## OCEAN TRANSPORT OF HEAT AND FRESHWATER—HOW GOOD ARE OUR ESTIMATES? HAS WOCE CHANGED THE VALUES AND UNCERTAINTIES?

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Determination of “the large scale fluxes of heat and freshwater, their divergences over five years, and their annual and interannual variability” was a major scientific objective of WOCE, related to its primary goal of “developing models useful for predicting climate change and collecting the data necessary to test them.” Today, 22 years after the outline of WOCE and seven years after the end of the observation phase, the determination of large-scale oceanic heat transports appears to be a successful achievement. Uncertainties remain in the freshwater transports.

The unprecedented data quality, quantity, and synchronism of the WOCE Hydrographic Program permitted the determination of an accurate picture of the large scale circulation and associated fluxes, while their examination reveals new scientific challenges, some of which were foreseen by the WOCE designers.

**Fluxes before WOCE**. Until the early 1970s, Sverdrup’s view of the ocean circulation suggested that “ocean heat transport was negligible compared with that of the atmosphere.” Although much progress had been made before the design of WOCE, the oceanic transports, their magnitude and sometimes their sign were poorly known for many regions of the world. The major unknowns were the oceanic variability and the validity of the steady state assumption used so far. Aware investigators discussed their potential effects without quantification, due to the lack of data.

**Heat**. Estimates of net heat flux from different data products have complementary spatial and temporal resolutions, operational products being used generally to force ocean models. One major concern of the World Climate Research Program is to obtain references to calibrate those products. There are now enough observations to construct monthly global fields from bulk air-sea fluxes, a resolution that was confined to limited areas of the North Atlantic and Pacific before WOCE. While the comparison on local scales from ship and buoy observations helped in calibrating flux products, on large scales, where fluxes have the most impact on climate models, the WOCE hydrographic data provides a unique and extensive reference for the time-mean oceanic heat transports. The impact of WOCE is most spectacular in under-sampled regions such as the South Indian and Pacific oceans, where past divergent flux products have progressively converged toward hydrographic estimates. Where hydrographic sections were repeated, consistent changes over the past 30 years were found in temperature and salinity, but no change could be detected in the horizontal oceanic heat transports.

Understanding the process by which the ocean transports properties is another important issue in climate modeling, as an incorrect partitioning would lead to incorrect sensitivities. For instance, the net transport through a hydrographic section derives from large “eddy” fluctuations that tend to cancel out, leaving a net energy transport sometimes 10 times smaller its fluctuations. To discriminate between the physical sources of energy transports, several decompositions of property transports have been done showing that, while heat transports could be appropriately accounted for by two-dimensional density coordinate models, freshwater transports could not. This confirms Wunsch’s statement that “there had never been an adequate hydrographic sample of the ocean before WOCE” that would properly measure instantaneous transports by eddies and strong currents.

Oceanic variability remains the major source of uncertainty on time mean estimates. Numerical ocean models and repeated sections suggest that the ocean is ergodic to first order, with little time variations on the large scale transports, in particular at depths. The uncertainty can therefore be reduced by combining sections taken at different time if not at the same location. An unexplored issue remains the effect of the seasonality in WOCE hydrographic coverage as uncertainty calculations assume random distribution. The surface Ekman transport is also source of uncertainty. While the ocean wind quality is constantly improving, its uncertainty on large scales remains unevaluated.

**Freshwater**. Air-sea exchanges of freshwater, that is, evaporation and precipitation, are an extremely important class of climate variable. Despite their key role in climate regulation, through their greenhouse effect and their controls on the global ocean circulation, freshwater transports are highly uncertain. Evaporation is estimated from empirical formulas based on either in situ observations or satellite radiometers and suffer, as does heat, from the accumulation of errors on large scales. Precipitation is much more challenging to estimate because of the sparse data distribution and their sporadic occurrence. Satellite microwave and outgoing longwave radiation sensors provide estimates for integral properties of water drops and ice particles, which can be related to precipitation. The relations used are affected by many factors and, lacking appropriate calibration data, result in highly uncertain estimates. "Quasi-standard" zonally integrated precipitation estimates deviate from each other by a factor of two. Freshwater estimates from atmospheric re-analyses are dynamically more consistent than empirical estimates although they too suffer from the lack of oceanic data and from the difficult parameterization of cloud physics.

Net ocean-atmosphere freshwater exchanges over large oceanic areas now can be derived from the mass and salt budgets between hydrographic sections. Because freshwater exchanges are small fractions of large horizontal mass transports, the noise in the mass budget is much larger than the freshwater divergences, and one has to use the small differences in salinities relative to mass to obtain meaningful freshwater divergences. Past hydrographic estimates have shown a consistency and, despite their large uncertainties, permit discrimination among several products such as the present estimates from radiometric satellites. Values for ocean-atmosphere exchanges are meaningful only when integrated over large areas, with for instance a net evaporation of 1.2 Sv globally between 30°S and 47°N. Hydrographic uncertainties will soon be reduced through numerical simulations and repeated measurements.

**Perspectives**. WOCE not only improved the sampling and the transport values, but it has allowed us to quantify more carefully the uncertainties. It is the basis from which we are now beginning to look at temporal variations. WOCE has brought people of different fields to work together, such as numerical modelers, atmospheric scientists and "wet" oceanographers. Grist and Josey, for instance, took a step beyond simple comparison and adjusted their bulk climatology to adequacy large-scale observations from hydrography. WOCE transport estimates have also stimulated improvements to ocean numerical models. In addition to their quality and quantity, the public availability of WOCE permitted many investigators to access the data, multiplying the wealth of scientific work.

The remaining uncertainties in hydrographic estimates suggest several directions for future work: Repeat measurements are necessary to improve time averages. Several methodological improvements are possible, such as estimation of noise in the anomaly equations. Further regional analyses of the WOCE data will improve the spatial resolution, as well as the wider use of other types of data such as neutrally buoyant floats and acoustic Doppler current profiles. If regional calculations employing much more data of all types are produced with complete uncertainty estimates, one envisions a new global synthesis from the combined regional products. In principle, such a synthesis would bring to optimize knowledge about all elements of the ocean circulation everywhere.

## WATER MASS FORMATION—A CLIMATE DYNAMICS PERSPECTIVE

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Water mass formation, transformation and ocean ventilation will be discussed from the climate dynamics perspective. We will describe the dynamics, formation strength, and link to interesting climate variability issues of the four schematic vertical cells of bottom water, deep water (NADW), intermediate and mode water, and shallow water or subtropical Ekman cells.

Model predictions for the way these cells are linked to dynamical issues from overturning circulation stability, to decadal ENSO variability, will be discussed. The model predictions and claims will be compared, to the extent this is possible, with the relevant WOCE data sets.

UPTAKE, TRANSPORT, AND STORAGE OF CARBON BY THE OCEAN—IMPLICATIONS FOR THE GLOBAL CARBON CYCLE

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The ocean represents the largest active reservoir of carbon on earth, containing about 60 times more carbon than the atmosphere. Furthermore, the exchange of carbon between the two reservoirs is relatively rapid, leading to an atmospheric $CO_2$ residence time relative to the ocean of only about a decade. As a consequence, the oceanic carbon cycle exerts a significant influence on atmospheric $CO_2$, and hence earth's climate. Our understanding of the ocean's role in the global carbon cycle has made great advances during the WOCE period. This is in large part due to a number of converging factors, of which the collaboration between the JGOFS and WOCE communities to undertake the global ocean $CO_2$ survey is among the most important ones. In my presentation, I will review a few of these major accomplishments, with a strong emphasis on the uptake of carbon dioxide from the atmosphere and the subsequent transport and storage of this carbon in the ocean. Special attention will be paid to the Southern Ocean, who appears to play a critical, yet not well understood, role in the ocean carbon cycle.

The first major development is that we are able now, with some confidence, to compute the air-sea flux of $CO_2$ across the air-sea interface directly on a global basis. This is due to the compilation of a large data base of observations of the air-sea difference in the partial pressure of $CO_2$. Second, the recent completion of the JGOFS/WOCE global carbon survey produced inorganic carbon measurements that are over an order of magnitude better than previous efforts, allowing us, for the first time, to describe the large-scale distribution of inorganic carbon in the ocean with high precision and accuracy. Third, a method has been developed recently by which the small anthropogenic $CO_2$ signal in the ocean can be separated from the large natural variability, allowing us to directly determine the oceanic inventory of anthropogenic $CO_2$. The fourth method is the continuing development and application of inverse methods to determine the transport of pre-industrial and anthropogenic carbon across hydrographic sections. The fifth and most recent factor is the use of inverse modeling methods that make use of the interior ocean carbon data from JGOFS/WOCE global survey in order to compute the air-sea flux of pre-industrial and anthropogenic $CO_2$.

These observations and analyses indicate that the ocean is the most important sink for anthropogenic $CO_2$ after the atmosphere by having taken up about a third of the anthropogenic $CO_2$ emissions, or about 2±0.5 Pg C/yr for the year of 1990. This estimate is corroborated by constraints based on measurements of atmospheric oxygen and the atmosphere-ocean balance of the stable isotope carbon-13. This estimate is also in excellent agreement with a large number of general ocean circulation models, that have made such simulations as part of the Ocean Carbon Model Intercomparison Project (OCMIP). While good agreement has emerged with regard to the total anthropogenic $CO_2$ uptake by the oceans, there exists substantial uncertainty with regard to the regional uptake. The most uncertain region is the ocean south of 45°S, which represents one of the largest sinks for anthropogenic $CO_2$, but neither the flux nor the storage of this anthropogenic $CO_2$ are well measured and understood. Direct observations indicate that only a small fraction of this anthropogenic $CO_2$ is stored in this region, with the rest likely being transported to more northern latitudes as a consequence of intermediate and mode water circulation. However, this northward transport has not been confirmed yet by direct transport estimates on the basis of transport inversions of hydrographic sections.

Even more puzzles still exist with regard to the uptake, transport, and release of natural (i.e. pre-industrial) $CO_2$. More than 13 years ago, Keeling et al. proposed the existence of large interhemispheric transport of $CO_2$ by the oceans (order of 1 PgC/yr), with the North Atlantic taking up $CO_2$ from the atmosphere and it to the Southern Hemisphere, where this $CO_2$ is released back into the atmosphere. The existence of such a large interhemispheric $CO_2$ transport by the ocean would have significant consequences for the interpretation of atmospheric $CO_2$ data, from which major conclusions about the nature and magnitude of the carbon sink on land are drawn. So far, neither the direct carbon transport estimates on the basis of the hydrographic sections, nor the forward and inverse modeling studies have confirmed the existence of an interhemispheric transport of the proposed magnitude. Nevertheless, nearly all methods tend to show a substantial net southward transport of carbon in the Atlantic and net outgassing in the pre-industrial Southern Ocean, but with a magnitude reaching maximally half of that suggested by Keeling et al. This implies that the absence of a large interhemispheric gradient of atmospheric $CO_2$ in the presence of fossil fuel emissions must be caused primarily by a strong net uptake of $CO_2$ by the land biosphere in the northern hemisphere. A wildcard exists in the form of the very poorly quantified interhemispheric transport of dissolved organic carbon stemming from northern hemisphere river input, which has the potential to increase the total carbon transport significantly.

Addressing these challenges as well as those arising from a possible future climate change requires long-term monitoring of the oceans together with the development of a hierarchy of diagnostic and predictive models that are based on a mechanistic understanding of the processes governing the ocean carbon cycle. It is very encouraging to note that many of these developments have been initiated and it is in now in our hands to make sure that they will succeed.

OCEAN EXCHANGES WITH THE ATMOSPHERE – DID WE LEARN ANYTHING DURING WOCE?

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When WOCE was being planned in the mid 1980s, the legacy of the Global Atmospheric Research Programme included formulae and transfer coefficients for calculating the air-sea fluxes which were similar to those in use today. Climatologies of the monthly mean air-sea heat, water vapour, and momentum transfers were available, but there were difficulties in reconciling the integrated fluxes with the global heat balance, with estimates of the meridional heat transport in the ocean, or with atmospheric budget techniques. At that time, the solutions adopted were to change the transfer coefficients to allow for observational errors, or to adopt different radiation schemes. The application of a further constraint, balancing the freshwater budget, was hindered by poor knowledge of precipitation fields. It was argued as to whether the best flux fields would in future be defined by numerical weather prediction (NWP) models, or determined globally by satellite remote sensing. Satellite scatterometer missions were considered vital for mapping the surface wind stress during WOCE. Meanwhile, needing to use surface forcing values, ocean modellers invented their own, balanced heat and water climatologies.

So now we've had WOCE, has anything changed? We still can't declare that the climatologies balance, that we know the precipitation fields, that we have reliable flux fields from satellites, or that the best flux fields are from the NWP models. Ocean modellers are still creating their own climatologies!

But this talk will suggest that much has changed. We have better knowledge of the error characteristics of our meteorological data and the resulting flux estimates. We have more certainty with regard to transfer coefficient values. Surface flux fields from NWP models have been evaluated and errors assessed. The WOCE Hydrographic Program has provided more constraints to apply to our surface flux climatologies. Satellite products are becoming available for wind stress, and, with varying accuracy, precipitation and components of the net heat flux. In approaching a consensus on surface flux magnitudes we now have a few flux reference sites to allow independent verification. The WOCE objectives included the development of an on-going climate observing system; significant progress has been made through the Ocean Observing System Development Panel, and now the Global Climate Observing System.

What is still needed? A wish list would include improved flux estimates from NWP "reanalyses", improved flux fields from remote sensing, better estimates of the accuracy and variability of ocean heat and salt transports. Perhaps most important, more reference quality data to check our flux values against reality.

## THE GLOBAL DATA SYNTHESIS: HOW FAR HAVE WE COME, HOW FAR MIGHT WE GET?

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An essential element of WOCE is the synthesis of all its observations into a global description of the changing ocean and to use of the results to study the changing ocean circulation and its interaction with the atmosphere. Ocean state estimation (data assimilation) is a suitable tool to reach this goal by bringing a numerical model into consistency with ocean observations and with air-sea fluxes.

Rigorous global ocean state estimation methods have reached a level of maturity that it can be used on a routine basis to produce dynamically consistent time-varying model/data syntheses, producing results that begin to form the basis for studies of a variety of scientifically important problems. In particular they allow computation of non-observable climate-relevant quantities such as ocean transports and air-sea fluxes of heat, freshwater and momentum. Results now emerging on a global and routine basis represent a milestone in the WOCE analysis and synthesis phase and provide the basis for a future ocean observing and synthesis system for climate.

We will summarize new insight that has emerged from ocean state estimation, compare it with traditional static inversion results and contrast it with the state of the knowledge that existed prior to WOCE. A particular synthesis focus is on the determination of transports and the budgets of mass, heat, freshwater, and energy in various regions of the global domain. Time-mean, heat and volume flux estimates obtained from complex time-varying ocean state estimation have come into agreement with those from simple box inversions of the static ocean. Because estimated fluxes of volume, heat and freshwater are variable on all time scales and show complex spatial patterns, the validity of static inversion approaches is questionable.

State estimates are being used to study ocean dynamics; to assess the accuracy of various estimates of air-sea fluxes of momentum, heat, and freshwater; to quantify the relative impact of different observing systems; and to improve forecasting skills. Beyond physical oceanography, output from the WOCE synthesis are being used to study biogeochemical tracer transport, including air-sea $CO_2$ fluxes, by driving a biogeochemical model with the constrained physical circulation fields. Moreover, they allow the determination of the ocean's angular momentum (OAM) fluctuations and their contribution to observed polar motion and Earth rotation. This type of integral comparison provides a strong independent consistency check on the estimated ocean state estimate and underlines the importance of such estimates for study of Earth rotation and polar motion. The estimation of the ocean circulation is intimately coupled with estimating the geoid over the ocean: Existing estimates of the mean sea surface height in combination with altimeter data in turn provides an improved estimate of the geoid. The results reported here show that the existing data-base and the available modeling and computing capability have advanced to the point where true three dimensional, skillful estimates of the global time-evolving general circulation are practical.

To a large extent, this statement is a vindication of the vision which drove the World Ocean Circulation Experiment—that such estimates could become possible by about the year 2000, and that they would be necessary for the advancement of the science. Sub-optimality in existing estimates is related to: (1) low model resolution; (2) incomplete use of ocean observations; (3) insufficient information about error covariance matrices; (4) unknown or underrepresented internal model errors. All those aspects need to be improved as part of a sustained long-term activity in support of quantitative climate research: We need to perform mathematically rigorous data assimilation into eddy-resolving models; we need improved knowledge of model and data error covariance matrices; ultimately we are required to constrain coupled models through observations to provide dynamically balanced initial conditions for climate forecasts. Potential limitations in each of those elements will be discussed.

The talk is given in consultation and with input from D. Behringer, J. Carton, B. Ferron, I. Fukumori, R. Schlitzer, J. Schroeter and C. Wunsch.

## HYDROGRAPHIC TRACERS – FROM DESCRIPTION TO QUANTIFICATION

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During WOCE, the number of tracer observations increased significantly in all oceans. The interpretation of this data set improved our knowledge of the ventilation and formation rates of water masses, of circulation pathways and of the time scales of spreading in the ocean's interior.

## THE INDIAN OCEAN

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WOCE hydrographic plans for the Indian Ocean had to account for the strong monsoon variability and it was concluded that sections in the monsoon regime north of about 10°S should be carried out at least once during the extremes of each monsoon season. While not all objectives of the WOCE plan could be met, a unique coverage was accomplished during the WOCE period, complemented by process studies in the northwestern Arabian Sea, equatorial regime and in the Indonesian Throughflow. Results derived from observations obtained during the WOCE period will be reviewed here in comparison with pertinent model studies. Concerning a central WOCE objective, the meridional circulation of the Indian Ocean, several inverse model solutions have been derived, combining WOCE surveys with earlier sections. One general finding is that the Indonesian Throughflow transport must be on the high side compared to earlier estimates, at the order of 10 Sv. However, large uncertainties continue as to the magnitude and vertical structure of the deep meridional overturning cell of the Indian Ocean, and on the mechanisms responsible for transforming deep waters into lighter species. In the upper 500 m a cross-equatorial meridional cell of about 6 Sv transport has been diagnosed, both from observations and models. It connects waters originating in the Indonesian Throughflow and in the southern subduction regions westward via the South Equatorial Current and then northward across the equator by the Somali Current with northern upwelling regions. The cell is closed by southward cross-equatorial Ekman transport in the interior. Models suggest that only part of the required northern upwelling amount occurs off the coasts of Arabia and Somalia but that upwelling in domes around India and Sri Lanka should also be important. Recent work has emphasized the importance of the Mozambique Channel. Not only do inverse results and models suggest that a major part of Indonesian Throughflow waters are passing through that channel, but apparently eddies triggered off at its northern entrance can migrate through it southward and may in the end even influence eddy shedding from the Agulhas retroflection into the Atlantic. Beyond the original Indian Ocean WOCE goals, large coupled ocean-climate anomalies were observed in the tropical and subtropical Indian Ocean during the WOCE period, particularly strong in 1994 and 1997-1998. These events, and earlier precursors, have been interpreted as an independent Indian-Ocean "dipole" or "zonal" mode by some investigators and as ENSO-forced anomalies by others. WOCE was obviously a big boost for our understanding of the physical oceanography of the Indian Ocean, but some of the WOCE questions still require answers while new questions have arisen, and an attempt at addressing these issues will be made.