THE VOLUNTARY OBSERVING SHIP (VOS) SCHEME

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ABSTRACT

The Voluntary Observing Ships (VOS) Scheme is an observing program for marine meteorology, continuing a record extending back centuries. VOS are an important component of the surface observing system, providing air and sea surface temperatures, humidity, pressure, wind speed and direction, cloud cover, waves, ice and weather data. Observational metadata allow biases to be diagnosed and corrected.

Despite its importance, the Scheme faces challenges. Observation numbers have declined as more data from satellites and buoys becomes available. However, buoys and satellites do not replace the full multivariate VOS record, which is needed for applications including climate monitoring, air-sea interaction and satellite validation. Other issues include changes to the transmission system and the security and commercial concerns of ship operators whose ships are identified in the data stream. Current initiatives are aimed at improving data quality, real time metadata availability and archival of data for climate applications.

1. INTRODUTION

1.1. Background

Seafarers originally made meteorological observations to aid efficient and safe navigation. More recently, observations have been collected and transmitted in real time for numerical weather prediction (NWP) and storm warnings as part of the Joint World Meteorological Organisation (WMO)/Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) Voluntary Observing Ship (VOS) Scheme (http://www.bom.gov.au/jcomm/vos/).

VOS observations are used in applications including weather forecasting, detecting and monitoring climate change, model and satellite validation and study of air–sea interaction.

1.2. VOS Scheme Management

Over 20 different National Meteorological and Hydrological Services (NMHSs) contribute to the Scheme through the recruitment, support and management of individual national VOS fleets and networks of Port Meteorological Officers (PMOs). The PMOs visit VOS to check and calibrate instruments, discuss observational problems and collect metadata and logbooks. PMOs recruit ships which regularly visit local ports and whose officers are willing to make observations. VOS include a variety of commercial ships and also other vessels including Coastguard and research vessels (RVs).

The national VOS fleets are overseen by the JCOMM Ship Observations Team (SOT). The WMO Commission for Basic Systems (CBS) specifies observational requirements for forecasts and warnings and manages the Global Telecommunications System (GTS) used to distribute observations in real time.

Some VOS also contribute to the wider observing system, providing deployment platforms for drifting buoys and profiling floats and as observing platforms for the deployment of some oceanographic instruments [1] and radiosondes.

1.3. VOS Observations

VOS typically report every three or six hours: surface wind speed and direction, air temperature, humidity, sea surface temperature (SST), atmospheric sea level pressure (SLP), cloud (type, amount and height), wave and swell parameters, weather and visibility information. Sea ice and precipitation can also be reported. Air temperature, SST, humidity and SLP are measured *in situ* by meteorological instruments, whilst waves, clouds and weather types are estimated visually. Wind reports are a mix of measurements and visual estimates. Observations are transmitted in real time and also recorded in paper or electronic logbooks. Such e-logbook software is also used to format observations, calculate derived parameters (e.g. dewpoint, true wind) and perform simple quality control.

Automated weather stations (AWSs) are increasingly installed on VOS, resulting in more frequent observations. A full high-quality AWS is expensive and some national services install lower cost systems making only a subset of the normal range of observations, typically SLP and one or two other variables. A systematic programme of intercomparison with traditional observations to ensure data continuity in keeping with climate monitoring principles [2] is presently lacking.

The International Maritime Organisation has encouraged participation in the VOS Scheme emphasising its importance to maritime safety [3]. It may become possible to convince commercial ship owners themselves to equip their ships with appropriate instruments as a contribution to environmental monitoring and maritime safety.

RVs using their own instruments have not been systematically recruited to the VOS as RV instrumentation can vary widely in type, quality and calibration. Additionally irregular time at sea and changing personnel can lead to a lack of continuity. Some RVs carry dual instrumentation: a sophisticated set of research instruments and the standard meteorological service instruments used for the VOS observations. The Shipboard Automated Meteorological and Oceanographic System Initiative (SAMOS, [4]) is beginning to address these issues.

The instrumentation and technology behind VOS can be simple and inexpensive. However, the scheme is expensive to run due to the costs associated with maintaining the networks of PMOs, data transmission and the provision and calibration of instruments. Approximate costs are: a basic VOS package US$1k; a full instrument set supplied with a laptop for e-logbook software US$5k; a basic stand-alone AWS US$3k; and a complete high-quality AWS integrated with the ships infrastructure with manual input and data logging facilities US$50k. Transmission costs vary considerably by method. Because of the importance of weather observations within the International Convention for the Safety of Life at Sea (SOLAS), many VOS observations are sent via the “Inmarsat” system, which is highly reliable and therefore expensive. The reduction of transmission costs is a priority for VOS operators.

One obstacle to developing countries becoming more involved in VOS is the lack of calibrated, certified instruments. Regional PMO workshops have helped to educate PMOs and Marine Programme Managers in developing countries on VOS requirements. Even without calibrated instruments, these countries could start by recruiting ships as "Auxiliary" ships, which use the ship’s own instruments.

2. VOS DATA MANAGEMENT AND QUALITY

2.1. VOS Data Management

VOS observations are transmitted in real time to a NMHS, which shares observations with other services using the GTS. Some NMHSs keep an archive of the data extracted from the GTS: archives can differ due to data conversion and storage formats used data extraction methods.

Real time observations are usually transmitted both from ship-to-shore and on the GTS in a compact ascii format "FM13" [5]. However, increasing transmission costs have led operators to develop compressed codes for ship-to-shore transmission, particularly for high data-volume AWS. The WMO have mandated that all GTS data exchange must use binary formats by 2012 [6] which are typically bulky compared with FM13. It is therefore likely that many different formats will be used for ship-to-shore transmission to save cost, impacting on the consistency of VOS observations. The definition of standards for ship-to-shore transmission is therefore a priority.

2.2. Delayed Mode Data Management and Archival

Extended format VOS observations are typically collected by PMOs in delayed mode from paper or e-logbooks. Paper logbooks are digitised by national services. Observations are quality controlled and sent to two JCOMM Global Collecting Centres (GCCs) then archived as part of the Marine Climatological Summaries Scheme [7]. Both real time and delayed mode observations form the climate record, available through the International Comprehensive Ocean-Atmosphere Data Set (ICOADS [8 and 9]), with the earliest observations currently available from 1662. ICOADS also produces simple summary statistics, from 1800, that have been extensively used in climate research. Researchers have developed improved-quality gridded datasets using ICOADS individual observations, using a variety of methods (e.g. [10]).

New data management initiatives, including a pilot project to manage observations within the framework of the WMO Global Integrated Observing System (WIGOS), should bring closer links between JCOMM and other WMO activities including the WMO Information System (WIS) and the Commission for Instruments and Methods of Observations (CIMO), and thus ultimately the Global Earth Observation System of Systems (GEOSS).

2.3. Observational Metadata

Limited metadata are available within reports, primarily measurement methods for wind and SST. Detailed metadata collected by PMOs includes information on instrumentation and heights or depths of sensors [11] and is published in the WMO-Pub. 47 [12]. Pub. 47 metadata can be linked to individual reports containing ship identifiers, allowing bias adjustments to be made [13]. Any reports with missing, masked or generic ship identifiers cannot be quality controlled or bias adjusted using these metadata.

The JCOMM META-T (Water Temperature (instrumental) metadata) pilot project is investigating potential for real time transmission of detailed metadata, initially focussed on sea temperature [14].

2.4. Data Quality

Instrument standards for VOS are set by CIMO in a handbook defining observation best practice [15]. Some NMHSs also produce their own guides. Observations are monitored to quality standards set by SOT using comparisons with NWP output. PMOs use monitoring feedback to highlight data quality issues.

VOS data quality has been extensively researched [e.g. [16], [17], [18], [19], and [20]. Consequently VOS datasets have been amongst the first to be fully characterised with estimates of data uncertainty [e.g. [21], [22] and [13].

VOS data contain large random uncertainties, but in many regions the mean uncertainty due to poor sampling dominates [23] and [24]. In well-sampled regions, the random uncertainties in gridded datasets are small as many observations are averaged. Sampling by multiple platforms allows extensive quality assurance, including near neighbour "buddy checks" and analysis of outliers. Typically, VOS grid box averages contain observations from multiple platforms, allowing measurement uncertainty and ship-to-ship biases to be reduced by the averaging process. For well-characterised observations (i.e. from known ships, which can be linked to Pub. 47 metadata) adjustments can be made for biases.

The VOS Climate Project (VOSClim) provides a reference model for VOS to define and spread good observing practice, initially for a subset of ships, but more widely in the longer term. Data from VOSClim ships are typically of higher quality [25]: VOSClim data are monitored using stricter quality limits than the VOS with a similar proportion of data rejected [26]. VOSClim is sometimes erroneously seen as the sole provider of VOS data for climate applications. Current proposals are for the integration of VOSClim into the VOS as a new reporting category [27]. This would enable additional parameters currently available for VOSClim ships, including associated model output data, delayed mode data, and metadata, to be integrated into ICOADS and more easily available to researchers.

3. APPLICATIONS OF VOS OBSERVATIONS

3.1. The VOS Scheme within GOOS and GCOS

The oceanic component of the global *in situ* surface observing system comprises many platforms and instrument types. The system has evolved from being primarily VOS-based through the 1960s, to include increasing numbers of moored and drifting buoy observations starting in the 1970s, the latter now dominate numerically. Figure 1 shows an example of how the number of *in situ* observations available in ICOADS has changed over time, with the impact of the drifting buoys clearly visible for SST.

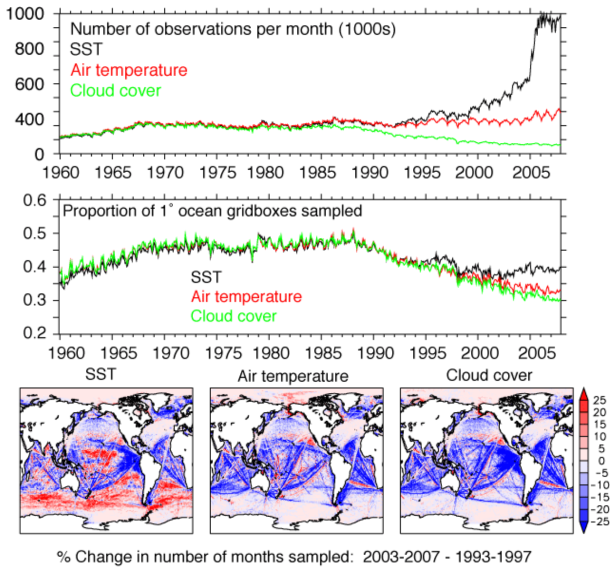

Figure 1. Top: Number of ICOADS observations (including VOS, moored and drifting buoys and fixed platforms). Middle: proportion of ocean 1° area gridboxes containing at least one observation of these variables per month. Lower: recent change in the sampling of (one) 1 monthly gridboxes.

The different observing system components are complementary, reporting different groups of parameters with different error and sampling characteristics. Tab. 1 summarises the GCOS (Global Climate Observing System) Essential Climate Variables (ECVs, [2]) observed by different platform types and shows the importance of VOS observations. VOS data are key to providing much-needed air-sea interaction datasets (Fig. 2, [28]). Satellites now provide near-global coverage for many variables but *in situ* data, including from VOS, are needed for calibration/validation, algorithm development or bias removal.

Whilst individual VOS reports can have larger random errors compared to other components of the observing system, these reduce on averaging across a large number of reports and ships. In well-sampled regions, VOS can therefore provide high quality datasets for validation, verification or error characterisation of other observing system components. The contributions of VOS data to ECVs include:

Humidity: VOS-based humidity datasets are available starting in 1973 [29] and [13]. Humidity is not observed by drifting buoys. A small subset of operational moored buoys has measured humidity since the late 1980s, but data quality was below WMO standards in the early period [30]. Relative humidity sensors suitable for long-term deployments on buoys have lower accuracy than wet and dry bulb measurements [31]. Examples of applications of VOS humidities include the calibration of satellite humidities [32] and [3], the adjustment of atmospheric reanalysis humidities for ocean model forcing fields [34] and the intercomparison of global hydrological and energy cycles [35].

Air temperature: VOS air temperatures provide gridded datasets starting in 1856 [36]. Air temperature is measured at moored buoy locations (largely coastal and tropical), and observations of unknown quality are made on a small subset of drifting buoys. Air temperature retrievals from satellites are improving (e.g. [37]) but remotely sensed air temperatures cannot yet contribute to GCOS and are not yet suitable for remotely-sensed heat fluxes, which rely on either using a Bowen ratio [38], assuming constant relative humidity [39] or using NWP, output [40]. Examples of VOS air temperature applications include the validation of global temperature trends [41], the calculation of satellite wind stress [42] and the derivation of satellite air temperature algorithms [43].

	GCOS ECV	VOS	R/Vs	Research Buoys/ OceanSITES	Operational Moored Buoys & Light Vessels	Drifting Buoys	Satellites
GCOS Area	Coverage	Global coverage but concentrated in shipping lanes	Worldwide but with sparse sampling	~ 20 locations	Coastal and tropical	Most ocean regions	Near-global, varying temporal resolution
Atmospheric	SLP	●	●	●	●	**O**	
	Air Temperature	●	●	●	●	○	
	Precipitation	◑	**O**	●			⊙
	Surface Radiation	◑	**O**	●			⊙
	Humidity	●	●	●	**O**		◦
	Wind Speed	●	●	●	●	○	●
	Wind Direction	●	●	●	●		**O**
Oceanic	SST	●	●	●	●	●	⊙
	Sea State	●	**O**	**O**	**O**		●
	Sea Ice	◑					●

● = routinely measured; **O** = measured by subset of platforms only;
○ = rarely measured; ◑ = coded or via parameterisation;
◦ = average in lower atmosphere rather than surface value.
⊙ = available but in situ data required for algorithm development or validation (precipitation, radiation) or bias removal (SST);

Table 1. Summary of surface meteorological parameters measured by the GCOS. Note that typically offshore platforms report in a similar manner to VOS.

Precipitation: Precipitation is difficult to measure at sea [31] and is not measured by most VOS, but estimates can be derived from the VOS weather codes [44].

Weather codes, and associated information on cloud types and amounts, give detailed information on type, intensity and phase of precipitation and have been used to understand the remote sensing of precipitation by satellite (e.g. [45] and [46]) and precipitation fields from reanalysis (e.g. [44]).

SST: Ships have provided SST datasets stretching back to 1850 [47], [36], [22], [48] and [49] which are essential for monitoring climate change and for providing information on multidecadal variability needed to interpret the significance of any changes [41]. SST data are now also available from both moored and drifting buoys, drifters now making the majority of *in situ* SST observations. Although SST data from buoys are typically more consistent than observations from ships [50], some buoys exhibit gross errors [51] and [52] demonstrating the need for observations from different sources to ensure quality through inter-platform comparison [53].

Within GCOS, the responsibility for surface marine data is split between the ocean (SST, sea state and sea ice) and the atmosphere (near surface air temperature, humidity, winds, and SLP, precipitation, clouds and radiation, Tab. 1). This is problematic when considering the contribution of VOS data to air-sea interaction [28].

There are currently no GCOS targets for VOS data collection to meet ECV requirements, nor routine monitoring of VOS observations against ECV requirements. The opportunistic nature of VOS observations, with a large number of contributing ships of varying types, makes quantification of the adequacy of their observations difficult, but recently progress has been made towards this (e.g. [54]). For the construction of climate datasets it is important to obtain data from a variety of different platforms (e.g. from a range of different ships), appropriately separated in space and time [53].

3.2. Applications of VOS-based Datasets

Datasets and analyses based on ICOADS are an important resource for climate research, especially large-scale estimates of ocean-atmosphere exchange of important resource for climate research, especially large-scale estimates of ocean-atmosphere exchange of heat, freshwater, momentum, and multi-decadal climate variability. Datasets using VOS observations include for SST [47], [36], [22], [48] and [49], SLP [55], [56] and [57], air temperature and humidity [36 and 29], surface fluxes [58], [59], [60] and [13] and surface waves [21]. Satellite observations in contrast typically only cover recent decades. Atmospheric model reanalyses, which are widely used for climate analysis, are heavily dependent on the assimilation of ship observations [e.g. [61], [62], 63], [64] and [65].

Assessments of climate change, including the Intergovernmental Panel on Climate Change (IPCC [41]), use VOS SST data in the assessment of global mean surface temperature changes. Confidence in the SST data is increased by its consistency with VOS air temperatures. VOS also contribute to the day-to-day monitoring of climate change, for example in the bias-adjustment of infrared satellite estimates of SST [e.g. [50] and [66]. VOS provide a consistent record of cloud changes since 1949 and a century-long wave record [67]. The timely availability of data products should allow an enhanced climate-monitoring role for the VOS, if sampling can be maintained or improved.

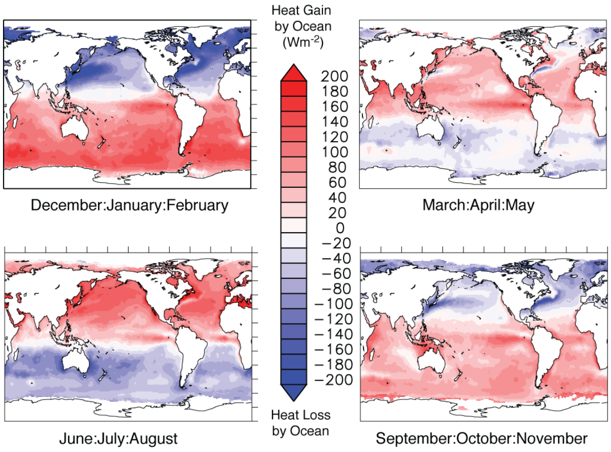

Figure 2. Net air-sea heat flux (W m^{-2}) 1970-2002 from VOS.

VOS datasets are currently underutilised for calibration and validation, new higher-resolution datasets characterised by uncertainty estimates should have wide application. Figure 3 compares daily mean air temperature from a VOS dataset with data from an operational moored buoy. Problems with the buoy air temperature are clear in the comparison, as are long gaps in the buoy operations. The different error characteristics can often explain where a particular error lies. In this case, the rapid offset and subsequent recovery, coincident with buoy deployment dates, indicates that the buoy is in error. Similar intercomparisons of SST data are being used to select operational buoys with sufficient long-term stability for assessment of a climate-quality satellite SST dataset [68].

A comparison of VOS and satellite surface humidity (Fig. 4) shows long-term differences with spatial patterns unrelated to VOS uncertainty (satellite uncertainties are not available). Satellites do not directly measure near surface humidity but are sensitive to conditions in the lowest 500m of the atmosphere. Any differences between the assumed relationship between surface and layer average properties will result in errors in the satellite surface humidity. VOS surface humidity is therefore a valuable resource for the improvement of satellite humidities, including from new atmospheric sounders with enhanced vertical resolution.

Datasets based on ICOADS have been used in other applications including air-sea interaction, fisheries, changes in coastal geological features, and assessments of global anthropogenic emissions from ships (see [69] and references therein). New and emerging applications include providing broad-scale context for process studies, NWP validation, validation of climate models, climate change attribution, decadal prediction, seasonal

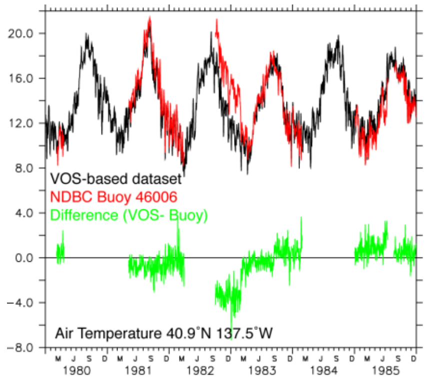

Figure 3. Daily air temperatures (˚C) from VOS [13] and a US National Data Buoy Center buoy.

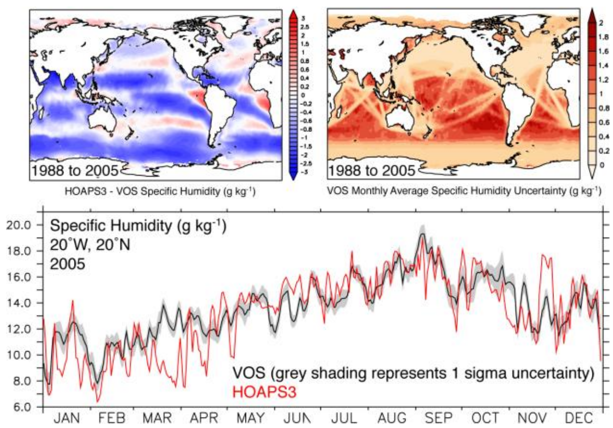

Figure 4. Upper left: Difference between humidities from satellite (HOAPS3, [39]) and VOS [13]. Upper right: VOS uncertainty estimate. Lower: Specific humidity at 20˚W, 20˚N.

forecasting, quantifying uncertainties in model prediction and ground truth for proxy data. VOS data are important for hindcasts, particularly winds, but also for air temperature and SST, SLP, and waves.

Real time applications include: assimilation into NWP, satellite SST bias removal, preparation of warnings for ship routing and avoidance of severe weather conditions, the preparation of forecasts and warnings for offshore industries. Applications of climatological information from the VOS include providing design criteria for ships and marine structures.

4. OUTLOOK

4.1. Operational Challenges

Automation of VOS has the potential to be extremely valuable for GCOS. However many of the AWSs installed on VOS are low cost, reporting a limited range of variables. Even high quality systems, which allow the simple recording of cloud, weather and wave information via a touch screen, have lead to a marked decline in the number these observations (Fig. 1) as observers are often reluctant to supplement the automated measurements with manual observations. Adding the capability for manual input adds to the cost and complexity of systems and is not always judged to be cost-effective by the NMHS. Automatic systems (including observations from moored and drifting buoys) may report more frequently than manual systems, but closely spaced observations are highly correlated and the impact on the uncertainty of gridded climate datasets is much smaller than for a similar number of more widely spaced observations. For climate applications, it is essential that the quality and completeness of the report, sampling and the availability of metadata all be accounted for in assessments of data adequacy.

The FM13 format used for both ship-to-shore transmission and GTS data exchange is due for replacement by 2012. However, the currently available replacement formats are extremely complex (e.g. BUFR, [6]), and focused on the homogenization of a wide range of data into modern scientific (SI) units, potentially to the detriment of the preservation of originally reported observations (e.g. combining measurements and codes). The implementation of format transitions requires careful management as it has implications for the consistency of the ship climate record. Links between those responsible for developing codes and those responsible for making the observations or assessing climatological impacts are not well-established. Consequently, JCOMM is establishing a single organizational focus across its program areas to consolidate requirements and interact more effectively with CBS on coding issues [70].

The public availability of real time observation locations from their ships in the public domain causes commercial and security concerns for VOS operators. Short-term solutions have been implemented to address these concerns. SOT is working toward a long-term solution providing ship security whilst allowing quality monitoring of individual ships and availability of observational metadata essential to ensure data quality.

Resource limitations mean that PMO networks have declined in recent years, whilst their responsibilities have diversified. Increasing internationalisation of shipping operations makes ship recruitment difficult. The VOS are directly affected by the economic climate and constant changes and volatility in trading patterns have led to ships being lost from national lists.

47 metadata delivery by WMO is erratic, causing difficulties for ship operators, PMOs and climate researchers. Either WMO must allocate sufficient resources to address these problems, or other solutions to timely metadata delivery should be developed.

These problems, and the increasing contribution of data from satellites and drifting buoys to NWP forecast quality, have led some NMHSs to question the need to maintain their VOS [71], despite their importance for applications outside NWP. Improved dialogue between those who fund and operate the VOS and those using their data in delayed mode is needed and the potential for providing funding from outside NWP centres should be explored.

More positively, there is future potential for supplementing VOS observations with meteorological data transmitted as part of the Automatic Identification System (AIS), a short range coastal tracking system used for identifying and locating vessels. Also, the challenges of ensuring ship safety and monitoring climate change may allow an effective case to be made for a greater direct contribution from ship owners to marine observing, perhaps via the International Chamber of Shipping. The growing importance of sustained observations to the research community should also result in an increased contribution of RVs to the operational collection of both meteorological and oceanographic data and to a wider range of measurements on some commercial ships.

4.2. Delayed Mode and Climate Applications

Relying on established data delivery systems has placed restrictions on content of the reports. An alternative may be to more clearly distinguish between the real time data, which serve the NWP community and the delayed mode data, which serve GCOS and climate research. This was previously the model when GTS reports were a subset of the more comprehensive keyed logbook data. Most VOS reports are now available in real time and some countries do not currently contribute to the delayed mode.

An approach that clearly distinguishes between NWP and climate user requirements might be advantageous. Ship operators may wish to contribute to GCOS to improve their environmental credentials. In delayed mode, the ship report could be extended to include extra variables, precision and metadata important for data quality; ships with AWSs could log additional reports for delayed transmission; and ship security and commercial issues would be ameliorated. It would become easier to plan and manage VOS data collection for climate applications. There are also potential benefits to NWP if high-quality datasets with error characterisation become quickly available for model validation.

However there may also be disadvantages: VOS operators may be unwilling to play a part in a climate observing system, the benefits of making observations for a forecast are more immediate; the delayed mode infrastructure would require modernising and reinvigorating [7]; it would be more difficult to associate reports with model output for quality assurance and additional resources would be required for monitoring, data analysis and maintenance of climate archives.

All applications should have access to the best data. One proposed initiative, tentatively called "Climate ICOADS", aims to achieve this though incorporating the results of research efforts, which have developed adjustments for a range of known biases, including diurnal ship heating, Beaufort wind adjustments, and for instrument height and type [9].

5. SUMMARY

The VOS Scheme provides continuity with shipboard observations going back centuries, but requires investment and greater recognition of its continuing importance. The role of the VOS as a sustained observing system is well recognised, but its future role in the observing system less so. VOS report many GCOS ECVs and are particularly important for air-sea interaction studies. VOS are our major source of air temperature, humidity and SLP information over the ocean.

There are operational challenges to overcome. The VOS Scheme operates from within NMHSs and resource pressures have caused operators to focus on the operational elements of the Scheme with applications in forecasting and warning, to the detriment of VOS as a climate resource. VOS has been operating with limited resources whilst costs and complexity increase. Recent challenges include ship security concerns leading to data loss and anonymous observations, lack of up-to-date metadata and the decline of the PMO network.

The focus for the future must be for a surface meteorological observing system meeting the needs of operational, climate and research data users. Improving data quality whilst retaining the consistency required for climate applications is a challenge. The extension of VOSClim to the wider VOS is therefore welcomed. The move toward automated measurements must be managed carefully to ensure data quality and consistency. AWSs making good quality observations of the full range of parameters, including the facility for observer input of manual observations, are needed to maintain climate quality. Given the high cost of quality

AWSs, the continuation of VOS making traditional observations is key to maintaining wide sampling and providing a baseline to ensure long-term data homogeneity. Integration of RVs into VOS, for example through the SAMOS Initiative [4], will help to improve sampling in regions where commercial shipping is rare. The benefits of some ships making both meteorological and subsurface observations are obvious. In the future, it is expected that a small subset of VOS will make what are currently research measurements, for example direct turbulence measurements for air-sea interaction studies.

The production and intercomparison of datasets, including those based on VOS data, is key to the raising of both data quality and dataset construction techniques. A wide variety of VOS datasets for climate applications have been developed using ICOADS, the most complete archive of surface marine data. Applications for these datasets include: climate change detection, variability and air-sea interaction studies and the calibration and validation of reanalyses, operational data and satellite datasets. Improvements in dataset construction techniques, for example new higher resolution datasets, will allow further exploitation of the VOS data. Investment is required to modernise the data management for VOS data, and for ICOADS development.

6. RECOMMENDATIONS

(1) Awareness of the contribution of the VOS Scheme to GCOS should be raised particularly within GCOS, the IOC and NMHSs.

(2) A review of user requirements for marine meteorological observations should be conducted including revision of the GCOS Implementation Plan. Target levels of VOS participation should be developed based on these requirements and adequacy assessments made operationally. Targets should address the number of regularly-reporting ships, spatial and temporal data densities, data quality, timeliness and the balance between AWS and manual reports. Initial targets should be to restore VOS participation levels to those achieved in the 1980s, approximately 5-7 thousand ships.

(3) The international bodies responsible for implementation of the marine meteorological observing system should ensure that the impacts of any changes to the observing system are assessed for all groups of users, including GCOS. This will require improved linkages between and within WMO, JCOMM and WCRP (World Climate Research Program). The potential for the IMO (International Maritime Organization) and International Chamber of Shipping to play an increased role in the observing system should be investigated.

(4) Traditional and automated VOS observations should be compared and recommendations to ensure data continuity developed.

(5) JCOMM and VOS operators should work with users of VOS data to understand and overcome operational and technical challenges to the provision of climate-quality observations from VOS.

(6) The development of standards for ship-to-shore data transmission should be a priority.

(7) Timely delivery of VOS metadata via Pub. 47 is required.

(8) Investment is required within NMHSs in the support services for VOS that are essential for maintaining data quality and volume. The potential for augmenting funding for VOS from new sources should be explored.

(9) A strategy to raise the quality and quantity of VOS data whilst maintaining consistency with the long-term record should be developed within JCOMM and GCOS.

(10) Research-based initiatives to make meteorological and oceanographic measurements should become better integrated with the VOS Scheme. For example, VOS making more use of suitable instrumentation on RVs, the reporting of weather information becoming routine for all RVs and the sharing of technology and expertise where appropriate. The potential for co-operative observing systems with research and commercial operators, which meet the standards required by the VOS Scheme, should be investigated.

(11) Development, intercomparison and characterisation of a wide variety of surface marine datasets, including from VOS, should be encouraged as essential to raising data quality.

(12) Investment is required in delayed mode data management for VOS observations to help ensure that the freely available ICOADS climate archive continues to be as complete as possible, and incorporates and disseminates the latest information on data quality.

7. CONCLUSIONS

VOS provide observations that maintain a surface marine climate record of over 300 years. Although VOS are now only one part of the surface marine observing system, their ongoing role is increasingly being recognised. It is clear that VOS data will remain widely used in datasets essential to monitor and understand climate change, for the validation, calibration and analysis of satellite observations of SST, precipitation, wind, cloud, air temperature and humidity, providing information on air-sea interaction and atmospheric stability and modelling applications including reanalysis, NWP and forcing fields for ocean models. New initiatives to improve data quality and integration with other observing programs should ensure that the VOS remain an important contributor to the Global Climate Observing System in decades to come.

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