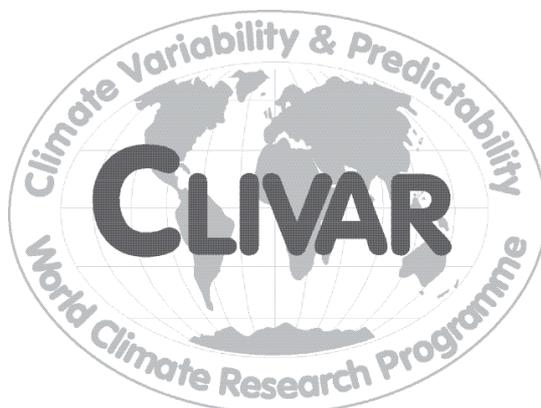


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## WORLD CLIMATE RESEARCH PROGRAMME



### **Report on the 1<sup>st</sup> CLIVAR Global Synthesis and Observation Panel Workshop on Ocean Velocity Measurements and their Application**

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## 1 Introduction, scope and expected outcomes of GVW-1

From the workshop announcement:

### 1.2 Scope of workshop:

To establish the requirements for ocean velocity measurements as part of an observing system for climate. This is a smaller task than a review of all possible future operational use of ocean velocities

### 1.3 Expected outcomes:

- 1) review, document and characterize ocean velocity data presently available or likely to become available in the near future;
- 2) review current dissemination and storage of ocean velocity data streams and identify enhancements to make their exploitation more effective;
- 3) identify critical ocean velocity data streams that may constitute a global network;
- 4) develop the scientific justification and requirements that define the need for the inclusion of ocean velocity measurements in the suite of ocean observations used in climate research and monitoring.

## 2 Measurements

The varied uses of velocity measurements include: construction of seasonal and longer-term fields of ocean velocity, verification of and assimilation into models for state estimation and seasonal to long-term forecasts; creation of near real time data bases for operational ocean models; providing reference levels for box inverse models; comparisons with historical measurements. In all cases, users emphasized the essential need for the measurements to be accompanied by instrument and representation error estimates, and in particular, any potential sources of biases (e.g., wind slip, mooring motion rectification, etc.) as well as random errors. These estimates must be made available to the user community.

### 2.1) Surface drifters

The global drifter array is composed of ~1250 drifters, ~1050 funded by NOAA's Office of Climate Observations, with a goal of five degree resolution of SST and 15 m depth velocity. These drifters dominate the spatial coverage of (near) surface velocity measurements in the Global Ocean Observing System (GOOS). The GOOS (OceanObs99) requirement for current measurements is one measurement per month, per 5° box, with an accuracy of 2 cm/s. The spatial resolution of this requirement comes from the SST requirement to reduce satellite SST bias, and does not conform to autocorrelation scales for velocity measurements. This is a topic that should be re-evaluated in the coming 2009 Ocean Observations meeting. So long as a drifter's drogue (sea anchor) remains attached, it measures currents at 15m depth, with a downwind slip of 1.2 cm/s at 10 m/s wind. Slip is larger than 10 m/s wind and wave conditions has not been measured. Drogue detection is done with a submergence sensor or tether strain. The former can be difficult to interpret and cannot be done in near real time. Drifters without drogues experience considerably more downwind slip (~8 cm/s at 10 m/s wind), quantified in drogued/undrogued studies in moderate wind conditions. Velocity information from undrogued drifters can be recovered if this slip is accounted, but the larger error must also be accounted.

Presently, raw drifter positions are distributed in real time on the GTS, and in delayed mode with quality control, interpolated to regular 6 hour intervals, by the drifter Data Assembly Center (DAC) at NOAA/AOML. Delayed-mode data have a 2 to 4 month lag. These data are also archived at NODC and MEDS. Service Argos provides position fixes for each drifter at a nominal temporal resolution of 1.2 hours globally. Drifters collect total velocity measurements that are relatively accurate, but are spatially and temporally inhomogeneous.

Drifter data can map mean ocean surface circulation at the decadal time scale, and eddy kinetic energy at high resolution (50 km) globally, for comparison with altimetry estimates. Drifter currents can be used to evaluate the global and/or regional accuracy of models and distinguish which models perform most realistically. Drifter velocities resolve seasonal and

interannual differences in circulation patterns, for example the NAO and ENSO related patterns. Because drifters measure total currents, including the Ekman component, their data can be used to test parameterizations of wind-driven upper ocean mixing. Drifter data can be synthesized with altimetry and satellite winds to provide global, homogeneously-gridded current time series of spatially-varying and time-varying accuracy (e.g., see "remotely derived currents" below), and for estimating the geoid.

**Recommendation:** *Careful evaluation of drifters' water-following characteristics in high wind (>10 m/s) and wave conditions is necessary. These conditions are experienced routinely at high latitudes and in hurricanes and typhoons, but current estimates of "slip" (movement of drifter relative to water at drogue depth) are based on extrapolation of measurements at lower wind/wave conditions.*

**Recommendation :** *Drogue lifetimes should be as long as feasible for the drifters. Statistics should be gathered to identify any systematic difference in performance of drogue retention between manufacturers. A close working relationship should be maintained with drifter manufacturers to assure that the best methods of drogue attachment are used by each. Drogue presence detection is critical, and should be as robust as possible. Manufacturer diversity is encouraged to (1) ensure the Global Drifter Program is not unduly exposed to risk of failure by one supplier and (2) direct manufacturers to respond to GDP requirements and to maintain cost effectiveness, performance and hardware quality control.*

## 2.2) Floats

The Argo float array reached the nominal target of 3000 active floats in November 2007, providing nominal spatial resolution of 3 degrees and generating approximately 100,000 displacement vectors per year. The most common mission profile has a float drifting at 1000 decibars, with a 10-day cycle consisting of approximately 9 days at the drift depth, 6 to 8 hours for each of ascent and descent, and 6 to 24 hours at the surface. Details of these timings vary between float hardware types and depend on the mission parameters selected by the float operator.

Floats transmit data while at the surface. In 2007, the majority of active floats use the Argos satellites for both position and data telemetry. A few experimental floats use Iridium for data telemetry, and GPS for position. These floats require minutes rather than hours at the surface. In 2007, the majority of new float deployments were still Argos, so Argos will remain the dominant technology of the active fleet for many years into the future. Any possible transition from Argos to Iridium will depend on the rate at which float operators choose to incorporate Iridium in the float hardware. Most floats use the Argos multisatellite service, to provide the greatest possible number of data telemetry opportunities and position fixes. Nevertheless, there can be periods of up to a few hours between the actual surface arrival(departure) and the first(last) reported Argos surface position.

Floats provide the potential to infer velocity at the drift depth and at the ocean surface. The errors and unknowns contributing to the drift depth velocity are: Argos position error; unmeasured displacement during the parts of surface cycle not bounded by the Argos fixes; unknown shear ( $\partial u/\partial z$ ,  $\partial v/\partial z$ ) during the ascent and descent time. The single inferred drift vector is an integral of velocity over the drift period. Error in the surface velocity estimate arises from Argos position error, and the floats not following the water ("slip"). The latter can be caused by wind and wave action. Floats could thus be regarded as undrogued drifters in a qualitative sense, although the exact slip is not yet known.

Each of the errors described in the previous paragraph can be estimated or corrected to some extent, using knowledge of float behaviour. The techniques for these corrections require knowledge of all the Argos position reports for a float surface cycle. At present, the only float data transmitted on the GTS are the 'profile' data. The profile messages include T and S profiles and a single position used to label the profile. Therefore if differences in the GTS position for successive profiles were to be used to infer drift velocity, this could only be done in

the crudest manner. Superior estimates can be made by using the full set of Argos positions, which are available in real time at the two Argo GDACs as trajectory data, and by the application of algorithms that are under development.

Ocean velocities are thus regarded as a 'product' in the Argo program.

At present, the most widely circulated velocity product from Argo floats is YoMaHa (<http://apdrc.soest.hawaii.edu/projects/yomaha/index.html>). YoMaHa includes subsurface and surface velocity estimates. The product is generated from traj.nc files at the Argo GDACs and uses the full set of Argos position fixes. It does not allow for surface extrapolation outside the first and last fix, or for the shear during float descent/ascent. Upper bounds on these errors have been estimated. Surface ocean velocity error due to wind and wave slip have not been estimated. The ocean surface velocity is a single linear vector fit to the reported positions, so it may be contaminated by non-straight-line transients including inertial, tidal and other motion.

Algorithms have been published that allow for the required surface extrapolation to ascent\_end and descent start time, and to separate the surface motion into a linear velocity and a circular inertial motion. Implementation of these algorithms is under development. Methods for handling the baroclinic shear have been discussed, but there are no agreed algorithms. If there was an explicit requirement, the surface fitting algorithms could be run automatically, to generate a real-time velocity product available at the Argo GDACs.

The Argo subsurface velocities have potential value for state estimation, assimilation and inverse model use. Assimilation models are very sensitive to bias errors: systematic error translates into large transport error. Some assimilation methods can make correct use of Lagrangian data, i.e. allow for the fact that the submerged displacement is an integral over 10 days. The technology exists for ocean basins to be ensonified with a modest number of subsurface sound sources. Floats could then listen and calculate their full subsurface trajectory with daily or even hourly resolution. There are added costs for maintaining sound sources, float hardware, and float energy budget leading to reduced float lifetime. Funding proposals could be developed if the user requirement is demonstrated.

**Summary:** Data reduction efforts to provide Argo-derived subsurface velocities are of high value for a range of users. Surface velocity products are of potential use in supplementing drifting buoy observations, provided the error due to slippage was quantified.

**Recommendation:** Resources should continue to support the evolution of Argo float velocity products, to incorporate improved error estimates and where possible correction for the effects of surface advection, baroclinic shear during float ascent/descent.

**Recommendation:** More rapid turnaround, towards the limit of near-real-time distribution, would allow these velocity fields to gain value in state estimation and ocean forecasting efforts.

**Recommendation:** The necessary investigation should be undertaken to improve value and confidence in the interpretation of Argo surface displacement vectors as ocean velocity, paying particular attention to float slip. Careful comparisons of floats, undrogued drifter and drogued drifter motion, along with wind and possibly wave products, should be conducted. This may enable Argo surface data to supplement drifters in an Integrated Ocean Observing System.

**Recommendation:** User requirements for products, such as gridded fields with error analysis reflecting spatio-temporal variations, should be monitored. Where GSOP becomes aware of such potential requirements, they should be communicated to the Argo Data Management Team, with a request that ADMT facilitates the generation of such products.

### 2.3) Moored instruments

Moored current measurements are made with single point current meters (CMs) or acoustic Doppler current profilers (ADCPs) that provide a profile over a vertical range that can be as small as 5 m or as large as a few hundred meters. Measurement error is a combination of instrument error, typically 1 - 2 cm/s, and sometimes unknown mooring motion; thus, field accuracy is mooring dependent. Acoustic side-lobe interference means that ADCP instruments cannot measure near the boundary, whether the boundary is the sea surface or the sea bed. Moorings at a typical depth of 300m miss the top 30 m of the water column. In several ATLAS-type moorings, a point acoustic CM is included at 10 m depth. This is different from the drifter-standard drogue depth of 15 m.

The tropical ocean observing array includes TAO in the Pacific, PIRATA in the Atlantic and the growing Indian Ocean array. ADCP data are available only in delayed mode, generally a few months after recovery. Although the point current meter measurements are telemetered to shore via Service Argos and made available in near-real time through <http://www.pmel.noaa.gov/tao/>, these data are not placed on the GTS. Current meter measurements are made at a subset of the overall array. In the Pacific, four equatorial sites have included current measurements for the long term. Other current measurements are supported through research grants and are not part of the sustained ocean observing system. At present there are no current measurements on off-equatorial TAO moorings.

Other mooring sites that have current measurements include the OceanSITES network (<http://www.oceansites.org/>). These data have uniform standards for data format, but in some cases, such as subsurface current data from the Hawaiian Ocean Time Series, the data haven't yet been released. In addition to being used in various different dynamical and thermodynamical analyses, moored current measurements can be used as a reference to evaluate models. The strengths of the moored current measurements are that they are not aliased by diurnal jets and eddy variability - high resolution time series at a fixed point resolve motion associated with diurnal, intraseasonal, seasonal, and interannual variability - and that the velocity data often have concurrent wind stress, heat flux, stratification, and other measurements. Moorings with ADCPs and/or sets of current meters can be used to determine the vertical shear; mooring arrays can be used to map fields and estimate horizontal gradients. A set of 5 current meters with temperature sensors placed in the top 25 m of a mooring at 2°N, 140°W shows that the near-surface shear is extremely sensitive to the near-surface stratification. On average, during the afternoon weak stratification averaging less than 0.2°C between 1 m and 25 m was associated with a diurnal jet in the direction of the wind with an average shear of more than 10 cm/s between 5 m and 25 m, while at nighttime the water became unstratified and the average shear was less than 4 cm/s. Surface current measurements which do not resolve the diurnal cycle can have significant errors due to aliasing.

In addition to the sustained observing system, many regional, research-focused efforts, in the past or ongoing, some in critical western boundary regions and ocean choke points, have included current meter measurements. During WOCE, many of these data were assembled by the Buoy Group at Oregon State University (OSU).

The British Oceanographic Data Centre (BODC) is identified as the CLIVAR moored instrument DAC. However, since it doesn't assemble data from some of the big mooring programs (e.g., the tropical mooring arrays), it does not provide a one-stop-shop for users to access all moored data. Activity at the BODC is resource-limited: 0.4 FTE confirmed until 2012. They are thus limited to responsive, rather than proactive, acquisition of data sets. Workshop attendees noted that the WOCE OSU archive has not yet been integrated with the post-WOCE CLIVAR archive assembled by BODC. Access to the WOCE data is essentially through the structure of the WOCE DVD. A copy of the DVD is available online at [http://woce.nodc.noaa.gov/woce\\_v3/wocedata\\_1/cmdac/](http://woce.nodc.noaa.gov/woce_v3/wocedata_1/cmdac/).

### **Timeliness of data release**

There was extensive discussion of the issues surrounding the timely release of moored datasets. PMEL efforts with the tropical ATLAS array demonstrate the added value in releasing the data to a broad audience, where they are used in climate research, state estimation, and operational use such as numerical weather prediction. In contrast, data withheld for PI-only analysis beyond the time when they have been cleaned up become more limited in usefulness for the overall climate research community. In particular, it was noted that adjoint model state estimation projects are run at the limit of computational resources. They keep reasonably 'up-to-date' with recent observations, and there is a limit to how often they can be re-run multiple times as extra data become available. Therefore data that are made available with many years delay may be omitted from such efforts, and may not be included in runs submitted to IPCC, for example. It was proposed that timeliness of data availability must be integral to being considered part of the observing system for climate.

**Recommendation:** *A CLIVAR DAC for moored measurements needs the funding and associated manpower to gather datasets and assemble them in a uniform format with a uniform inventory. This effort should include ICES, WOCE, pre-WOCE data, etc.). Recognising resource limitations, it is necessary to prioritise the datasets that will be of greatest value for climate science. These include key locations established in CLIVAR plans, such as boundary currents and low latitudes, with special emphasis on sites that will be maintained long term.*

**Recommendation:** *The ocean observing system in the Pacific should include off-equatorial current measurements in the equatorial wave band, to resolve the meridional structure of equatorial waves, tropical instability waves, wind-forced response in frontal regions, and more generally the role of advection in the off-equatorial evolution of mixed layer heat anomalies.*

**Recommendation:** *Noting that the standard drogue depth for the drifter program is 15m, but that some major programs deploy moored instruments at 10m, a better understanding is required of upper ocean shear; consideration should be given to including point current meters at 15m.*

**Recommendation:** *Funding agencies should be asked to apply and maintain pressure on PIs, to ensure data are released in a timely manner. Guidelines exist for this.*

#### 2.4) Shipboard and Lowered ADCPs

ADCPs use an active sound source in the range 38-300 kHz. Lowered ADCPs are either 150 or 300 kHz. They work by acoustic scattering from material in the water. The motion of water relative to the platform is inferred from Doppler shift of the return signal. Lower acoustic frequency gives better range (less acoustic attenuation) but worse spatial resolution. The measurement is remote from the instrument with a range of 100-1200 metres, depending on acoustic frequency. Instantaneous measurements are made and data logged, at intervals of a few seconds. The instruments have multiple beams in four directions. The beams are separated with a conical half-angle of 20 or 30 degrees which means that the 'footprint' is 10s-100s of metres. The following table summarises and compares aspects of shipboard and lowered ADCP operations.

	Shipboard	Lowered
Acquisition	Ship underway	Ship stationary
Extra measurements required to provide accurate velocity	Precise ship heading (better than standard gyrocompass) GPS ship navigation	GPS ship navigation
Data reduction	5 or 10-minute averages	All data from one station processed to single profile
Horizontal resolution	1-10 km	Determined by station spacing;

		typically 50 km open ocean; can be a few km in boundaries
Vertical resolution and coverage	10-20 metres resolution Upper ocean 200-1200m depth	10-20 metres resolution Full ocean depth
Universally adopted data reduction and reporting ?	No	No
Reliable error estimates	Sometimes on research ships with expert interpretation	No; Instrumental random and bias errors poorly understood.
QC procedure well defined and implemented ?	Not universal	No
Suitable platforms	Research ship (dedicated expedition) Research ship (unattended) VOS (limited success)	Research Ship (dedicated expedition)
Real-time/Delayed Mode ?	Not routinely transmitted in real time, but this could be achieved if it was required	Could be available in near real-time (few hours lag)
Strengths	Low cost on research ships; (but significant capital investment on VOS). Provides direct measurements of absolute velocity with good spatial resolution; critical in boundary regions where other hydrographic methods are limited.	As for shipboard. Full ocean depth. Only technique that provides detailed spatial description of eg DWBCs.
Weaknesses	Contamination with transients; Uncertain errors;	Contamination with transients; Uncertain errors Equipment vulnerability; recent failures attributed to changes in manufacturing process. Expected to be addressed in 2008.

### **Assembly of data at the Hawaii DAC**

The ADCP DAC at University of Hawaii (UH), otherwise known as the Joint Archive for Shipboard ADCP (JASADCP), a NOAA/UH collaboration, is presently supported by 15% of Pat Caldwell's time. This is sufficient to keep 'ticking over' on the ingestion of data that arrive in a recognisable format from the PI, and which require minimal QC. The assumption is that the PI has done the cleaning up and calibration.

The system for identifying and assembling important SADC data was effective during WOCE. Since then, the ADCP DAC has continued to work closely with the CLIVAR and Carbon Hydrographic Data Office (CCHDO). As with CCHDO, success since WOCE has been chiefly with cruises in the US CLIVAR program, and a small number of non-US partners. Out of 17 CLIVAR cruises (Repeats of WOCE One-Time Lines) received since 2004, 10 were from US sources, 6 from Japan, and 1 from the UK. The DAC is likely to receive all the SADC data acquired on cruises in the US CLIVAR program.

A German initiative will mean that the SADC will be operated continuously on their research ships. Some other countries have similar initiatives in place, or are considering them.

Data reduction: When shipboard ADCP were added to the US NODC archive in 1993, it was decided that an ASCII subset (hourly averages at 10 m depth bins) would facilitate access and satisfy most requests. A 5 m/s cruise speed gives 15 km spacing. The hourly subset as ASCII and NetCDF became the basis for the WOCE Global Dataset. For CLIVAR, this reduction should

be re-evaluated; for example, 20 minute averages (5 km spatial resolution) could be advantageous. Another option is the highest resolution in time and depth as made science-ready by data originators. Presently at the JASADCP, highest resolution data are stored in Common Oceanographic Data Access System (CODAS) format, which is part of the US NODC archive. This is a binary format that requires software for access. It has the advantage that all ancillary data are stored, which allow data quality evaluation as a function of time and depth. It also has a flagging system to ensure no original data are over-written. It comes with a detailed manual for processing, calibrating, accessing, and analyzing shipboard ADCP sets and has a wide distribution, primarily within the US. However, a more readily accessible format, such as ASCII or NetCDF, would facilitate use of the high resolution data. There are no plans at the US NODC to change the archive standard, CODAS and the ASCII hourly subset. But for the CLIVAR program, the JASADCP is willing to provide finer resolution as NetCDF. This targeted resolution needs to be defined by the ocean velocity community.

### **Exploitation of ADCP data**

Exploitation is mainly through providing reference level velocity for hydrographic sections, especially boundary currents; inverse calculations.

SADCP provides 'spatially continuous' sampling to aid interpolation and interpretation of 'discrete' hydrographic sections.

Variability can be obtained from repeat sections (especially 'chokepoints' & 'jets'). For example repeat sections can be combined with upper ocean temperatures from XBT to provide the seasonal variation of Ekman heat transport.

ADCP data seem to be regarded mainly as a 'research' data type. Generally, the data are used by the PIs who acquired the data, or their collaborators. This ensures a good level of expertise in exploitation of the data, which is especially important for LADCP data because there is no systematic agreement on the appropriate error fields. However, the limited exploitation of the data centre holdings (in ocean state estimation for example) also leads to a perception of lower urgency to submit data to the data centre. Compared with other data types, there is less extraction of data from DACs so the data delivery system is not 'exercised', nor stimulated to make improvements.

### **Lowered ADCP**

LADCP data were an 'orphan' during WOCE and continue to be so, with no uniform agreed procedure for QC, data reduction, metadata storage and error estimates. The longer this situation continues, the harder it will be to assemble the datasets, even though these datasets can provide critical information in undersampled boundary regions. Although some useful discussion took place late in WOCE about LADCP archiving, there remain critical unresolved questions about what is needed.

The archive of LADCP data will not be secure until the expert PIs responsible for acquiring the data reach agreement on what should be archived. In addition to 'processed profiles', PIs should agree the amount of raw data and metadata required to enable future reprocessing as methodology improves. The goal of a velocity product complete with agreed reliable error estimates will not be achieved without a specific initiative involving a range of PIs.

**Recommendation:** *The CLIVAR Ocean Velocity community, especially shipboard ADCP experts, should provide guidance to the JASADCP regarding (a) the resolution in time (and related horizontal distance) and depth appropriate for the archiving of modern SADCP data; (b) whether a new NetCDF product should be generated; (c) whether selected ancillary data (percent good, amplitude/gain, error velocity, etc.) should be included. This "new" product will supplement the hourly subset, which will continue as a standard.*

**Recommendation:** The DAC should consider what steps could be taken, and what resources would be required, to pursue missing data more proactively. If greater resources are required, a proposal should be generated. One action would be funding for JASADCP staff to attend CLIVAR meetings with ADCP data originators in attendance, in order to personally provide guidance for data submission requirements. The priority datasets are from regions with multiple repeats and an expectation of long-term support. Also those required for interpreting the long sections in the repeat hydrography program..

**Recommendation:** The DAC should identify ship operators that keep the SADC 'always operating' with a view to acquiring the data. Proposals by the UH Firing Lab and/or other NOAA data center entities (JASADCP), should seek to acquire resources for creating research-quality (science-ready) data sets. This specifically means support for staff to process and calibrate the data.

**Recommendation:** An international effort is required to enable PIs to reach agreement on the processing and archiving of LADCP data, and the generation of agreed processing protocols, QC procedures and error estimates.

## 2.5) Remotely derived currents

Gridded surface current products, either geostrophic, wind-driven, or total currents, are being derived from a synthesis of drifters, satellite altimetry, winds, and SST. An example of this synthesis is the Ocean Surface Current and Analysis in Real time (OSCAR, <http://www.oscar.noaa.gov>), which uses gridded AVISO altimetry, gridded COAPS scatterometer winds, and Reynolds SST to generate gridded surface currents from 1999 to the present, at 5 day temporal resolution. This product is updated every 5–7 days. Another product being developed at CLS is SURCOUF, which also uses AVISO, Scatterometer winds, and also directly adds drifter velocities through multivariate objective analysis.

Coefficients in OSCAR are tuned using drifter velocities, and the ongoing product is evaluated against independent drifting and moored buoy current measurements. Near the equator, OSCAR has less skill in deriving meridional currents; at high latitudes, OSCAR current magnitudes are systematically smaller than drifter velocity magnitudes. By incorporating the drifter data into homogeneous satellite-derived calculations, a product like SURCOUF becomes a time/space heterogeneous product. Time series at fixed locations have heterogeneous time-varying accuracy, while maps have heterogeneous spatially-varying accuracy. Comparisons between the SURCOUF and OSCAR products will be undertaken soon.

OSCAR is based on a much simpler dynamical model and tuning than data assimilation systems (DAS) such as ECCO or GODAS (the NCEP data-assimilated OGCM). Still, from ongoing evaluations of DAS products, OSCAR fidelity to velocity measurements such as mooring and drifter data is at least equivalent or higher. Satellite-derived products such as OSCAR therefore provide a useful tool to assess sources of discrepancy between DASs and (independent) velocity observations, but are still not widely utilized for such purpose.

Some of the data streams used by OSCAR and similar satellite-derived products are vulnerable, especially those from satellite missions subject to uncertainty. Calculation of high-resolution and global surface velocity fields, regardless of the method (OSCAR, ECCO, NCOM, etc.) requires the continuation of altimetry satellite missions. Evaluation and improvements require maintenance of the global drifter array and tropical moored array.

OSCAR maps show the evolution of surface currents in the three ocean basins, and notably in the tropical Pacific during past and on-going El Nino/La Nina events. OSCAR currents can be used to evaluate the role of heat and salt advection in upper ocean budgets (compared to 1D terms). Satellite-derived products including OSCAR now can provide a continuous description of high-resolution surface currents over at least 15 years, and can be used for decadal variability studies. Work in progress includes an operational processing system being

delivered to NOAA for NCEP Ocean Prediction Center operational uses. Ongoing upgrades and research focus on improved wind-driven current model and wind product, ongoing validation with in-situ buoy measurements, incorporating de-biased merged drifter and satellite-derived fields, pseudo-Lagrangian statistics, generating nowcast SSH fields (and thus currents) based on AVISO and Navy products, improving spatial resolution to 0.5 degree, and focusing on along-track altimeter analysis. OSCAR is used for wind speed corrections, oceanographic process studies, assimilation in models, animal migration and fishery studies, and educational purposes (e.g., NASA's <http://www.oceanmotion.org>).

The OSCAR dataset can be visualized and downloaded from the NOAA web server <http://www.oscar.noaa.gov>, and is also available from the NASA PO.DAAC web site (<http://podaac.jpl.nasa.gov>). The OSCAR product is stored at the NOAA and NASA sites above, and also both at the NOAA/NESDIS Laboratory for Satellite Altimetry and at Earth & Space Research, where the dataset is generated. The dataset can easily be completely re-generated if necessary (e.g., in case of loss of all archived files).

The OSCAR product is funded year-by-year by NOAA, pending funds availability in Research to Operations earmarks and the Office of Climate Observations. It also has funding through 2008 from NASA, via the Ocean Surface Topography Science Team and the Ocean Vector Winds Science Team, with an additional proposal to NASA seeking to secure funding through 2012. OSCAR also benefits from collaborations with Gary Mitchum (USF) and Mark Bourassa (FSU)

**Recommendation:** *Mesoscale-resolving ocean surface circulation products are valuable tools for a number of uses. In order to support the continued ability to create and improve these products, a number of ongoing efforts must be continued. Ocean surface topography and vector wind satellite observing systems are essential to resolve mesoscale motion and wind-driven transport; continuity of these satellite missions is critical for the continuation of near-real time high-resolution surface currents, as well as for the build-up of a consistent multidecadal surface current record. The surface drifter array must be maintained, as it provides key synergy with satellite-derived currents, essential data for improving satellite-based dynamical models, opportunities for global validation and error analysis, robust statistics (>1000 drifters), and the data needed for de-biasing and optimal interpolation. Moored current meter data are essential for quantifying and improving the skill of satellite-based currents at fixed locations, particularly near the equator.*

**Recommendation:** *A systematic intercomparison between data assimilated systems, satellite-derived currents and in situ observations must be undertaken to assess the current progress in generating high-resolution surface velocity output.*

## 2.6) Gliders

Several types of gliders are presently being operated. Gliders measure vertically-averaged absolute velocity, analogous to the ship-drift method. Glider CTD profiles are used to calculate geostrophic shear. There is the technical capability for gliders to carry ADCP, but as with all instruments extra payload impacts on cost and energy budget. Gliders make closely spaced (~5 km) dives to ~1km; their speed capability is ~1/2 knot and mission duration is up to ~4–6 months. Interpretation of data can be challenging: gliders can be swept over considerable distances in, e.g., western boundary currents; temporal variability can be superimposed on the 'mean flow'. SIO and UW gliders are operating in many areas. At present, there is no coordinated plan for global, sustained observations from gliders. Current operations are exploratory. Some tracks are starting to be repeated routinely, for example in the California Current area. At present, active intervention is required throughout a glider survey.

Gliders are an order of magnitude more technologically sophisticated than floats, meaning that mounting a glider survey requires considerable expertise and investment. It is very hard to imagine an internationally-coordinated effort within the next few years, because the techniques are still in research and development. There are efforts by countries such as

Australia to include a glider facility as part of a regional observing network, but we know of no similar initiatives elsewhere. It's a labour-intensive problem, and the community may not be big enough at present to generate a coordinated sustained program. NOAA's Office of Climate Observations is interested in supporting glider initiatives, with a budget placeholder for 50 or 100 gliders.

An example was shown of vertically-averaged absolute velocity from glider tracks between New Caledonia and the Solomon Islands, showing the North Vanuatu and North Caledonia jets.

***Recommendation:*** *Glider observations are an important new development in measuring velocity that should be encouraged by the various funding agencies.*

### **3) Exploitation of velocity measurements**

#### *3.1) Velocity measurements in adjoint assimilation efforts*

Two adjoint assimilation efforts were represented at the meeting: ECCO and GECCO. The computational cost in including extra data in such models is negligible. Modellers want access to all possible data. Currently, GECCO uses drifter mean velocities, hydrographic sections, TAO temperature profiles, global XBT data set, P-ALACE and Argo T, S profiles, and SSS observations; mean wind stress, and SLA from altimetry with Grace geoid. GECCO could also use subsurface velocity, e.g., from Argo floats. In ECCO, the only velocity measurements assimilated at present are the TAO moored measurements.

Issues with using velocity observations in state estimation efforts:

- Technically, velocity observations are no more difficult to fit than T or S observations.
- The ocean model's memory with respect to velocity is significantly shorter than for T or S.
- New velocity observations need to have an uncertainty specified, which must include both measurement error and unresolved processes.

Will additional velocity measurements be used in ECCO? Yes, but:

- The data should be as instantaneous and raw as possible (assuming conversion to oceanic units, e.g., m/s as opposed to an instrument voltage). The model can perform any necessary interpolation, consistent with model physics. In contrast, gridded and time-averaged data products derived from instantaneous velocities are of lesser value, because information has been discarded in the process of creating such a product. Use of such products in the model require that the model must be averaged in the same way, before appropriate constraints can be applied. Modelers have limited resources to identify unresolved (in the model) processes in the observations. Instantaneous velocity measurements should be accompanied by estimates of the magnitude of internal waves, tides, etc. to facilitate assimilation. These signals need not be removed from the data: unbiased errors can be accounted for by prescribing a representation error. However, there are examples (such as tides in altimetry) where removal of unresolved processes greatly facilitates the use of the data in the model.
- Accurate error estimates are needed (instrument, sampling, unresolved processes).
- Great care must be taken to account for systematic biases in observations (e.g., wind-driven slip).

Unresolved processes are a major limitation on the potential value of observations that include tides, internal waves, etc., and mesoscale dynamics in non-eddy-resolving models. Biases such as slip must be addressed by observationalists. Error bars must include unresolved processes, e.g., varying EKE field associated with unresolved mesoscale field.

The assimilated time-mean SSH in GECCO was compared to Niiler & Maximenko's absolute SSH. Differences between model-derived and GRACE absolute sea level are focused in boundary regions, western boundaries in particular. Are these errors in GRACE? Velocity fields can address this discrepancy. Improvements in the time mean and varying dynamic topography and transports need to be tested against in-situ measurements.

**Impact of velocity data in adjoint assimilation efforts:**

The biggest impact may be for mean currents and the seasonal cycle, especially in boundary currents. Velocities at 1000 or 2000m depth would primarily impact the time mean and maybe the seasonal cycle. Velocity analyses may need synthesis results for temporal de-aliasing, for example recent work by Russ Davis in Argo velocities.

**Obstacles to using velocity data:**

Concerns of potential biases in the data are limiting aggressive use of the data in ECCO. M. Mazloff presented a comparison of ECCO surface currents and drifter-derived currents, comparing currents from a  $1/6^\circ$  Southern Ocean run to slip-removed six-hourly drifter currents for 2005–2006 (Kim and Niiler), and a  $1^\circ$  global run to drifter-derived, slip-removed climatological currents (Lumpkin) and OSCAR mean velocities (Bonjean). In much of the Southern Ocean domain, systematic biases (up to  $\sim 9\text{cm/s}$ ) were seen, with drifter speeds consistently larger. For the global run, the drifter zonal mean currents were consistently offset from the ECCO 15 year averaged results in the Southern Ocean and tropics, with the differences (data minus model) matching the sign of the zonal wind. Systematic differences with OSCAR were concentrated in the tropics. Mazloff expressed concern that, while model biases are likely a partial source of these biases, the drifter data may contain undiagnosed downwind (or downwave) slip, and that assimilation of biased data would introduce artefacts such as spurious magnification of the Antarctic Circumpolar Current transport. Niiler and others noted that slip has been carefully quantified in lower wind conditions, seen in many of the tropical one-degree bins of the global run, and that a number of indirect tests (e.g., global absolute sea level from drifters and altimetry, estimates of Ekman plus geostrophic currents, compared to independent data such as Levitus climatology, vorticity balances, etc.) have supported the accuracy of the drifter data. Niiler pointed to potential model errors in parameterizing upper ocean mixing and the structure of velocity shear. It was suggested that the Southern Ocean results be recalculated for the subset of drifters that experienced wind speeds  $< 10\text{m/s}$ , to eliminate the role of undiagnosed slip in high-wind conditions, or poor simulation of upper ocean physics in intense wave breaking, bubble layers, etc. The overall conclusion of the discussion was that drifter velocities would improve the model results when either (a) model parameterization of upper ocean mixing improves, and/or (b) downwind slip is fully removed from the drifter data (including in high wind conditions). Regardless, an important point is that the models and data do not agree at present ... if they agreed fully in the absence of assimilation, the data would bring little added value to the model.

*3.2) Regional models and Operational Forecasting*

Coastal radar and ADCP-derived velocities are currently being used in regional models such as ROMS. Tropical mooring velocities are also compared to models and used to optimize them. The value of TAO for Pacific regional models was highlighted, as these observations are in a region of surface divergence (e.g., few drifter measurements) where geostrophy breaks down.

Velocity is an analysis variable in the Navy ocean data assimilation system, but velocity observations are not yet being assimilated. The assimilation is based on a 3D multivariate optimum interpolation, with plans to implement variational schemes (both 3DVAR and 4DVAR) in 2008/2009. Observations are passed through ocean data QC procedures (instrumentation error checks, comparison to prediction fields or climatology, etc) before being used in the assimilation, with potential feedback to other observations in the form of adaptive sampling guidance. At this point, velocity data QC needs to be integrated into the system for velocity data assimilation.

The system computes geopotential from temperature and salinity profiles, and the multivariate error correlations compute balancing geostrophic velocity increments from the geopotential innovations as part of the assimilation. When velocity observations are assimilated the error correlations will compute geostrophically balanced geopotential increments from the velocity innovations, which in turn will be used to update the model temperature and salinity mass variables through the equation of state. Assimilation of velocity data requires estimates of

instrument/measurement errors from the observationalists, and knowledge of the space/time sampling characteristics of the data (e.g., instantaneous values vs. daily averaged). Representation errors (e.g., inertial currents, tides and internal waves not resolved by the model) are state dependent and will be derived at the modelling end, given information from the data providers on velocity observation measurement and any subsequent processing, such as filtering and averaging.

**Timeliness:** With every 24-hr update cycle, the Navy's global 1/12° HYCOM analysis/forecast system performs a hindcast to -120-hr and a forecast to +120-hr. Velocity data can be received with up to 5 days delay for use in this scheme. The need for a 5 day hindcast is driven primarily by the latency of the altimeter sea surface height data, which after 5 days are still not more than ~90% complete.

US Navy systems will look to assimilate all sources of velocity observations. The near real-time global surface drifter velocities will be incorporated immediately into the global HYCOM system. In addition, the need for velocities at the reference level for the geopotential calculations will drive assimilation of Argo trajectories. At present, a mooring in the Florida Straits is collecting velocity data that will be used to develop some of the velocity data QC infrastructure and assimilated into a 1/25° degree regional HYCOM model in the Gulf of Mexico. The relative value of various velocity measurements can be quantified in data-withholding experiments, ongoing in the GODAE context.

### *3.3) Box inverse models*

Box inverse models use extremely simple physics, namely conservation of mass, salt, heat and net silica, to derive a plausible set of values for unknowns: reference velocities for hydrographic station pairs, and diapycnal transfers of the properties from one density layer to another, in a quasi-steady state solution. The latest generation of global models incorporate diapycnal transformation from air-sea fluxes in outcropping layers, and have been used to infer the basin-scale distribution of interior mixing. Because these models seek solutions to an underdetermined system, solutions are generally sensitive to the starting point; improved initial (pre-inversion) conditions can greatly drive down error bars on the solution and help resolve transport and mixing estimates. Such models can serve as a tool to propagate information from a regional set of velocity estimates in a globally consistent manner.

R Lumpkin noted that there are key regions where measurements of velocity in density layers (transports) are most important, generally regions where the barotropic component plays a crucial role. Specific recommendations for measurements in these regions may rest with regional panels. Regardless, some key sites can be noted in particular: choke points such as the Bering Strait, Denmark Strait, Faroe Banks, Florida Current, and the Drake Passage; western boundary currents (surface and deep) such as the Gulf Stream, Kuroshio, Agulhas, Kermadec Ridge and the Kerguelen Plateau; bottom water chokepoints and cul-de-sacs in various ocean ridges and rises; and dense flow out of the Weddell and Ross Seas and past Cape Farewell, Greenland.

Regional inverse models have incorporated ADCP measurements for improved resolution of current structures; error estimates for the lowered ADCP are dominated by representation errors, in particular the presence of high frequency and ageostrophic motion.

## **4) Conclusions and recommendations**

There may be an opportunity to assemble and publish the capability and requirement for a velocity observing system as part of the OceanObs09 conference, scheduled for late 2009. The OceanObs planning group next meets in early 2008, after which there will be more information available about the papers that will be solicited for the conference. If a paper is solicited on velocity measurements in a climate observing system, the process of preparing it will take over from this workshop the task of defining the requirement.

In that case, it is expected that GSOP would identify a collection of investigators with the necessary expertise to undertake the task. Thus the need for a further meeting of the group attending this workshop, or of an alternative group focussed around an OceanObs paper, will be decided by GSOP as OceanObs planning develops.

This workshop was mainly successful in describing the capability of the present observing systems. The interaction between investigators involved in acquiring and distributing velocity data, and those involved in global-scale synthesis, is expected to stimulate a number of valuable developments in data assembly and delivery. Priorities were defined or restated. Some shortcomings were identified. Of these, some can be addressed with existing resources; others will require successful proposals to generate extra resources.

The workshop discussion and this report of it fall short of 'defining and justifying the requirement for ocean velocity measurement for climate research and associated activities over the next ten years'. Such documents are not satisfactorily written by committee. An OceanObs09 paper would be a powerful and timely tool for preparing such a document.

The workshop regularly returned to the theme of western boundary currents and equatorial current systems as a gap in the velocity observing system. It is unclear whether the oceanographic community knows precisely what should be observed, or how those observations should be made. Analyses from process studies in these regions (e.g. KESS, CLIMODE, SYNOP), however, may provide some guidance.

The main conclusions from the discussion have been highlighted in the body of the report as 'recommendations'. Since the workshop has no self-standing authority, we consider these recommendations to be for the attention of GSOP, to generate action as they see fit.

This workshop report was circulated to attendees in draft form in the week after the meeting. Revisions were addressed by December 21, when the final report was sent to the GSOP cochairs for their consideration.

The workshop closed at 1200 on Friday 7 December 2007.

**List of workshop participants**

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**First GSOP Workshop on Ocean Velocity Measurements and their Application (GVW1)  
Convenors: Rick Lumpkin (AOML, Miami) and Brian King (NOC, Southampton)**

**Martin Johnson House, Scripps Institution  
December 5<sup>th</sup>, 6<sup>th</sup>, & 7<sup>th</sup> (until 1545 if needed), 2007.**

This second announcement includes the provisional agenda.

**Agenda**

**Wed 5 December**

**1 Introduction (Lumpkin, King, Stammer) [0845-0900]**

1.1 Local arrangements

1.2 Scope of workshop:

To establish the requirements for ocean velocity measurements as part of an observing system for climate. This is a smaller task than a review of all possible future operational use of ocean velocities

1.3 Expected outcomes:

review, document and characterize ocean velocity data presently available or likely to become available in the near future;  
review current dissemination and storage of ocean velocity data streams and identify enhancements to make their exploitation more effective;  
identify critical ocean velocity data streams that may constitute a global network;  
develop the scientific justification and requirements that define the need for the inclusion of ocean velocity measurements in the suite of ocean observations used in climate research.

**2 Measurements [0900-1700]**

For each measurement the discussion should cover:

- (a) what/how the instrument measures velocity.
- (b) accuracy, time & space resolution of measurements, etc. strengths/ weaknesses/ advantages/ disadvantages from a CLIVAR perspective
- (c) how the data are used.
- (d) data reduction issues: quality control, interpolation, assigning error bars.
- (e) data archiving, distribution, availability/timeliness.

After discussing each measurement type, the workshop should be able to evaluate and agree on the 'adequacy' of the observing system for this data stream. Since the adequacy depends in some sense on the desired use of the data, this evaluation will depend on Section 3 of the Agenda. We should also establish ideas about the future (funding) security of the observing systems and data management systems. Is the measurement undertaken by research PIs using research budgets or is it under financial control of 'operational' agencies? Will the answer to this question change over the next 5-10 years?

Presentations (approximately 1 hour each, with additional time for discussions)

- 2.1 Surface drifters (Niiler [a,b,c], Lumpkin [d,e])
- 2.2 Profiling floats (Hacker/Yoshinari [a-e])
- 2.3 Moored current meters (Cronin [a,b,c], Mowat [d,e])
- 2.4 ADCPs Shipboard and Lowered (King [a,b,c], Caldwell [d,e], Okamaki [d,e])
- 2.5 Remotely-derived currents (Bonjean/Lagerloef [a-e])
- 2.6 Others

If there are major data streams that are of importance to CLIVAR that have not been discussed, the workshop needs to identify them and propose a strategy for filling the gaps. Areas not covered in 2.1 to 2.6 at present: gliders, acoustically tracked subsurface floats, inverted echo sounders, coastal radar arrays.

**Thu 6 December**

**3 Exploitation [0830-1400]**

Types of exploitation

Modelling and Assimilation (introduction: Stammer)

Mazloff: use of velocity measurements in ECCO

Cornuelle: velocity measurements in ROMS

Forecasting (introduction: Cummings)

Inverse modelling, budgets and transports (introduction: Lumpkin)

3.4 Climate monitoring: direct comparisons between new and old data (introduction: Roemmich)

For each type of data use we should try to establish:

- a) Number of user groups involved
- b) Requirements for access
- c) Dependence on particular data streams
- d) Capacity of data exploitation to refine sampling strategy

**4 Recommendations (discussion led by Lumpkin/King) [1400-1700]**

We will need to produce a meeting report. This should, amongst other things, Define the requirement for ocean velocity measurement for climate research and associated activities over the next ten years.

Identify and document present capability to meet the requirement.

Identify inadequacies in present observing/data delivery system.

Identify gaps in the workshop discussion (were there things we couldn't resolve because we didn't have the right knowledge?)

Establish the possible requirement for a future workshop: When might one be required, and what expertise might be needed

**Fri 7 December (morning) [0830-1200]**

**5 Preparation of draft meeting report**

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