DESIGN AND APPLICATION OF AN APPROACH FOR CLIMATE PREDICTION IN TROPICAL AREAS

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Recent research on climate variability and long-range forecasting has lead to the development of easily accessible, comprehensive ocean data sets by various centers such as NCEP in the U.S. and the UK Meteorological Office. There is also regular monitoring of ocean variability by, e.g., the European Center for Medium Range Forecast (ECMWF) and the Bureau of Meteorology in Australia. Various workshops and conferences related principally to the WMO World Climate Research Program and the CLIPS projects have recommended capacity building within national meteorological services in tropical regions to seek the potential use of climate predictions in various socio-economic sectors. Following these recommendations the author explored the existing theories and knowledge of climate variability and prediction during his duty as head of the climate unit at the African Centre of Meteorological Application for Development, with a view to identify an operational system for climate prediction based on empirical models. The approach is based on basic statistical knowledge and empirical models using Sea Surface Temperature (SST) indices as predictors and seasonal rainfall indices as predictands. The approach provides steps for defining climatic zoning, teleconnection analysis based on Pearson correlation analysis with various SST indices, empirical modeling, and validation with past records. The approach was applied during several training workshops organized within Africa, and produced encouraging results, particularly during recent ENSO events in 1998, 1999, and thereafter. Such real time predictability assessment has been particularly useful in issuing seasonal forecasts.

THE FINGERPRINT OF OCEANIC CLIMATE CHANGE IN THE INDO-PACIFIC

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WOCE observations combined with historical oceanic observations indicate that there have been changes in the water masses of the Indo-Pacific over the last fifty years. With observations alone it is impossible to determine whether such changes are an indication of anthropogenic climate change or natural variability in the climate system. We have used the coupled climate model HadCM3 to investigate the observed changes. We find that when the model is driven by anthropogenic forcing there is a mode which is in good agreement with the observed pattern. This pattern may be thought of as an oceanic fingerprint of anthropogenic climate change. We have investigated the role of atmospheric fluxes in driving the changes in oceanic water masses. Detecting climate change in the ocean is advantageous because of the potential high signal-to-noise ratios in the ocean. Studies such as these indicate that as models become more accurate we may be able to use them to aid in the design of future observing systems.

STRETCHING WOCE IN TIME AND SPACE: THE ARCTIC-SUBARCTIC OCEAN FLUX STUDY (ASOF)

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ASOF is a new programme that aims to measure and model the variability of fluxes between the Arctic and the Atlantic Ocean with a view to implementing a longer-term system of critical measurements needed to understand the high-latitude ocean's steering role in decadal climate variability. It has long been known that the descent of cold, dense water from the Nordic seas is the principal means of ventilating the deep oceans and a key element of the global thermohaline circulation. The subsequent spreading of these deep and abyssal waters throughout the world ocean was a primary research focus of WOCE .

The main focus of ASOF is to identify and understand the broad range of upstream influences that might impose change on the Deep Western Boundary Current (DWBC) of the North Atlantic. Since these influences may originate in the Canadian Arctic or Nordic seas or both, ASOF intends to cover all the main ocean fluxes that connect the Arctic Ocean to North Atlantic. Such an extended and extensive observational effort will contribute to the study of anthropogenic effects on the stability of the thermohaline circulation and the ocean's role in rapid climate change.

The six main regional tasks around which ASOF is structured will be presented as well as details of its observational network, data management, model and collaboration with other projects.

CLIMATE PREDICTABILITY IN THE ATLANTIC SECTOR AND THE OCEAN'S ROLE IN DECADAL CLIMATE VARIABILITY

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WOCE data has helped to quantify the oceans´ storage, the redistribution of heat, water and carbon dioxide, and gave an unprecedented glimpse of strong, low frequency oceanic change that provides a firm knowledge base for CLIVAR (WCRP's Climate Variability and Predictability study). CLIVAR's interest in understanding and predicting climate variability associated with ocean-atmosphere interactions will focus in the Atlantic, where oceanic heat transport has an obvious impact on climate. Variations of thermohaline circulation on decadal-to-centennial timescales lead to changes in SST and ocean transport. Paleoceanographic data show that climate changes in the geological past were associated with changes in the thermohaline circulation. Some of these changes developed within a few decades. WOCE observations have shown that convective activity in the source regions of the deep thermohaline circulation undergoes substantial changes on decadal timescales likely associated with the North Atlantic Oscillation (NAO). NAO is the dominant mode of atmospheric behaviour in the North Atlantic sector, and its long-term variability has been suggested to determine or modulate decadal changes to considerable depths in the ocean. There is growing observational and modelling evidence that suggests the longer-period fluctuations of NAO are governed by the coupled ocean-atmosphere system. Substantial interannual and decadal variability is also observed in the Tropical Atlantic region; SST anomalies have been observed north and south of the equator, along with regional changes in winds and precipitation.

CLIVAR implementation in the Atlantic addresses the predictability of the above mentioned climate phenomena, and is overseen by an international panel that coordinates observational and modelling activities as well as promotes process studies. An overview of the achievements to date of the CLIVAR Atlantic panel will be presented in association with the major WOCE contributions that helped define the future challenge of predicting climate variability in the Atlantic Ocean.

THE PILOT OCEAN MODEL INTERCOMPARISON PROJECT (P-OMIP)

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The WOCE/CLIVAR Joint Working Group on Ocean Model Development has launched a "Pilot Phase" for an Ocean Model Intercomparison Project (P-OMIP). This pilot project is to designed to determine the feasibility and merit of a coordinated investigation of the performance of the ocean and sea-ice components of global coupled climate system models. Such an intercomparison is expected to complement ongoing intercomparison efforts for fully coupled models (CMIP) and their atmospheric components (AMIP). Work up to this point has concerned establishing the main elements of a protocol specifying a common integration and analysis strategy. The protocol builds on that used in a "mini-OMIP" conducted by AWI Bremerhaven and MPI Hamburg. A forcing data set based on adjusted ECMWF ERA-15 re-analysis products has been prepared. However, individual groups may also test alternative specifications of air-sea, air-ice, and ocean-ice interactions along with alternative choices of initial data and integration length. An integration length of 100 years, beginning from the Polar Science Center Hydrographic Climatology (PHC) is specified. Common output data sets and diagnostics for the pilot phase are being targeted to prime aspects of large-scale ocean circulation, i.e., fields that can be tested against WOCE climatologies and derived products such as overturning rates and meridional fluxes of heat and freshwater. A limited set of experiments have been completed and initial analyses are underway. An important task for the pilot project will be to refine the integration protocols, and to clarify organizational and technical service functions that need to be established before launching a full fledged OMIP.

** The P-OMIP Working Group consists of R. Bleck (LANL), I Ishikawa(MRI/JMA), G. Madec (LODYC), S. Marsland (MPIfM), F. Roeske (MPIfM), and H. Simmons (U. Alaska), along with the members of the WOCE/CLIVAR Working Group on Ocean Model Development: C. Boening (U. Kiel), F. Bryan (NCAR), E. Chassignet (RSMAS), R. Gerdes (AWI), S. Griffies (GFDL), H. Hasumi (U. Tokyo), A. Hirst (CSIRO), A.-M. Treguier (IFREMER) and D. Webb (SOC).*

ON THE ROLE OF THE CENTRAL PACIFIC IN MAINTAINING THE ENSO CYCLE

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While sea surface temperature (SST) anomalies in the eastern equatorial Pacific are dominated by the thermocline feedback, in the central equatorial Pacific other effects, such as zonal advection, are more important. El Niño-Southern Oscillation (ENSO) simulations with a linear model improve markedly when these effects are included as a local wind stress feedback on SST, both in forced and coupled runs. A statistical atmospheric model can only satisfactorily model the observed characteristics of the ENSO cycle if the wind depends on both the eastern and central Pacific SST. The model is driven by noise with a red component. The two patterns plus noise generate a realistic SST variability pattern, and a realistic value for the correlation between the Niño-3 and Niño-4 indices. As observed, modeled SST anomalies are more persistent in the central than in the eastern Pacific.

Due to local windstress effects on SST in the central Pacific, the spatial pattern of ENSO is not confined to the eastern Pacific, but extends into the central Pacific. In turn, compared to the situation with only thermocline feedback, the windstress pattern of ENSO extends more to the west as well, the amplitude of ENSO is enhanced, and the period increased.

VARIABILITY IN LABRADOR SEA WATER MASSES AS DEPICTED BY A NEW CLIMATOLOGY

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Long-term data coverage in the Labrador Sea makes the region a suitable choice for climatological studies. A pair of climatologies has been created with data extracted from the Climate Database maintained by the Bedford Institute of Oceanography. One climatology is based upon traditional averaging on geopotential levels, while the second one uses a more natural isopycnal formulation. The yearly climatologies are produced using an objective analysis scheme modified to suit the special requirements of this particular region. The results obtained from either of these climatologies successfully represent some of the well known characteristics of the Labrador Sea circulation. For instance, the deep water formation sites can be seen from temperature-salinity plots produced either on a depth level or on a sigma-surface. The dispersal paths for a particular water mass and downstream modifications of its temperature and salinity signature are observed by looking at the temperature-salinity fields on a particular sigma level. Although both averaging techniques, geopotential and isopycnal, have produced meaningful results, the overall level of quality achieved by isopycnal averaging was better. Seasonal climatologies have also been produced for Winter (January, February, March) and Summer (July, August, September).

It is generally accepted that there exists a strong relationship between the North Atlantic Oscillation (NAO) index and Labrador Sea Water formation rate. Motivated by these studies, a decadal analysis is performed over two time periods with opposite NAO indices. The strength of the convective overturning, as inferred from the depth of the LSW, is investigated during high and low NAO index periods. Temperature and salinity are the determining factors in the convective overturning process, therefore any long-term trends or changes in the T-S characteristics of Labrador Sea water masses should be considered carefully. Our results indicate a change in these characteristics and require further study to investigate their sources and effects.

THE TWO MAIN MODES OF VARIABILITY IN THE TROPICAL ATLANTIC MONITORED BY PIRATA

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The tropical Atlantic has two main modes of interannual climate variability: an equatorial mode, similar to the Pacific Ocean El Niño phenomenon, and a meridional mode, also known as the *Dipole*. The equatorial mode is responsible for the warm (and cold) sea surface temperature (SST) events in the Gulf of Guinea and is associated with thermocline slope displacements along the equator. The meridional mode is characterized by a north-south oscillation of the basin-scale SST. It was shown recently, from multi-year time series of observations and simulations, that these two modes are correlated and are both related to the variations of the wind intensity in the western equatorial region**.** A multinational program, the Pilot moored Research Array in the Tropical Atlantic (PIRATA) program, was created in 1997 to address the oceanic and atmospheric signals of climate in that region. The geography of the array was especially designed to observe the two main modes of variability. This work is an attempt, using the first available PIRATA data, to test the representativeness of these two modes, as well as their relationship. The results shown that it is potentially possible to reach to a description in real time of the two principal modes of climate variability in the tropical Atlantic using the PIRATA data. However, this is only one preliminary and partial result in the sense that the time series associated to this first data set are still very short, mainly because of the several data gaps occurring during the first years of the PIRATA program.

MODEL BENCHMARK CONFIGURATION FOR OVERFLOW ACROSS THE GREENLAND-SCOTLAND RIDGE IN THE FRAMEWORK OF DOME

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As part of the DOME (Dynamics of Overflow Mixing and Entrainment) Study, a benchmark for numerical ocean models is proposed that allows an intercomparison of overflow representation in the Subpolar North Atlantic in existing large-scale ocean models. Using a dam-break scenario with cold water north of the Greenland-Scotland Ridge spilling into a pool of warm water south of the sills, the establishment of the Denmark Straits Overflow and the Iceland-Scotland Overflow is examined over one model year in three models (MOM, MIT, C-HOPE) differing in resolution (from 1° to 1/15°), representation of bottom topography (full cells, partial cells) and parameterizations of mixing (horizontal, isopycnic, with/without density-driven downslope flows).

It is demonstrated that there is considerable amount of agreement between the models on the net transport across the sills and the large-scale properties of the overflow plumes. However, depending on resolution and model type, the processes involved in establishing the plumes, the time-scales of plume-spreading and the small-scale features of the plumes show large variations. While an eddy-resolving configuration stresses the lateral entrainment due to synoptic eddies, this process has to be represented by the parameterizations used in the coarser resolution experiments. The benchmark prescription is made available for use in the modelling community to allow diagnosis of the overflow properties of existing ocean and climate models and to serve as a basis for future model intercomparisons.

IMPROVING ENSO SIMULATIONS AND PREDICTIONS THROUGH THE ECCO OCEAN STATE ESTIMATION

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The global ECCO ocean state estimation procedure is used to simulate forecasts of tropical Pacific SST and sub-surface fields on seasonal time scale. As compared to traditional ENSO assimilation and prediction procedures, the hindcast of the constrained ocean state is much closer to observed conditions. The skill of the 12-month lead SST forecast in the equatorial Pacific appears to be similar in both assimilations, but the optimizations leads to better skills in the SST anomaly correlations. Although our current forecast system is strongly limited by the estimation of atmospheric forcing corrections, the results seem to suggest that the forecast system would benefit if adjoint optimizations are performed with coupled ocean-atmosphere systems in which the coupling is part of the control vectors of the adjoint optimization.

THE ROLE OF SALINITY IN PACIFIC SURFACE HEIGHT VARIABILITY AND IN DIAGNOSING THE HYDROLOGICAL CYCLE

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We present a preliminary analysis of Argo data, XCTD profiles, and results from the ECCO assimilation project with respect to the role of salinity in the variability of sea surface height and the use of salinity measurements to improve our understanding of the hydrological cycle in the ocean. The Argo Project—part of the legacy of WOCE—marks the first globally repeating measurements of subsurface salinity, with the data freely available in near real-time. A sparse but rapidly growing Argo array is now operating in the tropical Pacific, returning temperature and salinity profiles every 10 days from 1000 m to the sea surface. These data, plus XCTD profiles from several high resolution XBT/XCTD lines, are used to assess the quality of results from data assimilation activities in the Pacific Ocean. A synthesis of the data and a model will then be used to understand the magnitude of salinity variability and its contribution to density and sea surface height. They are also used for diagnosing precipitation minus evaporation (P-E) anomalies, both locally in surface waters and remotely in subducted water masses. Substantial interannual signals in salinity occur in the upper Pacific Ocean, whose understanding will help to unravel the puzzle of ENSO and other modes of climate variabilty.

LOCAL OCEANOGRAPHIC VARIABILITY AS RESPONSES TO OCEANIC UPWELLING IN THE PACIFIC BASIN OF COLOMBIA

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Upwelling events in the Pacific off Colombia seem be an ageostrophic response of the ocean to the Trade Winds jet across the Panama Bight. In this zone, the jet pushes water offshore, reducing sea level and lowering surface temperature. To evaluate the variability of conditions associated with these upwelling events, we studied wind fields, SST, surface chlorophyll, sea level variation, and geostrophic currents between November 1996 and June 1997, using OCTS, NSCAT and TOPEX-ERS1/2 data. Weekly average data for February-March 1997 were used to study the short-time variability of the upwelling events. These events were mainly consequences of wind curl due to Trade Wind stress and occurred throughout the study period with variable spatial distribution, often located toward the eastern part of the basin. Seasonal variability of SST and surface chlorophyll was related directly to the ICTZ migration and Trade Winds jet. We detected a high chlorophyll concentration (> 30 mg m^{-3}) in March, associated with vertical current intensification and the maximal rise of the thermocline on the northern side of Panama Bight. A second maximal surface chlorophyll was detected in November without relationship with wind stress. In this area, atmospheric processes transfer momentum to oceanic and coastal waters and modify the balance that maintains the structured mixed layer. All upwelling events were intensified by geostrophic anti-cyclonic circulation detected in the western zone and cyclonic circulation in the eastern zone. This association intensified the upward flow of sub-surface water with consequent phytoplankton biomass increase. On the other hand, the second chlorophyll bloom would be the result of a combined effect of positive wind stress curl, return of the Colombia Current, and eddies formed in the shelf break of Gulf of Panama that intensify offshore advection. Oceanic upwelling is commonly characterized by low phytoplankton standing stocks compared to coastal upwelling systems. However, primary production expected at upwelling systems in the Pacific basin off Colombia is relatively high, and their large area makes them important to the global carbon cycle.

HEAT CONTENT VARIABILITY RELATED TO THE ENSO EVENTS IN THE PACIFIC

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Interannual upper ocean heat content (OHC) variability in the Pacific is analyzed for a 45-year period with special reference to its relationship with El Niño/Southern Oscillation (ENSO) events. The cyclic and anti-clockwise propagation of the OHC anomaly is found in the northern tropical Pacific–that is, an eastward propagation along the equator, a northward propagation at the eastern boundary, a westward propagation along the latitudinal belt centered around 16°N, and a southward propagation at the western boundary. The OHC signal is enhanced at the western boundary and along 16°N west of the data line. Analysis of wind stress curl indicates that the enhanced OHC anomaly averaged over the entire equatorial region leads the Niño3 index by two seasons, which is approximately a quarter of the ENSO period or a little bit shorter. This fact supports the idea of the "recharge oscillator" model. Further it is shown that the magnitude of the OHC anomaly of the entire equatorial Pacific is directly related to that of the subsequent (two seasons or more later) Niño3 index, which means that the larger amplitude of the former corresponds to the larger magnitude of the latter, although there exists an asymmetry between the preceding positive and negative OHC anomalies and subsequent Niño3 index. These facts strongly confirm the previous findings. It is also shown that after the 1976/1977 regime shift the asymmetry is exaggerated and magnitudes of the OHC anomalies related to ENSO become greater.

A DESIGN STUDY FOR OBSERVING THE MERIDIONAL OVERTURNING CIRCULATION

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Using output from eddy permitting models (OCCAM, FLAME) we test methods for observing the meridional overturning circulation (MOC) in the North Atlantic. It can be shown that a relatively simple "monitoring array" is able to capture the time varying strength and vertical structure of MOC at a given latitude. The basic idea is to estimate the meridional flow by adding contributions related to Ekman transports to those associated with the vertical velocity shear. Ekman transports can be inferred from surface wind stress, while information about the vertical shear is obtained from vertical density profiles, similar to what vertical profilers could provide in the real ocean. Placed across a zonal section of the Atlantic, these profiles give an estimation of the velocity shear based on the thermal wind relation. The method is applied east of the Florida Strait at latitudes of 26.5°N (OCCAM) and 26°N (FLAME). The transport through Florida Strait is assumed to be known since in the real Atlantic cable measurements can provide accurate estimates of this transport. Based on these assumptions for the Florida Strait and for the eastern part of the Atlantic basin, both short term variability as well as long term evolution can be captured by the "monitoring array". Furthermore, it can be shown that the method works in two high resolution models with either weak (OCCAM) or vigorous (FLAME) MOC.

A HIGH RESOLUTION GENERAL CIRCULATION MODEL FOR THE TROPICAL PACIFIC OCEAN

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A 1/6° resolution general circulation model is investigated to study the dynamics of the equatorial Pacific Ocean from 1992 to 2000. The model has open boundaries at 26°N, 26°S and in the Indonesian Throughflow. Boundary conditions are prescribed from a 2° global model (ECCO project) which was constrained by altimeter data, NCEP surface forcing fields as well as monthly temperature and salinity climatologies. As a prerequisite to later assimilation runs, the model outputs are compared to ocean observations in terms of simulation of the flow field and in terms of statistics of eddy variability. In this context, sensitivity studies to forcing fields and model resolution are presented and discussed as well.

INTERANNUAL VARIABILITY IN WARM WATER VOLUME TRANSPORTS IN THE EQUATORIAL PACIFIC IN AN OGCM

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The volume of warm water (WWV) in the equatorial Pacific is likely to be related to the dynamics of the El Niño-Southern Oscillation (ENSO) cycle. The buildup and decrease of WWV before and after ENSO events and part of this variability was accounted by poleward transport across a wide range of longitudes in the interior region in previous studies. However, the contribution by the western boundary currents was also suggested. In this study, we have analyzed the results from a numerical experiment using a high-resolution ocean global circulation model to validate the model results and to investigate the role of the western boundary processes. The analysis shows that the model simulates the realistic mean and deviation distribution of depth of 20°C isotherm. The variation of the meridional transports across 8°S and 8°N in the interior region is also well simulated and comparable with the results in the previous studies using observational data. In the western Pacific, the model meridional transport across 8°S shows clear out-of-phase variation to that in the interior. The western boundary transport across 8°N shows similar out-of-phase variation but it is delayed relative to interior transport by several months in both the 1982/83 and 1997/98 ENSO events. This different behavior in the northern and southern hemisphere in the western boundary region may suggest different contributions to the variation of WWV in the equatorial Pacific.

THE 48°N ATLANTIC SECTION: CHANGES IN WATER MASSES AND TRANSPORTS DURING WOCE AND BEYOND

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Nine repeats of the WOCE/A2 section—situated between the subtropical and the subpolar gyre in the North Atlantic—since July 1993 show a significant interannual variability in the baroclinic structure; i.e. the variability in the intermediate and deep waters. In addition, data from two previous surveys in 1957 and 1982 are used. To quantify this temporal and spatial variability we calculated mass, heat and freshwater transports in different density layers and compared them with estimates in layers of neutral density. The eastward propagating Labrador Sea Water (LSW) stopped cooling in the western basin in 1995, in the eastern basin one year later. A warming period was observed at nearly constant salinity since. At the deep salinity maximum (ca. 2500 db) temperature increased in the eastern basin until 1994 with a slight increase of salinity and density, followed by cooling and a density increase until 1996. Since then, we observed a further warming and a density decrease.

In the western basin, deep waters continuously cooled until 1996 (0.4°C) with a slight freshening and increase in density. In 1993, a thick layer of Subpolar Mode Water SPMW with a temperature range of 1°C was reduced in the following years to form two sharp extrema. In 1997, these have both been 1°C warmer and 0.2 less dense then in the three previous years. Doming of the subpolar gyre and warming of the SPMW is correlated with the breakdown of the NAO in 1995-1996. Since then, a significant correlation between meridional heat transports and the meridional overturning rate (MOC), and the NAO index has broken down. The MOC was at a maximum in 1982 and 1996, at a minimum in 1957, 1997 and again in 2000. The response of the MOC to changes in atmospheric forcing as given by the NAO index peaks at phase lags of one and eight years, suggesting a change in the underlying processes.

SENSITIVITY EXPERIMENTS OF SEA-ICE PROCESSES ON WORLD OCEAN CIRCULATION BY USING A GLOBAL COUPLED OCEAN/SEA-ICE MODEL

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Recent dramatic changes of the cryosphere, including sea-ice, are a silent precursor of the effect of global warming which will be maximized in the polar region. Development of a reliable sea-ice model is an urgent issue for climate variability studies and the global warming assessment. As a branch project of the Earth Simulator initiative, we are collaborating with FRSGC to try to implement the IARC sea-ice model into our OGCM code optimized for the Earth Simulator. The basic design of the IARC sea-ice model is that of Hibler dynamics and Parkinson and Washington thermodynamics with some modifications in treating such physical processes as snow and open water as well as in coupling schemes and with a recent contribution on sea-ice and ocean interaction process by Zhang and Zhang. As a first step towards such a goal, we have implemented the IARC model into our MOM3-based OGCM with free ocean surface.

We give a brief description of the status of our coupled model development and show some basic physical performances of our model from a test validation of 50 years integration. In the validation, it takes five years for the sea-ice to reach a quasi-equilibrium state. Sea-ice distribution patterns and the seasonal cycle of thickness and concentration both in the Arctic and Antarctic oceans turn out close to the observed ones. Sea-ice thickness piles up from the Beaufort Sea to the Canadian Archipelago and the northern coast of Greenland. Around the Antarctic, the sea-ice remains as thin as tens of centimeters. We also performed experiments to explore the sensitivity of sea-ice to some physical parameters, e.g. ice strength. The results show sea ice motion and thickness are subject to changes of these physical parameters, which finally affect world ocean circulation.

EL NINO-SOUTHERN OSCILLATION AND THE ICEBERG DISTRIBUTION IN THE PACIFIC SECTOR OF THE ANTARCTIC

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Data on iceberg observations carried out with Russian research vessels from 1981 to 1994 in the Pacific Sector of the Antarctic demonstrate an interannual redistribution of icebergs. In the course of the study, there are displacements of icebergs of several degrees to the north in the eastern part of this sector and to the south in its western part in the El Niño years; in the intermediate years, similar displacements in the opposite directions are observable. An analysis of the charts of average monthly atmospheric pressure anomalies over the Southern Hemisphere shows that the initial reason for this redistribution of icebergs is a positive atmospheric pressure anomaly formed in the El Niño years over the Pacific Sector of the Antarctic, which is changed by an anomaly of the opposite sign in the intermediate years.

Calculation of the iceberg drift due to wind and currents is based on this analysis and the results of current measurements performed in 1992 in the Pacific Sector of the Antarctic during the WOCE Section S4 Pacific. A total meridional iceberg displacement of 660 km under the joint action of wind and currents obtained as a result of this calculation suffices for the observed iceberg redistribution to be explained.

TROPICAL PACIFIC SEA SURFACE AND DYNAMIC HEIGHT ANOMALIES: A DYNAMICAL VIEW OF SUBSURFACE SEASONAL TO INTERANNUAL VARIABILITY

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The variability on seasonal to interannual scales of the sea level and dynamic height in the Tropical Pacific are indices that describe the space time evolution of various El Niño events. We analyze TOPEX/Poseidon (T/P) sea surface height measurements and dynamic heights (relative to 500 m) from the TAO/Trition (T/T) array. These are compared to the corresponding parameters of the global ECCO ocean state on both two- and one-degree global grids. Only the one-degree ECCO solution assimilated all WOCE T/S profile data over the period from 1992 to 2001. We address two main questions:

(1) What are the differences between phases and amplitudes of the sea level and subsurface pressure fields of ECCO and T/T and T/P representations of the 1997-98 Tropical Pacific El Niño cycle, and
(2) To what quantitative extent is the different ECCO configuration responsible for the deviations from the observations?

LONG-TERM HYDROGRAPHIC VARIATIONS OBSERVED IN THE HAWAII OCEAN TIME-SERIES

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The Hawaii Ocean Time-series at Station ALOHA is now 14 years long, allowing us to study interannual and decadal variations in water properties from the near-surface layer to the bottom (4800 m), and in transport estimates for the upper 250 m. Despite energetic variations associated with mesoscale eddies, low frequency variability of temperature, salinity, dissolved oxygen and transports emerge without any sophisticated data processing. The dominant climate signals in the near surface properties are related to the local forcing of El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Variations in the pycnocline are attributable to large scale remote climate influences in the subtropical gyre system, such as the pronounced salinity trends attributed by Lukas and Santiago-Mandujano to North Pacific rainfall variations associated with the PDO. Variations in the deep ocean are more episodic, but not clearly related to passing mesoscale eddies. This poster presents key time series that illustrate the most important variability observed at Station ALOHA.

WATER MASS VARIABILITY IN THE HAWAII OCEAN TIME-SERIES

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Water mass variability at the HOT site is analyzed with the OMP method using data collected over 12 years. During 1989-1993, the water above 25 σ_θ (~200 m) was composed of high-salinity North Pacific Tropical Water (NPTW), reappearing suddenly in 1998 and persisting. During 1994-1997, Eastern Subtropical Mode Water was found above 24.3 σ_θ (~100 m), and low-salinity NPTW below this layer. Between 25 and 26.2 σ_θ (~350 m), Shallow Salinity Minimum Water dominated, slightly decreasing in 1992. Below this layer and above 26.5 σ_θ (~450 m) Middle Salinity Minimum Water dominated, showing an increasing trend and periodic peaks in 1990, 1994 and 1998. Between 26.5 and 27.15 σ_θ (~700 m) North Pacific Intermediate Water showed a decreasing trend between 1989 and 1996, increasing through 1999. Below this layer and above 1000 m, the Antarctic Intermediate Water dominated, showing a decrease during 1996-1999.

Short-term water mass variability between 25 and 26.5 σ_θ was generally due to waters from a region 1500 km east of the islands, identified as a source region of westward propagating eddies. The signature of a submesoscale eddy observed in January 2001 was accurately described by a water source just southwest of Baja California. Results from a numerical model of the North Pacific show that eddies generated near the west coast of Mexico can travel long distances and are able to reach the HOT site.

OCEANIC HEAT FLUX WITHIN THE PACIFIC BASIN: A WOCE SYNTHESIS

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Using data along hydrographic sections to form 60 closed boxes, an inverse model formalism is employed to diagnose the general circulation and associated water property flux divergences within the Pacific Basin. The model data are a synthesis of some 3000 hydrographic transect stations, the majority of which were measured as part the WOCE program. A few come from pre-WOCE surveys. These data are supplemented by direct velocity measurements and historical hydrography at nine longitudes about the equator. The heat flux divergence associated with both the meridional overturning and the horizontal circulation as estimated from this combination of high-resolution transoceanic data are compared to findings from the historical archive and numerical models. In particular, we report intercomparisons with time-mean air-sea heat flux estimates from the NCEP reanalysis, the COADS/de Silva climatology and recent results based on the Reid hydrographic data set.

ABSOLUTE SEA LEVEL FIELDS OF THE KUROSHIO EXTENSION DERIVED FROM DRIFTER AND SATELLITE ALTIMETRY DATA

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Lagrangian data from 657 SVP drifters are used to calibrate CNES/AVISO time-variable satellite altimeter sea level anomaly maps, and nine-year satellite altimery data are used to compute unbiased decade-mean near-surface circulation.Total mean sea level is then computed by integrating full horizontal momentumequations for the mean state and used as a reference to obtain instant maps oftotal sea level. Quasi-geostrophic approximation is corrected with respect to asymetric distribution of eddies on opposite sides of the Kuroshio Extension. Strongest eddies in the region are found to be cyclonic/anticyclonic ringsdetached from the Kuroshio Extension jet and persisting on its south/north. Importance of Bernoulli, eddy momentum convergence and wind stress terms isevaluated. Total sea level maps accord greatly with drifter trajectories and demonstrate tremendously complex patterns in the study area.

Unbiased mean velocities indicate double-jet structure of the Kuroshio/Subarctic frontal zone. Two quasi-stationary meanders of the Kuroshio Extension as well as its northward deflection east of the Shatsky Rise at 160E agree well with the mean temperature at 200 m depth. Historical hydrographic data are used to determine pressure field at 2000m depth and to outline the pattern of deep circulation. In larger area (20-50N, 120-180E) a set of recirculations is described in more details along the Kuroshio with the anticyclonic cell around Daito Island being a new discovery. Statistics of drifter trajectories is used to examine the rate and peculiarities of cross-frontal horizontal water exchange. Issues of smoothing and averaging of observational data are discussed and new methods are suggested.

TROPICAL-SUBTROPICAL WATER MASS EXCHANGES IN THE ATLANTIC OCEAN

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In this study, we examine circulation pathways, volume transports, and water mass properties in the subtropical and tropical Atlantic Ocean using historical hydrographic and surface drifter data spanning the 1950s to the 1990s. In both hemispheres, subducted Salinity Maximum Waters flow into the tropics in the pycnocline along both interior and western boundary pathways. North Atlantic ventilating trajectories are confined to densities between about 23.2 to 26.0 σ_θ and only about 2 Sv of water reaches the tropics through the interior pathway, while the western boundary contributes about 3 Sv to the equatorward thermocline flow. The pathways skirt around the potential vorticity barrier located under the Intertropical Convergence Zone and reach their westernmost location at about 10°N. In the South Atlantic, about 10 Sv of thermocline water reaches the equator through the interior (4 Sv) and western boundary (6 Sv) in a slightly higher density range than in the North Atlantic. The ventilation pathways are spread over a much wider interior window in the Southern Hemisphere than in the Northern Hemisphere, which at 6°S extends from 10°W to the western boundary. The equatorward convergent flows in the pycnocline upwell and return to the subtropics through poleward divergence in the surface layer. Geostrophic calculations indicate insignificant transport changes in interior pycnocline flow between 1954-1973 and 1974-1990, corresponding to low and high phases of the NAO index. However, in the pycnocline, significant trends towards higher temperature and salinity are seen in the tropical Atlantic. These temperature and salinity changes can be traced back to subtropical subduction zones in both the North and South Atlantic. Superimposed on these trends are decadal time scale variations in temperature and salinity in the pycnocline. Implications of these results for understanding ocean-atmosphere interactions in the Atlantic basin will be discussed.

ANOMALOUS UPPER-OCEAN CHARACTERISTICS AT THE WESTERN ANTARCTIC PENINSULA, WINTER 1998, IN RESPONSE TO ENSO

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We present a near year-round series of hydrographic and biogeochemical measurements from Marguerite Bay on the western Antarctic Peninsula, from 1998 to 2002. Data were obtained via CTD casts from an inflatable boat, or through holes cut in the ice in winter months. As well as strong seasonality in the data, there are large interannual signals apparent. The austral winter of 1998 is markedly anomalous, due to its very deep winter mixed layer; this created the deepest and most saline Winter Water (WW) observed during the sequence of measurements. Winter 1998 was a period of rapid decay of a warm ENSO event, and featured anomalously strong warm northerly winds over the Amundsen- Bellingshausen Sea area, and also significant negative sea ice anomalies. This apparently contradicts the high salinity of the WW formed in winter 1998, which is due to enhanced sea ice production. The explanation is that the locality of the measurements was kept largely ice-free due to the stronger northerly winds, and hence was able to more continuously form new sea ice throughout the season. It is known that primary production depends on stratification, and we observe a weak and delayed spring bloom following winter 1998. Given the quasi-cyclicity of ENSO events, one might expect recurrences of this feature. The western Antarctic Peninsula has undergone some of the strongest warming observed anywhere in the world over the last 50 years; associated with this has been a decrease in sea ice. As these trends continue, we expect to see secular trends in upper-layer stratification in our data, and consequent changes in primary production.

VARIABILITY OF PACIFIC PYCNOCLINE OVERTURNING IN A COUPLED GCM

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The upper subtropical and tropical Pacific Ocean are linked by a wind-driven overturning circulation that has been hypothesized to play a key role in Pacific decadal variability. Analyses of available measurements by McPhaden and Zhang indicate that this circulation varies considerably on decadal timescales, having decreased by about 50% between the 1970s and 1990s. We have examined the variation of Pacific pycnocline overturning found in control and forced climate change simulations made with the second-generation CCCma coupled global climate model (CGCM2). The control simulation exhibits decadal variations in equatorward meridional transport which correlate inversely with El Niño/PDO-like SST patterns. The global warming simulation exhibits a superimposed secular decline of about 10% by the year 2000. The ~50% decline observed by McPhaden and Zhang is consistent in sign but inconsistent in magnitude with the decline due to global warming simulated in the model. The implication is that the observed decline represents the combined effects of global warming and the strong ENSO/PDO-like conditions that prevailed in the 1990s as compared to the 1970s. We show that variations in subtropical/tropical heat exchange in the model are mainly due to anomalous transports operating on the mean temperature (v'T) which considerably outweigh variations due to transports of temperature anomalies by the mean circulation (vT').

RECENT CIRCULATION OBSERVATIONS IN THE WESTERN TROPICAL NORTH ATLANTIC

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Shipboard acoustic Doppler current profiler (ADCP), lowered ADCP measurements, and hydrographic observations are used to examine the flow field along 16°N and in the inflow region to the Caribbean Sea. The observations from two cruises are presented, one conducted in December 2000 and the other in June 2002. ADCP measurements were performed on both cruises using a 75 kHz Ocean Surveyor (OS) with a range of up to 600 m. Additionally, on the second cruise the new 38 kHz OS with a range of up to 1600 m was used. The flow field along 16°N turned out to be highly variable and characterized by an eddy field. This stands in contrast to the results of a high-resolution numerical model.

PRECIPITATION SENSITIVITY TO REGIONAL SST IN A HIGH RESOLUTION CLIMATE MODEL DURING THE WEST AFRICAN MONSOON.

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A 10-year (1983-1992) atmospheric simulation has helped to understand interactions between atmosphere, ocean, continental surfaces and hydrologic processes over West Africa (27°W-16°E, 5.5°S-27°N) where land and sea surfaces are approximately equal. Preliminary results show the sensitivity of precipitation derived from a regional climate model (RCM) to sea surface temperature (SST) during the monsoon. We compare results from three simulations of the years 1983 and 1984, considered the driest for West Africa during the 1951-1998 period. Two experiments are simulations of the years 1983 and 1984 initialized and forced with ECMWF reanalysis data. A third experiment is a hybrid simulation of 1983; it is the same as the first simulation except that the SST field is taken from the 1984 ECMWF. In this way, meteorological forcing fields at the boundaries are unchanged and only ocean surface conditions are modified.

Considering the two realistic experiments in comparison with observations, the RCM MAR (Modèle Atmosphérique Régional), running at a horizontal resolution of 40 km, can simulate the West African monsoon with its interannual variability and also the seasonal cycle with installation phase, the high rain period with abrupt northwards shift, and the southward retreat phase.

SST effects are analyzed by comparing the standard and hybrid simulations of 1983. The precipitation pattern obtained with the simulation of the year 1983 using the warmer SST of 1984 presents more similarities with the precipitation pattern of the year 1984 than with the one of 1983 in the standard experiments. SST at the regional scale then appears to be a major factor of the interannual monsoon flow variability. In particular, the increase of precipitation along the coast is associated with an increase of equivalent water content (EWC) in the low layers of the atmosphere. The warmer SST then induces larger evaporation flux and higher level of EWC. Southern advection of the monsoon flux then transports the water to the continent, and an increase of precipitation is obtained especially in the coastal zone.

OCEANIC PARTICULATE ORGANIC CARBON: AS SEEN WITH A WOCE GLOBAL SNAPSHOT

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A global set of transmissometer data has been collected during 17 WOCE expeditions (1991-1994) and several other large-scale hydrographic programs. These data include basin-wide transects in the North and South Atlantic, North and South Pacific, Indian, and Southern Oceans. Data were converted to Particulate Organic Carbon (POC) concentration using the beam attenuation:POC relationships derived earlier by our group during several studies. The POC distribution was analyzed for the entire water column as well as for the upper 500 m and basin-wide POC assessment presented. The large-scale phenomena like El Niño (1990-1995) events in the Pacific or high productive area in the Southern Ocean could be clearly seen in the POC sections. These data provide many opportunities to explore the relationship between facets of marine bio-optics, POC distribution and hydrographic conditions. A few of the topics we are pursuing include:

1. The relationship between mixed layer depth (MLD), hydrography, the distribution of POC and depth of POC maxima and minima.
2. The integrated stock of POC in the euphotic zone.
3. The standing stock of POC integrated to the depth to which ocean color sensors receive signals compared with the total integrated stock of POC in the euphotic zone (or the depth to "background" POC).
4. Prediction of POC based on various products of ocean color.

ICELAND BASIN EXPORT OF MODIFIED ICELAND-SCOTLAND OVERFLOW WATER AND LOWER DEEP WATER

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Three one-year long current meter arrays were moored at the southwestern and southern end of the Iceland Basin between 1997-2001. We use results from the 41 deep current meter records in ten moorings to study the export of Iceland-Scotland Overflow Water and Deep Lower Water. Unexpectedly, we identified only $2x10^3$ m^3s^{-1} (Sv) flowing westwards towards the northern channel of Charlie Gibbs Fracture Zone in 1999/2000. One year before we observed a steady eastward inflow of 5 Sv in the matching southern channel. Almost the same amount was exported southward between 24.5° - 29.5°W along 52°N. We compare the observations (i) with results from a regional high-resolution circulation model of the subpolar gyre in the North Atlantic and (ii) with tracer spreading data along the Mid-Atlantic Ridge recently presented by U. Fleischmann et al.

A STUDY OF THE RESPONSE OF RAINFALL, WATER RESOURCES AND CLIMATE TYPES OF INDIA TO GLOBAL ANOMALIES

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Global anomalies are always reflected in the rainfall and hydrologic balance, affecting the economy of developing nations like India that largely depend on the rain fed agriculture. Vagaries in the rainfall, especially of the monsoons, show wide inter-annual variations, changing moisture regimes and shifting the regional climate temporarily. In this paper, possible links between the nature of Indian rainfall and anomalies in the Pacific and Arabian Sea regions have been examined. Strength of the monsoon during different phases of the SOI during the last century has been studied. Changes in the hydrothermal coefficient have been analysed to check the response of water resources to global anomalies. Monsoons first hit the west coast of India and the influence of the sea here is more than in the interior, as the coast is covered by mountain chains. Shifts in climate type (Thornthwaite's classification) in this region during extreme years of SOI and which are also related to SST anomalies in the Arabian Sea and Nino regions have been computed, with special emphasis during the WOCE period. Data of WOCE and CDIAC have been used for the study. Results show that the positive rainfall departures have a correspondence with the high phases of the SOI. The climate type has undergone wide fluctuations related to the anomalies during the study period.

ROLE OF INTERBASIN WATER EXCHANGES THROUGH NARROW PASSAGES BETWEEN THE ATLANTIC OCEAN, THE GIN SEAS AND THE ARCTIC OCEAN IN THE FORMATION OF THE ATLANTIC DEEP CIRCULATION

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The deep circulation associated with the formation of North Atlantic Deep Water (NADW) carries a large amount of heat to high latitudes and is one of the most important factors characterizing the present state of the climate. Deep convection occurs in the Greenland, Iceland and Norwegian (GIN) seas, and the dense water formed there flows over the Greenland-Iceland-Scotland ridges, contributing to the NADW. Nakano and Suginohara succeeded in representing the overflow in an OGCM by incorporating a bottom boundary layer parameterization by prescribing the temperature and salinity in the GIN Seas. However, investigating the processes that are important for the dense water formation in the GIN Seas is also necessary for understanding the mechanisms which control the Atlantic deep circulation. Here, we show that proper representation of water exchanges at the narrow passages (e.g., Fram and Denmark Straits) is necessary for realistic deep water formation in the GIN Seas. We compare the results of experiments with different horizontal resolution at these narrow passages. In these experiments, we restore the sea surface salinity to the observed values. The Atlantic deep circulation is realistically reproduced in all the experiments where the southward volume transport associated with the production of NADW is about 15 Sv at the equator. But the experiment with coarse resolution at the narrow passages cannot reproduce realistic exchanges among the GIN Seas, the Arctic Sea, and the Atlantic, which leads to a density decrease in the GIN Seas. This decrease is compensated by unrealistic freshwater loss at the surface in the GIN Seas; the Atlantic deep circulation is also maintained by this unrealistic freshwater loss. Fine resolution at the narrow passages improves the water exchanges, and the unrealistic freshwater loss in the GIN Seas is largely reduced.

REPEAT HYDROGRAPHY ALONG WOCE LINE PR-6

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One of the Canadian contributions to the WHP has been continued observations along the line designated PR-6, also known as Line P. PR-6 is unusual among the WOCE Repeat Hydrography lines in that it already had a long history of observations before the WOCE field program began. This poster will outline:

a) the history of observations along PR-6 (Line P)
b) the variability observed along PR-6 during the WOCE observational period
c) the plans for continued observations along PR-6

In summary, though the first observations at Ocean Station Papa (50°N 145°W in the Gulf of Alaska) were made in 1949, useful observations date from 1956. Sampling strategies have varied along Line P and these variations will be outlined. Major El Niño events impact the distribution of properties along Line P. Although the events of 1991-1994 were relatively small, they had a cumulative effect on the surface waters of the Gulf of Alaska. By contrast the large El Niño event of 1997/98 had an immediate impact on oceanographic properties in the Gulf of Alaska and along Line P.

Observations along Line P are continuing, in most years we complete three cruises; typically in February, May/June, and August/September. These are complex surveys of the physical, chemical, and biological variables. With the advent of Argo it has now become possible to create artificial Line P surveys at about 10-day intervals, although only of the physical variables at the present time. These are of relatively low resolution and limited to water depths less than 2000 decibars, but offer very frequent visualisations of the climatic state of the Gulf of Alaska. Examples of such artificial surveys will be presented.

VARIABILITY OF COASTAL CURRENTS AND FRESH-CORE EDDIES IN THE WESTERN SUBARCTIC PACIFIC: LINKS TO CLIMATE VARIABILITY

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CTD observations from the western subarctic boundary current region of the Pacific during the past decade reveal large variability in the horizontal scale and dynamic topography of Oyashio eddies; observations from 2000 show properties similar to the pre-1990 regime. From 1990 to 1997, the Oyashio eddies trended toward decreasing upper layer T, increasing vertical stratification, strengthening of the coastal branch of the Oyashio, decreasing horizontal size, and decreasing dynamic heights. Observations in 2000, however, reveal properties like those prior to 1990: a large, deep eddy off Boussole Strait having high dynamic topography. Coincident with changes in eddy properties is strong interannual variability in sea level difference between stations off East Kamchatka and Hokkaido. This variation in coastal sea level is argued to be a steric effect associated with freshwater transport of coastal currents. Cross-strait sea-surface slope of the Strait of La Perouse is the main driving force for flow from the Sea of Japan to the Sea of Okhotsk. The variations of this slope are created by the East Sakhalin Current and Soya Current. These currents show strong seasonal and interannual variability in dynamic height in association with increased fresh water content and a deeper pycnocline. Variability in the western boundary current domain is also accompanied by trends in other climatological indicators, including the winter extent of sea-ice in the Sea of Okhotsk, the duration of sub-zero temperatures, annual precipitation in eastern Siberia, and the Arctic Oscillation index.

DEEP-WATER CIRCULATION AT THE EXIT OF THE LABRADOR SEA AND EAST OF THE GRAND BANKS

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As part of the IfM Kiel SFB 460 project "Dynamics of thermohaline circulation variability", observations of the Deep Western Boundary Current (DWBC) have been carried out at the exit of the Labrador Sea near 53°N during 1997-2001 and east of the Grand Banks since 1999, using moored arrays, profiling floats and repeat shipboard current profiling sections. The DWBC transports and variability on intraseasonal to interannual timescales are presented in comparison with comparable results from the IfM Kiel FLAME model. A recent focus of the model-observation intercomparisons is also addressed: while the observed southward DWBC export east of the Grand Banks alone is large enough for the deep overturning circulation across the WOCE A2 line, the results obtained by models of various type and resolution suggest significant contributions by interior pathways and recirculation of the DWBC flows. During the observational period of the Kiel SFB project, the production of Labrador Seawater has drastically decreased and these changes are also documented for the DWBC regime of the region.

A NEW FSU WINDS AND FLUX CLIMATOLOGY

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An objective technique developed by the WOCE Surface Fluxes SAC is used to create a new monthly climatology for surface fluxes and related fields. The wind (pseudostress) products are improvements over the subjectively analyzed FSU winds. Fields of turbulent surface fluxes and the variables needed to calculate these fluxes are also generated. The fields are created through minimization of a cost function, which maximizes information from the observational data and minimizes smoothing. This approach ensures internal consistency between the turbulent fluxes and the related fields. Comparisons are made between the new FSU fields (based on volunteer observing ships and buoy observations), the old subjective FSU fields, individual TAO buoys, the NCEP reanalysis, and fields based solely on the SeaWinds scatterometer observations.

Results from the new (objective) FSU winds will be presented for the tropical Pacific and Indian Oceans. The new FSU wind fields have stronger convergence zones (the ITCZ and SPCZ) as well as better zonal resolution. An ocean model, forced with a preliminary release of the winds, produced much more realistic currents than when forced with the old FSU winds. Comparisons for ENSO warm and cold phase years will be presented for the new and old FSU products. Turbulent heat fluxes and the challenges to producing heat flux fields will also be discussed.

NORTH ATLANTIC WATER MASS STRUCTURE, MERIDIONAL OVERTURNING AND MODES OF THE CIRCULATION

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Interdecadal and interannual climatic changes of thermohaline characteristics and circulation of the North Atlantic are considered. The results are based on the comparison of the Russian 1993, 1997, 1999 and 2001 WOCE sections along 36°N, 48°N, 53°N, 60°N and the western slope of the Mid-Atlantic ridge with historical data. Interannual changes in water mass structure and characteristics along these sections reflect changes both in water mass formation region and general North Atlantic circulation scheme.

The two scenarios of an interaction of the Meridional Overturning Circulation (MOC) with the full-depth circulation of the North Atlantic have been proclaimed by us earlier. Now we connect these scenarios with vertical and horizontal recirculations and reveal a new transition stage in the late 1990s. Our results proved the suggestion that the variability of the recirculation activity is out of phase with variations of MOC development and thus agree with observations of LSW formation. We assume that active recirculation tends to preserve the volume of water within the local horizontal circulation cell leading to its homogenization and limiting its meridional spreading. In the late 1990s the upper and deep water transport advection of heat were higher than normal. It might reflect a new transition to a one-cell MOC circulation similar to the situation of the early 1980s. But the situation of the last years was still far from that of the early 1980s because of the abnormal volume of rather dense LSW penetrating to mid-latitudes during the mid 1990s and conserving the situation for years. Now the North Atlantic appears to show a third stage with bifurcation. Of course, the return to the first stage is more probable. But the situation may shift to another intensive MOC mode with convection in the Labrador Sea down to the denser deep layer.

ECCO ESTIMATES OF LARGE-SCALE CHANGES AT THE HAWAII OCEAN TIME-SERIES STATION

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A comparison of ECCO ocean estimates is being provided with independent observations at the HOT deep-water station. The goal is to compare and identify similar inter-annual changes in the HOT observations and use the ECCO estimates to infer their origin. Based on the ECCO WOCE synthesis, a complete balance of temperature and salinity (freshwater) anomalies will be provided at the HOT station to help interpret the local time series measurements as a function of depth. In addition we will use the adjoint framework to identify the area (in space and time) that can in principle be influenced by the HOT measurements in a dynamically consistent assimilation framework.

FROM WOCE TO CLIVAR - MONITORING THE VARIABILITY OF THE MID-LATITUDE NORTH PACIFIC OCEAN

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The low frequency variability of the ocean's circulation and its relationship to the variability of marine populations has been explored to first order. In these papers, the authors explored the relationship between the low frequency changes in sea surface temperature (SST) with disturbances in the coastal ecosystems. Large scale interdecadal shifts of SST and atmospheric pressure are associated with a southward shift and intensification of the Aleutian Low. With the atmospheric pressure shift is a shift in the location of the prevailing westerlies over the mid-latitude central and eastern North Pacific. These changes also cause changes in the sea surface height (SSH) field reflecting cooler and denser water below the surface and which also may reflect an increase in mixing of nutrient rich waters. This paper gives an example of how a space-based monitoring system might be developed to help in the prediction of changes to various fish stocks. Through the use of satellite data (altimeter and infrared) and WOCE repeat section PR06, the model's realism is quantified. Once quantified, fields of 20 years of modeled (0.25 resolution Parallel Ocean Climate Model 1979-1998) sea surface heights and temperatures are used to develop an algorithm to monitor the low frequency variability in the heat content of the North Pacific's mid-latitudes associated with regime shifts in the coastal circulation patterns of the Alaskan currents and the California currents. The model shows that the mid latitude Pacific circulation subsurface variability is primarily due to the large, low frequency horizontal N/S movement.

During some years, changes may also be due to large scale atmospheric changes in local wind patterns. It is proposed that this type of monitoring might be useful to help with understanding the basin's variablity and its relationship to the variability in our fisheries. Initial related results from an on-going 40-year 0.2° resolution ocean simulation will also be given.

DEEP MIXING IN THE GREENLAND SEA

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The Greenland Sea is one of the source regions for the deep water masses of the world ocean. The work presented here is aimed at a better understanding of the processes which are responsible for the properties and the temporal changes of the deep water in the Greenland Sea. The focus is on the strength of vertical mixing as a means of deep water renewal as opposed to the sporadic deep convection. The data set for the study comprises measurements of the velocity field in the central Greenland Sea and near the surrounding ridge systems which have been obtained with a lowered ADCP (Acoustic Doppler Current Profiler) in 1998. The measurements of the vertical shear of the horizontal velocity, together with standard CTD measurements, allow us to determine diapycnal diffusivities and thus estimate the relative importance of mixing processes in the area. The results are discussed in the context of the local properties of the water column and the internal wave field.

CURRENT RESPONSE TO MONSOON ONSET AND MONSOON BREAKS ON THE SOUTH COAST OF WESTERN SUMBAWA, INDONESIA

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Direct current and temperature measurements at the Senunu shelf off the south coast of Western Sumbawa Island, in the north eastern part of the Indian Ocean record evidence of downwelling during periods of western monsoon onset and eastern monsoon breaks in 2000 and 2001. The downwelling is associated with the eastward coastal Kelvin wave that is the extension of the South Java current. Cooling associated with upwelling at the south coast of Sumbawa was recorded throughout the eastern monsoon of 2000 and 2001. Time-series measurements of weather and oceanographic parameters show strong interaction between the monsoon system, regional ocean circulation patternsand the local weather.

HadCEM — AN EDDY-PERMITTING GLOBAL COUPLED MODEL

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A global coupled atmosphere-ocean-sea-ice GCM with an eddy-permitting ocean (HadCEM) has now completed a 150-year control run and an 80-year idealised climate change run at the Hadley Centre. The model is a development of the successful HadCM3 model and uses exactly the same atmospheric and sea-ice components, with the ocean model having a full suite of physics and using a 1/3 degree resolution; parallel low resolution experiments have also been completed.

There are significant improvements in the ocean circulation at the higher resolution, including improved boundary currents, a more active equatorial circulation and Agulhas eddies shed into the South Atlantic. There is also a smaller mean water mass drift away from the initial conditions and improved large-scale flows. The impact on the mean atmospheric climate is locally significant, with improved SST's giving land temperatures which are several degrees closer to observations than found in HadCM3. However, the large-scale changes to the mean climate and its variability are rather more subtle, with little change seen in the ENSO cycle despite the improved ocean circulation.

The simulated climate response to a quadrupling of CO_2 does seem to be sensitive to ocean model resolution. Large-scale mass and heat transports are seen to change less in the high resolution model, leading to enhanced warming particularly in the Northern Hemisphere. At issue is whether these changes are a matter of different adjustment time scales for the different models, or whether ocean model resolution changes the simulated climate sensitivity.

CHANGES IN THE DEEP AND INTERMEDIATE WATERS OF THE SUB-POLAR GYRE OF THE NORTH ATLANTIC SINCE THE 1950S

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We map temperature and salinity on the density surfaces representing the cores of major deep water masses for different decades and show how the deep freshening is carried around the sub-polar gyre by the deep western boundary current and is spread then into the interior by the North Atlantic Current. The freshening has extended into the sub-polar gyre and is also being returned to the sub-polar gyre through the Gulf Stream - North Atlantic current exchange.

The Newfoundland Basin is a key location to observe these exchanges. While the freshening is observed there, the character of the time series are considerably different from those constructed for the Labrador Sea. These changes are interpreted as resulting from changes in the transport and mixing of waters as they pass around Flemish Pass out of the Labrador Sea.

While changes to the salinity field are dramatic, associated changes to the density field have greater dynamical consequences. The thickness of the density surfaces associated with the Labrador Sea waters have increased significantly between the 1960s and the 1990s over the entire sub-polar gyre. This means that the waters in the upper 1.5 km have become denser while those deeper than 2 km have become less dense. These changes will impact the strength and deep structure of the North Atlantic current.

To assess the excess of fresh water due to the freshening of the sub-polar North Atlantic we conducted volumetric T-S analyses of the water masses in the region and calculated the changes in the heat and fresh water in density layers and in the water masses. The total gain of fresh water in intermediate to bottom waters exceeds 4 meters of which 2.5 is associated with the Labrador Sea Water; 1 m and 0.6 m are contributions of Northeast Atlantic Deep and Denmark Strait Overflow water, correspondingly.

LONG-TERM VARIABILITY OF SURFACE TEMPERATURE IN THE KUROSHIO/ OYASHIO EXTENSION REGION

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Long-term variability on a time scale longer than 5 years of the surface temperature in the Kuroshio/Oyashio Extension region is investigated using an ocean general circulation model of the Meteorological Research Insitute (MRI-OGCM). It is shown that the long-term change in the surface temperature in the Kuroshio Extension region is dynamically distinct from that in the subarctic front region. In the subarctic front region, change in the surface temperature results from the shift of the boundary between the subpolar and subtropical gyres, which varies (by a lag of 4 years) with the wind stress curl in the central North Pacific at 40°N due to the meridional shift of the Aleutian Low. In the early 1980s, southward shift of the gyre boundary leads to the positive heat flux anomalies in the subarctic front region. In the Kuroshio Extension region, on the other hand, surface temperature changes due to the leading heat advection by the Kuroshio Extension and by the compensating surface heat flux. Transports of the Kuroshio and Kuroshio Extension increased in the mid 1970s lagging by three years the wind stress curl around 180°, 30°N. The increased heat advection induces the warming of the surface layer in the Kuroshio Extension region, increasing the heat release to the atmosphere. Heat budget analysis qualitatively supports the hypothesis of oceanic negative feedback to the atmosphere in the Kuroshio Extension region, and positive feedback in the subarctic front region. However, a quantitative comparison between the subarctic front and Kuroshio Extension regions shows that the surface temperature and heat flux are much larger in the subarctic front region than those in the Kuroshio Extension region. This means that positive feedback could be dominant in the Kuroshio/Oyashio Extension region.

HOW QUIKSCAT DAILY WINDS BRING SIMULATIONS OF THE SEA LEVEL IN THE INDIAN OCEAN CLOSER TO TOPEX OBSERVATIONS

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We explore the impact of daily winds from QuikSCAT on sea level changes in the Indian Ocean using a 4.5 layer model. Two experiments were performed, one forced by FSU monthly winds and the other by QuikSCAT daily winds with its monthly mean replaced by FSU, while heat and fresh water fluxes are climatological. Model results indicate that QuikSCAT winds bring the simulated sea level to a closer agreement with the TOPEX/POSEIDON observations. This suggests the importance of the daily wind variability observed by QuikSCAT, which is passed into the ocean to generate oceanic processes such as mixing and entrainment that are more consistent with reality. Compared to the spectrum of forcing winds, significant shift of energy toward lower frequency is found in the sea level both for TOPEX/POSEIDON and simulations. The ocean receives energy in high frequencies from QuikSCAT forcing and redistributes it to the lower frequencies in the sea level.

TESTING THE OCEAN COMPONENT IN A COUPLED CLIMATE MODEL

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A new coupled climate model, FGCM-0, was developed based on the IAP thirty-level and 1.875° x 1.875° OGCM, and the NCAR AGCM, CCM3. Different from the coupled models previously developed at IAP, the FGCM-0 is a "directly" coupled model, without the use of flux adjustment. A 60-year integration of FGCM-0 has been successfully completed, following a 1000-year run of the ocean-only model. The simulated wind-driven and thermohaline circulations were evaluated against available observations and in comparison with those of the ocean-only model. In particular, a quantitative testing was performed, focused on the mean climatology of SST and thermocline in the tropical Pacific Ocean. It is found that while the simulated permanent thermocline is greatly improved due to the use of the GM90 mixing scheme, there are still biases in the simulated upper-ocean thermal structure. Among others, the water around the thermocline in the tropical South Pacific is much colder than the observed as well as the simulated by the ocean-only model. As a consequence, the thermocline simulated by the FGCM-0 tends to be latitudinally symmetrical about the equator. This may represent an image of the "double ITCZ", a common problem in some "directly" coupled models, in the ocean component of a coupled climate model. Possible causes for the bias were discussed.