FOAM, GODAE and WOCE

Michael Bell [mike.bell@metoffice.com], Rosa Barciela, Adrian Hines, Paul Holland, Matt Martin, Michael McCulloch, David Storkey
Met Office, UK

A major objective for the first decade of this century is to develop a broad range of oceanographic services of value to government agencies, the general public and commercial activities. The Global Ocean Data Assimilation Experiment (GODAE) aims to contribute to this objective by providing a demonstration of the value of operational ocean forecasts for a wide range of applications. The GODAE partners will build on the technological achievements of WOCE in oceanographic measurements, modelling and data assimilation. A major aim of GODAE is to develop an operational ocean monitoring system, justified by the services it supports, which is needed to underpin the further development of oceanographic science and research programs such as CLIVAR. The Forecasting Ocean Assimilation Model (FOAM) system is one of the UK's contributions to GODAE. It is used on a daily basis within the Met Office's operational suite to provide oceanographic forecasts to 5 days ahead and for multi-year hindcasts to support seasonal forecasting and system development. It is usually driven by fluxes from Numerical Weather Prediction (NWP) systems and assimilates temperature and salinity profile, surface temperature, surface height and sea-ice concentration data. High resolution limited area FOAM systems are nested within lower resolution larger area systems. Daily data from a pre-operational North Atlantic model on a grid with 12 km horizontal spacing are freely available for research from http://www.nerc-essc.ac.uk/las. Exploration of results from the FOAM system can assist the development of ocean models for climate simulation. One year integrations of present ocean models are sufficient to reveal significant model drifts. Diagnostics from data assimilation systems can be used to study these. The nested FOAM configurations can be used to explore the effect of high resolution on model performance in a cost effective manner. Much of the development of atmospheric models has been driven by attention to the performance of NWP forecasts. Similar attention can be expected to improve ocean models over the next decade.

BUILDING ON WOCE ACHIEVEMENTS: CLIVAR RESEARCH IN THE ATLANTIC, PACIFIC AND SOUTHERN OCEANS

Roberta Boscolo [rbos@iim.csic.es], John Gould, Mike Sparrow
International CLIVAR Project Office, UK

WOCE offered for the first time a synoptic view of the global ocean circulation and the distribution of properties. These provide a firm foundation for understanding the role of the ocean in the climate system and a baseline against which decadal-scale ocean variability (human-induced or natural) can be measured. CLIVAR, the Climate Variability and Predictability study of WCRP started in 1995 with an ambitious plan to explore coupled climate variability and predictability at global scales from seasons to centuries. This includes the determination of the mechanisms of variability and predictability of climate fluctuations on Decadal-to-Centennial (DecCen) time-scales with a special emphasis on the role of the oceans in the global coupled climate system.

CLIVAR DecCen is now in its implementation phase and has identified five principal research areas that build on the strong foundations of WOCE global activities:

- Decadal ocean and atmosphere variability in the North Atlantic region involving the NAO
- Patterns of decadal variability originating in the tropical Atlantic.
- DecCen variability and the possibilities of rapid climate change associated with the Atlantic thermohaline circulation.
- Decadal variability and predictability in the Pacific and Indian Ocean basins, and its relationship with ENSO and teleconnections.
- Variability of the ACC, ocean overturning and water mass transformations in the Southern Oceans.

The implementation of CLIVAR in the three ocean basins are coordinated (and sometimes initiated) by three panels of worldwide experts. Ongoing and planned CLIVAR activities in the three ocean sectors are presented with particular reference to how these build on WOCE. We hope

SUBPOLAR MODE WATER AND THE NORTH ATLANTIC CURRENT; SUBPOLAR CIRCULATION AND SST CHANGES ASSOCIATED WITH THE NORTH ATLANTIC OSCILLATION

Maria Flatau[1], Lynne D. Talley[2], Pearn P. Niiler[2], Elena Brambilla[2] [ebrambilla@ucsd.edu]
[1]Naval Research Laboratory; [2]Scripps Institution of Oceanography

The northeastward extension of the North Atlantic Current (subarctic front) divides the Subpolar Mode Water into eastern and western portions. Surface flow, based on Lagrangian drifters, altimetric geostrophic velocities, and dynamic height, is generally northeastward throughout the eastern subpolar region. Thus the surface SPMW in the eastern North Atlantic feeds the Iceland-Faroe Front and the Norwegian Current but not the region west of the subarctic front. The SPMWs that feed the Labrador Sea originate from SPMWs on the north/west side of the subarctic front. The connection of these SPMWs to the thermocline waters below the sill depth of the Iceland-Faroe Ridge and hence below the eastern SPWMs is investigated using historical synoptic hydrographic sections supplemented by some subsurface float data. Throughout the subpolar gyre, the thickest SPMW layers are associated with topography and/or strong fronts. A particularly homogeneous pool of western SPMW is found along the Rekyjanes Ridge. The surface circulation that carries the SPMWs is documented using Lagrangian surface drifters. Time dependence associated with the North Atlantic Oscillation is evident in the surface velocity field, and is documented, along with changes in SST, for the switch in the NAO index from positive in the early 1990s to negative in 1995/1996. During the positive NAO years, with stronger westerlies, the northeastward flow in the North Atlantic Current was stronger and the Irminger Sea cyclonic gyre became more intense. The subarctic front was sharper and located farther east. SST gradients intensified in the North Atlantic Current, Irminger Basin and east of the Shetland Islands during the positive NAO phase. SST differences between positive and negative NAO years were consistent with changes in air-sea heat flux and SST advection as diagnosed from the drifters.

A 32°S INDIAN OCEAN TRANSECT, MARCH-APRIL 2002. CHARLES DARWIN CRUISE 139

H. Bryden[1] [hlb@soc.soton.ac.uk], L. Duncan[1], S. Cunningham[1], B. King[1], L. Beal[2], R. Sanders[1], A. Rios[3], M. Alvarez[3], J. Bullister[4]
[1]Southampton Oceanography Centre, UK; [2]Scripps Institution of Oceanography; [3]IIM, Spain; [4]PMEL

A new hydrographic section was taken across 32°S in the Indian Ocean during March-April 2002 aboard RRS Charles Darwin. The two primary objectives of this work were to measure the meridional overturning circulation and to quantify the decadal changes in water mass properties by comparison with earlier sections across 32°S in 1936, 1965 and 1987 (see McDonagh et al. poster). A total of 146 CTD/LADCP stations were sampled across the southern boundary of the Indian Ocean between South Africa to Australia during the austral autumn (March-April) of 2002. Hydrographic sections from this transect will be presented. In addition to high quality temperature and salinity profiles from the CTD, water samples from a 24-bottle rosette were analysed for salinity, dissolved oxygen and inorganic nutrients at each station. In addition water samples were collected and analysed onboard ship for CFCs, pH and alkalinity and were collected for shore-based analyses for He/Tr and organic nutrients. Full depth velocity measurements were made at every station by as many as three ADCPs mounted on the rosette frame. Throughout the cruise velocity data in the upper few hundred meters of the water column were provided by an ADCP mounted in the ship's hull. In addition, 25 Argo floats were deployed. This coast-to-coast, zonal data set represents the highest resolution and most comprehensive of its kind in this region.

INTERMEDIATE DEPTH CIRCULATION OF THE PACIFIC AND INDIAN OCEANS

Russ Davis [rdavis@ucsd.edu]
Scripps Institution of Oceanography

As part of WOCE, 523 autonomous subsurface floats were deployed in the South Pacific and Indian Oceans and the adjoining Southern Ocean to measure circulation near 950 meters depth. Maps of the absolute intermediate-depth circulation based on over 2650 years of velocity measurements from these and other deployments will be shown. Objective methods of analyzing these data will be compared. Examples of flow inferred from hydrographic sections will be compared with measured flow. Velocity variability implies a map of lateral eddy variability. Coupling lateral diffusivities with measured flow allows the processes leading to mid-depth property distributions to be examined.

TESTING THE MID-DEPTH CIRCULATION IN ECCO OCEAN ESTIMATES

Russ Davis[1] [rdavis@ucsd.edu], Detlef Stammer[1], Tong Lee[2]
[1]Scripps Institution of Oceanography; [2]Jet Propulsion Labratory

Improved model physics, better surface forcing fields and higher numerical resolution have made ocean circulation models more accurate. In addition, data assimilation has improved the agreement of model simulations with observations and provides a rational procedure for model testing using both the data that are assimilated and withheld information. Most data used for assimilation are satellite altimetry and temperature profiles from XBTs and profiling floats, data that are most descriptive of the upper ocean. In this study we use absolute mid-depth velocities from WOCE floats as independent data to test the results from ECCO ocean circulation estimates at depths removed from the majority of assimilated data.

The test will be performed at several stages of the assimilation: Comparisons of float data with adjoint and Kalman-filter models having nominal resolution of 1° to 2° generally show mean flows of generally similar shape but with the measured field being significantly stronger. Some high-resolution simulations show zonal flows that cannot be identified in the float data. Results from runs with and without insitu data will be used to identify their impact on the estimated mean flow field. Although the float measurement density is marginal for resolving variability of narrow currents, comparisons with annual and specific interannual variability is possible.

THE FRAM MODEL OF THE SOUTHERN OCEAN

D. J. Webb[1], B. A. de Cuevas[1] [bac@soc.soton.ac.uk], A. C. Coward[1], K. Doos[2], D. Stevens[3], N. Wells[1], and the remainder of the FRAM group
[1]Southampton Oceanography Centre, UK; [2]MISU, Stockholm University, Sweden; [3]University of East Anglia, UK

The Fine Resolution Antarctic Model (FRAM) was the first high-resolution model of the Southern Ocean and provided many new insights into the physical oceanography of the region. Here we review a number of the main results from FRAM, including the zonal momentum balance, the overturning stream function, the Deacon Cell, the heat and fresh water fluxes due to eddies and the mean flow, the vorticity balance and the topographic steering of the major large scale flows in the region.

THE USE OF AUTONOMOUS UNDERWATER GLIDERS TO SURVEY OCEAN CIRCULATION

Charles C. Eriksen [eriksen@u.washington.edu]
University of Washington

Much of the WOCE observational effort was dedicated to attempting a global description of ocean circulation, since it was recognized that the resources required to observe the seasonal and interannual variability were unavailable. Long range autonomous underwater vehicles offer the prospect of affordably observing these temporal aspects of subsurface structure. Buoyancy driven gliders can regularly survey ocean circulation at a small fraction of the cost incurred by ships and moorings, yet with much higher resolution and greater coverage in space and time.

Gliders are small, reusable, hand-launchable vehicles that sample the ocean along slanting paths at about half a knot. They have ranges of several thousand kilometers and mission durations of many months or more. They send the measurements they collect and receive instructions via satellite links and navigate by dead reckoning between GPS fixes acquired at the surface. In addition to sampling temperature and salinity, they may also sample other variables electronically, such as dissolved oxygen, chlorophyll fluorescence, and optical backscatter. Because their flight paths through the water can be calculated from knowledge of their buoyancy, pitch angle, and heading, they also return estimates of transport over the depth to which they dive. The transport estimates provide a reference for geostrophic shear, solving the principal problem that has faced hydrographers for more than a century.

One such long range vehicle, Seaglider, has recently been collecting sections across the eastern boundary current system off the Washington coast. The estimated cost of collecting tidally resolved, 1-2 m resolution sections of the upper 1 km of the ocean is about US $2/km of section. About half the cost is for real time data transmission. Seaglider transmits about 125 kbytes daily at a cost of about US $20. Examples of transport estimates and hydrographic sections at the eastern boundary near the North Pacific subtropical/subpolar gyre boundary will be given.

SEASONAL-TO-INTERANNUAL VARIABILITY OF THE OCEAN DURING WOCE ESTIMATED BY THE ECCO ROUTINE GLOBAL OCEAN DATA ASSIMILATION SYSTEM

Ichiro Fukumori [if@pacific.jpl.nasa.gov], Benyang Tang, Tong Lee, Dimitris Menemenlis, Zhangfan Xing, Benny Cheng, Lee-Lueng Fu
Jet Propulsion Laboratory

Seasonal-to-interannual variability is analyzed using WOCE observations in conjunction with products of a global ocean data assimilation system (ECCO, Consortium for "Estimating the Circulation and Climate of the Ocean"). The assimilation products help interpret the near decade-long WOCE observations placing them in context with seasonal-to-interannual variability, such as those associated with ENSO and the phase transition of PDO. Particular focus is placed on variability of the upper ocean in the Pacific and Indian Oceans. The model equivalent of WOCE hydrography is compared with that from observations. Seasonal-to-interannual variability is analzyed by examining changes in the hydrographic structure and their associated variabilities in transport. The model's coherent fields allow budgets of mass, heat, and salt to be analyzed and the origin and fate of water masses evaluated.

The data assimilation system is based on a near-global primitive equation model of high resolution (1° telescoping to 0.3° with 10-m near surface layers). The assimilation is based on a hierarchy of approaches that consists of a Green's function method, approximate Kalman filter and smoother, and the adjoint method. Measurements from satellite altimetry (TOPEX/POSEIDON) and in situ hydrography (CTDs and XBTs) are assimilated on a routine basis. Analyses are regularly updated and are available via a Live Access Server at http://www.ecco-group.org/las.

NUTRIENT DATA CALIBRATION FOR THE INDIAN OCEAN WHP ONE-TIME SURVEY

L. I. Gordon[1] [lgordon@coas.oregonstate.edu], C. W. Mordy[2], G. C. Johnson[2], A. A. Ross[1], J. C. Jennings, Jr.[1], J. Johnson[3]
[1]Oregon State University; [2]NOAA/PMEL; [3]Montana State University

We assess the quality of the WHP nutrient data sets in the Indian Ocean and derive corrections for individual cruise legs to make the basin-wide dataset as precise and internally consistent as possible. Two analyses were completed: an estimation of systematic errors inherent in the analytical protocol suggested for the WHP and JGOFS on the Pacific Ocean work, and an analysis of four to ten stations the Indian Ocean data where cruise legs crossed or overlapped. The number of stations depended on several factors including depth, distance from the intersection, and coherence of T-S plots. Data below 2500 m were plotted vs. sigma-3; data from each cruise leg were fitted with a LOESS function and interpolated to 25 evenly spaced sigma-3 levels. At each level, we calculated the percent difference (ca. ratios) between the two legs.

To develop an internally consistent, overall nutrient data set, we applied a weighted least squares model developed by G.C. Johnson et al. This model adjusts each cruise leg to minimize differences at station reoccupations in a least squares sense. Adjustments were determined by solving a set of linear equations per cruise leg. A data covariance matrix was used to weight equations by the uncertainty at each crossover, and by the connectedness of each crossing.

While the majority of offsets at reoccupations were within WOCE specifications, the WLSQ adjustments eliminated most of the large differences observed at some reoccupations. Ultimately we bring about 90% of the salinity discrepancies to within 1 ppm, and 90% of nutrient discrepancies to within 1% repeatability.

At this writing, the mean differences and rms deviations from the averaged differences between reoccupations examined exhibit a consistent, small dependence upon latitude, higher to the south. Thus, although most of the differences observed arise in analytical error, there might be small contributions from real, oceanographic variability. Regions closer to the energetic Southern Ocean

A NEW CLIMATOLOGY OF THE WORLD OCEAN BASED ON THE WOCE HYDROGRAPHIC DATA

Viktor Gouretski [gouretski@bsh.de], Klaus Peter Koltermann, Kai Jancke
Federal Maritime and Hydrographic Agency, Hamburg, Germany

In the frame of the WOCE Atlantic Hydrographic Atlas project a new World Ocean climatology was constructed using an extensive composite hydrographic dataset that includes both historical data (mostly from the NOAA WOD98 CDROM) and WOCE observations. All the original data were statistically quality checked to eliminate random errors, followed by a procedure to calculate systematic biases in the data. WOCE hydrographic data (along with selected historical data) were crucial to construct a reference subset of adjusted data against which the rest of historical data was checked. The resulting composite quality controlled and adjusted dataset provides the basis for an optimal interpolation of oceanographic parameters. Gridded fields are computed for temperature, salinity, dissolved ocean, and nutrients on a regular 0.5° grid. Along with the all data mean fields at 45 levels seasonal climatologies are also available for the upper 250 meters. Unlike the existing World Ocean Climatology, WOD98, spatial interpolation of the original data is performed on local isopycnal surfaces. This has an important advantage compared with the interpolation on isobaric levels in that no artificial water masses are produced and sharper gradients are preserved. The interpolation algorithm also guarantees the hydrostatic stability of the gridded density profiles. Optimal interpolation for closed or semiclosed oceanic basins is performed separately for the neighbouring open ocean areas. For the first time gridded fields of temperature and salinity are included for the Caspian Sea.

NEW TECHNIQUES FOR MEASURING RAINFALL FROM ABOVE AND BELOW

G. D. Quartly, T. H. Guymer [thg@soc.soton.ac.uk], M. A. Srokosz, K. G. Birch
Southampton Oceanography Centre

An improved knowledge of the precipitation field is clearly important for studies of the atmosphere-ocean freshwater flux, and the TRMM satellite has been launched with this aim in mind. This poster describes two other techniques for rain detection and measurement which have matured during the past decade. The first uses the attenuation observed by the dual-frequency TOPEX altimeter, which is a nadir-viewing radar system that predates TRMM by 5 years, but lacks the swath capability of the later instrument. The precipitation climatology derived from 10 years of TOPEX data is discussed, with special emphasis being given to the changes in the Pacific precipitation patterns during the 1997/98 El Niño. With the successful launch of further dual-frequency altimeters (Envisat and Jason-1) a long-term dataset should be guaranteed. We will also briefly discuss the validation of TOPEX's rain measurements, especially concerning its ability to resolve finer scale structures than passive microwave instruments can.

The second technology discussed is the use of Acoustic Rain Gauges (ARGs) to infer rain rate from the ambient sound levels noted below the surface. The poster will reprise the scientific methodology and the technological developments. In particular we will cover the buoy construction and testing program at Southampton Oceanography Centre, as the trials have developed from inshore and coastal locations to more exposed sites. Such local rain sensors would not only be useful for validating satellite measurements, but can also resolve the diurnal variations that are not sampled by polar-orbiting satellites. ARGs in combination with satellite remote-sensing will be able to deliver improved monitoring of the atmosphere-ocean freshwater flux, whose variability may be critical for the thermohaline circulation.

AN EFFICIENT EXACT ADJOINT OF THE PARALLEL MIT GENERAL CIRCULATION MODEL, GENERATED VIA AUTOMATIC DIFFERENTIATION

Patrick Heimbach[1] [heimbach@mit.edu], Chris Hill[1], Ralf Giering[2]
[1]Massachusetts Institute of Technology; [2]FastOpt, Hamburg, Germany

We describe computational aspects of automatic differentiation applied to global ocean circulation modeling and state estimation. The task of minimizing a cost function measuring the ocean simulation vs. observation misfit is achieved through efficient calculation of the cost gradient with respect to a set of controls via the adjoint technique. The adjoint code of the parallel MIT general circulation model is generated using TAMC or its successor TAF. The adjoint can be generated for a variety of configurations, including different mixing schemes such as KPP and GM, time-varying surface fluxor atmospheric state controls, and open boundary controls. To achieve a tractable problem in both CPU and memory requirements, in the light of control flow reversal, the adjoint code relies heavily on the balancing of storing vs. recomputation via the checkpointing method.Further savings are achieved by exploiting self-adjointedness of part of the computation. To retain scalability of domain decomposition based parallelism, hand-written adjoint routines are provided. These complement routines of the parallel support packageto perform corresponding operations in reverse mode. A unique feature of the TAF tool which enables it to dump the adjoint state and restart the adjoint integration is exploited to overcome batch execution limitations on HPC machines for large-scale ocean and climate simulations. The size of a typical adjoint application is illustrated for the global ocean state estimation problem. Results for a sensitivity study and an estimation problem are given by way of example.

ON THE SALINITY MINIMUM AT 32°S IN THE PACIFIC

Daniele Iudicone[1] [daiudi@lodyc.jussieu.fr], Gurvan Madec[1], Sabrina Speich[2]
[1]Université Pierre et Marie Curie, France; [2]Laboratoire de Physique des Océans, France

A global ocean circulation model (ORCA2-OPA), which is coupled to a sea ice model, has been used to examine the origins of the subsurface salinity minimum observed at 32°S in the Pacific Ocean, and to describe its relationship to recently formed Antarctic Intermediate Water (AAIW). We have used a 1500 year simulation with the ocean model, in conjunction with Lagrangian trajectory diagnostics to determine the pathways and watermass contribution to AAIW formation. Two mechanisms for AAIW formation have been previously proposed in the literature: a circumpolar mechanism whereby the northward export of freshwater occurs with relative zonal uniformity, and a local mechanism whereby the export for the Pacific occurs mainly near the Chilean coast. In the model, the AAIW is formed by waters flowing north of the Antarctic Circumpolar Current (ACC), entering the Southern Ocean essentially in the Pacific and the Indian sectors as western boundary currents. The freshwater exchange occurs along the sub-polar front. The northward diversion occurs to the southeast of the Chilean coast, where the along-path absolute minimum in salinity is found, without a local ventilation of this layer. The model's potential vorticity field is found to be consistent with the in situ potential vorticity field. In addition, as an extension of the model validation exercise, the model results have given insights into WOCE hydrographic fields.

WATER MASSES TRANSFORMATIONS AND FRESHWATER TRANSPORT IN THE SOUTHERN OCEANS

Daniele Iudicone[1] [daiudi@lodyc.jussieu.fr], Gurvan Madec[1], Bruno Blanke[2], Sabrina Speich[2]
[1]Université Pierre et Marie Curie, France; [2]Laboratoire de Physique des Océans, France

We have used a 1500-year simulation with a global ocean model (ORCA2-OPA), which includes sea ice, and lagrangian diagnostics to study watermass transformation processes occuring south of 30S. The contributions due to air-sea interaction and interior diapycnal processes have been considered separately. The geographical distribution of the upwelling of deep waters and of subduction/obductions processes is presented. A comparison of the model results with published inverse calculations using WOCE data is included. Using 30°S as a reference, both the origins and fate of the watermasses crossing this latitude are described quantitatively. Special attention is given to the processes controlling formation of the salinity minimum associated to the Antarctic Circumpolar Current (ACC). Most of this salinity-minimum water is found to be tranported northward by the Ekman transport and to be transformed into less dense mode waters.

THE DOWNS AND UPS OF THE MEDITERRANEAN WATER IN THE NORTH ATLANTIC IN A GLOBAL OCEAN MODEL

Yanli Jia [Yanli.Jia@soc.soton.ac.uk],Andrew Coward, Beverly de Cuevas, David Webb
Southampton Oceanography Centre, UK

The warm and saline Mediterranean Water enters the North Atlantic through the narrow and shallow (~300 m) Strait of Gibraltar. It then descends to a depth of about 1000 m within the Gulf of Cadiz and spreads widely in the North Atlantic basin. Though there is a general consensus that the Mediterranean Water contributes to the global thermohaline circulation by being a constituent of the flow that enters the Nordic Seas, what is unclear is how the Mediterranean Water rises and arrives at the entrance to the Nordic Seas (at a depth of about 600 m). Through numerical experiments with a global ocean general circulation model at a horizontal resolution of 0.25° and 36 vertical levels, we examine the pathways of the Mediterranean Water in the North Atlantic.

Two experiments were performed with integration length of 20 years, one with an open Strait of Gibraltar throughs which there is an outflow flux of approximately 1 Sv of the dense and saline Mediterranean water, and one with a closed Strait. Comparisons of the results from the two experiments indicate that without the intrusion of the dense Mediterranean Water, the flow field at depth in the subtropical region is very weak, whereas in the open Strait experiment there is a continuous westward current with speed greater than 0.5 cm/s that stretches from the Gulf of Cadiz to the central Atlantic and then northwestward to as far as the Grand Banks of Newfoundland. This current is at the depth range (600-1100 m) where the Mediterranean Water resides in the model, thus provides an effective pathway for the Mediterranean Water to spread across the basin. At the western boundary near Newfoundland, the saline Mediterranean Water is drawn upwards into the North Atlantic Current and then carried northeastward. Across 50°N, two distinct high salinity anomalies can be seen, one centred at 400 m between 20-25°W coming from the southwest with the North Atlantic Current, and another at 1000 m at the eastern boundary coming from the south carried by the eastern boundary undercurrent from the Gulf of Cadiz. Longer experiments are

THE SPATIAL-TEMPORAL CHARACTERISTICS OF KUROSHIO DEFORMATION AT LUZON STRAIT AND ANTICYCLONIC EDDY SHEDDING PHENOMENA

Yinglai Jia [jiayingl@lib.ouqd.edu.cn], Qinyu Liu
Ocean University of Qingdao, PRC

The goal of this work is to understand the features of the deformation of Kuroshio at Luzon Strait and eddies shed from the Kuroshio deformation. From the climate mean Sea Surface Height (SSH) of SODA (Simple Ocean Data Assimilation) data and POCM model results, the climate mean state of the Kuroshio deformation can be interpreted as the Kuroshio bend extends eastward from Luzon Strait to 117°E. From 7-year-long TOPEX/POSEIDON and ERS satellite altimeter data (from October 1992 to December 1998) and conductivity-temperature-depth (CTD) data during two oceanographic surveys in 1998, the periodical variation of Kuroshio bend, and anticyclonic eddies periodically breaking off from the Kuroshio bend, are observed. When the Kuroshio bend extends far into the SCS, an anticyclonic eddy breaks off from the Kuroshio bend. The breaking off of anticyclonic eddies from Kuroshio bend has very close relationship with the cyclone formed at the south of the Kuroshio bend. After examining all the eddy shedding events in the 7-year-long altimeter data, several features of the Kuroshio deformation variation and eddy shedding events are found: The primary eddy shedding period is from 60 to 90 days. The anticyclonic eddies are mainly shed in two areas; one is to the west of 118°E (116.5°E~117.5°E), and the other is to the east of 118°E (119°E~121°E). The eddy shedding behavior is different in winter and in summer. In winter, the anticyclonic eddies are mainly shed to the east of 119°E while the eddy shedding period mainly varies within 90 days. In summer, the eddies are more likely shed to the west of 119°E while the eddy shedding period mainly varies within from 40-120 days.

OPTIMAL OBSERVATIONS FOR VARIATIONAL DATA ASSIMILATION: OVERTURNING IN THE NORTH ATLANTIC

Armin Köhl [akoehl@ucsd.edu]
Scripps Institution of Oceanography

One important aspect of ocean state estimation is the design of an observing system that allows to study climate changes in the ocean in a most efficient way. A solution of a design problem is presented here and optimal observations are introduced as nondimensionalized singular vectors of the data resolution matrix. Optimal observations have been proven to perform better than section data in relocating scalar quantities. Here we focus on the overturning stream-function in the North Atlantic at 30°N in 900 m depth for the year 1997. Optimal observations are evaluated in the framework of an one degree global model for a state estimation over 10 years. Preferred hydrographic observations are primarily located along the western boundary north of 30°N and along the eastern boundary south of 30°N. Additional locations are in the Labrador, Irminger, and the Iberian Sea. By revealing the main processes that accompany anomalies of the overturning, they are ideally suited for studying causes and effects of anomalies. The response on short time-scales is mainly wind driven and includes Ekman transport and coastal up- and down-welling. A smaller part of the response is buoyancy driven and a slow response to primarily winter time anomalies in the Labrador Sea. Western boundary currents are mainly altered by temperature and salinity anomalies in the initial conditions. The overall picture for year 1997 is an east-west density contrast that manifests primarily along the boundaries in the upper 1000 m.

ATLANTIC OCEAN CIRCULATION STRUCTURE BASED ON ALTIMETER REMOTE SENSING

Yu-Heng Kuo [ykuo@plymouth.ac.uk], Robin D. Pingree, Samantha J. Lavender
Institute of Marine Studies, University of Plymouth, United Kingdom

This study used an 8-year period (from 22 October 1992 to 10 October 2000) time-series of ERS-1, ERS-2 and TOPEX/POSEIDON satellites Maps of Sea Level Anomalies (MSLA) data to obtain structures of ocean circulation in the Atlantic Ocean. The study area is from 100°W to 40°E in Longitude and from 70°S to 70°N in Latitude. Fourier analysis is used to analyze the Sea Level Anomalies (SLA) time series at each position with 0.25° resolution in longitude and latitude in the Atlantic Ocean. The Gulf Stream region and the North Equatorial Counter Current have a marked SLA annual amplitude. The phase of annual signal gives the timing for the SLA seasonal cycle. The North Atlantic Ocean reaches its maximum value near 270° (September/ October) whereas the South Atlantic Ocean reaches its maximum near 90° (March/April). Major meridional changes in annual phase occur in the tropical regions near 5°S and 17°N. Along the equator the annual signal propagates eastward. The semi-annual amplitude shows maximum values in tropical and equatorial regions. The semi-annual structure is essentially coherent along the equator but becomes westward propagating at 4°N. The semi-annual phase shows shorter (~500 km) wavelike westward propagation in the subtropics 20°N-50°N and 25°S-50°S. These mesoscale wavelike structures are believed to be largely noise, except near 30°-35°N where Pingree and Sinha showed that eddies (with a repeat scale of 500 km) can propagate westward with near semi-annual (200 days) periodicity.

GENERAL CIRCULATION IN WESTERN SUBTROPICAL NORTH ATLANTIC OBSERVED USING PROFILING FLOATS

Young-Oh Kwon [yokwon@ocean.washington.edu], Stephen C. Riser
School of Oceanography, University of Washington

Lagrangian and Eulerian perspectives of the circulation of the North Atlantic subtropics are investigated using observations made by profiling floats. 71 profiling floats were deployed beginning in July 1997 in the subtropical region of the North Atlantic as a part of the Atlantic Circulation and Climate Experiment (ACCE), a component of WOCE. The floats collected temperature and salinity profiles in the upper 1000 m at 10-day intervals, and also allowed velocity estimates to be made below the thermocline.

The two major characteristics of the general circulation in this region, which are apparent from the trajectories of the floats, are the strong depth dependence of the circulation and the topographic control over the most of the region. Special attention has been paid to (i) the depth and the topographic dependence of the size of the southern recirculation gyre; (ii) the path of the Gulf Stream and its North Atlantic Current extension in the subpolar region; (iii) meridionally oriented turbulent flows near the major topographic features, i.e. the New England Seamounts, the Corner Rise, and Bermuda; (iv) flow crossing the Mid-Atlantic Ridge near 33°N; and (v) zonal flow south of 30°N.

From the Eulerian perspective, the absolute geostrophic circulation of the North Atlantic subtropical gyre has been estimated using these observations. Traditionally such geostrophic calculations have had the problem of unknown reference level, and most previous studies were done without a large-scale knowledge of a deep reference velocity. Since the data collected from the floats consisted of simultaneous hydrography and velocity at a nominal depth of 1000 m, the full absolute geostrophic velocity field above 1000 m can be deduced without additional assumptions.

COMBINING ALTIMETER DATA AND IN-SITU TEMPERATURE AND SALINITY PROFILE MEASUREMENTS TO BETTER ESTIMATE THE 3-D THERMOHALINE FIELDS

Gilles Larnicol [gilles.larnicol@cls.fr], Stephanie Guinehut, Pierre-Yves Le Traon
C.L.S., Space Oceanography Division

WOCE experience shows that high spatial and temporal resolution is required to monitor the ocean and its interaction with the atmosphere. Thus, satellite measurements are essential components of the observing system. In particular, satellite altimetry provides synoptic observations of sea level that contains integrated information of the water column. On the other hand, deployment of a global array of temperature and salinity profiling floats, known as ARGO, began in 2000. The complementary information provided by these two major components of Global Ocean Observing System allows us to describe the variability of the ocean vertical structure. A companion poster (Guinehut et al., see Wednesday abstracts) focuses on the characterisation of the agreement and physical content of both data sets in terms of barotropic and baroclinic components. The objective of this study is to analyze how to effectively merge the accurate but sparse in situ profiles with the high spatial and temporal sampling characteristics of altimeter measurements,to better estimate 3-D thermohaline fields. Our methodology consists of first producing synthetic temperature and salinity profiles from the vertical projection of the altimetry data. Then an optimal interpolation method that accounts for analyzed error on the observations and particularly correlated errors of the altimeter measurements is used to merge the synthetics and in-situ profiles. Preliminary results from the French CLIPPER model show that the optimal combination is simultaneously able to reduce the aliasing due to mesoscale variability and to adjust the analysed field on the in situ field. This system of combining ocean observations was developed in the frame of the French MERCATOR project and is applied to the North Atlantic for the GYROSCOPE European project. 3-D thermohaline fields of the North Altantic will be produced in near real time using Jason and Envisat altimeter data, ARGO float profiles and sea surface temperature. The ability of a such system to monitor the physical state of the upper ocean is then analyzed. In addition, comparisons along WOCE hydrographic cruises (CDT, XBT) are made to characterize the accuracy of the method.

THE MID-DEPTH CIRCULATION OF THE SUBPOLAR NORTH ATLANTIC OCEAN AS MEASURED BY SUBSURFACE FLOATS

Kara L. Lavender[1] [klavender@whoi.edu], W. Brechner Owens[1], Russ E. Davis[2]
[1]Woods Hole Oceanographic Institution; [2]Scripps Institution of Oceanography

As part of WOCE and the ONR Labrador Sea Deep Convection Experiment over 200 subsurface P-ALACE and SOLO floats were deployed in the subpolar North Atlantic Ocean between November 1994 and February 1998 to measure the mid-depth circulation of the basin. The floats drift at nominal depths of either 400, 700, or 1500 m, where they measure average currents for a period ranging from 3.5 to 20 days. After this time the float ascends to the surface where its position is located by the Argos satellites. By March 2002 over 20,000 drift velocity observations were collected, equivalent to over 530 years (cumulative) of float data.

We present a statistical analysis of these drift velocity data and describe the features of the circulation at 700 m depth as measured by the floats. The time-lagged auto-covariances of velocity indicate a Lagrangian integral time scale of ~10 days throughout the basin. Space-time averages of velocity and associated error ellipses were constructed, and this information was used in an objective analysis for estimates of the multi-year mean flow. Estimates of eddy kinetic energy (EKE) were computed from the variance of drift data about the objectively analyzed mean field.

The mapped flow depicts a basin-scale cyclonic flow bounded in the south by the North Atlantic Current/Subpolar Front, which widens and decelerates as it traverses the basin. The strongest flows are in the boundary currents of the western basin (East Greenland, West Greenland, and Labrador Currents), where mean speeds may exceed 10 cm/s. Closed cyclonic recirculations appear just offshore of the boundary currents in the Labrador and Irminger seas, and in the region between the tip of the Reykjanes Ridge and the Charlie Gibbs Fracture Zone (CGFZ). Local accelerations appear in eastward flow through the CGFZ and the Kurchatov Fracture Zone (just north of the Azores Islands), and flow appears to be steered by the topography of the Mid-Atlantic Ridge. Flow in the interior of this basin-scale gyre is generally weak (O(1 cm/s)), as is flow south of the NAC/Subpolar

TRANSFORMATION OF ANTARCTIC INTERMEDIATE WATER AND ANTARCTIC BOTTOM WATER NORTH OF THE EQUATOR

Sergey S. Lappo[1], Iossif D. Lozovatsky[2] [i.lozovatsky@asu.edu], Eugene G. Morozov[3], Sergey M. Shapovalov[3], Alex V. Sokov[3], Sergey A. Dobroliubov[3]
[1]P.P. Shirshov Institute of Oceanology, Russia; [2]Arizona State University; [3]Moscow State University, Russia

The hydrographic measurements carried out during the 8th cruise of R/V "Akademik Ioffe" (July 13-28, 2000) at a slant trans-oceanic section in the equatorial Atlantic and the historical data from the WOCE are used to analyze the transformation of Antarctic Intermediate Water (AAIW) and Antarctic Bottom Water (AABW) north of the equator. A significant uplifting of AAIW, up to the depth of 250 m, which is associated with a combined effect of enhanced vertical mixing and mesoscale dynamics, was found between 42°W and 45°W at approximately 4.5°N. This suggests that the region of diapycnal upwelling of AAIW is not limited by the western part of the South Atlantic but extends also to the Northern Hemisphere influencing the rate of compensation of fresh water losses in the North Atlantic. Extremely low near-bottom potential temperature (0.963°C) was registered west of the Mid-Atlantic Ridge. A decrease in the temperature of AABW compared to the measurements made in 1993 and 1994 in the same region could represent a decadal-scale climatic response on the decreases in the Antarctic sea-surface temperature, which were recorded several times during the 20th century. The observed low temperature of AABW north of the equator could be also associated with a periodic annual intensification of the AABW inflow through the Equatorial Channel, and highly irregular bottom topography in the region. In July 2000, the northward transport of AABW between the Mid-Atlantic Ridge and the Ceara Rise was equal to 1.9 Sv.

TEN YEARS OF HIGH RESOLUTION AND HIGH ACCURACY ALTIMETER DATA FROM TOPEX/POSEIDON AND ERS-1/2: A CONTRIBUTION TO THE WOCE DATA SET

P.Y. Le Traon [letraon@cls.fr], J. Dorandeu, Y. Faugère, G. Dibarboure, M.H. De-Launay, F. Blanc
CLS Space Oceanography Division

Satellite altimetry, as an essential element of the WOCE global ocean observing strategy, has made a unique contribution to the observation and understanding of the global ocean circulation. The main requirement for satellite altimetry is that at least two altimeter missions are needed with one being a very precise long-term altimeter system. During WOCE, this minimum requirement has been fulfilled by the US/French TOPEX/POSEIDON (TP) and the European Space Agency ERS-1/2 missions. TP has been measuring the ocean topography with an unprecedented accuracy for more than 10 years, while ERS-1 and ERS-2 have provided a very useful complementary sampling. The merging of TP and ERS-1/2 has provided, in particular, a description of the ocean circulation variability with a resolution never before achieved. A complete reprocessing and merging of TP and ERS-1/2 has been done recently at CLS as part of the EC ENACT project and with support from CNES. It uses improved algorithms to correct altimeter data for geophysical corrections and orbit error, and an improved mapping technique is used to merge TP and ERS-1/2 data. This provides a 10-year homogeneous and high resolution altimeter data set. The main features of this data set will be summarized in this poster. Its contribution to the large scale and mesoscale ocean circulation monitoring and to eddy resolving model validation will then be illustrated. Comparison with WOCE in situ data (hydrographic sections, surface drifters, tide gauges) will also be shown. This unique data set (10 years of along-track and mapped T/P and ERS-1/2 data) is distributed by AVISO and will be available at the conference.

VISUALIZING THE PACIFIC OCEAN HELIUM-3 FIELD

John Lupton[1] [lupton@pmel.noaa.gov], Doug Pyle[2], Roland Well[3], William Jenkins[3], Peter Schlosser[4], Zafer Top[5]
[1]NOAA/PMEL; [2]University of Hawaii; [3]Woods Hole Oceanographic Institution; [4]Lamont-Doherty Erth Observatory; [5]University of Miami

Helium-3 is a stable, conservative tracer that is injected at mid-depth into the ocean basins via hydrothermal activity along the global mid-ocean ridge system. Other than the difficulty of precisely defining the source function, the boundary conditions for ^{3}He at the sea surface and at the ocean floor are simple, making it particularly useful for tracing ocean circulation and mixing. Because the mid-ocean ridges in the Pacific Ocean are volcanically very active, the ^{3}He signal in the Pacific is correspondingly stronger compared to the other major oceans and therefore very useful for tracer applications. Furthermore, during the past two decades, our knowledge of the ^{3}He field in the Pacific Ocean has increased dramatically owing to the thousands of helium samples collected during various WOCE and NOAA expeditions. We will present an overview of the ^{3}He field in the Pacific, with a focus on the particular regions where the circulation pattern is clearly defined by this tracer. We have employed two different visualization techniques in attempt to describe the complexities of the helium tracer field. In the first method, we have interpolated the ^{3}He values onto 42 different surfaces spaced at 100-m intervals from 1000 m down to 4200-m depth, and then produced maps of the ^{3}He values contoured on each surface. These surface maps provide a detailed view of the hydrothermal helium plumes on various depth surfaces. In the second approach, we combined the 2-D grids from each of the depth surfaces to form a 3-D grid, and then generated a 3-D isosurface views of the helium field. These depth slices show plumes of high ^{3}He emanating from hotspots beneath Hawaii at and Samoa at 1100-m and 1700-m depth respectively, and from active seafloor spreading along the Juan de Fuca Ridge and the East Pacific Rise at depths between 2000 and 2500 m. The helium plumes are elongated by the prevailing ocean circulation pattern. At depths below 4000 m, the northward intrusion of Antarctic Bottom Water is clearly visible as a tongue of cold, ^{3}He-depleted water penetrating into the north Pacific.

THE GENERAL CIRCULATION IN A 1/10TH DEGREE GLOBAL POP SIMULATION

Mathew Maltrud[1] [maltrud@lanl.gov], Julie McClean[2]
[1]Los Alamos National Laboratory; [2]Naval Postgraduate School

One of the goals of WOCE is to further understand the the ocean circulation by making meaningful comparisons between simulations using state of the art numerical models and the wide variety of data that has been made available from the field programs. In order to simulate both the mean and eddy components of the circulation in a realistic enough manner to perform many comparisons, very high resolution (smaller than the Rossby radius) is required. With the goal of investigating the wind driven circulation on time scales up to decadal, we are currently spinning up a fully global (including the Arctic) version of the Parallel Ocean Program (POP) with 1/10th degree equatorial resolution and 40 vertical levels. Surface fluxes are calculated daily using bulk formulae and a variety of atmospheric data and reanalysis products. We will be presenting results from a 15 year spinup of this model, focussing on global scale aspects of the mean state as well as the variability. This includes descriptions of the major current systems, heat and mass transports, inter-basin exchange, and eddy variability, all of which will be compared with data.

FREQUENCY, WAVENUMBER, AND SPATIAL DECOMPOSITION OF SEA-SURFACE-HEIGHT ESTIMATES FROM A WOCE DATA SYNTHESIS

Dimitris Menemenlis[1] [menemenlis@jpl.nasa.gov], Paulo Polito[2], Ichiro Fukumori[1], Tong Lee[1], Lee-Lueng Fu[1]
[1]Jet Propulsion Laboratory; [2]Instituto Nacional de Pesquisas Espaciais, Brazil

We describe and quantify changes in sea-surface height anomaly, region-by-region, and in twelve frequency-wavenumber bands, for an ocean data synthesis carried out by the ECCO (Estimating the Circulation and Climate of the Ocean, http://www.ecco-group.org) consortium. The frequency-wavenumber bands are obtained using 2D, finite-impulse-response filters and span, respectively, the large scale, non-propagating signal, Rossby waves at periods of 24, 12, 6, and 3 months, Kelvin waves at periods of 6, 3, and 1.5 months, tropical instability waves, and eddies. We aim to associate changes in individual model parameters and forcing fields to changes in specific bands of the 2D spectrum. Overall, the variance of the simulation is too weak by a factor of two or more; the ECCO synthesis has variability that is closer to, though still weaker than, that of TOPEX/POSEIDON. The model/data variance discrepancy is not equally distributed in the spectrum; some frequency bands are better reproduced than others. Most of the improvement is attributable to winds, but buoyancy fluxes and internal model parameters also play a role. This study provides insight on model representation errors as well as on the generation and dissipation mechanisms of planetary waves.

CLIPPER: HIGH RESOLUTION MODELING OF THE ATLANTIC OCEAN DURING WOCE

J.M. Molines[1], B. Barnier[1], A. de Miranda[1], C. Le Provost[2] , G. Madec[3], and A.-M. Tréguier[4]
[1]LEGI-CNRS, Grenoble; [2]LEGOS, Toulouse; [3]LODYC, Paris; [4]LPO, Brest

CLIPPER is a project that aims to model the Atlantic Ocean with a special attention drawn to the period of the WOCE field experiment phase (1990-1998). For this purpose, a state of the art primitive equation, ocean circulation model have been set up by a project team and associated scientists. In this poster, an overview of the project is given: model set-up (model characteristics, parameterization, horizontal and vertical resolutions), initial conditions (deduced from the WOCE based Reynaud et al. climatology), forcing fields (ECMWF analysis and re-analysis). The strategy for the model integration is described as well (spin-up, results archiving). General basin scale results of a 20-year integration covering years 1970 to 2000 are shown, pointing out strength and weakness of simulation. Numerical results produced by the CLIPPER project are shared with any scientific team interested in their use, and have been widely distributed. The results obtained by several scientific teams will be presented on separated posters.

OCEANS: OCEAN BIOGEOCHEMISTRY AND ECOSYSTEMS ANALYSIS

Patrick Monfray [monfray@cea.fr] et al.
CNRS, France

The primary goal of OCEANS is to understand the sensitivity of the ocean to global change within the context of the broader Earth System, focusing on biogeochemical cycles, marine food webs and their interactions. The overarching questions to see discussion are:

- How does global change, represented by changes in natural climatic modalities and anthropogenic forcings, impact marine biogeochemical cycles and ecosystem dynamics?
- How do these impacts alter the relationship between elemental cycling and ecosystem dynamics?
- What are the feedback mechanisms to the Earth System from these changes?

OCEANS seeks a comprehensive understanding of the impacts of climate and anthropogenic forcings on food web dynamics and elemental cycling, including the impacts of underlying physical dynamics of the ocean. It will strive also for mechanistic and predictive understanding of how these linked systems respond to global change resulting from natural climate modes (e.g., ENSO and NAO) and anthropogenic perturbations, and then feed back to climate, ocean physics, and marine resources.

RESOLUTION DEPENDENCE OF ZONAL FLOWS IN THE PACIFIC

Hideyuki Nakano [nakano@ccsr.u-tokyo.ac.jp], Hiroyasu Hasumi
Center for Climate System Research, University of Tokyo, Japan

Zonal flows in the Pacific are investigated using general circulation models with the horizontal resolution of 1°, 1/3°, and 1/6°. All the models use biharmonic Smagorinsky viscosity and are integrated from the Levitus climatology for several decades. The models reproduce the major current systems in the Pacific such as the subtropical gyre and the tropical gyre. In the finest resolution model, the Kuroshio realistically separates from the coast east of Japan. In the subtropical gyre, subtropical countercurrent and strong eastward zonal flow are formed between Eurasia and the Hawaiian Islands. In the equatorial current system, the subsurface counter currents (SCCs) are well represented when the horizontal resolution is 1/3° or 1/6°. A series of the zonal flows below the thermocline shows that the pattern slants poleward with increasing depth.

These flows at mid-depths correspond to those implied in the adjusted steric height maps derived from observations. Their main formation mechanism can be thought to be the response to the surface forcing. A semi-analytical model indicates linear response to the zonal averaged wind forcing can reproduce the basic pattern of the mid-depth zonal flows which reach down to several thousand meters. The basic pattern for the zonal flows are similar between the different resolution models. When the resolution becomes higher, however, the meridional strucutre of the alternating zonal flows becomes finer. In addition, the zonal flows for finer resolution models tend to stretch vertically. The zonal momentum balance analysis shows that the zonal flows are accelerated by the zonal advection and stretched in the vertical direction bythe vertical advection. Aside from the subsurface countercurrent, the effects of the Reynolds stress do not seem to strengthen the zonal flows. The vorticity analysis reveals that the advection of vorticity is increased at the depth of SCCs when the meridional resolution is sufficiently fine and the horizontal viscosity is sufficiently weak. A semi-analytical vorticity balance model including the advection of vorticity can create the eastward flow formed at the poleward fringe of the poleward flows, confirming the importance of the meridional

FORMATION AREAS OF MODE WATERS IN THE 165°E SECTION

Eitarou Oka, Toshio Suga
FORSGC, Japan

Temperature and salinity data of CTD, XCTD, and XBT and oxygen data from Niskin bottles along the 165°E meridian in spring of 1996-2001 obtained by the Japan Meteorological Agency were analyzed to examine formation areas of mode waters in relation to positions of several fronts. This section was formerly made in the WOCE Hydrographic Program (WHP) in summer 1991, summer 1992, and spring 1993 as WHP P13C, P13, and P13J, respectively.

In the northern part of the 165°E section between 30°N and 50°N, three thermohaline fronts, namely the Kuroshio Extension front, the Kuroshio Bifurcation front, and the subarctic front, exist around 34-35°N, 37-38°N, and 40-41°N, respectively. The Subtropical Mode Water is formed just south of the Kuroshio Extension front as a pycnostad in ranges of 25.15-25.75, 14.7-17.6°C, and 34.62-34.81 psu, which is consistent with the previous studies. The Central Mode Water (CMW) is formed separately in two regions between the Kuroshio Extension front and the Kuroshio Bifurcation front and between the Kuroshio Bifurcation front and the subarctic front. The CMW formed in the former region is in ranges of 25.85-26.35, 10.2-13.9°C, and 34.26-34.54 psu, while that formed in the latter region is in denser, colder, and fresher ranges of 26.25-26.55, 7.7-10.7°C, and 33.89-34.26 psu. This difference reflects that in condition of the wintertime mixed layer between the two regions.

Furthermore, another water of low potential vorticity was formed around 43°-45°N north of the subarctic front in 1999, 2000, and 2001, although it was not formed in 1996-1998. This water is in ranges of 26.40-26.60, 4.2-5.2°C, and 33.34-33.62 psu. Its density is only a little larger than that of the CMW, but its temperature and salinity are much less than those of the CMW and are within the typical ranges of the subarctic water. It is thus suggested that this pycnostad formed north of the subarctic front is a distinct water mass from the CMW.

ANTARCTIC INTERMEDIATE WATER CIRCULATION IN THE BRAZIL BASIN AND EQUATORIAL ATLANTIC

Michel Ollitrault [michel.ollitrault@ifremer.fr]
IFREMER, France

Three hundred subsurface MARVOR float-years collected near 800 dbar from 1994 to 2001 are analysed statistically to provide mean currents and associated errors (from EKE and Lagrangian time scales) within 1 degree square boxes, over the region comprised between 30°S and 5°N west of the Mid Atlantic Ridge.The WOCE goal of a few mm/s error on the interior mean circulation (and a few cm/s on the boundary mean currents) is reached only marginally but the present circulation already resolve neatly the Intermediate Western Boundary Current flowing northward at .5 knot along the Brazilian continental slope from 27°S to 2°S, the eastward flowing South Intermediate Counter Current at 2-3°S and a generally seasonally modulated zonal equatorial current structure which demonstrates how AAIW executes eastward excursions before leaking into the North Atlantic on the western boundary. A diffusive circulation in the western tropical interior (20°S-5°S) and a blocking effect by the Mid Atlantic Ridge are also identified.

ON THE INTERANNUAL VARIABILITY OF EKE IN THE NORTH ATLANTIC

T. Penduff[1] [Thierry.Penduff@hmg.inpg.fr], J.J. O'Brien[2], W.K. Dewar[3], B. Barnier[1]
[1]LEGI-CNRS, France; [2]COAPS; [3]Florida State University

Observational studies based on altimeter data have shown that the oceanic Eddy Kinetic Energy (EKE) significantly varies on interannual timescales in many regions of the World Ocean. According to these studies, this EKE variability seems to be linked to the NAO cycle in the North Atlantic, but might also be influenced by oceanic internal processes. However, existing datasets are too superficial, incomplete, and short in time to demonstrate the latter two hypotheses. In this study, these hypotheses are examined using 7 years of TOPEX/Poseidon altimeter data and a 20-year 1/6 degree-resolution Atlantic ocean model simulation (CLIPPER) forced by realistic air-sea fluxes. Our results confirm that, at least since 1994, the interannual variability of the large-scale EKE distribution follows that of the NAO index, via the fluctuations of the energy transferred to the ocean by the wind. In addition, oceanic baroclinic instability appears to control the observed EKE fluctuations over several areas of the basin.

A GLOBAL COMPARISON OF EKMAN PUMPING FROM SATELLITE SCATTEROMETERS AND OCEAN DATA ASSIMILATION ESTIMATES

Paulo S. Polito[1] [polito@ltid.inpe.br], Tong Lee[2], Ichiro Fukumori[3]
[1]Instituto Nacional de Pesquisas Espaciais, Brazil; [2]Jet Propulsion Laboratory

Ekman pumping, a form of wind-driven upwelling, plays important roles in upper-ocean dynamics, thermodynamics, and biology as well as in boundary-layer meteorology. Inverse models, such as those of ECCO (Estimation of the Circulation and Climate of the Ocean, http://www.ecco-group.org/), estimate wind forcing through ocean data assimilation. Scatterometer data provide a stringent test of the skill of the assimilation in estimating wind. Ekman pumping obtained from various scatterometers are compared with those derived from ECCO models which assimilate TOPEX-derived sea level anomalies using the adjoint and Kalman filter/smoother methods. Differences in Ekman pumping between scatterometer and assimilation estimates are quantified in terms of the mean, standard deviation, and correlation. Changes in the Ekman pumping due to the assimilation are analyzed to identify the spectral (frequency-wavelength) space over which the assimilation has a significant impact. The comparison also highlights aspects where the ECCO model and assimilation schemes need improvement.

INTERANNUAL VARIABILITY IN DRAKE PASSAGE FROM HYDROGRAPHY, SATELLITE ALTIMETRY, AND DEEP TEMPERATURE TIME SERIES

M. Price[1], K. Heywood[1], D. Stevens[2], B. King[3]
[1]School of Environmental Sciences, University of East Anglia, UK; [2]School of Mathematics, University of East Anglia, UK; [3]James Rennell Division, Southampton Oceanography Centre, UK

A number of modes of interannual variability have recently been discovered in the southern mid-latitudes, for example the Antarctic Circumpolar Wave and Antarctic Dipole. However, key questions remain about whether they are forced by tropical variability or intrinsic to the mid-latitudes, and whether they are significantly expressed in the sub-surface layers.

There now exist several sub-surface Southern Ocean time series, including seven repeat hydrographic sections on the WOCE SR1b (Drake Passage) line, and deep temperature records from bottom pressure recorders in the Scotia Sea. A combined analysis of these and the surface fields from Drake Passage has revealed a significant deep structure associated with the surface interannual variability. Particularly striking is a year-long cold anomaly in the bottom temperature at a location in southern Drake Passage, which is clearly correlated with a low sea level anomaly over a large area of the western Scotia Sea. The hydrographic sections reveal the presence of anomalously cold and dense Weddell Sea Deep Water at the same time, indicating a linkage with either the Scotia Sea circulation of these recently ventilated deep waters, or their overflow across the South Scotia Ridge.

ECCO 1° GLOBAL WOCE SYNTHESIS: THE METHOD

Elisabeth Remy[1] [dstammer@ucsd.edu], A. Köhl[1], Y. Lu[1], P. Heimbach[1], B. Cornuelle[1], D. Stammer[1], C. Wunsch[2] for the ECCO Consortium
[1]Scripps Istitution of Oceanography; [2]Massachusetts Institute of Technology

A global WOCE data synthesis describing the three-dimensional oceanic state in the 10-year period 1992 - 2001 now exists. The synthesis results from the combination of many of the WOCE data sets with a general circulation model. This combination solves the complete global time-dependent ocean state estimation problem, up to remaining approximations in the model and underlying statistics. The MIT ocean model used represents the global ocean between ±80° with 1° horizontal resolution, 23 vertical layers, and includes parameterizations for the surface boundary layer (KPP) and eddy tracer transfers (GM). At the cost of increased computational load, the estimation (assimilation) method is chosen specifically so that the resulting state estimate is dynamically consistent with the model equations. No artificial sources or sinks are introduced by the model/data combination, and the resulting time-evolution satisfies the equations of motion. The combination method used is based upon the method of LaGrange multipliers (adjoint method), in which the adjustable parameters (controls) include the initial temperature and salinity conditions, and the time-dependent surface fluxes of momentum, heat and freshwater. An important test of the result is passed: adjustments in these control variables are consistent with prior estimates of the expected errors in the oceanographic data and the meteorological analyses.

EDDY-RESOLVING SIMULATION OF THE WORLD OCEAN CIRCULATION; FIFTY YEARS OF INTEGRATION ON THE EARTH SIMULATOR

H. Sasaki[1] [sasaki@es.jamstec.go.jp], T. Kagimoto[2], N. Komori[1], K. Takahashi[1], Y. Masumoto[2,3], Y. Tsuda[1], M. Kanazawa[1], A. Ishida[2,4], Y. Sasai[2], K. Komime[1], R. Jung[1], Y. Yamanaka[2,5], S. Masuda[2], T. Motoi[2], M. Kitawaki[1], H. Sakuma[1], T. Yamagata[2,3], and T. Sato[1]

[1]Earth Simulator Center; [2]Frontier Research System for Global Change; [3]University of Tokyo; [4]JAMSTEC; [5]Hokkaido University

In the spirit of WOCE, and inheriting its achievement, the Earth Simulator initiative has embarked on eddy-resolving simulations on the global domain to assess simulated eddy dynamics together with phenomenological validations of our numerical experiments. To pursue this goal, we developed a high-resolution MOM3-based OGCM code optimized for the Earth Simulator, which can execute one model year simulation in approximately six hours.

The model was spun up from annual mean temperature and salinity fields (WOA98) without motion. Surface fluxes are specified from monthly mean NCEP reanalysis data in addition to a surface salinity restoring to climatological value. The simulated surface currents and temperatures tell that, overall, those fields are quite realistic. The meandering patterns of the Kuroshio with a realistic separation latitude are readily identified. Meso-scale eddies south of Honshu are also well simulated. Features such as the Gulf Stream and accompanying rings, Natal pulses in the Agulhas Current, the Indonesian Throughflow and the herringbone structures of the Legeckis waves in the eastern tropical Pacific, appear naturally in our high-resolution simulation.

We report those simulated features of the world ocean, and compare with in situ as well as remote sensing data of SST, SSH and subsurface T-S fields. Also compared intensively is WOCE hydrographic data. Preliminary examination shows that vertical cross sections of the simulated salinity and potential density along WOCE line P09 (137°E) agree well with the observation. This suggests that our eddy-resolving simulation successfully reproduced, without ad hoc meso-scale eddy parameterizations, the characteristic water masses in the North Pacific, which encourages us to extend our investigation further on variety of topics.

CIRCULATION OF THE KUROSHIO AND OYASHIO WATERS IN THE NORTH PACIFIC INTERMEDIATE WATER FORMATION AREA

Yugo Shimizu[1] [yugo@affrc.go.jp], Takanori Iwao[2], Ichiro Yasuda[3], Tomowo Watanabe[1], Shin-ichi Ito[1], Kimio Hanawa[4]

[1]Tohoku National Fisheries Research Institute, Japan; [2]Japan Meteorological Agency, Japan; [3]University of Tokyo, Japan; [4]Tohoku University, Japan

Circulation of the Kuroshio and Oyashio waters in the North Pacific Intermediate Water (NPIW) formation area are examined using CTD, ADCP and isopycnal floats in Japan WOCE and Subarctic Gyre Experiment (SAGE) programs. Using CTD and ADCP sections in spring 1994, the anti-cyclonic and cyclonic Oyashio eddies are found in the Kuroshio-Oyashio interfrontal zone. The anti-cyclonic Oyashio eddies have cold and low-salinity cores with low potential vorticity (PV) suggesting their origin is the Okhotsk Sea. The cyclonic Oyashio eddies with high PV are considered to originate from the western subarctic gyre. These Oyashio eddies are inferred to merge with the Kuroshio Extension (KE), forming new NPIW. In spring 1992 and 1994, the ADCP-referenced transports of Oyashio 5-6 Sv and Kuroshio 7-8 Sv in the density range 26.6-27.2 σ_θ are involved in NPIW formation. Dividing NPIW volume by the ADCP-referenced transports, the residence time of NPIW is estimated to be about 20 years. In winter and spring 2001, six isopycnal floats (APEX, Webb Res. Co.) parking at 26.7 σ_θ were launched in an anti-cyclonic Oyashio eddy (2 floats) and along KE (4 floats) near the east coast of Japan, in order to examine the formation process of NPIW. These floats moved eastward in the transition area, drifting in the Oyashio eddies, warm core rings and KE. The timescale for the floats to move from the vicinity of Japan (140°E) to the Emperor Sea Mounts (170°E) is about 1-2 years. Salinity profiles obtained by the floats changed drastically when the eddies in which the floats were trapped merged with other water masses, suggesting that strong mixing occurs in interaction between eddies. East of about 155°E in the transition area, the profiles smoothed to be almost consistent with the profile of new NPIW.

APPLICATIONS OF THE GENERALIZED COORDINATE OCEAN MODEL FOR BETTER REPRESENTING SATELLITE SENSING DATA

Y. Tony Song [song@pacific.jpl.nasa.gov]
Jet Propulsion Laboratory

It is found that two adaptive parametric functions can be introduced into the basic ocean equations to utilize the optimal or hybrid features of commonly used z-level, terrain-following, isopycnal, and pressure coordinates in numerical ocean models. The two parametric functions are formulated by combining three techniques: the arbitrary vertical coordinate system of Kasahara, the Jacobian pressure gradient formulation of Song, and a newly developed metric factor that permits both compressible (non-Boussinesq) and incompressible (Boussinesq) approximations. Based on the new formulation, a gneralized modeling strategy is proposed and a staggered finite volume method is designed to ensure conservation of important physical properties and numerical accuracy. Implementation of the combined techniques to SCRUM shows that the new modeling strategy can be applied to an existing ocean model without incurring computational expense or altering the original numerical schemes. Several representing oceanographic problems with different scales and characteristics, such as coastal canyons, basin-scale circulation, and global ocean circulation, are used to demonstrate the model's capabilities for better representing satellite sensing data. New results show that the model is capable of simultaneously resolving both Boussinesq and non-Boussinesq, and both small- and large-scale processes in a single model framework.

PATHWAY AND VENTILATION OF THE MID-DEPTH SALINITY MINIMUM WATERS OF THE SOUTHERN HEMISPHERE

S. Speich [Sabrina.Speich@univ-brest.fr], D. iudicone, G. Madec
LPO/UBO UFR Sciences, Brest

The purpose of this study is to investigate the pathways and ventilation of the mid-depth salinity minimum waters characterising the thermohaline structure of the three Southern Hemisphere oceans. We used the thermo-dynamical outputs of a general circulation model constrained by observed climatologies. First the results are analysed in the same way as classical box inverse models. For each basin a water-mass budget is computed. The results compare relatively well with existing results on observations.

To deepen the comprehension of the dynamics of these water masses their pathway and ventilation are recovered through a Lagrangian analysis applied on the monthly-mean numerical fields. The results for each Southern Ocean basin will be discussed. In particular our findings suggest that the subtropical gyres dynamics and the subantarctic mode waters formation play a key role in the development of these salinity minimum waters. In fact, in the model it appears that the strong fronts that separate the Antarctic Circumpolar Current from the subtropical gyres are the region where deep Subantarctic Mode Waters formation occurs. The steep mixed-layer base topography associated with these water masses formation could explain the northward (lateral) injection of these waters into the lower base of the subtropical gyres.

ESTIMATES OF SECULAR CHANGES IN THE ECCO GLOBAL WOCE SYNTHESIS

Detlef Stammer [dstammer@ucsd.edu], B. Cornuelle, A. Köhl for the ECCO Consortium
Scripps Institution of Oceanography

The ECCO global 1° WOCE Synthesis is analyzed with respect to large-scale changes on interannual and longer time scales. Emphasis is being put on deep temperature and salinity changes and their relations to variations in sea surface height. Changes in heat content on basin and global scale are compared to imbalances in net surface heat forcing and the problem of distinguishing numerical model drift from long-term changes in the ocean is being discussed.

GLOBAL OCEAN CIRCULATION AND MASS FIELDS AND THE EARTH'S VARIABLE ROTATION

Rui M. Ponte[1], Detlef Stammer[2] [dstammer@ucsd.edu], Carl Wunsch[3]
[1]Atmospheric and Environmental Research, Inc.; [2]Scripps Institution of Oceanography; [3]Massachusetts Institute of Technology

Advances in modeling and observational capabilities occurring in recent years as part of the WOCE legacy have made possible the realistic determination of the ocean circulation and mass fields on a global scale. With the ability to calculate these time varying fields came the opportunity to study globally integrated quantities such as ocean angular momentum (OAM). Global estimates of sea level, density, and horizontal currents are used to show that improved OAM estimates are being obtained from advanced ocean state estimation methods. Comparisons with independent Earth rotation data demonstrate the good quality of OAM estimates and reveal the importance of OAM variability in explaining observed signals in length of day and polar motion. The equatorial components of OAM are particularly relevant for the planet's rotation budget and can account for a major part of the Chandler and seasonal wobble excitation, thus providing an answer to a long standing unsolved problem in geophysics. Results point to the value of combining satellite altimetry and gravity data, Earth rotation data, and ocean models to address various oceanographic and geodetic research questions in the future.

HEAT AND SALT VARIABILITY IN THE INDIAN OCEAN FROM SATELLITE OBSERVATIONS

Bulusu Subrahmanyam[1] [sub@coaps.fsu.edu], James J. O'Brien[1], Wei Shi[2], John M. Morrison[2], V. S. N. Murty[3]
[1]COAPS, Florida State University; [2]North Carolina State University; [3]National Institute of Oceanography, India

The purpose of this work is to estimate heat and salt storage associated with the surface circulation in the Indian Ocean using the combination of sea-level anomalies derived from TOPEX/Poseidon (T/P) altimetry, and in-situ sea-level computed from climatological hydrographic data. We compared the synthetic salinity derived from T/P altimetry with the salinity estimated from satellite derived Outgoing Longwave Radiation (OLR). The accuracies of derived temperature and salinity, and heat and salt storage are evaluated using hydrographic data collected along the World Ocean Circulation Experiment (WOCE) Transindian Ocean Section I1. These estimates are used to study the seasonal and interannual variability, and the exchanges of heat and salt variability in Arabian Sea and Bay of Bengal.

SHALLOW, INTERMEDIATE AND DEEP COMPONENTS OF THE GLOBAL OVERTURNING CIRCULATION AND TRANSPORTS

Lynne D. Talley [ltalley@ucsd.edu], Joseph L. Reid, Paul E. Robbins
Scripps Institution of Oceanography

The ocean's overturning circulation and associated heat and freshwater transports are divided into contributions based on water mass ventilation, from: (1) shallow overturning within the wind-driven subtropical gyres to the base of the thermocline, (2) overturning into the intermediate depth layer in the N. Atlantic and N. Pacific, and (3) overturning into the deep layers in the North Atlantic and around Antarctica. The contribution to South Pacific and Indian transports from the Indonesian Throughflow and to all Pacific and Atlantic transports from the Bering Strait are computed separately. Meridional overturning streamfunctions for each ocean are calculated. The ocean basin circulations from Reid are the basis of these calculations. Sensitivity to differing wind stress climatologies used for Ekman transport is considered.

THE OCCAM GLOBAL OCEAN MODEL

D. J. Webb[1] [david.webb@soc.soton.ac.uk], B. A. de Cuevas[1], A. C. Coward[1], Y. Aksenov[1], K. Doos[2]
[1]Southampton Oceanography Centre, UK; [2]MISU, Stockholm University, Sweden

The OCCAM model was one of the first of the high resolution global ocean models. Here we review some of the main results from OCCAM including the zonal fluxes of heat and fresh water (due to eddies and the mean flow), the global overturning stream functions on level surfaces and density surfaces, the pathways and upwelling of North Atlantic Deep Water, the regions of high SSH variability in the South Indian and Pacific Oceans, the zonal jets of the South Pacific and the boundary current of the Arctic Ocean.

DEEP NORTH ATLANTIC FRESHENING: NATURAL VARIABILITY OR CLIMATE CHANGE?

Peili Wu [peili.wu@metoffice.com], Anne Pardaens, Michael Vellinga
Met Office, Hadley Centre for Climate Prediction and Research, UK

A recent paper has shown that there has been a rapid freshening of the deep North Atlantic Ocean observed over the past four decades. It would be interesting and important to know whether this observed freshening is consistent with internal, low-frequency variability of the climate system, or whether it is a signal of climate change. This paper presents some results from simulations with the Hadley Centre's coupled model (HadCM3). Using data from a control simulation (with fixed pre-industrial greenhouse gas concentrations) and several climate change scenario runs, it is aimed to help understanding the observations. An ocean-only model forced with the NCEP re-analysis data is also used to help interpreting the observed change.

HIGH-RESOLUTION HYDROGRAPHIC AND CURRENT SURVEY AROUND THE KUROSHIO EXTENSION AND THE FORMATION PROCESS OF NPIW

Ichiro Yasuda[1] [ichiro@eps.s.u-tokyo.ac.jp], Shinya Kouketsu[1], Yutaka Hiroe[2]
[1]University of Tokyo, Japan; [2]National Research Institute of Fisheries Science, Japan

Towed-CTD using Moving Vessel Profilor and shipboard ADCP survey were performed around the first meander of the Kuroshio Extension in the Soyo-maru May 25-June 9, 2001 cruise. About 5km-resolution data along ship track revealed the confluence of Oyashio and Kuroshio waters and salinity minumum formation process. Along the Kuroshio Extension, remarkable salinity minima were observed corresponding to frontal eddies, which is interpreted as a rotation of velocity with depth from vorticity balance. In the downstream Kuroshio Extension, original properties of Oyashio and Kuroshio waters rapidly disappeared and new NPIW were formed. Isopycnal mixing and cabbeling could dominantly contribute to this rapid modification.