SCCWRP Inclinometer Current Meters

Most of the measurements of coastal currents made by SCCWRP since 1974 have been accomplished with inclinometer current meters. The first current meters were modified film-recording models purchased from General Oceanic. In 1978, we designed and constructed current meters for the weak currents in the coastal waters off Southern California. Recently, we converted the film recording version, which used a simple electronic timer and camera, to a programmable, microprocessor controlled unit with solid state data storage. The objective of this report is to describe the design of the meters, and discuss their limitations, calibration in the laboratory, and intercalibration with other current meters in the ocean.

The principle of operation of the inclinometer current meter is relatively simple. Imagine a paper airplane suspended from a frictionless swivel at its nose. In still air the plane hangs vertically from the swivel. When the wind blows, the plane rotates to face into the wind and the tail rises. In a steady wind, the angle of the wings from the vertical (pitch angle) and the orientation of the airplane (yaw angle) are related to the wind speed and direction. Inclinometer current meters operate on the same principle — they measure and store the pitch and yaw angles at preset intervals.

Materials and Methods

Current Meter Construction

Externally, the SCCWRP inclinometer current meter (SICM; Figure 1) consists of: 1) a cylindrical pressure case, 2) a pair of fins aligned with and attached to one end of the pressure case, 3) a pivot-swivel system (PSS) clamped around the case, and 4) a "stand-off" attached to the PSS (not illustrated). The pressure case is made of aluminum (6061-T6) or polyvinyl-chloride (PVC) tube (Table 1). The aluminum cases are hard anodized and powder coated for corrosion resistance; they are negatively buoyant and hang down from the stand-off. The PVC cases are buoyant and hang up from the stand-off.

The current meter fins and the frame for the pivot-swivel system are made of high density polyethylene. A PVC clamp attaches the PSS to the pressure case by a pair of stainless steel pins that are also the pivot for pitch angle changes. Moving the clamp along the pressure case differ-

Figure 1.
SCCWRP inclinometer current meter (standoff not shown).

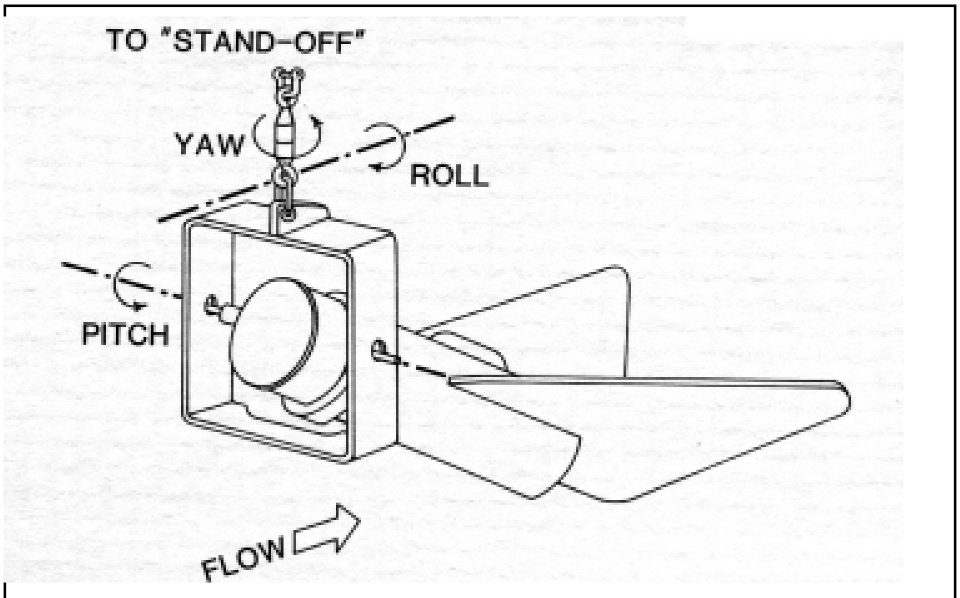


Table 1.
The characteristics of SCCWRP aluminum (6061-T6) and polyvinyl-chloride (PVC) inclinometer current meters.

	ALUMINUM	PVC
Pressure case length (cm)	50	50
Overall length (cm)	125	125
Pressure case diameter (cm)	14.0	14.0
Maximum width (cm)	49.5	49.5
Weight in air (kg)	17.0	11.6
Maximum deployment depth (m)	1500	60

entially changes the moment arms for the center of buoyancy and center of effort for the lift and drag forces. This changes the sensitivity of meter pitch angle to flow speed. The swivel portion of the PSS, which permits rotations about the yaw and roll axes, lies above (Al) or below (PVC) the axis of the cylindrical pressure case when there is a non-zero pitch angle. The offset suppresses undesirable roll induced by eddies shedding from the fins. Shedding is normally confined to a small range of pitch angles, and the accompanying roll is analogous to onset of a spin in an airplane. A fixed fin can be added to the PSS frame to increase directional sensitivity at very low current speeds without affecting pitch sensitivity.

Initially, tilt and direction were measured by photographing mechanical indicators with a single frame advance Super-8™ camera triggered by an electronic timer with a preset sampling interval of 15 min (Boylls and Hendricks 1985). In 1991, we replaced this mechanism with new sensors, microprocessor control of sampling, and data storage in solid state memory. Base sampling intervals for the new meters are 3, 30, and 300 s, but other intervals can be generated by the microprocessor. Sensors consist of a Shavitz AccuStar™ electronic inclinometer for tilt (pitch), a gimbaled Aanderaa model 1248 compass for heading, and a YSI Thermilinear™ thermistor pair for temperature. Access to components in the pressure case is by two end caps. The caps use an O-Ring™ "piston" seal and are held in place by a strip of Velcro™ when out of the water and by water pressure at depth. The case can release excess pressure during retrieval in event of a partial leak. Power is provided by eight AA manganese alkaline batteries — sufficient to sample at 5 min intervals for about 6 months.

Tilt angle is resolved to about one-sixth of a degree. A "look-up" table containing the calibration data for each meter converts tilt to current speed. Direction is resolved to 2° and temperature is resolved to 0.05°C. Temperature response is buffered by bolting the thermistor to the pressure cap (or to an aluminum plug in the PVC pressure cap).

The control program, calibration table, identification information, and parameters are stored in a 64 KB CMOS EPROM (erasable programmable read-only memory). Commands are transmitted to the CM, and data received from the meter, via a RS-232 serial port at 9600 bits/s. Commands include: 1) begin data collection, 2) zero the memory, 3) test the sensors, 4) return to collecting samples, 5) initiate calibration, 6) display number of samples collected, and 7) dump the binary data time-series through the serial port. The control program can be modified for special situations (e.g., burst mode sampling, delayed initiation of sampling, etc.). Current speed, direction, and temperature are stored in static random access memory (SRAM). Up to four SRAM chips can be used for about 43,000 speed-direction-temperature observations. For a 5 min sampling interval, this corresponds to a recording time of about 150 days. When the maximum memory capacity is reached, the MPU discontinues sampling, but retains the existing data and responds to communication requests.

Servicing a mooring buoy.

About 40 s are required to output one month of data collected at 5 min sampling intervals (9,000 observations). For the earlier film-recording meters, about 30 h were required to manually read one month of data (15 min sampling interval) from film and enter it into a computer (3,000 observations). With the electronic meters, the data can be examined onboard ship during servicing and the sensors can be tested in the field.

Laboratory Calibration

In a steady flow, the pitch (tilt) angle is related to the speed of the flow and geometric, kinematic, and dynamic characteristics of the SICM, including: 1) weight and center-of-mass, 2) displacement volume and center-of-buoyancy, 3) area of fins and case, and centers-of-effort of lift and drag forces, and 4) lift and drag coefficients of fins and case. The lift and drag coefficients varied in a nonlinear manner with changes in the tilt angle. Usually it was necessary to measure the relationship between flow speed and current meter tilt.

The meters were calibrated by towing them at known constant speeds (±0.5 cm/s) in the wind-wave channel at the Hydraulics Laboratory, Scripps Institution of Oceanography. During calibration, the SICM output tilt data at 1 s intervals to a personal computer on the tow cart (via two thin wires exiting a special pressure cap). Values were displayed on the computer screen and stored in a file on the hard disk. These data ensured that the current meter was towed until the tilt angle approached its equilibrium value (some extrapolation to equilibrium angle was required at the highest tow speeds due to the shortness of the channel). Equilibrium tilt angles were recorded at current speeds of 0-60 cm/s (1.2 knots) at increments of 1-5 cm/sec.

Tow tank calibrations were made in freshwater. Since meter response depended on net weight (or buoyancy), calibration in the freshwater tank was modified for calibration for the ocean. The relationship between current speed and the tilt of the current meters is (Hendricks 1985):

$$VV^2 = \frac{2\tau_{90}}{\rho A L_D C_D \cos\theta_o} \frac{\sin(\theta_t - \theta_o)}{\cos(\theta_t - \theta_f)} \frac{1}{\cos(\theta_t + \theta_D) + (C_L^R / C_D)\sin(\theta_t + \theta_D)} \tag{1}$$

where:

V = speed of the current past the current meter

θ_t = tilt angle (relative to the vertical)

θ_0 = tilt angle in the absence of any current

θ_D = angle between axis of current meter and center of lift and drag (apex is pitch angle pivot)

θ_f = angle between axis of current meter and chordline of fins

τ_{90} = torque required to support current meter at tilt angle of 90° in the absence of a current

A = area of meter (projected onto a plane parallel with the axis of the current meter

L_D = distance from pivot to center-of-effort of drag force

C_D = drag coeficient

C_L = lift coefficient

ρ = density of water

The only parameters that change significantly between freshwater and seawater are the torque, τ_{90}, and the tilt angle at zero current speed, θ_0. Both parameters depend on the immersed net buoyancy and its center of effort relative to the pitch and the fin axes. If the value of τ_{90} in freshwater and seawater is designated by τ_{fw}, τ_{sw}, and the value of θ_0 is designated by θ_{fw}, θ_{sw}, current speed in seawater, V_{sw}, at the tilt angle, θ_t, is related to calibration speed in freshwater, V_{fw}, at the same tilt angle by:

$$VV_{sw} = V_{fw} \frac{\tau_{sw}}{\tau_{fw}} \frac{\sin(\theta_t - \theta_{sw})}{\sin(\theta_t - \theta_{fw})} \frac{\rho_{fw}}{\rho_{sw}} \qquad (2)$$

Torque at a tilt angle of 90° was measured by suspending the current meter by the PSS in calm freshwater (tow tank) and in calm seawater (Hydraulics Laboratory deep tank) and measuring the force required to hold it horizontal with a spring scale attached to the end of the fins. Tilt angle in zero current was measured by suspending the meter in calm freshwater and seawater and reading the equilibrium angle. The freshwater calibration curve was converted to a seawater calibration curve by equation 2. Direction was calibrated by rotating the compass on a test bench and recording the corresponding the digital output values for a set of directions.

Primary temperature calibrations were made by immersing the current meter in the temperature calibration bath at the Hydraulics Laboratory. After the current meter came to thermal equilibrium with the water bath, digital output temperatures were recorded. Since response was nearly linear, the calibration was done at only a few temperatures. Secondary temperature calibrations were made by placing a primary calibration current meter in a water bath with the meter to be calibrated, then comparing the two output values, or by intercalibration with an InterOcean S4 current meter in the ocean.

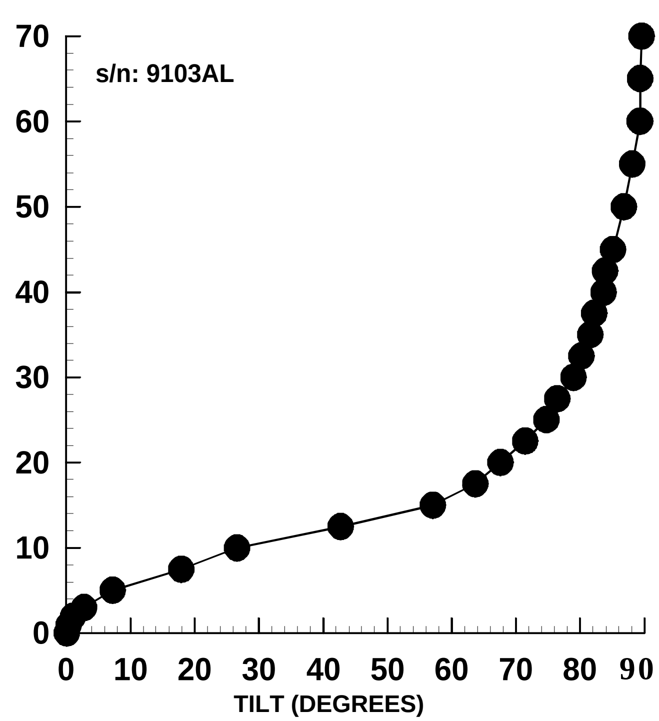
Ocean Intercalibrations

The calibration tow tank was an idealized representation of the ocean. The current (tow cart movement) was essentially constant and horizontal. Currents in the ocean vary over seconds (e.g., due to surface gravity waves) to years, and movements are not confined to a horizontal plane. Deviations from tow tank conditions may result in errors in estimates of current speed and direction. Twice, SICM measurements were compared with measurements simultaneously collected by a VMCM and an electromagnetic current meter. Both intercalibration studies used subsurface moorings at 12-14 m in water 52-56 m deep. Normally the SICMs are used at depths greater than 20 m, but intercalibration at the shallower depths provided a more stringent test of the meters in the presence of surface gravity waves. Calibrations were made during the winter to maximize the likelihood of sea and swell.

The first intercalibration study was made between 1/16/85 and 2/17/85 on the Palos Verdes Shelf. The reference meter was an EG&G Sea Link Systems Model 630 VMCM. The SICM was a film-recording model. The SCCWRP mooring was located about 250 m downcoast from the mooring with the VMCM. Unfortunately, the narrow shelf, mooring deployments made at different times, and ship drift during the deployments resulted in VMCM and SICM current meter depths that differed by about 2 m. When the water column is density stratified, there may be current shear across this interval.

The second intercalibration study was made between 1/24/92 and 2/18/92 off Newport Beach. The reference meter was an InterOcean S4 and the SICM was an MPU controlled model. Separation between the moorings was 50-100 m and both meters were deployed at the same depth. Burst mode sampling was used with the S4; measurements were made at 2 s intervals for 8 min (240 samples per burst). The burst pattern was repeated at 90 min intervals. Burst-mode sampling was used with the S4 to provide estimates of wave-induced currents. The average of the burst mode velocities was used to generate a time-series of longshore and cross-shore velocity components at 90 min intervals. Measurements with the SICMs were made at 5 min intervals. The average of three samples (i.e., spanning 10 min) that bracketed each S4 8 min burst averaging period was used for comparison with the 90 min burst-averaged velocity from the S4.

Figure 2.
Freshwater calibration curve for an aluminum case SCCWRP inclinometer current meter. The meters were calibrated by towing them at known constant speeds (±0.5 cm/s) in the wind-wave channel at the Hydraulics Laboratory, Scripps Institution of Oceanography.



Results

Laboratory Calibration

The relationship between tilt angle and current speed for inclinometer current meters was roughly S-shaped (Figure 2). The calibration curves were similar for meters of a specific material (aluminum or PVC). The differences were usually related to slight changes in alignment of the fin axis relative to the pressure case axis, or in fin dimensions and included angle.

At low current speeds, the meter would hang nearly perpendicular to the currents, so current speed was proportional to the square of the tilt angle. This resulted in the sharply rising curve near the origin (Figure 2). At tilt angles approaching 90°, the response of the meter fell off as the fins almost aligned with the flow (an infinite current speed is required to make the fins align exactly parallel to the flow). This resulted in the sharp rise near the end of the curve. In the intermediate region (between about 10°-70°), current speed roughly corresponded directly to tilt angle. In this region, the error in estimating current speed from the tilt angle was minimized. Therefore, meters were usually configured so that the most commonly observed current speeds fell

Figure 3.
Time series of the longshore component of velocity (270° magnetic) for the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter deployed at 12 m off Newport between 1/24/92 and 2/18/92.

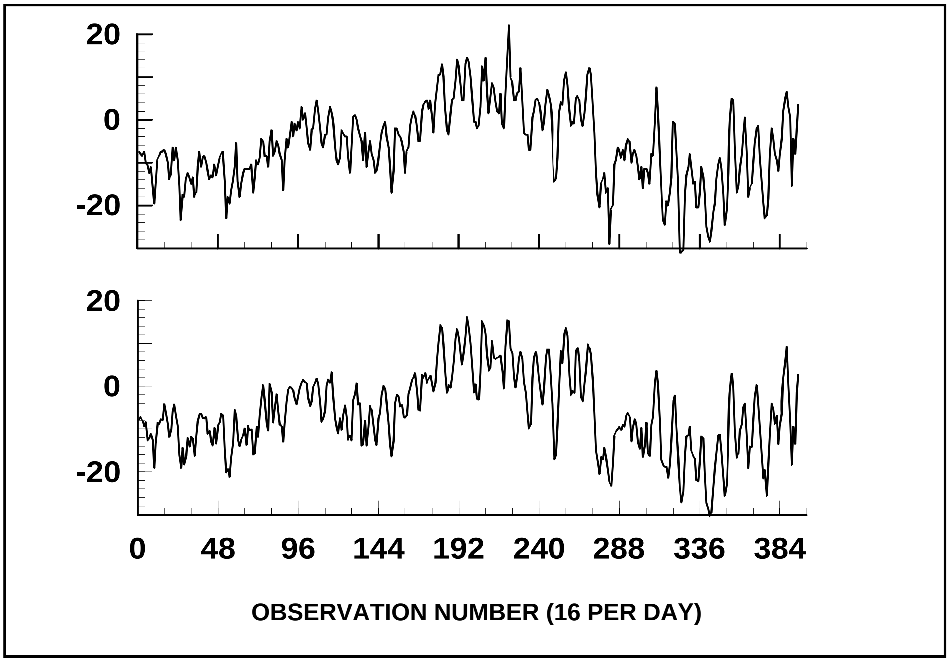
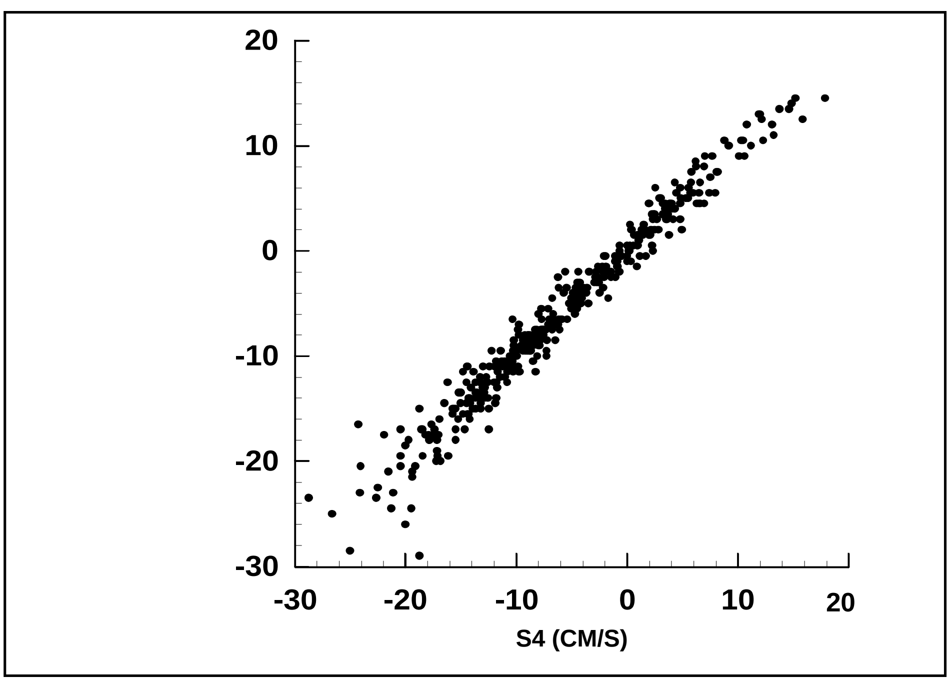


Figure 4.
Comparison of longshore velocity components measured by the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter (not all observations are visible because of overlap) deployed at 12 m off Newport between 1/24/92 and 2/18/92.



within the middle range of tilt angles.

Intercalibration Studies

In general, there was good agreement between the velocities recorded by the VMCM and SICM current meters Hendricks (1985) — although there were periods when the two records had the same variation pattern, but differed in magnitude (10-30%). Here, we focus on the intercalibration study with the InterOcean S4 current meter because: 1) the moorings were relatively close together, 2) the current meters were deployed at the same depth and, 3) intercalibration of the new SICMs has not been reported elsewhere.

The correspondence between the S4 and the SICM for the longshore component of the currents was high (correlation coefficient r=0.96) (Figures 3 and 4; Table 2). However, there were times with conspicuous differences between the measurements. The SICM record had occasional spikes with greater amplitudes than the record from the S4. This was not entirely unexpected if there were short period fluctuations in the currents (e.g., due to surface gravity waves) since the SICM values are the average of three observations, while the S4 values are the average of 240 observations. There correspondence between the two meters was not so good for the cross-shore component of the currents (r=0.76) (Figures 5 and 6; Table 2).

The longshore transports predicted by a simple integration of the time series were in good agreement (Figure 7a). The cross-shore transports showed less agreement (Figure 7b). Part of the difference was reduced by a small (≈3°) rotation in the alignment of the longshore and cross-shore axes for one of the meters (the rotation was within the accuracy of the calibration), but the two records were not identical. We could not determine how much of the residual difference was a result of changes in the cross-shore flow between the two moorings (correlation length-scales are short for cross-shore motions) and how much was related to differences in the measurements. The difference in cross-shore transport, however, was <0.5 cm/s in the average cross-shore velocities (e.g., Table 2).

The temperature probe in the SICM had a longer response time than the temperature probe in the S4 (Figure 8). Analog signal conditioning and the eight bit analog-to-digital converter in the SICM also had less resolution and accuracy than in the S4. Nevertheless, the SICM temperature time series contained most of the features in the record from the S4 and the correlation between the two temperature time series was high (r=0.99).

Table 2.
Mean longshore (e=E-W) and cross-shore (n=N-S) velocity (V) and variance (Var) for the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electronic current meter deployed off Newport between 1/24/92 and 2/18/92.

	SICM	S4	DIFFERENCE
Longshore Ve (cm/sec)	-5.95	-6.07	0.12
Cross-shore Vn (cm/sec)	-0.26	0.18	0.44
Longshore Var(e) $(cm/sec)^2$	83.1	84.6	1.5
Cross-shore Var(n) $(cm/sec)^2$	20.4	21.0	0.6

Discussion

Limitations of Inclinometer Current Meters

Inclinometer current meters have a number of potential limitations, the most important of which is the assumption that conditions in the tow tank are representative of conditions in the ocean. This is equivalent to assuming that: 1) vertical motions in the ocean are negligible, and 2) changes in current speed and direction are slow.

The response of the SICMs to changes in current strength and direction depended on the alignment of the change in flow relative to the axis of the current meter. The response of SICMs was examined by: 1) recording changes in tilt angle as the tow cart (and meter) was suddenly accelerated from zero to a constant speed, and 2) abruptly stopping the tow cart and then rapidly accelerating in the opposite direction to the initial speed. The second technique had the longest response times since a combination of pitch, yaw, and roll motions were required to reach equilibrium. Slow current speeds usually led to long response times and high current speeds led to shorter response times.

A more useful parameter is “response length” — the distance water is transported past the current meter before the speed predicted from the tilt angle is within 37% (1/e) of the actual current speed. Typical response lengths for along-axis variations in current speed are 2-4 fin chord lengths or 2-5 m (Hendricks 1985). By comparison, the response length for a VMCM-type current meter is about 0.1 m (Weller 1978).

We could not estimate the response length of the meters to a cross-axis change in currents. For a constant current speed, the response will be a change in the yaw angle (directional heading). Under these circumstances, the meter orientation will probably follow the rotational change in the flow (i.e., response length <<2 m). Rotations coupled with a change in speed are likely to have response lengths falling

Figure 5.
Time-series of the cross-shore component of velocity (90° magnetic for the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter deployed at 12 m off Newport between 1/24/92 and 2/18/92.

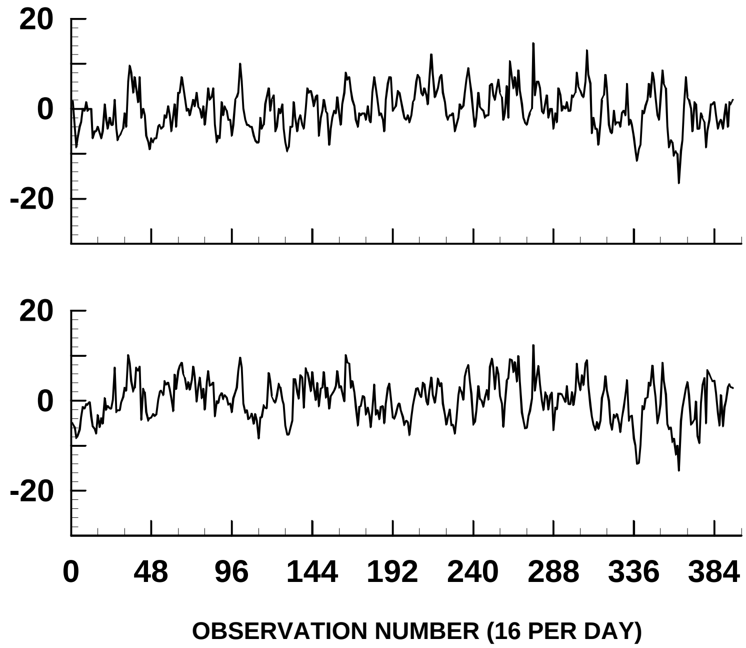
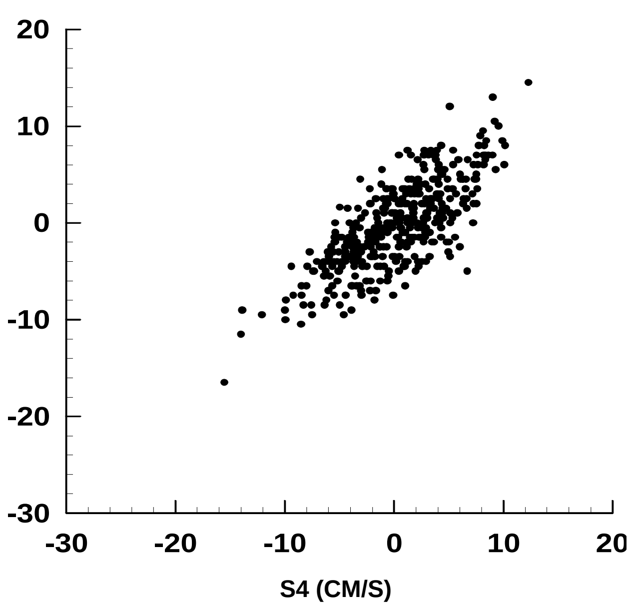


Figure 6.
Comparison of cross-shore velocity components measured by the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter (not all observations are visible because of overlap) deployed at 12 m off Newport between 1/24/92 and 2/18/92.



between the along-axis and cross-axis response lengths.

We used the burst samples from the S4 current meter to estimate the contribution of surface gravity waves to the currents at a depth of 12 m at our intercalibration site (Figure 9). During the first 12 days of the study, wave periods were 10-14 s. During the rest of the study, wave periods fluctuated between about 7 s and 10-12 s. Rms (root-mean-square) wave-induced current speeds at the current meter depth were typically 6-9 cm/s; occasionally falling as low as 4 cm/s, or reaching as high as 11 cm/s. These values were comparable with burst average current speeds (S4) or the three-sample average speeds (SICM). Since only three values were averaged for the SICM, significant wave-associated effects could have been introduced into the measurements. The maximum transport distance was about 0.5 m for a wave with a 13 s period and an rms speed of 8 cm/s; transport distance fell to about 0.15 m for an 8 s wave with an rms speed of 4 cm/s. These transport lengths were substantially shorter than the characteristic SICM along-axis response lengths estimated from laboratory studies. The SICM may have filtered out along-axis fluctuations associated with surface gravity waves.

The situation was not so clear for wave-induced cross-

Figure 7.

Predicted cumulative transport from the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter deployed off Newport between 1/24/92 and 2/18/92. a) Longshore component (positive vlaues are upcoast, 270° magnetic). b) Cross-shore component (positive values are onshore, 090° magnetic); the SICM3 line is a clockwise rotation of 3° for the cross-shore axes.

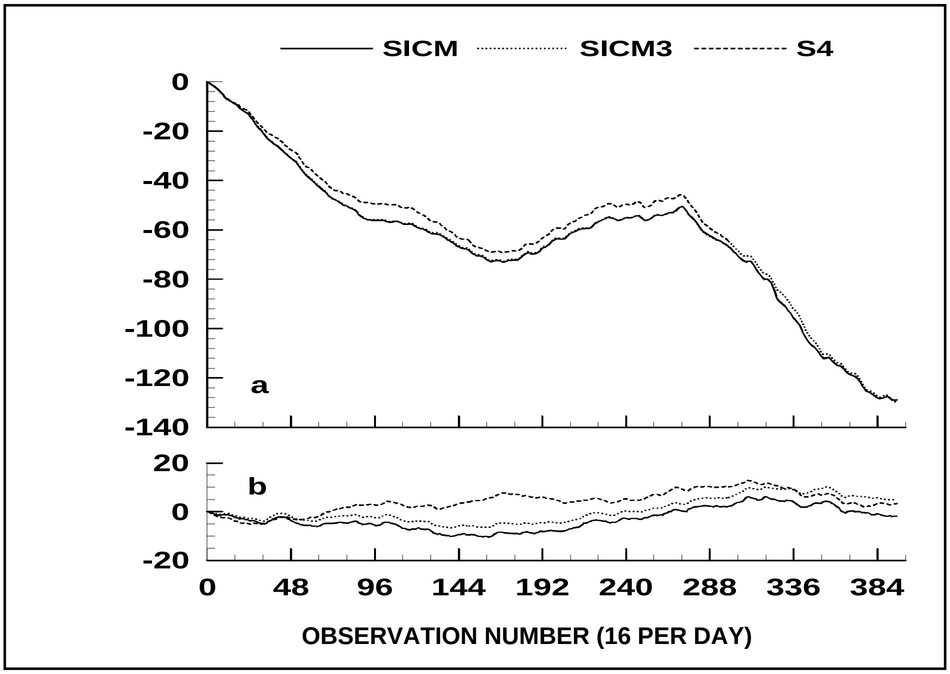
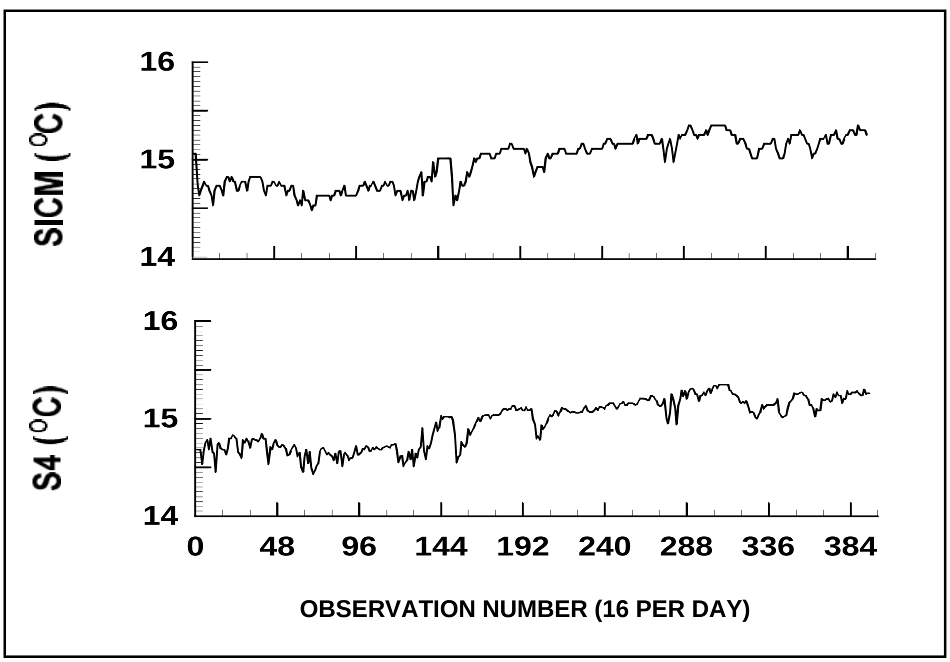


Figure 8.

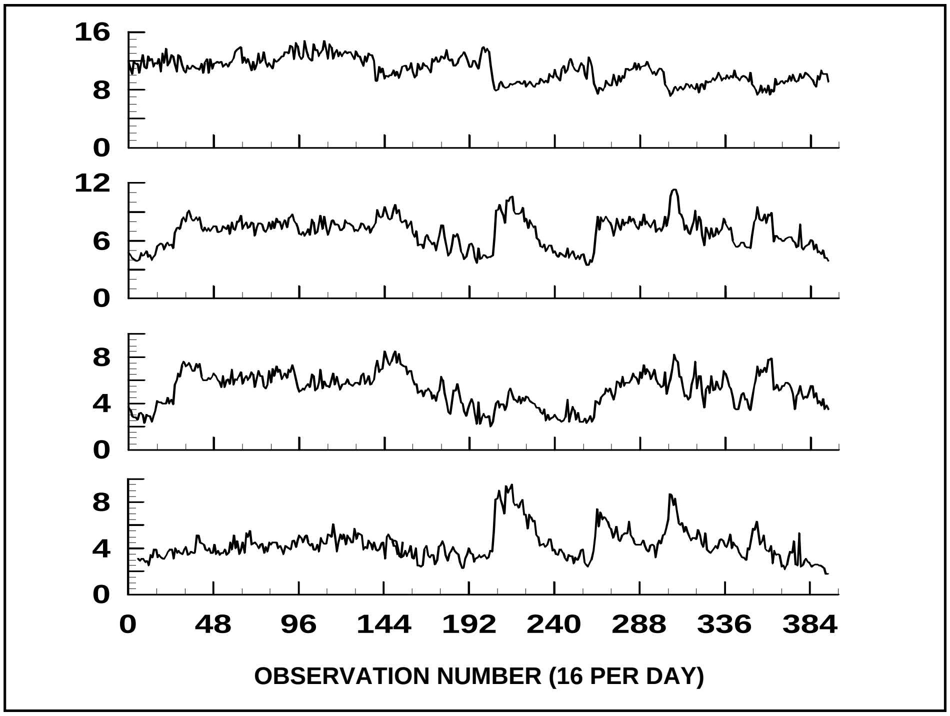
Water temperature time series from the SCCWRP inclinometer current meter (SICM) and the InterOcean S4 electromagnetic current meter deployed at 12 m off Newport between 1/24/92 and 2/18/92.



axis fluctuations since the response length was shorter. In the absence of surface gravity wave induced currents, the dominant flow in the study area was alongshore. Therefore, the presence of surface gravity waves would have had the greatest effect on cross-shore flows. This is consistent with the comparisons between the SICM and S4 longshore and cross-shore components of the currents (Figures 4 and 6). However, correlation length-scales for the cross-shore component are also reduced relative to the correlation length scales for the longshore component (Hendricks 1990, 1992).

Vertical motions caused by the surface gravity waves pose another problem for inclinometer current meters. As the tilt angle approaches 90°, small changes in pitch angle cause large changes in current speed (Figure 2). At tilt angles near 90°, the restoring (buoyancy) torque is nearly independent of the tilt angle ($\approx \sin \theta_t$), but the dynamic effects of the vertical motion are maximum ($\approx V^2_{vert} * \cos \theta_t$). Small vertical currents can produce significant changes in tilt angle. This type of contamination was usually identified in the data by large changes in current speed from observation to observation, which gave the time-series a “fuzzy” appearance. The SICMs were not as effective at “hiding” wave contamination as are other types of current sensors (e.g., Savonius rotor current meters). Some estimate of the long period flows could still be obtained by averaging the fluctuating speeds, but since the computed speed was a nonlinear function of the tilt angle, there was usually a bias toward somewhat higher speeds. For example, the estimated longshore component of velocity during a period of substantial swell was about 60% greater for an SICM than for an EG&G VMCM (Hendricks 1985).

Figure 9.
Wave climate measured by the InterOcean S4 electromagnetic current meter deployed at 12 m off Newport between 1/24/92 and 2/18/92. From top to bottom: wave period (s); rms wave induced speed (cm/s); rms wave induced longshore velocity (cm/s); and rms wave induced cross-shore velocity (cm/s).



Advantages of the SCCWRP Inclinometer Current Meters

The SCCWRP inclinometer current meters have a number of desirable features. Construction and maintenance costs are low due to the relative simplicity of the meters. There are no exposed delicate sensors (e.g., impellers) so the meters are relatively rugged and resistant to damage during handling, deployment, and recovery.

The SICMs can be deployed and recovered from small boats. The meters were designed for weak currents and are nearly neutrally buoyant in the ocean. As a result, little mooring buoyancy is required to support them — it need only be sufficient to ensure that changes in current meter depth due to drag are within acceptable limits. Part of the drag on a mooring is associated with the cross sectional area of the mooring flotation. Since the near neutral buoyancy of the meters reduces mooring flotation, drag associated with mooring floats is minimized. Moreover, the current meters align with the flow at high current speeds, minimizing frontal area and increasing streamlining. At tilt angles near 90°, the cross-sectional area presented to the flow approaches 200 cm^2. This is equivalent to the cross-sectional area of about 2 m of 0.95 cm (3/8 in) diameter mooring line.

High buoyancy requirements lead to increased mooring drag, which require increased anchor weight to ensure that the mooring is not moved by the currents. Increased anchor weight often requires the use of a larger and more expensive vessel for the deployment, servicing, and recovery of the mooring. In coastal waters where a large vessel is not required, the increased anchor weight can lead to substantially higher mooring maintenance costs. In the 1970s, SICM moorings in 55-60 m of water were often deployed, recovered, and serviced from a 4-5 m Boston Whaler™. One deployment and recovery in 350 m of water was made from a 6.5 m outboard powered skiff.

Conclusion

Current meter data are used to estimate the transport of wastewater discharged from submerged ocean outfalls and the replenishment of diluting ambient water near the discharge. Transport computed from data collected by the SCCWRP inclinometer current meters was comparable to transport estimated with data from VMCM and electromagnetic current meters at water depths >10-15 m. Wastefields generated by these discharges typically lie at greater depths, hence data collected by SICMs are suitable for estimating the transport.

The size of the SICMs tended to average out the short period fluctuations associated with surface gravity waves along the axis of the meter. However, the filtering action was reduced for wave-induced flows parallel to the average alignment of the meters. Therefore, the meters may not always resolve peak current velocities associated with short period fluctuations. Deployments in water depths <10-15 m may require averaging to reduce the effects of wave-induced currents that are across the direction of flow of the more persistent currents. Caution may also be required during periods of exceptionally large swell, when vertical components of the currents can produce measured velocities that are greater or less than the actual flow.

The SICMs have the advantage of simplicity, durability, low cost, minimal maintenance, and ease in handling and deployment from small boats.

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