OCEANOGRAPHIC TIMESERIES OBSERVATORIES

Uwe SEND[1], Bob WELLER[2], Stuart CUNNINGHAM[3], Charlie ERIKSEN[4], Tom DICKEY[5], Masaki KAWABE[6], Roger LUKAS[7], Mike McCARTNEY[2], Svein ØSTERHUS[8]

[1]IfM, Kiel, Germany; [2]WHOI, Woods Hole, USA; [3]SOC, Southampton, UK; [4]UW, Washington, USA; [5]UCSB, Santa Barbara, USA; [6]Univ. of Tokyo, Japan; [7]SOEST, Honolulu, USA; [8]Univ. of Bergen, Norway

ABSTRACT *-The establishment of oceanographic observatories at selected sites around the world's oceans is recommended. These observatories would collect time series of surface meteorology, air-sea exchanges of heat, freshwater, and momentum, and provide full depth sampling of ocean temperature, salinity, velocity, and biogeochemical variables. Such measurements also allow direct or geostrophic transport estimates at key sites or along selected sections. New mooring and instrumentation technology makes it possible to maintain such observatories at a fraction of the cost of the previous ocean weather stations. The ocean observatories will provide a critical component of the Global Ocean Observing System (GOOS) needed to develop a description and understanding of the ocean's role in climate. Time series from the observatories will provide the means to develop accurate fields of the air-sea fluxes, observe water mass formation and transformation, quantify the transports of the major ocean current systems, and assess the variability of the vertical structure of the ocean and the role of eddy processes in the transport of heat and other properties.*

1 - INTRODUCTION

To unravel the ocean's role in global climate change, oceanographers desperately need long-term observations of ocean water properties, circulation intensity and patterns, and of the exchange of heat, freshwater, and momentum between the ocean and the atmosphere. Such records are notably scarce today. One treasured source of such data is the network of ocean weather stations (OWS) established after World War II (Figure 1). This array was augmented in 1954 by an oceanography-only station offshore from Bermuda, euphemistically termed Station S in honor of Henry Stommel who initiated the idea, or the Panuliris Station after the first ship to service the site (Michaels and Knap, 1996). Unfortunately, in 1981 the international OWS program ended. At present only OWS M, off Norway, is routinely occupied.

The demonstrated value of the Bravo and Papa time series has led to efforts to continue at least annual sampling at these sites. Research vessels, for example, have occupied one or more central-Labrador-Sea stations in 16 of the subsequent 23 years after 1973, though obviously without superannual-frequency resolution. Regular ship-supported sampling at Station S does continue. In addition, a small number of new long-term measurement programs have been recently initiated, e.g., Bermuda Atlantic Time Series (BATS) program co-located with Bermuda Testbed Mooring (BTM) program; Hawaii Ocean Time-series (HOT) program; European Station for Timeseries in the Ocean Canary Islands (ESTOC). Some sites are also being maintained at present with annual mooring technology (Bravo, Bermuda, ESTOC).

The OWS time series played a critical role in early efforts to build an understanding of the variability of the ocean and its response to atmospheric forcing. At present, just as we seek to develop an understanding of the ocean's role in climate variability, we find we lack the continuing long time series stations critically needed to support such work. Thus, we recommend that new long time series stations, which we call Ocean Observatories be established.

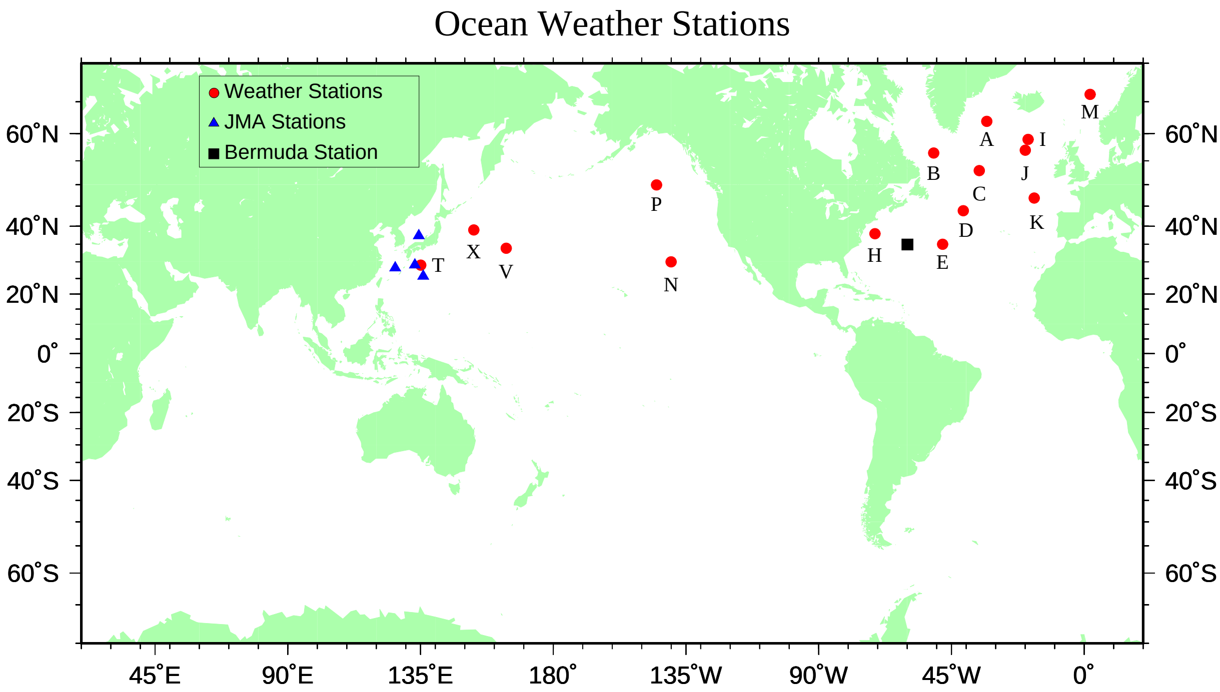


Fig. 1 - The historical Ocean Weather Stations (OWS) network

2 – BENEFITS OF EULERIAN TIMESERIES

Fixed-point Eulerian Ocean Observatories would represent one component of an ocean-atmosphere measurement network whose products will enhance our abilities to understand, model and predict global climate change. The Ocean Observatories concept complements other planned elements of the ocean observing system, such as that for a widely dispersed system of profiling quasi-Lagrangian floats (ARGO). Eulerian timeseries will, in particular, have the following benefits:

- Fixed point observing systems can provide information at high vertical and temporal resolution from the atmospheric boundary layer, down through the ocean mixed layer, to the abyss, on time scales of minutes to years. This type of information is not available from other types of observational systems. It is an ideal complement to systems which give spatial information.

- A large suite of sensors/types of measurements can be employed at fixed observatories, thus providing many linked variables at one place.

- In regions characterized by significant current, a ground-fixed measurement system can insure that continuous observations from a site are available. Observation of ocean features having small spatial scales may be more effectively carried out with coherent arrays of fixed instruments or integrating techniques between fixed instruments than e.g. by randomly seeded Lagrangian devices.

- Only at a fixed point station can autonomous/continuous measurements be combined over long times with in-situ sampling programs and high-accuracy analysis work requiring laboratory procedures, such as chemical, optical, and biological research. Thus, fixed-point stations provide a unique opportunity for multidisciplinary and interdisciplinary work, combining physical, chemical and biological observations.

- Fixed point observations made with periodically recovered and redeployed automatic measurement instruments may be corrected for sensor drift using post-recovery laboratory calibration data and occasional ship-based in situ measurements during site visits. Small climate change signals may thus be first detectable by ocean observatories.

- Fixed point observations can provide important reference/calibration information for freely drifting instruments (where the above calibration and in situ referencing is generally not possible) and for remote sensing data (wind stress and surface chlorophyll, salinity and other properties). In turn, the timeseries measurements can help relate observed changes in those surface properties to the underlying water column.

- Moored observatories are ideal for developing and testing new instrumentation (testbed concept), particularly when located within easy reach of coasts or islands. Some tested instruments may eventually be interfaced to drifters, floats, gliders, and AUVs .

3 – SCIENTIFIC OBJECTIVES

The measurement programs at the new Ocean Observatories would collect observations to begin a new set of long time series similar to those from the OWS. The objectives of establishing ocean observatories are to:

a) Investigate and monitor water mass formation or transformation
Ocean observatories would be established in key sites of water mass formation and/or transformation by air-sea interaction. Their observations aid in determining the depth of convection at a reference site, while simultaneous float data could be compared to give indications of its spatial variability and tomographic observations might provide the horizontal extent/average. From the meteorological data obtained by these stations, accurate air-sea fluxes will be estimated, which is one of the forcing functions for the water mass transformation. Another controlling factor, the initial (fall) stratification (buoyancy content) can be determined with surface-mooring techniques (see below). The change with time of ocean heat and fresh water content can be determined, and compared with the surface fluxes, this allows estimates of the horizontal advection/mixing. Altogether, such observation would provide insight into the mechanisms and variability of water mass transformation, and at the same time monitor changes at the origins of deep water masses and of elements of the thermohaline circulation. Links can thus be investigated with changes in these water masses or in the thermohaline circulation in other places of the ocean.

b) Establish air-sea flux reference sites

Well-instrumented surface moorings are recommended at a subset of locations in order to provide high quality, accurate reference data to be used to check, verify, and calibrate surface meteorological fields from models, remote sensing, and other in-situ measurements. Further, work in progress to upgrade the quality of the surface meteorology and air-sea fluxes on a global basis from the Volunteer Observing Ship (VOS) fleet is based on a strategy that will rely on the fixed reference sites. The reference sites will serve both as primary standards for quality control of the VOS data and as the basis for validating regional choices of flux formulae. The present drifting buoys provide a good example of how in-situ observations are used to calibrate satellite data; in their case, they provide the means to calibrate the AVHRR fields of SST. In addition to SST, the reference site surface moorings will provide surface winds, surface shortwave and longwave radiation, and rainfall for use in validating and calibrating remotely sensed values of these variables. (See also separate paper on surface fluxes and reference sites).

c) Measure the transport and variability of major current systems

At key sites, direct measurement of ocean currents is envisioned. The transport variability of important current systems is presently hardly known. Long term Eulerian measurements of e.g. surface and deep western boundary currents and of the dense overflows of Nordic Sea waters through the Denmark Straits and Faroe Bank Channel will help quantify changes in important elements of the climate system. Throughflow/outflow measurements will document the exchange (and its variability) between ocean basins or oceans and marginal seas, providing integral information on the basin average processes. Different approaches will be compared for such transport measurements, like boundary arrays of current meter moorings, dynamic height moorings on opposite sides of major ocean currents, acoustic transmissions or hydraulic reservoir height measurements. These data will prove valuable in estimating ocean heat and property fluxes and constraining models developed to extrapolate downward the remotely sensed fluctuations in sea level from altimetric satellites. Moreover, by instrumenting sites on opposite sides of ocean basins variations in the ocean's net meridional overturning circulation could be investigated.

d) Investigate the variability of the ocean’s interior

Moored velocity and water property measurements will be made of specific ocean regions and their associated eddy to long-term variability. Variability occurs on all time and space scales. Both the multi-annual and the eddy time scale pose a problem for current climate models. Such models cannot yet be run routinely in the "eddy resolving" mode, and eddy processes need to be parameterized. Field experiments will need to be designed and performed to achieve this goal. Some of the supportive field work will be focused on limited duration process experiments, but other elements will need to be sustained measurements programs, for example to document variability in eddy statistics. Efforts are also under way to assimilate statistical quantities into model. Fixed point, or Eulerian, measurements will be crucial for this. For the multi-annual timescale, very few observations of variability exist. The longest available record is of order one decade and there exist very few locations where currents have been observed for longer than 2 years over the water column. New technology is expected to permit durations of 5 years or longer and allow frequent transmission of data back to the lab. With this new capability we would propose to maintain moorings in a number of locations around the world to obtain a global picture of long term internal variability and its depth structure for comparison with that being obtained by the altimetric satellites.

e) Enable multidisciplinary and interdisciplinary research

The combination of physical, chemical and biological observations is a powerful argument for ocean observatories. A central theme for this work involves developing understanding of how synoptic-scale and annual-to-interannual variations in atmospheric forcing and ocean circulation, stratification, and water mass properties impact the ecosystem and biogeochemical properties and fluxes (e.g., nutrients, carbon dioxide, oxygen, and trace metals). Fixed-point timeseries observations can also serve as a reference and provide background information for multidisciplinary process studies and spatially distributed measurements.

4 – EXAMPLES FROM EXISTING TIMESERIES

The potential value of ocean observatories can be demonstrated by looking at results derived from the Ocean Weather Station records and from the few existing timeseries stations.

Surface meteorology and air-sea fluxes
While marine meteorological observations have long been obtained from merchant ships, the OWS time series are unique and valuable. Merchant ship reports are of lesser quality, do not provide time series at fixed points, and are biased by the avoidance by the ships when possible of severe weather. The 3-hourly OWS reports have provided the only means to produce time series of the exchange of heat at the surface in the open ocean that resolve the diurnal period. They have also provided the consistent, long-running time series needed to examine seasonal to interannual variability of the surface fluxes (e.g., the analysis of 11 years of data from OWS N in the eastern North Pacific by Ronca and Battisti, 1997).

Mixed-layer studies
The oceanographic data from these stations, having high temporal resolution relative to the seasonal cycle and the oceanic mesoscale, have also been used extensively. For example, much of the pioneering research on the ocean's surface mixed layer was based on data collected at Station Papa in the Gulf of Alaska (e.g. Denman and Miyake, 1973; Davis et al., 1981a,b). The upper ocean thermal data from the North Atlantic weather ships were used by Gill and Turner (1976) to intercompare a variety of seasonal thermocline models. More recently, Denman et al (1992) and Freeland et al. (1998) document significant freshening of the surface waters at Station Papa on inter-annual time scale. They speculate on the possible associations between the related increase in vertical stability and an observed decrease in surface nutrient concentrations.

Deep convection and long-term salinity changes
Upper-ocean salinity observations were collected at a subset of these weather ship stations. The suite of these stations in the subpolar and polar North Atlantic provided the means to allow recognition of the existence and decadal propagation of the Great Salinity Anomaly (Dickson et al., 1988) and its descendants (Belkin et al., 1998). More generally, description of the seasonal cycle of upper ocean salinity and its climatic change signal anomalies, has been thus far largely reliant on the weather ship data sets (Taylor and Stephens, 1980; Reverdin et al., 1997). Decadal-time scale variability of deep convection and water mass formation have been described using the observations from Stations Bravo (Lazier, 1980) and Mike (Østerhus et al., 1996) in the Labrador and Norwegian Seas respectively, and from Station S in the North Atlantic western subtropical gyre (Talley and Raymer, 1982; Talley, 1996). The interrelationships of these data form the core of Dickson et al's (1996) evidence for coordinated variation of deep convection in the North Atlantic possibly associated with the North Atlantic Oscillation.

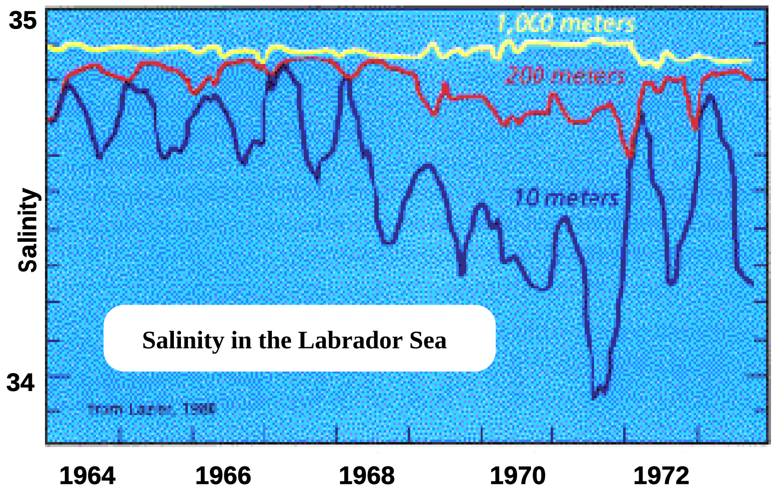


Fig.2 – Salinity evolution (10, 200, 1000m) showing convection variability at OWS Bravo (after Lazier, 1980)

Deep branch of the thermohaline circulation

Weather ship hydrography has also illuminated the cold limb of the meridional overturning circulation. Understanding this overturning system is a climate problem, for it is this circulation that dominates the poleward transport of heat by the ocean and the resulting heating of the mid-latitude, sub-polar and polar atmosphere it achieves. The stations Bravo and S data have been used together to deduce a time lag of about 6 years between the evolving deep convection produced water mass of the western subpolar gyre and signals at the base of the thermocline in the subtropics (Curry et al., 1998), defining the time scale for the communication pathway. An attempt to track the time lag signals farther south (Molinari et al., submitted) using deep western boundary current data near Abaco in the Bahamas suggests a 10-year lag, but the lack of high temporal resolution much limits the lag estimate from what could be done with weather ships - like sampling.

Deep interannual to decadal-scale water mass changes

At longer time scale, Joyce and Robbins (1996) discovered a 30-year warming trend in the deep water (1500-2500 m) offshore from Bermuda that, based on historical hydrographic stations near this site, may extend back in time to at least 1922. Curry et al. (1998) show that warming in this water at station S reversed in 1988, and with the subpolar source time series from Bravo showing cooling since 1980, and the documented time delay, these time series allows a prediction that station S will continue to cool at depth until at least 2005. Occasional basin scale hydrographic sections and surveys have shown the basin scale redistributions of heat and salt which accompany the station S record. The station S record, and the weather ship hydrography allows the interannual time scales involved to be identified and the general time evolution context to be sorted out, answering the question of whether sections widely separated in time can be differenced to produce meaningful images of long term oceanic warming/cooling and freshening/salinification.

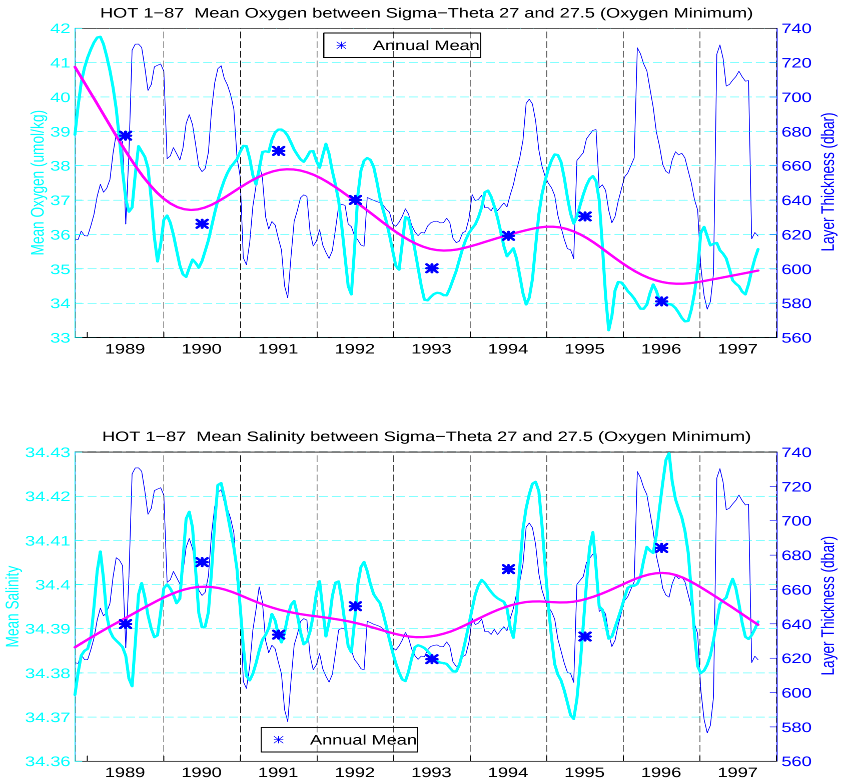


Fig.3 – Isopycnal oxygen (top) and salinity (bottom) variability at 700-1000m from the HOT station (near Hawaii).

Owing to the scarcity of the required timeseries observations, little evidence exists for such long-term variability at other sites around the world. An interesting study by Gordon (1982) and colleagues hints at decadal change in deep water properties within the Weddell Sea, possibly related to polynya formation. Another site sampled well for a decade now is the HOT station near Hawaii. Among other changes, it has revealed variability on density surfaces at 700-1000m depth in salinity (0.04psu changes), as well as a long-term trend in oxygen (fig.3). Such observations also caution against using the constancy of intermediate/deep water masses for calibrating float salinities.

Direct observations of ocean currents and transports

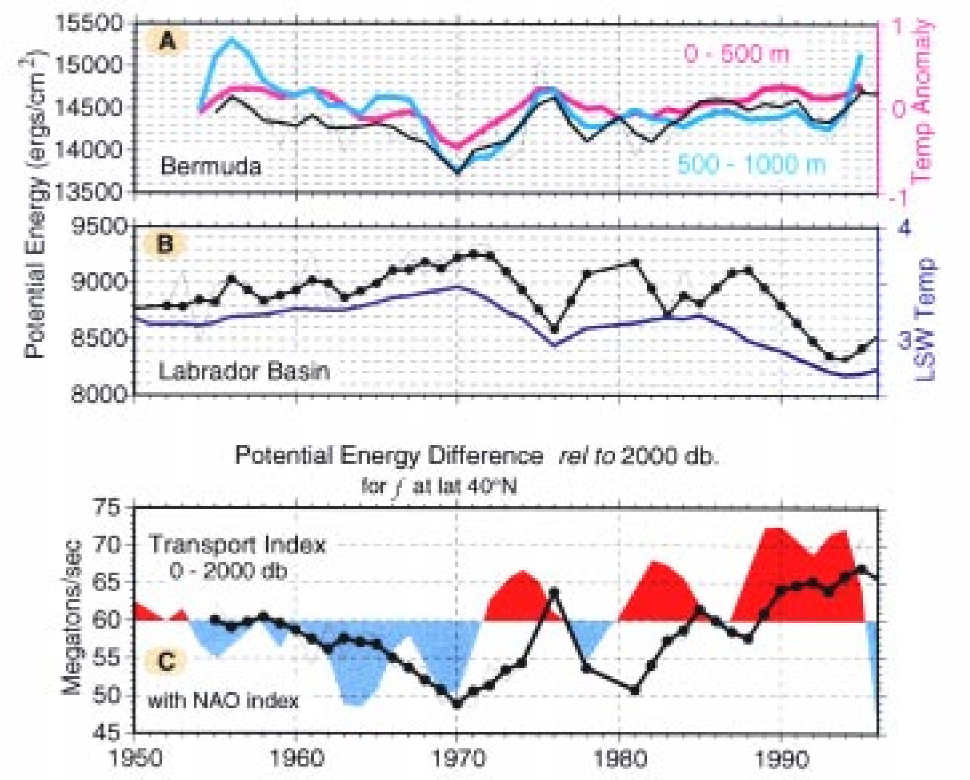
Perhaps our most prized and treasured pieces of information about the ocean circulation and its variability are based on Eulerian observations: long-term direct measurements of ocean currents and transports. The Florida Current is a good example, where also continuous cable measurements (Larsen 1992), supported by a program of ship-based velocity sampling, contributed to quantifying of the time-averaged volume transport of the Florida Current and its seasonal cycle. In turn, these results motivated a host of studies that worked to relate the observed transport to the dynamics of the wind-driven and thermohaline circulation of the North Atlantic (see Schmitz, 1996), and supported direct estimation of the N. Atlantic's meridional heat transport (e.g. Hall and Bryden, 1982). Estimation of the time-averaged net bottom water mass and temperature transport through Vema Channel by Hogg et al. (1982) has stimulated thinking about abyssal circulation dynamics and helped quantify the rate of turbulent dissipation and mixing at depth (e.g. Polzin et al., 1997). Extension of the Vema Channel record during WOCE has revealed bottom waters warming (Hogg and Zenk, 1997), though it is not yet clear if this is the manifestation of a long-term trend or of natural decadal-time-scale variability.

Studies of baroclinic circulation variability

Pairs of hydrographic time series stations spanning the full water column allow estimation of the time-dependent baroclinic circulation. Curry and McCartney (1998) have used the station S and station Bravo data to construct time series of upper ocean potential energy anomaly (PEA), Fig.4 A/B, with the difference series being an index of the net eastward oceanic flow passing between the two stations,

Figure 3 C. That flow occurs as the result of the confluence of the Gulf Stream and the Labrador Current and their combined eastward extension across the mid-latitude North Atlantic. The two PEA curves exhibit decadal variability, and tend to vary with opposing phase. The opposing phase translates into large baroclinic transport variability, from a low near 49 Sv at the end of a long period of low NAO index (weak westerlies) to a high of 67 Sv at the end of a long period of high NAO index (strong westerlies). It is expected that this +/- 14% fluctuation of baroclinic volume transport combines with concurrent fluctuations of heat content described by Sutton and Allen (1997) to yield a substantial fluctuation of ocean heat transport and potentially of oceanic heating of the overlying atmosphere.

Fig.4 – NAO and eastward north Atlantic transport index



Interdisciplinary studies

Interdisciplinary timeseries studies are now available which can target a variety of climate issues (e.g., Dickey, 1999). The ship-occupied station S and the nearby BATS (Bermuda - Atlantic Time-series Study) site, as well as the Bermuda Testbed Mooring (BTM) program, provide good examples, with data sets which enable sophisticated modeling of the system (e.g. Doney et al., 1998), ground-truthing of remotely sensed data (e.g., Deuser et al., 1990), and recognition of seasonal and interannual changes of climatically important quantities (e.g. carbon dioxide: Bates et al., 1996; primary production: Lorenz et al., 1992). Already, new scientific insights into interdisciplinary processes have resulted from concurrent, multi-sensor measurements from moorings. Examples include: the roles of seasonal and episodic forcing and eddies in increasing upper ocean nitrate and levels of primary productivity at mid- and high-latitudes (e.g., Dickey et al., 1998a; McNeil et al, 1999); monsoonal atmospheric and eddy forcing of productivity in the Arabian Sea (Dickey et al., 1998b), Figure 5; modulation of productivity in the equatorial Pacific through tropical instability waves, Kelvin waves, and El Nino/La Nina sequences (e.g., Foley et al., 1998); sediment resuspension via internal solitary waves and hurricanes (e.g., Dickey et al., 1998c); and variability in upper ocean heating caused by phytoplankton (e.g., Dickey et al., 1998b).

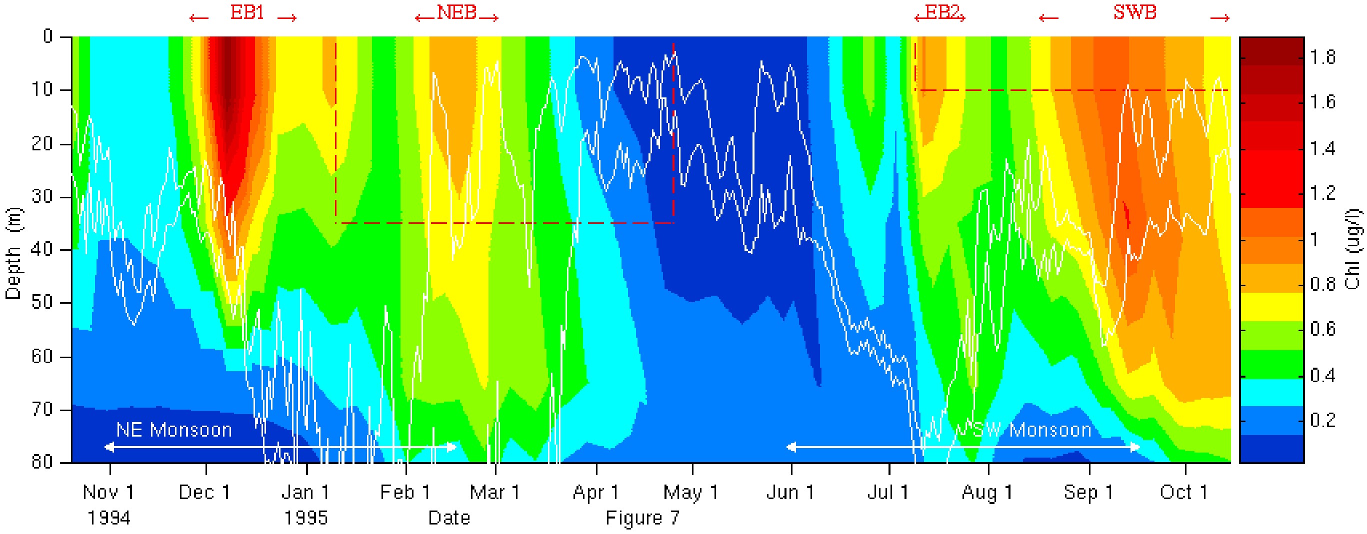


Fig.5– Chlorophyll (color) and mixed-layer depth (white) from mooring data in the Arabian Sea. Monsoon blooms (NEB,SWB) and eddy blooms (EB1, EB2) are marked.

5 – THE APPROACH

So-called Eulerian observations (measurements made at a fixed geographic site) are not new to ocean sciences. Almost all our theoretical structure is built in the Eulerian framework and we believe that the utility of moored measurements will remain very great. Two classes of oceanographic moorings have developed: surface moorings where buoyancy is provided by a surface float and subsurface moorings that have no surface expression. The use of subsurface ocean moorings to observe ocean currents and water properties dates to the 1960's. Surface moorings, that additionally provide a platform for meteorological sensors, are much older, but it wasn't until the 70's that reliable and accurate observations were possible. Both are now mature technologies, capable of sustained operation for long periods of time: 6 months or longer for surface moorings, up to two years for subsurface moorings. The development of a five-year-duration subsurface mooring with a telemetry to shore capability is anticipated. New mooring and instrumentation technology makes it possible to maintain ocean observatories at a fraction of the cost of the previous ocean weather stations.

Significant improvements in surface buoy technology made over the last 15 years have resulted in the ability to measure monthly mean net heat flux to better than 10 W m^{-2} and estimate the freshwater flux as well as the heat flux and wind stress. These buoys measure wind speed and direction, incoming shortwave radiation, incoming longwave radiation, relative humidity, air temperature, sea temperature, barometric pressure, and precipitation. The sensors perform reliably even in severe conditions and are typically deployed for periods of 6-9 months per setting. Data is both telemetered and recorded on board. Recent deployments of such buoys have demonstrated their ability to perform well in severe environments such as the Arabian Sea and to identify significant problems in the surface meteorology and fluxes from numerical weather predictions models. A few monitoring programs are also based on surface mooring technology. The ATLAS buoys presently forming an array in the equatorial Pacific

Ocean include surface meteorological sensors and a set of individual temperature sensors spanning the upper 500 m of the water column (Hayes et al., 1991). In similar fashion, surface moorings with discrete physical and biogeochemical oceanographic sensors are being maintained at stations offshore from Bermuda, Hawaii, and the Canaries respectively, providing high temporal resolution data which supplement and are supplemented by ship-based observation programs there (Dickey et al., 1998a; R. Lukas, personal communication, 1997; Llinas et al., 1994).

Subsurface moorings are subject to less stressful conditions and now routinely collect information for periods up to 2 years, without servicing. In the past 30 years WHOI, alone, has deployed almost 1000 subsurface moorings in all parts of the world's oceans. Information gathered from them has been used to characterize the temporal and spatial variability of the oceans with an emphasis on time scales less than a year or so. In some parts of the ocean, such as the Northwest North Atlantic, enough measurements have been made that it is also possible to construct schemes of the "mean" circulation and estimate the transport of important currents.

In addition to conventional discrete instruments used on these moorings, a new class of observing system is approaching operational status: moored profiling instruments. These devices, fitted with a suite of oceanographic sensors, move vertically along conventional mooring cables returning measurements of water properties and ocean currents at high vertical resolution (e.g. Doherty et al., 1998). Another approach, which is being developed, would use gliding profiling floats, programmed to maintain position like a fixed mooring. Use of one sensor suite reduces costs and simplifies sensor calibration issues, particularly when the instrument profiles to depths with stable, or slowly varying water properties (that thus provide in situ checks on the sensor readings). Current versions of these instruments are capable of making approximately 200 full-ocean-depth profiles per deployment; second generation instruments may double this. With these instruments, full-depth dynamic height profiles akin to those obtained from ships may be acquired. Addition of a bottom pressure sensor would allow monitoring of both barotropic and baroclinic fluctuations. The finescale velocity observations from these instruments facilitate study of low-frequency flows, eddy variability, and internal-wave motions.

Within the past decade, moorings have begun to be used to obtain chemical, optical, biological, and acoustical data in addition to the more common physical data (e.g., Dickey et al., 1998a, Dickey, 1999). A few examples of variables which can now be sampled from moorings include: nitrate concentration, dissolved oxygen, partial pressure of carbon dioxide, trace elements, primary productivity, scalar irradiance, spectral inherent and apparent optical properties, chlorophyll fluorescence, and size distributions of particles and zooplankton. Most variables can be sampled every few minutes. Durations of interdisciplinary moorings have typically been a few months to a year. The major constraint remains biofouling. However, new anti-biofouling methods are being developed and tested; encouraging results suggest that this impediment will be considerably less limiting in the future.

6 - PROPOSED OBSERVATORY SITES

The following is an initial list of possible sites for Eulerian timeseries stations (map shown in fig.6). This list will evolve as discussions proceed among those involved in studying the role of the oceans in climate, those in the remote-sensing and modelling communities, and those willing to deploy and maintain ocean observatories. Where known at the time of writing, the groups currently running or planning a station are listed.

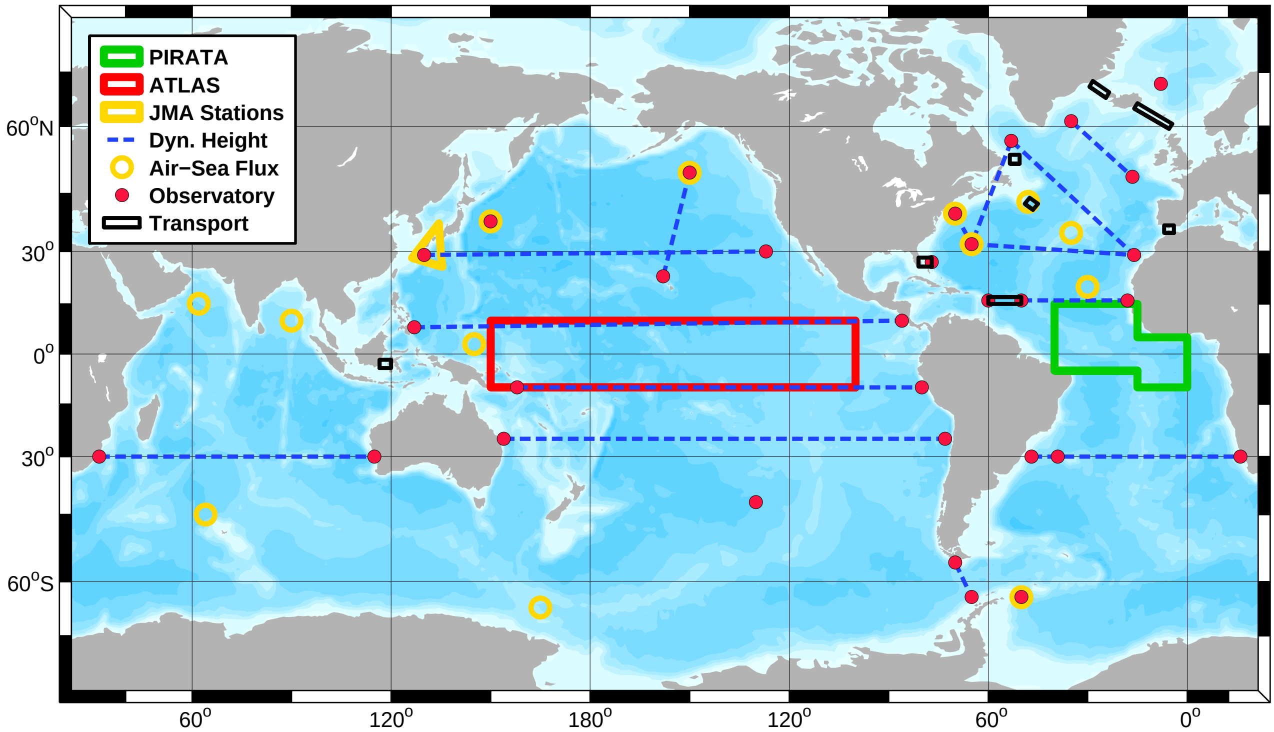


Fig. 6 – Map of proposed observatory sites, separately marking air-sea flux reference stations (yellow), transport sites (black boxes) and baroclinic dynamic height sections (blue dashed).

POSSIBLE ATLANTIC SITES:

lat lon	name/site	type/objective	run/pursued by
66N 2E	OWS M	properties of upper and deep waters in Nordic Seas	Norway
68N 30W to 60N 5W	Greenland/ Iceland/Scot-land overfl.	transports/properties of overflows from Nordic Seas	VEINS group IfM Kiel
57N 50W	OWS Bravo	- deep convection & water mass formation; - end point for baroclinic transport monitoring	BIO/UW IfM Kiel
53N 52W	Labrador Sea	transport of LSW export	IfM Kiel
61N 35W	Irminger basin	- convection and water mass formation - end point for baroclinic transport monitoring - interdisciplinary study site	IfM Kiel
49N16.5W	South of Rockall	- water mass transformation; - end point for baroclinic transport monitoring	SOC
43N 48W	Grand Banks	- Subpolar-subtropical exchanges - transport of warm and cold limb of MOC - Air-sea flux reference site	IfM Kiel WHOI
40N 70W	stationW/site D	- properties of deep western boundary current - end point for baroclinic transport monitoring - air-sea flux reference site	WHOI
32N 65W	Bermuda, BATS, BTM	- center of subtropical gyre, properties of 18C water - end point for baroclinic transport monitoring - air-sea flux reference site - interdisciplinary study site	many

35N 35W	Azores High	air-sea flux reference site	
29N 16W	Canaries (ESTOC)	- end point for baroclinic transport monitoring - interdisciplinary study site	ICCM, Bremen Univ., IfM Kiel
36N 5.5W	Gibraltar	transport/properties of Mediterranean/Atl. exchange	IfM Kiel, SIO
27N 77W	Abaco	end point for baroclinic transport monitoring	RSMAS
27N 79W	Florida Strait	transport of warm limb of MOC	PMEL/AOML
20N 30W	Trade Winds	air-sea flux reference station	
16N 60-50W	Lesser Antilles	- transport section for cold limb of MOC - end point for baroclinic transport monitoring	IfM Kiel
16N 18W	eastern trop.Atl.	- end point for baroclinic transport monitoring	
30S 39W	Vema Channel	transport/properties of AABW	WHOI, IfM Kiel
30S 47W	30 south line	end point for baroclinic transport monitoring	
30S 16E	30 south line	end point for baroclinic transport monitoring	
56S 70W	Drake Passage	end point for baroclinic transport monitoring	
63S 65W	Drake Passage	end point for baroclinic transport monitoring	
63S 50W	Weddell Sea	- transport/properties of newly formed bottom water - air-sea flux reference site	

POSSIBLE PACIFIC SITES

lat lon	**name/site**	**type/objective**	**run/pursued by**
50N 150W	OWS Papa	- upper ocean water mass changes - end point for baroclinic transport monitoring - air-sea flux reference site - interdisciplinary study site	
23N 158W	Hawaii (HOTS)	- upper ocean water mass changes - end point for baroclinic transport monitoring - interdisciplinary study site	SOEST
38N 150E	Kuroshio Extn.	- properties of subtropical mode water - air-sea flux reference site	KESS group JAMSTEC
29N 130E	Tokara Strait 30 north line	- transport/properties of Kuroshio - end point for baroclinic transport monitoring	
30N 127W	30 north line	end point for baroclinic transport monitoring	
8N 127E	10 north line	end point for baroclinic transport monitoring	
10N 86W	10 north line	end point for baroclinic transport monitoring	
10S 158E	10 south line	end point for baroclinic transport monitoring	
10S 80W	10 south line	end point for baroclinic transport monitoring	
3N 145E	warm pool	air-sea flux reference site	
25S 154E	25 south line	end point for baroclinic transport monitoring	
25S 73W	25 south line	end point for baroclinic transport monitoring	
42S 130W	subtrop.S.Pac.	air-sea flux reference site	
65S 165E	antarctic sector	air-sea flux reference site	

POSSIBLE INDIAN OCEAN SITES

lat lon	name/site	type/objective	run/pursued by
15N 62E	Arabian Sea	air-sea flux reference site	WHOI
3S 118E	Indones.passage	transport of Pacific-Indian exchange	LDEO
10N 90E	Bay of Bengal	air-sea flux reference site	
30S 32E	30 south line	end point for baroclinic transport monitoring	
30S 115E	30 south line	end point for baroclinic transport monitoring	
45S 64E	Kerguelen	air-sea flux reference site, eddy statistics	

7 – LINKS WITH OTHER PROGRAMS

ARGO: A close complementarity between the planned global float network ARGO and the Eulerian observatories is envisioned. The timeseries will provide good temporal resolution and statistics, plus a wide range of variables, while the float network and remote sensing will allow spatial coverage for a few basic quantities. The observatories can also provide reference or calibration information for the float observations.

DEOS: The global network of geophysical observing stations will require substantial investment and infrastructure/technology for large moorings around the globe. Such moorings could be used jointly for the geophysical applications and as oceanographic observatories (incl. air-sea flux measurements). In such cases, the logistical and financial burden could be shared.

Acoustic Tomography: Moored observatories can in some cases be used to carry tomographic instrumentation and thus acoustically sense the sections between several mooring sites. This way, at little extra cost a significant enhancement of the moored observing system would be possible. It seems that especially the Atlantic would lend itself to this approach, due to the density of planned observatory locations.

RAFOS floats: Observatory moorings could be equipped to carry RAFOS sound sources, providing "moorings of opportunity" for insonifying ocean basins. In fact, this may be merged with the tomography sources mentioned above, since efforts are under way to turn tomography sources into dual-purpose instruments transmitting also RAFOS signals.

REFERENCES

Bates, N.R., A.F. Michaels, and A.H. Knap. Seasonal and interannual variability of oceanic carbon dioxide species at the U.S. JGOFS Bermuda Atlantic Time-series Study (BATS) site. Deep-Sea Res. II, 43, 2-3, 347-383, 1996.

Belkin, I.M., S. Levitus, J.I. Antonov, and S.-A. Malmberg, "Great Salinity Anomalies" in the North Atlantic, Progress in Oceanography, 41(1),1998.

Curry, R.G., M.S. McCartney, and J.M. Joyce, Oceanic transport of subpolar climate signals to mid-depth subtropical waters. Nature, 391, 575-577, 1998.

Davis, R.E., R. deSzoeke, D. Halpern and P. Niiler, Variability in the upper ocean during MILE. Part I: The heat and momentum balances. Deep-Sea Res. 28A, 1427-1451, 1981a.

Davis, R.E., R. deSzoeke and P. Niiler, Variability in the upper ocean during MILE. Part II: Modeling the mixed layer response. Deep-Sea Res. 28A, 1453-1475, 1981b.

Denman, K.L. and M. Miyake, Upper layer modification at Ocean Station Papa: Observations and simulations. J. Phys. Oceanogr. 3, 185-196, 1973.

Denman, K.L., H.J. Freeland and J.F. Garrett, Climate change in the subarctic Pacific Ocean, Part 1: Atmospheric and oceanic evidence. North Pacific marine science Organization (PICES), PICES Scientific Workshop, Seattle, 10-13 Dec. 1991, Part A - Summary Report and Review Papers, 1992.

Deuser, W.G., F.E. Muller-Karger, R.H. Evans, O.B. Brown, W.E. Esaias and G.C. Feldman. Surface-color and deep-ocean carbon flux: how close a connection? Deep-Sea Res., 37, 1331-1343, 1990.

Dickey,T., Instruments and New Technologies, in book Assessment of the State of Marine Science and Its Contribution to Sustainable Development, International Oceanographic Commission, submitted, 1999.

Dickey, T., D. Frye, H. Jannasch, E. Boyle, D. Manov, D. Sigurdson, J. McNeil, M. Stramska, A. Michaels, N. Nelson, D. Siegel, G. Chang, J. Wu, and A. Knap, Initial results from the Bermuda Testbed Mooring Program, Deep-Sea Res. I, 45, 771-794, 1998a.

Dickey, T., D. Frye, J. McNeil, D. Manov, N. Nelson, D. Sigurdson, H. Jannasch, D. Siegel, A. Michaels, and R. Johnson, Upper ocean temperature response to Hurricane Felix as measured by the Bermuda Testbed Mooring, Mon. Wea. Rev., 126, 1195-1201, 1998b.

Dickey, T., G. Chang, Y. Agrawal, A. Williams, 3rd, and P.S. Hill, Sediment resuspension in the wakes of Hurricanes Edouard and Hortense, Geophys. Res.Lett., 25, 3533-3536, 1998c.

Dickson, R.R., J. Lazier, J. Meincke, P.Rhines and J. Swift, Long-term coordinated changes in the convective activity of the North Atlantic. Prog. Oceanogr., 38, 241-295, 1997.

Doherty, K.W., D.E. Frye, S.P. Liberatore and J.M. Toole, A moored profiling instrument. J. Atmos. Oceanic Tech., submitted, 1998. Freeland, H.J. K.L.

Doney, S.C., D.M. Glover, and R.G. Najjar. A new coupled, one –dimensional biological-physical model for the upper ocean: Applications to the (BATS) site. Deep-Sea Res. II, 43, 591-624, 1998.

Foley, D., T. Dickey, M. McPhaden, R. Bidigare, M. Lewis, R. Barber, C. Garside, and D. Manov, Time-series of physical, bio-optical, and geochemical properties in the central equatorial Pacific at 0, 140 W February 1992-March 1993, Deep-Sea Res. II, 44, 1801-1826, 1998.

Dickson, R.R., J. Meincke, S.-A. Malmberg, and A.J. Lee, The "Great Salinity Anomaly" in the northern North Atlantic 1968 - 1982. Prog. Oceanogr., 20, 103-151, 1988.

Dickson, R.R., J Lazier, J. Meincke, P. Rhines, and J. Swift, Long-term coordinated changes in the convective activity of the North Atlantic. Prog. Oceanogr., 37, 207-262, 1996.

Gill, A.E., and J.S. Turner, A comparison of seasonal thermocline models with observation. Deep-Sea Res. 23, 391-401, 1976.

Gordon, A.L. Weddell Deep Water Variability. J. Mar. Res., 40 suppl. 199-217, 1982.

Hall, M.M., and H.L. Bryden, Direct estimates and mechanisms of ocean heat transport. Deep-Sea Res. 29, 339-359, 1982.

Hayes, S.P., L.J. Mangum, J. Picaut, A Sumi, and K. Takeuchi, TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. Bull. Amer. Meteorological Soc., 72, 339-347, 1991.

Hogg, N., P. Biscaye, W. Gardner and W.J. Schmitz, Jr., On the transport and modification of Antarctic Bottom Water in the Vema Channel. J. Mar. Res. 40 suppl, 231-263, 1982.

Hogg, N.G. and W. Zenk, 1997: Long-period changes in the bottom water flowing though Vema Channel. J. Geophys. Res. 102, 15639-15646.

Joyce, T.M., and P. Robbins, The long-term hydrographic record at Bermuda. J. Climate, 9, 3121-3131, 1996.

Karl, D.M., and R. Lukas, The Hawaii Ocean Time-series (HOT) program: Background, rationale and field implementation. Deep-Sea Res. II, 43, 129-156, 1996.

Larsen, J.C., Transport and heat flux of the Florida Current at 27N derived from cross-section voltages and profiling data: theory and observations. Phil. Trans. R. Soc. Lond. A, 338, 169-236, 1992.

Lazier, J.R., Oceanographic conditions at O.W.S. Bravo, 1964-1974. Atmos. and Oceans, 18, 227-238, 1980.

Llinas, O., A. Rodriguez de Leon, G. Siedler and G. Wefer, The ESTOC time series station started operation. International WOCE Newsletter, 17, 20- 21, 1994.

McNeil, J. D., H. Jannasch, T. Dickey, D. McGillicuddy, M.Brzezinski, and C. M. Sakamoto, New chemical, bio-optical, and physical observations of upper ocean response to the passage of a mesoscale eddy, accepted, J. Geophys. Res., 104, 15,537-15,548, 1999.

Michaels, A.F., and A.H. Knap, Overview of the U.S. JGOFS Bermuda Atlantic Time-Series study and the Hydrostation S program. Deep-Sea Res. Part II, 43, 157-198, 1996.

Molinari, R.L., R.A. Fine, W.D. Wilson, R. Curry, J. Abell, and M. McCartney, The arrival of recently formed Labrador Sea Water in the deep western boundary current at 26.5o N. Geophysical Res. Letters., submitted.

Østerhus, S., T. Gammerlsrõd, and R. Hogstad, Ocean weather ship station M (66o N, 2o E): The longest homogeneous time series from the deep ocean. International WOCE Newsletter, 24, 31-33, 1996.

Polzin, K.L., J.M. Toole, J.R. Ledwell and R.W. Schmitt, Spatial variability of turbulent mixing in the abyssal ocean. Science, 276, 93-96, 1997.

Reverdin, G., D. Cayan, and Y. Kushnir, Decadal variability of hydrography in the upper northern North Atlantic in 1948-1990. J. Geophy. Res., 102, 8505-8531, 1997.

Ronca, R. E. and D. S. Battisti, Anomalous sea surface temperatures and local air-sea energy exchange on intra-annual time scales in the northeastern subtropical Pacific, J. Climate, 10, 102-117, 1997.

Schmitz, W.J., Jr., On the World Ocean Circulation: Volume I, Some global features /North Atlantic Circulation. Woods Hole Oceanographic Institution Technical Report WHOI-96-03, 141 pp, 1996.

Sutton, R.T., and M.R. Allen, Decadal Predictability of North Atlantic sea surface temperature and climate, Nature, 388, 563-567, 1997.

Talley, L. and M.E. Raymer, Eighteen degree water variability. J. Mar. Res. 40, suppl. 757-775, 1982.

Talley, L., North Atlantic circulation and variability. reviewed for the CNLS conference. Physica D, 98, 625-646, 1996.

Taylor, A.H., and J.A. Stephens, Seasonal and year-to-year variations in surface salinity at the nine North-Atlantic Ocean Weather Stations. Oceanol. Acta, 3, 421-430, 1980.