Overcoming barriers to an effective Marine Surface Global Climate Observing System

The CLIMAR Organising Committee (www.marineclimatology.net)

Summary

To play an effective role in climate change studies through the European Earth programme GMES (Global Monitoring for Environment and Security), the EU will require a well-designed *in situ* observational and data management system. While internationally the needed infrastructure already exists, it is neither designed nor resourced primarily around climate research requirements. This paper will argue that targeted investments are needed to augment that existing infrastructure with the overall aim to better support climate observations and services.

Our first challenge is to better define the observational and data management requirements for marine climate monitoring, and then assess the extent to which those are met by the existing observing system. This critical assessment will allow weaknesses to be identified, which undermine the contribution of observing system components to climate monitoring, but may be unimportant for other roles. The benefits of this approach will extend beyond climate monitoring and include satellite calibration and validation, model validation, assimilation activities such as reanalyses, climate change detection and attribution, monitoring in support of policy requirements, and the development and stewardship of well-characterised data products for climate research. Furthermore, these observations will significantly improve the ability to conduct and interpret assessments of marine ecosystems – and also ultimately underpin EU support of adaptation and mitigation policies.

Within the scope of an Essential Climate Variable (ECV) framework at the "Marine Surface," this document describes barriers to the implementation of an effective climate observing system, which include: inadequately defined user and system requirements; lack of methods to determine observing system adequacy; and insufficient international coordination. Suggestions for overcoming these barriers internationally are: (i) developing a more systematic approach to climate observing system design, implementation and assessment; (ii) implementing a more integrated approach to the management of observations, metadata and documentation needed to monitor the marine climate; (iii) improving the climate record through data and metadata rescue and (iv) adding value to the marine climate record through research. Specific actions, initially within the EU but contributing proactively to enhancing the existing international system, are proposed for funding.

Essential Climate Variables at the Marine Surface

The Global Climate Observing System (GCOS) has identified a set of ECVs gauged to be of high impact on the United Nations Framework Convention on Climate Change (UNFCCC) requirements – and feasible to observe globally. Here we consider physical variables measured near the sea surface, in both the marine atmosphere and the ocean. Primarily these are: marine surface air temperature, wind speed and direction, water vapour, surface pressure, precipitation, surface radiation budget, cloud properties, sea surface temperature, sea surface salinity, surface currents and sea state. However, many of the issues outlined in this paper are also relevant for other surface ECVs, for example, sea level, greenhouse gas and aerosol concentrations in the atmosphere and pCO_2 – furthermore some issues are equally relevant to subsurface ocean and coastal measurements. Also briefly considered are the requirements for research measurements to support the development of new ECVs, not currently thought feasible for routine monitoring.

Contributors to the Marine Surface GCOS

The *in situ* Marine Surface contribution to the GCOS (MS-GCOS) is an amalgamation of separate observing systems deployed primarily to support many different activities, ranging from operational forecasting to scientific research. A unified and coherent design for the MS-GCOS does not yet exist – however its constituents have evolved with expert guidance and may already be assessed against user requirements for other applications. Some components, for example the OceanSITES time series stations and measurements from Research Vessels (RVs), have the potential to provide extremely high quality observations. The remainder of the data are from the operational and research moored and drifting buoy networks, Voluntary Observing Ships (VOS), fixed platforms, coastal observatories, tide gauges and measurements made on an opportunistic basis. Near surface measurements from ocean profilers such as Argo floats also make an important contribution to the MS-GCOS, and highlight the need to also plan for integration with observations spanning the entire water column. In many cases these networks are operated by National Meteorological and Hydrological Services (NMHSs).

The primary mission for many of these systems is to support operational requirements, such as forecasting on timescales from hours to seasons, monitoring in support of policy requirements, and hazard monitoring. Data (and platform and instrument metadata) from these systems are of variable quality, and their flow through to archival repositories is often highly fragmented and managed in many different ways. For several ECVs, satellites provide essential coverage to supplement these *in situ* observations, but require verified and stable *in situ* observations for calibration and validation to be able to meet the standards required for climate monitoring.

Organisation and infrastructure

Organisationally the GCOS, and its data collection systems, fall into three domains: atmosphere, ocean and terrestrial. Generally, atmospheric weather and climate observations are developed by NMHSs, and supported by WMO through guidance and capacity building activities. Similarly in the oceanic domain the Intergovernmental Oceanographic Commission (IOC) facilitates the observational and data management system, including through its International Oceanographic Data and Information Exchange (IODE). Cross-cutting the atmospheric and oceanic domains, the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) has a remit to develop observing systems for climate and other applications under the guidance of GCOS and the Global Ocean Observing System (GOOS). JCOMM takes responsibility for the coordination of operational (e.g. buoys and VOS) and some research-oriented measurements (e.g. OceanSITES). Other relevant observational measurements originating in the research community (e.g. RVs) are more loosely associated with JCOMM. Responsibility for observations in the coastal zone is largely *ad hoc*. Within the WMO the separate Commissions responsible for instrument standards and for data transmission infrastructure and formats, including the definition of data transmission protocols and formats, are historically closely tied with the operational and numerical weather prediction (NWP) community.

The reliance of the MS-GCOS on a wide range of operational forecasting and research measurements means that the climate observing system is largely managed and resourced from outside of the climate community. This is a barrier to its effectiveness as a climate-monitoring network. Delivery is typically by organizations with remits to deliver improved weather forecasts or to support research excellence, rather than to deliver an effective climate observing system. Observing systems from the research community tend to lack sustained funding. The role of both the operational forecasting and research communities in delivering the climate observing system must be explicitly recognised and managed. The requirements and standards for surface marine observations in support of climate research, monitoring and services have yet to be adequately defined, probably as direct result of the disparate nature of the observations. An effective MS-

GCOS requires co-ordination amongst research and operational data providers and amongst organizations taking responsibility for observations in both the atmospheric and oceanic domains.

Requirements

A climate observing system requires data of verifiable and high quality combined with sufficient sampling to provide the required global coverage. GCOS refers to the following different categories of observing networks, where the definitions primarily originate from a land station perspective. A **global reference network** provides highly detailed and accurate observations at a few locations for the production of stable long time series. An important part of ensuring stability is traceability to internationally recognized measurement standards. A **global baseline network** involves a larger number of selected locations that are globally distributed and provide long-term high-quality data records of key global climate variables and enable calibration for **comprehensive networks** – which can be regional, national or international, may include satellite observations, and their role is to provide observations at the detailed space and time scales required to fully describe the nature, variability and change of a specific ECV. An analogous framework does not presently exist for surface marine observations. The development of such a framework must account for the difficulty of (a) meaningfully relating marine observations – often made on sizable platforms that may influence their environments – to traceable standards and (b) greater reliance of the marine network on moving platforms (e.g. ships or drifters) than nominally fixed stations (e.g. moored buoys).

Requirements for the MS-GCOS from the WMO Rolling Review of Requirements are presented in terms of accuracy, spatial resolution, timeliness, and observing cycle (temporal resolution). None of the present climate requirements contributed by the GCOS panels are defined at the monthly or longer timescale particularly important for the long-term record and there are no specific requirements for temporal stability. The European Space Agency Climate Change Initiative (ESA CCI) has placed a high priority on capturing user requirements for climate products, providing a substantially improved picture of user needs for a range of climate services, albeit for a subset of variables. This work on user requirements needs to be expanded to include the full range of ECVs. It is not trivial to convert user requirements into an observing system design. In their current form it is impossible for an observing system operator to understand how they should contribute to the MS-GCOS. A further challenge is to assess whether the observations subsequently collected meet the requirements.

It is increasingly recognised that a more sophisticated approach to assessing adequacy against user requirements is needed, taking into account both the correlation structure of the underlying field in the calculation of sampling uncertainties and the correlations between errors in observations that may depend on, for example, observing platform or ambient conditions and cannot therefore be viewed as entirely random or entirely systematic. This is timely as researchers are increasingly providing estimates of uncertainty for gridded products, so an inversion of these methods can provide guidance on observation requirements. Improved understanding in this area will eventually feedback into an ability to better define user requirements.

The elements of an effective MS-GCOS

There are no marine observing systems that GCOS formally identifies as either **global reference** or **global baseline networks**. The marine community has not attempted to construct a **reference network**, the need for substantial platforms and unattended operations makes the meaningful tracing of marine observations to international reference standards extremely challenging. OceanSITES is an umbrella organization for high quality sustained observations in the deep oceans and, using the GCOS definitions, is a candidate for a **baseline network**. GCOS however refers to OceanSITES as a reference network, despite the lack of a formal mechanism for the use of the OceanSITES observations as a reference network (or probably even a good idea of how that can be done). Technology development is required to measure in harsh environments and achieve global sampling. Some progress is expected in the US Ocean Observatories Initiative planned expansion to more remote and harsher environments.

There are several outstanding issues that must be addressed before OceanSITES can be formally considered as a GCOS **reference** or **baseline network**. These include for each ECV: the number and locations of measurement sites; how accurate and stable the measurements must be; the requirement for traceability to international standards; how the network performance can be assessed; and how to link the reference observations to the wider observation network and hence assess the accuracy of climate monitoring products.

A further contribution of buoy networks to the climate record is needed. Some progress has been made with a subset of the tropical moored buoy array being integrated into OceanSITES. Both moored and drifting buoys are relied on for calibration and validation (cal/val) activities, for example by the satellite community. However unified access to calibrated, quality assured data, characterized with appropriate metadata, bias and uncertainty estimates and with adequate documentation is not available. An assessment of which moored buoys would make the best contribution to the climate baseline network, using information such as existing length of record, range of variables sampled, location, quality of past record and commitment from operators, should be made. For the future this subset of buoys should be managed from a climate perspective with higher levels of calibration, sensor redundancy, metadata, range of variables, quality assessment and feedback. Platform assessments are required, for example to determine heating errors and the effects of airflow distortion.

Research Vessels (RVs) have the potential to make a greater contribution to the MS-GCOS. RVs are managed nationally and there is no international co-ordination of the activities of the research community as a contribution to the MS-GCOS, although examples of good national practice do exist. In the marine surface domain, there is no unified access to observations from RVs; whereas for example underway oceanographic data are managed internationally by the Global Ocean Surface Underway Data Pilot Project (GOSUD). As for the buoy networks the data collected from RVs is expected to vary in quality. Part of the challenge is to increase the number of routine observations of basic surface meteorological variables from RVs whilst ensuring data quality. This is starting to be addressed, for example by the US Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) initiative, but no systematic international approach has yet been developed.

Some RVs should be identified as meeting higher standards for data quality as might some ships from the Climate Subset of the JCOMM Voluntary Observing Ships (VOS) Scheme (VOSClim). As mobile platforms, their role as part of **reference** or **baseline network** is not as straightforward as for a moored platform, but the value of observations of verified high quality, particularly in remote ocean regions, and near climate reference stations, should not be underestimated. The RVs also have a role to play in providing a wider range of variables and could be organized to provide, for example, specialised observations required for the cal/val of satellites, or to support research into expanding the range of ECVs that are feasible to measure. RVs should play an important role in making observations for the GCOS, with a subset contributing to its assessment and development.

The remainder of the observations, from VOS, the non-climate subset of operational moorings, surface drifters and opportunistic measurements act as the **comprehensive network**. Research is needed to understand what is required from these observations and then engagement with the operational and satellite communities in order to address these requirements. It is recognised that this part of the observing system will always have a primary focus outside the GCOS, but we need to devise a mechanism whereby mutual advantage is gained from maintaining sampling and raising quality.

What needs to be done?

Some of the barriers to an effective MS-GCOS have been briefly outlined above. However many of the elements of the observing system are already in place, and examples of good practice, investment, integration, data rescue and technology development are easily found. What is missing is an overview of the different components of the MS-GCOS: an assessment of the roles played by the different components in terms of stability, sampling, calibration and verification in the generation of products which can be shown to be adequate for application in climate research, monitoring, assessments and services. The envisaged MS-GCOS would rely on existing observing systems and infrastructure. The approach outline below should identify both "quick fixes" where a small change may produce a benefit at little additional cost, and also major gaps where investment and technology development are required to ensure that the observing system meets the needs of its users.

A systematic approach to observing system design, implementation and assessment

A more systematic approach to observing system design and assessment is needed, requiring collaboration between the research community and the operators of existing observing systems. Building on the achievements of the ESA CCI in capturing user requirements, a better picture must be developed of what the climate observing system should look like. Specifically for the MS-GCOS this should consider for each relevant ECV: the requirements for reference and baseline networks in terms of ensuring the stability of the climate record; the requirements for a comprehensive network to fill the gaps between these sparse high quality time series; and also how the connection between the different types of observations giving stability (the **global reference network**) and sampling (the **comprehensive network**) can best be made. User requirements must be translated into clear guidance for observing system operators. The role of measurements from RVs in helping to tie together the spatially fixed components of the observing system with field calibration and verification should be considered. Regular assessments of observing system adequacy are needed, with appropriate feedback to observing system operators and to GCOS.

Specific requirements include:

- The development of user requirements for the MS-GCOS
- Research to turn user requirements into an observing system design including an assessment of the need for formal **reference** and **baseline networks**
- Assessment of data quality from **reference networks**, and hence the **comprehensive networks**
- Engagement with data providers regarding the adequacy of the **comprehensive network** to properly address multiple disciplines, including MS-GCOS and emerging requirements for climate services
- Assessments of observing system adequacy against a range of relevant requirements
- Expanded role for research vessels as providers of high quality observations for reference, calibration and verification, and also of both routine and specialised data.

An integrated approach to the management of observations, metadata and documentation

The reliance on data delivery systems designed for NWP to populate climate archives has resulted in the loss and degradation of data. For example, not all observations made are captured in real time, and data formats do not always allow for the desired precision or consistency over time. Continuity and stability are not as high a priority for the real-time system as for climate applications. Links to necessary observational metadata and documentation are highly fragmented and rarely adequate. From the research side the availability of either research quality or routine observations for climate is extremely patchy.

Data management, archival and discovery are not integrated across the different platform types of the marine climate observing system. A few initiatives exist which collate observations of selected surface marine variables, with the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) as one example. However, integrated international access to observations made at high temporal resolution, spectral data, or other more specialised data types is typically not presently available.

Links between land and ocean activities at the margins are currently poor and management of coastal data can be inconsistent between networks and countries. The value of measuring a common subset of parameters at buoys and land stations (for example daily maximum and minimum temperatures) should be considered. Cross-validation between land and coastal networks has the potential to improve data quality from both domains.

Specific requirements include:

- A consolidated data collection and management system meeting the requirements of the climate observing system in terms of completeness, consistency, resolution, range of variables and appropriate metadata
- Appropriate archival for observations, which may depend on the type of data or its resolution
- Integrated access to archived observations, metadata and value-added information
- Traceability of observations to their source and appropriate platform and processing metadata

Improving the climate record through data and metadata rescue

The climate record clearly depends critically on observations that have already been made extending back hundreds of years, many of which are not integrated into climate archives. Resources are required for cataloguing and recovering historical and legacy data and metadata and their subsequent integration into the climate archives. The identification of available data sources is a huge and urgent task; archives around the world are decaying or reliant on obsolete technology. Prioritisation of activities is needed: reanalysis is one important framework for assessing the value of candidates for digitisation – it may however not give the full value for all applications, including for climate products. One example is the need for the recovery of historical buoy metadata and its integration into climate archives. Rescued data for the climate archive needs careful evaluation before integration.

Specific requirements include:

- The cataloguing of historical and legacy data and metadata
- Prioritisation of candidate data and metadata, including value for climate data products
- Resources for imaging, digitisation, uniform translation and evaluation of data and metadata
- The incorporation of rescued data and metadata into climate archives
- Assessment of the added-value of rescued data
- Improved co-ordination between land and marine digitization and analysis activities.

Adding value through research

The enhancements of the climate record, its accessibility and characterisation with metadata, outlined above will benefit researchers both in the climate community and beyond. Examples include: improved data for assimilation into models, including reanalyses; satellite calibration and validation activities; model validation; climate change detection and attribution; and improved products for climate research. The knowledge gained through research activities regarding the accuracy of the observing system should be captured and made available to other users. Such added value can be in the form of bias adjustments, improved quality assurance, metadata or the quantification of uncertainty. Examples include assessments of heating errors in temperatures from ships and moored buoys, the merging of data and metadata archives to give observing methods and heights/depths and the results of homogenisation assessments for marine data at fixed stations.

The research community already plays a major role in the provision of data products for climate research and monitoring. The results of assessments of uncertainty for gridded data products must feedback into assessments of observing system adequacy and the refinement of user requirements.

The research community has an important role to play in the development of GCOS. This includes: the development of platforms capable of measuring in harsh environments for extended periods; new technologies for sensors, power and communications; and the assessment of new technologies in the field.

Specific requirements include:

- Mechanisms for the provision of information which adds value to observations, alongside the observations themselves
- An assessment of the need for independent verification of adjustments (e.g. algorithm benchmarking) as is being developed for land observations.
- The development of high quality data products
- The development of methods to assess observing system adequacy and feedback to the development of user requirements
- The provision of expert advice on the quality of data and data products
- Technology development to expand range and quality of observations.

What role can the EU play?

The development of an effective *in situ* component of the marine climate observing system must be tackled as an international effort. The EU can however play a leading role in the development and co-ordination that is required internationally. Although several European programs, including Eurofleets, EMODNET (including its infrastructural data component SeaDataNet) and EuroSITES, are addressing some aspects of the integration of marine observations, none has specific focus on the quality, consistency, integration and adequacy of the marine climate record. This focus is needed to ensure that the *in situ* data collected are adequate to support the climate services envisaged by GMES.

Following is a list of specific actions for the EU, proposed to be considered in the GMES framework for funding, and which would contribute over the longer-term to an improved international framework for the global climate observing system at the marine surface:

1. Collection and assessment of user requirements, building on the ESA Climate Change Initiative.

2. Funding for research and workshops to convert user requirements into an observing system design using existing platforms and infrastructure where possible, but including the identification of key locations where climate-relevant observations are most needed.

3. Funding for the development and implementation of a framework for the ongoing assessment of the adequacy of the MS-GCOS and the feedback of results to users, to observing network operators and to GCOS. This must include mechanisms for the assessment of added value, for example, from extensions to the observing network, improved metadata or from data and metadata rescue.

4. Investment in the development and implementation of needed networks on a sustained basis, in line with GOOS and GCOS requirements.

5. Support capacity building activities, which expand the climate observation network in important and data-sparse regions.

6. Data and metadata rescue targeted at improving climate data products, for example: data of high quality, in data sparse regions and periods, and metadata essential for quality assurance and bias adjustment.

7. In collaboration with international partners, the development of integrated infrastructure for the traceable measurement, recording, archival and delivery of climate data, metadata and added value information in support of climate monitoring, climate research, reanalysis, model verification and satellite calibration/validation.

8. Provide an integrated EU contribution to the development of internationally integrated data delivery and quality management for Research Vessels.

9. Invest in technology development to ensure that the MS-GCOS includes data from harsh environments and remote regions.

10. Research to quantify uncertainties in data, their correlation structure, the development and assessment of bias adjustments and their uncertainty and the need for independent verification of bias adjustments.

11. Research to provide improved data products, dataset uncertainties and observing system assessments, including the integration of data with different characteristics (*in situ*/satellite; reference/comprehensive) into climate data products.