A STUDY OF THE NORTH ATLANTIC SEA SURFACE TEMPERATURE SENSITIVITY TO ATMOSPHERIC FORCING

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The objective of this work is to better understand the lagged ocean response to atmospheric forcing, in terms of Sea Surface Temperature (SST) and superficial heat content over a season and over a year. Our interest is the North Atlantic during the last decade for large spatial scales (>O (100 km)). The work is based on a numerical simulation using the MIT-GCM over the years 1993-1996. We attempt to use the MIT-GCM adjoint to explore some physical properties of the simulated ocean state, namely the influence of atmospheric forcing on SST in the subpolar gyre. We investigate the differences of sensitivity between years characterized by different atmospheric conditions (1993-1994 and 1995-1996). First results provide evidence on the seasonal dependence of wind forcing influence on SST. They emphasize the impact of the "de-stratification" processes during late summer on both early and late winter SST. As expected, the sensitivity of SST to past local atmospheric forcing is shown to depend mostly on the mixed-layer depth history. The sensitivity to past remote forcing suggests more complex mechanisms associated to convection in the subpolar gyre, such as wind effect on the cyclonic activity.

QUANTIFYING THE HEAT BUDGET AND OVERTURNING CIRCULATION IN THE ARABIAN SEA DURING THE 1995 SOUTHWEST MONSOON

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We investigate the variability of the circulation, water masses, heat and salt fluxes in the southern Arabian Sea over the course of the southwest monsoon. Two zonal sections taken along 8°N in 1995 as part of the Indian Ocean WOCE hydrographic program are used. The first was occupied in early June at the onset of the southwest monsoon winds, the second in late September, at the wane of the monsoon. In September the section was found to be generally warmer (+0.32°C) and saltier (+0.04) than in June despite a drop in mean sea level of 50 mm. Therefore, the common assumption that an increase in sea surface height follows an increase in heat content (the hydrostatic response) does not hold in the monsoonal Arabian Sea. Instead, heat content varies due to the advection of Arabian Sea Surface Water and Red Sea Water onto the section from the north, and the drop in sea level must indicate a loss of mass, rather than heat, from the water column.

There are large uncertainties involved in diagnosing the heat flux divergence across the Arabian Sea, because the seasonal variability of the water masses and circulation in the basin make it difficult to treat our data as representative of a long term mean. We find an oceanic heat export of -0.72 PW in June and -0.19 PW in September, implying a basin cooling rate of about -0.36 PW in June and a slight heating of 0.12 PW in September. In June the mass and heat balances are dominated by the Ekman layer and the Somali Current, with very flat density surfaces resulting in a small interior transport. By September the Ekman transport has reduced and it is primarily the interior transport which balances a strong Somali Current. There are two main overturning cells in June and September: A shallow one of magnitude 5 Sv that reaches depths of no more than 500 m and is driven by Ekman divergence at the surface, and a deep cell of magnitude 1 Sv representing a weak inflow and subsequent upwelling of Circumpolar Deep water. The deep cell implies a basin-averaged upwelling velocity of 3.2×10^{-5} cm/s through 2200 m depth.

UPTAKE AND SPREADING OF ANTHROPOGENIC CO_2 IN AN EDDY-PERMITTING MODEL OF THE ATLANTIC OCEAN

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In the framework of FLAME (Family of Linked Atlantic Model Experiments) an eddy-permitting model of the Atlantic Ocean was used to hindcast the uptake and spreading of anthropogenic trace gases, CO_2 and CFC, during the last century. With a horizontal grid resolution of 20 km and 45 vertical levels, the model is the first experiment that includes the effect of mesoscale eddies during a hundred-year integration. The thermohaline and wind forcing of the model consists of a mean climatology for the first half of the century; after that reanalyzed monthly NCEP fluxes are prescribed. Interannual and longer-term variations are therefore also represented.

Compared to existing coarse resolution tracer simulations (OCMIP) this model shows a detailed structure of the surface tracer fluxes, especially in the subpolar North Atlantic where most of the uptake takes place. This structure can be related to various physical processes, for example local uptake due to mixed layer dynamics. Because of the long (compared to other trace gases, e.g. CFC) equilibration time of CO_2, the oceanic circulation and its variability might play an important role for the amount of uptake of CO_2 into the ocean.

Other topics of this study are the total uptake in comparison with a non-eddy resolving model version and the strong correlation of meridional heat and CO_2 fluxes. Both fluxes are directed northward and are strongly related to the meridional overturning in mid-latitudes on seasonal and interannual time scales. It will be questioned if (and where) heat fluxes might be a proxy for CO_2 fluxes and vice versa.

THE WOCE PACIFIC CFC SURVEY

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The World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) provided an unprecedented set of high quality dissolved chlorofluorocarbon (CFC) measurements. CFC data from zonal and meridional sections occupied during 1991-1996 as part of the WOCE Pacific One-Time Survey have undergone data quality evaluation. Here the focus is on the large-scale circulation features in the Pacific Ocean. Distributions of CFC-derived apparent ages on selected density surfaces are presented. Since the WHP Pacific Basin survey extended over about five years, techniques are discussed for normalizing the CFC measurements from individual sections to the mid-point of the survey period. The techniques involve using models of atmospheric CFC increase as a function of time. Maps of vertically integrated water column CFC inventories and CFC inventories on selected density intervals in the North and South Pacific are presented. These results are used to examine the mechanisms, pathways and time-scales by which CFC-bearing waters spread and ventilate the upper and intermediate waters of the Pacific. CFCs were below detection limits in the deep waters of the North Pacific at the time of the WHP Pacific survey. However, CFCs were detected in high latitude deep waters along a number of sections in the South Pacific and in the deep western boundary current flowing northward in the Southwest Pacific Basin. In summary, observed CFC fields during WOCE will provide a baseline for future work. These results will be useful for testing the ability of numerical ocean models to simulate ventilation processes and the uptake of carbon dioxide in the Pacific.

SEASONAL AND INTERANNUAL EVOLUTION OF THE MIXED LAYER IN THE ANTARCTIC ZONE SOUTH OF TASMANIA

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The Antarctic Zone (AZ) of the Southern Ocean is characterized by cold Winter Water, extending to around 200 m in winter and surmounted by Antarctic Surface Water (AASW) in summer. The AZ spans the Antarctic Divergence where the zonal wind regime reverses. AASW is subject to large air-sea fluxes and is modified by sea-ice interactions to the south. AASW is constantly advected northward by Ekman transport north of the Polar Fronts where it mixes with the mode and intermediate waters. Monitoring variations in AASW water-mass characteristics is important because it can have a direct impact on the oceanic ventilation and water mass properties.

In this study, repeat CTD and XBT observations south of Tasmania (1991-2000) are used to examine the variations of AASW. CTD observations show that the winter mixed layer depth (MLD) is found around 100 m in the southern part of AZ and is controlled by the vertical salinity field and its associated halocline. In the northern part, both temperature and salinity structures influence the winter pycnocline, and the winter MLD is deeper (120 to 150 m). The shallowest winter MLD is found at the Antarctic Divergence where Circumpolar Deep Water upwells. In summer, the seasonal thermocline coincides with the pycnocline along the entire AZ, and a temperature criterion rather than a density one can be used to determine the MLD. The summer MLD characteristics are similar in the northern and southern AZ.

Interannual variations in the summer MLD are evaluated using eight years of XBT data. Summer MLD variations in the AZ are small except between 58-60°S where MLD varies from 55-60 m to 90-110 m. Comparisons with ECMWF forcing show that MLD variability is correlated with three-months-averaged wind forcing: stronger wind stress leads to more vertical mixing and a deeper MLD. Heat flux has the inverse role: heat flux increases the stratification and acts to reduce the MLD. Interannual variations in the thermal content of AASW transported north across the PF are also estimated.

FLOW AT INTERMEDIATE DEPTHS AROUND MADAGASCAR BASED ON ALACE FLOAT TRAJECTORIES

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During 1994-1996, 215 ALACE floats were released at 900 m depth in the Indian Ocean. 55 entered around Madagascar (2-30°S, 35-55°E), generally at 800-900 m. Floats approaching the island from the east moved north or south depending on latitude, the bifurcation point being near 20°S. Mean southward velocities in the boundary current were 15 $cm \cdot s^{-1}$ during each 25-day observation period, with mean northward velocities of 12 $cm \cdot s^{-1}$. Velocities past Cape Amber were about 11 $cm \cdot s^{-1}$, comparable to current meter data. Floats moving north around the island often drifted north of the Comores for many months at less than 5 $cm \cdot s^{-1}$ with no discernable pattern, before exiting the region either to the north in the East African Coastal Current and the equatorial current system or to the south via the Mozambique Channel. Floats passing south of Madagascar tended to move steadily westwards towards the African coast, becoming entrained in the Agulhas Current and its recirculation gyres near 28°S. Similarly, floats released within the southern portion of the Channel all tended to move south and west. Mean flow in the Agulhas was about 18 $cm \cdot s^{-1}$, with maximum velocities up to 35 $cm \cdot s^{-1}$. All flows were extremely variable because of the ubiquity of eddies. In essence, the flow observed near 800 m mirrored that seen at the surface from TOPEX altimetry and at 845 m in the OCCAM global model. Float temperature data showed when a given float was acted on by an anticyclonic eddy. Deviations from the background temperature field, of 0.5°C or more were found only south of 12°S and in about 9% of Mozambique Channel float records. The results support the idea of a net southward flow of water through the Channel, with eddies affecting the transport in the southern part of the region. In the north, however, eddies were far less prevalent and topographic steering by the Mascarene Ridge became important.

NORTH ATLANTIC SIMULATIONS WITH THE HYBRID COORDINATE OCEAN MODEL (HYCOM): IMPACT OF VERTICAL COORDINATE CHOICE, REPRESENTATION OF DENSITY, AND GRID RESOLUTION

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Previous studies with MICOM-based North Atlantic simulations have focused on comparisons to observations, to results obtained from depth-coordinate simulations and on the impact of lateral boundary conditions and horizontal grid resolution in relation to the water mass transformations and pathways simulated by the model. We continued these North Atlantic studies by taking advantage of the built-in vertical coordinate flexibility of the hybrid coordinate model, HYCOM, to assess the importance of the vertical coordinate choice on the model results. We first compare HYCOM results to those from MICOM with identical basin configuration, forcing, and lateral boundary conditions. We then focus, within HYCOM simulations, on determining the effect of the coordinate representation of density (sigma-theta, sigma^2, sigma^2 with thermobaricity) on the model's ability to accurately represent the water mass distributions and three-dimensional circulation of the Atlantic.

LARGE CONTRIBUTIONS OF THE GULF STREAM TO HEAT CONTENT

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Heat balance in the Gulf Stream region, November 1992 to December 1999, is studied using two methods—a simple 3-D thermodynamic model and subsurface temperature profile analysis—to understand the relationship of observed large-scale fluctuations in heat storage to changes in surface fluxes and advection. The model is forced by surface heat flux derived from NCEP variables, with geostrophic surface velocity specified from SSH measurements from the TOPEX/Poseidon altimeter and Ekman transport from NCEP wind stress. The model's mixed layer temperature agrees well with observations on seasonal and interannual time scales. As expected, surface heating dominates seasonal and interannual variations in the mixed layer temperature and seasonal variations in upper ocean heat content. However, interannual variations in the latter are dominated by the advection-diffusion term. In addition to increasing heat storage, a positive advection-diffusion anomaly forces a net heat loss to the atmosphere. Within the advection term itself, the largest variations are from the geostrophic advection anomaly. Changes in oceanic advection, heat storage, and surface heat flux are related to the state of the Gulf Stream: in an "elongated" state, it transports more heat northward, more heat is stored in the region, and there is a net loss of heat to the atmosphere. The converse is true for the "contracted" state.

The second analysis uses temperature profiles in the Gulf Stream region objectively mapped to a uniform grid. Interannual variations in upper ocean heat content show good agreement with the model's. Subsurface data also show good correspondence between heat content and the 18°C isotherm depth and layer thickness—a deep and thin 18°C layer corresponds to a positive heat content anomaly (an "elongated" Gulf Stream state). Upper ocean heat content is a more robust indicator of the potential contribution of the ocean to interannual heat flux anomalies than is SST. The analysis here shows that the anomalous heat flux and heat storage in the Gulf Stream region is also related to the heat advection by geostrophic currents.

DO HYDROGRAPHIC SECTIONS DISCRIMINATE SOURCES OF THE SOUTH ATLANTIC THC?

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Data from a global ocean general circulation model (OCCAM) has been used to investigate the upper branch of the thermohaline circulation in the South Atlantic ocean using a Lagrangian path following technique. The results have been compared with various inverse model and observational studies addressing the origin of the northward flowing upper branch of the thermohaline circulation (THC). To facilitate comparison, section-integrated transports in specific density classes for the same boxes as used in the observational studies have been calculated for OCCAM. The OCCAM model shows a dominant role for thermocline water, both for the feed of the Benguela Current, as the contribution to the THC. More than 90% of the upper branch at the equator comes from the Indian ocean via Agulhas leakage. Only 1 Sv of water from Drake Passage directly enters the North Atlantic, without recirculating in the Indian Ocean. Agulhas leakage occurs to 2000 m depth, but transport below 1000 m does not contribute to the upper branch of the THC. Six Sv of intermediate water from Drake Passage transforms to surface water and leaves the South Atlantic south of Africa. Several observational studies have indicated a dominant role for intermediate water or direct inflow low from Drake Passage for the northward upper branch of the THC in the South Atlantic. The section averaged transports in OCCAM are largely in agreement with the observational estimates, while our Lagrangian analysis shows no dominant role for water from Drake Passage or for the intermediate water. The flow across sections often features recirculations that may be subject to water mass transformation on their pathway. As a result, the pathways deduced from integrated fluxes across the sections often are ambiguous or even misleading. Also, the neglect of non-negligible eddy fluxes leads to biased estimates. The detailed Lagrangian analysis suggests that rendering conclusions about the source of the upper branch from integrated fluxes across ocean sections is arguable and to this end a more detailed information of the flow field is necessary.

A NEAR-SYNOPTIC SURVEY OF THE SOUTHWEST INDIAN OCEAN

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A regional, quasi-synoptic survey of the Southwest Indian Ocean carried out as part of the WHP from May through July of 1995 occupied a cruise track that comprised a closed box. Full-depth water properties and direct-velocity measurements were used to diagnose the circulation patterns as a function of depth, estimate the transports of the major currents, and address regional vorticity dynamics. The synoptic circulation was quantified by the construction of a referenced geostrophic velocity field.

The upper-ocean Agulhas transport was estimated to be 76 Sv. Contributions to the Agulhas consisted of 29 Sv from the westward limb of the subtropical gyre south of 25°S, 20 Sv from poleward flow east of Madagascar that subsequently turns to move west about 25°S, and an additional poleward flow of 18 Sv through the Mozambique Channel. Bathymetry strongly controls the deep and bottom circulation: The African Coast, the Mozambique Plateau, and the Madagascar Ridge support deep western boundary currents along their eastern margins, however, the Natal Valley and the Mozambique Basin are blocked to meridional flow beneath 2800 m and 3000 m, respectively. East of the Madagascar Ridge, net northward deep transport is small. In the Madagascar and Mascarene Basins a deep cyclonic circulation is present: high-latitude deep waters move northward along the western boundary while North Indian Deep Water flows southward in the basin interior. The deep western boundary current along the east coast of Madagascar carries 2.56 Sv of bottom water northward.

Although all contributions to the regional potential vorticity budget could not be quantified, those terms estimated suggest that and advective flux divergence of potential vorticity is balanced by wind-stress curl, possibly assisted by boundary friction. Individual terms in the regional potential vorticity budget were small, implying that to first order the circulation can be thought of as inviscid and inertial.

IMPACT OF 4D-VARIATIONAL ASSIMILATION OF WOCE HYDROGRAPHY ON THE MERIDIONAL CIRCULATION OF THE INDIAN OCEAN

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WOCE hydrographic sections and a sea surface climatology are combined with a ocean general circulation model through a 4D-variational method to analyze the meridional overturning of the Indian Ocean. The regional model is run with realistic surface forcings over year 1995 for which most of WOCE Indian Ocean sections were made. The assimilation controls the initial temperature and salinity fields, surface forcings and open boundary velocities, temperature and salinity.

When no observations are assimilated, the model shows that the deep (below 1000 m) meridional overturning is weak (6 Sv) compared to observation-based estimates. This is a common feature of general circulation models. In contrast, after the assimilation, the model develops a deep overturning of 17 Sv at 32°S when a 10 Sv Indonesian Throughflow is prescribed. The mass flux of bottom waters that moves northward below 3200 m is balanced by a southward mass flux of deep waters between 1000 and 3200 m. The intensity of this deep overturning changes only by ±2 Sv when the annual mean Indonesian Throughflow is zero or 30 Sv. The upper circulation is less contrained by the assimilation because of the large temporal and spatial variability of this ocean and also because of limitations in the representation of the mixed layer physics during the assimilation process. Limitations in the physics of the model are also thought to be the source of the slow erosion of the deep overturning when the model is run for several years from its optimal state.

VENTILATION OF THE INDIAN OCEAN FROM THE SOUTH

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Near-synoptic chlorofluorocarbon (CFC) data from WOCE are employed to describe basin-scale ventilation patterns for the Indian Ocean. Thermocline and intermediate ventilation, which is from the south, differs from the Atlantic and Pacific oceans, as there is no subpolar or subtropical North Indian Ocean. CFC-derived ages increase and concentrations decrease from south to north. Ventilation times for the subtropical gyre of the South Indian Ocean are less than 15 years for thermocline water, and less than 25 years for intermediate water. The major ventilation source for the Indian Ocean south of 12°N is the Southern Hemisphere via the western boundary, not the marginal seas. Two fronts, north and south of the throughflow, act as barriers to meridional exchange in the interior of the Indian Ocean. The deep waters of the Indian Ocean are not ventilated with CFCs, as they are isolated from contact with the atmosphere on multi-decadal time scales.

CFC-bearing bottom waters are transported into the subtropical South Indian Ocean by western boundary currents; ventilation times are 30 years or more. In 1995, the leading edge of CFC-bearing bottom waters reached about 30°S in the Perth Basin, and in the Mascerene Basin further equatorward, to 20°S. Comparing these CFC concentrations with those of the Pacific and Atlantic oceans at comparable latitudes, bottom water CFCs were more diluted in the Indian. The high dilutions and low CFC concentrations in Indian Ocean bottom waters are consistent with what is known of the relative effectiveness of local mixing, circulation pathways, and water mass sources.

GLOBAL CFC INVENTORY DURING WOCE

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WOCE data are used to estimate the size of the global oceanic CFC sink by calculating inventories from oceanic CFC-11 concentration data. The total oceanic uptake was 5.5 x 10^8 moles of CFC-11, which represents about 1 percent of total emissions to the atmosphere through 1993. In the oceans about 50 percent of the CFC-11 inventory is in the Pacific, consistent with its volume being about equal to the sum of the other oceans. About 30 percent of the inventory resides in the Atlantic, due to the influence of well-ventilated deep and bottom waters there. Maps of the CFC-11 column burden show that there are three major sinks of atmospheric gases, such as CFCs, in the ocean: North Atlantic Deep Water (NADW), the Subantarctic Mode Waters (SAMW)/Antarctic Intermediate Water (AAIW), and Antarctic Bottom Water. Highest CFC-11 inventories are found in the North Atlantic high latitude and western subtropics. Other studies have estimated that the NADW is about one-third of the oceanic uptake of CO_2 from the atmosphere. The SAMW/AAIW are also a major sink for atmospheric gases, because of their cold temperatures (which correspond to high CFC solubility) and large volumetric distribution in the Southern Hemisphere. Generally, low CFC-11 inventories are found in regions where the subsurface waters have not recently been ventilated, like large areas of the tropical oceans. Errors in the inventory numbers are likely propagated by the averaging and gridding algorithms, particularly in regions where data are sparse. The impact of these errors on the inventory, though difficult to estimate, is considered to be about 20 percent. The global inventory provides a test for models and a quantification of the physical impact of the air-sea exchange of atmospheric gases.

AN OPEN-CIRCUIT AND A SHORT-CIRCUIT IN THE PACIFIC OCEAN SUBTROPICAL-TROPICAL EXCHANGE

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Water mass exchange between subtropical and tropical regions of the Pacific Ocean has been hypothesized as being part of a mechanism controlling inter-decadal changes in the nature of ENSO. The pathway of this exchange is analyzed using model estimates from 1980 to 2001 of the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO; http://www.ecco-group.org). A passive tracer and its adjoint are employed, the evolution of which describe, respectively, where the tagged water mass goes to and where it comes from. Over ten years, on average, water mass of the Niño3 region can be traced back to eastern subtropical thermocline waters of the northern (27%) and southern hemispheres (39%). The Niño3 water subsequently returns to these subtropical latitudes in the upper ocean. But in contrast to the hypothesized “Subtropical Cell” (STC), this circulation is an open-circuit with water returning to the western regions of the two hemispheres (subtropical gyres) and to the Indian Ocean.

Temporal variability causes the tropical circulation inferred from a time-mean state to differ significantly from the average circulation. In particular, non-seasonal, intra-annual variability significantly enhances the magnitude of the so-called interior pathway relative to that of the circuitous western boundary pathway. Such short-circuit in the subtropical-tropical exchange may help better explain observed tracer distributions. Significant differences in circulation pathways are also identified that are associated with El Niño and La Niña events. The strength of the subtropical-tropical water mass exchange is found to have weakened during the 1990s.

AN EDDY-RESOLVING STATE ESTIMATE OF THE OCEAN CIRCULATION DURING THE SUBDUCTION EXPERIMENT USING A NORTH ATLANTIC REGIONAL MODEL (ECCO)

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An eddy-resolving ocean state estimate during the Subduction Experiment is made by bringing a 1/6 degree North Atlantic regional model into consistency with data through the adjoint method. A novel aspect of this work is the search for an initial eddy field and eddy-scale open boundary conditions by the use of an adjoint model. The adjoint model for this region of the ocean is stable and yields useful information despite concerns about the chaotic nature of an eddy-resolving model. Observations employed in this study are TOPEX/POSEIDON satellite altimetry and mooring data from the Subduction Experiment. When rigorous, statistical consistency is found between this dataset and the model, we not only have a best estimate for the ocean state, but we have also acquired a best estimate for the initial eddy field, open boundary conditions, wind stresses, and air-sea fluxes. This study quantifies the ability of the data to constrain both the large scale circulation and the eddy scale. Individual eddy trajectories can also be determined. The final state estimate is dynamically consistent with the General Circulation Model. Thus, we can readily diagnose subduction rates, heat and other budgets from the result in a physically interpretable context. In particular, the state estimate permits improved understanding of the impact of eddies on the large scale process of subduction. This work is part of the ECCO Consortium effort directed at greatly improved estimates of the oceanic general circulation through state estimation methods.

CONCENTRATIONS OF ANTHROPOGENIC CARBON IN THE INDIAN OCEAN INFERRED FROM WOCE CFC12 DATA USING TRANSIT TIME DISTRIBUTIONS

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We apply a new technique to infer anthropogenic carbon (Delta-DIC) concentrations to WOCE CFC12 data from the Indian Ocean. In contrast to several recent studies the technique makes no assumptions about transport being dominated by bulk advection and does not require separation of the small anthropogenic signal from preindustrial carbon. Mixing is included implicitly by using CFC12 data to constrain "transit time distributions" (TTDs) from the outcrop to interior points of an isopycnal. The time-varying signal of Delta-DIC at the outcrop is propagated directly into the interior by the constrained TTDs. We have tested the TTD approach in an idealized model, where it proves to be more accurate than techniques relying on single tracer "ages." The bounds inferred for the Indian Ocean Delta-DIC distribution are similar in shape to CFC12, but Delta-DIC has penetrated more deeply. We obtain inventory bounds of 13-19 Gtons of anthropogenic carbon in the Indian Ocean north of 35°S. The range is consequence of the incomplete constraint on the TTD provided by CFC12, and represents the natural uncertainty of Delta-DIC inferred from a CFC tracer.

CHLOROFLUOROCARBON CONSTRAINTS ON NORTH ATLANTIC VENTILATION

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The North Atlantic Ocean vigorously ventilates the ocean interior. Thermocline and deep water masses are exposed to atmospheric contact there and sequestered in two principal classes: Sub-Tropical Mode Water (STMW) and Sub-Polar Mode Water (SPMW). Their ventilation rates and pathways are uncertain and a powerful way to estimate them is to monitor the penetration of chlorofluorocarbon (CFC) tracers. Here, we combine a CFC dataset of over 44,000 observations, taken between 1982 and 1998, with a non-eddy-resolving general circulation model of the North Atlantic ocean. The CFC data are assimilated with the model by optimizing the uncertain air/sea CFC flux. The assimilated CFC fields are then systematically compared to the observations to identify the best fit, and hence the most realistic ventilation. Three GCM experiments are performed this way to find the dependence on model thickness diffusivity. Each GCM solution is close to being statistically consistent with the CFC observations and likely sources of error. Lower diffusivity gives the best match to data although some systematic bias in sequestering tropospheric CFC remains. Lower diffusivity permits a stronger circulation with a more realistic North Atlantic Current. For this experiment, around 16 Sv is formed in the subtropics and eastern subpolar Atlantic ($26.35 < \sigma_\theta < 27.13$) averaged over 1975-1995. Around 26 Sv is formed in the Labrador and Irminger Seas ($27.58 < \sigma_\theta < 27.8$). Only about 40% of the CFC carried into the subpolar interior by this flux remained there in 1998, however. The rest was returned to the subpolar mixed layer after an average period of 6-8 years. In contrast, 70% of the CFC subducted into the subtropical interior remained there in 1998.

WATER MASS TRANSFORMATIONS DIAGNOSED FROM DATA ASSIMILATION

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This paper presents results from a data assimilation experiment with the global ocean OCCAM model with 1/4° resolution and 36 vertical levels, forced with ECMWF winds. Temperature profiles each month and altimetric sea level anomalies every 10 days, are assimilated from the period 1992-1996. Comparison with independent WOCE sections data indicates the important role of the temperature profile assimilation in maintaining the sharp thermocline gradients in the model. The rest of this paper is aimed at quantifying how assimilation compensates for model drift. Diagnostics of Walin water mass transformations over the North Atlantic are then shown that are implied by the procedure of assimilation. It is seen that the altimeter assimilation contributes very little to water transformation but the temperature profile assimilation is transforming a lot of water in order to prevent drift in water volumes for potential temperature classes $\theta_0 > 7°C$. Furthermore the temperature profile assimilation is effective at producing subtropical mode waters at a rate of 16 Sv, which the poor representation of surface fluxes in this model run is unable to do. The possibility for separating the assimilation transformation fluxes into deficiencies in physical processes such as air-sea fluxes and internal mixing is then discussed. The paper represents a new use of data assimilation methodology in order to quantify the physical biases in the fundamental processes of surface forcing and mixing and advection, in a way that is independent of explicit model parametrizations.

FLUXES AND EXCHANGES OF THE NORDIC SEAS

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The Nordic seas provide the main connection between the Arctic and the deep global oceans via the dense northern overflows into the North Atlantic. An understanding of the circulation and exchanges of this region is vital for any consideration of the implications of high latitude climate change to variability in the Atlantic thermohaline circulation and consequences for regional (European) climate. In particular the circulation of the Nordic seas influence both the long-term variability of the overflows into the North Atlantic, and the formation mechanisms of Denmark Strait Overflow Water, which remain two of the outstanding problems of polar marine physics.

Our work aims to quantify the full Nordic Sea flux field (volume, heat and freshwater), studying the exchanges between the Nordic seas and the Arctic Ocean to the north, the Barents Sea to the east, and North Atlantic to the south, via North Atlantic Current inflow and the Denmark Strait and Iceland-Scotland overflows.

We have a unique data set, collected under the auspices of the NERC thematic programme ARCICE (Arctic Sea Ice and Environmental Variability), of near synoptic hydrographic and LADCP (lowered acoustic doppler current profiler) measurements across the entire region during summer 1999. The box inverse method has been applied to hydrographic data, using computed geostrophic velocities referenced to detided LADCP measurements. Hydrographic measurements were also obtained over a reduced region during winter 2000. Further work will incorporate the winter data and the full Nordic Sea summer 1999 flux field to describe the large scale mean circulation. ERS-2 open ocean and ice data will provide information on temporal variability and justification for the determination of a mean circulation.

SOURCES AND FATE OF THE EQUATORIAL UNDERCURRENT IN THE ATLANTIC

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Using Lagrangian trajectory analysis, we quantify the sources and the fate of the EUC in the Atlantic. Data from a global high-resolution ocean model (OCCAM) is used. The eddy-induced transport is explicitly accounted for in the data. With this technique a 3-dimensional picture can be obtained of subtropics-tropics interaction in the Atlantic. It is found that the main subduction sites that ventilate the EUC are located along the South Equatorial Current. These water masses transfer along the South Equatorial Current towards the western boundary and then northward in the North Brazil Current towards the EUC. A small portion (about 10%) takes an interior route. Only 5% of the transport in the EUC originates from the North Atlantic. EUC water upwells primarily in the equatorial region. Other upwelling sites are found close to the African continent and along the Gulf Stream. One-third of the EUC transport recirculates back to the EUC. That is, after upwelling the water downwells again at the subduction sites along the South Equatorial Current. This transport takes part in the Subtropical Cell. Two-thirds of the EUC transport does not recirculate, but leaves the Atlantic basin at the southwestern side after being transformed to North Atlantic Deep Water. This portion of EUC transport participates in the global meridional overturning cell.

ON THE SPATIAL VARIATION OF THE VERTICAL THERMAL DIFFUSION COEFFICIENT IN A SIMPLE OCEAN MODEL

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Numerical experiments were conducted on a simple model of the North Atlantic Ocean consisting of a thermocline region above an abyssal region with the surface mixing (Ekman) layer excluded. The western ocean boundary (in both the thermocline and abyss) layers are also excluded. It is also assumed that zonal variations in temperature can be neglected. The model temperature field is required to agree with the observed ocean temperature field as given in the Levitus climatological atlas of the world ocean. This requirement results (when the upwelling velocity from the abyss into the thermocline is of order 2 x 10^{-7} m^2 s^{-1}) in a spatial variation, for the vertical thermal diffusion coefficient, over the combined thermocline/abyss with values for this coefficient of 1.35 x 10^{-4} m^2s^{-1} in the tropical thermocline; 0.675 x 10^{-4} m^2s^{-1} in the combined subpolar/subtropical thermocline; a range 1.49 – 1.69 x 10^{-4} m^2s^{-1} in the abyss. These values are similar in magnitude to the calculations of Munk and Wunsch. When the upwelling velocity is appropriately reduced, as suggested by the Webb and Suginohara, then the resulting values for the vertical thermal diffusion coefficient are close to 3 x 10^{-5} m^2s^{-1} (on average) as advocated by Webb and Suginohara.

AGE DISTRIBUTIONS DERIVED FROM TRACER DATA IN NORTH ATLANTIC DEEP WATER IN THE SOUTH ATLANTIC

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An important application of transient tracer data is to estimate water ages, i.e., transit times of a water parcel from its source area(s) in the mixed layer to the location of observation in the interior. Conventional dating concepts like tracer concentration age or tracer ratio age model the in-between transport as purely advective pipe flow, but in reality the transport follows an ensemble of trajectories, so that the parcel sampled is a composite of contributions of different ages. We account for this fact by using an age distribution formally corresponding to one-dimensional advection and mixing, which is a Gaussian distribution function with free parameters mean age and age variance; additionally, we allow for a dilution by water old enough to be tracer-free. Parameter values are obtained by fitting predicted tracer concentrations (folding the distribution function with realistic, time dependent tracer concentrations in the mixed layer) to observations from WOCE and pre-WOCE cruises for different tracers (CFC11, CFC12, CCl4; for the latter, an estimated inner-ocean loss rate is applied), ~5°-30°S. In upper NADW close to the western boundary, typical mean ages of the tracer-bearing component and dilution factors are 30 years and 10, respectively, with values increasing southward and eastward. The fitted age distributions allow the construction of realistic tracer concentration time histories all through the tracer period, which can serve as inner-ocean tracer boundary conditions in models.

WHAT CONTROLS THE DISTRIBUTION OF TRANSIENT TRACERS IN THE SOUTHERN OCEAN?

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We examine the distribution of transient tracers in the Southern Ocean using an idealized, zonally-averaged model based on residual mean theory which stresses the importance of mesoscale eddy processes.

Scatter plots of CFC11 against bomb δC^{14} from WOCE data reveal a negative correlation at the surface but a positive correlation in thermocline beneath. We show that this change in the depth dependence of the correlation of the two tracers is a consequence of advection by the residual circulation and the large difference in the air-sea gas exchange timescales of CFC11 and bomb δC^{14}.

Since the air-sea gas exchange timescale of δC^{14} is on the order of 10 years, comparable to the advective timescale, bomb-δC^{14} is depleted in regions where deep water upwells, and increases as water parcels move equatorwards at the surface. In contrast, CFC11 equilibrates very rapidly with the atmosphere and surface water concentrations reflect the equatorward decrease in solubility.

Both CFC11 and δC^{14} are subducted into the thermocline close to the core of the ACC. The two tracers are positively correlated in the subducted waters where they are transported along isopycnals by a combination of residual circulation and isopycnal stirring. Both tracers decrease in concentration moving from their source at the surface along isopycnals in to the thermocline.

This simplified model illustrates, we believe, the key mechanisms that set the flux and transport of transient tracers in the ACC. We expect that it will also provide insights in to the uptake and transport of anthropogenic CO_2 in the region and the interpretation and reconciliation of three dimensional, coarse resolution simulations in large-scale ocean models.

DIRECT DETERMINATION OF THE INDONESIAN THROUGHFLOW USING THE TRITIUM CLOCK

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The Indonesian throughflow is a major oceanographic feature of the Indian and Pacific oceans' equatorial belt and an important component of world ocean circulation. It results from the pressure gradient which exists between the Indian and Pacific oceans, as the mean sea level is higher on the Pacific side than on the Indian side. The various methods used to estimate its strength lead to much scatter, with values comprised between -2.6 ± 9 Sv and 18.6 ± 7 Sv. Here we focus on the tritium (^3H) distribution. ^3H was injected in the atmosphere by atmospheric thermonuclear weapons tests during the 1950s and 1960s. The comparison of the ^3H inventory on both sides of the Indonesian seas, in the Pacific and Indian oceans, allows us to derive a transit time of the flow through the Indonesian archipelago of 7.1 ± 0.6 years. This tritium budget of the Indonesian seaway implies a flow of waters originating from the north Pacific in the range 13.3-16.9 Sv. Unlike direct current measurements or geostrophy, this new estimate represents an average over the transit time of the water masses, thus removing the seasonal as well as much of the interannual variability.

CROSS-EQUATORIAL TRANSPORT OF DRIFTERS, TRACERS AND SALINITY ANOMALIES IN AN INDIAN OCEAN MODEL

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The monsoons cause a large annual change in the circulation in the northern Indian Ocean with currents reversing directions north of theequator and in the Somali Current. In spite of this large annual signal, drifter trajectories, computed from a numerical upper ocean model, show across-equatorial circulation emerge as a clockwise gyre. It has southward flow in the mixed layer of the interior of the Indian Ocean, and a northward flow in the western boundary current region, in the mixed layer as well as subsurface layers. Transport of salinity anomalies and passive tracers show that a cross-equatorial path of low-salinity or freshwater transport is associated with this circulation: Relatively fresh Bay of Bengal water is transported southward across the equator throughout the year east of 90°E, but during the southwest monsoon as far west as 60°E. In the western part of the ocean, northward transport of low salinity across the equator takes place in a narrow region of positive relative vorticity flows within the Somali Current. Southward cross-equatorial exchange of high-salinity Arabian Sea water occurs as far east as 95°E, primarily from May to September, and also penetrates into the Bay of Bengal. In contrast, southward Ekman transport during the onset of the southwest monsoon prevents Bay of Bengal water intruding into the Arabian Sea. During the northeast monsoon the net transports are small, but large variability in the exchange of Arabian Sea water is associated with planetary equatorial waves.

BALANCING THE SOC AIR-SEA FLUX CLIMATOLOGY USING WOCE OCEAN HEAT TRANSPORT CONSTRAINTS

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Results are presented from a linear inverse analysis of the SOC air-sea flux climatology using various hydrographic ocean heat transport constraints that were primarily obtained during WOCE. A solution is found which results in an adjusted set of fluxes that is consistent with all of the available constraints within their estimated error bounds. The global mean net ocean heat loss to the atmosphere with these adjustments is -5 Wm^{-2}, compared with a gain of 30 Wm^{-2} for the original climatology. The primary changes to the net heat flux arise from an increase of 15% to the latent heat and reduction of 9% to the shortwave flux. The analysis has been extended to include the additional constraint that the global mean net heat flux lies in the range 0 ± 2 Wm^{-2}. In the latter case, the solution is modified such that the adjustment of the latent heat increases to 19%, the reduction of the shortwave decreases to 6% and the global mean net heat flux is -2 Wm^{-2}. The adjusted SOC fluxes with both solutions agree to within 6 Wm^{-2} with large scale area average estimates of the heat exchange made by Ganachaud and Wunsch using temperature and salinity data from WOCE. Good agreement is also found with recent estimates of the global ocean heat transport obtained using residual techniques and from atmospheric model reanalyses. However, additional comparisons of the adjusted fluxes with measurements made by various Woods Hole Oceanographic Institution research buoys indicate that further improvements to the inverse analysis are still required.

MONITORING THE MERIDIONAL OVERTURNING CIRCULATION IN THE TROPICAL WEST-ATLANTIC

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MOC is an important element of the climate system; low-frequency fluctuations of the former are thought to impact the latter. Such fluctuations are common features in models but observational proof has been missing. Here we present the Feb. 2000-Jan. 2002 results from the Meridional Overturning Variability Experiment (MOVE, which aims to acquire multi-year time series of variations of the meridional transport and hydrographic conditions of the NADW and to interprete these in terms of forcing factors of the MOC.

The experiment strategy uses horizontally integrating geostrophic end-point moorings to monitor transport fluctuations on the basin scale. Simulations have shown that modern equipment and an optimized experiment design reduce the uncertainties sufficiently. The MOVE moored array is at 16N, monitoring deep transports through the 1000 km section between the Lesser Antilles and the Mid-Atlantic Ridge. Three moorings, each covering the depth range of 1200 - 5000 m, are equipped with density sensors to calculate the dynamic height transport; external fluctuations are obtained from precise bottom pressure recorders. A current meter mooring on the western boundary slope captures that part of the DWBC inshore of the geostrophic array. The data set incorporates moored direct current measurements on each mooring and hydrographic sections along 16N as well as RAFOS float trajectories.

Results presented include rapidly changing hydrographic conditions at the mooring locations, indications of an interior recirculation of the southward DWBC, and a large temporal variability of the meridional NADW transport, at times exceeding 10 Sv on a monthly scale. As a step towards interpretation, the forcing of the observed fluctuations is examined. All those steps are accompanied by comparisons with models results. This experiment will continue until 2005 and there exists a close collaboration with GAGE (Guyana Abyssal Gyre Experiment, WHOI).

WATER MASS FORMATION AND TRANSFORMATION IN THE SOUTH PACIFIC

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Our knowledge on the hydrographic structure of the South Pacific improved substantially during WOCE and based on the new data sets available we present here a rather comprehensive picture on how the upper, wind driven, water masses in the South Pacific are formed and transformed. The South Pacific has three main ventilation/subduction regions: the Tasman Sea, the Eastern South Pacific and the ACC frontal zone. Water subducted in the Tasman Sea is advected to the east in a well defined core at about 30°S. During its transit the water is freshened and cooled from south as well as from north. The quasi linear zonal modification in T and S along 30°S suggest a balance of zonal advection and meridional diffusion which reveals an isopycnal diffusion of about 1800 $m \cdot s^{-2}$. The southern source for cooling/freshening is the mixed layer outcrop south of 30°S, the northern source is through mixing with the north/northwest flowing water subducted in the South East Pacific. The Southeast Pacific subduction re-ventilates the upper part of the modified Tasman Sea water and forms the “Shallow Salinity Minimum” and the South East Pacific Mode Water. The re-ventilated water flows northward while part turn towards the equator were it upwells in the east and part flows south and participates in the Tasman Sea subduction. The ACC frontal zone allows water to be driven lateral into the lower thermocline ventilating lower Mode Water and Antarctic Intermediate Water. Concentrated off the South American Coast and for densities between the re-ventilated water and the Mode/Intermediate Water an oxygen minimum zone establishes as a balance between the large scale ventilation and the upwelling of oxygen depleted/nutrient rich waters transported southward from the equator in subsurface boundary currents.

DEEP-WATER CIRCULATION AT LOW LATITUDES IN THE WESTERN NORTH PACIFIC

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CTD-oxygen profiler data at low latitudes in the western North Pacific (winter 1999) are analyzed and concur that the deep circulation current carrying the Lower Circumpolar Water (LCPW) bifurcates into eastern and western branches after entering the Central Pacific Basin.

The eastern branch flows northward in the Central Pacific Basin, supplying water of 0.94-0.98°C to the Melanesian Basin through narrow gaps. It passes the Mid-Pacific Seamounts between 163°30'E and 170°10'E at 18°20'N; i.e., not only the Wake Island Passage but also the western passages. Except near the bottom, dissolved oxygen decreases significantly going northward in the Central Pacific Basin, due to mixing with the North Pacific Deep Water (NPDW).

The western branch carries LCPW warmer than 0.98°C into the Melanesian Basin and splits to four streams at the observation. The westernmost stream may turn cyclonic around the Solomon Rise, but the other three streams join and form a current with transport of 4.2 Sv in the East Mariana Basin. The current proceeds along the basin's western boundary, turns north at west of 150°E, and bifurcates around 14°N south of the Magellan Seamounts, where dissolved oxygen decreases sharply due to mixing with NPDW. Half the current turning east crosses 150°E at 14°-15°N, divides at the Magellan Seamounts, and passes 18°20'N northward as double streams around 153°E and 155°E (2.2 Sv). The other half flows northward west of 150°E, turns cyclonic probably after passing 18°20'N, and comes down to the southern end of the Mariana Trench along its western flank. This current seems to detour around the Mariana Trench and proceed eastward along the Caroline Seamounts to the northern flank of the Solomon Rise, partly flowing into the West Mariana and East Caroline Basins.

A shallower deep current at 2000-3000 m depth above LCPW proceeds further into coastal regions than the deeper current. Part of this flows from the Melanesian Basin to the East and West Caroline Basins, while another part flows into the East Mariana Basin.

THE WATER MASS CIRCULATION IN THE WESTERN SUBPOLAR NORTH ATLANTIC, STUDIED BY AN INVERSE MODEL

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One of the key regions for water mass transformation is the western subpolar North Atlantic. Involving WOCE-line AR7W, a comprehensive data set consisting of hydrographic data, ADCP and tracer measurements has been collected since 1990 to quantify deep water transports and study the relation to the variability of water mass formation and distribution in the subpolar western North Atlantic. During 1997, ship tracks of the german Meteor-cruise M39/4 formed several boxes in the Labrador/Irminger Sea region, which allowed the application of a linear box inverse model. Since the circulation in the western subpolar North Atlantic shows a strong barotropic component, the primary objective is to determine the capablity of such an inverse model to give realistic estimates for absolute velocities and transports in this region. Based on the 1997 data set we present large-scale property maps together with transport estimates and circulation schemes derived from inverse solutions. The model combines hydrographic measurements with information from direct acoustic doppler velocity measurements which serve as additional constraints. This is compared to results of the inverse model based on hydrography alone.

TRACER FIELDS AND AGE DISTRIBUTIONS IN THE SOUTH ATLANTIC

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The WOCE tracer data set for the South Atlantic (CFCs, helium and tritium) has been quality controlled and the internal consistency of the entire data set has been ascertained. The quality controlled tracer fields have been interpolated on several isopycnal surfaces which represent the major water masses in the South Atlantic. CFC concentration ages have been computed on all isopycnal surfaces and are used to obtain a synoptic view of the thermohaline circulation. Spreading of North Atlantic Deep Water is evident on all deeper isopycnals (depth > 1200 m) as a confined western boundary current. For the upper and lower components of NADW (Labrador Seawater and Denmark Strait Overflow Water) the eastward branching at the equator is prominent in the distributions. The signal in the western boundary current in these two compartments of NADW thus becomes weaker after passing the equator and is difficult to detect beyond 10°S, although it can be traced to about 30°S. Iceland-Scotland Overflow Water shows the highest ages of the three NADW components and a weak eastward branch at the equator, which does not reach into the eastern basin. In the bottom layer the spreading of Antarctic Bottom water is found displaced eastward from the western boundary current into the interior of the Argentinian and Brasilian Basin.

Helium distributions are particularly useful to specify the contributions of pacific origin in the South Atlantic. Upper and lower parts of the Circumpolar Deep Water which are the counterparts at the Labrador Sea Water and Denmark Strait Overflow water level are characterized by much higher δ^3He levels then the northern hemispheric waters. Distributions of ^{3}He added from local sources in the Mid-Atlantic Ridge have been calculated using water mass analyses and are also presented on isopycnal surfaces.

THE ECCO 1-DEGREE GLOBAL WOCE SYNTHESIS. THE ESTIMATED MEAN STATE

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The global time-dependent WOCE data synthesis made by the ECCO Consortium over the 10-year period 1992 - 2001 aims at estimating the time-dependent ocean state that is, within error bars, consistent with the global data sets and the dynamics imbedded in the numerical model. We compare the estimated state with the WOCE observations that went into the synthesis. Overall, the agreement with the data is close to consistent with the prior error statistics for the data and model. The remaining misfit and a comparison with the reference state provides information about the quality of both the state and about and model errors. The state estimation procedure is able to correct for many of the traditional shortcomings of the flow field. However, as adjustments are made through changing the surface boundary conditions and initial conditions only, not all deficits can be properly represented. Mean meridional heat transports, meridional overturning and volume transport through passages are slightly reduced in comparison with the unconstrained reference run.

ABOUT CURRENTS AND FLOW WEST AND ACROSS THE MID-ATLANTIC RIDGE AT 47°N

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Several years of data from moorings west of the Mid-Atlantic-Ridge (MAR) on the 48°N section WOCE-A2/AR19 reveal that the newly formed Labrador Sea Water (LSW) arrives only in early spring of each year. Temperatures and salinities during these periods show little variation, indicating a rather homogeneous water mass. The changes from periods dominated by the LSW to those dominated by waters from the subtropical gyre are abrupt and occur within a week. For the rest of the year, the warm and salty waters from the south show strong variations in temperature and salinity of 20-30 day periods. The vertical temperature profiles at the mooring sites are dominated by long warming and short cooling phases. Additional data since 1996 from C-PALACE/APEX floats seeded in the vicinity of the moorings provide valuable information on the development of temperature and salinity for the top 1500 m layer, particularly in winter. Flow at that depth is mainly in recirculation gyres on both sides of the MAR. Crossing the ridge occurs only, if at all, through the Faraday and Maxwell Fracture Zones. In the Eastern Basin those floats follow the bathymetry to circumnavigate the Azores plateau. No float has yet made it to Europe.

OCEAN TIDAL CURRENTS: MODELLING AND PREDICTION

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With the significant improvements of our knowledge of the ocean tides at the global scale that occurred over the late 1990s, it is now possible to accurately characterize the intensity and direction of the barotropic component of the tidal currents worldwide and at any time. Our more recent solution is issued from a new version of the hydrodynamic model CEFMO-2. Basically, the model formulation is spectral in time, resolving the barotropic wave equation through a finite element method. The last improvements are a parameterization of the internal waves, an increased resolution by a factor of 3 of the finite element grid, a complete geographical coverage, a new bathymetry adapted to the new grid, and the parameterization of the friction effect from sea ice cover. Several data sets have been assimilated,following the represented method: T/P data at crossing points (337 points uniformly distributed, distant of 900 km), ERS2 data at crossing points (1211 points over coastal areas and at high latitudes), an ocean-or-island data set and a coastal data set (671 points). The FES2002 solutions include the amplitude and phase of the major tidal components. The quality of these solutions is greatly improved compared to the previous FES solutions. One interest of these FES2002 solutions is that tidal currents can be derived through the hydrodynamic equations. This derivation is not straightforward, though, because FES2002 sea level solutions are issued from a data assimilation process, and thus do not exactly fit the hydrodynamic equations. A method has been developed to compute a set of tidal current solutions that can optimally equilibrate the misfits on the continuity and the dynamic equations. An atlas of the characteristics of the major tidal current components has been produced. A model of prediction is associated and available on our web site (http://www.omp.obs-mip.fr/omp/legos). Aside from their scientific interest (see another poster presented at this WOCE conference), these products are of interest for many applications, including for example the elimination of the tidal contribution to ADCP ocean current measurements, or the introduction of an explicit tidal friction in OGCMs.

CFC-11 INVENTORY DISTRIBUTIONS IN THE WATER MASSES OF THE NORTH ATLANTIC DURING THE WOCE PERIOD

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CFC-11 concentrations measured between 1995 and 1998 are presented in this study of the deep meridional overturning circulation of the North Atlantic Ocean. Included is a map of the depth-integrated total CFC-11 inventory and inventories integrated between neutral surfaces that define the vertical extent of several water masses. Classical Labrador Sea Water (LSW) and 18° Water inventories highlight the convective formation of those water masses, with high inventories associated with large layers thickness. Away from their formation regions, inventories and layer thickness of 18° Water, Upper LSW, and Classical LSW decrease, reflecting mixing with lower concentration waters and spreading from less stratified formation regions to more stratified regions downstream. Iceland-Scotland Overflow Water and Denmark Strait Overflow Water initially show the opposite trend downstream from the sill where the overflow enters the North Atlantic as a thin, rapidly flowing bottom current; further downstream inventories decrease due to mixing.

Total water mass CFC inventories directly reflect the water mass formation rate during the period of CFC input, and the inventory distribution reflects the role that exchange between the Deep Western Boundary Current and the interior has in modulating the propagation of climate anomaly signals from the northern source regions. This will be illustrated with a comparison of boundary current region and interior CFC-11 inventories. Water mass formation rates calculated from CFC-11 inventories in Classical Labrador Sea Water, Iceland-Scotland Overflow Water, and Denmark Strait Overflow Water will also be presented and compared to previous estimates.

INTERANNUAL-TO-DECADAL VARIATION OF TROPICAL-SUBTROPICAL EXCHANGE IN THE PACIFIC OCEAN: BOUNDARY VERSUS INTERIOR PATHWAYS

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Tropical-subtropical exchange of water masses is important to interannual-to-decadal variability in the tropical Pacific. On average, the exchange is accomplished by a shallow (< 400 m) meridional circulation that connects the equatorial upwelling, poleward transport of surface Ekman flow, and equatorward transport of pycnocline waters originating from the subtropics. Pycnocline waters arrive at the tropics via western-boundary and interior pathways. It is well established that, on average, the two pathways re-enforce the net exchange. However, less is known about their relative role on interannual-to-decadal time scales and underlying physical processes. In this study, we address these issues using sea level measurements obtained by the TOPEX/Poseidon satellite altimter and circulation estimated by the Consortium for Estimating the Circulation and Climate of the Ocean (ECCO; http://www.ecco-group.org). Variation of pycnocline transport viathe boundary is found to be (1) anti-correlated to and (2) smaller in magnitude than that of the interior. These features are attributed to the combined effect of two different forcing mechanisms: (1) the variation of local wind stress curl changes the strength of horizontal circulation and results in variation of boundary flow that is opposite in direction and comparable in magnitude to that of interior flow; (2) the variation of equatorial zonal wind stress which affects the strength of meridional circulation with net pycnocline flow opposing the surface Ekman flow. Due to the partial compensation by boundary flow, the convergence of pycnocline waters into the tropics is about 50% of that inferred from interior pycnocline flow alone. The net pycnocline transport reflects ENSO forcing on interannual time scales. There is less equatorward intrusion of pycnocline water in the 1990s than in the 1980s, consistent with recent observation. In the North Pacific, variability of interior pycnocline transport is larger than that through the boundary. This is different from the time mean where the interior transport is substantially smaller than that through the boundary.

SURFACE FLUXES AND OCEAN STATE ESTIMATES IN THE EASTERN SUBTROPICAL NORTH ATLANTIC

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A coarse resolution regional ocean model of the eastern subtropical North Atlantic is used in a 5-year run to investigate the effects of two different surface forcing formulations and of several strategies to minimize a cost function in the context of ocean state estimation. The model is a 2-degree resolution application of the MITgcm which is forced at the open boundaries by temperature, salinity and current velocities obtained from a global implementation of the same OGCM. The assimilated data consist of T/P and ERS altimetry, a mean sea surface estimate, and Reynolds SST, and the results are compared with independent buoy data obtained from the Subduction Experiment. Different strategies to bring the model into consistency with ocean observations are being discussed. All of them use the models adjoint to adjust control variables, such as the initial state, lateral boundary conditions and surface forcing. Control terms include either the surface fluxes of momentum, net heat and freshwater fluxes, or the atmospheric state as control variables. Early results indicate that there are distinct differences in magnitude and behavior of the cost function depending on the type of forcing and the manner in which control variables are included and adjusted. While a bulk-formulae type forcing leads to better initial agreement between model and data, the optimization is more effective (faster decay) with the traditional type of flux forcing.

THE ANNUAL CYCLE OF THE HEAT BUDGET IN THE UPPER PACIFIC OCEAN

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This study quantifies uncertainties in closing the annual cycle of diabatic heat budget over the Pacific Ocean from 20°S to 60°N through a synthesis of WOCE products over 1993-1999. We utilize reanalysis products from the following sources: diabatic heat storage from the Scripps Institution of Oceanography; near-surface geostrophic and Ekman currents from the Earth and Space Research; and air-sea heat fluxes from Comprehensive Ocean-Atmosphere Data Set (COADS), National Centers for Environmental Prediction (NCEP), and European Center for Mid-Range Weather Forecasts (ECMWF). We utilize the latter products to simulate the annual cycle in diabatic heat storage for comparison with that observed. The root-mean-square (RMS) of the differences between the observed and model DHS is < 4 Watts m^{-2} over most of the ocean except in the Kuroshio Extension. Everywhere latent heat flux residuals dominate sensible heat flux residuals, while shortwave heat flux residuals dominate longwave heat flux residuals, with advective heat flux residuals important only in the Kuroshio Extension region and in the Cold Tongue. ECMWF air-sea fluxes produce smaller RMS differences than those of NCEP, which are in turn smaller than COADS. Radiative heat fluxes from bulk formulae produce smaller RMS differences than those derived from satellite cloud measurements. Both NCEP and ECMWF latent and sensible heat fluxes yield smaller RMS differences than those produced with satellite winds. Since RMS differences derive from biases in winds and clouds, least-squares minimization is conducted on turbulent heat flux, radiative heat flux, and Ekman heat flux residuals. This procedure reduces RMS differences < 1.0 Watt m^{-2} everywhere except in the Kuroshio Extension, finding zonal wind and cloud residuals in the trade wind zone and in the stratus deck off the west coast of the Americas underestimated by factors ranging from 1.0 to 1.8.

INDONESIAN THROUGHFLOW IN A COUPLED GCM AND ITS INTERANNUAL VARIABILITY RELATED TO ENSO AND IOD

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The interannual variability of the mass transport of the Indonesian Throughflow (ITF) has been noted by many observational and numerical studies. It is very possible that the interannual variability of ITF is connected with the ENSO in the Pacific and/or the Indian Ocean Dipole (IOD). The IPSL (Institute Pierre-Simon Laplace) coupled general circulation model (CGCM) was employed to examine the interannual variability of ITF and understand its relationship with the climatic variation in both basins. A 1000-years integration was conducted, and annual mean model output was utilized. The pathways of the simulated ITF are reasonable within the Indonesian Sea. The major transport occurs in the upper 300 m, with annual mean transport of 15.68 Sv, of which 13.83 Sv through the Makassar Strait is the principal component. Interannual variability of ITF transport is significant at a 2-4 year period. The relationship between sea level differences across the Indonesian seas and the ITF transport is straightforward at an interannual timescale (simultaneous correlation = 0.82). Further investigation indicates that the preceding tropical Pacific climatic variation is related to the ITF transport anomaly. The ENSO-like pattern leads the extreme of ITF transport by one year (correlation of the El Niño 3 SST index to ITF transport = 0.37). This means that there tends to be an El Niño anomaly in the Pacific one year before a large ITF transport (simultaneous correlation = -0.34). The patterns of sea surface temperature and sea surface height are not, however, typical of ENSO. The ITF transport is more related to the concurrent interannual variability over the Indian Ocean (simultaneous correlation of ITF transport to Dipole Mode Index = 0.46. Moreover, the pattern of anomaly in the upper layer is much like the IOD. The component of wind stress over the Indian Ocean, which relates to the ITF variability, favors the air-sea feedback supposed by Saji et al. for the formation of IOD. It implies that the interannual variability of ITF transport is a possible cause for the generation of IOD.

SEASONAL VARIATION FEATURE AND FORMATION MECHANISM OF SUBTROPICAL COUNTERCURRENT IN NORTH PACIFIC

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Based on the analysis of NECP marine data, it is revealed that the eastward Subtropical Countercurrent (STCC) in the Northern Pacific can be divided into two branches. They are the one in the Northwestern Pacific and the other one in the middle part of the North Pacific (the west to the Hawaiian Islands), and the formation mechanism of them is different. The blocking effects of the Hawaiian Islands on the easterly wind and the westward current play an important role in the forming of the subtropical countercurrent in the middle part of the North Pacific. Owing to the blocking effect of the Hawaiian Islands to the sea surface wind, there are a center of the positive wind-stress curl to the north of the Hawaiian Islands (20-23°N) and another one of the negative stress-wind curl to the south (16-19°N). Thereby, a wind stress curl dipole appears near the Hawaiian Islands. The dipole is stronger in the summer and disappears in the winter. The Sverdrup relation and numerical experiments indicate that the dipole of the wind stress curl is helpful in the forming of the subtropical countercurrent in the middle part of the North Pacific. Furthermore, numerical experiments of the ocean circulation and the WOCE drift buoy data also indicate that owing to the blocking effect of the Hawaiian Islands to westward current, the vortex streets form in west of the Hawaii Islands, and they intensify the eastward subtropical countercurrent in the west to Hawaiian Islands.

NORTH ATLANTIC LOW-FREQUENCY CHANGES OF VOLUME AND HEAT TRANSPORTS IN THE ECCO STATE ESTIMATES

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From a solution of the global ECCO state estimation we diagnose the low-frequency (seasonal to interannual) variability of meridional volume and heat transports between 20°N and 60°N in the North Atlantic Ocean. The model transports are compared with estimates across the nominal "48°N"-section (WOCE/A2)—reaching from the English Channel to the Grand Banks—where a coherent hydrographic data set was obtained during seven cruises from 1993 to 2000.

The standard deviation of the monthly-mean anomalies of the simulated overturning rate at "48°N" amounts to 2 Sv and of the heat transport to 0.08 PW, respectively; the year-to-year variability is half of those numbers. In contrast to the model simulations, the observed amplitudes lie 50% above the model transport variations on interannual timescale. The percentage of the different components contributing to the total heat transport in the model is consistent with the estimates from the observations: In the time-mean, the baroclinic component of the heat transport contributes 80% to the total integral and the Ekman component 10%. However, latter explains 90% of the diagnosed low-frequency variability. In the observations the baroclinic component is mainly responsible for interannual variations and thereby changes in the sign of the horizontal component appears to be dynamically relevant. From the model output we compute error bars on the observed transport estimates to test their representativeness of low-frequency variability.

INTERANNUAL VARIABILITY IN AIR-SEA FLUXES OF CARBON DIOXIDE AND OXYGEN

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We use an ocean general circulation model to study the mechanisms of air-sea O_2 and CO_2 flux variability, and consider the importance of this variability to the estimation of global CO_2 sinks. Mean O_2 and CO_2 concentrations and air-sea fluxes are estimated from a multi-decadal (1980-98) model integration of the global offline MITgcm. The mean air-sea CO_2 flux is consistent with the study of Takahashi et al. in all regions, and the mean O_2 flux is consistent with the results of Ganachaud in all regions except the Southern Ocean. Interannual variability in air-sea CO_2 and O_2 fluxes has extremes of ±0.5 PgC/y and +70/-100 Tmol/y, respectively. Globally integrated variability in O_2 and CO_2 air-sea fluxes is dominantly forced by the El Niño/Southern Oscillation cycle. Interannual variability of the O_2 flux in the North Atlantic is also significant on the global scale. The global impact of high latitude CO_2 flux variability is small. We find the interannual variability of air-sea O_2 fluxes to be large enough such that it should not be neglected in estimates of the interannual variability in land and ocean CO_2 sinks based on atmospheric O_2/N_2 observations. In conclusion, we illustrate that estimates of CO_2 sink variability from independent methods are converging toward an ocean sink variability of <1 PgC/y and a land sink variability of approximately 2 PgC/y for the 1980's and 90's.

MODELLING STUDIES OF THE MERIDIONAL OVERTURNING CIRCULATION WITH C-HOPE

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The C-grid version of the Hamburg Ocean Primitive Equation model (C-HOPE) is a hydrostatic Boussinesq z-coordinate coupled ocean-sea ice model on a spherical grid. We present an overview of several studies related to the Meridional Overturning Circulation (MOC). The model has subgridscale parameterisations of isopycnal diffusion and GM eddy mixing, along with a bottom boundary layer representation of slope convection. C-HOPE features a bipolar curvilinear grid that allows for arbitrary placement of the poles to permit improved simulation of the Arctic ocean and sea ice system. Forced with NCEP/NCAR daily reanalysis data, the model can reproduce the Labrador Sea salinity anomalies of the 1970s, 1980s and 1990s. A major contribution is anomalously large sea ice export through the Fram Strait associated with large scale wind forcing over the Arctic ocean. These negative salinity anomalies in the Labrador Sea dampen the wintertime deep convection that is a source for the lower limb of the North Atlantic MOC. A second application of the model relies on arbitrary pole placement for construction of regionally high resolution global grids that avoid open or closed boundary problems. One setup studies the formation of High Salinity Shelf Water (HSSW) associated with the Mertz polynya in the Adelie Depression. Observations suggest that 25% of Antarctic Bottom Water may be attributable to the East Antarctic coastal polynyas, of which the Mertz is notable. The model suggests that HSSW production exhibits high interannual variability, with peak outflow around 1 Sv. C-HOPE has also been coupled to the atmospheric GCM ECHAM5 and run for multiple centuries without flux corrections. Studies of multidecadal variability of the modelled North Atlantic MOC show high correlation with the SST index (40°-60°N, 50°-10°W), suggesting a means to monitor MOC anomaly strength using satellite observing systems. Due to a dominant low frequency component, there is the possibility to predict the slowly varying component of the North Atlantic climate system.

INDIAN/ATLANTIC INTEROCEAN EXCHANGES

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In this poster we analyze the Indian/Atlantic interocean exchanges in an eddy-permitting numerical simulation of the global ocean circulation. Our analysis focuses in the Cape Basin, a region of the southeastern Atlantic limited to the northwest by the Walvis Ridge and to the south by the subtropical convergence. To quantify the relative importance of the different dynamical mechanisms involved in the interocean exchange we separated the climatological mean circulation from the transients. The analysis indicates that Agulhas eddies not only influence the transient fluxes but also to those associated with the mean circulation (eddy fluxes, for example, supply most of the energy of the Benguela Current). A distinct characteristic of the eddy variability within the Cape Basin is the co-existence of cyclonic and anticyclonic vortices in dipole structures that resemble the heton model of Hogg and Stommel. Anticyclones are surface intensified vortices that, in spite of their baroclinic structure, reach to deep layers. Cyclones, are bottom-intensified vortices with dominant barotropic structure that projects into the upper layer. The propagation of cyclones and anticyclones is strongly affected by the bottom topography. Our analysis shows that the Walvis Ridge and the Vema Seamount block the passage of bottom-intensified cyclones and rectifies the trajectories of the upper-intensified anticyclones. Although most anticyclones are able to escape the basin the deep compensation generated by the ridge generates an energy loss of approximately 30%, and a rectification of the eddy trajectory to a more westward direction.

OCEANIC FLUXES IN THE SOUTH ATLANTIC

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Data from two WOCE one-time hydrographic sections, A10 and A11, are combined in a regional inverse of the South Atlantic Ocean. This includes careful study of detailed aspects of the flow across each section, such as boundary currents, flow in deep channels, the effect of discrete eddies on the flux of properties and changes in circulation in different solutions.

A previous single-section analysis by Saunders and King (1995) left unresolved questions, which have been addressed by a new analysis combining the WOCE A10 and A11 sections (30°S and 45°S) that were occupied near simultaneously in 1993. A solution is found that gives consistent fluxes of mass, heat, salt and silicate through the sections. The new solution gives a heat flux of 0.40 PW across the A11 section, lower than the 0.53 PW derived by Saunders and King. The main difference between the old and new solutions is where the A11 section cuts the subtropical gyre, where the latter has a weaker circulation. The new solution has a near-zero salt flux (close to that of S+K) and is therefore still inconsistent with a salinity flux of 26.7 Sv psu at Bering Strait and a net freshwater loss of 0.7 Sv through the Atlantic Ocean.

DECADAL VARIABILITY IN THE SOUTHERN INDIAN OCEAN

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A high quality data set collected at 32°S during the austral autumn of 2002 (CD139) is compared to the 1987 Toole and Warren CTD data set, 1995 WOCE I5W CTD data and the bottle data from the 1965 and 1936 cruises at approximately the same latitude across the Indian Ocean. Analysis of the 2002 CTD data and the temperature and salinity profiles returned from ARGO floats shows that the isopycnal cooling and freshening of thermocline waters that occurred in the 25 years prior to 1987 (as reported by many authors) has reversed in the upper thermocline. Since 1987 thermocline waters warmer than 10°C have become appreciably warmer and more saline on isopycnal surfaces by as much as 0.34°C and 0.09 psu. In addition, the change in properties of upper and lower thermocline water that occurred pre-1987 appears to have happened at different times. The lower thermocline cooled and freshened between 1936 and 1965 while the upper thermocline properties changed between 1965 and 1987.

TRACING ANTHROPOGENIC CARBON IN THE OCEANS USING $DI^{13}C$—MOVING FORWARD WITH THE WOCE/JGOFS ^{13}C DATABASE

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Data collected during the WOCE/JGOFS programs in the 1990s have provided a global picture of the $\delta^{13}C$ of dissolved inorganic carbon ($DI^{13}C$) in the oceans for the first time. The paired time history of changes in atmospheric CO_2 and $^{13}CO_2$ make changes in $DI^{13}C$ an excellent tracer of anthropogenic CO_2 in the ocean that is often more sensitive than the changes in DIC itself. Decreases in the $\delta^{13}C$ of atmospheric CO_2 (~-7 ppt, pre-industrial) from fossil fuel and biomass (~-25 ppt) burning can be tracked in surface ocean waters with precise measurements of $DI^{13}C$. Using the new dataset to evaluate the ocean CO_2 uptake rates between 1970 and 1990 has yielded estimates ranging from 1.7 to 1.9 Gt C/yr. To evaluate CO_2 uptake over longer timescales, we are currently modifying and extending the "MIX" approach of Goyet et al. to reconstruct the total changes in $DI^{13}C$ that have occurred since pre-industrial times. In the approach, we "unmix" the entire water column using an multiparameter mixing model, and use an inversion scheme to find the functionality for uptake of CO_2 and $^{13}CO_2$ in each of the mixtures endmembers that best matches the present day $DI^{13}C$ distribution. The mixing model is less precise than previous reconstructions of the 1970s-1990s change but is not limited by uncertainties due to mixing and transient tracer dating techniques and does not rely on $DI^{13}C$ measurements from the past. Thus our modified "MIX" approach affords unprecedented global estimates of the anthropogenic $^{13}CO_2$ change since pre-industrial time that enhance the utility of $DI^{13}C$ as a tracer for anthropogenic CO_2.

CHARACTERISTICS OF INDONESIAN THROUGHFLOW

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Based on the SODA data analysis, the characteristics of Indonesian Throughflow were studied. The results show that ITF volume transport is mainly confined between surface and deep layer and ITF heat transport is confined to the upper layer. There is significant seasonal variation of the upper part of ITF volume transport, such as larger transport in summer and smaller transport in winter, which is in good agreement with the former study. The value of ITF volume and the heat transports are in the accepted range. The results also show that there exists the variation of the volume and heat transport of ITF with interannual and dacadal time scales. The mechanism of ITF decadal variation is studied with COADS wind data and Godfrey's island rule and Wyrtki's large scale pressure gradient between Pacific Ocean and Indian Ocean. A good explanation for the decadal variation of ITF can be given with Godfrey's island rule. ITF's decadal variation is mainly determined by zonal wind stress of tropical Pacific and south Pacific. The phase of decadal variation of ITF is mainly determined by zonal wind stress of tropical Pacific. By analyzing the sea level and sea water pressure in the adjacent zone of Pacific Ocean and Indian Ocean, we can find that the large scale pressure gradient between Pacific Ocean and Indian Ocean has a good relation to the annual, inter-annual and decadal signal of ITF's volume transport.

INDONESIAN THROUGHFLOW AS A BRIDGE BETWEEN PACIFIC OCEAN AND INDIAN OCEAN

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Indonesian Throughflow's bridge role in Pacific Ocean and Indian Ocean is further studied in a numerical simulation with high resolution OGCM. By the contrasting experiment of open and closed ITF passage, ITF's importance to Pacific Ocean and Indian Ocean is demonstrated. It is found that ITF's closure can change the Sverdrup circulation of Pacific Ocean and Indian Ocean, especially in the region of south Indian Ocean and south Pacific Ocean. The zonal currents in tropical Pacific and Indian Ocean are greatly influenced by ITF's closure. ITF's passage closure has a different influence about them. It can decrease SECC, NECC and increase SEC, NEC, EUC in Pacific Ocean, and increase SECC and decease SEC in Indian Ocean. ITF's blockage has an important influence on the thermal field distribution in Pacific Ocean and Indian Ocean. ITF's closure makes a heterogeneous decrease of the temperature field in Indian Ocean and causes temperature increment in some regions and temperature decrement in some regions in Pacific Ocean. The depth of thermocline characterized by 20° is lifted in tropical Pacific and lowered in tropical Indian Ocean. The choice of topography and resolution has some influence in simulating of ITF.

OBSERVED ANTHROPOGENIC CO_2 IN THE OCEAN BETWEEN AFRICA AND ANTARCTICA: WOCE/I6 SECTION

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The distribution of anthropogenic CO_2 in the ocean (C^{ant}) is estimated along the WOCE-I6 section using data collected in February-March 1996 (CIVA-2 cruise at 30°E from Africa to Antarctica). The estimation of C^{ant} is based on a "back-calculation" technique which corrects preformed total dissolved inorganic carbon for biological processes, both organic and carbonates pumps. A reference value is selected in CFC-free North Atlantic Deep Waters recognized at 3000 m in the Agulhas Basin. The C^{ant} penetration in subsurface and intermediate waters is most pronounced north of the Polar Front Zone (north of 50°S) associated to the formation of mode and intermediate waters. In the Agulhas Current System (30-42°S), C^{ant} distribution follows the meandering of isopycnals from the surface down to 2000 m. Significant C^{ant} concentrations are detected in Antarctic Bottom Waters (AABW) below the NADW cores. In the Circumpolar Deep Water, C^{ant} is homogeneous and low (10 µmol/kg). Below the CDW, C^{ant} increases continuously to reach high values (> 20 µmol/kg) in the core of the AABW of Weddell Sea origin. Greater C^{ant} values (>25 µmol/kg) are detected along the continental shelf in bottom waters presumably formed on the eastern side of the section (e.g., Prydz Bay). The C^{ant} distribution is remarquably well correlated with CFCs, although transient tracers are not used in the back-calculation technique employed here. These new results could help to explain the contradictory pictures of large or low CFCs and C^{ant} inventories in the Southern Ocean simulated by different large scale ocean models.

SEASONAL CHANGE OF THE NORTH PACIFIC SUBPOLAR GYRE OBSERVED WITH SURFACE DRIFTERS

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Seasonal mean current fields in the subpolar gyre of the North Pacific Ocean are calculated from surface drifter data after correction for wind-driven Ekman current that has been estimated by applying a steady state Ekman theory and by using climatological wind data. The mean current field shows big seasonal changes. Distribution of the mean current in summer is similar to the previous schematic view, while that in winter shows big difference displaying the Alaskan gyre with bigger horizontal scale. Being associated with this, the bifurcation point of eastward North Pacific current at the coast of North America shows a clear meridional change by season. The point moves north in summer and south in winter, and it is well in accordance with the location where the wind curl changes its sign. The result suggests that the previous map (for example, given by Ohtani) may reflect more the circulation condition in summer than in winter when smaller number of observations has been available, and that the seasonal change in the Alaskan gyre is caused by a fast response to the change of the wind field.

AN ANALYSIS OF A REGIONAL MODEL OF THE SUB-POLAR NORTH ATLANTIC

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A series of numerical experiments have been performed using a regional model of the sub-polar North Atlantic (SPOM) to examine how the model represents the circulation and hydrography of this northern region (concentrating on the Labrador Sea) and how several aspects of the numerical formulation affect the model sensitivities. A partial cell topographic representation is used to improve circulation pathways in the Labrador Sea and to modify the formation locations and properties of sub-polar mode water and Labrador Sea Water (LSW). An unexpected result of the partial cell topographic representation is a marked decrease of the freshwater content of the Labrador Sea during the early stages of the integrations, leading to the model forming overly salty and dense LSW. The freshwater content decrease in the model seems to be related to an increase in baroclinic instability in the frontal regions along the Labrador slope, driving a stronger poleward countercurrent offshore of the Labrador Current, which entrains more warm, saline North Atlantic Current water and transports it to higher latitudes. Ongoing experiments are examining the role of eddy-parameterizations in the model and implementation of a spatially varying eddy-transfer coefficient. A flux forced version of the model has also been produced and results suggest the importance of the air-sea interaction in producing the cold intermediate layer along the Labrador shelf.

THE SCOTIA SEA CAULDRON: THE ANTARCTIC CIRCUMPOLAR CURRENT IN A HIGH MIXING ENVIRONMENT

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Immediately downstream of Drake Passage, the Antarctic Circumpolar Current (ACC) crosses the Scotia Sea, a small region of complex bathymetry where injection of newly ventilated waters from the Weddell Sea leads to intense modification of the structure and property fluxes of the current system. The abruptness of this modification is unparalleled along the rest of the ACC, and strongly conditions the way in which the South Pacific and South Atlantic oceans interact.

We present results of a box inverse model of the Scotia Sea incorporating quasi-synoptic hydrographic, tracer and current measurements from the ALBATROSS cruise in March-April 1999. The model simultaneously determines lateral property transports, diapycnal fluxes in the ocean interior and diapycnal fluxes driven by air-sea interaction that are mutually consistent within error bars. The ACC undergoes substantial densification, cooling and freshening, and its volume transport increases by approximately 6 Sv in crossing the Scotia Sea, importing 5-6 Sv of Antarctic Bottom Water from the Weddell. A marked change in the lateral structure of the ACC transport occurs after interaction with bottom topography. Topographically- and eddy-induced fluxes combine to lead to an overturning-like circulation of approximately 8 Sv across ACC streamlines in the Scotia Sea, with deep water flowing southward and intermediate water returning north along isopycnals. This circulation induces a poleward heat flux and an equatorward freshwater flux that agree with current meter measurements of the eddy heat flux and with large-scale studies of heat and freshwater budgets south of the ACC. The overturning is partially closed by diapycnal fluxes driven by Ekman transports across outcropping isopycnals and upper-ocean mixing processes in the southern ACC. The model diagnostics suggest that deep diapycnal mixing rates in the Scotia Sea interior are amongst the highest values inferred in ocean basins, but that they are largely decoupled from the overturning circulation across ACC streamlines observed at shallower levels.

RECONSTRUCTION OF DECADAL VARIABILITY OF THE ARCTIC OCEAN CIRCULATION FROM HYDROGRAPHIC DATA

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An inverse 3-D finite-element ocean circulation model has been designed and used to study variability of the Arctic Ocean circulation in the last four decades. The model grid spacing varies between 30 km in the regions with strong bottom topography gradients and 100 km in the open ocean, with 22 levels in the vertical. We seek for stationary model solutions with the temperature and salinity fields close to the ones given in the Environmental Working Group Atlas. Transports at the open boundaries, wind forcing and hydrographic fields are treated as unknowns, which are varied to minimize a quadratic cost function subject to model constraints. The inverse problem is solved for ten hydrographic data sets obtained by averaging EWG data over four decades (50s to 80s) and over the whole period of observations (1948-1993) documented in the Atlas. Additionally, each climatology is separated into two (winter and summer) data sets and seasonal analysis is performed.

The results show that Arctic circulation in the last four decades has undergone significant changes, which manifest themselves in a) 10% reduction of the ventilaiton rate in the Atlantic sector of the Arctic Ocean; b) intensification of anticyclonic gyres in the Pacific sector; c) 10-15% increase of the advective heat and freshwater export at the lateral boundaries; d) spinning down of the cyclonic gyre in the northern Greenland sea, which is partly driven by deep convection; e) 2500±300 km^3 increase of the fresh water storage, especially in the Atlantic sector of the Arctic Ocean. Most of these changes are similar to the ones observed on seasonal transition from winter to summer climatologies, indicating that Arctic Ocean experiences a shift towards a warmer state.

NEAR-SURFACE BOLUS TRANSPORT AND THE VERTICAL TRANSPORT STREAMFUNCTION

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Simple Eulerian averaging of velocities, density and tracers at constant position over time and/or zonal position is the most natural way of averaging. However, this Eulerian averaging gives incorrect watermass distributions and properties as well as spurious diabatic circulations such as the Deacon Cell. Averaging on isopycnals removes this fictitious mixing, and, when applied to transports, eliminates the Deacon Cell. However, this averaging onto isopycnals is normally performed at constant lateral (x,y) position, so height information is lost.

Here we consider instead averaging at constant height and zonal position x onto isopycnals, so the coordinates become (x,ρ, and z). Height information is now retained at the cost of losing lateral spatial information. Both properties and velocities can be averaged in this manner, and we may define a zonally averaged streamfunction in ρ-z space similarly to the conventional zonally averaged meridional overturning streamfunction in y-ρ space.

We also discuss the relationship of the overturning streamfunctions in y-ρ and ρ-z to the Transformed Eulerian Mean (TEM) eddy-streamfunctions based on horizontal and vertical eddy fluxes. Near the surface the match between the horizontal streamfunction and its TEM analogue is poor, but there is a much better match between the vertical streamfunction and its TEM analogue. This suggests that near surface bolus transports are better handled by these vertical streamfunctions.

ATLANTIC INFLOW TO THE NORDIC SEAS, 1995-2002

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The Atlantic inflow (AI) of warm and saline water into the Nordic Seas is of great importance becauce of its impact on climate and ecology in Northern Europe and Arctic. In this study we present a synthesis of our findings from moored current meters,VM-ADCP and SeaSoar-CTD observations in the Svinøy section, cutting through the AI just to the north of the Faroe-Shetland Channel. We show that the Norwegian Atlantic Current (NwAC) established north of the Scotland-Greenland ridge, continues northward through the Nordic Seas toward the Fram Strait as a two-branch current. The western branch of the NwAC appears as a jet in the Polar Front and the eastern branch as a shelf edge current along the Norwegian shelf. This two-branch structure of the NwAC as a shelf edge current and a frontal jet was identified in the Svinøy section by Orvik et al. The Svinøy section observation program has been concentrated on the eastern branch of the NwAC, denoted the Norwegian Atlantic Slope Current (NwASC), which is the major branch of the AI into the Nordic Seas. We show that long-term monitoring of the NwASC can be performed by using one single current meter suitable placed in the flow, using a simple regression model. Accordingly, we now can present a more than 7 year continuous time series of the volume flux of Atlantic water into the Nordic Sea in the NwASC, ranging from 1995 to 2002.

ROLE OF EASTERN BOUNDARY CURRENTS IN THE INTER-OCEANIC EXCHANGES OF THE SOUTH INDIAN OCEAN

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Among the eastern boundary currents, the south Indian Ocean eastern boundary currents are distinct in its structure and characteristics. The Leeuwin Current off west Australia flows towards south whereas the direction of eastern boundary current is towards equator in the Pacific and Atlantic. Further, the flow along the coast of South Java reverses seasonally. Earlier studies on eastern boundary currents of the Indian Ocean are meager due to the paucity of observations. Recent programmes of WOCE, TOGA and other experiments enhanced the quality and quantity of oceanographic observations of this region.

The present study analyses the structure, variability and transports of the eastern boundary currents in the south Indian Ocean. Employed the historic hydrographic observations, various observations made during WOCE, TOGA and other experiments conducted in the study region. The long-term average bimonthly dynamic topography with reference to 400 db is prepared to infer the spatial and temporal current pattern. In addition to the temperature-salinity profiles, the temperature profiles are also included in the estimation of dynamic height employing the correlation between heat content and dynamic height. Intra-annual variability of the eastern boundary currents is clearly illustrated in the bimonthly maps. Estimated the transport of the currents at different latitudes and in different years. Sections of hydrographic properties are also prepared in different locations to determine the water characteristics as well as the inter-oceanic influences.

GLOBAL PATTERNS OF HEAT STORAGE ASSOCIATED TO TROPICAL INSTABILITY WAVES

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Tropical Instability Waves (TIW) are detected in global sea surface height anomaly data from the TOPEX/POSEIDON altimeter. The heat storage anomaly time series is organized in zonal-temporal diagrams for each latitude and band-pass filtered. The filters separate the spectral band with periods on the order of 45 days and wavelengths on the order of 1500 km within 12.5° of the equator. The main objective is to identify regions with persistent variability in this spectral band, to characterize the propagation patterns, and to analyze their temporal dependence. The analysis is done by two independent methods, decomposition in complex empirical orthogonal functions and correlation-weighted averages. Both methods show essentially the same results within their inherent features and limitations. Results show TIW patterns in the Atlantic (5°-10°N, 35°-60°W), Pacific (2°-10°N, 100°W-180°), and in two areas of the Indian Ocean (7°-12°N, 95°-120°E and 5°-10°N, 50°-60°E). In the Pacific the larger amplitudes occur during boreal spring months of La Niña events. In the Atlantic the larger TIW amplitudes also occur during La Niña events, with no significant seasonal differentiation. In the southern Indian basin the amplitudes reach their maxima during spring months of La Niña. However, in the northern Indian basin the largest amplitudes are recorded during the boreal fall of El Niño events.

INTRA-DECADAL VARIABILITY IN THE MERIDIONAL EKMAN HEAT FLUX FROM SCATTEROMETER WINDS

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We examine evidences of low frequency variability in the Ekman heat flux due to changes in the global temperature and wind patterns. The 10-year long time series of high resolution surface wind vectors was provided by the European Remote Sensing Satellites 1 and 2. A linear regression of the zonally averaged Ekman heat flux shows a latitudinal trend for the period between 1992 and 1997. This trend indicates a decrease in the poleward Ekman heat flux of warmer waters from the tropics and a slight decrease in the equatorward flux in the high latitudes. This intra-decadal trend ended after the 1998 El Niño event. These variations are mostly due to changes in the wind stress field. The decrease in the poleward Ekman heat flux may have far reaching consequences involving the global heat balance.

DOES THE OCEAN VARIABILITY ACCOUNT FOR THE DECADAL AND INTERDECADAL MODES OF NORTH ATLANTIC OSCILLATION?

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Goal of presentation is to discuss the ocean-related mechanisms in generating the decadal and interdecadal NAO modes. Characteristics of Azores High/Iceland Low (AH/IL), surface heat fluxes, modified NAO index and associated interannual-to-interdecadal variability of sea surface temperature (SST), heat content of the upper 200-m layer (HC) and upper mixed layer (UML) thickness in the North Atlantic Ocean were analyzed using historical data sets. Interannual, decadal and interdecadal modes have been extracted. The significant negative (positive) correlation of the NAO index and SST/HC anomalies in the tropical and high-latitudes (subtropical and mid-latitudes) occurs for all the scales. Thus, the well-known NAO-induced tripole can be identified at different scales. However, the decadal-scale mode is characterized by the maximum correlation of the NAO index, HC and UML parameters in the NW subtropical and NE mid-latitudes, while on the interannual/interdecadal scale the absolute correlation is at a maximum in the NW tropical Atlantic/(NW subtropical Atlantic and high-latitudes). The causes of these differences with strong focus on the role of the ocean and coupling in the decadal/interdecadal NAO mode generation are discussed. The following geophysical processes are analyzed: meridional North Atlantic Ocean circulation and tropical-extratropical interaction, gyre adjustment and coupling. This is concluded that all analyzed mechanisms occur, but the relative importance of each of them varies from one region to another. However anyway, the ocean variability is the crucial factor in generating the decadal and interdecadal NAO modes.

INTERANNUAL VARIABILITY OF THE KUROSHIO EXTENSION AND ITS IMPACT ON SST FIELD

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Recent coupled ocean-atmospheric modeling experiments have suggested a dynamic role for ocean western boundary currents in decadal climate variability. Indeed, the largest SST variability on the interannual-to-decadal time scale in the North Pacific resides in the outflow regions of the Kuroshio and the Oyashio, the two prominent ocean western boundary currents. Analyzing sea surface height data from multi-year satellite altimetry missions reveals that the large-scale, interannual changes of the Kuroshio Extension are characterized by the oscillation between an elongated state and a contracted state. In the elongated state, the Kuroshio Extension has a larger eastward surface transport, a greater zonal penetration, and a more northerly zonal-mean path. All these characteristics are closely connected to the presence of an intense, zonally-elongated southern recirculation gyre. The large-scale, interannual changes in the Kuroshio Extension system have a significant impact on the regional wintertime SST anomaly field: the warm (cold) wintertime SST anomalies tend to persist in years when the Kuroshio Extension is in its elongated (contracted) state. A diagnostic analysis of the surface ocean heat balance indicates that the nonseasonal geostrophic advection by the ocean circulation works to reduce (increase) the wintertime SST anomalies when the Kuroshio Extension changes from an elongated (contracted) state to a contracted (elongated) state. The SST anomalies associated with the large-scale changes of the Kuroshio Extension have an area-averaged, peak-to-peak amplitude > 1°C and appear independent of the interannual SST changes in the tropical Pacific Ocean.

THE NORTH ATLANTIC CURRENT IN THE SUB-POLAR GYRE: 1991–2001

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During the decade 1991-2001 many surveys were made in the Northeast Atlantic. In this poster we consider four made by the U.K. Each was designed to map part of the sub-polar gyre. From south to north Vivaldi '91, CONVEX-91, Vivaldi '96 and FISHES 2001 overlap in space, but not in time. While there are differences that may be stochastic, there is sufficient similarity to trace the North Atlantic Current through the sub-polar gyre and document its changing strength and characteristics.

As it flows eastwards across the Mid-Atlantic Ridge the North Atlantic Current forms a pronounced boundary between the sub-tropical and sub-polar gyres. As it turns northwards into the Iceland Basin and leaves sub-tropical waters behind, the flow becomes less distinct. Vivaldi '91 showed 20 Sv of water flowing eastwards from the Mid-Atlantic Ridge and turning northwards into the Iceland Basin west of 20°W. CONVEX-91 found about 12-16 Sv flowing northwards through the Iceland Basin with an additional 7-9 Sv branching westwards into the Irminger Basin. Vivaldi '96 found 10-20 Sv entering the basin but the majority of this appeared to re-circulate cyclonically around the North Iceland Basin and along the eastern flank of the Reykjanes Ridge. FISHES 2001 showed no obvious flow out of the north of the Iceland Basin and the fate of the North Atlantic Current was unclear. It is hypothesised that this is one aspect of the natural variability of the sub-polar gyre.

CIRCULATION OF THE INDIAN OCEAN

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Water enters the Indian Ocean from the Atlantic and from the Pacific through the Indonesian Seas and from the Ross Sea and Adelie Coast.

Water from the Circumpolar Current enters the Indian Ocean along three paths: with the north-westward-flowing part of the anticyclonic gyre; from a deep northward flow that passes just east of Madagascar; and from a deep flow along the eastern edge of the Central and Southeast Indian ridges.

At and below 3500 m, water from the Ross Sea and Adelie Coast flows around the Australia-Antarctic Basin and northward through the gap in the Southeast Indian Ridge near 125°W and into the eastern basins.

Water leaves the Indian Ocean by rejoining the circumpolar current and flowing eastward into the Pacific. Above 2000 m it leaves with the southward flow along the western boundary. From 2000 m to 3000 m it leaves with the southward flow just west of the Central and Southeast Indian ridges. At 3500 m and below this southward flow cannot cross the central ridges. Instead it joins the northward extension of the Weddell-Enderby Gyre and flows westward to the Weddell Sea.

MOORED CURRENT OBSERVATIONS IN THE MOZAMBIQUE CHANNEL

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Observations from an array of current meter moorings across the narrowest section of the Mozambique Channel are used to present and discuss the general characteristics of the current field in this ocean region. The observations cover a period of about 20 months in 2000 and 2001. The currents can be characterised by two different regimes: one with strong and coherent currents, the other one with weak currents. The former lasts much longer than the latter. During the strong current regime a southward jet seperates from the African coast and forms a large anti-cyclonic eddy which subsequently moves southward. The formation of these Mozambique eddies occurs rather regular, with 4 eddies formed in the first year of observations and 5 in the second period of 9 months. The mean volume transport through the channel is estimated to be 17 Sv southwards. The time variability of the volume transport is oscillatory with minimum and maximum values varying roughly between 10 Sv northward and 40 Sv southward at a frequency similar to the frequency of the formation of the anti-cyclonic eddies. No seasonal variability has been found. At intermediate and deep levels against the African continental slope (1500 m and 2500 m) a relatively strong and northward flowing Mozambique Undercurrent is observed. The mean northward speed is 4.6 cm/s (1500 m) and 4.5 cm/s (2500 m).

REGIONAL DISTRIBUTION OF AIR/SEA OXYGEN FLUX IN THE PACIFIC OCEAN

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Hydrographic data from the World Ocean Circulation Experiment are used to construct an inverse box model of the Pacific basin. A circulation based in an initial choice of geostrophic reference levels is adjusted to satisfy property constraints within the ocean interior. The convergence/ divergence of O* (oxygen + 170 * phosphate) in the surface layers is employed to diagnose air/sea oxygen exchange. Concurrent estimates of surface heat flux allow for the separation of the total air/ sea oxygen flux into thermal and biotic components. The signature wind-driven poleward heat flux is seen in an equatorward flux of oxygen. The biotic oxygen flux is characterized by uptake at high latitudes and outgassing in the tropics and along the eastern boundary.

MEAN AND TIME-VARYING MASS AND HEAT BALANCE OF THE TASMAN BOX

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The role of oceanic advection in the seasonal-to-interannual balances of mass, heat, and salt is studied using a 10-year time-series of quarterly eddy-resolving XBT surveys along the perimeter of a region we call the Tasman Box in the southwestern Pacific. The region contains the South Pacific's subtropical western boundary current system and strong mesoscale variability. Mean geostrophic transport in the warm upper ocean (> 12°C) is about 7.7 Sv southward into the box across the Brisbane-Fiji line, 9.6 Sv eastward out of the box across Auckland-Fiji, and negligible across the southern edge between New Zealand and Australia. Mean Ekman convergence is about 2 Sv. Transports are seasonally varying with a range of about 4 Sv in each transect, and maxima about March in both the southward inflow and eastward outflow. Interannual variability is also substantial. Net water mass conversions in the upper ocean — inflow of waters at about 26°C and 35.4 psu, balanced by outflow at 18°C and 35.7 psu — reflect the net evaporation and heat loss in the formation of Subtropical Mode Water. The 10-year mean heat balance shows good agreement between ocean heat transport into the box and heat loss to the atmosphere, averaging 35 w/m^2. The seasonal balance is between air-sea flux and storage, with a smaller contribution from transport. An interannual balance in the heat budget is achieved to 11 w/m^2. Anomalies in all three terms are substantial, with largest interannual variability (30 w/m^2) in ocean transport and interior storage. Maxima in the heat transport into the box occurred in 1993, 1997 and 2001.

QUANTITATIVE ESTIMATE OF INTER BASIN TRANSPORT EXCHANGES IN THE MEDITERRANEAN SEA FROM LAGRANGIAN DIAGNOSTICS APPLIED TO A GCM

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We use Lagrangian diagnostics to quantify mass transport in the main pathways of the upper and lower cells of the Mediterranean thermohaline circulation (THC), as they result from GCM simulation. About 500,000 particles are integrated off-line using daily averaged velocity fields from a Mediterranean GCM; the time characteristics of the THC are studied by means of the pdf distribution of transit times between different regions in the basin.

The Mediterranean is an evaporative basin; the deficit of water is supplied by the inflow of Atlantic Water via Gibraltar. The net result of air-sea interactions in the entire Mediterranean is an outflow at Gibraltar of salty water, mainly the Levantine Intermediate Water formed in the eastern basin. Despite this simplified pattern, circulation in the Mediterranean Sea remains complex. Most of the bathymetrically distinct Mediterranean sub-basins are characterized by water mass formation processes and the existence of sills and straits strongly influence both the spreading and the mixing of intermediate and deep waters. The role of the Mediterranean outflow in the North Atlantic Deep water formation is an open scientific issue that is noteworthy to consider due to the fact that several experimental studies have documented that the Mediterranean circulation is now experiencing significant changes in the hydrological characteristics of the intermediate and deep layers. These changes, which started in the Aegean Sea (Eastern Mediterranean), are currently propagating westward. The complexity of the interactions between water masses makes the predictability of the future equilibrium (if any there will be), together with an estimate of the final impact in the Mediterranean outflow, a difficult task due to the strong feed-backs existing between dense water masses. In this context it is useful to adopt the Lagrangian approach to quantify both mass transport between different regions and the associated spectrum of transit times. Some quantitative estimates, obtained in the context of the UE funded TRACMASS project are shown in the poster.

INTERDECADAL/DECADAL VARIATIONS OF NORTH PACIFIC TROPICAL WATER OBSERVED ALONG THE 137°E SECTION

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The temporal changes in the properties of North Pacific Tropical Water (NPTW) observed along the 137°E section include the information of the climate regime shift occurred in the 1970s and the 1980s. These changes may reffect the change of air-sea flux in the formation region of NPTW associated with the climate change. Here, we examine how air-sea flux in the formation region of NPTW relates with the properties of NPTW along the 137°E section. We use E-P, wind stress curl, Sverdrup transport and salt flux data from 1979 to 2000. Before a year when the maximum salinity of NPTW in the wintertime 137°E section increases, Ekman pumping increases in the formation region of NPTW and subtropical gyre spins up. Then, E-P and salt flux increase in the central portion of the formation region. On the other hand, these oppositely decrease in the western part. These results correspond with the finding of Suga et al., who showed that the advection time from the formation region to the 137°E section is approximately a year. We examine the relation between these changes in the formation region of NPTW and the atmospheric variabilities representing by the teleconnection pattern indices. It is found that changes of air-sea flux in the formation region have the relation with EP and AO patterns. It strongly suggests that the properties of NPTW in the wintertime 137°E section has the relation with the activities of EP and AO patterns from 1979 to 2000.

RATES AND MECHANISMS OF WATER MASS TRANSFORMATION IN THE LABRADOR SEA: INFERENCES FROM TRACER OBSERVATIONS

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Time series of hydrographic and transient tracer (^3H and ^3He) observations from the central Labrador Sea collected between 1991 and 1996 are presented to document the complex changes in the tracer fields as a result of variations in convective activity during the 1990's.

Between 1991 and 1993, as atmospheric forcing intensified, convection penetrated to progressively increasing depths, reaching ~2300 m in the winter of 1993. Over that period the potential temperature (θ)/salinity (S) properties of Labrador Sea Water stayed nearly constant as surface cooling and downward mixing of freshwater was balanced by excavating and upward mixing of the warmer and saltier North East Atlantic Deep Water. It is shown that the net change in heat content of the water column (150-2500 m) between 1991 and 1993 was negligible compared to the estimated mean heat loss over that period (110 W/m^2), implying that the lateral convergence of heat into the central Labrador Sea nearly balances the atmospheric cooling on a surprisingly short time-scale. Interestingly, the ^3H-^3He age of Labrador Sea Water increased during this period of intensifying convection. Starting in 1995, winters were milder and convection was restricted to the upper 800 m. Between 1994-1996, the evolution of ^3H-^3He age is similar to that of a stagnant water body. In contrast, the increase in θ and S over that period implies exchange of tracers with the boundaries both via an eddy-induced overturning circulation and along-isopycnal stirring by eddies (with an exchange coefficient of O(500 m^2/s)). The transport of freshwater by eddies into the central Labrador Sea (~140 cm between March and September) can readily account for the observed seasonal freshening. Finally, we discuss the role of the eddy-induced overturning circulation with regards to transport and dispersal of the newly ventilated Labrador Sea Water to the boundary current system and compare its strength (2-3 Sv) to the diagnosed buoyancy forced formation rate of Labrador Sea Water.

THE DISTRIBUTION OF 3HE IN THE INTERMEDIATE WATERS OF THE INDIAN OCEAN: IMPLICATIONS FOR THE MID-DEPTH CIRCULATION

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The WOCE Hydrographic Program for the first time provided a full, high-resolution survey of the ^3He distribution in all major ocean basins. Here, we report and discuss the distribution of ^3He in the intermediate waters of the Indian Ocean. To construct the ^3He maps we included data from the GEOSECS survey, as well as from smaller cruises that aimed at definition of sources on the Mid Ocean Ridges. The results allow us to visualize the vertical and lateral spreading of the ^3He plume that results from injection of helium at the Mid Ocean Ridges via hydrothermal activity. This plume is well resolved from those originating from the Indonesian Throughflow or the Gulf of Aden. The plume originates in the western basin and spreads throughout the Indian Ocean. It appears as if the injection is concentrated around a limited region on the MOR near to, but distinctly off, the Triple Junction. It is concentrated at depths between 1500 and 3500 meters with maximum ^3He concentrations (about 18%) found around 2500 meters depth. The plume can easily be traced over distances of 2500 km or more. Implications of the ^3He field for mixing and spreading of the intermediate waters are discussed.

TRITIUM AND 3HE IN THE SHALLOW INDIAN OCEAN

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The distribution of tritium and its stable, inert daughter ^{3}He in the shallow Indian Ocean reflects the invasion of bomb-produced tritium into the upper main thermocline and its subsequent redistribution. We present for the first time basin-scale distributions of these isotopes as obtained from the WOCE expedition. Perhaps the most striking feature of the observations is the influence of waters penetrating from the North Pacific via the Indonesia Throughflow. The tritium signature this inflow can be seen across the basin, and results in an elevated tritium inventory relative to that expected from local deposition sources alone. This can be used to place crude constraints on the time-integrated throughflow. An unexpected feature of the throughflow is evidence of a deep primordial ^{3}He signature.

Crude estimates are made of subduction and oxygen consumption rates from tritium-^{3}He dating in the Indian Ocean main thermocline, and used to estimate export production rates.

MEAN FLOW AND DECADAL CHANGES: TWENTY YEARS OF KIEL276 MOORED OBSERVATIONS

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Covering the WOCE period, measurements taken (1980-2000) from consecutive moorings in the eastern North Atlantic (KIEL276, nominal position 33°N, 22°W, ±5285 m depth) probably provide the longest moored time series ever obtained in the global deep ocean. The mooring site lies in the northeastern part of the North Atlantic anti-cyclonic subtropical gyre. Müller and Siedler. showed low-order dynamical modes to dominate. Wunsch found this modal structure to be a general property of the low- and mid-latitude deep ocean. Decadal/interdecadal changes in the moored data were found both in the mesoscale fluctuating part of kinetic energy and in the annual means, with high values in the early 1980s and later in the 1990s, and low values in the late 1980s. We expect that such changes can be caused either by a variation of mean flow amplitude and shear and corresponding change in instability, and/or by a displacement of the core of the gyre flow. Correlations of current and temperature variations suggest a considerable influence of gyre core displacement. The temporal scales of long-term changes correspond to scales known from the North Atlantic Oscillation (NAO). Curry and McCartney had demonstrated that the baroclinic mass transport, obtained from potential energy anomalies between the Labrador Sea and Bermuda, has the same temporal structure as the NAO index, with some lag in the ocean signal. We find that mean amplitudes of currents and fluctuating kinetic energies from our moored measurements also have the same temporal structure during the period 1980-2000. The maxima of the NAO index and the moored time series are essentially in phase in the 1980s, while the transport index is delayed by several years. In the 1990s, we find a better correlation between the moored data and the transport index which again lags against the NAO index. The differences in the temporal structure between the transport index and the mooring results may be caused by differing time lags for gyre transport changes and core displacements.

THE ECCO 1° GLOBAL WOCE SYNTHESIS: ESTIMATES OF SURFACE FLUXES

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Surface fluxes of stress, heat and moisture are included in the control vectors of the ECCO global ocean state estimate. As such, the prior values (from NCEP) are adjusted, along with other control variables, to bring the model into better agreement with the WOCE observations. Here we test the adjusted estimates against independent ones derived from bulk formula and satellite observations. All ECCO adjustments are within the crude prior error bars prescribed for these fields. On the large scale, adjustments are therefore consistent with known deficiencies in the NCEP products. On the large scales, the inferred adjustments to NCEP winds are consistent also with values obtained from satellite wind measurements. However, on regional scale wind adjustments exhibit features that reflect ocean model inability to resolve intense boundary currents. Further improvements in the surface flux estimates obtained using data assimilation are anticipated as the estimation procedure becomes more complete, and the ocean model more accurate.

THE ECCO 1° GLOBAL WOCE SYNTHESIS: MASS AND PROPERTY TRANSPORTS

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The ECCO global WOCE synthesis is used to analyze ocean volume, heat and freshwater transports. Time-mean horizontal transports, estimated from this fully time-dependent constrained circulation, are now generally consistent with the time-independent inverse estimates from box inversions, with especially good agreement in the southern hemisphere. The estimated mean circulation around Australia involves a net volume transport of 11 Sv through the Indonesian Throughflow and the Mozambique Channel. This flow regime exists on all time scales longer than one month—rendering the variability in the South Pacific strongly coupled to that in the Indian Ocean.

Dynamically consistent variations in the model show temporal variability of oceanic heat transports, heat storage and atmospheric exchanges that are complex and with a strong dependence upon location, depth, and time-scale. One can now study the dynamics of both the mean and time variability from the model with the reassurance that it is consistent with the great bulk of the WOCE observations.

CFC-CONCENTRATION AGES IN THE NORTH ATLANTIC

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Measurements of chlorofluorocarbons (CFCs) taken in the North Atlantic in the framework of WOCE are used to analyse the thermohaline circulation of this region, especially the spreading of North Atlantic Deep Water (NADW). The calculation of ages from the in situ CFC-concentrations allows an synoptic view on the data from the WOCE period, as the concentration-age shows less temporal variability than the concentration itself.

The three main components of NADW, Labrador Seawater, Iceland-Scotland Overflow water and Denmark Strait Overflow Water can be clearly identified and separated by their relative CFC-maxima. The CFC-concentration age on the respective isopycnals decreases from the Labrador Sea to the Tropical Atlantic by about 20 years for each of the three water masses, indicating a joint spreading of the NADW-components.

More detailed information on the water mass composition can be inferred from the age spectrum rather than from the concentration age. From measurements of different transient tracers it is possible to reconstruct at least some features of the age distribution such as mean age, width and the part of young and old water. Using the age distribution it is also possible to calculate the apparent change of the concentration age with time, giving an error estimation for the synopsis of the CFC-data from the whole WOCE-period.

HYDROCHEMICAL TRACERS OF SYNOPTIC EDDIES IN ANTARCTIC ZONE (S4 PACIFIC WOCE SECTION)

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The main part of S4 section lay on 67°S in the south periphery of Antarctic Circumpolar Current where it spread out on meanders and eddies. To determine eddies movement it would be well to make observations on the synoptic scale grid (step about 10 miles) but real distances between stations on the section were 30 or 40 miles. This is why only large scale water transport was calculated with S4 data in which eddy variability was smoothed. But one can say some words about eddies (or meanders) on S4 section (warm or cold, time and place of origin and so on) by using the information on variability of hydrochemical parameters (HCP) and some biological data in the surface layer. The reason is diversity of HCP and their modification by biota and exchange with atmosphere with different inherent time. For instance, characteristic exchange time for O_2 is 5-10 days but for CO_2 it is one order longer. Another instance, concentration of silicate changed on the section more than four times, but the temperature varied only on 0.3°C; nevertheless there was intimate connection between their variations. Moreover, strong variability of HCP may be used as the basis for analyzing weak variability of temperature and salinity. It gives the possibility to receive information both for horizontal and vertical movement of water in synoptic eddies. According to HCP, there were 16 anticyclonic eddies (meanders) and 13 cyclonic eddies (meanders), the latter more frequently occupied 2 or 3 adjacent stations.

VENTILATION OF THE NORTH PACIFIC SUBTROPICAL GYRE

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A climatology of the winter mixed layer in the North Pacific was constructed using hydrographic data from historical archives and recent observations including the WOCE Hydrographic Programme. This new mixed layer climatology is utilized along with the isopycnally averaged climatology, HydroBase, to investigate ventilation of the North Pacific subtropical pycnocline. Our main aim is to provide better knowledge about formation areas of mode waters as major agents ventilating the permanent pycnocline. Maps of the potential vorticity field within the permanent pycnocline are presented using HydroBase. Three distinct lateral minima of potential vorticity are identified as Subtropical Mode Water (STMW), Central Mode Water (CMW) and Eastern Subtropical Mode Water (ESTMW), in the western, central and eastern parts of the subtropical gyre, respectively. The formation sites of these mode waters are searched in the mixed layer climatology by comparing the water pro perties of the mode waters and those of the mixed layer. The STMW and ESTMW formation areas are associated with the mixed layer front and the small horizontal gradient of the mixed layer density, respectively, which confirms previously proposed formation mechanisms. That is, the low potential vorticity of STMW and ESTMW results mainly from the large lateral induction and the small cross-isopycnal flow, respectively. The CMW formation area is not primarily associated with the mixed layer front, which contrasts with previous ideas. It is suggested that low potential vorticity of CMW is mainly caused by small cross-isopycnal flow rather than large lateral induction rate. Additional new features of subtropical pycnocline ventilation revealed by the present climatology are also discussed.

IAPSO SSW COMPARISON EXPERIMENTS THROUGH 2002 AND FUTURE

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As global efforts continue to re-sample the oceans following the WOCE survey, it is important that we maintain the highest possible accuracy in measurements of deep water salinities. In this effort, our principal work to is to establish the traceability of IAPSO Standard Sea Water (SSW) at a level of 0.001 in salinity. We have published a table of SSW offsets up to P129. Furthermore, SSW comparison experiments have been carried out systematically in 1999, 2000 and 2001 by JAMSTEC/MRI group. The batch-to-batch difference calculated by the same technique of Aoyama et al. ranged from -0.0011 to -0.0018 in salinity. We have also begun a "synchronized SSW comparison experiment" both at JAMSTEC/MRI and WHOI beginning in 2002 and extending into the future for at least two years. Two sets of SSW ampoules from P133 to P142, each containing 55 ampoules, were measured in each laboratory in 2002. The preliminary results at the two laboratories were in good agreement: within 0.0005 in salinity for seven batches among P133 to P142, and revealed that there is a significant batch-to-batch difference among the recent batches of SSW. These results give us important information to determine the salinity in the deep water with an accuracy of 0.001. Compiling the results of SSW comparison experiments during these four years together with our previous published results, a table of SSW offsets up to P142 has been prepared. We keep 31 ampoules of SSW each with the batch number of P137, P139 and P142 for future comparison experiments in 2003 and 2004. We believe that our effort will contribute to oceanographic and climate studies from the viewpoint of improved estimates of salinity and the freshwater budget of the ocean.

THE DEEP EXPRESSION OF THE INDONESIAN THROUGHFLOW JET

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In the Indian Ocean, a narrow westward jet (South Equatorial Current) carrying freshened water is centered at 14°S. The jet's properties, origin and transport are explored using WOCE data in the Indian and Pacific, and the Arlindo data supplemented with historical data within the Indonesian s eas. The jet is remarkable for its zonality, with almost no deviation in its central latitude from the eastern Indian Ocean to just east of Madagascar. It is well known that the fresh surface waters in this jet originate as Pacific waters flowing through the Indonesian archipelago. At intermediate depths (about 1200 m), the jet also carries water from the Indonesian seas, with a source in the Pacific, traced by lower salinity and higher silica than the ambient Indian Ocean waters. The depth of these waters in the eastern Indian Ocean corresponds to the maximum passage depth through the Indonesian seas. The core of this deeper Indonesian throughflow jet is marked by a vertical salinity minimum, referred to as Banda Sea Intermediate Water or Indonesian Intermediate Water. The jet separates higher oxygen and lower nutrient waters of the subtropical gyre from the oxygen-depleted waters of the tropics. The water in the jet is formed within the internal Indonesian seas, through mixing of the Pacific Ocean water masses, and also upwelling and mixing with the deeper saltier water masses of Indian Ocean origin.

ON SUBDUCTION AND MASS BALANCE IN THE SUBTROPICAL NORTH PACIFIC

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Subduction process and mass balance in the subtropical North Pacific is investigated by performing a numerical simulation of the North Pacific circulation with a high resolution general circulation model. In the model, the key features of the circulation that are important for the formation process of mode waters, such as separation of western boundary currents, frontal systems, mixed-layer processes, and eddy activities, are well reproduced. Annual subduction rate calculated by following the mixed layer base has three major peaks.

Each of them is related with the deep winter mixed layer at the south of fronts that develop in the western North Pacific; the Kuroshio Extension, the Kuroshio bifurcation front, and the subarctic front. The lightest one corresponds to the subtropical mode water (STMW); it is formed at the south of the Kuroshio Extension and enters the main pycnocline as it crosses the mixed layer depth front to the south that is caused by the difference in heat loss to the atmosphere in winter. The second one corresponds to the central mode water (CMW); it is formed around of the Kuroshio bifurcation front and enters the main pycnocline as it crosses the mixed layer depth fronts to the east. The heaviest one may be called the denser type of central mode water (DCMW); it is formed at the south of the subarctic front and enters the main pycnocline as it crosses the mixed layer depth fronts to the east. Among the waters that are subducted in the subtropics, the cores of STMW and CMW circulate around the wind-driven subtropical gyre, while those at the outer edge of the gyre enter the tropics via the western half of the tropical-subtropical gyre boundary. They amount to about 24 Sv, which almost coincides with the northward surface Ekman transport at this latitude.

SIMULATING THE TEMPORAL EVOLUTION AND INTERANNUAL VARIABILITY IN CFC'S AND IDEAL AGE IN THE NORTH PACIFIC OCEAN DURING THE WOCE PERIOD

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Transient tracers such as the chlorofluorocarbons (CFCs) were measured extensively during the WOCE era to quantify large-scale ocean circulation patterns and ventilation rates. Using a realistically forced, global 3-D numerical ocean general circulation model (OGCM), we examine how well CFC tracer age approximates "ideal age" in the North Pacific thermocline as a function of time and explore the magnitude of interannual variability in both age measures. The CFC and ideal age fields are calculated using the Parallel Ocean Program with the KPP vertical mixing scheme and the Gent-McWilliams eddy parameterization. The horizontal resolution is approximately 1 degree, with 40 levels in the vertical. Surface momentum, heat and freshwater fluxes were computed using a bulk flux forcing scheme from NCEP reanalysis data from 1958 to 2000 (winds, air temperature, humidity) and satellite data products (clouds, insolation, precipitation). Overall, the modeled CFC-12 penetration is generally shallower than observed over the North Pacific basin except in the area between 5-10°N associated with the divergence of North Equatorial Current and Counter current. The CFC tracer age distribution is computed on isopycnal surfaces through the main thermocline using the partial pressure approach. The CFC tracer age agrees broadly with the simulated ideal age fields in the subpolar and subtropical upper thermocline but tends to underpredict ideal age in the lower thermocline and tropics. These deviations are expected due to non-linear mixing effects where the mean ideal age values approach the length of the CFC transient. An analysis of the simulated interannual variability in CFC and ideal age along isopycnals shows substantial rms variability, with implications for geochemical rate estimates and the representativeness of individual WOCE sections. In addition, simulated physical interannual variability compares well against historical observations.

ROLE OF MESOSCALE EDDIES ON FORMATION AND TRANSPORT OF THE NORTH PACIFIC SUBTROPICAL MODE WATER DEMONSTRATED WITH ARGO FLOATS

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The role of mesoscale eddies on the formation and transport of the North Pacific subtropical mode water (STMW) in the Kuroshio recirculation region is investigated using the data taken by Argo Profiling floats during 2001. Temperatures of STMW became spatially uniform in summer and autumn in the region, which suggested that STMW formed in the previous winter was prevailed there, while the distribution of their potential vorticities and thicknesses showed mesoscale-like features, which also suggested by the thermocline undulation.

Potential vorticity and thickness showed linear relations with thermocline depth both in summer and autumn: Thicker (thinner) STMW with lower (high) vorticity was associated with deeper (shallower) thermocline. This fact suggested that anticyclonic eddies contained thicker STMW than cyclonic ones. The analysis for the properties of the mixed layer in the previous winter south of the Kuroshio Extension (formation region) showed that STMW seen in summer and autumn was formed mainly north of 34°N, and that winter mixed layer depth as well as STMW thickness in summer and autumn also had a positive correlation with thermocline depth.

From the above results and the fact that mesoscale eddies are generated in the Kuroshio Extension region and move southwestward through the Kuroshio recirculation region, it is speculated that anticyclonic (cyclonic) eddies contained thicker (thinner) STMW during their traveling.

QUANTITATIVE DETERMINATIONS OF MERIDIONAL AND ZONAL MASS FLUX IN THE SOUTH ATLANTIC

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A set of WOCE and some pre-WOCE data is used to determine meridional and zonal fluxes in the South Atlantic. The aim is to identify the structure and amounts of transports in the North Atlantic Deep Water (NADW), and thus improve understanding of the character of the global overturning cell in this region. A linear box-inverse model is used, with closed boxes provided by sections and the continental boundaries of Africa and South America. Based on a detailed analysis of the water mass structure, 11 layers with 10 neutral density interfaces are selected. Constraints for the inverse model are: integral meridional salt and phosphorus transports, overall salt and silica conservation, and transports obtained from WOCE current meter moorings. Net meridional overturning is determined for 4.5°S to 45°S. The strength of the meridional overturning cell changes from 25 $Tg \cdot s^{-1}$ near the equator where the upper layer of the NADW dominates, to 19 $Tg \cdot s^{-1}$ in the south where the relative importance of deeper NADW layers increases. Zonal mass fluxes in the NADW layers are divided horizontally into bands according to significant changes in cumulative transports. Regionally persistent transport bands are found; e.g., a well defined band of eastward transports between 20°S and 25°S from the western boundary to the Rio de Janeiro Fracture Zone. Westward transport is found between 10°S and 20°S; typical layer transports in these zonal bands are 2-5 $Tg \cdot s^{-1}$. These features of the flux pattern roughly correspond to the float observations of Hogg and Owens in the region. When studying individual water mass properties, the eastward flow consists of relatively young NADW while the westward counterflow to the north carries older NADW. The axis of the eastward transport band corresponds to the core of property distributions, suggesting "Wüstian flow". Part of the eastward flow apparently crosses the Mid-Atlantic Ridge at the Rio de Janeiro Fracture Zone. The present analysis indicates considerable zonal transports in the western South Atlantic as part of the overall meridional overturning cell of the large-scale thermohaline circulation in the Atlantic.

DISTRIBUTIONS OF ANTHROPOGENIC CFCS IN THE SOUTHERN OCEAN

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Dissolved CFCs measurements made during the WOCE one-time survey and other CFC data collected in the Southern Ocean during the WOCE period are included in this study. The data have now been quality-controlled as a basin-wide data set to identify any problems.

CFCs in the surface ocean are generally undersaturated with respect to the atmosphere south of the Subantarctic Front (SAF). This results from upwelling of low-CFC Circumpolar Deep Water (CDW), vertical mixing, and sea ice coverage. Shoaling of CDW to the surface results in extremely high vertical CFC concentration gradients at shallow depths in this zone.

The highest column inventories of the CFCs are generally located in the Subantarctic Zone, between the Subtropical Front and the SAF The bulk of the inventory in this region is associated with the thick mode water layers. There is a great deal of zonal heterogeneity in the column inventories, with the SE Pacific and the South Atlantic haivng the highest CFC inventories.

CFC distributions in the Southern Ocean range from the cold surface waters (CFC-11 > 6 pmol/kg) to the CDW (CFC-11 < 0.05 pmol/kg). This contrast greatly assists in identifying the deep-water formation locations along Antarctica. The water that sinks off the shelf carries high CFC concentrations that decrease as the sinking waters entrain CDW. The high-CFC content AABW is generally delineated poleward of the southern ACC front, except in the SE Indian sector and Scotia Sea region, where AABW carries significant CFC signals farther northward. CFC signals associated with bottom waters formed in the Weddell Sea, the Ross Sea, and along Adelie Land show the paths by which these waters spread away from the continent. CFCs also can identify locations where waters not dense enough to reach the seafloor form plumes at mid-depth.

INFERRING TRANSIT TIME DISTRIBUTIONS FROM MULTIPLE TRANSIENT TRACERS

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Measurements of transient tracers can be used to derive timescales (“tracer ages”) for the oceans. However, because of mixing processes, these tracer ages differ for tracers with different temporal variations, and in general tracer ages are not fundamental transport timescales. We present an approach to use the ages from multiple tracers to infer information about the “transit time distribution”, which is a fundamental descriptor of the transport. In particular, the ages from tracers with sufficiently different temporal variations are used to constrain the first two moments (mean age and width) of the distribution. The method is first applied to simultaneous measurements of three CFCs, SF6, tritium and helium made in Lake Issyk-Kul, and it is shown that these measurements tightly constrain the mean age and width. We also apply the method to locations in the northern Pacific and Atlantic Oceans where two or three transient tracers were measured. In these cases the uncertainties in the mean age and width are larger, but useful constraints on the transport timescales and infiltration of anthropogenic carbon are still obtained.

TEMPORAL VARIABILITY OF THE TRANSPORT DETERMINED BY COMBINED ASSIMILATION OF SATELLITE AND WOCE DATA

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Results of a 4D-VAR data assimilation, which combines the dynamics of a general circulation model, altimetry data and the WOCE hydrography are presented. The mean and time varying ocean fluxes estimated from the constrained global ocean model are analyzed. The focus is given on the seasonal and interannual variability of volume, heat and freshwater transport in different ocean regions and depths. The comparisons with independent observations (e.g., TOGA-TAO, tide gauge data, etc) demonstrate the improvement of the model capabilities to predict the ocean variability. The results revealed the impact of the subsurface data on the deep meridional overturning circulation. The combination of altimetry and hydrography data together with the ocean model is beneficial for global ocean time-dependent analyses. The analysis reveals strong geographic and temporal variability. The physical processes (e.g., vertical vs. meridional advection, etc.) associated with the different behaviour of the variability are examined as well.

COMBINING ALTIMETRIC HEIGHT WITH BROADSCALE PROFILE DATA: A TECHNIQUE FOR ESTIMATING SUBSURFACE VARIABILITY

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Temporal and spatial variability are vastly undersampled by in situ measurements in the world ocean. In order to reduce errors caused by undersampling, in situ data can be combined with data from the TOPEX/Poseidon (T/P) altimeter, which has excellent spatial and temporal coverage. A new technique is presented for combining these data to provide improved estimates of upper ocean quantities. Using this technique, an estimate of large-scale, 0/800 m steric height variability is produced that has substantially smaller errors than estimates from either data set alone. The technique uses profile data to identify parts of the altimetric signal due to temperature variability in the upper 800 meters. The remaining deep baroclinic and barotropic signals can then be excluded from the altimeter data while still maintaining its spatial and temporal resolution. Because steric height is strongly correlated with heat content and subsurface temperature structure, improved estimates of these quantities can be calculated in a similar way. This technique is demonstrated over a region in the southwestern Pacific enclosing the northern Tasman Sea. Error bars in interannual time series of heat content and subsurface temperature are approximately 5.4 W/m^2 and 0.23°C, respectively. Application of these techniques on a global scale could provide new insight into variability of the general circulation and heat budget in the upper ocean.

SOUTH PACIFIC EASTERN SUBTROPICAL MODE WATER

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We analyze the structure, formation and destruction of South Pacific Eastern Subtropical Mode Water (SPESTMW). Geographic extent and mode water properties are discussed by using high quality CTD sections collected between 1991 and 1996. The density-compensating covarying patterns of late winter surface temperature and salinity in the ventilation region of SPESTMW are shown to contribute to the strength of the mode water. Defined as having a planetary potential vorticity magnitude of less than 3×10^{-10} m^{-1}s^{-1}, SPESTMW has a volume of 9.8×10^{14} m^3 estimated from the CTD data. The ventilation of this mode water is described by using data from a high-resolution XBT section in concert wtih nearly 2-year time series from profiling CTD floats, some of the first Argo deployments. SPESTMW spreads northwestward from its ventilation region within the subtropical gyre, eventually joining the South Equatorial Current. Published subduction rates allow a mode water formation rate estimate of 7.9×10^6 m^{3}s^{-1}. Combining this estimate with the volume yields a residence time of 3.9 years. We show that while the destabilizing salinity gradient in SPESTMW contributes to its formation, it may also hasten its destruction by leaving it susceptible to the double-diffusive type of convective mixing.