A LAGRANGIAN NUMERICAL STUDY OF THE SALINITY MAXIMUM WATER IN THE ATLANTIC OCEAN

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The Atlantic Salinity Maximum Waters formed through excess evaporation in the tropics and subtropics of both hemispheres contribute to the high salinities of the North Atlantic upper layers which, through their preconditionning effect on the formation of North Atlantic Deep Water, are a key element of the global thermohaline circulation. The origins and fates of the SMW are studied using monthly outputs of a numerical simulation of the world ocean climatological circulation. After defining formation domains from the surface salinity field and the vertical stratification, a Lagrangian technique is used to estimate the formation rates and main pathways in each hemisphere, and the role of this water in the framework of the warm water return flow of the meridional overturning cell.

Formation rates around 9 Sv and 11 Sv are found in the southern and northern hemisphere, respectively. While the export of the southern SMW from its formation area is realized by the western boundary currents, that of the northern SMW mainly results from interior subduction. Equatorward of the formation regions, a fraction of each SMW variety is entrained in the subtropical cells that connect the subtropics to the equatorial region. Poleward of them, both varieties feed the regions of Subtropical Mode Water formation around 35° of latitude in both hemispheres. The bulk of the transport associated with each variety eventually turns northward: this amounts to ~6 Sv of southern SMW gathered in the North Brazil Undercurrent, and ~10 Sv of northern SMW found in the Gulf Stream at 35°N. Of the 13.4 Sv northward transport of the meridional overturning cell estimated by the model at 47°N, more than 50% (6.9 Sv) is associated with water which has transited through at least one of the SMW formation regions.

EDDY-TOPOGRAPHY INTERACTIONS IN THE ARGENTINE BASIN

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The role of topography in the large scale circulation of the ocean has been an uncertain issue in physical oceanography for some time. Recently, independent but simultaneous developments in theory, observations and models in physical and geological oceanography came together to support the existence of the Zapiola Anticyclone, a previously unknown topographically forced circulation in the South Atlantic whose strength rivals that of the Gulf Stream. Further, the phenomenon in question may well be found to play a role in climate, meteorology and biological oceanography, as well as physical and geological oceanography. Theory argues the anticyclone is driven by ocean turbulence along topographically controlled pathways. The role of the eddies has been substantiated by numerical experiments and physical and geological observations argue for the existence and persistence of the feature. Numerical simulations have reproduced several aspects of the anticyclone, including such features as the surface manifestations of eddy variability over the circulation as measured by satellites.

ON THE FORMATION AND CIRCULATION OF ADÉLIE LAND BOTTOM WATER IN EAST ANTARCTICA

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Recent studies suggest that the Adélie Land coast is the second largest source, by volume, of Antarctic Bottom Water. Oceanographic and mooring work in the source region next to the Mertz Glacier off the Antarctic coast between 145°E and 150°E was undertaken to determine the production rate of Adélie Land Bottom Water.

Time-series data from Seabird micro-cats and ADCP current meters deployed on the continental shelf, across the shelf break and within the Adélie Depression show the volume of dense shelf waters increasing until August. In August the dense shelf water reaches the depth of the sill and escapes over the shelf break. A process modeling experiment applying the C-HOPE global ocean model to the region provides comparisons with the observed results and greater scope for understanding the sensitivities of the overall system to seasonal variations. The peak outflow of these dense water at the shelf break is > 2 Sv with an annual average between 0.2 and 0.4 Sv for the 1998 and 1999 years. The observed outflows from the Adélie Depression agree well with the ocean model for these years. Using the observed bottom water masses found offshore from WOCE sections we estimate that the contribution of the Adélie Land Depression to Antarctic Bottom Water formation to be between 0.6 and 1.0 Sv.

MODEL RESPONSE OF NORTH ATLANTIC HEAT TRANSPORT AND OVERTURNING TO CHANGES IN THE PROPERTIES OF OVERFLOWS ACROSS THE GREENLAND-SCOTLAND RIDGE

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The response of the large-scale circulation of the North Atlantic to prescribed changes in water properties north of the Greenland-Scotland Ridge is examined in an eddy-permitting GCM. The properties of the plume of Denmark Strait Overflow Water in a reference experiment are compared to synoptic observations and indicate a reasonable representation of density-driven downslope flow by the model's subgrid-scale parameterization.

In a series of process studies, it is demonstrated that the meridional overturning and heat transport are sensitive both to the density of the overflows and to the lateral mixing parameterization of the model. While the change in throughflow in the Denmark Strait is rather moderate (± 0.3 Sv for ± 0.05 sigma-units in prescribed density), after the descent of the plume the response is considerably amplified by entrainment (± 2 Sv for a reference value of 17.8 Sv). Timescales of the adjustment to a new steady state of the overturning are 5-10 years.

The ocean model is part of FLAME (Family of Linked Atlantic Model Experiments), a PE-model based on the GFDL-MOM code. Horizontal resolution is 1/3 degree * cos (latitude), with 45 levels in the vertical.

ANALYSIS OF THE CIRCULATION IN THE WESTERN TROPICAL ATLANTIC THROUGH LADCP MEASUREMENTS AND INVERSE MODEL RESULTS

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Direct velocity measurements carried out during two WOCE cruises in September 1995 and April 1996 brought to light the spatial structure and intensity of the main top-to-bottom currents in the western tropical Atlantic Ocean for two opposite seasons. An inverse model was applied to the data to estimate the transport budgets. The circulation is very vigorous close to South America and becomes sluggish closer to the mid-Atlantic ridge. The Warm Water budget, from the surface to the Antarctic Intermediate Water (AIW) layer, presents fundamental differences. In April 1996 the North Brazil Current/North Brazil Undercurrent (NBC/NBUC) was stronger at 35°W and 7°30'N than in September 1995, during the NBC retroflection season. Inverse modeling gives a net eastward transport at 35°W in April 1996, north of the NBC/NBUC, while it shows to be slightly westward in September 1995 due to a particularly strong South Equatorial Current.

In the Cold Water layers, current measurements and inverse model results display a very strong southeastward flowing Deep Western Boundary Current (DWBC) at 7°30'N (~40 x 10^6 m^3s^{-1}) in the upper range of previous estimates. This large transport is confirmed by LADCP measurements from April 1996 south of 7°30'N at 44°W. The southeastward flowing boundary flow (~100 km wide) was compensated by interior northward recirculation west of the mid-Atlantic ridge. At 35°W, net eastward export of cold water amounts to ~9 x 10^6 m^3s^{-1} during the two cruises.

The DWBC location at 35°W was found at 3°S in September 1995, and at 1°30'S in April 1996. An interesting feature of the current measurements is the absence of Deep Equatorial Jets at 45°W, north of 0°25'N. There the DWBC is quite well defined, while other data sets suggest the presence of Deep Equatorial Jets close to 44°W-Equator.

VARIABILITY OF AABW CHARACTERISTICS IN THE EQUATORIAL CHANNEL AT 35°W

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Hydrological data and tracer (silicate, oxygen and CFCs) analyses have been performed, in order to describe the time and space variability of characteristics and transport of the Antarctic Bottom Water (AABW) entering the equatorial channel at 35°W. The 35°W sections have been sampled during several cruises from 1990 to 1999 as part of the international WOCE and CLIVAR efforts. There is no evidence for an AABW warming during the 1990s besides the great seasonal variability principally linked to LNADW/AABW transports variability. Three additional cruises made in the 1970s and 1980s complete the time-series which shows that, during the last three decades, the maximal AABW input occurred in the early 1990s.

THE DEEP EQUATORIAL AND EXTRA-EQUATORIAL JETS IN THE ATLANTIC OCEAN

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Deep velocity profiles have been taken in the western and central equatorial Atlantic Ocean during WOCE (CITHER, ROMANCHE and ETAMBOT) and EQUALANT cruises. They identify equatorially trapped deep jets with similar features to those of the Indian and Pacific Oceans with a zonal velocity of the order of 10 to 20 cm/s. The EDJs, observed between 1°30'N and 1°30'S, are embedded in a large vertical-scale current that changes direction with time, and are surrounded by columns of permanent eastward currents (the ExtraEquatorial Jets or EEJs) at 2°N and 2°S. The EDJs-EEJs system has been observed from the western boundary to 10°W. Velocity and tracer measurements confirm the direction reversal of the stacked EDJs which is not seasonal. During the only experiment that took place in the eastern basin during the boreal summer of 2000, the deep equatorial jets were observed to vanish towards the African coast (0°E and 6°E).

In addition to direct velocity measurements, tracer distributions (mostly CFCs) give indications of water-mass feeding of the EDJs and EEJs by the Deep Western Boundary Current. Furthermore, the comparison at 10°W of currents measured one year apart (in boreal summer 1999 and 2000) along with CFC distributions confirm the existence of a permanent eastward route along the equator for part of the North Atlantic Deep Water, which reaches the African coast near the equator.

DIRECTLY-MEASURED MID-DEPTH CIRCULATION IN THE NORTHEASTERN NORTH ATLANTIC OCEAN

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As part of a large international effort to directly observe the circulation throughout the subpolar North Atlantic Ocean, several research groups from the U.S., the U.K., Germany and France collaborated in a major initiative to measure the absolute velocity at two levels in the northeastern North Atlantic using acoustically tracked subsurface floats. The northeastern North Atlantic is important to the thermohaline circulation; this is where warm subtropical water is transported to high latitudes. A total of 223 float tracks, representing 328 float-years of data, were combined to generate maps of mean absolute velocity and eddy kinetic energy at the thermocline and Labrador Sea Water levels. We find that most of the mean flow transported northward by the North Atlantic Current at the thermocline level recirculated within the subpolar region and relatively little entered Rockall Trough or the Nordic seas. Saline Mediterranean Water reached high latitudes not by continuous, broad-scale, mean advection along the eastern boundary as previously described, but by a combination of narrow slope currents and mixing processes. At the Labrador Sea Water level, a strong, topographically constrained current associated with the overflow of dense water from the Norwegian Sea flowed around the northwestern Iceland Basin along the continental slope and Reykjanes Ridge, and closed, counterclockwise recirculations existed adjacent to this boundary current. At both levels, currents crossed the Mid-Atlantic Ridge, eastbound and westbound, preferentially over deep gaps in the ridge. The latter result demonstrates that seafloor topography can constrain even upper ocean circulation patterns, possibly limiting the ocean's response to climate change.

CIRCULATION IN THE WESTERN ARABIAN SEA AND ITS VARIABILITY FROM INTRASEASONAL TO INTERANNUAL

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Current transports and water mass properties in the western Arabian Sea are analysed using shipboard surveys, moored stations and altimetry. Strong year-to-year variability is found in the strength, position and decay of the "Great Whirl" during the summer monsoon. The result of numerical simulations indicates no deterministic relation between the variability of the Great Whirl and its forcing. Moored temperature and current records show large amplitude fluctuations on intraseasonal timescales from 30-60 days. The analysis of altimetric data reveals that these fluctuations are concentrated in a region about 1000-km wide off the Somali and Arabian coasts north of 5°N. The seasonal cycle of the flow field is mainly confined to the upper 400 m in the interior Somali Basin. Near the western boundary topography, it penetrates to greater depths, possibly forced by the reflection of annual Rossby waves propagating across the Arabian Sea. The role of the circulation in the western Arabian Sea within the shallow overturning circulation of the Indian Ocean is also discussed.

GRAVEST EMPIRICAL MODE-3: MONITORING INTEROCEAN THERMOHALINE FLUXES

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Interocean thermohaline and mass fluxes are still poorly resolved by both observations and models, and their effect on global climate is not well understood. Their pertinent length scales range from tens to hundreds of kilometers, which makes effective and accurate measurement of interocean fluxes problematic, even on a one-time basis. Their temporal variability remains almost completely uncharacterized. A quantitative understanding of the global thermohaline circulation, its sensitivities and its feedbacks requires new measurement techniques and interpretive methods to provide high-resolution assessment of interocean exchanges over long time periods.

To improve the measurement of interocean fluxes, we developed a method to determine the vertical thermohaline structure of a given oceanic regime over appropriate spatio-temporal scales. This method, the Gravest Empirical Mode III (GEM-3), utilizes satellite-derived sea surface height and in situ vertical acoustic travel time to produce synoptic and inexpensive coverage of large-scale water mass transports. GEM-3 employs a simple stochastic assumption that allows regional historic data to be interpreted as temporally sampled. High-quality WOCE-era measurements provide the historic in situ data required to develop and employ GEM-3 in many of the oceanic regions critical to global thermohaline circulation. We examine GEM-3 using historical data from both the Agulhas Retroflection and the Carribean Sea, two regions critical to interocean thermohaline exchange. GEM-3 will be employed and rigorously tested during the Agulhas-South Atlantic Thermohaline Transport Experiment (ASTTEX) in January 2003. ASTTEX moorings will measure in situ VATT at ~80-km intervals, and combined with SSH from Jason and interpreted using GEM-3, will supply the first detailed, vertically resolved timeseries of the South Atlantic component of the "warm water route". Such time series are a fundamental prerequisite for understanding how such regions respond to and force global climate on many time scales.

THERMOHALINE CIRCULATION SENSITIVITY TO INTERMEDIATE-LEVEL ANOMALIES

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The competition between multiple equilibria in the circulation of the ocean and their relevance to the observed climate fluctuations is among the most challenging questions in the field of climate dynamics. Simplified ocean models play a substantial role in the development of models useful for the prediction of long-term climate changes because they are mostly conceived to give a complete description of single interactions between the components of the climate system. Thus, they help understanding how the basic processes contribute to the observed climate variability.

Focusing on the effect of Mediterranean outflow on Atlantic Ocean thermohaline circulation, a 2-D Boussinesq ocean model was used to investigate the effect of intermediate level thermal and saline anomalies on the known multiple equilibria structure of the thermohaline circulation under mixed boundary conditions. These anomalies serve as a crude representation of the Mediterranean outflow in the Atlantic Ocean. The perturbation associated with these anomalies drives the system towards an overturning that resembles the present average Atlantic thermohaline circulation. We found that near-surface anomalies are more efficient in affecting the structure of the equilibria.

This result complements that of other OGCM experiments that attribute only a minor quantitative role to the Mediterranean outflow. We suggest that important qualitative changes in the structure of the equilibria may arise from poor representation of marginal seas and of intermediate waters, especially when deep convection processes are involved. Thus, marginal seas with their outflow should be fully solved in numerical models designed for the prediction of climate changes.

In addition, the interaction with a simple energy balance model is investigated to assess the stability of the solution found under mixed boundary conditions when the atmospheric feedback is taken into account.

NEAR-SURFACE VELOCITY STRUCTURE OF THE ANTARCTIC CIRCUMPOLAR CURRENT IN DRAKE PASSAGE

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The Antarctic Circumpolar Current (ACC) is a critical element to global climate. Both WOCE and CLIVAR have identified the Drake Passage choke point as a key location for repeat sampling of the ACC. In 1999 we began a program of high-resolution current profiling with shipboard acoustic Doppler current profilers (ADCPs) from the U.S. Antarctic icebreakers RVIB *Laurence M. Gould* and *Nathaniel B. Palmer*. Both ships presently have shipboard systems based on RDI narrowband ADCPs, with precision P/Y code GPS navigation and heading corrections from Ashtech AGU2 GPS attitude sensors. These systems offer the prospect of routine current profiler measurements in the top 300 m along a variety of cruise tracks through otherwise rarely sampled waters of the Southern Ocean. In particular, these vessels cross Drake Passage throughout the year, with measurements made on about 100 crossings to date. We present the mean structure and variability of the ACC in Drake Passage determined from these measurements made during 1999-2002.

THE ECCO 1-DEGREE GLOBAL WOCE SYNTHESIS: ESTIMATED OCEAN VARIABILITY

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The global ECCO ocean state estimate is compared directly to observations from the World Ocean Circulation Experiment's (WOCE) one-time CTD sections. The goal is to determine the goodness of fit and examine the degree to which individual sections are representative of means. Sections from the WOCE repeated high-resolution expendable bathythermograph (HRXBT) network in the Pacific are used to compare means, seasonal cycles, and interannual variability with those in the model. HRXBT sections with at least 7 years of data are used to estimate the seasonal march of temperature, heat content, and steric height for comparison with the model.

EARLY RESULTS FROM A 1/12 DEGREE GLOBAL OCEAN MODEL

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Early studies with quasi-geostrophic models showed that at mid-latitudes ocean models of 1/10th degree or better were needed to realistically represent both narrow boundary currents and the mesoscale eddy cascade. Here we report on early results of a version of the OCCAM global ocean model run at 1/12th degree resolution. The model starts from Levitus and the first two years the model it is forced with monthly averaged NCEP fluxes. For the third year it is forced with six-hourly fluxes.

The major initial changes are associated with narrow western boundary currents. From the start, the Gulf Stream cleanly separates from the coast at Cape Hatteras and shows no tendency to reattach. The path of the Kuroshio near Japan and the Agulhas Current off South Africa are also in very good agreement with observations. The model's high resolution also means that it able to accurately resolve many important straits and overflows including the straits through the Canadian Archipelago and the Mediterranean Outflow, where a series of meddies are formed.

EULERIAN AND EDDY-INDUCED MERIDIONAL OVERTURNING CIRCULATIONS IN THE TROPICS

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Inspired by recent measurements of the eddy-induced Meridional Overturning Circulation (MOC) in the Tropical North Pacific Ocean by Roemmich and Gilson, we analyze an OGCM for its Eulerian and eddy-induced MOCs throughout the Tropics. In the model, the mesoscale eddy-induced circulation is parameterized by Gent and McWilliams. There are also rectified contributions to the time-mean MOC due to seasonal and interannual fluctuations. The eddy-induced circulation is similar in all tropical basins. It has a strength of about 10% of the Eulerian circulation, and its contribution to the meridional heat flux is a similar fraction. The pattern of the meridional streamfunction is one of double cells in the vertical and antisymmetry about the equator. Similar to the wind-driven Eulerian MOC, the seasonal cycle in the eddy-induced MOC has a magnitude comparable to the time-mean circulation, although for an entirely different dynamical reason associated with seasonal changes in the buoyancy field that are primarily diabatic. There is also a circulation anomaly during the 1997-98 El Niño-Southern Oscillation event that nearly cancels the time-mean, counter-rotating, eddy-induced cells nearest the equator and surface. The rather good agreement between the measurements and the model solution gives support to the theory underlying the parameterization of eddy-induced circulation, and it indicates that the associated eddy transport coefficients are larger in the Tropics (i.e., 2×10^3 m^2 s^{-1}) than in middle and high latitudes.

MAINTAINING ABYSSAL STRATIFICATION IN THE TROPICAL NORTHERN INDIAN OCEAN

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The average deep meridional overturning circulation of the Indian Ocean and its associated heat transport are still a matter of scientific debate. Contrary to general circulation model simulations, which show only weak deep meridional overturning (< 4 Sv) north of 30°S, results from the analysis of the geostrophic flow field and from inverse box models suggest much higher rates of up to 27 Sv. Much of this overturning takes place in the tropical and northern Indian Ocean (11 Sv north of 8°S, 4-12 Sv north of 8°N), requiring large diapycnal mixing and deep water upwelling rates.

In this presentation the vertical advection/diffusion balance is examined using direct velocity measurements and hydrographic profiles from seven WOCE cruises in the tropical northern Indian Ocean. Vertical shear spectra and buoyancy profiles are used to infer turbulent dissipation rates and eddy diffusivities. For the Bay of Bengal and the region south of Sri Lanka, no enhancement of eddy diffusivity relative to the oceanic background value of 10^{-5} m^2 s^{-1} is found. In contrast, in the Somali Basin and in the central Arabian Sea, eddy diffusivities increase with depths and reach values of $1\text{-}4 \times 10^{-4}$ m^2 s^{-1} below about 3000m. In this region eddy diffusivity can be parameterized as being proportional to N^{-2}. Convergence of vertical velocity is largest between 3000 m and 1500 m depth in support of a deep overturning cell in the Arabian Sea. The monsoon wind is thought to be a major energy source for maintaining the abyssal stratification, but even though the seasonal variability of the abyssal upwelling is small.

WOCE ICM6 — THE LEEUWIN CURRENT OFF NINGALOO REEF IN NORTHERN WESTERN AUSTRALIA

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The Indian Ocean current meter array 6 (WOCE ICM6) was designed to estimate the seasonal variability of the Leeuwin Current at 22°S, off Ningaloo Reef in northern Western Australia. The array consisted of six moorings with a total of twenty two instruments–ADCPs, RCMs and ACM2s–along a section spanning water depths between 250 and 3050 m. Five cruise surveys had the opportunity to collect CTD and SADCP observations during the period of the experiment, August 1994 to June 1996. Results are as follows. On one hand, an anticipated annual peak in the poleward transport of the Leeuwin Current was absent in April/May 1995; on the other hand, the current meter time series revealed an interannual fluctuation consistent with ENSO. CTD data proved not useful for geostrophic calculations using the thermal wind relation. Large discrepancies in geostrophic velocities compared to direct estimates were observed as a result of significant ageostrophic motion (i.e., internal tides). Nevertheless CTD data were helpful to identify water originally from the Indonesian Throughflow in the upper 200 m in the offshore portion of the section during May/June 1996, when the Leeuwin Current was flowing strongest adjacent to the coast. That fresh and warm tropical water was associated with a southeastward (inshore) flow as revealed in the current structure (top 300 m) derived from the SADCP observations. A sea surface temperature image (courtesy of I. Barton) of the same occasion showed that the influence of the warm water extended to a considerable offshore region and presumably mixed with surrounding cooler water and augmented the Leeuwin Current further south. Although the WOCE ICM6 corresponds to the longest direct observations of the Leeuwin Current, it is likely that its time-mean transport, less than 1 Sv, did not represent the total transport of the current at 22°S during 1994/96.

EVALUATION OF OCMIP-2 OCEAN MODELS: DEEP CIRCULATION DEDUCED FROM NATURAL ^{3}He SIMULATIONS

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During the second phase of OCMIP (Ocean Carbon Model Intercomparison Project), simulations with mantle ^{3}He were made to evaluate and compare models of the deep water circulation. First, we explore the potential of natural ^{3}He to help compare and evaluate modeled deep-ocean circulation. This tracer is injected in the deep ocean through hydrothermal activity; it is then adapted for testing the connection between the deep ocean and the subsurface. For these simulation, natural ^{3}He was injected along axes of mid-ocean ridge, with fluxes linearly proportional to the spreading rates. There we investigate with model sensitivity tests if this parameterization is adapted for reproducing the large scale ^{3}He distribution in the Pacific, Indian and Atlantic basins. Previously, a ^{3}He simulation with one model suggests that this simple parameterization leads to ^{3}He fluxes that are too large in the Atlantic. Then, we will use the information from both natural ^{14}C and ^{3}He distributions to help constrain the transport and ventilation of deep water with particular focus on comparison with measurements collected during major global scale ocean observation programs (GEOSECS, WOCE).

SPECTRAL RESPONSE OF THE SOUTHERN OCEAN SURFACE CIRCULATION TO WIND

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The surface circulation south of 30°S is investigated by using the drifter-derived velocity measurements from the WOCE Surface Velocity Program. The objective of this study is to quantify and understand how the surface circulation is related to local wind forcing. For this study, Holey Sock drifters are used. These consist of a drogue centered at 15 m linked to a surface buoy which transmits the apparatus' position via the ARGOS satellite tracking system. NCEP/NCAR reanalysis 10-m wind fields are used to investigate the relationship between the surface circulation and the wind forcing. Along 40-day drifter trajectories, wind velocities are interpolated to form a time series contemporaneous to the drifter time series. These temporal time series are analyzed using spectral and coherence techniques that allow the motions to be decomposed and studied as a function of frequency. For the complete data set, the wind velocity spectrum is uniform across the whole frequency range, whereas the drifter-derived velocity spectrum exhibits a decrease in energy for higher frequency bands (1/10 to 1/2 cpd band). Both wind and ocean rotary energy spectra are found to be slightly biased towards anticyclonic motions for most of the frequency bands. However, the ocean motion in the 1/5 to 1/2 cpd band is preferentially cyclonic. This polarization reversal indicates a change in the ocean dynamics that is to be investigated.

The levels of coherence between the local wind and the surface current are very low but statistically significant. The phase of the coherence shows the coherent drifter-derived velocity vector to be directed fairly constantly 42.2 ± 4.1° to the left of the wind vector over the 1/40 to 1/2 cpd band. The coherent part of the signal is attributed to the local Ekman forcing. The portion of ocean velocity that is not coherent with the wind may be attributed to processes such as large-scale geostrophic motions. The data set is also sorted to examine seasonal variations.

LOW FREQUENCY VARIATIONS OF WATER MASS PROPERTIES IN THE WEDDELL SEA

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The Weddell Sea is known to feed freshly formed deep and bottom waters into the Antarctic circumpolar water belt from where it spreads into the contiguous basins of all three world oceans. To measure the water mass properties in the Weddell Sea a total of 8 hydrographic surveys including CFCs were carried out during WOCE and subsequently CLIVAR with RVs POLARSTERN and METEOR. Temperature and velocity vector time series were obtained from moored instruments in the northwestern Weddell Sea from 1989 to 1998 and on the Greenwich Meridian from 1996 to 2000, and profiling floats have been deployed since 1999 in the eastern Weddell Sea. The Weddell Sea Convection Control (WECCON) programme is ongoing in the framework of German CLIVAR.

The data collected hitherto reveal the large-scale structure of the cyclonic Weddell gyre with inflow of Circumpolar Deep Water and recently ventilated deep water from the east and formation of deep and bottom water in the southwest. The repeated surveys suggest the parameter fields are dominated by a rather stable, large scale structure. However, high-resolution measurements reveal an increase of temperature and salinity in the Warm Deep and the Weddell Sea Bottom Waters on decadal time scales and over large areas, which is probably related to variations in the atmospheric forcing. Due to the spreading of the deep and bottom waters into the global ocean, these observed variations are posed to affect larger ocean areas in the long term.

THE MERCATOR TROPICAL AND NORTH ATLANTIC PROTOTYPE: COMPARISON OF THE 1993-1998 OCEAN REANALYSIS TO WOCE DATA

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MERCATOR is an international oceanography project and France's contribution to the Global Ocean Data Assimilation Experiment (GODAE). It will test and operate a series of prototypes, either regional or global, of increasing complexity to develop a mature ocean analysis and prediction system. The first MERCATOR prototype has operated since 17 January 2001 and produces regular weekly bulletins. It is based on routine assimilation of near-real-time altimetry into a 1/3 North Atlantic (20°S–70°N) configuration and uses for that the primitive equation OPA ocean model and the SOFA optimal interpolation scheme driven through the PALM coupler for data assimilation.

In order to evaluate the system, a 1993-1998 ocean reanalysis has been performed, where the TOPEX/Poseidon and ERS altimetry data have been assimilated. The initial state of the reanalysis is not climatological but comes from a 20-year spin-up simulation. The bias of this state has been evaluated through a comparison with the Reynaud's climatology and is proved to be non-significant over more than 50% of the domain. It is then possible to compare the results of the simulation towards in situ data. In particular we are interested in the representation of the seasonal cycle in the reanalysis. The results are compared to mooring time series, which allows determination if the water mass distribution is correctly simulated. Meridional heat transports are also calculated at different WOCE sections and compared to the observed ones.

A COMPARISON BETWEEN ALTIMETER DATA AND IN-SITU TEMPERATURE AND SALINITY PROFILE MEASUREMENTS OVER THE GLOBAL OCEAN DURING 1993-2001

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The aim of the study is to analyze the differences and complementarities between altimeter and hydrographic data. It is performed to analyze the physical content of altimeter measurements (e.g. barotropic / baroclinic signals) and to better understand the vertical structure of the ocean. It is also needed to prepare the joint assimilation of these two different types of data. Data used include combined TOPEX/Poseidon and ERS-1/2 altimeter measurements (CLS) and temperature (T) and salinity (S) profile data from XBT, CTD and profiling float measurements (SISMER and WOCE data centers). The analyses have been performed globally over the 1993-2001 period. A general methodology for the comparison of altimeter measurements and T/S profile data (in equivalent dynamic height) is defined and developed. It requires the definition of a mean dynamic height inferred from a combination of the hydrographic and altimeter measurements, to calculate dynamic height anomalies comparable to altimeter SLAs. Then, the altimeter/in-situ differences are analyzed in term of dynamic height anomalies at the reference level. The main result of this work is the excellent agreement between collocated altimeter and in-situ SLAs. Time-varying spatial averages of the altimeter/in-situ differences are found to be related to changes in Sverdrup transport (deduced from ERS-1/2 scatterometer measurements) in several areas of the Pacific and Indian Oceans. Moreover, interannual variability of the global mean sea level anomalies, studied using all collocated altimeter and in-situ data, indicate that during the years 1993 to 2001, thermal expansion of the ocean (as sub-sampled by the in situ measurements) was significantly higher than total sea level change measured by T/P at the same positions than the in situ measurements. The vertical structure of the ocean is also described and partitioned into barotropic and baroclinic modes needed for altimeter assimilation purposes.

COHERENCE OF SUB-SURFACE PRESSURE VARIATIONS AROUND ANTARCTICA

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Changes in sub-surface pressure (SSP) measured by coastal tide gauges (or alternatively changes in bottom pressure (BP) measured by ocean floor recorders off-shore) have been known for some time to be coherent over large distances around the Antarctic continent for timescales of several days to seasons. In this poster we present evidence for near in-phase coherence of SSP (or BP) around two-thirds of the Antarctic coast, using data from a network of 9 stations from Faraday (Vernadsky) on west side of the Antarctic peninsula eastwards to Cape Roberts south of New Zealand. The establishment of such a network is an excellent international achievement by scientists from the UK, Ukraine, USA, Japan, Australia and New Zealand, with the potential for more stations to be added in future. Information derived from several numerical ocean models suggests that the coherent SSP signal is associated with fluctuations in Antarctic Circumpolar Current (ACC) transports. This offers the possibility for long term ACC monitoring, in an ice-covered area largely inaccessible to year-round monitoring by altimetry, by the network of permanent coastal tide gauge stations (part of the Global Sea Level Observing System), supplemented as necessary by BP deployments.

TIME SERIES OF TRANSPORT AND SURFACE FLOW FIELD OF THE KUROSHIO DERIVED BY COMBINING IN SITU OBSERVATION AND SATELLITE ALTIMETRY DATA

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Part I: In 1993-1995, the ASUKA (Affiliated Surveys of the Kuroshio off Cape Ashizuri) Group intensively observed the Kuroshio south of Japan (WOCE PCM5), including direct current measurements and repeated hydrographic surveys along a subsatellite track of TOPEX/Poseidon. Estimated transports have a high correlation with SSH differences across the Kuroshio. Having this relationship, and using the altimeter data, we obtained a time series of Kuroshio transport for 1993-2001 at ten-day intervals. Excluding contributions by local recirculations, it is estimated to be 43 Sv on average. The range of annual fluctuation is much smaller than expected from the interior wind stress curl. This is explained by a simple two-layer numerical model: around the Izu-Ogasawara Ridge, most seasonal, barotropic signals from the interior are prevented from propagating west, and some are converted to upper-layer signals through coupling of barotropic and baroclinic modes, resulting in the seasonal signal of Kuroshio transport. Applying the Gravest Empirical Mode method, we estimate a time series of baroclinic Kuroshio transport.

Part II: Sea-surface velocity may be divided into the temporal mean and its anomaly. Velocity anomaly is derived from altimeter data with geostrophic approximation. The information on temporal mean lost in altimeter data processing is recovered by combining surface drifter data. The sum of thus obtained mean and anomalies gives us a time series of the total velocity. The method is applied for the North Pacific, using TOPEX/POSEIDON and ERS-1/2 altimeter data, and WOCE-TOGA surface drifter data during 1992-2001. Estimated total flow field shows the energetic variability of the Kuroshio and Kuroshio Extension vividly.

A SIMULATION OF FORMATION AND SPREADING PROCESSES OF NPIW SALINITY MINIMUM BY A HIGH-RESOLUTION MODEL

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Long-term integration of a high-resolution North Pacific Ocean model was conducted to clarify the formation and spreading processes of the intermediate low salinity water associated with the North Pacific Intermediate Water (NPIW). The model domain is 100°E-75°W and 15°S-65°N with 1/4° (EW) x 1/6° (NS) horizontal resolution and 52 vertical levels. Restoring fluxes of heat and salinity are specified at the surface, below 2000 m, and in the Okhotsk and Bering Seas. The monthly-mean climatological data of the NCEP reanalyzed wind stress was used.

It was found that, with this horizontal resolution, the computational diffusivity contained in the QUICK scheme for tracer advection (proportional to the fourth order spatial derivative) was too large to fully develop small-scale disturbances in the Kuroshio-Oyashio confluence zone east of Japan. In this case the central values in the salinity minimum were greater than those observed by about 0.2 psu.

When the coefficient of subgrid-scale diffusivity (biharmonic type), including the computational one in the QUICK, reduced to about $1x10^{17}$ in cgs unit, the mixing of the Kuroshio and Oyashio waters was promoted in the confluence zone to continuously form the vertical salinity minimum centered around the 26.8 sigma-theta density surface. The low salinity water was spread by mean-flow advection and by diffusion due to explicit eddies. The difference in central salinity minimum values between simulation and observation was reduced to about 0.05 psu.

SEASONAL AND INTERANNUAL VARIABILITY OF INTERMEDIATE OYASHIO TRANSPORT OFF THE SOUTH COAST OF HOKKAIDO JAPAN

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To estimate the transport of the Oyashio in the intermediate layer (26.6-27.4 density) which flows south of the coast of Hokkaido Japan, we set a intensive observation line along the T/P orbit 060. The observation line extends from Cape Erimo to the southeastward (from the Oyashio region to the mixed water region) and we named this line OICE (Oyashio Intensive observation line off Cape Erimo). On the OICE, we had repeated CTD observations and maintained the mooring systems. Around Hokkaido there are other three repeating observation lines; PH-line (41-30°N) and 144°E-line by JMA, and A-line by HNFRI. Using these data we estimated the intermediate Oyashio transport into the mixed region across the Subarctic Front (defined by the 4°C isotherm on 100 m depth) to clarify the quantity of the source of the North Pacific Intermediate Water (NPIW).

The annual averaged transport of the intermediate Oyashio water across the Subarctic Front was 3.8 Sv on A-line, 7.7 Sv on OICE, 4.7 Sv on PH-line, and 1.0 Sv on 144°E-line, though the resolution of observations is not sufficient to resolve the Oyashio current on the 144°E-line. The seasonal variation showed the maximum in winter and minimum in summer on OICE, whereas it showed the maximum (about 6 Sv) during winter-spring and the minimum in autumn on A-line and PH-line. Because the time series is longer on the A-line and PH-line than on OICE, the seasonal variability is more reliable on these lines. Interannual variability was very high and the Oyashio transport across the Subarctic Front increased since 2000. The results on OICE reflected this strengthening of the Oyashio especially in winter 2001.

SPATIAL AND TEMPORAL STRUCTURE OF THE EQUATORIAL DEEP JETS IN THE ATLANTIC AND PACIFIC OCEANS

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We compare the temporal and spatial structures of the equatorial deep jets (EDJs) in the Atlantic and Pacific oceans using vertical strain estimated from all available deep CTD data. In the Atlantic we find a distinct energy peak at 661-sdbar vertical wavelength, with a corresponding 0.15 m/s phase speed; in the Pacific the dominant vertical wavelength is 400 sdbar, with a phase speed of 0.10 m/s. Atlantic EDJ meridional energy structure, with an off-equatorial maximum, suggests a first meridional mode equatorial Rossby wave on a scale of 120 km; the Pacific EDJ equatorial energy maximum is more consistent with an equatorial Kelvin wave. The Atlantic EDJ phase propagates downward at about 130 sdbar/year, yielding a 5-year time scale coherent over at least the 14-year long portion of the historical record; the Pacific EDJ propagation rate is only 13 sdbar/year downward, coherent over the entire 22-year record, implying a correspondingly longer 30-year time scale. Atlantic EDJs are strongest at about 1200 dbar near the western boundary and zonally coherent over at least 3500 km; Pacific EDJs are strongest near the crest of the East Pacific Rise at 110°W and coherent over at least 5000 km. The Atlantic EDJ zonal scale is about 65°, with westward phase propagation, corresponding very well with the phase propagation and 73° zonal wavelength of a first meridional mode equatorial Rossby wave given the observed EDJ vertical wavelength and time scale. The best estimate of the Pacific EDJ (poorly determined) zonal scale is about 670° with eastward phase propagation, consistent with the 850° wavelength and phase propagation of an equatorial Kelvin wave. EDJs with short vertical, long zonal, and long temporal scales are present in the Atlantic and Pacific Oceans, both consistent with linear equatorial wave dynamics, but a Rossby wave in the former ocean and a Kelvin wave in the latter.

LONG EXTRA-TROPICAL PLANETARY WAVE PROPAGATION IN THE PRESENCE OF SLOWLY VARYING MEAN FLOW AND BOTTOM TOPOGRAPHY

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The most successful theory to date to explain why observed planetary waves propagate westwards faster than linear flat-bottom theory predicts has been to include the effect of background baroclinic mean flow, which modifies the potential vorticity waveguide in which the waves propagate. (Barotropic flows are almost everywhere too small to explain the observed differences.) That theory accounted for most, but not all, of the observed wave speeds. A later attempt to examine the effect of the sloping bottom on these waves (without the mean flow effect) did not find any overall speed-up. This paper combines these two effects, assuming long (geostrophic) waves and slowly varying mean flow and topography, and computes group velocities at each point in the global ocean. These velocities turn out to be largely independent of the orientation of the wavevector. A second speed-up of the waves is found (over that for mean flow only). Almost no eastward-oriented group velocities are found, so that features which appear to propagate in the same sense as a subtropical gyre would have to be coupled with the atmosphere. The predicted speeds agree well with observations of planetary waves deduced from sea surface height data.

HOW REPRESENTATIVE IS THE WOCE DATA SET? AN ASSESSMENT OF VARIABILITY OBSERVED IN DRAKE PASSAGE

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We present an analysis of representativeness and variability in transport at Drake Passage in the 1990s from WOCE repeat hydrographic sections, and comparison with ISOS data from the 1970s. The implications for future monitoring and detection of decadal change are discussed.

Properties, transports and circulation schemes inferred from the analysis of one-time cruises in the WOCE Hydrographic Program (WHP) are usually assumed to be representative of some sort of ocean mean circulation. An obvious and (usually) acknowledged limitation of such analyses is the lack of knowledge about the ocean variability. To address this ignorance, the WHP identified the need for some sections to be repeated many times. The range in volume transport on this section is about 10% either side of the mean. Seasonal effects compound the problem: the seasonal heating can increase the heat flux through Drake Passage by 0.2 PW between November and February, independent of changes to the velocity field. Global synthesis calculations need to take a view of the uncertainty and variability at each one-time section; repeat sections give a clue as to how large that uncertainty should be permitted to be.

The interannual variability means that even with seven determinations in each of the ISOS and WOCE epochs, a change of 10% in the mean transport is not statistically significant. The variability of the southern ocean presents a challenge for climate change studies post WOCE. Frequent, perhaps continuous, monitoring will be needed to extract decadal-scale changes from the high interannual variability. A program of occasional measurements, for example a few sections per decade, would mean that only very large and persistent signals could be distinguished from shorter-term fluctuations.

HEAT AND SALT VARIABILITY IN THE UPPER LABRADOR SEA, 1990-2002

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Convection in the central Labrador Sea was exceptionally deep during the early 1990s due to a series of severe winters. Since 1995 the winters have been less severe with wintertime convection limited to ~1000 m. Our examination of the heat content of the upper layer and the cumulative air/sea heat flux during these years shows a high correlation between the two along with a net loss to the atmosphere each year. We conclude that there exists a constant horizontal flux of heat into the central Labrador Sea from the boundary currents that is modulated by the air/sea heat flux. When the cumulative heat flux to the atmosphere exceeds the horizontal flux the upper layer cools and the depth of convection deepens as in the early 1990s. When the cumulative heat flux is less than the horizontal flux the depth of convection remains shallow and the temperature of the mixed layer increases. Precipitation exceeds evaporation in the region but it is small compared to the volume of fresh water from ice-melt and runoff. However the salt flux that accompanies the heat flux from the boundary currents approximately balances the total input of fresh water at the surface so that the average salinity of the upper 2000 m remains roughly constant from year to year.

EDDY MASS TRANSPORT FOR THE SOUTHERN OCEAN IN AN EDDY-PERMITTING OCEAN MODEL (OCCAM)

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The eddy-induced mass transport is diagnosed for the Southern Ocean in an eddy-permitting global ocean model (OCCAM). The focus is on the transport by transient eddies in the deep ocean. The transport streamfunction is calculated in four different combinations of coordinate systems. Depending on the coordinate system employed, the strength of transient eddy transport varies from 6 Sv meridional transport in latitude-density coordinates to 20 Sv across-streamline transport in streamline-depth coordinates. It is shown that transient eddies as well as standing eddies are necessary for cancelling the Deacon cell. In the Antarctic Bottom Water density layer, the major contribution of the transient eddies towards net equatorward transport occurs (a) as a strong transport over the narrow Drake Passage and (b) as a weaker but systematic transport over a broader region in the southeast Pacific where the Antarctic Circumpolar Current breaks up into multiple jets. In contrast, in the North Atlantic Deep Water density layer the net poleward eddy transport is spread out almost everywhere. This suggests that attention to eddies should not be restricted to places where the eddy transport has large magnitude.

SOURCE WATERS OF THE WESTERN EQUATORIAL INDIAN OCEAN: RELATIVE CONTRIBUTIONS BY THE PACIFIC AND INDIAN OCEANS

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The strongest upwelling in the Indian Ocean occurs in the western equatorial region, resulting in cooler temperature than that in the east. This part of the ocean participates in air-sea interaction actively. Therefore, understanding the origins of the upwelled water is important to the studies of various climate variabilities associated with the Indian Ocean. Estimates of mean volume transports from the Pacific into the Indian Ocean and from the southern Indian Ocean do not elucidate the relative contributions of various sources to surface water of the western equatorial Indian Ocean. This is because not all the water from from any source will end up there, apart from the difference in transit time for different sources. In this study, we examine regional contributions using the adjoint model of a passive tracer which tracks the history of surface water in the western equatorial Indian Ocean back in time. The estimate of circulation (velocities and mixing coefficients) used to represent the advection and diffusion of the tracer is produced by the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO; http://www.ecco-group.org). Because the destination of the tracer is in the Indian Ocean (initialization in the adjoint sense), the contributions by the Pacific (Indian) Ocean increases (decreases) with lag time. At 10-year lag, the contribution by the Pacific (Indian) Ocean is about 30% (70%). The two oceans have almost the same contribution at 20-year lag time. Further back in time, the contribution by the Pacific is expected to be more dominant. At any lag time, the contribution by the North Pacific is larger than that by the South Pacific. The opposite is true for the Indian Ocean. The pathways of various sources are also presented. Effect of time-varying circulation on tracer transport is discussed.

CONSTRAINING THE NORTH ATLANTIC CIRCULATION WITH TRANSIENT TRACER OBSERVATIONS

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We explore the capability of transient tracers to constrain the ocean circulation in the North Atlantic. Study of an idealized tracer shows that inferences of circulation properties from its transient tracer distributions are influenced by uncertainties in the time-varying boundary conditions. Comparison of CFC, tritium, temperature and salinity (T-S) observations with model results in the North Atlantic shows that regions of important model-data disagreements in the transient tracer fields can also be readily identified in the T-S distributions. In the model, excessive vertical penetration of convective adjustment leads to problematic production and outflow of the NADW, again appearing in both transient tracer and T-S fields.

Sensitivities of the model fields were determined using the adjoint model. In the dual solutions, CFC-11, CFC-11/CFC-12 ratio age, and T-(β/α)S (where α and β are thermal and haline expansion coefficients, respectively) exhibit the major ventilation pathways and the associated time scales in the model. High sensitivity fields are candidates for providing the most powerful constraints in the corresponding inverse problems. Assimilation of both CFC and tritium data, with different input histories, sampling distributions, and radioactive decay constants, shows that by adjusting only initial-boundary conditions of CFCs and tritium, a 1°x 1° offline model and the transient tracer data can be brought into near-consistency, in the domain between 4.5° and 39.5°N of the North Atlantic.

Constraining a GCM with transient tracers is thus fully practical. However, the large uncertainties in the time histories of transient tracer boundary conditions and in the interior transient tracer distributions, renders them less effective in determining the circulation than are more conventional steady tracers and known oceanic dynamics.

THE SIMULATION OF INDONESIAN THROUGHFLOW IN A HIGH RESOLUTION OCEANIC GCM

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The horizontal resolution of the third generation oceanic general circulation model (OGCM) of IAP/LASG, named L30T63, has been enhanced to uniform 0.5° x 0.5° grids (excluding the Arctic). Under the circumstances the main straits and passages in the Indonesian Archipelago can been resolved. The model has been integrated for 45 years forced by climatological monthly data. After that, a 15 year-long experiment has been conducted using ERA15 daily wind stresses.

The simulated pathway and the water source of ITF are both basically coincident with the observations. Above the thermocline, the North Pacific water from the Mindanao Current passes the Makassar Strait and Maluku Strait, and exits into the Indian Ocean through Lombok Strait. Below the thermocline, the South Pacific water enters from Maluku Strait and exits through Ombai Strait. Makassar Strait is the primary passage for ITF transport. The simulated annual mean mass transport of the ITF is 12.2 Sv. The maximum transport of 18.5 Sv occurred in September and the minimum 6 Sv in December and January. The simulated ITF transport is small during El Niño and large during La Niña. The relation coefficients between ITF transport and both Niño3 and DMI indices indicated that ITF is more affected by the Pacific Ocean than the Indian Ocean on the interannual time scale. The interannual variation of the ITF is decided by the difference in sea surface height (SSH) between the western Pacific Ocean and the eastern Indian Ocean. The interannual variation of SSH on the Pacific side is controlled by both local Ekman pumping and anomalies propagating from equatorial Pacific on the Indian Ocean side, however, the remote force dominates.

OCEAN MIXED LAYER DEPTH: A SUBSURFACE PROXY OF OCEAN-ATMOSPHERE VARIABILITY

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The spatial and temporal variability of dominant atmospheric forcing mechanisms setting up the structure of the ocean turbulent surface layer are well documented. To quantify, understand and ultimately predict ocean-atmosphere interactions on climate relevant time scales identifying the depth of this layer, in addition to the SST, is cruical. However, observed ocean mixed layer depths (MLDs)—in the quality of SST observations—do not exist yet.

We investigate hydrographic data with high and low vertical resolution obtained during the WOCE period to determine the variability of the observed ocean MLD applying two criteria for this depth provided by the recent literature. Considerable differences in the results motivates us to optimize a criterion estimating ocean MLDs that takes into account the complexity of the upper ocean vertical structure. We include a solution for the turbulent layer depth from the global ECCO state estimation in our analysis to test the sensitivity of both observed MLDs and modeled turbulent layer depths and their climate variability to different selection criteria.

ASSESSING THE IMPORTANCE OF NON-BOUSSINESQ EFFECTS IN A COARSE RESOLUTION GLOBAL OCEAN MODEL

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The advent of the GRACE mission presents the opportunity to accurately measure variations in bottom pressure. Such a data source will prove valuable in state estimation and for constraining general circulation models (GCMs) in general. However, conventional GCMs make the Boussinesq approximation as a consequence of which mass is not conserved. Thus Boussinesq models have an implicit drift in bottom pressure. By use of the height-pressure coordinate isomorphism implemented in the MIT GCM, we can evaluate the impact of non-Boussinesq effects. We find that although implementing a non-Boussinesq model in pressure coordinates is relatively straight-forward, making a direct comparison between height and pressure coordinate (i.e., Boussinesq and non-Boussinesq) models is not simple. Here we present a careful comparison of the Boussinesq and non-Boussinesq solutions ensuring that only non-Boussinesq effects can be responsible for the observed differences. As a yard-stick, we also compare differences between the Boussinesq hydrostatic and non-hydrostatic models, another approximation commonly made in GCMs. We find that model errors (differences) due to the Boussinesq approximation are apparently smaller than the errors due to the hydrostatic approximation. We also compare these model errors with uncertainties associated with model parameterizations and find that non-Boussinesq and non-hydrostatic effects are much smaller than these uncertainties. We conclude that non-Boussinesq effects are negligible with respect to other model errors. However, since there is no additional cost incurred in using a pressure coordinate model, non-Boussinesq modeling is preferable simply for puristic reasons.

BOTTOM TOPOGRAPHY AS A CONTROL PARAMETER IN AN OCEAN CIRCULATION MODEL

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Bottom topography is a major factor in determining the general circulation of the ocean. It is, however, inaccurately known in many regions, and even where accurately known, the best way to represent (parameterize) it in models is obscure. To begin to understand the influence of errors in topography and of misrepresentations of both resolved and sub-grid scale structures, a linear barotropic shallow water model and its adjoint are developed in which depth is used as a control variable. Simple basin geometries are employed to explore the extent to which topographic structure determines the sea-surface elevation in a steady flow and, more directly, the information content about the bottom contained in elevation measurements. Experiments show that even perfect measurements of sea-surface elevation in a steady state cannot, by themselves, uniquely determine the full structure of the bottom topography. (There is a null space.) As in most control problems, a priori knowledge of its structure is useful in the best topographic determination. Resolution of the bottom topography as a function of position is greatest where the flow velocities are greatest. Spatial correlation between the resolution of the bottom topography and the flow field is weaker (as expected) when noise with realistically large variance is introduced into the data. Ultimately, bottom topography will likely be included generally as a control variable in GCMs of arbitrary complexity along with other controls such as friction and lateral boundary conditions.

THE ECCO 1° GLOBAL WOCE SYNTHESIS: DATA CONSTRAINTS AND THEIR ESTIMATED ERRORS

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The ECCO global ocean state estimate over the 10-year period 1992-2001 is obtained by fitting WOCE data sets to a general circulation model. Data included are most of the in situ and satellite observations available during WOCE itself, and continuing since then. These data include satellite altimetry, scatterometry and SST fields, in situ hydrographic sections, XBT, P-ALACE, ARGO and TAO profiles, surface drifter velocities and Levitus climatological hydrography. As with all statistical estimation problems, one must provide a priori error covariances for all data sets, and the values and structures used in the estimation procedures are described here.

VORTICITY BALANCE IN THE ECCO GLOBAL WOCE SYNTHESIS

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From an ocean model that was constrained by WOCE data sets as part of the NOPP-funded ECCO assimilation project, we analyze the barotropic vorticity budget of the global ocean. For the depth-integrated circulation, it is found that the bottom pressure torque (BPT) dominates over the curl of friction in the western boundary currents and in the Southern Ocean. This important role played by BPT in the dynamics of the western boundary currents and the Antarctic Circumpolar Current (ACC), as found in this 2° resolution simulation, is consistent with the recent theoretical argument and the analyses of eddy-resolving simulations. In the upper layer of the model, the classical Sverdrup balance holds only in the eastern sub-tropical basins. The vorticity stretching/compressing associated with the vertical velocity is important near western boundary currents and at high latitudes. In the intermediate layer, the vorticity stretching/compressing associated with vertical motions drives the meridional flow in the interior basins. For the deep ocean, it is the combination of BPT and the vertical velocity that balances the advection of planetary vorticity. The meridional flow in the abyssal ocean is driven by the combined effect of BPT and vertical motions. The simulated abyssal circulation in the interior basins bears little resemblance with the prediction of the Stommel-Arons theory.

THE MESOSCALE VARIABILITY OF THE EAST AUSTRALIAN CURRENT AT SUBTROPICAL LATITUDES

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Mesoscale variability of the East Australian Current (EAC) is studied via analysis of in situ oceanographic data (from September 1991 to March 1994 off the east coast of Australia at 30°S) together with remotely sensed observations and outputs from a global ocean model. Analysis reveals the EAC to have a mean southward transport of 22.1 ± 4.6 Sv associated with strong variability (~30 Sv rms), dominated by periods of 90-140 days. Occasional intense northward flows are observed when total transports reach up to 50 Sv northward. On those occasions, the southward boundary current changes from a surface-intensified and mainly baroclinic feature to flow northward approaching a barotropic condition. Satellite altimetry observation clarifies aspects of these findings; e.g., showing that the northward migration of the separation point of the EAC is linked to the formation of large eddies south of the array at periods of ~100 days. During those events, the normally southward current swiftly assumes a more zonal configuration near the separation latitude, allowing cyclonic circulation to develop. Analysis also reveals that eddy formation relates to the propagation of sea level anomalies along slope. The propagation signature begins in the vicinity of 25°S; the sea level anomalies grow as they travel south, eventually being pinched off in the form of large eddies at ~32°S. Examination of GCM outputs indicates that both barotropic and baroclinic instabilities may play a role in the growth of these anomalies as they propagate south. Close to the separation latitude of the EAC, the instabilities draw energy from the mean flow to feed the anomalies. The relatively small area where these instabilities can develop provides an explanation to the observed rapid growth of the anomalies as they approach the separation latitude. However, further east of the main poleward jet of the EAC, there is evidence of the opposite condition, where the eddies may be feeding back potential energy to the mean flow.

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

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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 momentum equations for the mean state and used as a reference to obtain instant maps of total 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 is evaluated. Total sea level maps agree well with drifter trajectories and demonstrate tremendously complex patterns in the study area. Unbiased mean velocities indicate the 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 160°E agree well with the mean temperature at 200 m depth. Historical hydrographic data are used to determine the pressure field at 2000 m and to outline the pattern of deep circulation. In larger area (20°-50°N, 120°E-180°) a set of recirculations is described in more detail along the Kuroshio with the anticyclonic cell around Daito Island being a new discovery. Statistics of drifter trajectories are 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.

MEANDERING FLOW ACROSS THE REYKJANES RIDGE

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Warm waters from the western subtropics flow eastward across the Mid-Atlantic Ridge to the north of the Azores, turn northward into the eastern subpolar North Atlantic, and envelop the Rockall Trough and Plateau and the eastern Iceland Basin. Some of this water ends up transformed into the dense Nordic Seas Overflow Waters. But the rest forms an “Irminger Current” from the Iceland Basin to the Irminger Basin, with transformation into dense waters along the pathway to the western subpolar gyre. Two alternative interpretations for the Irminger Current’s origin have been in the literature for decades. In the first, the Irminger Current receives its warm water by a direct northward flowing branch of the North Atlantic Current, involving northward flow in the central and western Iceland Basin. In the second, a more circuitous route is involved, westward flow from the eastern Iceland Basin and Rockall Plateau that undergoes a southward meander while crossing the Reykjanes Ridge to the Irminger Basin. In the former alternative the flow over the eastern flank of the Ridge is northward, while in the second alternative it is southward. We have assembled hydrographic, surface drifter, RAFOS float, PALACE float and ADCP data sets from the WOCE activities in the subpolar North Atlantic to resolve this dilemma in favor of the second interpretation. Measured flow over the eastern Ridge flank is indeed southward, and parallels the deeper flows of recirculating intermediate waters and Iceland-Scotland Overflow waters.

HOW TO AVOID THE NON-CONSERVATIVE PRODUCTION OF HEAT IN OCEAN MODELS

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Mixing processes in the ocean conserve enthalpy and mostly destroy potential temperature in a similar fashion to how entropy is universally produced by mixing processes. Potential enthalpy—the enthalpy that a water parcel would have if raised adiabatically and without exchange of salt to the sea surface—is shown to be more conservative than potential temperature by more than two orders of magnitude. This work proves that potential enthalpy is the quantity whose advection and diffusion encapsulates the physical meaning of the First Law of Thermodynamics in the ocean. A new temperature variable called "conservative temperature" is advanced which is simply proportional to potential enthalpy. It is shown that present ocean models contain typical errors of 0.1°C in their sea surface temperatures due to the neglect of the nonconservative production of potential temperature.

STRUCTURE OF THE SUBANTARCTIC FRONT AND THE ABSOLUTE HORIZONTAL AND VERTICAL VELOCITY ASSOCIATED WITH THE FRONT

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The mean "synoptic" structure of the Subantarctic Front (SAF) is estimated by a stream coordinates analysis of data from overlapping arrays of inverted echo sounders (IES) and horizontal electric field recorders. The stream coordinates are derived from a daily objective mapping of the temperature field obtained from combining IES travel times with an empirical vertical mode structure constructed from hydrography acquired during WOCE (SR3 line). Full-water-column stream-coordinates sections of T, S, and absolute horizontal and vertical velocity are compared with prior observations. The mean along-stream current has a single peak with surface velocities reaching ~50 cm/s, and a total transport of 75 Sv over the SAF's 220-km width. Vertical structure of the along-stream current is roughly consistent with a combined external and first internal normal mode description, with some significant differences. The mean barotropic current along the SAF, using Fofonoff's definition of barotropic, is small (8 Sv over the SAF width), although weeklong periods of deep (3500 dbar) flows exceeding 10 cm/s were observed. Cross-stream flows reveal that SAF currents are divergent at 144°E, primarily baroclinically; divergence of ~16 Sv per degree of longitude at 51°S suggests significant recirculation. Vertical velocity estimation from density conservation produced time-mean values of 200-1000 dbar of roughly 4 m/day regardless of the averaging coordinate system. Throughout most of the SAF range, mean vertical flow was downward. Vertical shear in the vertical velocity was small except surrounding the 100-dbar pressure level; vertical velocity signals above and below 100 dbar were uncorrelated; and the magnitude of the vertical velocity signal above 100 dbar was much smaller than within the main pycnocline depth range. Standard deviations of vertical velocity ranged from 4 m/day at 100 dbar to 30 m/day below 300 dbar, while peak vertical velocity values were roughly ±100 m/day.

CALIBRATING THE ECCO OCEAN GENERAL CIRCULATION MODEL USING WOCE DATA AND MODEL GREEN'S FUNCTIONS

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Model Green's functions provide a simple, yet effective, method to test and calibrate General-Circulation-Model (GCM) parameterizations, to study and quantify model and data errors, to correct model biases and trends, and to blend estimates from different solutions and data products. These properties are demonstrated within the context of the ECCO (Estimating the Circulation and Climate of the Ocean, http://www.ecco-group.org) ocean data assimilation project using a subset of WOCE data.

TRANSPORT OF THE ANTARCTIC INTERMEDIATE WATER IN THE SOUTH ATLANTIC

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The Antarctic Intermediate Water is a low-salinity, oxygen-rich water mass that spreads northward in the South Atlantic Ocean in the 700-1200 m depth range. The circulation of this water mass and its role in the global thermohaline circulation are the subjects of intense debate. During the World Ocean Circulation Experiment (WOCE), hydrographic sections and free-drifting floats sampled the Antarctic Intermediate Water. We used these data sets in a 1° resolution finite-difference inverse model to estimate the circulation of this water mass in the South Atlantic Ocean, between Antarctica and 2°S. The steady-state dynamics of the inverse model includes geostrophic balance, mass and heat conservations. The model is forced by ERS1 wind-stresses and ECMWF air-sea heat fluxes averaged for the WOCE years. The main pathways of the northward spreading of the Antarctic Intermediate Water are revealed, including western boundary currents that are major contributors to the meridional circulation of this intermediate water mass. Transports are quantified.

BOTTOM CURRENT VARIABILITY THROUGH XBT AND ALTIMETRIC DATA

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A method for estimating temporal changes in deep, depth independent currents is proposed. These changes are assumed to be related to the variability of "barotropic height" slopes. Barotropic height (BTH) is operationally defined as the local difference between sea surface height (SSH) measured by the TOPEX/POSEIDON altimeter and dynamic height calculated from XBT casts (through the use of a temperature salinity relationship). Results are restrained to temporal variability because geoid uncertainties in the SSH data render impossible the use of BTH slopes for absolute current estimations. The method was tested against current meter data in the Shikoku Basin off southern Japan, where the moorings (WOCE PCM5) were along a satellite track and there was good XBT spatial and temporal coverage. Visual inspection indicate the variability of currents near 4500 m was well captured by the method. Differences in spatial and temporal resolution between the data sets make quantitative comparisons difficult and unreliable. In order to perform a more objective validation, the method was applied to data from the OCCAM World Ocean Model (1/4° version). Currents calculated from model-derived BTH slopes were compared to the model's own barotropic velocity. This was done for the whole Pacific north of 10°S. Results varied in space, but the method performed well in general. Correlation coefficients between method derived and OCCAM's currents varied from 0.6 to 0.9 in most of the area. In the northern Shikoku Basin, the correlations were between 0.7 and 0.9. The method performed poorly along 35°-40°N in the western Pacific and along the eastern boundary.

EDDY FLUXES OF HEAT AND SALT IN THE SOUTHEAST INDIAN OCEAN

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The temporal and spatial evolution of warm-core eddies generated at the eastern boundary of the southeast Indian Ocean are described, using a combination of TOPEX/Poseidon and ERS altimetry and in situ hydrological data. These warm-core eddies have a role in transporting warm, low salinity water from the coastal zone into the ocean interior; they also act to modify the T-S characteristics of deeper water masses (upper thermocline and mode waters). We are particularly interested in "long-lived" warm-core eddies, which maintain a sea-level anomaly of > 10 cm for more than 6 months or for more than 1500 km in distance. These "long-lived" eddies are mostly formed at the coast in May when the Leeuwin Current is strongest. The number varies from year to year; for example, more warm-core eddies are generated during years of anomalous low-density water at the eastern boundary (e.g., 1996). After separation from the current, the warm-core eddies drift WNW following isopycnal contours, and are strongly steered by bathymetry. The majority drift past 90°E and some traverse the entire Indian Ocean. In September 2000, the TIP2000 research campaign made hydrological sections through 3 of these warm-core eddies. These eddies were observed some 350 km offshore from the Leeuwin Current in September, their vertical structure and temporal evolution show they were indeed formed at the coast in May. These eddies penetrated to at least 1500 m depth; the strongest eddy B influenced isopycnals to 2500 m. The strength of Eddy B was due to it being trapped and intensified by a Leeuwin Current squirt which directed warm, low salinity water offshore from August to October. The average annual eddy heat and salt fluxes associated with these warm-core eddies is estimated at 0.004 PW and 2.6×10^{5} kgs^{-1}, respectively. This represents 20-30% of the annual mean heat and salt budgets in the eastern Indian Ocean, and these eddies could play an important role in transporting heat into the southern Indian ocean and contributing to the large ocean-atmosphere heat transfer in this region.

ADJOINT COMPILER TECHNOLOGY AND STANDARDS

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Adjoint models are important for understanding both the sensitivity of the ocean state to initial/boundary conditions and model parameters of all types, and in a secondary role as a numerical method for doing data assimilation. Although also important in engineering, economics, and most scientific disciplines, they have thus far found their widest and most advanced applications in physical oceanography. While oceanographers have long experience in constructing "direct" or forward models, the construction of the corresponding adjoint model has proven, for many, burdensome and tedious. The advent of compilers capable of generating the adjoint model nearly automatically from the forward code has been revolutionary.The adjoint corresponds to taking the derivatives of the direct model with respect to any field or parameter subject to change. Its numerical values can be computed using either a tangent-linear or an adjoint model both of which can be generated by compilers for Automatic Differentiation (AD). The problems arising from making this source transformation fully automatic are investigated as part of a collaborative NSF-ITR funded research project between MIT, Rice University, and Argonne National Laboratory/University of Chicago. The project's goals are to develop a fully-automatic, easy to use open-source tool for AD that is immediately applicable to Fortran and C codes and that is designed to allow community extension to include more elaborate code transformations, for example Hessian calculation. A primary focus of the project is geophysical applications. The poster gives an overview of how compilers for AD work in principle. Various successful applications illustrate the feasibility of the general approach. Some of the major challenges in the field are discussed. Features of forward model implementations that are favorable from the point of view of automatic adjoint code generation are proposed.

VISUALIZATION TOOL FOR THE WORLD OCEAN SURFACE CURRENTS

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FORTRAN-based software for the world ocean surface currents visualization functioning on the Windows platform (95 and higher) has been developed. The software works with the global interpolated drifting buoys data set (1979-2001) from the WOCE Surface Velocity Program and the global bottom relief five-minute resolution data set (ETOPO5). These data sets loaded in binary form into operative memory of a PC (256 Mb or more), together with the software compose the world ocean surface currents visualization tool. The tool allows researchers to process data on-line in any region of the world ocean, display data in different visualization forms, calculate current and velocity statistics and save chosen images as graphic files. It provides displays of buoy movement (animation), maps of buoy trajectories, averaged (by prescribed time and space grid intervals) current vector and modulus fields, fields of current mean and eddy kinetic energies and their ratio, current steadiness coefficients and sea surface temperature. Any trajectory may be selected simply by clicking on a summary map of trajectories (or by given buoy number). It may then be viewed and analyzed in detail, while graphs of velocity (components, module and vector) and water temperature variations along this trajectory may be displayed.

The description of the tool and some screen shots are available at http://csit.ugatu.ac.ru and http://zhurnal.ape.relarn.ru/articles/2001/154.pdf.

APPLICATION OF WOCE SECTIONS TO THE STUDY OF MIXING IN THE ATLANTIC OCEAN

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We use WOCE data to find regions of enhanced mixing on a global scale. From the transatlantic WOCE CTD sections it appears that internal tides propagating from submarine ridges strain the vertical structure of hydrographic fields and can be registered by CTD-profiling. These internal waves and oceanic finestructure seem to be caused by the breaking of large amplitude internal tides. The changes in the vertical structure are reflected in the one-dimensional spatial spectra of the CTD vertical profiles. Spectral densities (dropped spectra) near submarine ridges are several times greater than in the regions far from abrupt topography where they are close to the background spectra described by the Garrett-Munk model. Enhanced mixing occurs near the bottom over the Mid-Atlantic Ridge. It is stronger in the South Atlantic. We found strong mixing associated with bottom water spreading in the Equatorial Channel and Strait of Denmark.

WHY WERE COOL SST ANOMALIES ABSENT IN THE BAY OF BENGAL DURING THE 1997 INDIAN OCEAN DIPOLE EVENT?

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The most important centre of atmospheric convection associated with the Indian summer monsoon is located in the Bay of Bengal. This tendency was enhanced during the 1997 Indian Ocean Dipole (IOD) event in the tropical Indian Ocean, and cool SST anomalies due to upwelling in the east were restricted to the south of about 5°N in the bay. However, sea surface height anomalies associated with the upwelling propagated all the way to the north of the bay. Using XBT data collected in the bay and a high resolution ocean general circulation model simulation during the IOD, we propose that the permanent, low-salinity, highly stratified, near-surface pool in the bay prevented the IOD-related upwelling from influencing the SST. The strong near-surface stratification in the bay cannot be broken down by the observed winds there. The existence of the barrier layer in the bay ensures that internal ocean dynamics cannot have an impact on SST. As a result, atmospheric convection over the bay may be decoupled from ocean dynamics.

TWO DISTINCT SYSTEMS OF MESOSCALE EDDIES IN THE KAMCHATKA CURRENT AND OYASHIO

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Two distinct major currents–the Oyashio and the Kamchatka–comprise the Pacific's western subarctic boundary current system. These are characterized by equally distinct systems of anticyclonic eddies, even though the Oyashio is itself a continuation of the Kamchatka Current. For example, hydrographic data and visible and infrared satellite images reveal a chain of intense oceanic eddies in the Kamchatka Current between 50°-60°N. These eddies move southwestward in wave-like patterns with typical speeds of ~6-7 cm/s. An individual eddy thus requires about six months (from January to June) to travel from the Kamchatka Strait (~56°N) to the southern tip of the Kamchatka peninsula (~51°N). Oyashio anticyclonic eddies, on the other hand, move northeastward at a much slower speed (about 1 cm/s).

We show that (a) transport of mass by Kamchatka eddies has the same value (~7-11 megatons per second) as the geostrophic transport by the mean flow of the Kamchatka Current (~6-16 MT/s); and (b) there is significant interannual variability of the properties of the eddies and their associated mass and fresh water transports. Seasonal variations of wind stress and fresh water flux are the most pronounced signals in the Pacific subarctic and can be related to these features.

A mechanism is proposed for the generation of these wave-like disturbances in the boundary currents. We suppose them to be annual planetary waves whose speed is determined by the mean gradient of potential vorticity, and therefore directed northeastward. The critical latitude for annual planetary waves with a planetary value of β (meridional gradient of Coriolis parameter) exists near 51°N. However, the mean vertical gradient of potential vorticity is greater than planetary value of beta, so that annual planetary waves can exists far beyond their "beta-limit".

CIRCULATION OF THE WESTERN TROPICAL ATLANTIC: FROM WOCE TO CLIVAR

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Currents, transports and water mass properties of both the upper-layer warm water masses and the deep water layer along the western boundary between 10°S and the equator as well as on cross-equatorial sections were observed by shipboard surveys, moored stations and profiling floats. Mean transports of the different current branches as well as variability over the decade-long observations are being presented. In particular, from six repeated shipboard profiling sections off Brazil near 5°S a northward warm water transport above 1100 m of 25.0 ± 4.4 Sv is determined, of which 13.4 ± 2.7 Sv occur in the thermocline layer supplying the Equatorial Undercurrent. For the southward flow of North Atlantic Deep Water a section-mean transport of -31.7 ± 9.2 Sv was determined at 5°S. Significant differences between seasonal averages of the zonal currents at 35°W are found down to 2500 m depth with an intermediate maximum in the depth range of the Equatorial Intermediate Current. The seasonal variation in the equatorial flow field is in general confirmed by the analysis of TOPEX/POSEIDON sea surface height data.

ON THE ENERGETICS OF AN OCEAN GENERAL CIRCULATION MODEL

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The sources and sinks of kinetic energy (KE) and potential energy (PE) and the subsequent conversion and transport of energy in a global, coarse-resolution, Boussinesq, steady-state general circulation model (GCM) run are discussed. In general, the globally integrated budgets of KE and PE are quite sensitive to both model parameters and surface forcing. For our "standard" configuration, the KE budget is as follows: the work done by wind at the surface (the only external source of KE) provides 0.6 TW, which is balanced by viscous dissipation of 0.4 TW with 0.2 TW converted from KE to PE. Wind energy input occurs primarily over the Antarctic Circumpolar Current (ACC) and the equatorial Pacific, whereas dissipation (mostly due to horizontal shear) occurs both in these regions of large wind energy input and in boundary currents. While there are very large local exchanges between KE and PE, on the order of 10 TW in a model grid column, these energy fluxes are balanced by work done by vertical flows against hydrostatic pressure gradients. Thus, the global 0.2 TW energy conversion of KE to PE is a small residual, a function of work done by horizontal pressure gradients. It is shown that the magnitude of this residual term can be interpreted as being due to ageostrophic velocities. In the global PE budget, given a background diapycnal diffusivity of $0.3 \times 10^{-4}\ m^2 s^{-1}$, the work done by mixing is 0.3 TW, primarily in the tropical thermocline. This PE gain is approximately offset by the PE release through the Gent-McWilliams eddy parameterization, occurring primarily in the ACC and in the Gulf Stream. Hence, in this model configuration there is a remaining approximate balance between PE gained through conversion from KE, and PE lost via convective mixing.

The GCM results are compared to those from a simple analytical channel model, crudely representing the dynamics of the ACC, which provides a somewhat different representation of the energy cycle. Both models are discussed in the context of the real ocean.

SPATIAL VARIABILITY OF MIXING IN THE SOUTHERN OCEANS

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The meridional overturning circulation refers to the flow of bottom and deep water from high latitude sources and the compensating return of less dense upper-ocean water. The sources of deep and bottom water are limited to a few high-latitude sites in the present-day ocean. Diapycnal fluxes of mass, temperature and salt in the southern oceans close the bottom and deep circulation and are therefore a key element of the meridional overturning circulation. The 2-dbar WOCE CTD profiles in the Southern Ocean and subtropical Atlantic, Indian and Pacific Oceans are used to calculate N^2 (buoyancy frequency), whose variability can be used to estimate mixing. CTD profiles from different ocean basins and topographic regions (downstream of and parallel to mid-ocean ridges, and over abyssal plains) are used to determine the spatial variability of mixing in the southern oceans.

VARIABILITY OF SOUTHERN OCEAN FRONTS SOUTH OF AUSTRALIA DERIVED FROM REPEAT WOCE SECTION SR3 AND SSH ANOMALY OBSERVATIONS

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Variability of the major fronts between Australia and Antarctica is described on the basis of six occupations of the World Ocean Circulation Experiment (WOCE) repeat section SR3 and 7-year altimeter sea surface height (SSH) anomaly observations (the CLS/AVISO "Mean Sea Level Anomaly" maps). The WOCE sections were obtained between 1991 and 1996 and cover each season of the year. To produce maps of absolute SSH, we added the mean surface dynamic height (relative to 2500 dbar) from the Olbers et al. climatology. The mean dynamic height estimated from the six repeats of SR3 agree well with the climatology, although the climatology is somewhat smoother.

We have found satellite altimeter maps of SSH to be of great value for synoptic mapping of Southern Ocean fronts. Even relatively weak and small-scale features of the density field are reflected in SSH. This correspondence supports the conclusion of Rintoul et al. that the altimeter signal south of Australia primarily reflects changes in the full-depth baroclinic field. Each of the fronts identified on the repeat sections corresponds to a narrow range of SSH values. These SSH streamlines are also found to correspond to large lateral gradients of SSH (i.e. fronts) east and west of the repeat section. Maps of sea surface height are then used to determine the path and variability of the fronts. The maps confirm the multi-filament structure of the fronts in the Southern Ocean and show that streamlines merge and split along the path of the fronts. Each of the ACC fronts extends throughout the water column; as a result, the path of the fronts and the width of their meander envelopes is strongly influenced by bathymetry. Meridional displacements of the fronts are correlated with variations in SST, suggesting shifts of the fronts contribute to SST variability observed on interannual timescales.

DEEP PROPERTY DISTRIBUTIONS IN A WOCE SOUTH ATLANTIC CLIMATOLOGY

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We have constructed new hydrographic and tracer climatologies of the South Atlantic by adjusting modern section data, using locally defined temperature ranges of minimum property variability. The resulting isopycnal fields contain significantly less small-scale features at all depths and show much better agreement between different tracers than existing climatologies. The distributions of tracers (e.g. oxygen and salinity) at the level of North Atlantic Deep Water (NADW) are characterized by large zonal gradients on both the eastern and the western flanks of the Mid-Atlantic Ridge (MAR). Potential vorticity (PV) maps (f / layer thickness) at the same level derived from the new climatology show a surprisingly simple pattern, with the zonal gradients almost entirely restricted to the eastern ridge flank, with zonal PV contours in the abyssal basins and on the western ridge flank. Salinity varies along PV mainly above the western flank in the Brazil Basin. Elsewhere, salinity and PV are roughly aligned, suggesting a different net effect of mixing above the two flanks of the ridge. We relate the tracer observations to the velocity field derived using advection-diffusion balances, derived from the new climatology.

INSTANT: MEASUREMENT OF THE INDONESIAN THROUGHFLOW

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During the WOCE years, many successful monitoring programs provided a first look at the variability of the Indonesian Throughflow (ITF) from its Pacific source region, through the internal seas, and out to the southeast Indian Ocean. The Indonesian measurement programs include one year mooring deployments in Makassar Strait, Timor Passage, Ombai Strait and the South Java Current; a three-year shallow pressure gauge array in the exit passages; decade-long XBT transects (WOCE IX1, PX2, IX22); and numerous repeat hydrography sections in the southeast Indian Ocean (WOCE IR6C, IR6 and I10). However, these ITF measurement programs lacked temporal coherence: the observational data cover different time periods and depths in the different passages of the complex pathways leading to the Indian Ocean. This has lead to ambiguity of the mean and variable nature of the ITF, and the transformation of the thermohaline and transport profiles within the interior seas. To remedy this, a coordinated international effort known as INSTANT (International Nusantara Stratification ANd Transport) combining a mooring array with existing observational networks, will be implemented by the PIs on this poster. The 3-year mooring array will be deployed in late 2003. INSTANT is designed to provide a time series of ITF transport and property fluxes and their variability from intraseasonal to annual time scales, along the ITF pathway from the intake of Pacific water at Makassar Strait and Lifamatola Passage, to the Lesser Sunda exit channels into the Indian Ocean. The poster will review some of the ITF measurements during WOCE, and preview the INSTANT program.

OBSERVING THE AGULHAS AND MADAGASCAR RETROFLECTIONS FROM SPACE

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The oceans around South Africa contain two important retroflecting current systems–the Agulhas Retroflection to the south of South Africa and a smaller system to the south of Madagascar. Both are implicated in the transfer of Indian Ocean water into the S. Atlantic. Both are rapidly evolving, with considerable change in the position of the currents and the shedding of eddies. To understand their behaviour we use data from three different spaceborne sensors–ATSR (Along-Track Scanning Radiometer), TMI (TRMM Microwave Imager) and SeaWiFS. ATSR and TMI provide infrared and passive microwave measurements of sea surface temperature (SST), respectively; while SeaWiFS gives ocean colour measurements of chlorophyll. None of these provide a direct measurement of currents, but all give an indication of coherent flow features, such as eddies. For the Madagascar Retroflection the observations suggests that it is a much more intermittent phenomenon than the Agulhas Retroflection. The TMI SST data, though limited latitudinally, show westward progradation of the Agulhas Retroflection (associated with ring shedding) about eight times per year in the period 1997-1999. This agrees with previous estimates. However, this behaviour is seen to change in the 2000-2001 period, with the Agulhas Retroflection occurring further to the east. Another new observation from the TMI data is that, although the first northward meander of the Agulhas Return Current is constrained by bathymetry, its position does vary intermittently, remaining fixed in a given location for up to six months at a time.

ESTIMATES OF OCEAN MIXING COEFFICIENTS

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The global ECCO synthesis procedure is used to estimate horizontal and vertical ocean mixing coefficients (viscosity and diffusivity) that are consistent with WOCE data sets, the atmospheric forcing fields and the model physics. Those coefficients are estimated as time-constant but geographically varying fields and are adjusted along with surface momentum and buoyancy forcing so as to bring the model into consistency with global data sets over the period 1992 through 2000. Information is provided about the estimation procedure and and the resulting changes of the mixing coefficients is being described. While the estimated coefficients lead to a reduced model drift, their physical interpretation in terms of eddy transfers is not always as expected.

HOW DOES THE INTRUSION OF ANTARCTIC BOTTOM WATER AFFECT THE OUTFLOW OF NORTH ATLANTIC DEEP WATER?

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Numerical experiments and observations indicate a delicate balance between the southward flow (outflow) of North Atlantic Deep Water (NADW) and the northward flow of Antarctic Bottom Water (AABW) across 30°S. Rather than emerging as a well confined deep western boundary current, the core of NADW seems to veer eastward south of 20°S. At the equator, phases of strong AABW intrusion have been observed to coincide with phases of weak southward flow of NADW, and vice versa. Numerical experiments reveal weak variations in AABW intrusion giving rise to stronger variations in NADW outflow, both occurring on a decadal time scale, and the former leading the latter. Finally, hypothetical climate periods in which AABW intrusion is near zero yield a substantially enhanced North Atlantic overturning, along with a subtantially larger northward heat flux than at present-time climate conditions. These findings are supported by numerical experiments that we conduct using a global primitive-equation sea-ice-ocean general circulation model. Ultimately, these experiments suggest that the formation rate of AABW has a substantial impact on the rate of NADW outflow and the strength of the North Atlantic overturning.

SOUTH INDIAN OCEAN CIRCULATION DIAGNOSED BY A FINITE DIFFERENCE INVERSE MODEL

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A finite-difference inverse model is used to quantify the large-scale ocean circulation in the South Indian Ocean. It is applied to a historical hydrographic data set, complemented with the CIVA and JADE data acquired as part of the French contribution to WOCE. The inverse model resolution is 1° in latitude and 2° in longitude. The dynamics are steady-state. The estimated circulation is in geostrophic balance and satisfies mass, heat and potential vorticity conservations. The wind and air-sea heat forcings are annual means from ERS1 and ECMWF respectively. It is shown that the heat flux conservation controls the zonal-averaged meridional mass flux and that the potential vorticity balance is needed for realistic bottom circulation patterns.

The main features of the various current systems of the South Indian Ocean are quantified and reveal a topographic control of the deep and bottom circulation. The cyclonic Weddell Gyre is mainly barotropic, it transports 45 Sv, and has an eastern extension limited by the southern part of the Antarctic Circumpolar Current.

The bottom circulation north of 50°S is complex. However, the Deep Western Boundary Currents are identified as well as cyclonic recirculations.

Between 26°S and 32°S, the meridional overturning circulation amounts to 15 Sv, the maximum transport being observed at 1400m. The main contribution to the overturning circulation comes from east of the Mozambique Ridge due to a weak Aguhlas Current of 55 Sv. At 32°S, east of the Mozambique Ridge, 15 Sv are transported by the Agulhas Undercurrent. The heat gain south of 32°S is 0.33 PW.

STUDY FOR ESTIMATION OF AIR-SEA CO_2 GAS TRANSFER BY WAVE BREAKING MODEL USING SATELLITE DATA

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CO_2 transfer velocity at air-sea interface, associated with mechanisms such as turbulence and wave breaking which are closely related to wind speed, has been studied from satellite data. Determination of wind friction velocity from satellite-derived wind data will play an important role in the computation of CO_2 flux transfer. It is necessary for understanding the relation between wind speed and wind friction velocity to determine that between non-dimensional roughness length and wave age. Because of the large variation of the non-dimensional roughness length, it is difficult to describe wave influence by the single wave age.

We observed directional wave spectra at the Hiratsuka Tower in Sagami Bay, Japan. The data set was separated into two directional spectrum types: Case 1 contains only swell and wind waves; Case 2 consists of a lot of component waves due to different wind fetch in the bay. Results show Case 2 was associated with large variations in the relation between non-dimensional roughness length and wave age. A new relationship between non-dimensional roughness length and wave age was proposed, based on in situ wind and wave data after considering the wind fetch effect.

A new method was proposed to estimate u*, based on the new relationship between non-dimensional roughness and wave age after considering fetch and wave directionality. Results are compared with those estimated from the Charnock formula, and the influence of wave effects on the wind stress is also discussed. A new relationship was established to determine the CO_2 exchange coefficient based on the whitecap model, using the U_{10}-u* relationship in the North Pacific Ocean, satellite data from NOAA/AVHRR (SST) and DMSP/SSM/I (wind speed) in Oct., Nov., and Dec. 1991. The CO_2 exchange coefficient estimated by other models is also compared with these results. The results show the importance of the wave breaking effect.

EVOLUTION AND ENERGETICS OF TROPICAL INSTABILITY WAVES DURING 1996-2000

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A high resolution model of the tropical Pacific Ocean is used to investigate eddy energetics associated with tropical instability waves (TIWs) in the equatorial Pacific Ocean from 1996 to 2000. The model is forced with optimized forcing from the ECCO global ocean state estimation, and boundary conditions are taken from the optimized solution. Agreement between the model and upper ocean observations in the tropics is detailed in another poster. The geographical dependence of the balance of the perturbation energy equation is explored, and the sensitivity of the results to the wind forcing and the model resolution is investigated.

Eddy kinetic energy reaches large values in fall 1998 during La Niña; TIWs are absent during El Niño (spring 1997 to spring 1998). At 135°W, the large mean to eddy kinetic energy conversion is dominated by $\overline{u'v'}\,\partial U/\partial y$, $\overline{v'v'}\,\partial V/\partial y$ and $\overline{u'w'}\,\partial U/\partial z$. All those terms are subject to seasonal and interannual variability. Baroclinic instability also provides energy to the TIWs between 1° and 4°N through the conversion of eddy potential to eddy kinetic energy.

Large eddy energy production is observed at the surface at 4°N within the anticyclonic shear between the SEC and NECC, where eddy kinetic energy is maximum. $\overline{u'v'}\,\partial U/\partial y$ is maximum just north of the equator at ~50 m depth in fall 1996 and is maximum at the surface in fall 1998 and fall 1999, suggesting that the TIWs derived their energy from the EUC-SEC shear in 1996 and from the shear within the SEC in 1998 and 1999. $\overline{v'v'}\,\partial V/\partial y$ and $\overline{u'w'}\,\partial U/\partial z$, which generally tend to weaken the waves just north of the equator, are also subject to interannual variability. Their combination with $\overline{u'v'}\,\partial U/\partial y$ leads to weaker TIWs in fall 1996 compared to fall 1998 and 1999.

DYNAMICS OF DEEP ZONAL FLOWS IN THE BRAZIL BASIN

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WOCE data (Lagrangian floats, tracers, hydrography) in the Brazil Basin of the South Atlantic reveal a regime of alternating zonal flows in the interior below the thermocline. High resolution models reproduce those flows, and allow us to investigate their dynamical origins. A primary mechanism for the deep zonal flows in the models is the response to the wind stress, as recently argued to be the case for a model of the Pacific Ocean. However, thermohaline flow is of similar strength, and the deep currents appears to be linked to the depth of the mid-ocean ridge. Models show that the meridional scale of the zonal jets is dependent on horizontal mixing. This dependence is further investigated using an idealized shallow-water model.

NORTH ATLANTIC DEEP WATER IN THE SOUTH-WESTERN INDIAN OCEAN

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From hydrographic observations and current measurements, obtained during the Dutch ACSEX programme, and similar public data from the World Ocean Circulation Experiment, the circulation in deep water in the south-western Indian Ocean has been studied. The three major water masses involved are the saline North Atlantic Deep Water (NADW), its derivative in the Antarctic Circumpolar Current, Lower Circumpolar Deep Water (LCDW), and the aged variety of deep water, North Indian Deep Water (NIDW). Although bound by the shallow topography near Madagascar, about 2 Sv from the upper half of the NADW core appears to flow across the sill in the Mozambique Channel into the Somali Basin, while the remaining NADW is transformed into LCDW by isopycnal and diapycnal mixing. In the Mascarene Basin, east of Madagascar the deep circulation is dominated by the southward flow of NIDW which blocks any inflow from the south. Northward inflow of LCDW therefore only can take place in the eastern half of the Indian Ocean, along the Southeast Indian Ridge and the Ninety-East Ridge.

ON THE MINDANAO UNDERCURRENT A SUBSURFACE COUNTERCURRENT BELOW THE STRONG WESTERN BOUNDARY CURRENT

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The Mindanao Undercurrent (MUC), a subsurface northward flowing current offshore and below the Mindanao Current (MC), was examined by comparing the assimilation data produced with the GFDL MOM3 and the NODC data set and 7-survey observations gathered in autumn 1986-1991. The MUC with two velocity cores were similarly described with the assimilation and observation data along 8°N. The MUC was found in the assimilation data flowing from 5°N to 11°N along 127-128°E and deepening along isopycnals. The two cores seemed to be related to the eddy-like circulation at depth southeast of the Mindanao, especially the east one connected with the southern recirculation of the Mindanao Eddy (ME) below 200 m. The MUC had significant seasonal variation. It was noteworthy that the two velocity cores each revealed different seasonal cycles, implying that the formation of the MUC might be composed of different processes.

The MUC consisted of two water masses with respective salinity 34.52 at $27.2\sigma_t$ and 34.6 at $26.9\sigma_t$, which were remnants of the Antarctic Intermediate Water and the lower part of the Southern Pacific Subtropical Water and show that the MUC was not a local transient but originated from the South Pacific.

Based on a simple conceptual model of a stratified ocean, the criterion of the geostrophic velocity inversion in and below the thermocline was derived as $h' \cdot \eta < 0$ and $\rho|\eta| \leq \Delta\rho|h\ |$, meaning that the slopes of the thermocline (h') and sea surface (η) must be opposite to each other, and that h' must be strong enough to satisfy the latter inequality. The features and dynamics of the western boundary undercurrents below the thermocline, such as the MUC, are discussed with the criterion, which suggests that the MUC probably should be attributed to the combined effect of the basin-scale wind-driven circulation and local geostrophic balance.

GEOSTROPHIC RELATIVE VORTICITY METHOD: A SIMPLE METHOD FOR OBTAINING BAROCLINIC ROSSBY WAVES USING ALTIMETER DATA

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A new method, called the Geostrophic Relative Vorticity (GRV) method in this paper, to derive distribution of oceanic baroclinic Rossby waves from the altimeter data is presented. It is based on the principle of potential vorticity conservation and obtains the time-varying geostrophic relative vorticity distribution from the altimeter data. The GRV method could reflect the thermocline signals from the relative vorticity distribution.

We applied the GRV method to the TOPEX/Poseidon dataset over the Global Ocean basins. Comparing the results with the work by Chelton and Schlax for detecting baroclinic Rossby waves, we found the wave signals obtained by the GRV method are stronger. Additionally, westward propagation east of Hess Rise also originated at the eastern boundary, but the method of Chelton and Schlax has not detected the westward signals and they suggested topography may be a source of the waves.

This method does not remove the meso-scale eddy signal, so another characteristic about this method will be discussed further.

THE AGULHAS CURRENT - A LOGARITHMIC, WESTERN BOUNDARY CURRENT

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Most theories of fluid flows near a boundary assume that the size of the eddy field increases as one moves away from the boundary and that this also results in an increasing eddy viscosity, acting on the large scale flow. However oceanography used to be an exception in that before WOCE, the standard theory used to describe western boundary currents (that due to Munk) assumed that the eddy viscosity was a constant, independent of the distance from the coast.

A recent current profile across the Agulhas Current emphasised the problem. It showed a region of strong current shear near the continental slope and a relatively gentle exponential decay of the current offshore. When the standard Munk solution was used to fit the current profile, it could account for only 76% of the variance in the data. The fit was poor. In an attempt to do better, the problem of a logarithmic western boundary current, one with a linearly increasing eddy viscosity, was solved analytically for the first time. It was found that the new solution could explain 97.3% of the variance in the data. The addition of a constant viscosity inshore layer produced a further significant improvement, the final solution explaining 98.2% of the total variance.

The results indicate that at least one western boundary current is logarithmic with the effective eddy viscosity increasing away from the coast but that between the current maximum and the coast the effective viscosity is dominated by a single size of eddy.

VERTICAL MIXING IN THE OCEAN

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Historically the thermohaline circulation of the ocean was considered to be a result of downwelling at high latitudes and upwelling, due to turbulent mixing, throughout the rest of the ocean. However when the scheme was investigated in detail, it was found to require a much larger average vertical mixing rate than that actually observed.

Observations made during the WOCE experiment emphasised the problem, but model studies and analyses of the hydrographic data also provided us with a new picture of the thermohaline circulation. In this new picture, a significant amount of upwelling, is associated with Ekman suction in the Southern ocean. At the same time the Antarctic Bottom Water part of the thermohaline circulation is seen to be separate from that associated with North Atlantic Deep Water. In this poster we discuss this new picture in detail and show that the amount of turbulent mixing required is generally consistent with the observed values.

WHY DOES SEA LEVEL CHANGE LOCALLY?

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Causes for local sea level change are estimated by analysing an optimised Ocean General Circulation Model for the WOCE period. The model is global with a resolution of 2 degrees. Satellite altimetry and NCEP fluxes are used to constrain the model while WOCE hydrography acts as validation. The analysis distinguishes between local changes due to

- local warming/cooling,
- local differences in salinity,
- change in the wind field, and
- change in total mass due to increased inflow by rivers and melting ice.

Results reveal large differences in local sea level trends and substantial differences in their explanation. This is another indication that one has to be careful in deriving global sea level trends from tide gauges that are distributed unevenly around the globe.

PRODUCTION, SPREADING AND FATE OF THE LABRADOR SEA WATER IN THE SUB-POLAR NORTH ATLANTIC

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Labrador Sea Water (LSW) results from deep convective mixing induced by high heat losses during winters. From 1987 to 1994, years of exceptionally severe winters, we observe a year-to-year deepening of winter convection (> 2300 m), increase in LSW density, and cooling of the 0-2000-m layer; we call this LSW1987-1994. From 1995, winters were milder, with mixed layer depths < 1500 m. In the winter of 2000, convective mixing reached the depth of 1600 m and produced a distinctive modification of LSW (hereafter LSW2000), as dense as LSW produced before 1990, but fresher and less dense than deep LSW1987-1994. Away from convection, LSW becomes warmer and saltier, producing a characteristic point in time series and T-S diagrams. We constructed time series of T, S, density, thickness (volume) and depth of LSW1987-1994 and LSW2000 in the deep basins in the vicinity. We used the points of change in the tendencies, lag-correlated LSW densities, and the year-to-year change to estimate the time required for a vintage of deep LSW to arrive at each basin. It took about two years for LSW1987-1994 to reach the Irminger Sea, five years to the Iceland Basin, and at least seven years to the Rockall Channel. These spreading times are double those reported by Sy et al. Water similar to LSW2000 was found in the Irminger Sea and later in the Iceland Basin. LSW2000 moved faster than the earlier and deeper formation. We attribute its origin to the Labrador Sea because it was saltier in other basins. We constructed maps of LSW properties and thickness for the late 1960s and mid-1990s and estimated the lower margin of the LSW production rate to be 2 Sv. This estimate also represents the 25-year mean rate of LSW accumulation in the North Atlantic, which can be used in the study of the non-linear response of the ocean overturning to the abrupt change in the climate system.

ON THE EXTRATROPICAL ORIGINS OF ISOPYCNIC VARIABILITY

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We investigate the origin and transport of density-compensating anomalies of temperature and salinity using a model forced with realistic 1958-1997 surface products. On the surface σ_0=25.5, anomalies as high as 1.2°C and 0.6 psu are generated on the isopycnal near regions of winter outcropping in the eastern Pacific and can be tracked all the way to the equator in the western Pacific, where they persist as decadal variations of the order 0.2°C and 0.1 psu. The extratropical regions where the largest spiciness anomalies originate are characterized by low mean density stratification and deep winter mixing, both coinciding with highly negative upper ocean salinity gradients maintained jointly by evaporation and surface transport. The southeast Pacific, in particular, is ideally conditioned for the generation of large spiciness anomalies near the base of the winter mixed layer when anomalous surface forcing acts on a column of highly isopycnic upper ocean water. Anomalously strong winter forcing can result in spiciness anomalies of either sign. This suggests that isopycnal variability signals cannot be traced unambiguously to surface forcing anomalies at the outcrop region. Smaller but comparable anomaly generation is seen in the northeast Pacific, and we identify zones and density surfaces in other basins where large interannual spiciness variability appears to result from similar upper ocean conditioning.

DENSITY RATIO DISTRIBUTION IN THE NORTH PACIFIC FROM WOCE DATA

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The activity of double diffusive convection is investigated through the density ratio distribution from the upper 1000 db WOCE dataset. The frequency of occurrence of density ratio values is plotted to analyze the most favorable mode of double diffusive convection. Results are summarized as follows.

(1) In the high latitude north of 45°N and the eastern North Pacific, the mode value (the peak of frequency of occurrence) indicates that the almost fluid column stratified in statically stable. In the tropical region between equator and 15°N, the mode values exceed 4, suggesting that salt finger convection is not so active. On the other hand, in the mid-latitudes, the mode values were 3 to 4, suggesting weak salt finger convection. This is in contrast to the North Atlantic where the mode of the density ratio takes the value of 2.

(2) Looking at the mode value distribution more precisely in each layer, salt finger convection is active in the shallower layer between 100 to 300 db in the region east of Hokkaido (40°-45°N, 145°-150°E) and in the Eastern North Pacific (20°-30°N, 135°-130°W). These regions correspond to the region where the North Pacific Intermediate Water (NPIW) and the Eastern Sub-Tropical Mode Water (ESTMW) are formed. As for in the area east of Hokkaido, diffusive convection is anticipated to be active in the layer below 300 db to 700 db.

(3) Vertical diffusivities of salt are estimated from the laboratory flux law for each region, and are about $4x10^{-4}m^2$/sec and $1x10^{-4}m^2$/sec, respectively.

The detailed analysis on the potential density surfaces are now underway, and are presented in the poster.