direction is that it generates a torque that is only opposed by skin friction and form drag of some fittings on the housing. Consequently, the whole package tends to rotate, which reduces the efficiency of the thruster and tangles the tether. To overcome this, a pair of fins (305 mm wide and 90 mm high) shaped from 4 mm thick polyvinyl chlorid sheet provide sufficient opposing drag to stop any noticeable rotation while profiling. The small angular deflection that occurs during the thruster cycle is restored when the profiler pulls tight on the tether at the base of each profile.

The battery pack makes the SUCA unit moderately heavy (>1 kg weight in water). While this is inconvenient, it simply requires that the profiling package have more buoyancy near the upper part of the profiling ensemble (Fig. 2B), aiding stability. Syntactic foam rings (Flotation Technologies) are used to provide this buoyancy.

Because none of the packages that we attach to the SUCA have built-in locator technology, the combined vehicle is tethered (~4 mm diameter, 1200 kg breaking load spectra line from Belitronic) to a floating surface beacon that transmits GPS-derived location over a VHF link (BigEye GPS/VHF beacon). The SkinDeEP profiler tether arrangement uses a single attachment point near the base of the sensors (Ward et al. 2004*b*), which works well. However, the single attachment point does not work well when using the SUCA because the powerful thrust at the base of the unit results in the profiler tilting and directing the thrust at an oblique angle away from the surface float, rather than vertically. This results in very slow sinking rates and is very energy-inefficient because most of the work involves pulling the surface float along in the water. A simple two-point bridle (B in Fig. 1) solves this problem by keeping the profiler more or less vertical in the water column.

With regard to downward profiling, the SUCA-driven package will work if inverted. However, the tethering arrangement requires the package to pull down to somewhere relatively beneath the surface float. This doesn't work in the reverse situation as the profiler will be dragged along as it tries to descend. Additionally, a goal is to keep the profiler positively buoyant.

Assessment

Field operation—Two field experiments in quite different environments were used to illustrate the operation of the SUCA. Note that fine-tuning with respect to ballasting was not required. The thruster worked well with almost any reasonable level of buoyancy so there is little need to fine-tune the buoyancy as required with SCAMP or SkinDeEP. Deployment was from a 6-m rigid-bottom zodiac workboat. As the TRAMP/SUCA package is in excess of 2 m, it was awkward to deploy in choppy conditions. The effort/profile for the combined vehicle compared to single-profile deployments was substantially greater, regardless of factors relating to hull-generated flow distortion. Additionally, while the tether and beacon provided security and ready location for recovery, they added the complications of tether-entanglement and line-drag due to wind action on the surface float. However, the tether actually aided package recovery. It is relatively easy to get the beacon aboard the work boat. At which point, the profiler is hauled in, regardless of whether the thruster is on or not.

The first trial was carried out in a coastal situation in 10 m of water in the Hauraki Gulf near Auckland in the presence of a reasonable windchop (6 m s^{-1}). The pressure

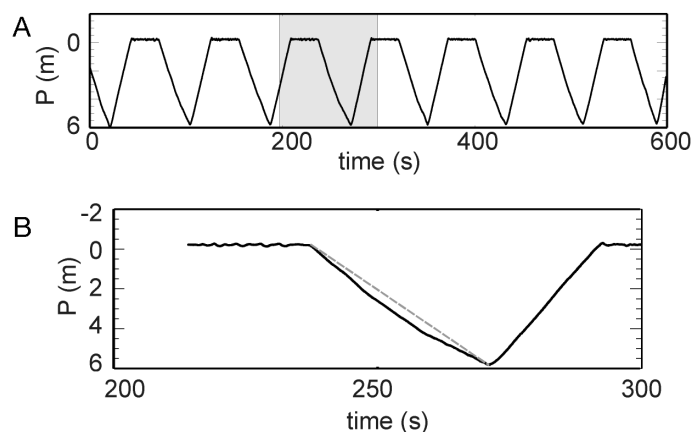


Fig. 3. (A) Example pressure time series segment using a single-point tether, which, in this configuration, shows (B) a nonlinear descent (dashed line is linear reference line) followed by a linear ascent.

sequence shown in Fig. 3 shows the effect of using a single-point tether to connect from the profiler to the locator buoy. The descent was nonlinear due to line drag, whereas the rise to the surface when the profiler package samples was linear. In this application, the descent period was 60% longer than the rise time. The nonlinearity is indicative of an inefficient profiling regime.

The second set of data comes from the open ocean during the R.V. *Tangaroa's* 2004 SAGE-ANZ-SOLAS voyage in swell exceeding 1.5 m significant wave height. The SUCA/TRAMP deployments were from the *Tangaroa's* 6 m work boat. An improved bridle was used in this deployment, which resulted in a more linear downward motion than before (Fig. 4A). For this application, the descent time was substantially shorter than the rise time. The tilt (Fig. 4B) and acceleration (Fig. 4C) records exhibited significant motion due to the significant swell when the profiler was resting on the surface. This also manifested itself during the nonpowered rising phase of the profile sequence as significant perturbations in tilt, which increased near the ocean surface (Fig. 4B). A robust shorting sensor (ISW Wassermesstechnik) on TRAMP was used to detect the surface, enabling explicit identification of the profile. Note that when the profiler was sitting at the surface this detector bobbed in and out of the water (Fig. 4A). All field experiments were carried out running at 25% of full thruster power.

During the passage of some of the larger waves, the tether line would pull taut, generating a clear impulse on the acceleration, shear, and tilt sensor records. The only way to avoid this, other than deploying without the surface tether, was to profile upwards at a greater rise rate. We use an elastic tether to reduce the shock-loading on the bridle. However, to completely smooth out the impulse could potentially mask the effect rather than remove it. At least in the present configuration, the events could be identified and removed in post-processing.

Excessive package vibration reduces the quality of microstructure measurements (e.g., Miller et al. 1989) and so

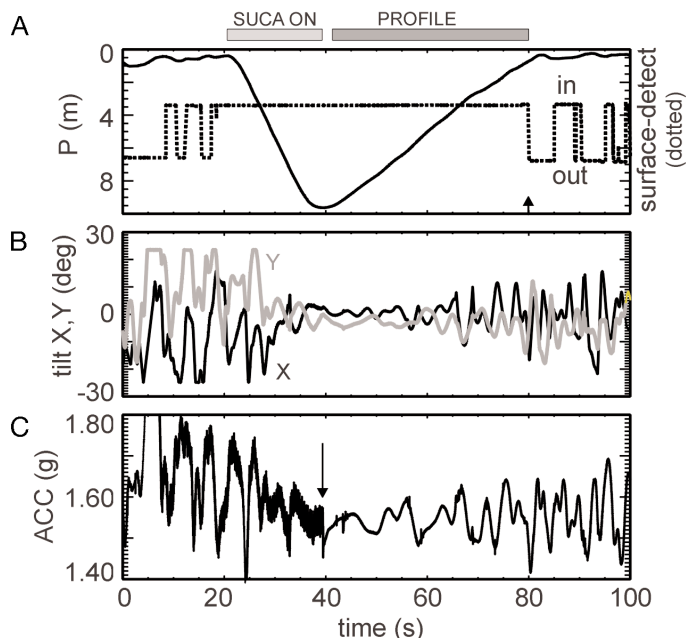


Fig. 4. Properties from an individual profile subsection, using a bridle tether, showing (A) pressure and surface detection, (B) tilt around two orthogonal axes, and (C) vertical acceleration. The arrows show the point where the sensors break through the water surface at the end of the profile (panel A) and where the engine switches off (panel C). Markers above the figure show when the SUCA is on and where the “profile” is temporally located.

needs to be minimized. The combined SUCA/Tramp package is relatively long (>2 m) and aided in lowering the frequency of whole-package oscillation (Fig. 5). However, high frequencies likely to affect microstructure readings are typically caused by guard or cable vibration. This is a separate issue to the actual operation of the SUCA as individual sampling packages will have their own characteristics. The SUCA application should not suffer from cable vibration because this should be slack during upwards profiling. The SUCA/TRAMP combination shown in Fig. 5 clearly sustained some vibration at approximately 3 Hz in vertical acceleration and a slight increase above 20 Hz. Note that these spectral levels are four decades less than the variations due to surface waves seen at lower frequencies.

The conclusion from these trials was that the SUCA-driven profiler provides reasonably linear profiles and that vibration of the long combined package was not a significant issue. Example temperature structure from the Hauraki Gulf data (Fig. 6) showed reasonable temperature structure and significant variability even at 60-s intervals. This points to the usefulness of the SUCA before even considering the importance of quantification of turbulence. Any single profile from this sequence is only weakly representative of the whole. In addition, this example shows that variability exists at quite reasonable levels of temperature difference. A temperature step of 0.1°C at 19°C has some dynamical significance. For example,

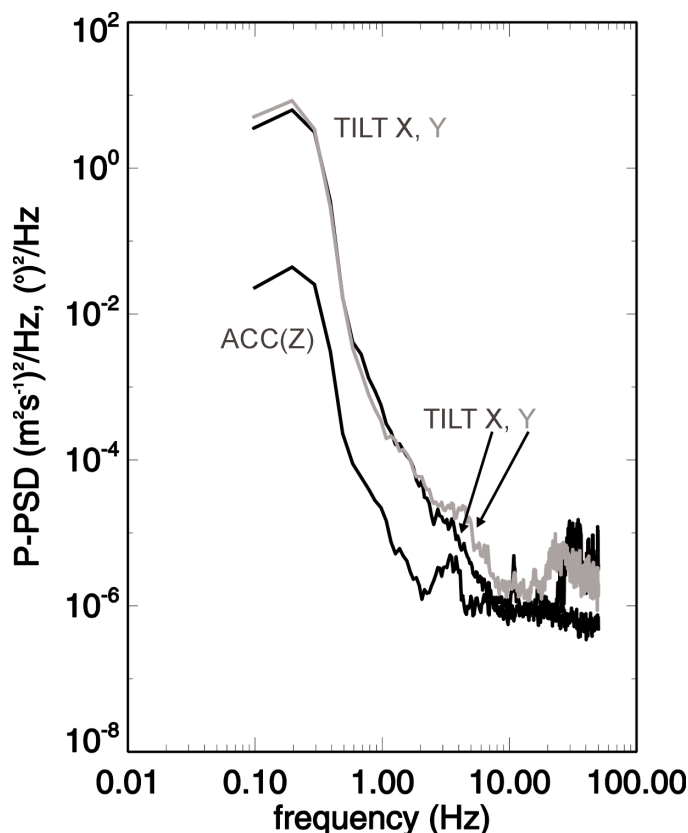


Fig. 5. Pseudo-power spectral densities of averaged vertical acceleration and tilt from 45 profiles. The package was the SUCA/Tramp combination.

such persistent small-scale stratification is a common feature in surface tracer release experiments (e.g., Law et al. 2003) and acts to substantially retard vertical mixing.

Modeled performance—Two main questions arise when considering operation of the SUCA. (1) How many profiles are

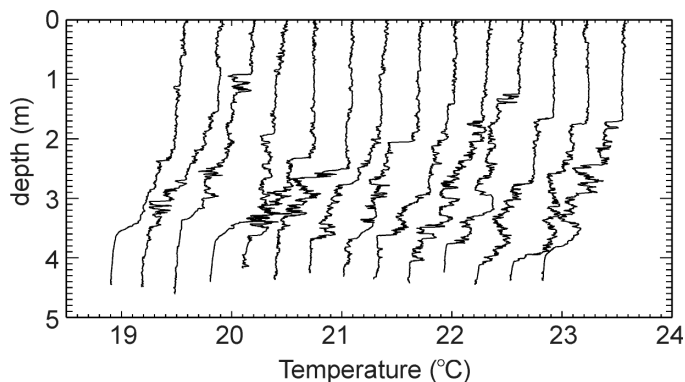


Fig. 6. Temperature profiles using SUCA and SCAMP over the top 5 m of the water column during SURFEX. Each successive profile is offset by 0.3°C and separated by 60 s. There was reasonable package drift during this deployment so it should be coincidence that the first profile is “cleaner” than the subsequent profiles. Suspect profiles will often have extreme overturns and should be discarded.

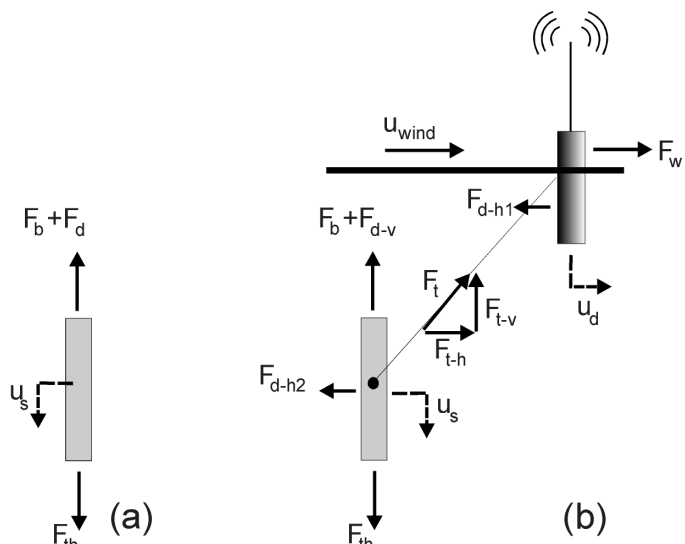


Fig. 7. Free-body force diagram showing engine/sampler (A) without tether (profiler sinking rate u_s , drag force F_d , buoyancy force F_b , and thrust F_{th}) and (B) with tether to surface buoy (horizontal drift rate u_d , wind speed u_{wind} , wind drag force F_w , water drag force on drifter F_{d-h1} , and profiler F_{d-h2} , components of line tension F_{t-v} , F_{t-h}).

possible? (2) How deep can the package descend under any given wind condition? Here we provide estimates based on a simplified dynamic balance. Consideration of a variety of secondary issues is beyond the present scope given that different applications will be moving different sensor packages.

The number of profiles is limited by the battery power. Given a required profile depth z_{max} , the period the engine runs per profile (z_{max}/u_s) factored by the power gives the number of Joules used per profile where u_s is the downward sinking rate. The turnaround time is z_{max}/u_s plus the profile time plus the programmable at-surface delay. In our standard mode of operation this is set to 30 s but could easily be as little as 5 s. It has to be enough time for the profiler to reach the surface from the trigger depth P_s .

The essential components of the vertical force balance are due to buoyancy (F_b), drag (F_d), and thrust (F_{th}) so that $F_{th} + F_b + F_d = 0$ (Fig. 7A). Experience showed that terminal velocity is reached rapidly at these scales (within a few seconds) so a steady-state perspective is sufficient. The sampling packages used here have buoyancies typically around 0.1 to 0.25 kg (including SUCA) and maximum thrust with the Tecnyde 250 is 50 N. By selecting a particular thrust (less than or equal to the maximum), it is possible to solve for the downward velocity u_s in the drag force component given by $F_d = 0.5\rho_0 C_d A u_s^2$, where ρ_0 is water density and C_d is a drag coefficient for a long cylinder with a cross-sectional area of A . The force balance is made more complex with the addition of tether effects (Fig. 7B), which we will address later.

The model enables estimation of the number of profiles calculated as a function of thruster power for any given package

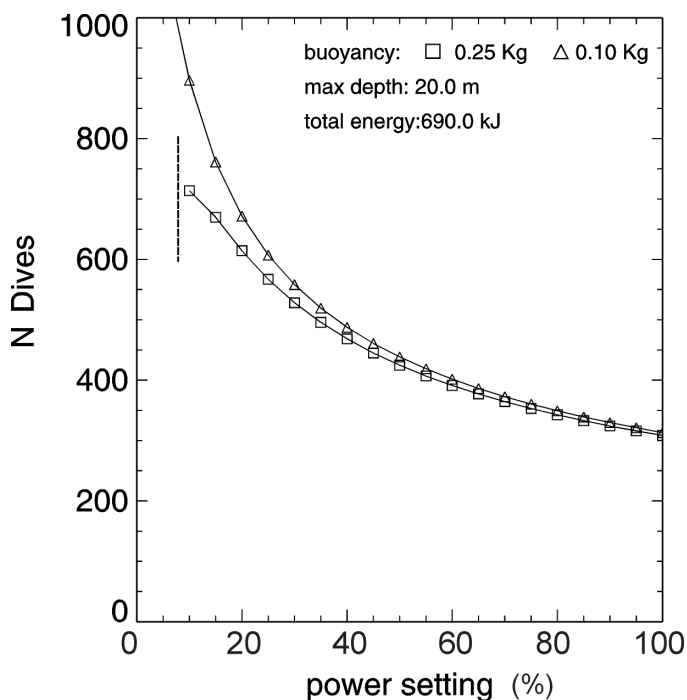


Fig. 8. Modeled number of profiles possible as a function of proportional power percentage for a given maximum depth of profile (20 m) and two different package buoyancies (square 0.25 kg; triangle 0.1 kg). Note that the very lowest power setting (5% of full) generates insufficient thrust to overcome 0.25 kg of buoyancy (limit shown with dashed vertical line).

buoyancy (Fig. 8, 0.1, 0.25 kg). The F_{th} dominates the force balance so that, except at very low power settings, the thruster overcomes buoyancy. Consequently, adding buoyancy makes little difference to the number of profiles (see Fig. 8). The efficiency increases at slower thrust-levels because of the quadratically varying drag. Note however that the time required for profiles increases. This estimate is certainly under optimal conditions but gives an upper bound on what is possible.

An additional factor in adverse conditions that limit maximum practical depth, which has not been considered in the modeling for Fig. 8, is line tension due to wind-force on the surface beacon (Fig. 7B). The vertical force component of the line tension (F_{t_v}) can retard the downward motion. This precludes the use of low-power slow-descent profiles during periods of high wind speed. This effect is quantified here in terms of a line-angle criterion using first a horizontal force-balance to get the line tension, then adding the vertical component of the resulting tether tension force into the previously derived vertical force balance.

The horizontal force balance requires an approximate description of the beacon and the proportion of the beacon above the water surface. Here we model the BigEye beacon as a 0.25 m diameter tube that is 1 m long with 0.3 m exposed above water. The limiting tether angle at which wind-drift generated tether tension overcomes downward thrust, for

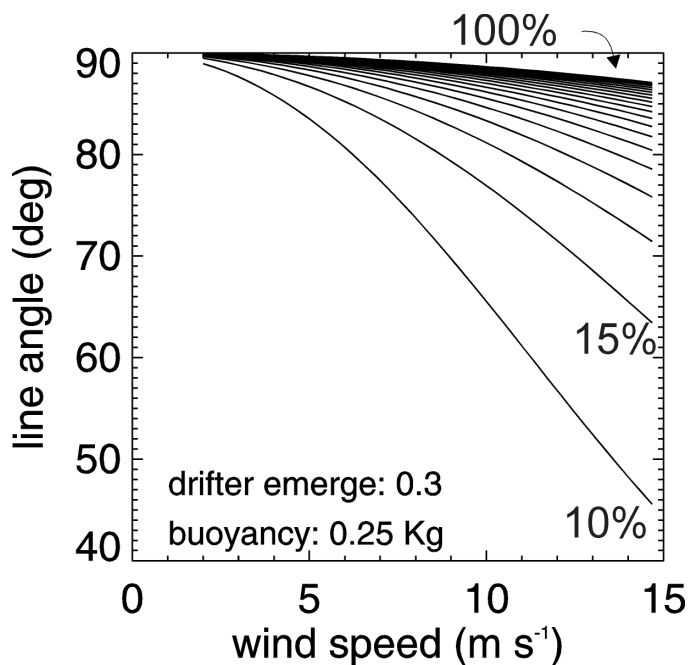


Fig. 9. Modeled theoretical maximum line angle from the horizontal as a function of wind speed for a particular surface float configuration (see text) and profiler buoyancy (0.25 kg) at 5% intervals of maximum power (righthand side).

the same package buoyancy as Fig. 8 (0.25 kg), can be described as a function of wind speed, SUCA thruster power (Fig. 9), and some nominal minimum downward speed (here set to $10 cm s^{-1}$). The minimum downward speed is required because whereas the sampling cycle is feasible as long as the downward velocity is greater than zero, there is a practical limit so that the repeat interval is not too great. The maximum possible depth is then a function of the angle and the tether-line length.

Other practical issues—A number of issues arose in trials that are worth describing. The shorting pin that initiates the profile sequence needs to be protected. A problem encountered in early trials involved the shorting pin being knocked or bent during deployment over the side of a work boat. This reset the program to its input phase so that it waited for keyboard response rather than starting the profile cycle. Alternate approaches would be to have either a magnetic switch or to store the parameters in an auto-executable file that commenced upon power-up.

A second issue is that care needs to be taken when setting the “surface” pressure, that is, the setting that indicates to the SUCA that it has risen near enough to the surface to switch the engine on again, after a programmable delay. When swapping between sampling packages of different length, it is possible that longer packages will not get close enough to the surface to trigger the repeat cycle. Initial trials with the 1.5 m long TRAMP profiler were successful. However, as we fine-tuned the buoyancy to give slower rise-rates, the profiler did not rise

through the water surface as far, nor overshoot its level of neutral buoyancy, and, therefore, it failed to trigger the “surface” detection. Only occasionally, through the passage of wave troughs, would it approach sufficiently close to the water surface to trigger “surface” detection. The result was a temporally sporadic sequence of profiles. This was remedied by setting the “near-surface pressure” to a deeper value ($P_s = 4$ m). This conservative value assumes that the profiler will definitely pierce the surface within the 30-s delay period.

Discussion

Gargett (1999) discussed the frequency distribution of energy dissipation rate ranging from log-normal through to arithmetic-normal. Very near the sea-surface this will be influenced by the frequency distribution of wave breaking (e.g., Smith et al. 1996). Consequently, representative values of dynamic quantities such as energy dissipation rate will be affected by the sampling and averaging. In their landmark study, Anis and Moum (1995) recorded approximately 160-plus microstructure profiles over 7 sampling periods, taking care to discard profiles contaminated by ship wake. The SUCA combination makes it possible to resolve this number of profiles in a 5-h period well away from the vessel. The SUCA combination makes at least an order of magnitude increase in sample space size possible. It also opens up the possibility of biogeochemically-relevant measurements free of vessel flow-distortion that also have some statistically reliable basis.

The fins prove to be a little awkward in deployment and provide a possible source of vibration although the vibration originates a long way from the sensors. An improvement would be through use of a pair of thrusters rotating in opposite directions to nullify the total applied torque but for the thruster used here that would require a custom screw. It is also possible to obtain a counter-rotating pair of screws in a single thruster housing (Ward 2004 pers. comm. unref.). Dual or counter-rotating thruster configurations get around the need for fins but substantially increase the cost of the unit hardware.

There is a possibility of self-contamination whereby the package profiles through its own wake. It is possible that a wake from a single cast can persist for 45 min and, in low-current situations, this could cause sample contamination (MacIntyre 2005 pers. comm. unref.). Profiles need to be carefully examined for such events. SkinDeEP avoids this by having a long wait period at the base of its profile. Prandke et al. (2000) suggested a side-thruster could move the profiler horizontally. A simple mechanical solution was trialed for SUCA with the addition of a fin on a bearing so that the fin is parallel to the flow during rising but at an angle during sinking, thus providing a horizontal force (c.f. Carter and Imberger 1986). An angle of 45° generates a substantial deflection from a vertical trajectory sufficient to move away from the core of the wake, which should be comparable to perhaps two times the width of the profiler initially (~ 200 mm). This mechanical adjustment will enable the device to work in low winds (pos-

sibly not in no wind). In a lake experiment if there were no wind and the lake were large enough, it would be possible to deploy the device without the tether and with the tilting plate. If the lake were small, the beacon could be dispensed with and a much smaller surface float used.

The SUCA has been developed to perform as a robust repeat-profile engine for near-surface waters. It can provide more than 200 profiles over the upper 10 to 20 m of the ocean in a relatively short period. Design curves for power consumption as a function of descent speed have been generated to enable prediction of the number of possible profiles. Another major limiting feature is the requirement for a surface buoy and the wind-drag on this. We have shown that the effect of the wind on limiting the maximum depth of the descent can be estimated. The SUCA has proven to be a relatively simple and robust device that is flexible enough to work with a range of sampling packages in a variety of locations, including long-swell southern ocean conditions and choppy coastal waters. The potential for it to facilitate better understanding of near-surface variability is substantial.

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