Meteor 60-5: Weekly Report #1

Meteor 60 Leg 5 departed Fort-de-France (Martinique) at 1330 (local) on March 9. Some of the 26-strong scientific staff had already enjoyed a short holiday in Martinique, while others arrived two days prior to departure. We all spent a pleasant Sunday together on the beach at our hotel: swimming, wind-surfing (well, almost), and diving. On Monday morning the planned bus transfer to Meteor was cancelled due to the roads to our part of Martinique having been completely blocked by a strike or demonstration. This reminded us that Martinique is part of Europe despite the relaxed Caribbean atmosphere. After some momentary confusion, which was not helped by the Chief Scientist's incomplete mastery of French, we obtained alternative transport in the form of ferryboats. We finally reached Meteor, two hours late, to find our containers already on board and ready to be unloaded. Unpacking and laboratory set up continued right up until the time of departure, but we were then able to relax a little and enjoy the view as we sailed along the western coast of Martinique.

The main theme of Meteor 60-5 is to resample a set of hydrographic stations that were occupied in 1981 during the US-led Transient Tracers in the Ocean program (TTO). We have therefore given Meteor 60-5 the nickname: 'TTO Revisited'. The TTO expedition was itself, partly a reoccupation of the famous GEOSECS expedition of the early 1970's. Both GEOSECS and TTO were concerned with the penetration into the ocean of tracers derived from nuclear fallout: particularly tritium (^{3}H) and radiocarbon (^{14}C). The atmospheric weapons testing of the early 1960's had initiated a global-scale tracer-labeling experiment that was monitored by worldwide expeditions such as GEOSECS and TTO. These expeditions and the tracers measured, returned major new insights, as well as some new questions, concerning the circulation of the deep ocean.

By the time of TTO however, concern was already shifting away from the decaying problem of man-made radioactivity towards the growing problem of man-made CO_2. Hence the TTO cruises included extensive measurements not only of fallout tracers but also of oceanic CO_2.

Twenty-three years on from TTO, there has still been no carbon equivalent of the Nuclear Test Ban Treaty, and the result is that the CO_2 problem continues to grow. Human beings continue to release more and more CO_2 into the atmosphere, with 30-40% of the amount released 'disappearing' into the ocean. The consequence of the ocean uptake is that ocean CO_2 levels are rising. The major goal of the Meteor 60-5 cruise is to collect data to document and quantify this increase of oceanic CO_2 over time. Comparison of our data with the high-quality data collected 23 years ago during TTO, should give us an unprecedented view into the magnitude of this change and its geographical distribution. This information in turn can be used to check and improve the models that try to predict how much CO_2 the ocean will take up in the future.

During Meteor 60-5, we will travel along the long path trod by the RV Knorr, 23 years ago. The result is an strange looking cruise track that zigs and zags across the mid-latitude Atlantic in order to reoccupy as many TTO stations as possible. The Meteor 60-5 cruise, combined with a northern North Atlantic cruise of Meteor and two related US-led cruises last year, will provide an almost complete 'snapshot' of the North Atlantic for the period 2003-2004. This can be compared directly with how the Atlantic looked in 1981. In addition to the expected CO_2 increase, we are looking for changes in temperature, salinity, oxygen, nutrients and tracers such as the Freons using the high-quality TTO data as a baseline.

At the time of writing this report, all planned measurement programs are underway and a routine has developed. Almost every measurement group has experienced one or two initial problems so that we have kept the Meteor's excellent electronics department very busy, but now everything is functional with the exception of an in-situ fluorometer.

We have already sampled 6 of the old TTO stations. Overall the data quality looks very good, with our nutrient and oxygen data falling exactly on top of the older data. We can already see evidence for a significant increase of CO_2 in the top 700-800m of the water column. Last night we sampled at TTO station 22 (25° 47'N; 66°W) and then made a right turn, so that we are now heading northeast towards a cluster of TTO stations located 750 nautical miles south of Newfoundland. As we travel slowly north, we keep a close eye on the weather charts. So far its been warm and calm, and the immediate forecast also looks good, however storms will undoubtedly play an increasingly important role for our cruise in the coming weeks.

In addition to the TTO reoccupation, we have several other science programs on board, including an extensive biological program of observations and experiments. In the next weekly report, I will introduce the various groups and their scientific activities.

Douglas Wallace
Chief Scientist, Meteor 60-5

Meteor 60-5: Weekly Report #2

Since last week's report we have made good progress and have now occupied 17 stations. Eleven of these have been re-occupations of stations occupied by the Transient Tracers in the Ocean expedition of 1981. Data collection has settled down to a more-or-less routine operation and we have been continually examining and fine-tuning the analytical systems on board to ensure the highest accuracy possible. The CTD/rosette operations are going well and Christopher Smarz managed to repair our fluorometer with some ingenious 'Bastelei'. We've also had a little fun: the 'West Atlantic' leg of the table football championship was hard fought and the winners were rewarded with fantastic prizes.

Our comparison with data collected in 1981 requires chemical measurements of extremely high accuracy. The atmospheric pCO_2 has increased by about 35-36 μatm since 1981: the time of the TTO expedition. This is an ~10% increase in the carbon content of the atmosphere but the equivalent increase in the surface ocean is 25 μmol/kg: just over 1% of the background seawater carbon content. Obviously detecting anthropogenic changes of 1% or less over 23 years requires extremely accurate measurements. And the problem doesn't stop with carbon: ocean carbon is subject to natural variability associated with photosynthesis and respiration. To correct for variable amounts of carbon respired in subsurface waters we use dissolved oxygen: these data have to be accurate to about 1-2 parts in 300. To interpret any changes in oxygen we need the most accurate measurements of temperature and salinity, and so it goes on with the accuracy needs cascading down from one measurement to another. At this point of the cruise however we are confident that the required accuracy levels are being attained.

From a first look at our data from southern stations we can see a very clear signal of the post-1981 anthropogenic CO_2 increase down to depths of about 700m, or to seawater potential densities of about 1027. Further north there are indications of the signal being found in deeper and denser waters. The CO_2 measurements are being made on board by a team of 5 IfM-GEOMAR analysts who are working shifts around the clock to keep up with the samples being collected (see photo). Samples are also being collected for shore-based analyses of ^{13}C at Kiel University's Leibniz Labor für Altersbestimmung. These analyses can provide an independent estimate of anthropogenic CO_2, by detecting the progressive dilution of the heavier isotope of carbon by 'lighter' carbon released into the environment with the burning of fossil fuel.

To complement the CO_2 measurements, we have a significant transient tracer measurement program on board, including measurements of CFCs 11 and 12, CH_3CCl_3, CCl_4, and for the first time in this region, SF_6. All of these compounds are man-made and have, like CO_2, increased in the atmosphere and hence in the ocean over the past 40 (SF_6), 60 (CFC11 and 12), to 80 (CCl_4) years as a result of human emissions. Unlike CO_2, these compounds have no natural background. In addition to these 'tracer' gases, we are measuring a range of naturally-produced gases. These include the important greenhouse gas, N_2O, and a wide range of halocarbons including some 'exotic' brominated and iodinated compounds that play key roles for atmospheric chemistry. More about the results of these groups in a later report.

Our biology program has two components: one group is catching particles and 'marine snow' with a custom large-volume water sampler ('Snow Catcher') deployed on a hydro-wire. They then disappear into one of the Meteor's cold rooms for hours and hours to identify them and determine their characteristics. The larger 'Bioassay Group' has been working independently: pumping their sample water from a towed 'fish' rather than relying on the CTD/rosette. This group is conducting a series of elaborate on-board experiments to determine which nutrient(s) limit(s) biological production. Following on from work of this type initiated on Meteor 55, the results of which are soon to be published in *Nature*, the group is using our wide-ranging cruise track to sample as wide a variety of Atlantic conditions as possible. Their third experiment has just been completed: a total of 7-10 separate experiments are planned. This project is a collaboration between IfM-GEOMAR, the University of Essex, the University of Plymouth and the Southampton Oceanography Centre.

A special feature of Meteor cruises is always the support from the crew and officers. This trip has been no exception, with the support and excellent cooperation of the deck crew having been especially important to us over the past week. Another notable feature of this cruise, has been the route-planning assistance provided by the Bordwetterwarte of the Deutscher Wetterdienst. Last week we were able to 'snatch' an extra, northern TTO station out of the jaws of two storm depressions thanks to insight into model predictions from our meteorologist, Herr Joppich.

Herr Joppich will likely have to help us again next week as we head off along a long northeasterly transect. We will retrace an old TTO cruise track and the even older GEOSECS-Atlantic track as far as 42°N 42°W, 350 miles east of the Tail of the Grand Banks. Along the way we will sample at a CLIVAR station occupied by our US colleagues last year. These stations are important to us but getting them may be a challenge: needless to say the historical cruises were not conducted in March.

Photos:
1. The CO_2 Lab. set up in the Universallabor (photo: Birgit Quack).
2. Getting ready to deploy the 'Snowcatcher' after a CTD cast (photo: Sylvia Walter).

Meteor 60-5: Weekly Report #3

At the time of writing the third weekly report, we have just completed one of our main objectives for the cruise: our northernmost station at 42°N, 42°W. This station completed a long week-long section along old TTO and GEOSECS stations. On the way we also stopped at a station occupied last year by US colleagues during a US CLIVAR-Carbon of WOCE line A20 (29°34'N 52°20'W). The intention had been to resample this station as a cross-check on data intercomparability. Unfortunately at this station we encountered our only major technical difficulty of the cruise to-date when signal transmission to/from the CTD was interrupted during two separate attempts at a deep cast. Both times the connection was lost at depths of about 5000m. Eventually we left the station with complete CTD downcast profiles available for comparison, but only 7 water samples. While limited in scope, comparison of these 7 deep water samples with their CLIVAR equivalents was encouraging, with the chemical properties such as nutrients, oxygen and carbon agreeing to within the desired tolerances. We will get another chance at an intercomparison later in the cruise when we cross the WOCE A16N line in the eastern basin. This section was also occupied last year by US investigators.

In general, weather conditions have been remarkably favourable, including sunny and warm conditions at our northernmost station today. Given the conditions in the region over the past few weeks, which we have been monitoring, we have been lucky. In general our region of the Atlantic has been filled with high pressure systems, both north of the Azores and SW of Newfoundland. Nevertheless, mid-week found us located directly at the air mass boundary between the two Highs which gave us strong winds and swell and forced us to miss one planned station. The missed station was a shallow TTO station that had been occupied on top of a seamount with relatively few chemical measurements: our failure to 'collect' it, is therefore not damaging to our program.

In some ways, Meteor 60-5 is two separate expeditions sharing the same vessel and cruise track. The program of physical and chemical measurements of the deep water column occupies the majority of the scientific staff on board. However there is another group on board who never even go near the CTD/rosette system and whose activity is almost completely out-of-phase with that of the rest of the staff. For example, this group, will be working feverishly round the clock for the next 2 days while most people take a much needed break as we steam southwards, without stations, to resume our transect eastwards towards Lisbon. This other group is the 'Bioassay Group'.

Photo: The Bioassay Group ready for a long night in the Clean Lab. Container. From left to right: Mark Mills, Rebecca Langlois (IfM-GEOMAR), Angie Milne and Eric Achterberg (Plymouth Univ., UK). Not shown are: Mark Moore (Southampton Oceanogr. Centre) who took the photo, Kerstin Nachtigall and Peter Fritsche (IfM-GEOMAR). Assistance with nutrient measurements is provided by Frank Malien (IfM-GEOMAR).

The Bioassay Group is seeking to determine the nutrient(s) (nitrogen, phosphorus, or iron) that limit the productivity and biomass of the phytoplankton, the fixation of nitrogen (N_2) by the microbial community, as well as the bacterial productivity. They have been conducting a series of on-board experiments involving manipulations of surface seawater pumped from a towed 'fish'. Each experiment consists of filling approximately 150 1-liter bottles under trace-metal clean conditions in our on-board clean laboratory container. Nutrient forms of nitrogen, phosphorus, iron are then added to these bottles in all possible combinations. The bottles are incubated on-deck for 48 hours. Parameters such as phytoplankton productivity and chlorophyll, as well as nitrogen fixation, and bacterial productivity are made both at the beginning and end of the incubations in order to determine the effects of the different nutrient additions. Samples are also being collected for molecular analysis of DNA and RNA in order to identify and quantify organisms responsible for nitrogen fiaxation.

At this time, the group has already successfully completed four of these experiments, and they plan to complete another 4 prior to arrival in Lisbon. The experiments benefit from the wide range of conditions we have encountered on the cruise so far, ranging from oligotrophic surface waters of the tropics to pre-bloom, 400-m deep mixed layers of the northern Atlantic. Initial results seem clear and show that nitrogen additions stimulate phytoplankron productivity and chlorophyll concentrations, whereas a combination of nitrogen and phosphorus is required to stimulate bacterial productivity. This may run counter to some recent work suggesting a primary role for phosphorus in limiting productivity. Further conclusions have to await more detailed analysis of the results including analysis of stored samples in Kiel.

The Bioassay Group is also examining how dust derived from the African continent might affect these biological processes. Atmospheric transport of dust from the Saharan desert is well known to be an important source of iron. During Meteor 55 to the tropical Atlantic, similar bioassay experiments suggested that additions of Saharan Dust might stimulate nitrogen fixation by relieving both phosphorus and iron limitation. Presently, experiments are being conducted on board to determine the amount of N, P and Fe released when dust is added to seawater.

In the next weekly report, I will discuss the results of the transient tracer measurement programs.

Douglas Wallace
Fahrtleiter, Meteor 60-5

Meteor 60-5: Weekly Report #4

The fourth week of Meteor 60-5 saw fewer stations being occupied in part due to a long transit southwards in order to resume our eastward transect along about 33°N. This planned gap was followed later by an enforced ~24-hour halt to stations due to strong winds and high seas. The transit time was used by the various chemical measurement groups on board to make adjustments to their systems, perform more extensive calibrations, and work up data. It also allowed our CTD operators to take a much-needed break. Despite the bad weather, we managed to sample at, or close to, all planned TTO stations and we are still on schedule. At the time of writing we have just completed a re-occupation of TTO station 49 at 33° 46'N 25° 8'W. Immediately after this we will make a biological CTD and particle-catching station in about 280m of water on top of the nearby Atlantis Seamount.

Photo 1: A small ceremony was held to honour our CTD operators, Jens Schafstall and Christopher Smarz when the thousandth water sample was collected. (photo by Sylvia Walter).

We also took the opportunity of the long transit at the beginning of the week to hold our 'Bergfest'. This included the cultural highlight of the cruise with the awarding of prizes for the Meteor 60-5 photo contest. Twenty excellent entries were submitted in the categories: 'Science', 'Life on Board', and 'Art: Hands or Feet'. Upon examination of the entries, the judges were forced to add an additional category: 'uncategorisable'. One of the winning photos (under 'uncategorisable') was of a seaman riding a cow on deck. We are still looking for the cow. Captain Jakobi awarded the prizes to the winners. Later in the week, on April 1, the Chief Scientist was the victim of an extraordinarily elaborate hoax that some people found quite amusing.

A major activity during Meteor 60-5 is the analysis of a wide range of dissolved gases and volatiles. In addition to measurement systems for dissolved CO_2 and O_2, we have a total of 5 gas chromatographs on board that are measuring a wide range of trace compounds both in deep ocean profiles and the air. The compounds range from man-made chlorinated and fluorinated compounds that can be used as circulation tracers, through a variety of naturally-produced chlorine-, bromine- and iodine-containing compounds that are potentially important for atmospheric chemistry, to the important greenhouse gas N_2O.

Photo 2: with so many different analyses being made on the same sample, there is strong competition for water from the sampling bottles. (photo by Sylvia Walter)

The circulation tracers that we are measuring include the chlorofluorocarbons 11 and 12 (CCl_3F and CCl_2F_2), together with CCl_4 and SF_6. CFC-11 and CFC-12 have been measured worldwide since the 1980's. We have already re-sampled some stations where the very first North Atlantic measurements of these compounds were made, during TTO, in 1981. Not surprisingly, our data reveal a large increase in the concentrations of these compounds, at all depths, since that time. Much less commonly measured are CCl_4 and SF_6. Both compounds are also exclusively man-made, but have very different time-histories of input to the oceans compared to the CFCs. CCl_4 has been used widely as a solvent since the early 1900's, and has had significant environmental concentrations since the late 1920's. SF_6 in contrast has increased rapidly in the environment since the 1960's. Taken together, the suite of compounds covers input timescales of <80 years (CCl_4), <60 years (CFCs 11 and 12) and <40 years (SF_6). We can refer to these timescales, perhaps optimistically, as: 'senior', 'middle-aged' and 'young'. The distributions of the tracers that we have measured so far in the western basin reveal the impact of ventilation of the interior ocean over these three distinct timescales.

In the deep waters of the western basin we have seen some striking variations in the relative distributions of CFC11 and CCl_4. On some density horizons we have found relatively high levels of CCl_4 in the near-absence of CFC11. This signals tracer associated with a water mass component that was ventilated at a time when CCl_4 was already present in surface waters but CFC levels were still low: this is the 'senior' water. At other density surfaces and locations we have found similar levels of CCl_4 associated with much higher CFC11 levels. This water therefore includes a 'middle-aged' component that was ventilated when both CCl_4 and F11 were present in surface waters. Only in the upper 1000-2000m and in North Atlantic-derived deep water masses along the boundaries do we find evidence of a 'young' component containing detectable SF_6. The 'senior' water contains no detectable SF_6. The deep water distribution of SF_6 shows some strong similarities with the distribution of CFC11 as it was at the time of TTO.

One of our goals is to employ this diverse tracer information to help us interpret the patterns of increase of CO_2 that we measure through our comparison with TTO data. The tracer data should also help us with the interpretation of the distribution of other halocarbon compounds that we are measuring on board. More about these and N_2O in next week's report.

As is usual on Meteor we are being very well looked after by the stewards department and able to concentrate on our measurements. Next week sees us following the footsteps of Larry Armi's TTO Leg 3 into the Canary Basin. The 'bioassay group' will start another of their experiments at our southernmost point.

Then we make a northwards transect, to the east of the Azores, and start the final transect eastwards towards Lisbon along 37°N, following the path of TTO Leg 4 (Chief Scientists: Wally Broecker and Claes Rooth).

Douglas Wallace
Chief Scientist, M60-5

Meteor 60-5: Weekly Report #5

The 5th week of Meteor 60-5 started with an attempted biological station on top of the Atlantis Seamount (33 deg 59'N 30 deg 5 W). We found a good shallow location for the station and collected an interesting-looking fluorescence and oxygen profile with the CTD. Unfortunately difficult wind, current and wave conditions then forced us to cancel the particle catcher deployment. We then headed southeast into the Canary Basin, gradually encountering a stronger influence of Salinity Maximum Water (SMW, sometimes known as the Subtropical Underwater). This water mass is formed convectively in the eastern Atlantic as a result of strong evaporation driven by dry winds leaving NW Africa. The salinity of this water mass has increased over the past several decades, perhaps reflecting large-scale changes in the hydrological cycle. However this water mass appears to be of significance not only for climate but also for biogeochemistry.

The same hot, dry winds that drive evaporation also deposit dust carried from the Sahara/Sahel onto the ocean surface. And our experimental and field results from Meteor 55 had strongly supported the hypothesis that dust addition can stimulate nitrogen fixation. During the first week of our cruise we had already sampled SMW as a subsurface layer off the Caribbean Islands, where it is marked by high levels of nitrate relative to phosphate. This 'excess nitrate' signal has been attributed to high rates of oceanic nitrogen fixation in the source regions of this water mass. Our transit towards the SMW formation region therefore provided a perfect opportunity for our biologists to start their 7th nutrient limitation bioassay experiment. Interestingly, along the transit, the on-board iron measurements revealed increased levels of Fe (II), perhaps a signal of increased dust deposition. We now have to await shore-based analyses to determine whether we did in fact encounter enhanced nitrogen fixation. We collected DNA samples in the region for characterization of nifH genes coding for the nitrogenase enzyme. This will help us to determine the type of organisms responsible for any enhanced nitrogen fixation measured there.

This part of the cruise was marked by flat calm conditions, sun and warm temperatures and was very, very pleasant.

Abbildung 1: Warm. sunny skies and calm seas in the Canary Basin.

The southernmost point on this part of the cruise was reached on the 6th of April at 30° 49'N 26° 44'W. We then returned along a line of TTO stations, in a northeasterly direction, towards the Azores. Upon approaching the Azores it was decided to make a detour to Ponta Delgada to offload a sick crewmember. Thanks to thorough preparations by Captain Jakobi and the other Officers, the entire operation consumed the absolute minimum of time. Only one station was cancelled and this, fortunately, was not a TTO station. Despite the detour, we will be able to complete our planned program within the allotted time.

Scientifically, as data collection becomes more routine, we have been looking more intensely at the data collected earlier in the cruise. The patterns of CO_2 increase in different water masses, in particular, are striking and not completely what we expected. We have also been looking more closely at the distributions of a range of naturally produced gases that we are measuring on board.

These biogenic gases range from the important greenhouse gas, N_2O, through to a variety of naturally produced halocarbons. For N_2O, it is the relation to dissolved oxygen that dominates its sub-surface distribution. The Meteor 60-5 data can be compared to data from earlier zonal sections collected by the IFM-GEOMAR group at 42°N and along 10°N over the past 3 years. A strong correlation with O_2 is present in all the data sets, but the regression slope and intercept varies with latitude and between the western and eastern basins for reasons that are not yet clear.

On a separate gas chromatograph, we have been measuring the concentrations of a range of compounds including bromoform ($CHBr_3$), chloroform ($CHCl_3$), dichloromethane, dibromomethane, and methyl iodide. These compounds play potentially significant roles in atmospheric chemistry. We have been measuring their distributions in vertical profiles, surface water and air. The vertical profiles, in particular, are quite different between western and eastern Atlantic basins and these differences likely contain clues to the underlying oceanic production and consumption processes. Of particular interest is the behaviour and sea-to-air flux of $CHCl_3$: an important trace gas that definitely has oceanic sources but about which very little is known. A great deal of effort during Meteor 60-5 has gone into calibration and quality control of these very difficult measurements; it now appears that we have a high-quality data set available for interpretation.

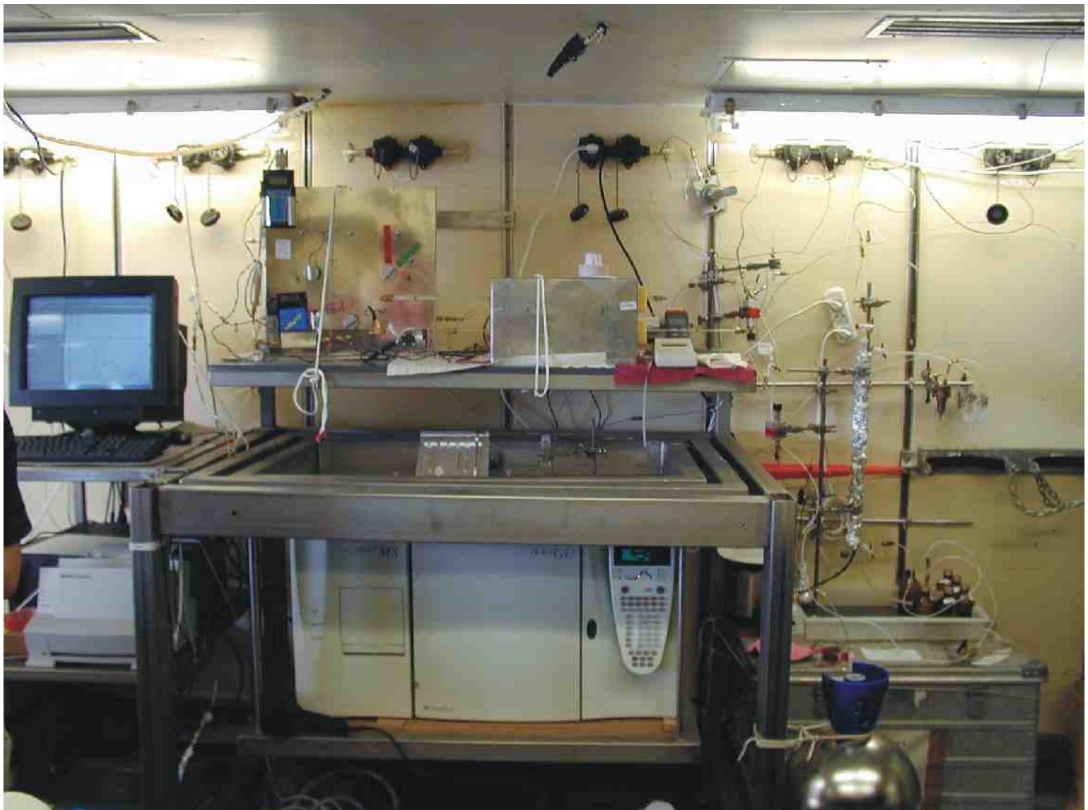

Abbildung 2: Gas-chromatograph/Mass spectrometer system in the GeoLabor.

Today we were able to celebrate Easter Sunday in a relaxed manner, with an excellent lunch. Life on board Meteor has settled into a routine and we have been well cared for by the crew. But now, as the cruise draws to an end, we are increasingly thinking about the end of the voyage and looking forward to returning home. There are only 4 more stations left to sample with the last station scheduled for Tuesday evening. After that we still have a great deal of work to do: making the final measurements, dismantling equipment and packing before our arrival in Lisbon on Thursday morning.

Douglas Wallace
Chief Scientist, Meteor 60-5