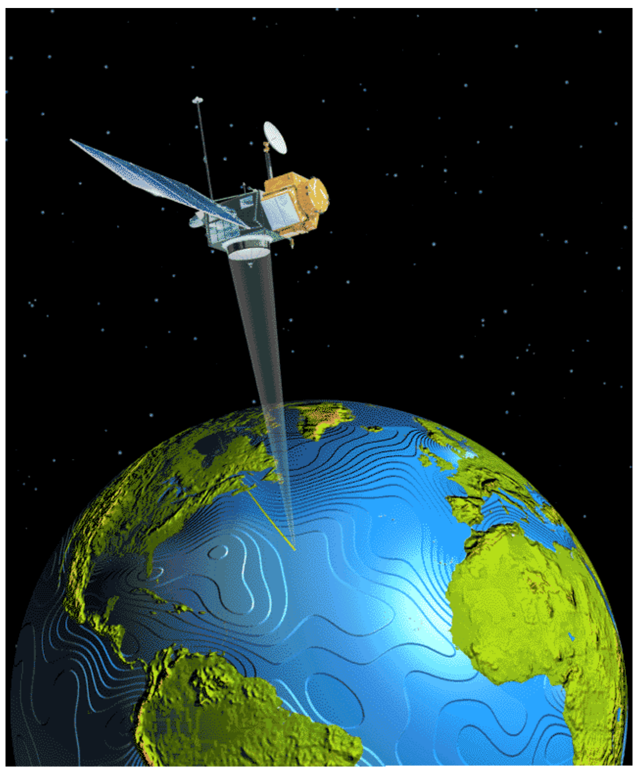
GEOid and Sea level Of the North Atlantic Region - GEOSONAR

Final report



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Summary

Satellite altimetry has successfully been used to monitor the ocean surface and has provided valuable information about the dynamics of the worlds oceans and the marine gravity field. Other Earth observing sensors onboard satellites have provided an enormous amount of information about the sea surface temperature and the ocean colour. The goal of the interdisciplinary GEOSONAR project is to develop methods for integrating multi mission, multi sensor, and multi channel satellite data for improved determination and analysis of the sea level.

Improve the recovery of the sea level
Altimeter satellite missions operate in different orbit configurations collecting sea surface heights along different ground tracts at different times. To improve the recovery of the sea surface heights, an optimal interpolation technique that take both spatial and temporal correlations into account, has been considered. Statistical properties such as empirical correlations have been analysed to improve the estimation techniques. Both sea surface height data from satellites and from tide gauge instruments have been used for that study. The results show that non-isotropic and non-homogeneous covariance functions should be used in order to reflect the dynamic of the westward propagating waves in the North Atlantic Ocean. In the North Sea the variations in sea level decorrelate after 1-2 days. Hence, the variatility cannot be described fully using satellite altimetry. A technique for integrating satellite altimetry and in-situ tide gauge data for improved recovery of the sea level has been developed.

Improve the recovery of the gravity field
Satellite missions aims at improving the geoid to enhance the analysis of satellite altimetry for ocean studies. Due to computer limitations, only regional models have been considered. With the increase in computer capacity and speed our regional methods may likely be feasible for the construction of a global model at the time of the (expected) launch of the GOCE satellite that ESA is planning. The estimation of the gravity field at the surface of the Earth from satellite data is an unstable problem, the solution of which requires regularization. To improve the recovery of the gravity field new ideas developed by collaborators in another research project on Inverse Problems have offered promising new solutions. It is shown that there exist positive definite preconditioners, which lead to sparse systems of equations. These systems of equations can then be used within the method of conjugate gradients for the solution of the original very large system of equations. Furthermore, the recovery of the marine gravity field from satellite altimetry has been improved.

Analysis of ocean tides and meteorological effects on the sea level
Short period tidal movements and more random meteorological induced sea level variations were analysed to improve the estimation of those signals and to improve the correction of the satellite data subsequently. It has been shown that reliable empirical estimates of several major shallow water constituents could be obtained from TOPEX/POSEIDON by combining along-track and crossover observations. Furthermore, it has been shown that the magnitudes of the main tidal constituents have significant seasonal differences. The more random meteorological induced sea level variations was analysed using a hydrodynamical model. The calculated sea levels have been compared to altimeter data and were found to explain a significant part of the sea level variability.

Fusion of multi source remote sensing data

Other Earth observing sensors onboard satellites have provided an enormous amount of information about the sea surface temperature and the ocean colour. A global coverage of altimetry is only provided every 10 or 35 days. Hence, the sea level information may be improved dramatically, if other tyres of data can be utilised together with the altimeter data. The studies of the correlations between the sea level and the sea surface temperature are carried at different regional scales and at different periods in order to take different physical states into account. At local scales a study of hydrographic data from a light-ship combined with AVHRR surface temperatures demonstrates the link between seasonal changes of sea level height and surface temperature. At larger scales some correlation between height and temperature were found; especially at longer time scales and in relation to phenomena such as El Niño. Ocean colour data are analysed and included in the studies. Using a fuzzy c-means clustering technique six classes of sea water were identified. An ACE algorithm was used to detect correlations with the sea level height. In the North Sea the correlations between sea level and surface temperature were significant. In the coastal regions the correlations between sea level and ocean colour were found to be significant.

Modelling of ocean circulation and processes

Regional studies in the North Atlantic showed that the overflows across the Greenland-Scotland ridge of dense bottom water through the Faroe Bank Channel and the Denmark Strait can be detected with satellite observations. The overflows can be detected during all seasons and during all years and there is thus a potential that the satellites can be used to monitor changes in the thermohaline circulation. The high accuracy of satellite observed sea surface height and sea surface temperature provide an opportunity to estimate the winter mixed layer depths using only these two types of satellite observations. In the project we have also used in situ observations in the North Atlantic. These observations were used to determine the validity of the assumptions involved in the conversion of height and temperature changes into a mixed layer deepening. It was shown that it is possible to estimate the late winter mixed layer depths within 50 meters in the eastern part of the North Atlantic subtropical gyre. Finally, the synergetic use of satellite altimetry and sea surface temperatures has improved the analysis of interannual changes in sea level and the temperature.

The goal of the project is reached. Methods for integrating multi mission, multi sensor, and multi channel satellite data for improved determination and analysis of the sea level have been developed. Hence, the value of existing and new earth observation data has increased. The results have improved the understanding of the various sources contributing to the sea level and its variations.

Introduction

The sea surface responds to a variety of geophysical processes. If the ocean was homogeneous and motionless, the surface of the ocean would coincide with the geoid, which is an equipotential surface of the earth's gravity field. However, the ocean is not homogeneous and motionless. Differences in the ocean water density may cause the ocean surface to depart from the geoid and contribute to the forcing of the general circulation in the oceans. Furthermore, the ocean responds to meteorological effects such as atmospheric pressure changes and winds, and these plays also an important role in the determination of the sea surface. Figure 1 illustrates the scenario and the geodetic, oceanographic, and meteorological parts of the sea level.

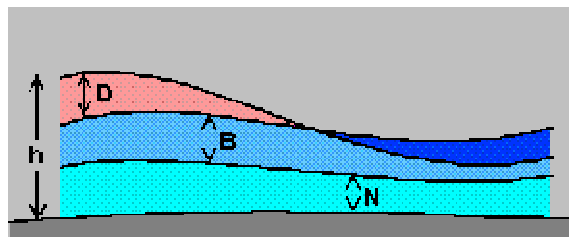

Figure 1. The sea level, h, comprises the geoid, N, and oceanographic and meteorological contributions, D and B, respectively.

For more than a decade, satellite altimetry has successfully been used to monitor the ocean surface and has provided valuable information about the dynamics of the worlds oceans and the marine gravity field. Other Earth observing sensors onboard satellites have provided an enormous amount of information about the sea surface temperature and the ocean colour. Satellite missions such as the recently launched ENVISAT mission are dedicated to integrate earth observation data from multiple channels and sensors.

The present marine geoid models only represents the global signatures of the geoid adequately, and they cannot be used for detailed studies of the ocean dynamics. In order to make further progress in the analysis of the ocean dynamics a more accurate geoid information is required. Until then the total flow and, consequently, the total heat transport of the ocean currents cannot be estimated. Therefore, both geodesists and oceanographers support a dedicated gravity field satellite mission, such as the GOCE mission that ESA is currently preparing.

The goal of the GEOSONAR project is to develop methods for integrating multi sensor and multi channel satellite data for improved determination and analysis of the sea level height. This is carried out at regional scales (10-20 km) in the North Atlantic region as well as at local scales (3-5 km) in the Danish seas.

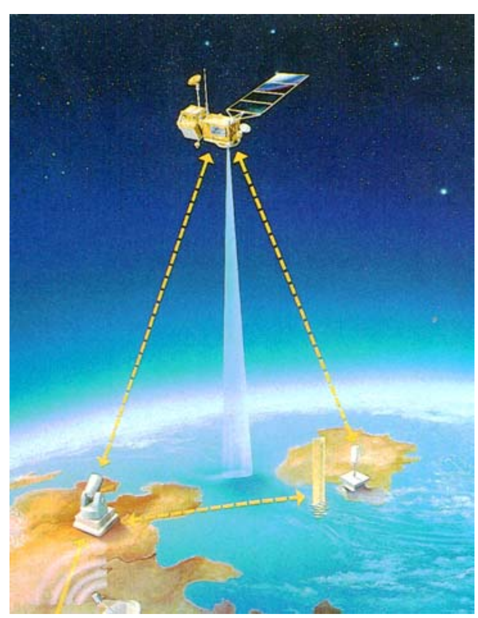

Figure 2. The altimetric observational principle. The satellite emits a radar pulse and measures the return time of the signal reflected at the sea surface.

Results of the GEOSONAR project

I) Improve the recovery of the sea level

This part of the GEOSONAR project focuses on the determination of the sea surface height. The purpose of the activities is to improve the recovery of the sea level by improving the techniques so that information from different satellite missions and in-situ tide gauge data can be integrated. Altimeter satellite missions operate in different orbit configurations collecting sea surface heights along different ground tracts at different times. To improve the recovery of the sea level statistical properties such as empirical correlations are analysed and implemented in statistical estimation techniques.

A) Analysis of in-situ sea level data from existing Danish tide gauge stations

In order to evaluate the accuracy of the satellite altimetry, in-situ sea level data obtained at tide gauge stations along the Danish coasts are used. An analysis of the temporal characteristics of the sea level time series provided important information when the signal content of the satellite altimetry.

The sea level at the coast is influenced by local effects. Especially, near the tide gauge station at Esbjerg such effects are strongly present which make a comparison with open ocean sea level very difficult. A detailed investigation was carried out in the North Sea where an off-shore ocean bottom pressure gauge is established in order to evaluate local effects at the coastal stations. (Huess, 2001, Høyer, 2002)

The off-shore instrument deployed by the GEOSONAR project at Horns Rev in the eastern North Sea 50 km west off the Danish North Sea coast has provided useful observations. The observations have been used to validate both altimetry observations and model simulations for this near-shore and shallow water area. Furthermore the off-shore observations have been used to identify local effects on the sea level variations obtained by the existing on-shore tide gauges, such as local changes in the tidal pattern. Figure 3 shows a scatter plot of sea level observations at Horns Rev against sea level observations from Esbjerg and a straight line has been fitted and added to the plot. The slope of 0.5 shows that coastal effects are affecting the sea level variability at Esbjerg, so that they are twice as large as at open ocean.

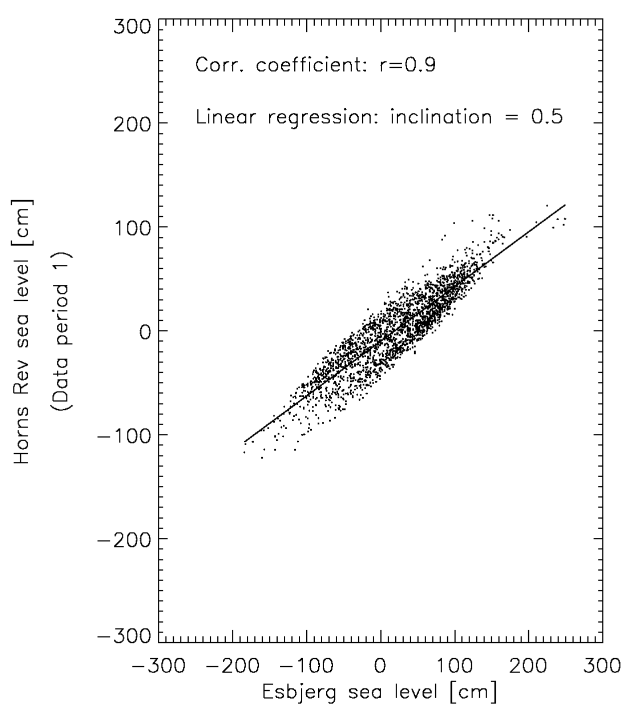

Figure 3: Off shore sea level observations at Horns Rev versus sea level observations at the Esbjerg tide gauge station. A straight line has been fitted to the

data and added on the plot.

B) Develop spatial and temporal interpolation method to integrate altimetry from multiple satellite missions

The satellite altimeter data are available along the satellites ground tracks. Usually, the satellites operate in an "Exact Repeat Mission", so that the measurements are repeated at regular intervals. Due to different orbit configurations the spatial distribution of the ground tracks vary as well as the period at which the measurements are repeated. Hence, an optimum interpolation technique that take both spatial and temporal correlations into account, must be developed in order to interpolate between the discrete measurements measured along different tracks and at different times.

Geostatistical methods as least squares collocation and kriging are based on the autocovariance or the semivariogram of the data to be interpolated. The usual spatial autocovariance can be extended to allow for temporal autocovariance also. Empirical correlations have been analysed and the results implemented in the estimation technique. (Ersboll and Ersboll, 1997, Knudsen et al., 2001, Leeuwenburgh, 1997, Leeuwenburgh, 1998, Leeuwenburgh, 2000, Nielsen et al., 2000, Tscherning, 1999)

The spatial and temporal characteristics of the sea surface height variations was analysed using the empirical autocovariance functions. This was done in both latitude and in longitude directions taking time into account. Analyses of the time-longitude plots of sea level variability in the North Atlantic Ocean have demonstrated that most of the meso-scale energy is associated with (primarily) westward propagating features. While most mapping studies neglect this fact, it was shown that using a covariance model that accounts for westward propagation leads to reduced formal mapping errors. The spatial and temporal scales of sea level variability in the North Atlantic were estimated by fitting the proposed covariance model to empirical functions as estimated from TOPEX/POSEIDON altimetry. As an example of the covariance functions are shown in Figure 4 where the sloping covariances indicate the westward propagation. This exercise additionally resulted in estimates for phase speeds and uncorrelated process and measurement noise.

C) Combining satellite altimetry and in-situ sea level data

The shallow waters in the North Sea means that the weather induced sea surface height variability has time scales on the order of a few days. This is evident from the hourly coastal observations at Hvide Sande where the autocorrelation is shown in figure 5. Fluctuations with periods of a few days cannot be resolved with satellite observations with repeat periods of 10 or 35 days. However, the satellite observations still contain the information and statistical methods can be used to extract the information about the spatial structure. The knowledge about the temporal scales from the coastal recorders and about the spatial scales from the satellites has been used to combine the two types of data to obtain an improved description of the sea level in the North Sea. (Høyer, 2002)

Observations from coastal water level recorders around the North Sea revealed a counter clockwise propagation of weather-induced surges with time scales of 10-60 hours. Satellite altimetry observations from the interior demonstrated that the spatial scales of these surges were several hundred kilometers. When tides were removed consistently from both types of observations, very good agreement between altimetry and in situ observations was found at the times when satellite observations were available.

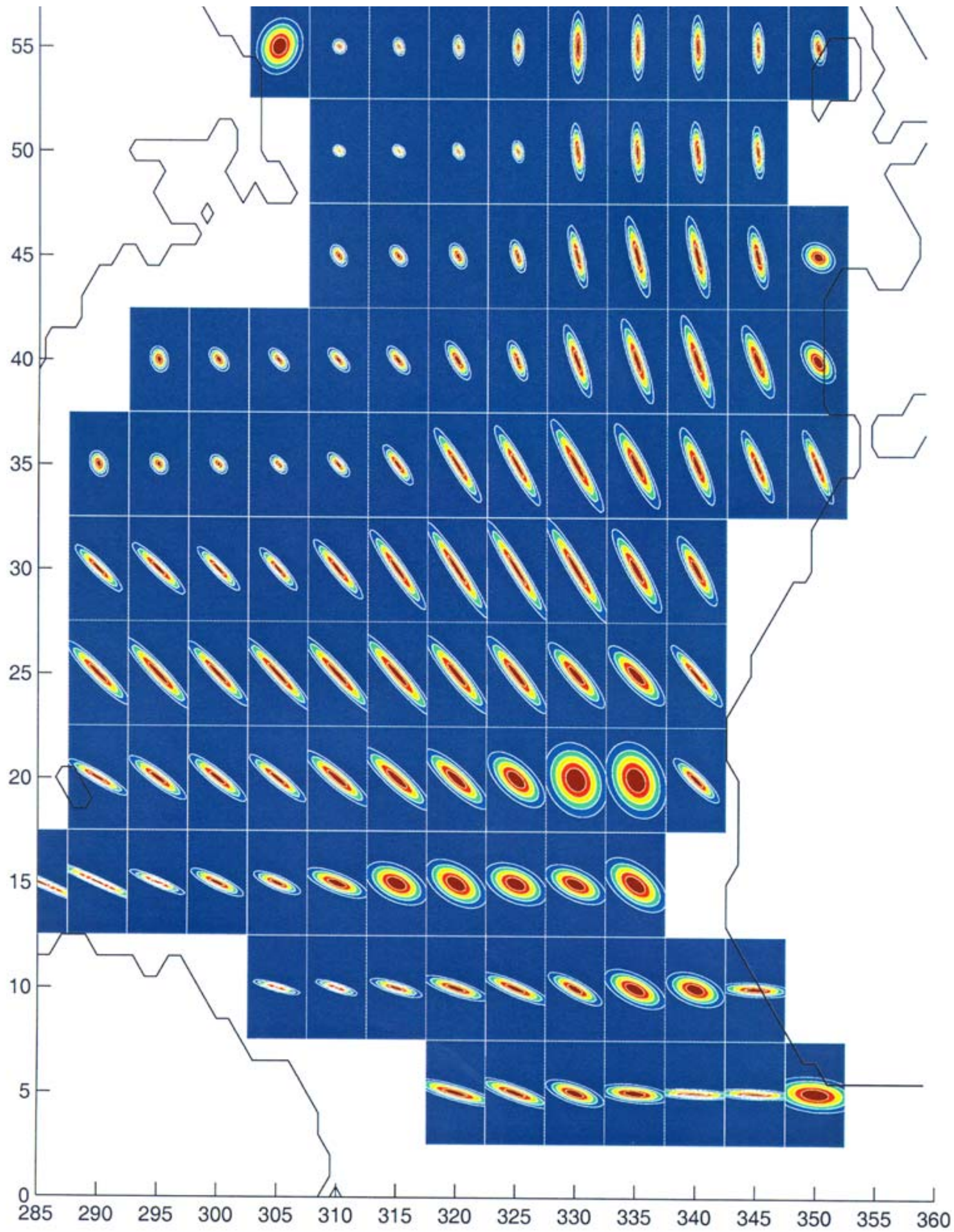

Figure 4: Fitted zonal-temporal autocorrelation models derived from TOPEX/POSEIDON observations in the North Atlantic. The small squares represent spatial lags from –500 to 500 km (x-axis) and temporal lags from –200 to 200 days (y-axis). Contour interval is 0.1 and red indicate high correlations above 0.9.

The high temporal resolution of the water level recorders and the good spatial sampling of the TOPEX/POSEIDON satellite were combined in a multivariate regression model that estimated the sea level to all times and all over the North Sea with an accuracy of ~8 cm. Figure 6 below shows an example of how much sea surface height variance the model can explain along the ground tracks of the T/P observations

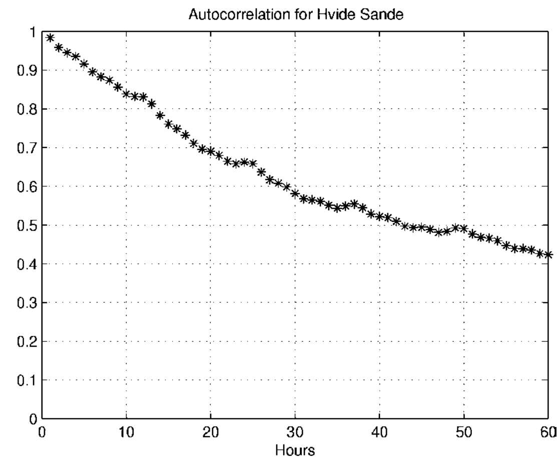

Figure 5: Autocorrelation for the Hvide Sande tide gauge. After only 50 hours, a correlation of less than 0.5 is obtained.

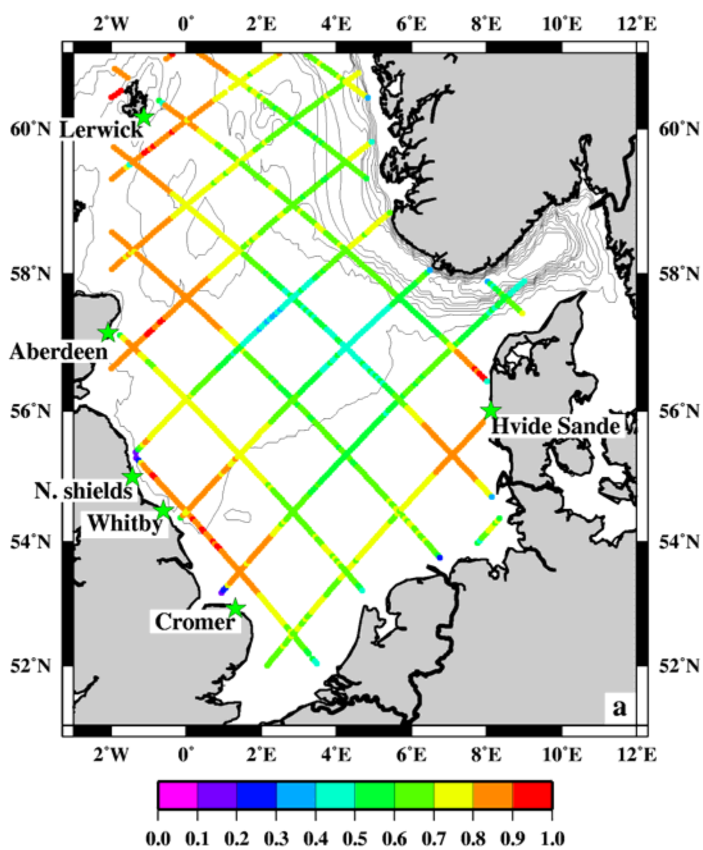

Figure 6: Performance of the multivariate regression model is shown as hindcast skill. The explained percentage variance of the sea level (divided by 100) from the satellite altimetry and tidegauges are shown. The water level recorders used as input to the the model are shown with the green stars. In large parts of the North Sea the model explains more than 80% of the sea surface height variance.

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II) Improve the recovery of the gravity field

This part of the GEOSONAR project focuses on the determination of the geoid, which is an equipotential surface associated with the Earth gravity field. The geoid is the reference surface for the sea surface. Satellite missions aims at improving the geoid to enhance the analysis of satellite altimetry for ocean studies. To improve the determination of the geoid an improved recovery of the Earth gravity field by the dedicated gravity satellite missions are essential.

A) Evaluate existing geoid models as a geopotential reference surface in the Danish Seas using mean sea surface heights from satellite altimetry

The gravity field in the Nordic countries are quite well known from in-situ measurements. These measurements have been used in a determination of the geoid to provide the geopotential reference surface for land geodetic surveying. At sea, however, ship gravity measurements are not available to the same extent of accuracy. A comparison of existing geoid models with mean sea surface heights derived from satellite altimetry can provide valuable information about the accuracy of the geoid models as well as the mean sea level. (Tscherning, 1998)

Existing geoid models and altimetric mean sea surfaces were compared in the North Sea. Three available gravimetric geoids were compared with altimeter data from the NASA Pathfinder dataset. The comparison showed that two new geoids (GEONZ97 and EGG97) both were superior to the EGM96 geoid. New gravity data were furthermore collected during a ship survey in the North Sea to complete the data coverage. Those data have been used in the new geoid computation and improved the reference surface.

B) Develop methods for geoid determination from a dedicated gravity field satellite mission

The satellite gravity field missions aims at determining an analytic gravity field model from which geoid estimates may be computed. Due to computer limitations, only regional models were considered. With the increase in computer capacity and speed our regional methods may likely be feasible for the construction of a global model at the time of the (expected) launch of the GOCE satellite mission that ESA is planning. Both theoretical work and the development of new algorithms are needed. The algorithms must permit an optimal combination of many data types with due consideration of the individual noise characteristics. The estimation of the gravity field at the surface of the Earth from satellite data is an unstable problem, the solution of which requires regularization. Here new ideas developed by collaborators in another research project on Inverse Problems seem to offer promising new solutions, which has been further developed and investigated. (Forsberg and Tscherning, 1997, Moreaux, 2000, Moreaux, 2001, Moreaux, 2001a, Moreaux et al.,1999, Tscherning, 2001)

In 1998, a new spherical harmonic expansions became available complete to degree 1800 (11 km resolution). This expansion is very convenient for gravity field representations, and it enabled us to attack the problem of characterizing globally the statistical characteristics of the gravity field. However, a theoretical break-through was achieved when a method for representing the statistical information was found. To construct a more homogenous field, the topographic effects must be removed in a consistent manner. This was done, by calculating the spherical harmonic coefficients of the expansion of the isostatically compensated topography. The ideas were tested using actual information about terrain and bathymetry. It was found that the data contained very large errors, so the idea has not been further pursued.

The method of least-squares collocation is an optimal estimation method, which is well suited for the determination of gravity field models. The problem is that the number of equations to be solved equals the number of observations, which means millions with the new gravity missions. We have shown that there exist positive definite preconditioners, which lead to sparse systems of equations. These systems of equations can then be used within the method of conjugate gradients for the solution of the original very large system of equations. The preconditioners are different finite covariance functions, which have been studied, and the consequences of their use have been described. Important new ideas have been obtained which brings us very much closer to a solution of the problem. Furthermore, software to produce global gravity field models using sparse matrices and iterative techniques has being developed.

The use of sparse matrices is difficult if more than one data-type is being used. Alternative procedures have been developed after the completion of the project in collaboration with F.Sansò, Politecnico di Milano.

C) Improve recovery of the marine gravity field using satellite altimetry

During the project, the marine gravity field has been improved. These improvements have resulted in a release of the KMS99 gravity field in 1999 and the KMS2001 gravity field and mean sea surface. These gravity fields represented a significant improvement in comparisons with marine observations. (Andersen and Knudsen, 1998, Andersen and Knudsen, 2000, Andersen et al., 2001, Knudsen and Andersen, 1999)

The mapping of the gravity field was carried out relative to the EGM96 geoid with an adaptive collocation scheme used to interpolate the sea surface height observations from the satellites. In this all parameters were determined empirically. The KMS 2001 gravity field anomalies are shown in Figure 7. The resolution of the mean sea surface is 2 minutes. This corresponds to 1/30 degree which is equivalent to 5 km at the Equator. Fifty million altimeter data from the entire Geosat and ERS-1 ERM and Geodetic Missions have been used to derive the gravity field and mean sea surface between 82S and 82N. The resolution of the marine gravity field is 2 min by 2 min (1/30 degree) globally.

A comparison in the Gulf Stream region was carried out using unclassified marine gravity observations from NIMA within the area bounded by 45N – 55N, 80W - 60W. A total of 52500 observations were used and the gravity field showed a standard deviation of the differences of 5.53 mGal and a mean difference of –0.14 mGal. This was shown to be superior to other global marine gravity products currently available.

To a large extend, the changes in the gravity field are caused by changes in the depth of the ocean because of the large density-contrast between water and rock. This assumption applies for spatial structures between 10 and 200 km wavelength, and consequently the altimetric derived gravity field can be used to improve the bathymetry in poorly surveyed regions of the global ocean. A new global bathymetry model on 4 km resolution has been derived. In a test region around the Antactica, it improved the comparison with marine observations from 1100 meters (ETOPO5/Terrainbase) to roughly 300 meters (KMS Bathymetry 2001) in terms of standard deviations between observed and modelled ocean depth.

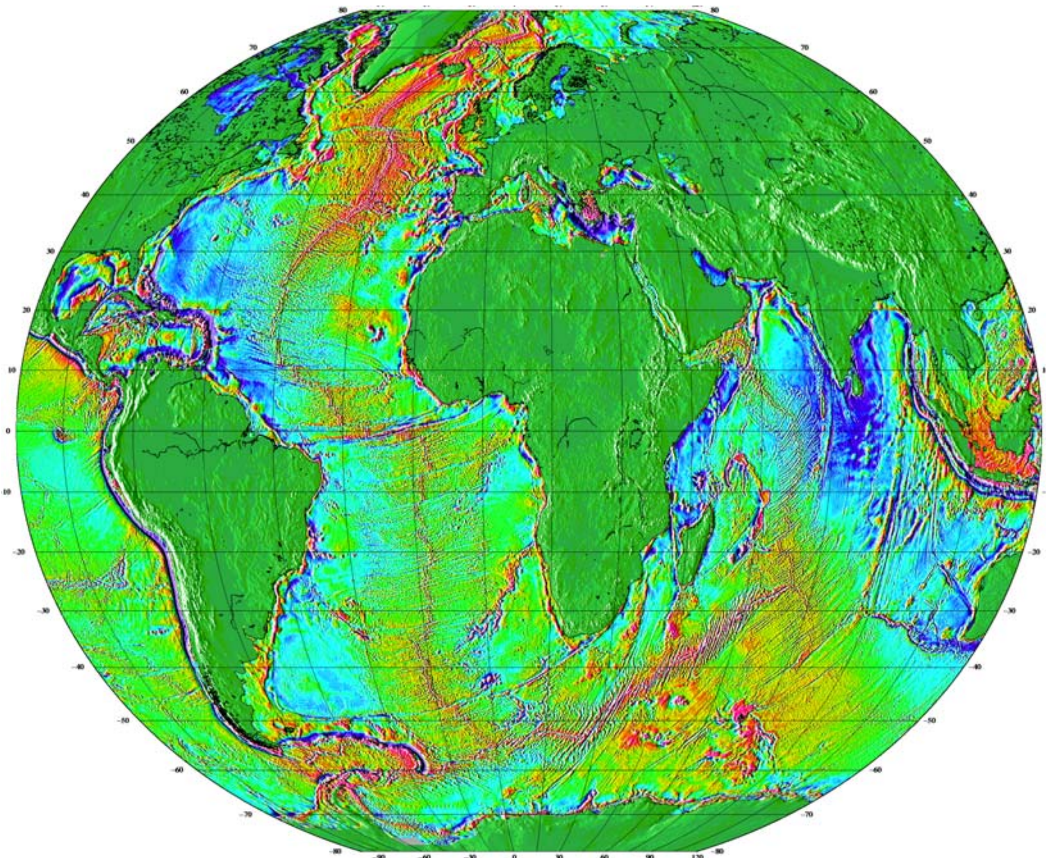

Figure 7: The KMS global marine gravity anomaly field, color ranges are from –60mGal (blue) to +60 mGal (red).

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III) Analysis of ocean tides and meteorological effects on the sea level

This part of the GEOSONAR project focuses on the determination of the sea surface height variations that are caused by ocean tides and meteorological signals such as wind and atmospheric pressure. To improve the estimation of those height variations time series of sea level data are analysed. Furthermore, numerical storm surge models are used.

A) Analysis of ocean tides

During recent years the accurate measurements from the TOPEX/POSEIDON satellite have been used to improve the global ocean tide models considerably. However, these global ocean tide models are still not accurate enough on the continental shelves where shallow water constituents exceed 50 cm at several locations on the northwest European shelf. Within the project, it has been shown that reliable empirical estimates of several major shallow water constituents could be obtained from TOPEX/POSEIDON by combining along-track and crossover observations. Furthermore, it has been shown that the magnitudes of the main tidal constituents have significant seasonal differences (Andersen, 1999, Andersen, 1999, Andersen, 2001, Andersen and Leeuwenburgh, 1997, Huess and Andersen, 2001, Leeuwenburgh et al.,1999).

Data from the existing tide gauges have been analysed. Both statistical and tidal analyses of these on-shore observations have been performed. The sea level residual (i.e. the sea level subtracted the tidal signal) shows that the meteorologically induced signal is correlated for time lags of several days. For a time lag of 10 days - the repeat period of the TOPEX/POSEIDON altimeters, the residual from the tide gauge at Esbjerg harbour gives a small but still significant correlation coefficient.

Coastal tide gauges around the British Isles have observed seasonal variations in the main tidal constituents. The altimetry observations have an accuracy that enables an estimation of the modulations in the M_2 constituent. The altimetric data have, therefore, provided valuable new knowledge for the interior North Sea with information about the spatial behaviour of these seasonal variations. This information has in combination with the coastal tide gauge data set been used to validate results from numerical models. The model suggests that the seasonal modulation arise from non-linear shallow water effects and e.g. a large part of the seasonal signal in the M_2 constituent is barotropic, caused by non-linear interaction between the tidal waves and the surges.

The largest shallow water constituent on the northwest European shelf, the fourth diurnal M_4, could be derived accurately from altimetry. A comparison with 168 tide gauges showed that it compares better with pelagic tide gauges a high-resolution hydrodynamic shelf model (3.60 versus 4.29 cm RMS comparison). Coherent results could also be obtained for the major sixth-diurnal constituent, M_6. This constituent has such short spatial wavelengths that the resolution of the empirical model is close to reaching its limit. On the other hand, the T/P model compares marginally better with tide gauges than the hydrodynamic shelf model used for operational storm surge warning in Britain (Proudman oceanographic laboratory), particularly in the open parts of the shelf such as the North Sea and the Celtic Sea.

The hydrodynamic shelf model is more accurate than the empirical model in the most complex parts of the shelf such as the Irish Sea and the English Channel and generally close to the coast, where the empirical model has problems. The model compares better with tide gauges than the T/P derived model for the MS_4 constituent, having a RMS comparison of 2.27 versus 2.86 cm for the T/P model. The reason for this was found in the alias period for this constituent being equal to 3 years, which apparently causes leakage of interannual variability into this very small constituent.

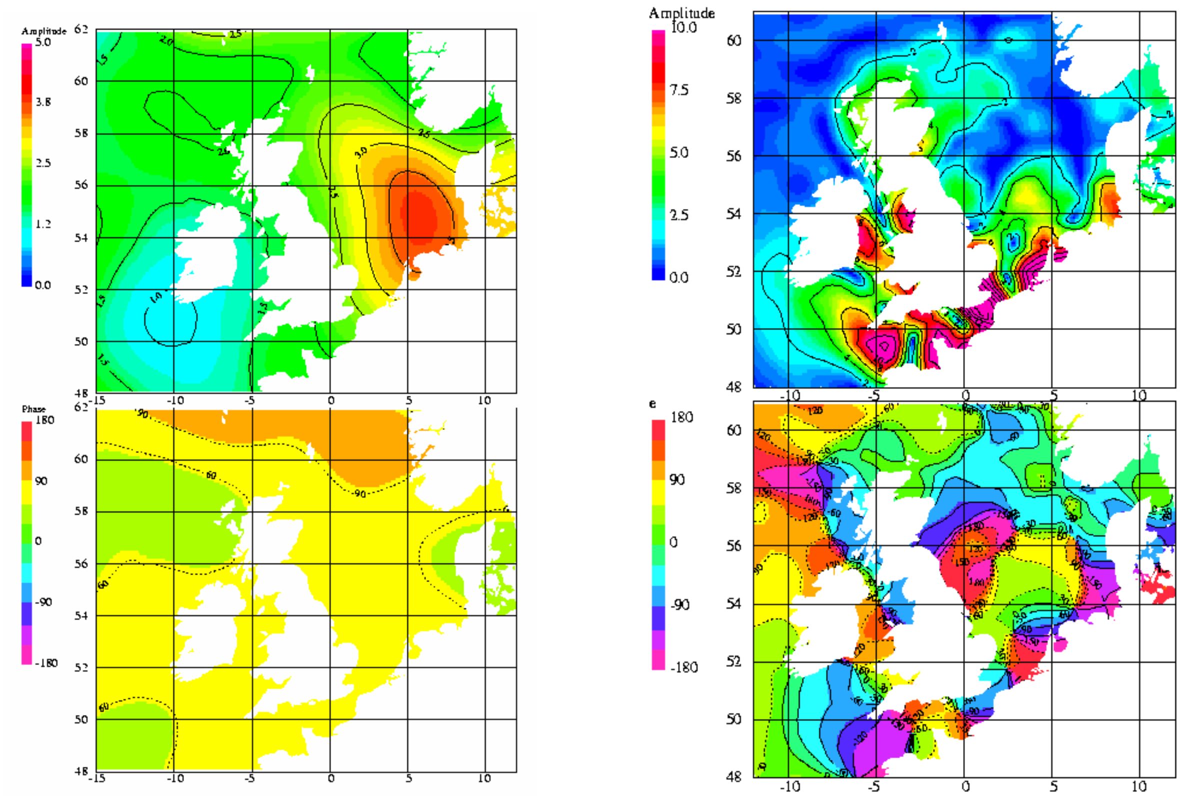

Figure 8: Left: The amplitude and phase of the annual modulation of the M2 ocean tide. Right: Amplitude and phase of the M4 shallow water tidal constituent.

B) Compute sea level from meteorological models and compare with sea level data

In order to obtain a cleaner signal, contributions from deterministic short period tidal movement and more random meteorological induced sea level variations, has been removed from the observed tide gauge time series by means of a hydrodynamical model. The resulting sea level maps can be directly be compared to altimeter data and an evaluation of the possible improvement of the remote sensed determination of the sea surface using the additional information from the hydrodynamical model (and there by meteorological effects) has been carried out (Huess, 2001).

Numerical model runs with the 2 dimensional hydrodynamic model, Mike 21 have been performed with the objectives to validate the simulated sea level variations, and to estimate the meteorological effect on the variations. The atmospheric forcing fields were generated from both a high resolution model (DMI-HIRLAM-E) and low resolution model (ECMWF). The sea level predicted by the model was validated against TOPEX/POSEIDON observations in 948 data points in the North Sea. The inter-validation gave rather encouraging results and more than half of the variability observed in the altimetry data, was captured by the model.

Furthermore, the model simulations have been used to estimate the atmospheric influence on the main tidal constituents. The most crucial difference between the two atmospheric forcing fields applied was the time resolution, as the 6 hourly values from the low resolution atmospheric forcing field implies the critical frequency to be at the frequency of the second largest tidal constituent S_2. However, no significant difference in the models ability to resolve the S_2 constituent were observed, and the low resolved ECMWF atmospheric field seems to resolve the atmospheric solar tidal contribution to the same degree as the high resolved HIRLAM field (figure 9).

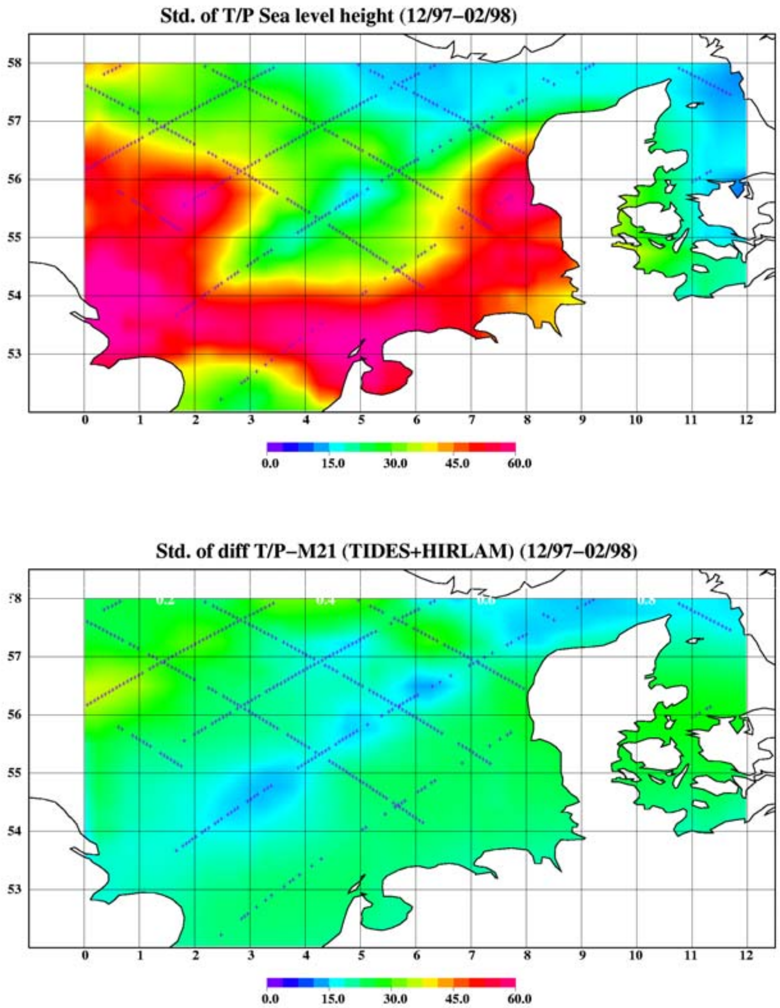

Figure 9: The standard deviation for the T/P observed sea level heights (top), and the sea level anomalies from the difference between the T/P observations and the model simulations (bottom). Both plots are calculated on basis of the 426 points in space and 5 points in the time domain.

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IV) Fusion of multi source remote sensing data

This part of the GEOSONAR project focus on the sea surface height variation that are caused by changes in the ocean water temperature and salinity. The purpose of these activities is to evaluate how the determination of the those height variations can be improved using other types of remote sensing data. Other Earth observing sensors onboard satellites have provided an enormous amount of information about the sea surface temperature and the ocean colour. The AVHRR and the ATSR instruments provide almost global coverage daily. SeaWiFS and MERIS collect information about the colour of the oceans. Also this type of information covers the ocean densely. Since global coverage of altimetry is only provided every 10 or 35 days, then the density of the sea surface temperature data as well as the ocean colour data are much higher.

A) Combine sea level data with sea surface temperature data

The ocean temperature is known to be significantly correlated with the sea level. Hence, the sea level information may be improved considerably, if the sea surface temperature data can be utilised together with the altimeter data. The ATSR sea surface temperature data are influenced by changes in the operational algorithms. Long term studies of changes are therefore problematic. At the mid.term evaluation of the project, we were advised to use the AVHRR data from the NOAA satellites as these have similar resolution and accuracy and better coverage than the ATSR data. Nearly all results are therefore based upon AVHRR data.

The correlations between the sea level and the sea surface temperature are analysed empirically. This is done in different regions of the North Atlantic and at different periods in order to take different physical mechanisms into account such as different vertical temperature profiles. Then the two data sources are integrated in an improved recovery of the sea level utilising the empirical correlations .The multi-temporal analysis in this context consists primarily of canonical correlations analysis (CCA). Two- or multi-set CCA can be used to find variates that show decreasing similarity over either time or spectral wavelength. This can be used to find structures that change little over time (maximum similarity variates) or structures that change much over time (minimum similarity variates).See Højerslev and Andersen, 2001, Leeuwenburgh and Stammer, 2001, Nielsen and Conradsen. 1997, Nielsen et al., 1998, Nielsen et al., 2002,Nielsen, et al. 2001, Nielsen, 2002, Nielsen, 2001.

Regional study in the Kattegat

On regional scales, variations in sea level on annual scales derived from satellites have been compared with observations from a unique 100-year hydrographic time series from the lightship Anholt Knob Syd (Figure 10). By using the AVHRR high-resolution sea surface temperature data from the NOAA satellites (1992-2000), and a simplistic model in which the vertical heat transport is assumed to be caused by turbulent diffusion steric changes in the sea level could be computed (figure 11). A subsequently compared with the steric height changes estimated from 100 years of data at the Weathership Anholt Syd, showed very high agreement. The variations from year to year like the warm summer in 1997 followed by a cold summer in 1998 was also revealed by the AVHRR data.

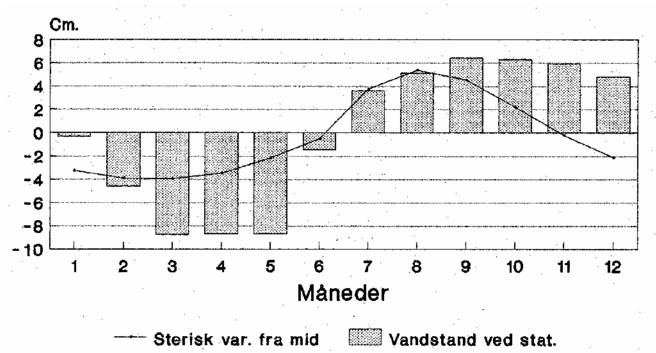

Figure 10: Computed steric effect at the lightship Anholt Syd averaged over 100 years, along with the actual sea level observations on a monthly base.

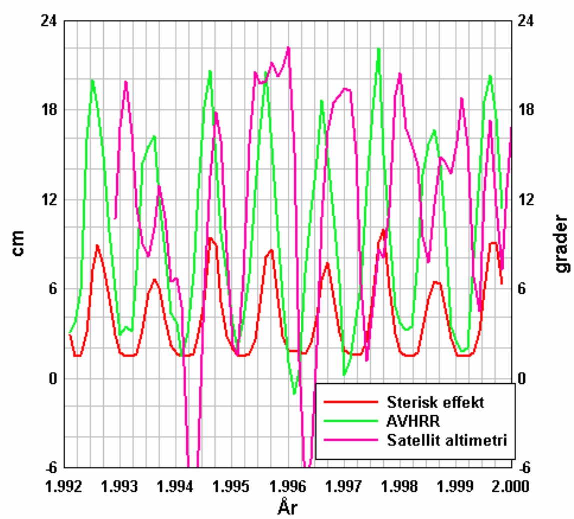

Figure 11: The observed sea surface temperature at the Lightship Anholt Syd from the high-resolution AVHRR satellite data in 7-days periods (purple). The computed steric effect is also shown (red), along with the actual sea level observations from satellite altimetry (green). Notice the ability to study the significant variations from year to year in both the sea surface temperature and the steric effect which this data enables.

Global large scale analysis of SSH and SST

Monthly values of sea surface temperature and sea surface height observations from 1996-1997 have been used in a linear canonical correlation analysis. The motivation for using a bivariate extension (instead of e.g. the univariate EOF analysis) stems from the fact that the two fields are interrelated as for example an increase in the SST will lead to an increase in the SSH. The large scale analysis clearly showed the build-up of one of the largest El Niño events on record. In addition, the analysis indicated a phase lag of approximately one month between the SST and SSH fields.

A nonlinear canonical correlation analysis (CCA) of EOF transformed data was performed by applying the alternating conditional expectations (ACE) algorithm. Both the linear CCA and the ACE analysis seemed to be able to extract relevant ocean configurations from the temporal data. ACE, however, looks for high correlations between the involved variables through nonlinear mappings, and finds components with higher correlations in comparison to those found by a linear analysis.

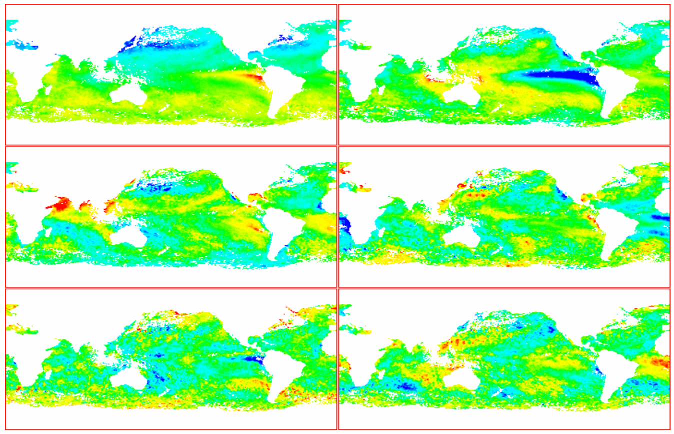

Figure 12: SST, linear canonical variates 1-6 row-wise.

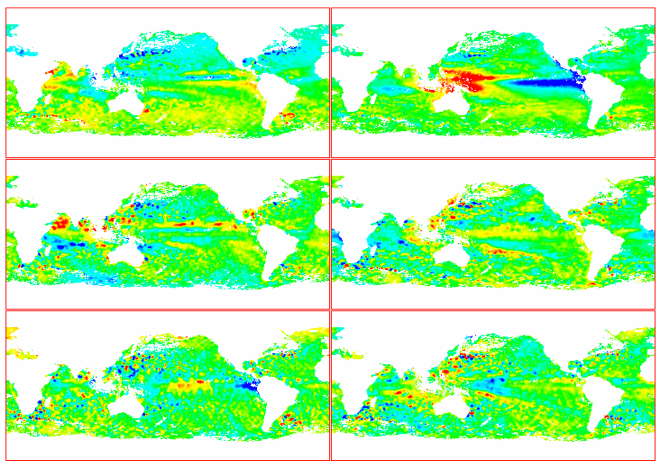

Figure 13: SSH, linear canonical variates 1-6 row-wise.

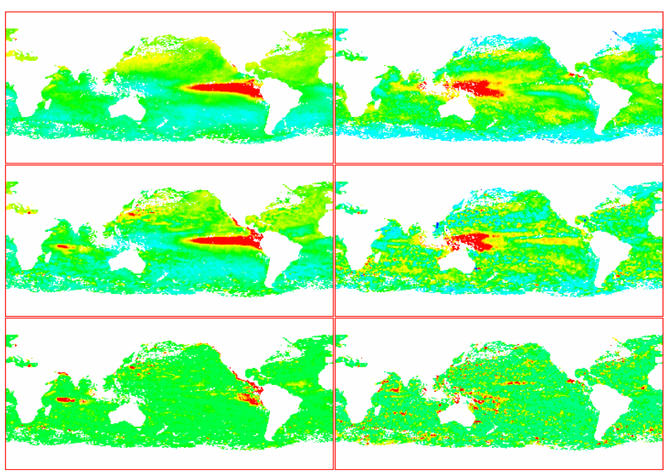

Figure 14: The columns contain the first respectively the second (nonlinear) ACE canonical variate (CV) pairs, and their squared differences. Each column (top-down): The ACE CV of the SST-EOFs, the ACE CV of the SSH-EOFs, The squared differences in the bottom panels shows the areas where the ACE algorithm is problematic due to the presence of small scale signals.

The linear and the nonlinear analyses are purely data-driven and thus constitute useful exploratory tools for a data analyst when looking for insight into the structure of data. Simultaneous inspection of spatial patterns of the canonical variates and the correlations between the original and transformed variables from the analysis gave good indications of an anomaly off the South American west coast taking place in the second half of 1997. This is in good agreement with established oceanographic knowledge on the build-up of one of the largest El Niño events on record.

Global meso-scale analysis

When sea surface temperatures and sea surface height observations are combined for studies at meso-scales, it is important to realize that the dominant scales of temperature variability are closer to those of the synoptic scales of the atmosphere than to the meso-scales of the ocean. To use information from the sea surface temperature in estimating the oceanic meso-scale sea level fields, it is therefore necessary to perform a scale decomposition.

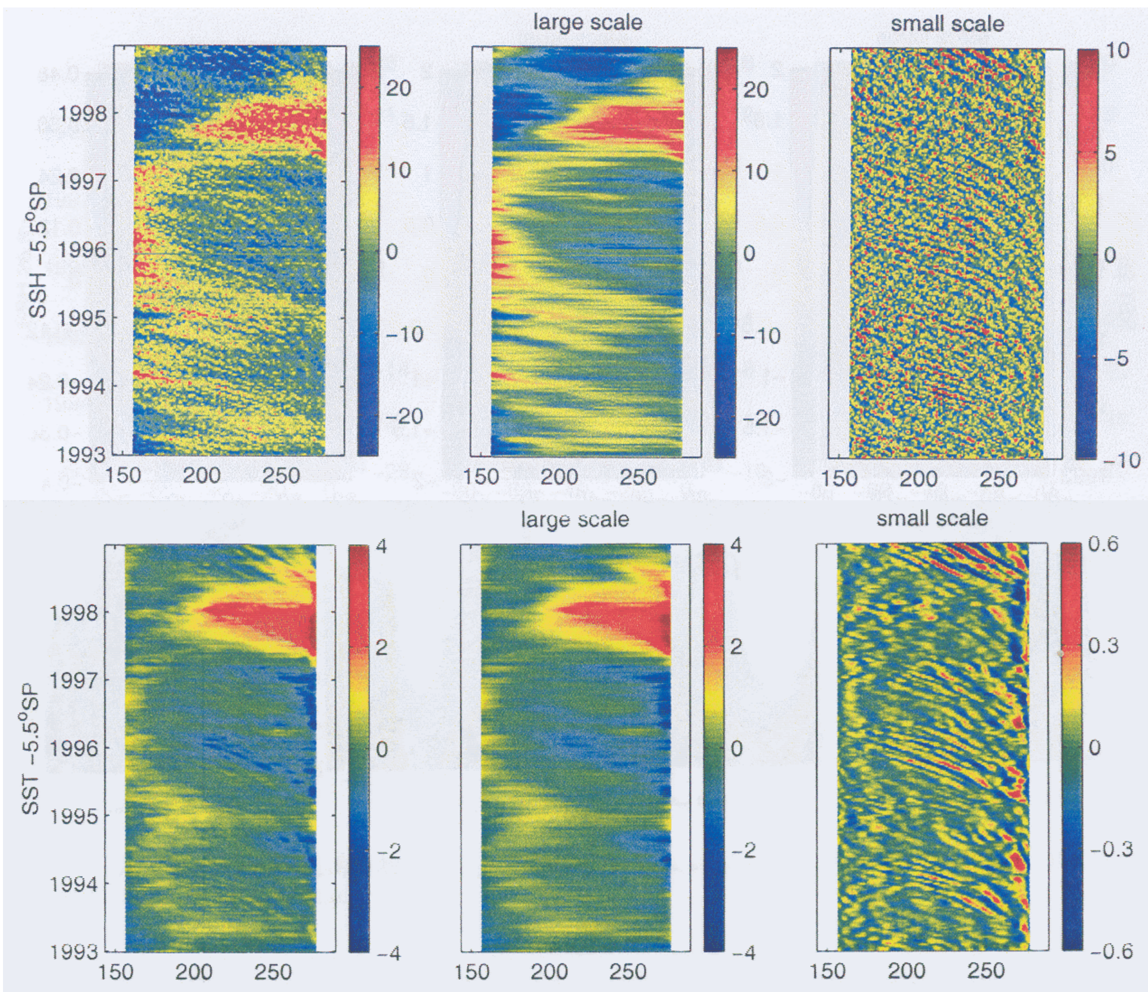

Figure 15: Time versus longitude plot of the SSH for a section at 5.5°S in the tropical Pacific (Leeuwenburgh 2000). The presence of propagating waves in both the small and large scales filtered SSH and SST data are seen.

The meso-scale decomposition was obtained by proper filtering and the time-longitude plots of temperature showed propagation tendencies similar to those in the sea level. Furthermore, a wavenumber-frequency analysis showed that spectral peaks in both temperature and sea level lie close to the dispersion curve for first mode baroclinic Rossby waves. The relationship is not one-to-one and other factors play a role in setting the surface temperature.

In experiments with a simple temperature model forced by ocean advection acting on a mean background temperature gradient suggested that strong damping mechanisms were at work. Correlations between sea level and temperature variability were thus strongly dependent on both location (ocean dynamical regime, latitude) and time (e.g. season).

B) Analysis of the multi channel data for empirical detection of ocean water types

From space the ocean surface is known to "look" different in different regions. By combining the visible channels, the blueish ocean water has been distinguished from the brownish water near populated land areas. Hence, the visible channels may be used to distinguish between light fresh surface run-off water and heavier saline ocean water. Data from the AVHRR and the SeaWiFS instruments has been analysed to characterize the different ocean water masses using the full multi channel data sets, i.e. both visible, near visible, and infra red.sea surface temperatures and other products such as concentrations of chlorophyl, coccolites, and yellow substance have provided very useful information about the ocean processes in the Danish Seas. Furthermore, to secure a full benefit of the results provided by the empirical fusion of the multi channel data from the AVHRR and the SeaWiFS satellite missions, an oceanographic interpretation of the empirical classification of water masses and processes has been carried out (Hilger, 2001, Hilger and Nielsen, 2002).

An empirical classification has been carried out on "weekly" (eight days) level 3 processed SeaWiFS data from 10 February to 29 September, 1999. The data have been transformed into signal maximum autocorrelation factors (SMAF), and classified into six classes using fuzzy *c*-means clustering (FCM) (see Figure 16).

The six classes are clearly seen to group pair-wise into three distinct phenomena: Class 1/2, shown in grayscale, represents the "undisturbed mean properties" of the area. Class 3/4, shown in blue and green, represents a seasonal phenomenon. This could be related to spring melting from central Europe followed by northern Europe/Scandinavia. Class 5/6, shown in red and yellow, represents another seasonal phenomenon, widespread throughout the area, although primarily near the coasts. These classes are most likely related to algal blooms.

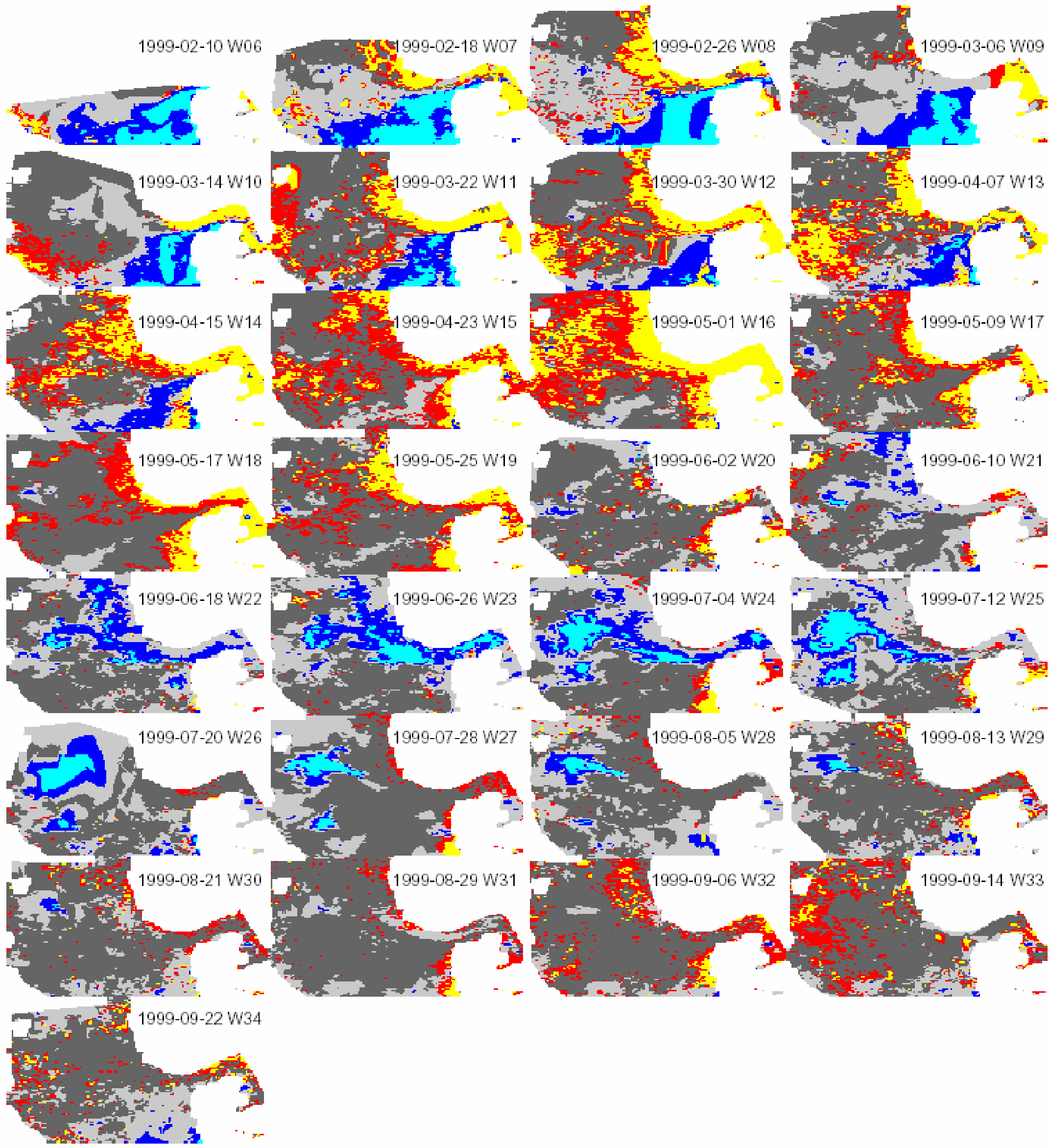

Figure 16: Classified water masses based on SeaWiFS constituents.

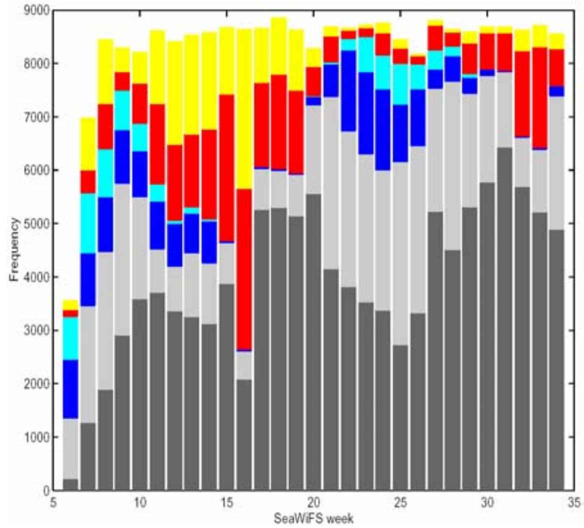

Figure 17: The temporal evolution of the different classes. Same class colouring as in Figure 16.

The temporal evolution of the classes is summarized in Figure 17, which shows the number of pixels assigned to each class for every week number. The seasonality outlined above is seen very clearly here.

C) Fusion of sea surface temperature and ocean colour data with sea level data

> *Globally, images of all channels are now available daily. An enormous amount of information about the ocean is provided by the satellites. It has been shown that by integrating sea level observations with sea surface temperature observations (ATSR, AVHRR) and in situ observations, a substantial improvement of the accuracy of the sea level in both the temporal and spatial domains. The multi channel data was furthermore analysed together with the sea level data in order to extract empirical correlations,and integrated in an improved recovery of the sea level utilising those empirical correlations. (Hilger, 2001, Hilger et al., 2001)*

Alternating Conditional Expectations Algorithm (ACE) have been used to obtain the highest correlation between sea level height, ocean surface temperature and ocean colour data from SeaWIFS during 1999. ACE was applied restricting the algorithm to unit variance on both the response (SSH) and the predictor set (SST and selected SeaWiFS products, like Chlorophyll). The analysis may help interpreting the correlated effects of the individual predictors on the response.

The area of investigation and three separate regions of interest of the North Sea are shown in Figure 18b. Red lines correspond to positions where ERS altimetric height observations are available dotted lines show where TOPEX altimetry is available. For each SeaWiFS week we interpolate the SeaWiFS and SST data to the location and time of the TOPEX observations.

The results from the western and the middle region in Figure 18b are described elsewhere. Here we will focus on the effects found in the Skagerrak region. When predicting the sea surface height from the SeaWiFS and the SST data a reduction in the residual variance of 39% is obtained by means of ACE based CCA.

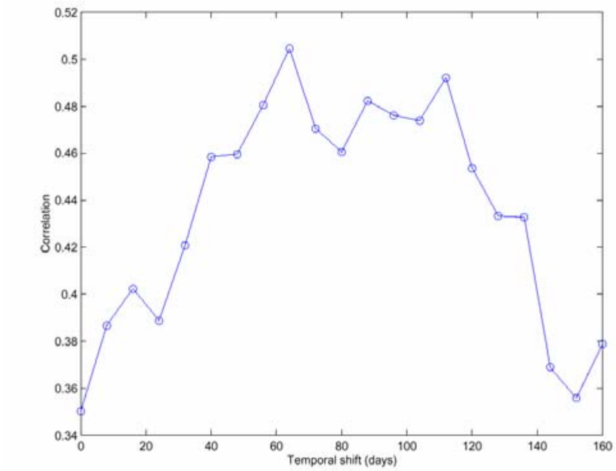

Figure 18a. Correlation of the SSH residual and the SST as a function of a temporal lag.

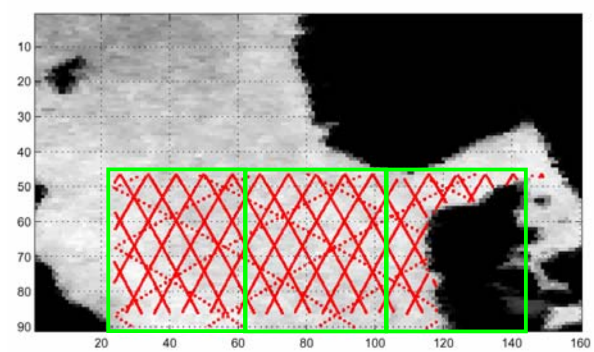

Figure 18b. ERS and TOPEX as red track tracks, and the regions of interest marked by green boxes. The grey levels are the integrated data coverage of the SeaWIFS data.

Moreover, if (noninvertible) nonlinear transformation of the SSH residual is introduced the residual variance reduction amounts to 50% (results not shown). This empirically established a non-linear relationship between changes in sea level height and sea surface temperature and the amount of biological substance.

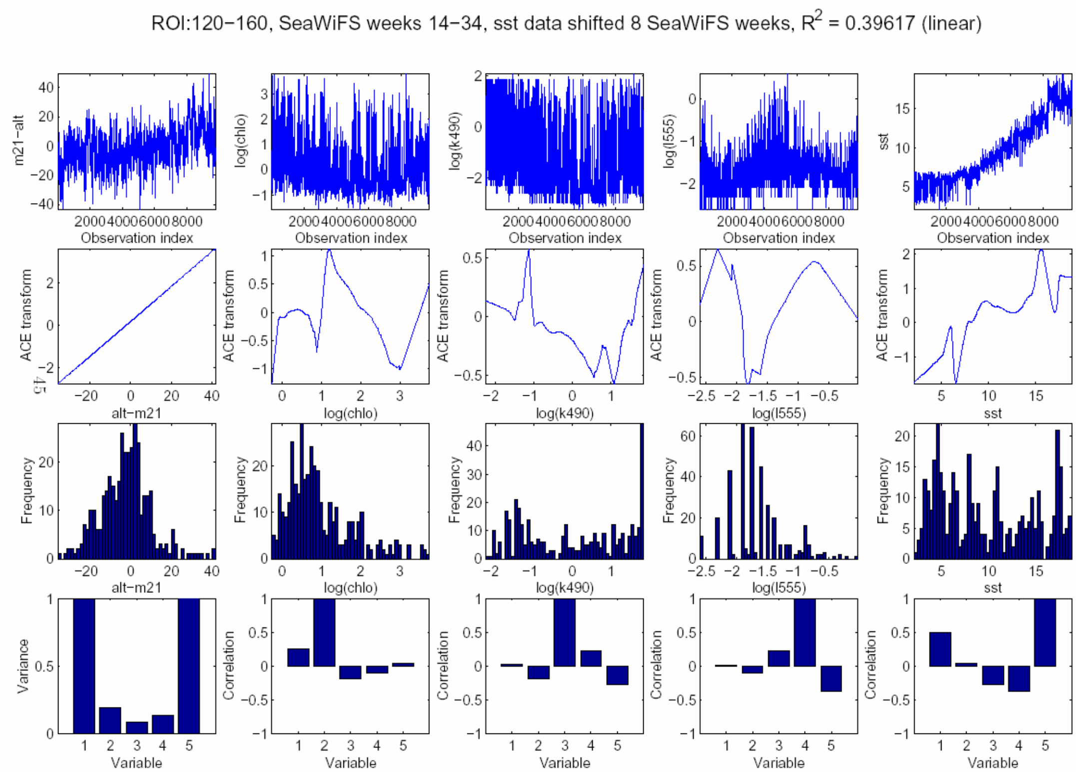

Figure 19. Column-wise the figures show: The sea surface height residuals (m21-alt) and the 4 variables used to model the sea surface changes; chlorophyll (CHLO) and channel K490 (proportional to the optical depth of sight), L555 (color green), and sea surface temperature (SST). Row-wise the figures show: the variables versus the observation index, the estimated ACE transformation, the frequency of the observed measurements (illustrates where data are important for the sea surface height modelling), and the covariance between the variables involved.

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V) Modelling the ocean circulation and processes

This part of the GEOSONAR project focuses on the evaluation of oceanographic processes using satellite altimetry combined with other types of remote sensing. Synergetic use of satellite altimetry and other types of remote sensing may improve the analysis of the ocean dynamics and the analysis of Global Change. The increased information may reveal interesting properties related to the internal structure of the ocean as well as internal ocean processes.

A) Analysis of the deep overflow in the North Atlantic region

> *The variability of the thermohaline circulation and the impact on global climate on decadal to millennial time scales have been debated since decades. The dense overflows across the Greenland-Scotland Ridge, through the Faroe Bank Channel and the Denmark Strait, are part of this circulation. Changes in the strength of the total overflow will have a large impact on European climate and monitoring the overflows is therefore important from a climatic perspective. (Høyer, 2002, Høyer and Quadfasel, 2001, Høyer et al., 2002, Høyer et al., 2001)*

Regional studies in the North Atlantic showed that the overflows across the Greenland-Scotland ridge of dense bottom water through the Faroe Bank Channel and the Denmark Strait can be detected with satellite observations. In situ observations of temperature and currents reveal large fluctuations in the overflow plumes downstream of the sill, with a maximum located about 30 km from the sills. These fluctuations are associated with meso scale eddies and give rise to sea surface height changes due changes in vertically integrated density and hence steric heights. In agreement with in the situ observations, the TOPEX/POSEIDON and ERS satellites detect enhanced sea surface height variability (2-5 cm) and eddy kinetic energy (75-300 cm2/s2) with maxima immediately downstream of the sills. Figure 20 shows an example of the satellite derived eddy kinetic energy from the Denmark Strait. The overflows can be detected during all seasons and during all years and there is thus a potential that the satellites can be used to monitor changes in the thermohaline circulation.

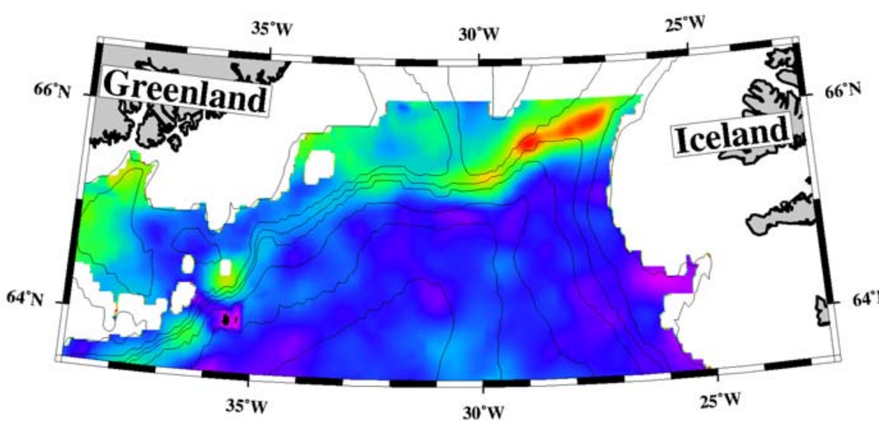


Figure 20: The figure shows the eddy kinetic energy in the Denmark Strait region in colors and bathymetry contoured. The eddy kinetic energy is derived from TOPEX/POSEIDON altimetry observations of sea surface height and the enhanced variability is associated with fluctuations in the Denmark Strait overflow.

B) Mixed layer deepening estimated from satellite observations

The mixed layer in the ocean is the layer that communicates with the atmosphere in terms of air-sea heat exchange. Due to the large heat capacity of water, the mixed layer is a reservoir of heat with a thermal inertia that far exceeds the thermal inertia of the atmosphere. As the thickness of the mixed layer determines the size of this reservoir, mixed layer depths are crucial parameters in the ocean-atmosphere interactions. (Høyer, 2002)

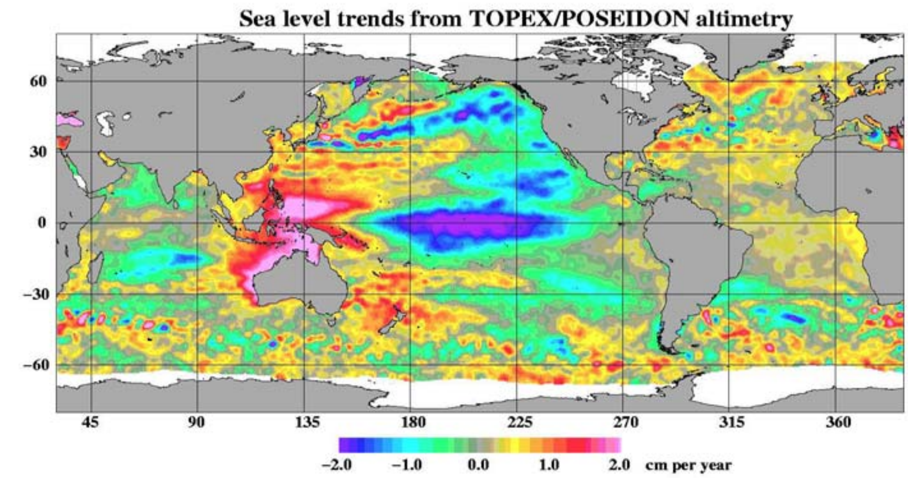
The high accuracy of satellite observed sea surface height (SSH) and sea surface temperature (SST) provide an opportunity to estimate the winter mixed layer depths using only these two types of satellite observations. In the project we have also used in situ observations from the Ocean Weather Ship Mike and from the repeated XBT line AX03 in the North Atlantic. These observations were used to assess the performance of the model and to determine the validity of the assumptions involved in the conversion of SSH and SST changes into a mixed layer deepening. It was shown that it was possible to estimate the late winter mixed layer depths within 50 meters in the eastern part of the North Atlantic subtropical gyre. A thorough error analysis was carried out with the in situ observations. The largest errors arise from the assumption that seasonal SSH changes correspond to changes in the local heat content. These errors dominate in regions with swift currents such as the Gulf Stream Extension. The method can be applied to other regions in the North Atlantic with weak currents such as the Irminger Sea. However, the general limitation of this method is that the spatial averaging scales needed for the SSH tend to be larger than the spatial scale of mixed layer depth variations.

C) Sea level changes and Global Change

The satellites provide a unique opportunity of monitoring both changes in sea level and sea surface temperature as the ERS satellites are equipped with an altimeter to measure sea level height as well as an Along Track Scanning Radiometer to measure the sea surface temperature (SST). High quality observations are carried out with these satellites on both global and regional scales due to the combination of regular sampling and high spatial coverage compared with observations from either ship or tide gauges. Data from the two European Space Agency satellites ERS 1 and ERS 2 are used to evaluate regional changes in sea surface temperature and sea level of the oceans over an eight-year period ranging from September 1992 to September 2000. Subsequently the results have been compared with similar sea level observations from the TOPEX/POSEIDON satellite and sea surface temperature observations from the NOAA AVHRR data. (Andersen and Knudsen, 2001, Andersen and Knudsen, 2001, Andersen and Knudsen, 2001, Andersen et al., 2002, Knudsen and Andersen, 1997).

Consistent increase in both sea level and sea surface temperatures are found in most parts of the Atlantic Ocean over this period. In the Indian Ocean and particularly the Pacific Ocean the trends in both sea level and temperature are still dominated by the large changes associated with the El Ninõ Southern Oscillation (ENSO).

The regional changes detected by ERS sea level and sea surface temperature observations are highly correlated with independent finding from TOPEX/POSEIDON sea level observations and the ATSR sea surface temperature observations.



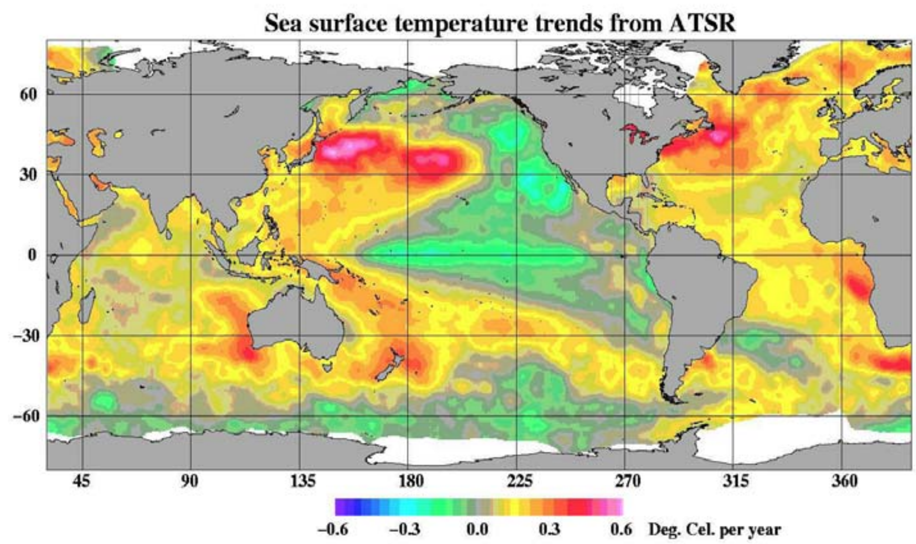


Figure 21: Global sea level and sea surface temperature eight-year trends estimated from TOPEX/POSEIDON altimetry and ATSR (ERS 1+2).

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VI) Supporting Activities

A) Fix reference heights of tide gauge stations around the Danish coast using GPS

The heights of the tide gauge stations are usually measured in a local datum with respect to the geoid. In order to compare the tide gauge data consistently with satellite altimetry, the heights of the stations need be measured with respect to a global geodetic reference ellipsoid. This was done very accurately using the Global Positioning System (GPS) during two campaigns in 1998 and 1999. The heights of the permanent tide gauge stations around the Danish coast was fixed to an absolute in-situ reference frame (Weber, 1998).

B) Determination of optical parameters

A Secchi depth data mining study has been carried out for the North Sea – Baltic Sea region to be able to better interpret the SeaWIFS satellite observations. 40,829 measurements of Secchi depth were compiled from the area as a result of this study. The earliest Secchi depth measurement retrieved in this study dates back to 1902 for the Baltic Sea, while the bulk of the measurements were gathered after 1970. The spatial distribution of Secchi depth measurements in the North Sea is very uneven with surprisingly large sampling gaps in the Western North Sea. Average Secchi depth and standard deviation for a 0.5°×0.5° box grid have been calculated for the transition area between the North Sea and the Baltic Sea (4°E-16°E, 53°N-60°N) (see figure 22). (Aarup, 2002)

The so-called K algorithm allows the penetration depth to be calculated. A"Global" K-algorithm has been established in 1986 and earlier by N. Hoejerslev and it is to be implement in a so-called Global Climatology made by the American Ocean Naval Research according to my informations. The K-algorithm was validated by means of spectral optical data from the North Sea and the Kattegat-Skagerrak. (Højerslev, 2001, Aas and Højerslev, 1999).

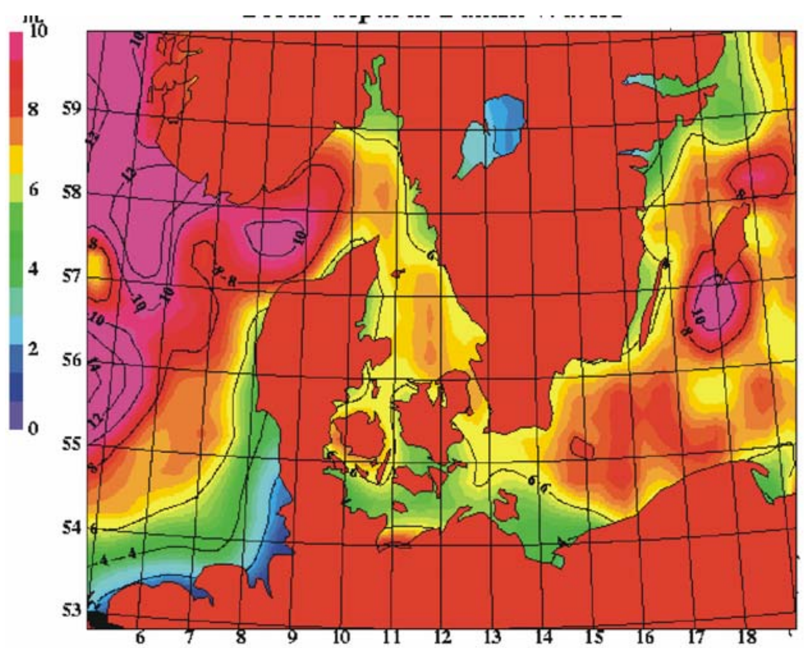

Figure 22: Optical depths calculated from Secchi discs in the Danish waters

C) Cloud detection in SeaWiFS multi channel data

New methods for enhancing ocean-related signal from the multivariate SeaWiFS images have been developed. Clouds often corrupt the images and the influence must be minimized before decomposing the signal into new variables that maximize different spectral or spectral-spatial criteria. The signals related to different sources are first identified by unsupervised clustering, thereby obtaining the undesired cloud spectra. Minimizing the influence of the cloud signal leads to a projection of the data onto a subspace orthogonal to the undesired spectra. An example is shown in Figure 23. Temporal studies have been applied to validate the proposed technique. Despite the difference in cloud cover, new variables are obtained that contain enhanced ocean signal clearly correlated over time. Hilger and Nielsen, 1999, Hilger and Nielsen, 2000, Hilger et al., 1999)

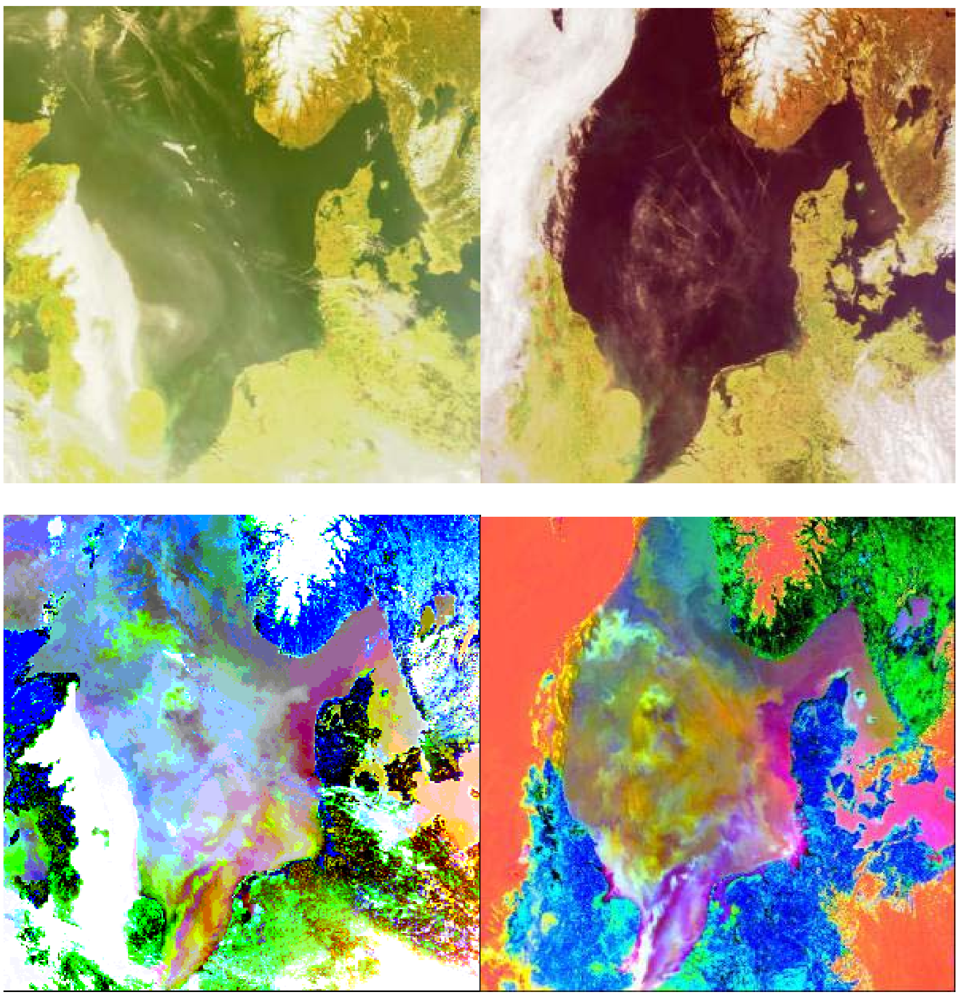

Figure 23. An example of how the ocean water variability can be enhanced by unsupervised clustering. The upper figures show two SeaWIFS RBG images (band 5,4, 1) from day 133 (left) and 135 (right) in 1998. The lower figure shows the results after the effects from clouds have been removed.

D) GIS for data management

To handle and process the Seawifs images and time series, the spatio-temporal map algebra and the data selection routine was fine tuned in the Busstop GIS program. Work was also put into improving the spatio-temporal gridding with focus on establishing of an internal data organization that allows highly efficient selection of point data in the vicinity of each grid node. It was evident that the existing but somewhat rudimentary visualization facility of the Busstop spatio-temporal GIS seemed very fit for our purposes. (Knudsen, 1999, Knudsen and Olesen, 1998, Knudsen, 1998, Knudsen, 1998)

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Value for money

The GEOSONAR project has contributed to the national scientific work in the fields of remote sensing and earth observation. Hereby, the project has taken an active role in increasing the level of knowledge and know-how in Denmark, so that Denmark can benefit from new satellite technologies and stay competitive internationally. Furthermore, the project has contributed to a better understanding of the marine environment supporting a sustainable development.

The project has established a platform for inter-disciplinary work in Denmark in the fields of remote sensing and marine environment. By supporting developments towards a more efficient hydrographic surveying and a more precise storm surge warning systems the project has contributed to an increased safety in navigation, rescue missions, and ship traffic.

The project has contributed to the international scientific work and the Danish position in the international scientific community and secured the important transfer of knowledge to Denmark. The project has contributed to international science working team and supports international space programmes.

Finally, the project has taken an active part in the education of young scientists by supporting the Ph.D. programme and the results have been reported in more than 50 international peer-reviewed publications.

Spin-off effects at involved institutions

The research has increased the general knowledge about remote sensing methodology that is of great value for the involved institutions. The universities have gained more Ph.D. students to support their education of other students. At the institutions the increased knowledge has a positive effect on the sectorial research within other fields of public administration and service. At KMS the increased knowledge about remote sensing and digital image analysis is being utilised in developments of the topographic mapping techniques. At DMI the increased knowledge about sea level variations is being utilised in the developments of a new storm surge warning system. At FRV the increased knowledge about sea level is to be used in the developments of the hydrographic surveying.

The collaboration in the GEOSONAR project has increased the knowledge of the scientific capabilities at the involved institutions. Hereby, the basis for other fields of collaboration has been formed, i.e. in the above-mentioned fields and developments.

Personel and education

The project was carried out with participation from

- Geofysisk Afdeling, NBIfAFG, Københavns Universitet
- Institut for Matematisk Modellering, Danmarks Tekniske Universitet
- Danmarks Meteorologiske Institut
- Kort & Matrikelstyrelsen

Five Ph.ds have been employed and graduated through the GEOSONAR project:

- Guilhem Moreaux, graduated January 2000, title of Ph.D. thesis: *Gravity field and implementations of methods for global gravity field determination from dedicated gravity field satellites*.
- Olwijn Leeuwenburgh graduated July 2000, title of Ph.D. thesis: *Combined analysis of sea surface height and temperature for mapping and climate studies*
- Vibeke Huess graduated October 2000, title of Ph.D. thesis: *Sea level variations in the North Sea – from tide gauges, altimetry and modelling*.
- Klaus B. Hilger graduated December 2001, Title of Ph.D. thesis: *Exploratory Analysis of Multivariate Data (Unsupervised Image Segmentation and Data Driven Linear and Nonlinear Decomposition)*.
- Jacob L. Høyer graduated June 2002, title of Ph.D. thesis: *On the Combination of Satellite and In Situ Observations to Detect Oceanic Processes.*

In addition, two post. docs have been involved in this project:

- Thorkild Aarup was employed from 01/1998 to 12/1998 working mainly on collecting and processing of secchi depths data
- Thomas Knudsen was employed by the project from 01/1998 to 09/1998, working mainly on processing the Seawifs data and on development of the spatio-temporal GIS program “Busstop”.

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