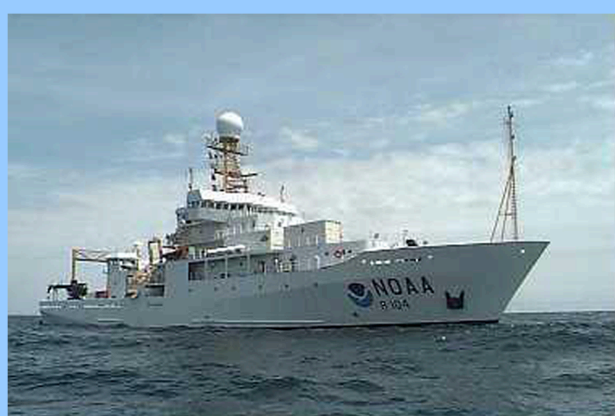
Report and Recommendations from the Workshop on High-Resolution Marine Meteorology



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Report and Recommendations from the Workshop on High-Resolution Marine Meteorology

3-5 March 2003

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Abstract

The report presents a summary of the discussions and recommendations from the "Workshop on High Resolution Marine Meteorology" held in Tallahassee, Florida, USA from 3-5 March 2003. Workshop objective and format are described. Abstracts for the invited talks are included along with a synopsis of the round table discussions. The thirteen workshop recommendations are listed and a discussion of each is included. The report concludes with action items and a time table to begin implementation of the workshop recommendations.

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Executive Summary

On 3-5 March 2003, the Center for Ocean-Atmospheric Prediction Studies (COAPS), directed by Dr. James J. O'Brien, hosted the "Workshop on High-resolution Marine Meteorology" in Tallahassee, Florida. The workshop was sponsored by the NOAA Office of Global Programs to identify scientific objectives that require high-resolution, high-accuracy marine meteorological observations and to discuss a sustained U.S. effort to obtain and disseminate these data in a manner consistent with the identified scientific goals. The workshop focused on *in-situ* marine meteorological observations from ships and buoys. Central discussions included data accuracy, calibration and inter-calibration, improved access to quality-assured, high-resolution (sampling interval ≤ 1 hr.) observations for the scientific community, and a sustained observing system to meet short- and long-term science objectives.

Co-chairs Dr. R. Michael Reynolds (Brookhaven National Laboratory) and Mr. Shawn R. Smith (COAPS) organized a workshop panel with representatives from both the scientific and operational marine observation communities. Participants included personnel from four NOAA laboratories, the Naval Research Laboratory, the U. S. Coast Guard, and the U. S. CLIVAR Office. The university community was represented by the Woods Hole Oceanographic Institution, the Scripps Institution of Oceanography, the University of Miami, Oregon State University, and the Florida State University. International attendees included representatives from CSIRO (Australia) and the Southampton Oceanography Centre (United Kingdom).

The workshop was organized around four main topics: (1) science objectives; (2) status of U.S. high-resolution observing programs; (3) accuracy, calibration, and inter-calibration; and (4) a sustained data collection, distribution, and archival system. Invited speakers began each session with talks to stimulate topic-oriented discussions. Round-table discussions provided a free exchange of ideas for improving both the quantity and quality of marine observations. Several discussions focused on the need to improve instrument calibration and to provide for routine inter-calibration between instrument systems and platforms (e.g., ships versus buoys). Currently, only a select set of well maintained ships and buoys are capable of determining air-sea interaction variables to a sufficient degree of accuracy for climate studies (e.g., 10 Wm^{-2} net heat flux uncertainty for monthly averages desired by CLIVAR). Participants noted that while research vessels are able to provide the highest quality data, often in under-sampled regions of the ocean, this resource is not being effectively utilized and data essential to climate studies are being lost. Discussions included the need to improve instrument siting on ships and to standardize measurement of meteorological and ship motion parameters and metadata formats. In addition, attendees addressed improving data quality and access for the user community. The discussions resulted in thirteen recommendations that the attendees agreed to disseminate widely through the scientific and operational marine communities and at the program level.

Recommendations

1. Develop a sustained system of calibrated, quality-assured marine meteorological observations built around the surface flux reference sites, drifting buoys, research vessels (R/Vs), and volunteer observing ships (VOS) to support science objectives of national and international climate programs.
2. Improve global data coverage, especially from important but data sparse regions (e.g., Southern Ocean), by working with and making use of national and international observing efforts, research programs, and infrastructure development initiatives.
3. Establish a data assembly center (DAC) for U.S. R/V (e.g., UNOLS, NOAA, Navy, Coast Guard) meteorological observations to unify data collection, quality assurance (QA), and distribution. The DAC will also provide for permanent data archiving and long-term availability of data at national archive centers.
4. Establish standards for sensor calibration and data collection on ships and moorings, including accuracy and resolution, sampling rates and averaging periods, data acquisition and display software, data transmission, recommended instrument siting, and provision of metadata.
5. Produce a reference manual of best procedures and practices for the observation and documentation of meteorological parameters, including radiative and turbulent fluxes, in the marine environment. The manual will be maintained online and will be a resource for marine weather system standards.
6. Develop a portable, state-of-the-art, standard instrument suite and implement on-board inter-comparison between the portable standard and shipboard instruments to improve R/V and VOS automated meteorological observations.
7. Endorse development of robust sensors for use in severe environments to improve data accuracy and allow accurate data to be collected from data sparse regions.
8. Implement a program in computational fluid dynamics (CFD) modeling of the wind flow regime over ships to determine optimal wind sensor siting, wind correction factors, and effective measurement heights.
9. Encourage (i.e. fund) R/Vs to schedule meteorological inter-comparisons with surface flux reference sites and, where appropriate, with one another.
10. Recommend that certain ship data not currently logged be made available to researchers (e.g., pitch/roll, heading, currents, speed of ship in water). These data should be routinely recorded to improve flux calculations and QA.
11. Encourage funding agencies to require that new shipboard meteorological instrumentation purchased within research grants be installed and operated, and the measurements distributed and archived according to the principles embodied in points 3-6 above.
12. Establish sources/contacts where expertise can be obtained by operators and made available for QA development.
13. Strongly encourage funding agencies to support human capital development through education and training.

Introduction

A "Workshop on High-Resolution Marine Meteorology" was held at the Center for Ocean-Atmospheric Prediction Studies (COAPS) from 3-5 March 2003. The purpose of the workshop was to identify scientific objectives addressable using high-resolution (sampling rates ≤ 60 minutes), high-accuracy marine meteorological observations and to discuss a sustained U. S. effort to obtain these data in a manner consistent with the identified scientific goals. The workshop was attended by members of the scientific and operational marine observation communities, including representatives from government laboratories and agencies, the university community, and two international oceanographic institutions.

Workshop goals included: (1) identifying scientific objectives which can be best achieved using high-resolution marine observations, (2) providing the community with a current status of U. S. sponsored, high-temporal frequency, shipboard meteorological data collection (including data distribution, availability to meet science objectives, and current quality control practices), (3) identifying technical and management issues related to instrument accuracy, calibration, and inter-calibration that will benefit scientific application of high frequency shipboard data, (4) developing a plan that insures routine delivery (real-time and delayed) of calibrated, high quality surface meteorological observations consistent with science objectives, (5) identifying areas where a sustained high-resolution observing system can evolve to better meet science objectives in the future, and (6) identifying areas where collaboration and joint activities would increase both the quality and quantity of data to better meet science objectives.

The workshop focused on in-situ marine meteorological measurements collected at wide range of sampling rates on ships and moored buoys. Shipboard measurements primarily include two groups of vessels: Volunteer Observing Ships (VOS) and oceanographic research vessels (R/V). Until recently VOS weather observations were collected by the ship's bridge officers at sampling intervals of one, three, or six hours. These VOS reports were logged onboard the ship and frequently were transmitted to shore via satellite or other communication system. The advent of automated weather systems (AWS) for marine applications has made it possible for VOS to continuously record meteorological observations. This new class of VOS-AWS can provide data at multiple sampling rates. Typically data are recorded onboard at one to ten minute intervals (some may record even higher sampling rates); however, it is currently not cost effective to transfer these high-resolution data to shore via satellite. Instead, VOS-AWS often transmit hourly samples via INMARSAT or some other transmission service. The high-resolution data are collected from the vessels at regular intervals when the VOS-AWS reach a suitable port. R/Vs are frequently outfitted with one or more suites of meteorological instrumentation and are the test bed for new marine AWS systems. The R/Vs typically record meteorological data continuously at sampling rates of one minute or less and these data are logged through an onboard computer system. These high-resolution R/V data are collected from the vessel's computer at the end of each cruise. It is worth noting that these "scientific AWS" data are often logged independently of the standard bridge observations collected by the crew of the R/V. The scientific data are rarely sub-sampled and transmitted from the ship in real-time.

The classes of shipboard platforms discussed at the workshop are listed in Table 1. A number of shipboard data collection programs are listed for each data class along with some typical applications for each type of data. VOS data and some VOS-AWS data (e.g., SeaKeepers) are the primary real-time data to be assimilated into models and used for numerical weather prediction forecasts. The delayed-mode, higher sampling rate data from AWS are used for a wide range of validation studies (e.g., model fields, satellite observations) and in the case of R/V-AWS for regional process studies.

Table 1: Sampling rates, representative programs/systems, and common uses of three classes of marine meteorological observations from vessels.

Data Class	Real-time sampling	Delayed-mode sampling	Data Programs or Sensor Systems	Uses
VOS	1 to 6 hour	N/A	VOSClim PMOs GOOS	Assimilation NWP Forecasts
VOS-AWS	1 hour	>10 min.	ASIMET AutoIMET SEAS SeaKeepers	Assimilation Validation
R/V-AWS	Rare	1 min. or less	AutoFlux ETL Flux System SCS (NOAA/USCG) R/V specific systems IMET	Independent Validation Climate products

Buoys can be separated into two large groups, moorings and drifters. Moorings are nearly-stationary in space and provide a platform that can measure most parameters observed on ships. Limitations to operating AWS on buoys include the size of an instrument, instrument power requirements, and the ability of an instrument to operate unattended for long periods of time. Moorings can further be divided into research and operational categories. Operational moorings (e.g., NBDC buoys, TAO/TRITON) typically record data onboard the buoy and regularly transmit a subset of their data in real-time via satellite. Research mooring collect data at high sampling rates (<10 min) and record these data onboard until the buoy is retrieved. The research moorings may also transmit a subset of data in real time, but these data are often withheld from NWP products for validation purposes. Drifters provide a more limited suite of meteorological observations (pressure, SST, and sometimes winds) that are typically transmitted via satellite; however, drifters were not a primary focus of the workshop.

AWS are deployed on ships and buoys to provide observations in support of both operational and research science objectives. Although improvements are made yearly, the spatial and temporal coverage by AWS is still limited in large regions of the oceans (especially outside the tropics). Supporting current and future science objectives for the operational and research communities requires a commitment to improving both the quantity and quality of AWS observations in the marine environment. For example, R/Vs are often equipped with AWS, but access to these climate data are currently limited. Expanding access to R/V data will provide researchers potentially valuable climate data far outside normal VOS shipping lanes. Achieving the full potential of AWS on marine platforms requires a sustained, end-to-end measurement system that includes improved sensor calibration, platform inter-calibration, standardized data collection, quality assurance, distribution, and archival. The requirements of and recommendations for this system were the focus of discussions at the "Workshop on High-Resolution Marine Meteorology".

Meeting summary

The meeting was formulated around four topic areas (1) science objectives, (2) status of U. S. high-resolution data programs, (3) accuracy, calibration, and inter-calibration, and (4) developing a sustained data collection and distribution system. The meeting was opened with a welcome from the local host, James J. O'Brien, and from the co-chairs, Shawn R. Smith and R. Michael Reynolds. Michael Johnson, the workshop sponsor, followed with a brief introduction of issues that NOAA wished to receive input from the workshop participants. The four topic-oriented sessions followed these introductory remarks, and each session began with talks by invited speakers. Abstracts for each talk are included in the following section and portable document format (PDF) files of the speakers talks are available online at *http://www.coaps.fsu.edu/RVSMDC/marine_workshop/Workshop.html*. At the end of each session, round table discussions provided for a free exchange of ideas relevant to the four topic areas.

Several scientific objectives that require high-resolution, high-quality marine meteorological data were discussed. One primary objective was producing accurate estimates of the air-sea fluxes. All components of air-sea heat, momentum, radiation, and carbon fluxes were discussed as important to achieving short and long term science objectives. The need for both continuous direct flux measurements and estimates using bulk algorithms was raised. High-quality air-sea fluxes from vessels and buoys are essential to address problems of validating new satellite sensors and providing uncertainty estimates for operational and research flux fields (from GCMs or other data assimilation methods). The goal of reducing uncertainties in flux fields is an essential component of several international climate initiatives (e.g., CLIVAR, GODAE). Participants discussed the need for more interaction and collaboration between the in-situ marine data and modeling communities. Another scientific activity addressable with high resolution marine data is the investigation of diurnal cycles over the oceans.

A current status of their high-resolution meteorological measurements programs was provided by NOAA/ETL, NOAA/AOML, NOAA/MAO, NOAA/PMEL, U.S. Coast Guard, U.S. Navy, SIO, WHOI, UM/RSMAS, and OSU. The presentations revealed a diverse level of both scientific and technical expertise that is devoted to collecting marine meteorological measurements with a wide range of instrumentation deployed on R/V, VOS, and buoys. In some cases, there was concern raised that personnel collecting the data were lacking sufficient scientific and technical input on critical elements including, but not limited to, sampling rate, data accuracy, and instrument siting. Calibration practices and the level of data quality control also varied widely between organizations. Some institutions noted that data collection and QC have been explicitly separated in the funding process, with QC falling on the shoulders of the chief scientist, not the data collector. The presentations and subsequent discussions also showed that a level of duplication in efforts to develop instrumentation, data logging and display software, and other technology existed between the groups. Finally, a large number of R/Vs (e.g., additional UNOLS vessels) and some mooring programs (e.g., NDBC) were not represented at the workshop that clearly are a part of the U. S. effort. Round table discussions made it clear that further work (see action items) was needed to evaluate the current status of the U. S. high-resolution observing program.

The technical discussion on accuracy, calibration, and inter-calibration of high-resolution marine systems highlighted several areas where improvements and new initiatives would lead to more, higher quality observations. Discussions showed a clear need to improve lab calibration practices for marine AWS. Better calibration will lead to improved accuracy of fluxes calculated from high-resolution ship and buoy data. The need for uniform calibrations practices across marine platforms and the need to better distribute information on these practices was discussed. Platform to platform and instrument to instrument inter-calibrations were both topics of many of the round table discussions. Plans are moving forward to develop ocean flux reference sites and the workshop participants agreed that inter-comparisons between these sites and nearby vessels is essential. Further discussions centered around development of a reference AWS to be used for onboard inter-comparison with different AWS deployed on the U. S. R/V fleet.

Discussions related to data collection, quality assurance, distribution and archival varied by data class. Much of the needs for VOS are being handled through long established data pipelines. The VOSClim program is working to improve metadata for the VOS fleet and has been working with a subset of the VOS fleet to provide validation data for models. A wide range of QA practices exist for the VOS-AWS programs. For example, SeaKeepers completes manual QA of data retrieved for submission onto the GTS while VOS-IMET observations undergo post-cruise evaluation at WHOI. Currently R/V data collection and distribution is handled on a ship-by-ship, institute-by-institute basis, making high-quality R/V data difficult to obtain and harder to use for operational and research purposes. Data pathways, QA, distribution to users, and long term archival of both real-time and delayed-mode VOS-AWS and R/V -AWS data are key issues that were discussed as part of an overall management plan for U. S. sponsored high-resolution marine meteorological data.

Speaker Abstracts

Session 1: Science applications using high-resolution marine meteorology

Climate Quality Buoy and Ship Observations

Robert Weller, Dave Hosom, Frank Bahr, Lisan Yu
Woods Hole Oceanographic Institution

The state of the art of high resolution buoy and ship observations of marine meteorology is briefly reviewed as are plans for the elements of the global ocean observing system using these techniques. The motivations for collecting these data and payoffs associated with using the data are summarized. Finally the next steps associated with resolving present issues and continuing to make progress are listed.

Surface moorings are now deployed for up to 1-year, instrumented to obtain the fluxes of heat, moisture, and momentum by bulk formulae methods. Most locations in the world's oceans are now accessible, but high current, high sea state, and ice-covered regions are not. National and international planning has been done to identify locations for a global array of time series stations, a subset of which (known as Surface Flux Reference Sites) would have as one goal to collect high quality, rapidly sampled (~1 minute) surface meteorological and air-sea flux time series. High quality observations are also made on research vessels and Volunteer Observing Ships (VOS), a subset of which are being equipped with IMET systems. The intent is to eventually upgrade the surface meteorological/air-sea flux capability of the ships that carry out the high-resolution XBT lines in each basin. Well-equipped research vessels complement these data by going to sparsely sampled regions and be being able to carry out more sophisticated observations, such as turbulent fluxes.

Accuracy that can be achieved in air-sea fluxes using mean meteorological sensors and bulk formulae has greatly improved over the last 20 years. The accuracy of weekly averages of the net heat flux now approaches 10 Wm^{-2}. With that accuracy buoy observations have proven to be very valuable in identifying biases and errors in numerical weather prediction and climatological fluxes, pointing to the monthly averages of net heat flux from these sources as sometimes having the wrong sign and being in error by up to 100 Wm^{-2}. This capability has led to the development of a strategy to improve basin scale air-sea flux fields in which high quality time series stations are used as anchor points to identify problems with gridded fields from models and remote sensing and where high quality ship observations are used to quantify the spatial structure of those errors. The goal is to produce daily, 1°x1° gridded fields of improved fluxes. This is being done in a pilot project in the Atlantic and has been done as a trial example in the Indian Ocean for 1988-1994.

At this point there is the need to work on sensor improvements (particularly incoming longwave radiation and gimbaling/correction of incoming shortwave for motion an/or tilt), for implementing a sonic anemometer as a more robust sensor for mean winds, and for measuring platform tilts (mean and instantaneous) to allow correction of errors associated with tilt and to develop the capability to measure surface waves. We should also work to implement the capability to measure turbulent fluxes on buoys to continue to address the uncertainties in the bulk formulae and to continue to evaluate, test, and perfect the calibration of all sensors. Communication bandwidth from buoys should be improved as should on board power generation capability. Buoys are being developed under the NSF Ocean Observatories Initiative (OOI) that should address some of these issues and also provide improved access to severe environments. The observing programs need to engage the following communities in the effort to develop basin scale fluxes: remote sensing, numerical weather prediction and more generally the atmospheric modelers, climate modelers and investigators, and those using surface meteorological and air-sea flux fields to force ocean models and quantify air-sea coupling.

Actions items are thus: work on sensors, work on calibration and inter-calibration across the observing elements, work of performance characteristics of the platforms (flow disturbance, heat island effects, RF radiation issues, motion effects), work on turbulent observing capability and flux algorithms, and attention to working with users including developing data archiving and quality control.

Uses of high quality meteorological observations in climate studies

Elizabeth Kent, Peter Taylor, Margaret Yelland, and David Berry
Southampton Oceanography Centre

This abstract describes some of the research projects at the Southampton Oceanography Centre which use surface meteorological data in climate-related studies.

AutoFlux is an autonomous atmospheric measuring system developed by a group of partners under the MAST-3 programme of the European Union. AutoFlux measures surface stress, sensible and latent heat flux and also carbon dioxide flux along with mean surface meteorological parameters. The system is aimed primarily towards unattended use on Voluntary Observation Ship (VOS) and buoys and has been successfully deployed unattended on research ships. The fluxes are derived from the turbulence spectra using the "inertial dissipation" method. Hourly summaries of flux and meteorological information are transmitted by satellite and received by email to allow remote routine monitoring and maintenance planning. The system is modular and so will take advantage of improved flux instruments as they are developed.

VOSClim is the World Meteorological Organization VOS Climate Project. The aim is to provide a high-quality set of marine meteorological observations from VOS with detailed information on how the data were obtained. The VOSClim data will be used for operational marine forecasting and provide high-quality data for model validation and ground truth for the calibration of satellite observations. A further use for the data will be the characterization of meteorological data from VOS necessary for climate studies. Currently more than 70 ships are providing 6-hourly meteorological reports which are collected in real time by the UK Met Office and merged with the output of their numerical weather prediction model. The merged data are then sent to NCDC (the US National Climatic Data Centers) along with delayed mode data containing extra parameters which the ships have agreed to report. Port Meteorological Officers are collecting extensive metadata which will allow us to understand the factors that affect the quality of marine meteorological observations from this subset of VOS. It is expected that the VOSClim dataset will be available in the spring of 2003 with regular updates as the project continues.

Marine meteorological data with high time resolution are particularly important for studies where the diurnal cycle is important. An example is an attempt to remove the effects of radiative heating from ships measurements of air temperature. The aim of this research is to model the effects of solar radiation on the air temperature using an analytical model with empirically fitted coefficients. The model will be used to correct VOS air temperatures which are reported every 6-hours but testing of the model has started with higher resolution data to ensure the diurnal cycle is adequately modeled.

Near-real-time wind and surface pressure from SeaWinds

James J. O'Brien
COAPS, The Florida State University

Partial pressure of CO_2 measurements from VOS: Why do we need high-resolution observations?

Rik Wanninkhof
NOAA/AOML

The overall objective of the interagency US Carbon Cycle Science Program is to reduce uncertainties in fluxes between the major labile carbon reservoirs. The ocean is the largest of the three reservoirs containing approximately fifty times more carbon than either the atmosphere or the terrestrial biosphere. A focus of the ocean work is quantification of exchange of CO_2 between the ocean and atmosphere on regional and seasonal basis to 0.2 Pg C yr^{-1} (1 Pg = 10^{15} gr). To determine this exchange on seasonal time scales, the surface water gaseous partial pressure of CO_2 (pCO_2) must be determined along with the gas transfer velocity, which is the kinetic driving force of gas fluxes. The latter is often parameterized with wind.

To increase the number of pCO_2 samples and create regional pCO_2 maps, autonomous measurements are being started on research ships and volunteer observing ships (VOS). The calculation of the pCO_2 from the instrument readings on the ships requires accurate co-located temperature and salinity information. Quality controlled temperature and salinity has often been the Achilles heel for the overall accuracy of the pCO_2 measurements. Translating the pCO2 to an air-sea flux requires high-resolution winds on time scales of hours. Interpolation over larger space and time domains can be done with regional temperature, salinity and wind products. Therefore, measurements of surface physical parameters and marine meteorology both in-situ and remotely is a high priority for ocean carbon research.

Role of high-resolution marine meteorological observations in global climate research

David M. Legler
U.S. CLIVAR Office

The Climate Variability and Predictability program (CLIVAR) focuses on the physical aspects of the coupled climate system, and addresses the question: What causes the changes of the earth's climate on time scales from seasons to centuries and can we predict it? Examples of changes (or variability) can be found in the worlds ocean basins. Mechanisms that govern and generate modes of variability such as El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation, Northern Annular Mode (i.e. NAO), and the Tropical Atlantic Variability (TAV) are not well known, but the ocean plays a critical role, and the coupling between the ocean and atmosphere in particular must be better quantified, described, and monitored in order to accurately model the coupled system (particularly the ocean) and indicate any change. Air-sea fluxes of heat, momentum, and fresh water are the measures of this coupling, but global fields of these variables are difficult to obtain and the uncertainties of many currently available fields are unacceptably large. The prospect of a network of high-resolution, high-quality surface marine meteorology observations that will anchor flux fields at select locations and also provide characteristics of these fields in the spatial domain is especially welcomed by CLIVAR. Such an observation network could be used to validate any number of flux fields (satellite, NWP) and products, on a wide variety of time and space scales. A plan to develop this network address these needs of the climate research community:

- Consistent data and metadata
- Data quality attributes and better inter-calibration within the network
- Delivery of data as much as possible in real-time
- Value-added products helpful to users, and
- Assessment of these observations in context of other observing systems and products (routine VOS, satellite, other products)

An example of the use of high-resolution research vessel data was the recent comparison of a large collection of this data to the NCEP reanalysis surface meteorology and air-sea flux fields. The study highlighted numerous deficiencies in the NCEP fields and the NCEP flux algorithms.

Session 2: Current status of high-resolution observing programs

Shipboard monitoring of stratocumulus cloud properties in the PACS region

Chris W. Fairall
NOAA Environmental Technology Laboratory

In this project we implemented a modest ship-based cloud and flux measurement program to obtain statistics on key surface, mean boundary layer (MBL), and low-cloud macrophysical, microphysical, and radiative properties. The measurements were made as part of the PACS/EPIC monitoring program for the 95°W and 110°W TAO buoy lines in the tropical eastern Pacific (Cronin et al. 2002). Our goal was to acquire a good sample of most of the relevant bulk variables that are commonly used in GCM parameterizations of these processes. These data are being compared to known relationships in other well-studied regimes. While not comprehensive, these data are useful for MBL/cloud modelers (both statistically and for specific simulations) and to improve satellite retrieval methods for deducing MBL and cloud properties on larger spatial and temporal scales.

The primary objectives are to

1. Obtain new measurements of near-surface, cloud, and MBL statistics for comparison to existing data on northern hemisphere stratocumulus systems.
2. Obtain quantitative information on cloud droplet and drizzle properties and probability of occurrence of drizzle and possible links to deviations from adiabatic values for integrated cloud liquid water content.

3. Examine applicability of existing bulk parameterizations of stratocumulus radiative properties for the Peruvian/Equatorial regime.
4. Characterize surface cloud forcing and possible ocean-atmosphere coupling through stratocumulus SST interactions.
5. Provide periodic high quality near-surface data for inter-comparison with ship-based IMET and buoy-based meteorological measurements.
6. Provide high quality measurements of basic surface, MBL and cloud parameters for 'calibration' of satellite retrieval techniques.

Status of the SEAS program

Steve Cook
NOAA/AOML

NOAA's Global Ocean Observing Systems (GOOS) Center has developed the SEAS 2000 software package which will support the automated real-time transmission of high resolution meteorological data from those selected vessels (both research and Voluntary Observing Ships) outfitted with climate quality sensor packages. Plans are to have three Voluntary Observing Ships on line by the end of 2003. Additionally, plans are evolving to integrate the NOAA research fleet as high resolution reporters. The GOOS Center will continue to integrate sampling systems into SEAS 2000, assist in the data QC, management and coordination of those systems as well as continue to act a focal point to the Voluntary Observing Ship network.

Underway systems on SIO vessels

Woody Sutherland and Carl Mattson
Scripps Institution of Oceanography

Overview of the R/V *Wecoma* DAS system

Linda Fayler
Oregon State University/COAS

The manner in which the meteorological and flow-through systems are implemented on the UNOLS intermediate class research vessel *Wecoma* is detailed. A quick overview of the various types of equipment used and their placement on the ship is included. The manner in which the data are collected, including the sampling rates, periods over which data is averaged, and the program language is described. Data record structure is presented along with the other types of documentation files, which are included with the data CD created for each science cruise. Why this system is not a high-resolution system is then discussed. In summary, ways in which the system on *Wecoma* might be improved are outlined.

Status of vessels operating with SCS

Dennis Shields (presented by M. Reynolds)
NOAA/MAO

<u>Marine Meteorological Measurements from the USCG Polar Class Icebreakers.</u>

Phil McGillivary
US Coast Guard Icebreaker Science Liaison

The USCG operates three icebreakers for high latitude logistics and research for the U. S. government and all federal agencies, with the ships based out of Seattle, Washington. These vessels include two 399 ft. Polar class icebreakers, *Polar Star* (NBTM) and *Polar Sea* (NRUO), which are the principal ships tasked with the annual mission to break an ice channel in to McMurdo Station in the Ross Sea, Antarctica, to permit re-supply of the base during the austral summer (northern winter). Typically this mission is carried out by one of the Polar icebreakers, with the second vessel held in reserve. However in the past two years, heavy ice conditions have required the use of two icebreakers, a condition anticipated to persist for the foreseeable future. Normally, one or both of the Polar Class icebreakers also conducts research in the arctic during the northern summer, typically calling at Barrow, Alaska, during their summer missions. A new icebreaker, the 420 ft. *Healy* (5LZE), began its' mission as an arctic research vessel in 2001. In transiting from the eastern to the western arctic, the *Healy* has gone through the Canadian Northwest Passage once, and once transited through the Panama Canal. Future transits of the arctic will likely involve these routes again, as well as periodic transits across the North Pole.

The annual cruise track of the Polar class icebreakers from Seattle to Antarctica to Seattle to Barrow, Alaska, provides them an annual latitudinal range of standard operations greater than any other U. S. research vessel. This great latitudinal range drives many of the research objectives of meteorological measurements from these ships. Principal research objectives for which marine meteorological measurements from the icebreakers have been or can be used include: (1) high latitude inputs to weather/climate models; (2) satellite calibration/validation of existing and newly launched environmental observing satellites (including taking identical satellite sensor systems aboard the ship); (3) air-sea flux measurements involving elemental budgets, including hydrogen, carbon (as CO2), sulfur, and halogens; (4) correlation of ship sensors with those from radiosondes, Global Ocean Observing System (GOOS) floats, ARGO floats, SOLO floats, ice buoys, and autonomous underwater vehicles (AUVs) deployed during icebreaker missions; (5) comparison with data from high latitude underwater observatories now existing (e.g., on Little Diomede Island) and planned (the PRIMO observatory in McMurdo Sound, Ross Sea, Antarctica); and, finally, (6) studies of physical and chemical fluxes relating to "ice breeze" phenomena at the edge of pack ice, as well as similar flux studies at leads and polyn'yas in the ice. In the future, high latitude ship-collected marine meteorological data can be useful for several studies proposed to focus on the relation of solar/sunspot maxima to Earth's meteorological fields as well as "space weather" (c.f. CAWES, the 2003-2007 program on Climate And Weather in the Sun-Earth System).

A wide range of issues are presented related to sensor calibration, data management, and the complications of placing additional sensors on the icebreakers. Sensor calibration is typically done before and after each scientific cruise. The annual track of the ship to Barrow, Alaska combined with the fact that the ship instrumentation are identical to those installed at the Barrow ARM site allows for regular sea-truth and instrument inter-calibration with the Barrow ARM instruments. Onboard data management is handled by the NOAA SEAS-V software. Standard data are transmitted via INMARSAT at four hour intervals to NODC. At the end of each mission, a CDROM of all data collected are provided to scientists involved. Requests to improve or add sensors to the icebreakers have been increasing; however, maintaining additional sensors properly is beyond the ship's current force capabilities. Deployment and use of new sensors can be accommodated when personnel serving as instrument minders are provided through separate funding (e.g., university or government agencies).

An important value of marine meteorological sensors on the Polar Class icebreakers is to provide data for satellite calibration and validation over the great latitudinal range they cover during their annual transits. Ship wind sensor data can be used for validation of winds obtained from the currently operational QuikScat satellite. Calibration/validation of these winds over the sea will soon be of increasing importance as QuikScat winds are about to be incorporated into Navy global operational wind and weather models. In the near future shipboard wind data may be used to calibrate/validate wind data obtained from the NASA SeaWinds sensor on the Japanese ADEOS-II satellite. Currently all three USCG icebreakers have been active in providing sea truth data for ENVISAT, the first satellite to be able to distinguish snow depth as separate from sea ice thickness when sea ice is snow-covered. A radar system similar to that on ENVISAT was mounted on the *Healy* in summer of 2001 in the eastern arctic by ENVISAT PI Son Nghiem (NASA JPL). Similarly the icebreakers will be used during the 2003 and subsequent seasons to measure sea ice thickness for calibration/validation of ICESat, launched by NASA in March 2003, and can provide similar data for ice thickness estimates from the MODIS sensors on NASA's AQUA satellite. Atmospheric moisture and aerosols are particularly important aliasing components of satellite remote sensing data, and additional sensor information on these parameters can further broaden the range of satellite calibration and validation information for the new suite of NASA-launched earth-observing satellites.

In summary, the annual cruise tracks of the Polar Class icebreakers, *Polar Sea* and *Polar Star*, from 70°North to 70°South latitudes permit collection of high resolution marine meteorology data that can make a significant contribution to a wide range of scientific community interests, as well as global weather and environmental models.

Aerosol Observations and Modeling Briefing: T-AGS 60 Class Ship Battle-space Characterization

Jeff S. Reid
Aerosol and Radiation Modeling Section, NRL Monterey CA

The Marine Meteorology Division of the Naval Research Laboratory in Monterey, CA has an ongoing program to model and monitor significant aerosol events globally. The Navy Aerosol Analysis and Prediction System (NAAPS) is a global 1x1 degree prognostic aerosol model that runs out to 120 hours. Current aerosol species modeled include dust, smoke and urban pollution. While NAAPS captures large visibility reducing events well, there is an ever-increasing need to predict visibility to finer and finer resolution. Hence, a development program has begun using 9 km mesoscale models. As aerosol forecasts move to high resolution, validation methods must follow similarly. Our section intends to develop a mobile package capable of deployment on the Naval Oceanographic Office (NAVOCEANO) T-AGS 60 survey vessels. In this talk, we describe our package for measuring visibility, aerosol particle size and chemistry, micro-pulse lidar, and high resolution meteorology.

IMET (Improved METeorology) Status for Buoys, Research Vessels, and Voluntary Observing Ships

David Hosom
Woods Hole Oceanographic Institution

IMET was designed starting in 1988 to meet the WOCE standards for measuring heat flux to 10 Wm^{-2}. The sensors were tested to meet these standards and consist of: wind speed and direction, barometric pressure, relative humidity and air temperature, precipitation, sea surface temperature, shortwave radiation, and longwave radiation. The system architecture consists of individual modules that can be polled using a modified SAIL protocol, using a central data logger via RS485 or RS232. Calibration constants are internal to the module for ease of replacement in the field.

There are three versions of IMET. (1) The original "Old IMET" consisting of the selected sensors and a set of PC boards for analog interface, A/D conversion, and communications. (2) ASIMET uses the same sensors with lower power improved electronics and more rugged titanium housings. These modules can be polled by an external computer as well as operating stand-alone using internal batteries and a data logger. (3) AutoIMET (for VOS) uses the same sensors and electronics as ASIMET in a lower power integrated package that operates from batteries and has wireless communications to the ship bridge and to the sea surface temperature located inside the hull at the waterline. Of special interest is the HullCom acoustic modem that uses the ship hull as a data path for SST. A 99% data return has been achieved on ocean cruises from this device.

A list of operational IMET systems includes 7 R/V's, 45 buoys, and 2 VOS (with 2 more VOS planned). Buoy options at WHOI include 3-meter discus buoys with two complete systems and coastal buoys with single simplified modules and data logger.

The IMET data accuracy and precision was specified to meet the WOCE requirement of 10 Wm^{-2} and has demonstrated this in the field. A critical part of the accuracy is a six month (one year on ocean buoys) calibration cycle that is performed at WHOI.

Shipboard Radiometric Measurements of Some Surface Meteorological Parameters

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Some of the variables required for high resolution ship-board data sets can be measured using well-calibrated radiometers. These variables include skin sea-surface temperature and air temperature. If measurements of the atmospheric emission in the infrared are taken with sufficient spectral sampling, then atmospheric profiles of temperature and humidity can also be obtained. One instrument capable of providing such measurements is the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a Fourier-Transform Infrared Spectroradiometer that has been used on many ships over several years. One such deployment is on the Royal Caribbean Cruise Lines ship “The Explorer of the Seas” which undertakes a weekly cruise round the Caribbean region from the Port of Miami. A M-AERI has been installed on this cruise ship for over two years and has provided a valuable data set which has been used in the validation of SST measurements from satellites. Other instruments, lacking the spectral coverage and resolution of the M-AERI, are also providing skin SST measurements for satellite validation, and many of these were brought recently to the University of Miami for cross-calibration against NIST reference standards, and for a short cruise. The results of these exercises show that these radiometers are sufficiently well calibrated and stable that they can be deployed independently yet have their measurements combined to supply merged data sets for satellite validation. With funding from NOPP, a new project is getting underway to develop and demonstrate an autonomous, self-calibrating, automatically-reporting radiometer suitable for deployment on the VOS fleet, primarily for satellite skin SST validation.

An important contribution of the M-AERI to marine meteorological measurements is the measurement of near-surface air temperature. This measurement is largely independent of heat-island effects of the ship and direct solar heating of a thermometer. Also air-sea temperature differences can be measured with a single well-calibrated sensor. Comparisons of radiometrically and conventionally measured air temperatures show marked differences, especially in the tropics, where the radiometric measurements show very much reduced diurnal signals

On radiation measurements at sea

R. Michael Reynolds
Brookhaven National Laboratory

Inter-comparison of WHOI, PMEL, JAMSTEC, and BNL meteorological observations

Paul Freitag
NOAA/PMEL

During May and June 2000, an inter-comparison was made of buoy meteorological systems from the Woods Hole Oceanographic Institution (WHOI), the National Oceanographic and Atmospheric Administration (NOAA), Pacific Marine Environmental Laboratory (PMEL), and the Japanese Marine Science and Technology Center (JAMSTEC). The results of this inter-comparison have been published as a WHOI report (WHOI-2002-10) by R. Payne et al. (2002). Two WHOI systems mounted on a 3 m discus buoy, two PMEL systems mounted on separate buoy tower tops and one JAMSTEC system mounted on a wooden platform were lined parallel to, and 25 m from, Nantucket Sound in Massachusetts. All systems used R. M. Young propeller anemometers, Rotronic relative humidity and air temperature sensors, and Eppley short-wave radiation sensors. The PMEL and WHOI systems used R. M. Young self-siphoning rain gauges, while the JAMSTEC system used a Scientific Technology ORG-115 optical rain gauge. The PMEL and WHOI systems included an Eppley PIR long-wave sensor, while the JAMSTEC had no longwave sensor. The WHOI system used an AIR DB-1A barometric pressure sensor. PMEL and JAMSTEC systems used Paroscientific Digiquartz sensors. The Geophysical Instruments and Measurements Group (GIM) from Brookhaven National Laboratory (BNL) installed two Portable

Radiation Package (PRP) systems that include Eppley short-wave and long-wave sensors on a platform near the site.

It was apparent from the data that for most of the sensors, the correlation between data sets was better than the absolute agreement between them. The conclusions made were that the sensors and associated electronics from the three different laboratories performed comparably.

Improving Flux Measurement Accuracy: Experiences of the TOGA-COARE Air-Sea Interaction (Flux) Group

Frank Bradley
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The TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) "Flux Group" was formed to coordinate analysis of the surface meteorological and ocean data-sets obtained on the 10 ships and the central IMET mooring. COARE planners had set a goal of 10 Wm^{-2} for the accuracy of net heat exchange which, in the context of bulk fluxes, implied that sea and air temperatures, humidity, and wind speed must be measured to within 0.2 K, 0.2 gkg^{-1}, and 0.2 ms^{-1} respectively. However, initial analysis of two days of underway inter-comparisons between the platforms revealed discrepancies in these variables and also the radiative flux components which exceeded these targets. Examples are given of such errors and the correction procedures for some of the more critical variables for flux calculation. The legacy of this experience of improving measurement accuracy in COARE is illustrated for subsequent air-sea measurement programs in the Indian (JASMINE 1999) and eastern Pacific (EPIC 2001) oceans. Calculations of sea skin temperature using the cool skin and diurnal warm layer models in the COARE 3.0 bulk algorithm are compared with direct measurements by an IR radiometer. Results of rainfall measurement by various *in-situ* sensors aboard ship are also given. Many of the sensor types used in COARE remain in widespread use today, but better accuracy can be obtained by improved practice; frequent calibration and maintenance (particularly for radiation sensors), on-line monitoring of signals, replication and attention to location of instruments, and inter-comparison with other platforms on site.

Application of R/V Data to Satellite Calibration/Validation

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The accuracy of vector winds from the SeaWinds scatterometer on the QuikSCAT satellite is assessed through comparison with observations from research vessels. Several factors that contribute to uncertainty in scatterometer winds are isolated and examined as functions of wind speed. The independent sources of uncertainty considered herein are ambiguity selection, wind speed, wind direction (for correctly selected ambiguities), variability associated with spatial separation between scatterometer and ship observations, and random errors in the ship observations. Ambiguity selection refers to the selection of a unique scatterometer wind direction from multiple likely solutions. For SeaWinds on QuikSCAT, ambiguity selection is found to be near perfect for surface wind speed (w) >8 ms^{-1}; however, ambiguity selection errors cause the directional uncertainty to exceed 20° for $w < \sim 5$ ms^{-1}. Improved statistical methods that account for the spatial variability in the winds and uncertainty in the ship data are applied to determine uncertainties in speed and direction separately for correctly selected ambiguities. These uncertainties (averaged over the full comparison set) are found to be 0.45 ms^{-1} and 5° for the QSCAT-1 model function and 0.3 ms^{-1} and 3° for the Ku-2000 model function.

Fine temporal resolution observations are needed to apply effective automated quality assurance (QA) to the observations. A QA technique is developed to flag suspect data. Problems we have identified are often associated with changes in the ship motion and with flow distortion. The differences in comparisons of satellite and in situ observations, with and without flagged data, are statistical significant. Flagged data is not used in the final comparison.

A wind speed dependent model for the uncertainty in the magnitude of vector errors is developed. For the QSCAT-1 (Ku-2000) model function, this approach shows ambiguity selection dominates uncertainty for $2.5 < w < 5.5$ ms^{-1} ($0.6 < w < 5.5$ ms^{-1}), uncertainty in wind speed dominates for $w < 2.5$ ms^{-1} and $5.5 < w < 7.5$ ms^{-1} ($w < 0.6$ ms^{-1} and $5.5 < w < 18$ ms^{-1}), and uncertainty in wind direction (for correctly selected ambiguities) dominates for $w > 7.5$ ms^{-1} ($w > 18$ ms^{-1}). This approach also shows that spatial variability in the wind direction, related to inexact spatial co-location, is likely to dominate rms differences between scatterometer wind vectors and in-situ comparison measurements for $w > 4.5$ ms^{-1}. Application of these techniques leads to more accurate estimates of observational uncertainty.

Session 4: Developing a unified, sustained distribution system for high-resolution data

VOS IMET data retrieval, processing, and distribution

Frank Bahr, David Hosom, and Robert Weller
Woods Hole Oceanographic Institute

We describe the current data retrieval, processing, and distribution steps for data sets from VOS ships equipped with WHOI IMET systems. We introduce our web site, which provides general information on these ships as well as specific information on individual deployments, including plots of raw data and example data products. Obtaining a complete GPS record has been difficult until now, but we list several possible solutions that will address this problem in the near future.

The current data retrieval and processing steps for data sets from VOS ships equipped with WHOI IMET systems are described. A web site is introduced that provides information on these ships and on the data processing, and includes plots of the raw data and of example products. A remaining problem of obtaining GPS time series reliably is addressed. We identify several possible solutions that should alleviate this problem in the future.

International SeaKeepers Society high-resolution VOS data system

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The International SeaKeepers Society (http://www.seakeepers.org) is a privately funded, non-profit organization which has developed and deployed an inexpensive ($50k), autonomous meteorological and oceanographic sensor and data transmission package on dozens of ships. The SeaKeepers meteorological data have been provided as a component of the VOS (Volunteer Observing Ship) program since June of 2001 through routine delivery of WMO FM-13 and FM-62 formats to the National Weather Service. NOAA's National Center for Environmental Prediction (NCEP) routinely tracks the quality and quantity of data from the global VOS program, and they agreed to help the International SeaKeepers Society assess their new system by tracking their new observations independently as well. How have the SeaKeepers meteorological systems performed? During the 18-month period from June 2001 until the end of 2002, 16 different SeaKeepers systems reported 13,803 observations from locations around the world's oceans under the SeaKeepers anonymous call sign KSnnn (where nnn is a 3 digit number). While these limited observations were not as geographically widespread as the 142,190 observations from the rest of the global VOS fleet -- comprised of 1,715 ships -- during the same time period, they are far more efficient and demonstrably more accurate due to the automated data collection and the high quality of the instrumentation installed. By NCEP's measure, the SeaKeepers vessels' data quality ranged from about the same (barometric pressure) to significantly better (wind speed, air temperature, and sea surface temperature) with regards to bias and scatter than the rest of the VOS fleet. While the measurement systems have already proven to be more accurate and prolific than that of the typical VOS, SeaKeepers and its science advisors are pushing ahead with new data quality controls and data management systems that will raise the quality of the measurements to an even higher level. The SeaKeepers program is currently expanding beyond super-yachts and cruise ships, and new systems are currently installed on a variety of ferries, piers, buoys, lighthouses, and merchant vessels. The SeaKeepers network will be in a position to make an even more substantial contribution to the daily monitoring of the ocean's weather and climate during the upcoming years. In particular, SeaKeepers would like to target the data-limited areas of the Indian and South Pacific oceans for expansion, as well as the coastal areas of many developing nations in the Caribbean, South American, and African regions.

Vision for a delayed-mode high-resolution marine meteorology data center

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A vision for establishing a delayed-mode data assembly center (DAC) for automated weather system (AWS) observations from research vessel (R/V) and select volunteer observing ships (VOS) is outlined. The vision is based on COAPS' eight years of experience as a data center that collects, quality controls (QC), and distributes surface meteorological data collected by R/Vs. Past experience with the World Ocean Circulation Experiment and TOGA/COARE allowed COAPS to develop the contacts, tools, and expertise to quality process and distribute delayed-mode AWS data. These data typically include full resolution (1 minute or less sampling rates) navigation, meteorology (wind, temperature, pressure, moisture, rain, radiation), and some ocean (SST, salinity, conductivity) parameters. Currently, these data are managed on a ship-to-ship basis, with data being provided primarily to scientist from each cruise and sometime being placed in a data library at the vessels home institution. For researchers, these data are difficult to obtain, especially when a large number of cruises are desired.

The vision promoted would establish a single central DAC who would be tasked with obtaining all delayed-mode data from U.S. sponsored R/Vs and select VOS equipped with AWS. Agreements would be established with vessels and their home institutions to regularly transmit the full-resolution delayed-mode data to the DAC. The DAC would then place the data in a common format, perform analyses to assess the data quality, produce value-added data (with QC flags) and quality reports, provide feedback to vessels, and subsequently distribute the value added data. The DAC would survey the user community to determine their needs and to provide products in desired formats. In addition, the DAC would work with national data archive centers to assure permanent archival of the original and value added data. The DAC would also collaborate with established data initiatives (e.g., Ocean.US, GOOS) to further disseminate VOS-AWS and R/V-AWS observations. The data efforts would also support international climate programs (i.e., CLIVAR, as several U.S. vessels would be completing CLIVAR hydrographic surveys). Overall, the system would be designed to improve user access to the valuable resource provided by VOS-AWS and R/V-AWS.

Sustained Data Management and I-COADS

Scott Woodruff
NOAA Climate Diagnostics Center

The Comprehensive Ocean-Atmosphere Data Set (COADS) was recently renamed the International COADS (I-COADS) in recognition of its multinational basis. I-COADS, the most extensive collection of surface marine data available for the world ocean, presently covers 1784-1997 (delayed-mode archive). Our plans include a 1997-2002 update by the end of 2003 based on data from the Global Telecommunication System (GTS), and future monthly updates of this "real-time" archive. Plans also include the creation of "add-on" datasets, available in I-COADS formats prior to blending into the delayed-mode archive, and improved quality control (QC). In addition, a new International Maritime Meteorological Archive (IMMA) format is being developed under the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), which will provide the flexibility to store both historical and contemporary I-COADS data. Data from the Research Vessel Surface Meteorology Data Center (RVSMDC) should form an important addition to I-COADS by enhancing data coverage and quality. Among the issues to be resolved are how to utilize and blend existing RVSMDC metadata and QC flags, and how to average and sub-sample the high-resolution data to produce (e.g., hourly) reports that may be more compatible with the Voluntary Observing Ship (VOS) and buoy data that make up much of I-COADS. The upcoming Second JCOMM Workshop on Advances in Marine Climatology (CLIMAR-II; 17-22 November 2003, Brussels) is suggested as a potential forum for presentation of results and recommendations from this workshop.

Discussion of Recommendations

The round-table discussions that followed sessions of invited talks allowed the participants to formulate thirteen recommendations. Discussions focused on areas of the marine observation system that need improvement and enhancement, new initiatives to improve data accuracy, quality, and availability, and collaboration with new and ongoing programs/initiatives. Key points raised by workshop attendees are outlined below for each recommendation.

1. Develop a sustained system of calibrated, quality-assured marine meteorological observations built around the surface flux reference sites, drifting buoys, research vessels (R/Vs), and volunteer observing ships (VOS) to support science objectives of national and international climate programs.

Discussion focused around the need for a higher volume of calibrated, quality-assured marine meteorological observations to achieve several scientific objectives. In addition to the published objectives of established climate programs (e.g., CLIVAR, GODAE), participants suggest that observations from VOS-AWS and R/V-AWS are valuable for satellite and model validation, turbulent flux estimation, and assessing diurnal cycles over the oceans. Participants agreed that all AWS marine measurements should contain sufficient parameters and have accuracy that allows computation of high quality turbulent fluxes. These calculated fluxes and the parameters needed to calculate the flux are ideal data sets for evaluating fields derived by NWP, climate, and coupled models. In addition, VOS-AWS and R/V-AWS data sampling rates provide sufficient resolution of the diurnal cycle. In one application, AWS measurements would be very helpful to remove diurnal cycles from polar orbiting satellite data.

Many validation studies are best achieved using full resolution, delayed-mode AWS data; however, the attendees also addressed real-time applications of AWS observations. Currently there is great interest in homeland security, improving safety at sea, and better monitoring coastal environments. Many of these areas can be addressed by marine AWS systems; however, the sustained system must consider the added cost and commitment to provide quality measurements in real-time.

The sustained system discussed was an end-to-end program starting from instrument deployment and calibration, through data collection and quality assurance, and on to data archival and distribution to the user community. The collection system would include AWS deployed on research vessels, VOS, and moored and drifting buoys. The attendees acknowledged that the suite of parameters measured would vary due to the limitations of some platforms. The system would be anchored by a series of surface flux references sites and a portable standard instrument suite. The surface flux reference sites are part of an NSF Ocean Observatory Initiative and are envisioned to be some form of nearly stationary observing platform (e.g., moored buoy). The portable standard instrument suite would be used to improve the quality of underway meteorological systems on both R/Vs and VOS. Vessels are encouraged to have onboard instrumentation inter-compared to the reference standard and to periodically participate in inter-comparisons studies with other vessels or the surface flux reference sites.

Finally, the workshop attendees discussed the need to engage the in-situ data user community. Partnerships need to be extended with the atmosphere and ocean modeling groups in a way that will provide both communities with desired data and products. Further collaboration is needed with the satellite communities to encourage real-time distribution of satellite data for both modelers and in-situ data QA/validation projects.

2. Improve global data coverage, especially from important but data sparse regions (e.g., Southern Ocean), by working with and making use of national and international observing efforts, research programs, and infrastructure development initiatives.

Participants reiterated a continuing need to improve data coverage in the Southern Ocean and other data sparse regions. Taking full advantage of the R/V fleet would be a step in the right direction. Several of these vessels (e.g. *Polar Star*, *Polar Sea*, *Healy*, *Nathaniel Palmer*) routinely operate in high Arctic and Antarctic latitudes and other U. S. R/Vs operate in data sparse regions of the south Pacific and Indian Oceans. Currently data collection from these vessels is disorganized, making the data hard to find and utilize for climate research.

Establishing surface flux reference sites in data sparse regions can also provide a key resource. There are several technical challenges to overcome prior to deployment of reference stations in severe environments; however, once established these sites will provide key benchmarks for air-sea flux fields.

Several attendees suggested that autonomous vehicles and profiling floats can provide some additional observations in data sparse regions. These systems were not discussed at length primarily because they can only provide a limited set of parameters and would not be sufficient (at present) to determine in-situ surface fluxes. Some of these sensors can be applied to improve single variable fields (e.g., atmospheric pressure from floats or drifters).

Several of the programs discussed as candidates to improve data coverage are well established (e.g., ARGO, drifting buoys). The focus of discussion was primarily on how to improve data coverage using AWS on VOS and R/Vs and through an expanded mooring program. Attendees also discussed the need for interaction between the satellite community. Satellites provide good spatial and temporal coverage; however, they are limited to a few parameters (SST, winds, altimetry). In-situ observations can work in concert with satellite data, providing validation data and parameters unavailable from the satellite (e.g., moisture).

3. Establish a data assembly center (DAC) for U.S. R/V (e.g., UNOLS, NOAA, Navy, Coast Guard) meteorological observations to unify data collection, quality assurance (QA), and distribution. The DAC will also provide for permanent data archiving and long-term availability of data at national archive centers.

A clear need for a data assembly center (DAC) to collect, QA, and distribute R/V-AWS observations was established by workshop participants. Both NSF and NOAA have expressed their interest in having a center for this activity. Data collected by VOS and some VOS-AWS (e.g., SEAS, SeaKeepers) have established programs where the data are collected, receive some level of QA, and finally are deposited in a permanent archive. Such a system is lacking for R/V-AWS and as a result, scientifically valuable data are being lost. In addition, the DAC will be able to expand to handle VOS-AWS orphans (those systems without a plan for data QA, distribution, archival).

Participants discussed the need for a DAC to handle both real-time and delayed-mode R/V-AWS data (see Table 1). The real-time data pathway should pull data from the ships, provide for real-time QA, place data on the GTS, and provide feedback to vessels when problems are detected. Some R/Vs and VOS-AWS already have proven systems for real-time data transfer (e.g., SEAS), so discussions focused on consolidating these data at a common center for QA and feedback to operators. In addition, attendees outlined several possible ways to get real-time transfer systems on R/Vs not currently equipped for this task.

Delayed mode data could be sent to the DAC via land-line or digital media, but this transfer must be regularly scheduled. For R/Vs this may be at the end of each cruise, while some VOS-AWS may only provide delayed data when it is retrieved from the VOS-AWS system (every 3-6 months).

The DAC was envisioned by some participants as providing a single access point to all R/V-AWS meteorological observations. Though a single DAC was the vision, participants agreed the DAC may be part of a distributed data system. For example, one institution may be responsible for pulling the data from the vessels in real-time and then forwarding these data to both the GTS and to the DAC for QA. Regardless of how the DAC is structured, the workshop discussion pointed to the need for one or more PIs to undertake the responsibility of representing all R/V-AWS observations.

The role of the DAC was discussed as being more than a data collection and distribution center. The DAC would work with established and new data initiatives to expand user access to these data. The DAC should work with programs like I-COADS and several national data archives (e.g., NODC, NCDC) to ensure long term archival and availability of the data. Another example would be involvement with the Integrated Ocean Observing System (Ocean.US). Finally, the DAC should act as a liaison with the user community (e.g., model, satellite) and other climate programs (e.g., CLIVAR, GOOS).

4. Establish standards for sensor calibration and data collection on ships and moorings, including accuracy and resolution, sampling rates and averaging periods, data acquisition and display software, data transmission, recommended instrument siting, and provision of metadata.

Standards are a concern for any measurement program. A set of standards must be defined before new AWS can be designed or installed, and before any inter-calibration programs begin. Several discussions raised the need for a definitive list of parameters to be measured that would allow for computation of quality air-sea flux estimates. To this end, several attendees agreed to compare standards currently under development (e.g., IOOS, WCRP/Air-Sea Fluxes, etc.). In a parallel effort, comparisons of several metadata standards (IOOS, VOSClim, RVSMDC, I-COADS) will be undertaken to develop metadata standards for high-resolution marine AWS observations.

Discussions on standards also pointed to the need to limit the current duplication of efforts between multiple ships or institutions. Once common standards are agreed to, resources can be better allocated to meet the standard, and funding agencies will have some metric to determine if purchased instrumentation are meeting standards desired for scientific applications.

Participants agree that adhering to a standard does not obligate all AWS to operate with instruments from a single manufacturer or source. The intention of the standard is to set minimum accuracy and resolution of measurements and promote desired sampling rates and averaging periods. Whatever instrumentation is deployed on a ship or buoy should meet these standards.

5. Produce a reference manual of best procedures and practices for the observation and documentation of meteorological parameters, including radiative and turbulent fluxes, in the marine environment. The manual will be maintained online and will be a resource for marine weather system standards.

Several participants from the operational marine community voiced interest in a common resource to find information on instrument siting, calibration, etc. This discussion lead to the idea of establishing a reference manual containing the best procedures and practices for observation and documentation of marine meteorological parameters. The manual would be based on the standards determined through the previous recommendation and would be maintained online for ease of access and updating.

Discussions identified several items to be included in the content of the reference manual. Of interest to fleet improvement committees (for designing new vessels) and marine technicians would be recommended instrument siting. The resource would also be designed to include user comments, frequently asked questions, access to user tools (e.g., display software, flux algorithms, etc.), and links to various groups involved with the acquisition of high-resolution marine meteorology. Instrument recommendations and expert contacts for various marine measurements should be provided. In addition, results from instrument inter-calibration studies could be made available to aid planners in choosing sensors with appropriate accuracy for marine meteorology applications.

6. Develop a portable, state-of-the-art, standard instrument suite and implement on-board inter-comparison between the portable standard and shipboard instruments to improve R/V and VOS automated meteorological observations.

Several discussions focused on how to improve on-site calibration and inter-calibration of marine AWS. For R/Vs, one proposal included using a single vessel as a gold-standard for ship-to-ship inter-comparisons; however, further discussion determined that this would not be cost-effective. The alternative proposal was to develop a portable, state-of-the-art, instrument suite that could be moved from one ship to the next in the U. S. R/V fleet. The workshop attendees agreed that this method would be most cost effective and would permit AWS on more ships to be evaluated in a shorter period of time.

The portable system is envisioned to include two complementary components. The first would be a state-of-the-art flux instrument suite optimally mounted to evaluate ship's operational AWS. The second part would be a set of individual instrument standards to be sited next to ship's instruments for direct sensor-to-sensor comparisons.

Once developed the participants envision the portable standard being placed on a R/V by a technician trained in onboard calibration and inter-calibration. The system and technician will ideally stay on board for a period of days to weeks to complete comparisons while the R/V is at sea. While onboard, the system technician will work with R/V technician to evaluate inter-comparison results in the field and recommend improvements to R/V AWS. Evaluations will be provided to the R/V's home institute so that they can pursue resources to modify or upgrade their AWS.

7. Endorse development of robust sensors for use in severe environments to improve data accuracy and allow accurate data to be collected from data sparse regions.

A key component of a sustained network of high-resolution marine meteorological observations is the collection of data in remote locations and a high latitudes. These environments pose serious challenges to instrument designers. Sensors capable of performing to the desired accuracy in the tropics, often fail in harsher polar latitudes. Icing, severe platform motion, and other factors contribute to the challenges. The workshop participants noted that scientifically interesting regions of the globe can not be adequately sampled with current technology; thus, resources should be allocated to improve sensors and platform design for these regions.

8. Implement a program in computational fluid dynamics (CFD) modeling of the wind flow regime over ships to determine optimal wind sensor siting, wind correction factors, and effective measurement heights.

Distortion of the air flow by a ship or buoy has adverse impacts on the accuracy of most all measurements made on these platform. The workshop participants discussed the need to define and reduce the influence of flow distortion on AWS measurements. CFD modeling has the ability to identify regions over a given vessel (not sure if this has been done for buoys) where flow distortion is minimized. Advances in CFD modeling have made the process cost effective and participants agreed that such modeling should be completed for all vessels participating in the high-resolution marine meteorology program. CFD model results can aide in developing recommendations for instrument siting and can be used to develop corrections factors for flow distortion at AWS sites on various R/Vs. Finally the participants encourage the use of CFD modeling during the design phase of new vessels. This will allow for the best siting of meteorological instrumentation on the new vessel.

9. Encourage (i.e. fund) R/Vs to schedule meteorological inter-comparisons with surface flux reference sites and, where appropriate, with one another.

A key component of a sustained system to collect high-quality R/V-AWS observations is to encourage inter-comparison activities at surface flux reference sites and between two or more vessels. Ship-to-ship and ship-to-buoy inter-comparisons have been shown to be of great value (e.g., TOGA/COARE, EPIC) for improving data quality.

Discussions focused on how best to implement these inter-comparison activities. First off, inter-comparison activities must be considered when scheduling ship time and routing. Minimum time needed for a good inter-comparison was debated, with the minimum being one full diurnal cycle. Longer inter-comparison activities are encouraged. Data collected during the vessel's approach to and departure from the surface flux reference site would be useful to obtain a measure of the spatial variability, even if the vessel's stay at the reference site was limited in time.

Additional discussion pointed to technical issues that should be considered when the surface flux reference sites are designed. Inter-comparison activities could be enhanced by allowing the approaching vessel to poll the reference site for higher resolution data (say 1 min. vs. 1 hr. intervals). This would require development and implementation of wireless communication on both the vessel and the flux reference station.

Finally, inter-comparison activities must be considered when scheduling ship time and cruise plans. Clearly this will require some rethinking of the way scheduling is currently implemented and would need to be worked out several years in advance. One of the criticisms that arose during the workshop is the seeming lack of coordination between different vessels. A new way of thinking is needed. R/Vs must begin to consider their role in a global observing system of both the atmosphere and ocean. In some cases the inter-comparisons may be fairly easy to plan with adequate forethought. For example if a flux reference site is located near the north-south track typically taken by the USCG icebreakers on their way to the Antarctic, a ready opportunity for twice a year inter-calibration exists. With adequate planning it should be possible to have a day or two of wingtip-to-wingtip inter-comparison between vessels, providing there is no serious scientific or logistical objections, when R/Vs are planning to operate in the same region of the oceans.

10. Recommend that certain ship data not currently logged be made available to researchers (e.g., pitch/roll, heading, currents, speed of ship in water). These data should be routinely recorded to improve flux calculations and QA.

Many measurements are made onboard vessels and buoys that are not routinely transmitted or recorded in the "standard" meteorology report. Workshop participants noted that several of these parameters (e.g., pitch/roll, heading, currents, etc.) would be important for improving surface flux estimates and QA procedures. On some vessels, these measurements are available to the bridge crew, but are not part of the data recorded by the R/V-AWS. Where possible, these variables should be added to the routinely collected AWS data stream.

11. Encourage funding agencies to require that new shipboard meteorological instrumentation purchased within research grants be installed and operated, and the measurements distributed and archived according to the principles embodied in points 3-6 above.

The general impression of the workshop attendees was that the funding agencies are very willing to provide resources for new instrumentation; however, no provisions/requirements are made on how institutions operate new instruments. In some cases, home institutions are informed that their job is limited to data collection while data quality, distribution, and archival are the responsibility of the chief scientist. In the absence of a major international ocean experiment (e.g., WOCE), this management model is ineffective with R/V AWS data generally lacking quality control and having poor availability to scientists. Workshop participants feel that funding agencies can influence the data management practices for instruments purchased with their funds. Institutes receiving funds for new/improved AWS should be required to adhere to data collection standards, distribution and archival practices, and onboard calibration/inter-calibration programs proposed in these recommendations.

12. Establish sources/contacts where expertise can be obtained by operators and made available for QA development.

Several attendees expressed the need to make technical expertise available to the persons responsible for data collection, instrument maintenance, calibration, and quality assurance. Participant noted that it is difficult for a single technician to be an expert on the wide range of instruments needed to collect marine weather observations at the accuracy desired for science applications. In turn, there are experts in the science and operational communities that specialize in one or more parameters (e.g., radiation, winds, etc.). This recommendation encourages these specialist to make their knowledge available by serving as a point of contact for questions related to their area of expertise.

13. Strongly encourage funding agencies to support human capital development through education and training.

People are key to delivery of high-quality meteorological observations. The role of marine technicians can not be overlooked and discussions revealed a need for a commitment by funding agencies to develop education and training programs to support these personnel. A serious limitation is the turnover of marine technicians. Without adequate training programs, replacement personnel are at a disadvantage. Establishing standards for AWS measurements, calibration practices, etc. will allow for the development of tools to train onboard personnel. Such training should include rudimentary QA of data for troubleshooting purposes, proper field maintenance procedures, and accepted calibrations practices. In addition, marine technicians and ship/buoy operators (home institutions) must be shown that marine AWS observations are important to achieve the objectives of the climate community. Workshop participants strongly encourage funding agencies to provide funds to develop tools to keep technicians informed and up-to-date with desired observational practices.

Distribution of Recommendations

The workshop recommendations will be distributed to the widest possible target audience of vessel operators, scientists, and government and funding agencies involved with the collection and application of marine meteorological data. Recommendations and planned activities will also be addressed to a number of national and international committees (WCRP, OOPC, IOOS) to stimulate interest and determine whether collaboration is possible with ongoing activities. The dissemination primarily will be achieved through electronic and regular mail and through representatives of the workshop panel attending key meetings. In addition to this report, visual aids (e.g., poster, PowerPoint slides) will be made available for use by workshop attendees to disseminate the recommendations. In time the co-chairs hope to prepare a brochure describing our planned activities. A subset of this report will also be submitted for publication in a journal with wide readership (e.g., *Bulletin of the AMS, EOS*).

Timeline

May 2003	• Present recommendations at NOAA Climate Observation Program Workshop
June 2003	• Present recommendations to NSF • Distribute final workshop report
July 2003	• Present recommendations/progress at VOSClim and Ship Operations Team meetings
Summer 2003	• Submit proposals to fund recommended activities in FY04 and beyond • Publish workshop recommendations (BAMS, etc.)
November 2003	• Present recommendations/progress at CLIMAR-II
January 2004	• Complete standards for data collection and metadata
May 2004	• Second HRMM workshop (possibly in conjunction with NOAA COP Workshop
FY 2004	• Open DACs for R/V marine meteorology and TSG • Field test portable instrument suite concept on NOAA ship Ronald H. Brown using existing ETL flux system
FY 2005	• Begin construction of flux standard. Field test on UNOLS ship • Complete first on-line reference manual
FY 2006	• Complete construction of flux standard. Perform inter-calibration study on one ship • Fully implement sustained system for HRMM on R/Vs (meaning TBD - number of ships, etc.)

Action Items

A. Bob Weller will summarize currently available standards of marine meteorological observations needed for bulk flux determination.
B. Liz Kent will provide example of VOSClim metadata standard form to Shawn Smith and Scott Woodruff for use in developing metadata standards.
C. Scott Woodruff, Liz Kent, and Shawn Smith will evaluate metadata standards used by VOSClim, WMO pub47, COAPS, I-COADS and draft a minimum metadata standard.
D. Peter Minnett will provide committee with a short summary of the current status of skin SST measurement from vessels. It would be helpful if summary includes various sensors available and some comment on advantages/disadvantages of sensors (e.g., cost, size, etc).
E. Shawn Smith will draft letter to Sandy Shor (NSF) with recommendations from workshop. The letter will include the possibility of using UNOLS periodic inspections to evaluate science quality of meteorological instrumentation (using portable standard suite, when feasible).
F. Shawn Smith will develop table containing current status of U.S. sponsored marine AWS data collection. This effort will include surveying vessel operators (either written or by phone).
G. Woody Sutherland and Steve Cook will provide feedback on vessel survey questions that will provide a picture of the current status of high-resolution measurements. Draft list will be emailed by Shawn Smith.
H. Chris Fairall will investigate ETL developing the portable reference standard instrument suite and provide estimated costs/timeline for development.
I. All workshop speakers will provide a short (one paragraph) abstract summarizing their talk to Shawn Smith by 28 March 2003. Abstracts will be included in the workshop report.
J. Shawn Smith will present workshop recommendations at Climate Observation Program Workshop in May 2003 (Silver Spring, MD).
K. Steve Cook will present workshop recommendations at SOT (Ship Observation Team) II in London, UK (28-31 July 2003).
L. Liz Kent will present workshop recommendations at next VOSClim workshop.
M. Shawn Smith and R. Michael Reynolds will submit an abstract related to workshop activities/recommendations to CLIMAR2 in November 2003 (Brussels, Belgium). Shawn Smith or Scott Woodruff will present workshop recommendations.
N. Shawn Smith will prepare PowerPoint and poster presentations of workshop recommendations and distribute these to attendees for use at future meetings.
O. Liz Kent (SOC) will estimate costs of CFD modeling.
P. Bob Weller will write to the present chair of Ocean Observation Panel for Climate (OOPC) and the chair of World Climate Research Program (WCRP) Working Group on Numerical Experimentation (WGNE) outlining the workshop and its recommendations, progress on establishing further high resolutions meteorological measurements, and restating the interest of the in-situ community in partnerships with the modeling centers.

Appendix A: Acronyms

AOML	Atlantic Oceanographic and Meteorological Laboratory
ARM	Atmospheric Radiation Measurement program
AWS	Automated Weather System
BNL	Brookhaven National Laboratory
CFD	Computational Fluid Dynamics
CLIVAR	Climate Variability and Predictability program
COAPS	Center for Ocean-Atmospheric Prediction Studies
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Data Assembly Center
ETL	Environmental Technology Laboratory
GCM	Global Climate Model
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
GTS	Global Telecommunication System
I-COADS	International Comprehensive Ocean-Atmosphere Data Set
IMET	Improved Meteorology system
INMARSAT	International Mobile Satellite organization
IOOS	Integrated Ocean Observing System
JAMSTEC	Japanese Marine Science and Technology Center
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
MAO	NOAA Marine and Aviation Operations
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OSU	Oregon State University
PMEL	Pacific Marine Environmental Laboratory
PMO	Port Meteorological Office
QA	Quality Assurance
QC	Quality Control
RSMAS	Rosenstiel School of Marine and Atmospheric Science
RVSMDC	Research Vessel Surface Meteorology Data Center
R/V	Research Vessel
SCS	Shipboard Computer System
SEAS	Shipboard Environmental data Acquisition System
SIO	Scripps Institution of Oceanography
SOC	Southampton Oceanography Centre
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean project
TOGA/COARE	Tropical Ocean Global Atmosphere/Coupled Ocean-Atmosphere Response Experiment
UM	University of Miami
UNOLS	University - National Oceanographic Laboratory System

USCG	United States Coast Guard
VOS	Volunteer Observing Ship
VOSClim	WMO VOS Climate project
WCRP	World Climate Research Program
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
XBT	Expendable Bathythermograph

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