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Synthesis of the STOWASUS-2100 project: Regional storm, wave and surge scenarios for the 2100 century

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Content:

SYNTHESIS OF THE STOWASUS-2100 PROJECT

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1. Introduction and scientific background

In addition to the direct impact on man made constructions and nature on land, severe extra-tropical storms constitute the basic physical process to force devastating ocean waves and surges. Over the past 10-20 years or so there has been an increasing public as well as scientific concern, that storm activity was increasing along the North Western European area and that this change was related to global warming. Due to its large impact any changes in the mean or fluctuations of the storm activity in the North East Atlantic (NEA) region could well be the most important manifestation of climate change and variation in the European region. This has motivated a number of European projects dealing with observed trends/variations and future scenarios of extra-tropical storms and their impacts. The project of most immediate relevance was the WASA project (see WASA, 1998). The overall objective of STOWASUS-2100 was to study severe storms, surges and waves in the present climate and in a scenario with increased greenhouse gas concentrations. More specifically, the project has been a joint atmospheric / oceanographic numerical modelling effort aiming at constructing, analysing and understanding the potential change in storm, wave and surge climatologies for the North Atlantic/European region in a climate forced by increasing amounts of greenhouse gases.

1.1 Mechanisms

It is highly uncertain what the changes in severe storms in a warmer climate - if any - will be. Changes in the atmospheric long term mean flow are related to changes in extra-tropical storm activity as discussed in Kaas and Andersen (2000). Thus the development of a given extra-tropical depression is influenced by the following changes in the atmospheric background flow characteristics:

- Decreased horizontal temperature gradients in the lower troposphere. Most global coupled atmosphere - ocean climate models (O-A-GCMs) simulate the strongest warming over the far Northern regions in winter (DJF). This is illustrated in Fig. 1.1 which shows the typical warming pattern in the global high resolution simulations used in STOWASUS-2100. The polar near surface warming is associated with a reduction of the north-south temperature gradient, i.e. the baroclinicity in the lower part of the troposphere. From an isolated point of view this change should lead to a *reduced* intensity of extra-tropical storm activity, according to theory of baroclinic instability (Holton, 1992) as argued by Branscome and Gutowski (1992) and Hall et al. (1994).
- Increased baroclinicity in the upper troposphere. While the baroclinicity in the lower part of the troposphere decreases, an increase is simulated aloft, since temperatures in the tropical regions increase more than the corresponding temperatures near the poles where they actually decrease at high altitudes, as can be seen from the lower panel of Fig. 1.1. This change in background flow is - again from an isolated point of view - associated with an *increase* in extra tropical storm activity.

- Increased amounts of moisture available for condensation. The content of water vapour in the lower part of the atmosphere is generally increased as temperature increases, and this is also the case in global warming scenarios with climate models. Latent heat released in connection with condensation in extra-tropical low pressure systems will lead to increased conversion rates of potential to kinetic energy and thereby to faster development rates relative to what would happen in a dry atmosphere (e.g. Kuo and Donall, 1990; Kuo and Low-Nam, 1991; Gutowski et al., 1992; Langland et al. 1996). Therefore, one can expect increased amounts of water vapour available for condensation to result in *more intensive* extra tropical storms. Moreover, this effect may tend to influence small-scale phenomena more than the large-scale ones, Sardia and Warner (1983).
- Decreasing static stability. Fig. 1.1 also shows another feature which seems general to many climate models: an increasing lapse rate to the north of approximately 50N. This means that the static stability decreases at high northern latitudes when the concentrations of greenhouse gases are increased. An increased lapse rate impacts the process of baroclinic instability, since the horizontal scale of those atmospheric waves which are most unstable (i.e. growing most rapidly) is decreased and at the same time these smaller scale weather systems grow faster (see. e.g. Holton, 1992). Thus the isolated effect of the simulated decrease in static stability is a shift towards *smaller scale* and *more intensive* low pressure systems at high latitudes.

One may be tempted implicitly to assume that changes in

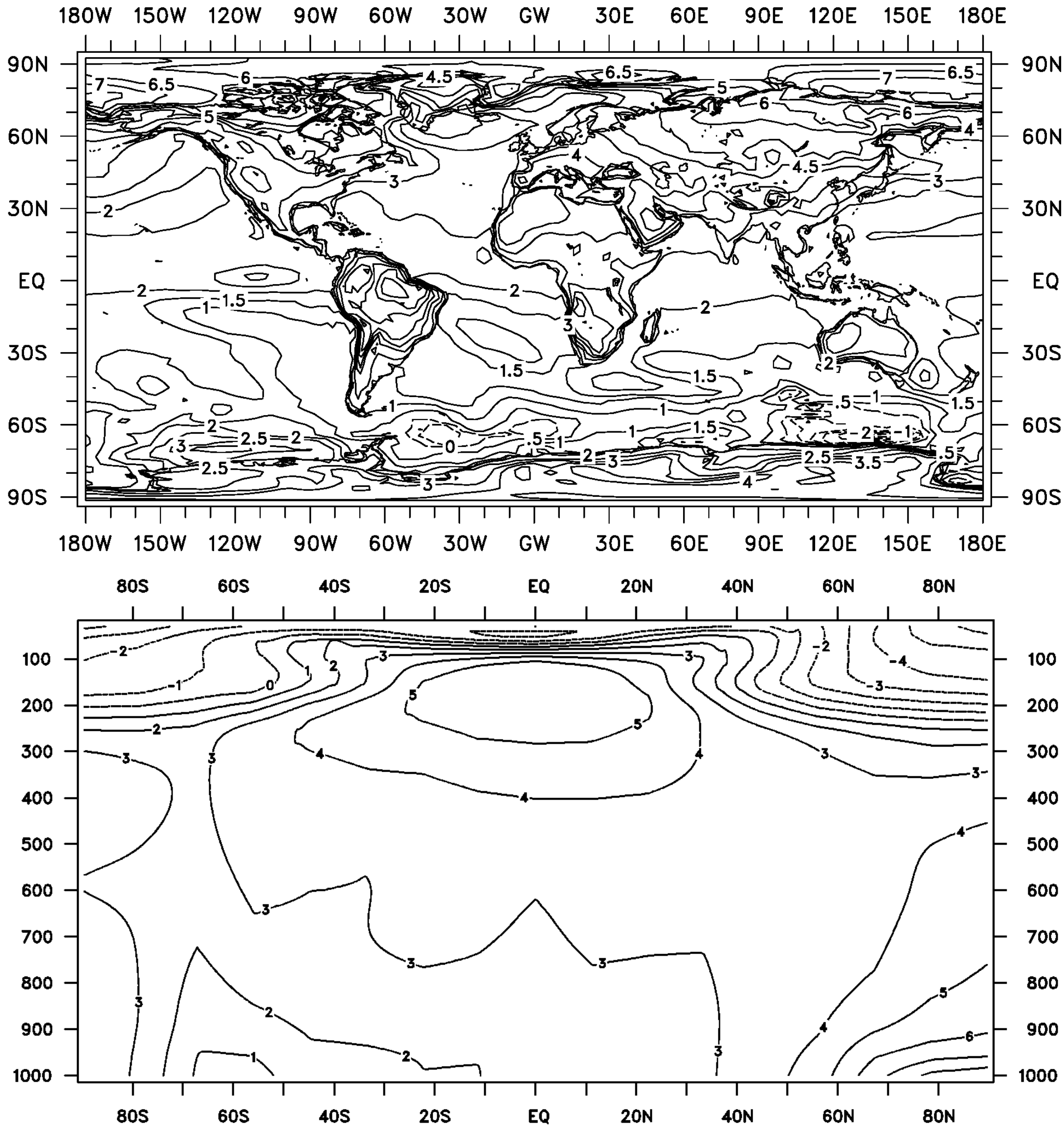


Figure 1.1. Simulated change in annual mean temperature (°C) at 2m level (top) and the corresponding zonal mean temperature change in DJF (bottom) as function of pressure (hPa) and latitude. Adopted from May (1999).

atmospheric long term background conditions is the main *cause* of changes in extra-tropical storm activity. This point of view is quite wrong as it can be argued that the background flow (and its change) is a consequence just as much as a cause of the existence of the actual extra-tropical storm activity and the associated eddy heat and momentum transports. A complete description of the problem must therefore consider the mutual balance between the equator-to-pole heating gradient, the poleward eddy heat flux, and the eddy momentum flux convergence (and associated indirect circulations) which all determine the meridional temperature gradient and thus the strength of the eddies (e.g. Lindzen and Farrell, 1980; Hoskins and Valdes, 1990; Zhang and Wang, 1997; Hall et al., 1994).

Arguing along similar lines (e.g. Branscome and Gutowski, 1992; Held, 1993; Zhang and Wang, 1997) it is important to note that water vapour - in addition to the enhancing effect - also plays a very important indirect role which tends to weaken the extra-tropical storm activity. This is because an increasing tropical/extra-tropical humidity gradient (associated with the Clausius-Clapeyron relationship) will make the cyclones more efficient in meridional vapour transport. Thereby the number and possibly the intensity of cyclones that are needed to maintain a certain heat transport is reduced.

In the above item list of background flow changes the first is associated with decreased extra tropical storm activity while the last three are favourable for increased activity. Theoretical considerations, diagnostic budget calculations and idealised model experiments can help to judge and understand their relative importance. Concerning the different change in meridional temperature gradient at low and high altitudes (item 1 and 2) it has been suggested by Held and O'Brien (1992), using an idealised quasi-geostrophic model, that eddy heat flux is more sensitive to lower level than to upper level mean temperature gradient. The implication could be a net decrease in storm activity regarding these two items as is also indicated in the results by e.g. Branscome and Gutowski (1992).

The above considerations are quite general and relevant to the overall level of extra tropical storm activity. From a regional impact perspective, however, climatic changes in the position and strength of the quasi-stationary planetary waves are likely to be more relevant, although it must still be kept in mind that causality is complicated as these large scale waves interact with the smaller scale transient eddies (i.e. the storms). It is thus well known that the large scale flow anomalies - as the so called North Atlantic Oscillation (NAO) - interact and is mutually dependent on organised variations in the small scale high frequency eddies, i.e. storm tracks (e.g. Nakamura et al., 1997, and references therein).

There has been a number of empirical studies (e.g., Hurrell and van Loon, 1997; Rogers, 1997; Kaas and Schmith, 1996; Schmith et al., 1998) identifying these physical relationships. These findings indicate that climatic changes in the storm activity closely will go along with corresponding changes in, e.g., the NAO and in its larger scale counterpart, the Arctic Oscillation (AO).

It is difficult to judge which basic mechanisms may lead to greenhouse gas forced changes in the AO, but it has been suggested by Shindell et al. (1999), that radiatively forced changes in the stratosphere may change the characteristics of the dynamic wave interactions between the stratosphere and the troposphere in such a way as to strengthen the AO, i.e. decrease/increase the surface pressure in the arctic/subtropical areas. Another possible mechanism leading to increased AO is a thinning/melting of the arctic sea ice. From the atmospheric point of view this will act as a large lower boundary heating anomaly. Such a heating anomaly tends to decrease the surface pressure via mechanisms equivalent to those in monsoons circulations. An enhanced release of latent heat at high latitudes associated with enhanced high latitude winter precipitation simulated by most modern GCMs (IPCC, 2001) also constitute a major anomalous regional heat source which may in part explain the increase in AO which is also simulated by most models

The observations show a moderate upward trend in the storm activity in the NE Atlantic during the last 30 years or so (see e.g. WASA (1998). It is as of now unclear whether this change and the associated increase in the NAO and AO indices is exited by increasing greenhouse gas concentrations, but it is at least consistent with many (but not all) of the climate model scenario simulations including the one used in STOWASUS-2100 (see Fig. 1.2.).

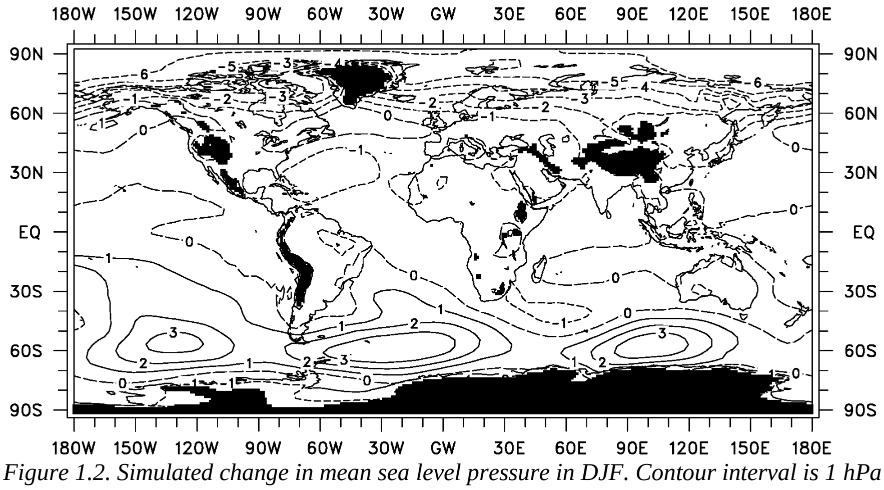


Figure 1.2. Simulated change in mean sea level pressure in DJF. Contour interval is 1 hPa with negative contours dashed. Adopted from May (1999).

1.2 The backbone of STOWASUS-2100

The above discussion clearly shows that an estimate of possible changes in extra-tropical storm activity in a warmer climate is far from simple. It is generally accepted that coupled atmosphere-ocean climate models constitute the best tools available for estimating this change, because, in principle, they do include the basic non-linear feedback mechanisms of which some important examples are mentioned above. It is of relevance to consider models with high spatial resolution because many of the fundamental processes – particularly for extreme developments – take place on relatively small horizontal scale.

Based on these considerations the backbone in STOWASUS-2100 was chosen as two so called time slice simulations with the ECHAM4 atmospheric climate model at T106 (i.e. 100 -150 km) horizontal. This resolution is the highest achievable with present day computers. These simulations (May, 1999; May, 2001; May and Roeckner, 2001) were carried out at DMI as a co-operation between DMI and the Max Planck Institute for Meteorology (MPI). They consist of one 30 year "present day" (*PRD*) period, nominally 1970-1999, and one 30 year greenhouse gas scenario period (*GHG*) period, nominally 2060-2089. The simulations were both forced by greenhouse gas concentrations according to the IPCC IS92a scenario (Houghton,1996) emission scenario. Only the forcing due to greenhouse gases were imposed, i.e. there was no anomalous aerosol forcing due to e.g. sulphate emissions. It should be noted, however, that the radiative forcing in the *GHG* period relative to the *PRD* period is quite similar to the forcing one obtains in the newest IPCC SRES scenario “A2” (IPCC, 2000) when the estimated direct and indirect aerosol forcing are taken into account. This is basically because the net change in sulphate emission in the new SRES scenarios is small. The ECHAM4 T106 version was provided with sea surface temperatures and sea ice conditions from a previous so-called transient simulation made at MPI with the coupled ECHAM4/OPYC3 atmosphere - ocean – sea ice model at medium (T42) horizontal resolution. The experimental design of the time slice simulations is described in more detail in May (1999), May (2001), May and Roeckner (2001). The underlying T42 simulation is described in Roeckner et al. (1998). The general structure of the simulated climate change in the North Atlantic region – including the change in NAO/AO and storm tracks – is fairly similar in the coupled T42 simulation and in the atmospheric T106 time slice simulation (see Andersen et al. 2001).

1.3 The working tasks

The basic T106 time slice data were used in STOWASUS-2100 as boundary conditions to drive different configurations of regional atmospheric climate models and regional surge and wave oceanic models. The regional simulations were needed to construct the scenarios relevant for the European coastal regions and for analysing the changes. For ocean waves a “conditioned statistical wave generator” was developed and tested with the purpose of cost effective scenario calculations for e.g. construction planning.

The investigations in STOWASUS-2100 have been distributed in a total of 12 “tasks”:

1. Statistical analysis of T106 data
2. Baroclinic developments
3. Polar lows
4. Mediterranean systems
5. Surge statistics based on 30 year T106 time slices: North-western European shelf seas
6. Surge statistics based on 30 year T106 time slices: The Adriatic Sea
7. Downscaling of surge statistics to estimate local variations
8. Influence of resolution of atmospheric forcing on surge statistics: North-western European shelf seas
9. Case studies: The Adriatic Sea
10. Wave simulation in The Mediterranean
11. The northern seas
12. Ocean wave generator

Tasks 1-3 deal with changes in the atmospheric conditions (i.e. the change in simulated extra-tropical storms, polar lows and convective Mediterranean systems), tasks 4-9 with surges in North Sea, The Norwegian Sea and the Adriatic Sea and tasks 10-12 with waves.

The following 12 sections of this synthesis report describes the main findings for each task while the general conclusions are summarised in section 14.

It should be mentioned that the deliverables produced so far within the project are listed in the appendix.

2. Statistical analysis of T106 data (Task 1)

The statistical analysis (Andersen et al., 2001) of the T106 data was done for the boreal winter (November to March) climate in the northern part of the North Atlantic and in Europe. The boreal winter was chosen as this is the time of most frequent and intense mid-latitude storms in the Northern Atlantic.

In the *GHG* run the sea level pressure is gradually reduced relative to the *PRD* run from around 55N latitude and northward reaching a 6 hPa reduction at the northern boundary of the region (Fig. 2.1b). This enhances the meridional pressure gradient north of 60N.

The storm activity was calculated as the short term (2.5 -6 days) standard deviation of the 500 hPa geopotential height (Blackmon, 1976). In the *GHG* run there is a decrease of this quantity over Newfoundland and the Atlantic Ocean south of 50N, and increased values over Northern Europe (Fig. 2.2b), especially over the North Sea and Britain and north of the Black Sea, where values are increased with 6 m. These changes can be viewed as a downstream (i.e. north-east) displacement of the storm track. The simulated changes are consistent with the changes in the sea level pressure with an increase in the pressure gradient over Scandinavia and the

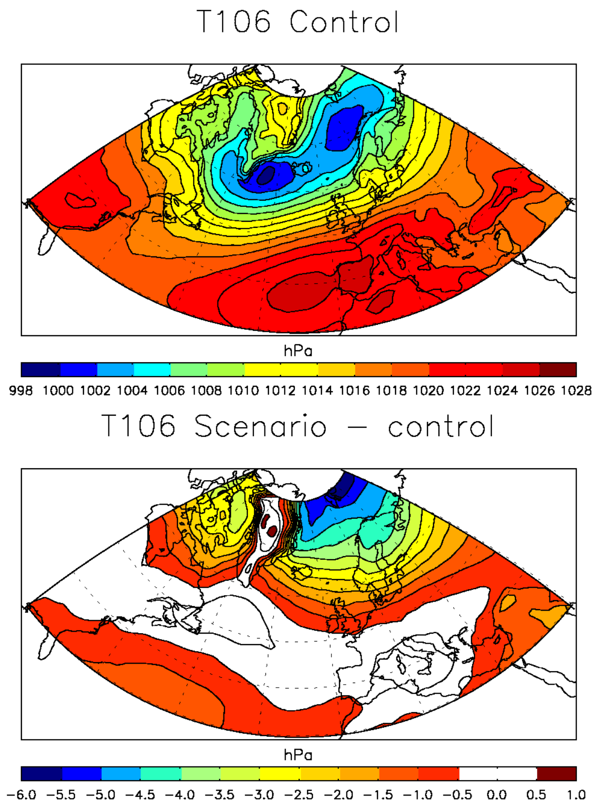


Fig. 2.1. The winter (NDJFM) mean value of the sea level pressure from a) the control run, b) the difference between the scenario and the control.

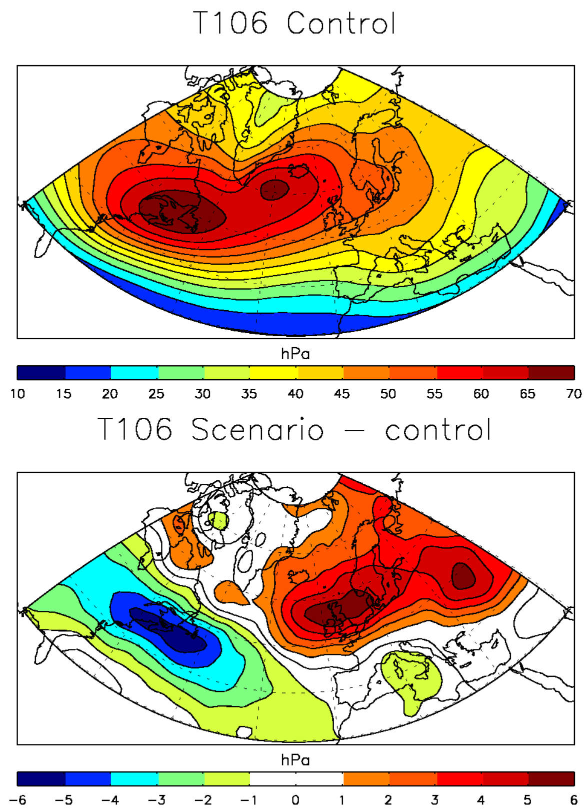


Fig. 2.2. The winter (NDJFM) storm track intensity (the short term variability of 500 hPa height) from a) the control run, b) the difference between the scenario and the control. Units: m.

Arctic Atlantic Ocean. Enhancement of the storm activity over the North Sea and western Europe is found in several other GCM experiments (see e.g., Lunkeit et al., 1996; Beersma et al., 1997; Cubasch et al., 1997; Ulbrich and Christoph, 1999; Knippertz et al., 2000). In some experiments (Hall et al., 1994; Schubert et al., 1998; Lunkeit et al., 1998) this is interpreted as a downstream displacement of the storm track.

The statistical significance of the changes was investigated using a Mann-Whitney test. This revealed that the changes in sea level pressure and storm track intensities are significant on a 1% level. To test if the *GHG* minus *PRD* changes could be due to long term internal variability in the model a 300 year long run with the underlying atmosphere-ocean model was used. Running means of sea level pressure were calculated for each grid point. The maximum difference between any two 29-year mean values is shown for each grid point in Fig. 2.3. Maximum values of 4.3 hPa are found over Southern Greenland and west of Ireland. Assuming that the runs with the model in T106 resolution have the same long term internal variability these numbers can be compared to the *GHG* minus *PRD* differences of the sea level pressure (Fig. 2.1b). The largest *GHG* minus *PRD* differences (> 2.5 hPa) occur where the corresponding maximum differences between any two 29-year mean values is less than this value. It is thus very unlikely that these *GHG* minus *PRD* differences should be caused by long term internal variability. More detailed descriptions of the statistical analysis can be found in Andersen et al. (2001).

As a measure of the extreme winds the mean value of 10m maximum winds exceeding the 0.1 % percentile level (corresponds to the 0.3 strongest events each winter) was calculated for each grid point. The changes in the wind speeds shown in Fig. 2.4 reveal a much more noisy pattern than the changes in the 500 hPa variability, but some similarities can be seen: In the area where the 500 hPa variability is increased (i.e. North Sea, Scandinavia and eastern part of Europe) there is a small (2.5 m/s) increase in the wind speed. Correspondingly, there is a small reduction in the extreme wind speed where the 500 hPa variability decreases (i.e. in the Atlantic Ocean near Newfoundland and

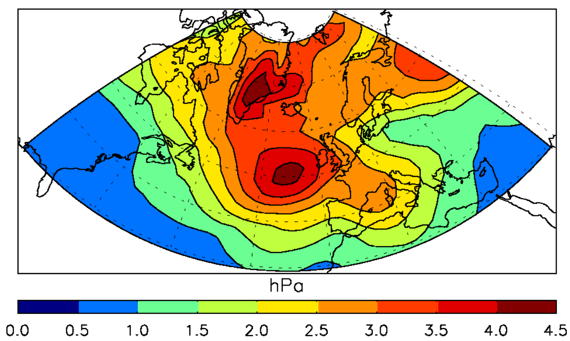


Fig. 2.3. Maximum difference between any two 29-year running mean values of sea level pressure. The data are from a 300 year long control simulation with the coupled ECHAM4-OPYC model . The atmospheric model is in T42 horizontal resolution.

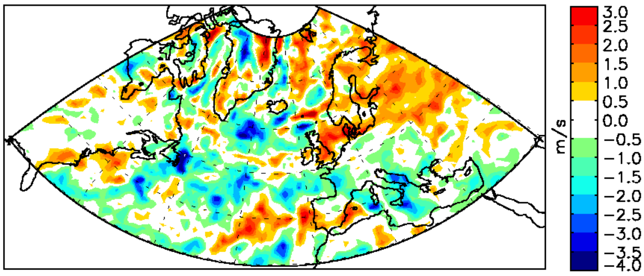


Fig. 2.4. The difference between T106 scenario and control in mean value of the 10m maximum wind speed exceeding the 0.1% percentile level. Only values from winter (NDJFM) are included.

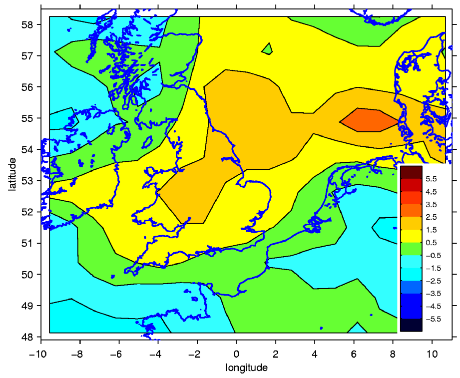


Fig. 2.5. Difference between scenario and control situation in the 50 year return (based on a fit to an exponential function) value of the wind speed.

generally in the Mediterranean area).

The extreme winds in the North Sea area were investigated further by fitting the highest wind speeds to an exponential distribution. The changes in the 50 year return value of the wind speed between the *PRD* and the *GHG* simulations are shown in Fig. 2.5. The 50 year wind speed increases with 0.5-3.5 m/s in the North Sea while it decreases in the English Channel and west of UK and Ireland. The analysis is described further in the contribution from RIKZ.

Cyclones in the Mediterranean area have been identified in the *PRD* and *GHG* runs and ranked according to their depth. The cumulative number of cyclones was larger in the *PRD* run for cyclones up to depths of 35 hPa. For cyclones deeper than 35 hPa the number from the *GHG* run was larger than the *PRD* run. The significance of the *GHG* minus *PRD* differences was tested using Students T-test and a Mann-Whitney test showing that the changes for the total number of cyclones deeper than 15 hPa were significant on a 95% confidence interval. The extreme cyclone events were investigated by fitting the distribution of cyclones to a Gumbel distribution. The data confirms that the *GHG* represents the deepest cyclones. The differences between the *GHG* and *PRD* are significant, although small. Statistics of cyclones in the Mediterranean are described further in the contribution from UP.

3. Baroclinic developments (Task 2)

As stated in the introduction possible changes in the amount of water vapour in a greenhouse gas warmed climate may influence the extra-tropical storm climate. In task 2 the influence of increasing water vapour in a warmer climate was investigated by re-simulating selected North Atlantic storms from the T106 simulations in HIRHAM high resolution regional model (Christensen et al., 1998). The physical parameterizations using HIRHAM are basically the same as in the ECHAM model used for the T106 time slices.

All the selected storms from both the *PRD* and the *GHG* were simulated with the HIRHAM model in a normal version and in a 'dry' version where the release of latent heat was turned off. The storms simulated in the normal version were deeper (average pressure minimum was 23 hPa lower) and stronger (maximum pressure gradient changed from 11 Pa/km in the normal run to 7 Pa/km in the dry run) than the simulations with the 'dry' version of the model. The changes took place on a small horizontal scale (distance between pressure minimum and the maximum pressure gradient changed from 280 km in the normal run to 450 km in the dry run). There were no statistically significant differences between the normal minus dry changes in the storms from the *PRD* and from the *GHG* runs.

In the second set of experiments 13 of the storms from the *PRD* run were re-simulated in a normal and a dry version of the model as well as with temperature perturbations of -10 K, 3 K and 10 K, respectively. In the temperature perturbations the relative humidity was kept constant. Temperature perturbations of -10 and 10 K corresponds to contents of absolute humidity of approximately half and double, respectively, as compared to the normal case. The 3 K temperature perturbation corresponds to the warming in the North Atlantic region as predicted by the *GHG* minus *PRD* T106 simulations (May, 1999). The -10 and 10 K temperature changes are rather strong perturbations that were included to check the robustness of the results.

In Fig. 3.1 the minimum pressure, maximum pressure gradient and the maximum 10m wind from the simulation of the storms are plotted as functions of the vapour content. There is a remarkable similarity between the response of the different storms due to the perturbations. In Fig. 3.1a the central pressure of the lows is shown. As expected the lows are deeper when there is more vapour available for condensation, due to release of latent heat. The maximum pressure gradient increases with increasing vapour (Fig. 3.1b). For the 3 K perturbations the pressure gradient increases by 0.6 Pa/km. For the 10 K perturbations the mean value of the changes is 2.3 Pa/km. While the maximum wind speed decreases in the runs with less vapour there are virtually no changes between the runs with perturbations of 3 K and 10 K, respectively. In the 3 K perturbations the 10m maximum wind increases by 0.6 m/s compared to the normal runs.

The changes in the parameters describing the storm strength are all consistent. The more vapour available for condensation the stronger the storm develops in terms of deeper low, stronger gradient and higher wind speed. The exception is the wind speed at the 10 K perturbation where the wind seems to have reach a 'saturation'.

As an overall conclusion we can state that on one hand the model reacts to the 3 K perturbation as expected. The pressure gets lower, the wind and the pressure gradient get stronger. One the other hand these changes are smaller than expected. There may be several reasons for this:

- The true physics of the storms prevent very strong growth. I.e. the local water vapour induced enhancement of storms in a warmer climate is relatively small.
- The length of the simulations is too long. Since the selected cases represent extremes in the ECHAM4 model, any deviation in the simulation with HIRHAM is likely - in a statistical sense - to represent a weaker development than that in ECHAM4. This problem becomes progressively worse the longer the simulation. In the extreme case of very long HIRHAM simulations (where a global HIRHAM would be needed) the statistics of these simulations would tend to converge towards model climatology. This is a basic motivation for limiting the simulations to 24 hours.
- The HIRHAM model could have some deficits which prevent small scale explosive cyclogenesis exceeding a certain strength. Such model deficits may be due to insufficient spatial resolution, too strong or unrealistic filtering via horizontal and vertical diffusion, inconsistencies in the formulation of convection etc. One may say that the model is saturated and cannot develop more intensive lows than ECHAM4 already does.
- The length of the simulations is too short. If this is the case there will not be sufficient time for the full deepening of the depression. The relative difference between the different simulations should, however, not be very sensitive to this problem.

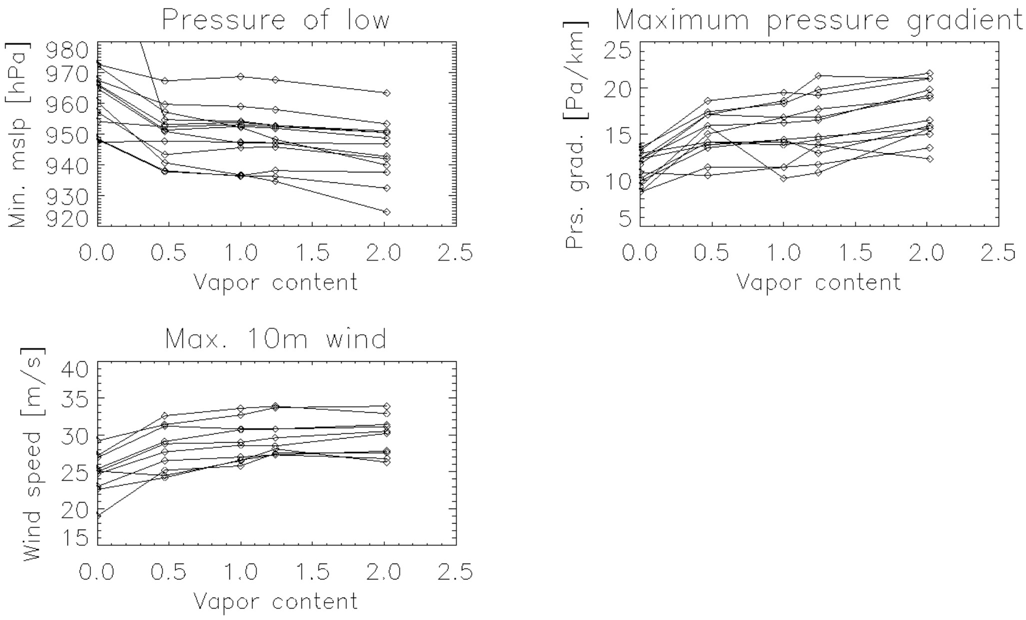


Fig. 3.1. Simulations of the 13 storms with different perturbations. The results are shown as a function of the vapour content, relative to the vapour content of the normal simulation. Starting from the left the points corresponds to the dry version, -10 K, normal version, +3 K, and +10 K a) Minimum pressure of the low, b) Maximum pressure gradient and c) maximum 10m wind speed.

4. Polar lows (Task 3)

Polar lows are convectively active meso-scale weather systems developing in certain large scale flow situations dominated by strong cold air advection over relatively warm open sea. In the North Atlantic region they are most common over the Barents Sea and the Norwegian Sea. STOWASUS-2100 has investigated to what extent the activity of such systems may be expected to increase or to decrease in a warmer climate.

Polar lows have a horizontal scale which is too small to be resolved in climate simulations. This also regards the T106 resolution used in the time slice simulations. It is therefore not possible to analyse any changes between the *GHG* and the *PRD* simulations by e.g. counting the occurrence of polar

Figure 4.1. Average count per year of 12-hour intervals where the polar low criteria is fulfilled for the control run (left) and the scenario run (right). The counting only includes the calendar months Oct., Nov., Dec., Jan., Feb., Mar. and Apr. Isolines are for the following numbers: 10,50,100,150,200,250.

lows in these data. Polar lows are, however, very sensitive to changes in the large-scale three-dimensional structure of the atmosphere. The idea has therefore been to calculate a change in probability for polar lows to develop in the larger-scale flow resolved by the time slice simulations. To do this it was needed to define a set of objective criteria for flow configurations which are favourable for development of polar lows. The criteria developed within the project reflects physical knowledge of the atmosphere. Qualitatively, the favourable conditions are: 1) the existence of an upper atmosphere trough in a situation of cold air advection, 2) unstable atmospheric conditions i.e. strong vertical temperature gradient, 3) relative warm ocean providing a strong source of sensible and latent heat. More information about the criterion can be found under the contribution from partner number 7 (DNMI).

To verify that the criterion gives reasonable estimates it was applied to 3 years of observed data (1982-1985) where the occurrence of polar lows was known. The result of this test was somewhat disappointing in terms of deterministic detection of individual polar lows. It should, however, be mentioned that this could be expected since convection plays a major role in the development of most polar lows. I.e. a large component of local chaotic behaviour dominates in the individual large scale situations.

Fig. 4.1 shows the number of counts (only months October through April) based on 12 hourly data where the objective criterion was fulfilled in the T106 *PRD* and *GHG* simulations. It can be seen that in both simulations there is a maximum close to the ice border and a secondary maximum outside the Norwegian coast close to 70N. Furthermore, there is an enhanced tendency towards favourable initial polar low conditions in the *GHG* relative to the *PRD* in the area west of Spitsbergen. Overall there is a moderate increase in the number of favourable conditions per 30 years in the *GHG* relative to the *PRD*.

In addition to the objective criteria selection, 10 of the strongest developments (according the criteria) were selected for further study with the regional HIRHAM model. For each case the simulation was compared with the global simulation. A general finding seems to be that the HIRHAM only develops the individual lows slightly more than the ECHAM4 at T106 although the HIRHAM winds are somewhat stronger.

A scientific report (Haakenstad et al., 2001) describing the findings regarding polar lows and including more details is planned for publication in 2001.

5. Mediterranean systems (Task 4)

One of the most intense and typical weather features of the Mediterranean region is the development of hurricane-like, small scale cyclones during the fall and winter season, when the air is warmed at the sea surface by intense turbulent fluxes of heat. These *Mediterranean Lows* (ML) are characterised by the presence of a shallow (below 500 hPa) mesoscale vortex, having a diameter of the order of 100-200 km, located in the central part of a synoptic scale trough of moderate intensity. Deep convection is observed in the region prior and during the formation of the small scale vortex. Numerical experimentation with high resolution mesoscale models indicates that sustained, turbulent fluxes of sensible and latent heat at the sea surface are very important in the deepening and maintenance phase of the mesoscale vortex (Pytharoulis, Craig and Ballard; 1999. Because of these characteristics one may suspect that the frequency and intensity of such systems could increase in a warmer climate where the SSTs come closer or above the classical lower limit of 27C for development of tropical storms. Task 4 of

STOWASUS-2100 is dedicated to the investigation of this eventuality.

Since the T106 model has too coarse spatial resolution to properly resolve the mesoscale structure of ML, direct examination of *PRD* and *GHG* may lead to erroneous conclusions. Hence, the problem was tackled by downscaling episodes of marine storms potentially developing into ML using the mesoscale regional model BOLAM at a horizontal resolution of 0.25 deg). The episodes were selected in the active season October to January from an objective criteria based on

- the strength of surface fluxes of latent
- the strength of surface fluxes of sensible heat
- moist static stability of the lower troposphere
- lower tropospheric geostrophic vorticity

Table 5.1 summarises the basic findings from these simulations for the 9 most intensive storms (according the criteria) in the 30 year *PRD* and *GHG* periods. The basic results can be summarised as follows:

1. According to the T106 simulations, Mediterranean lows may become less severe in the 21st century climate (this results does only apply to the 9 storms selected via the objective index and not to all types of lows where a weak tendency for deeper lows is seen as discussed further in section 2 and in the partner contribution from University of Padua).
2. There are no systematic differences between *GHG* and *PRD* runs concerning the intensification associated to the increase of resolution. Therefore, the downscaling to high resolution does not support the a priori hypothesis that Mediterranean lows should be more intense in the

***PRD* selected cases**

Initial date yy	mm	dd	hh	Index *1.E+07	T (ºC)	Pmin (Bol) (hPa)	Wind (Bol) (m/s)	Pmin (T106) (hPa)	Wind (T106) (m/s)	Dp (T106-Bol) (hPa)	Pmin noflux (hPa)	Dp (noflux-flux) (hPa)
27	12	24	12	17.543	17	991	24,7	1004	19,9	13	1004	13
15	01	20	00	16.150	16	980	29,9	990	23,4	10	989	9
20	11	21	12	15.274	18	995	21,1	999	21,1	4	1004	9
18	12	28	12	11.509	16	990	22,5	995	21,6	5	1002	12
17	01	02	00	11.505	16	998	18,8	999	18,7	1	1007	9
18	12	06	12	9.858	16	980	29,6	990	24,0	10	996	16
12	01	18	12	7.186	17	986	27,4	992	24,5	6	995	9
17	12	07	00	6.400	16	981	22,5	984	21,2	3	989	8
27	12	19	00	5.963	17	1002	18,0	1009	19,1	7	1008	6
MEAN VALUES :					*16,6*	*989,2*	*23,8*	*995,8*	*21,5*	*6,6*	*999,3*	*10,1*

***GHG* selected cases**

Initial date yy	mm	dd	hh	Index *1.E+07	T (ºC)	Pmin (Bol) (hPa)	Wind (Bol) (m/s)	Pmin (T106) (hPa)	Wind (T106) (m/s)	Dp (T106-Bol) (hPa)	Pmin noflux (hPa)	Dp (noflux-flux) (hPa)
31	12	25	00	30.301	17	988	26,3	997	17,8	9	999	11
10	01	05	12	14.469	18	998	23,0	1002	22,0	4	1009	11
35	01	21	12	13.953	18	989	21,6	992	19,1	3	994	5
22	11	11	00	8.812	24	992	22,0	1001	24,3	9	1007	15
39	12	01	00	8.381	24	990	26,1	995	27,7	5	1004	14
35	11	09	00	7.204	25	993	22,2	996	17,3	3	1006	13
22	11	26	00	6.117	24	989	22,6	998	17,8	9	1002	13
35	01	13	12	5.943	18	991	21,8	994	21,8	3	1005	14
10	01	26	00	5.223	18	986	23,4	996	20,9	10	996	10
MEAN VALUES :					*20,7*	*990,7*	*23,2*	*996,8*	*21,0*	*6,1*	*1002,4*	*11,8*

Table 5.1. Statistics for the 9 most intensive Mediterranean lows according to the objective index I. The first four columns show the date in the PRD and GHG run of the cases and column 5 shows the value of the objective index. Hereafter: column 6 the SSTs, column 7 the center minimum pressure as simulated with Bolam, column 8 the maximum 10 m wind as simulated with Bolam, column 9 the center minimum pressure as simulated with ECHAM4 (T106), column 10 the maximum 10 m wind as simulated with ECHAM4 (T106), column 11 the difference between column 9 and column 7, column 12 the center minimum pressure as simulated with Bolam when the surface fluxes are turned off, and column 13 the difference between column 12 and column 7.

GHG due to the increase of SST.

3. The influence of the surface fluxes (last columns of table 5.1) may be more important in the *GHG* then in the *PRD* cases. This feature indicates that the physical processes associated to surface turbulent heat fluxes play a more important role in the development of ML in the *GHG*, suggesting that a slight “tropicalization” of these phenomena could take place in the 21st century climate.

6. Surge statistics based on 30 year T106 time slices: North-western European shelf seas (Task 5)

Storm surges are changes in sea level generated by storms. Along with high tides and changing mean sea level, they contribute to high sea levels that can cause coastal flooding. Changes in surge statistics could be due to changes in "storminess"; i.e. shifted storm tracks or changes in the frequency of occurrence or intensity of storms. Estimates of any changes are important for the design of coastal defences and for assessing changes in coastal flood risk and impacts.

The objective of task 5 was to use surge models forced by the T106 atmospheric data to generate climatologies of storm surges within the *PRD* and *GHG* climates, and to attempt to understand and quantify any changes. More details regarding the surge simulations on the North-western European shelf can be found in Flather and Williams (2000)

6.1 Experimental design

The task includes storm surge simulations at POL with the 35 km shallow water model (NEAC) and with the 12 km model (NISE) nested into NEAC. The simulations have been analysed by POL and DNMI. All simulations with NEAC cover the region shown in Fig. 6.1 (left panel) while the NISE simulations only cover the southern part of the North Sea, the Irish Sea and the English Channel, Fig. 6.1 (right panel).

The NEAC simulations were

- NEAC1 forced by astronomical tide only 1955-1999
- NEAC2 forced by astronomical tide only 2060-2089
- NEAC3 forced by astronomical tide1955-1999 and by "observed" forcing during the years 1955-1997 (hindcast based on a DNMI 50 km gridded analysis of sea level pressure)
- NEAC4 forced by astronomical tide 1970-1999 and by T106 *PRD* data
- NEAC5 forced by astronomical tide 2060-2089 and by T106 *GHG* data

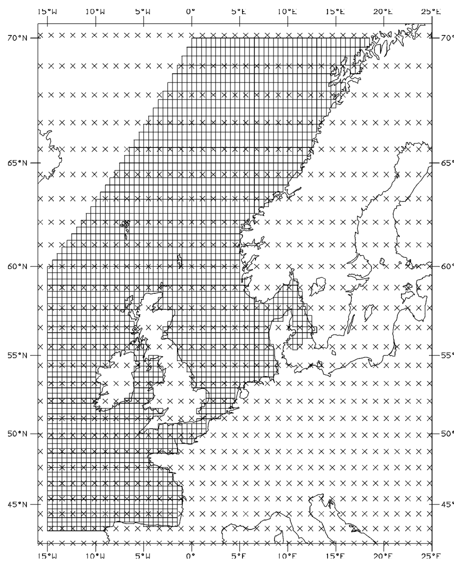
The NISE simulations are similar, but don't include the 1955-1997 hindcast period:

- NISE1 forced by astronomical tide only 1970-1999
- NISE2 forced by astronomical tide only 2060-2089
- NISE3 forced by astronomical tide 1970-1999 and by T106 *PRD* data
- NISE5 forced by astronomical tide 2060-2089 and by T106 *GHG* data

It should be noted that the results obtained with the NISE model are generally similar to those shown below for NEAC. Some plots from the NISE simulations can be found in the partner contribution from POL.

6.2 Comparison of hindcast and *PRD* simulations

Fig. 6.2 shows the computed 50 year return surge elevation for NEAC3-NEAC1 (i.e. the hindcast surge) and for NEAC4-NEAC3 (i.e. *PRD* minus hindcast). The 50 year return values were calculated from the "r largest" method described by Smith (1986) and Tawn (1988). The plot in fig. 6.2 is based on r=7 independent surges per year and a fit of these data to a Generalised Extreme Value (GEV) distribution. The maximum value in the German Bight region in the hindcast run (left panel) is about 4.5m. It is encouraging that the maximum differences (right panel) in the German Bight are "only" 60 cm, since this is much smaller than obtained in the WASA project (Flather and Smith, 1998). On the other hand the differences (in the right panel) cannot simply be attributed to poor fitting to the GEV distribution, indicated by the standard error of fitting (middle panel) which is considerably smaller. To summarise, the *PRD* run underestimates the "hindcast" extreme surges by about 10 per cent in coastal regions.



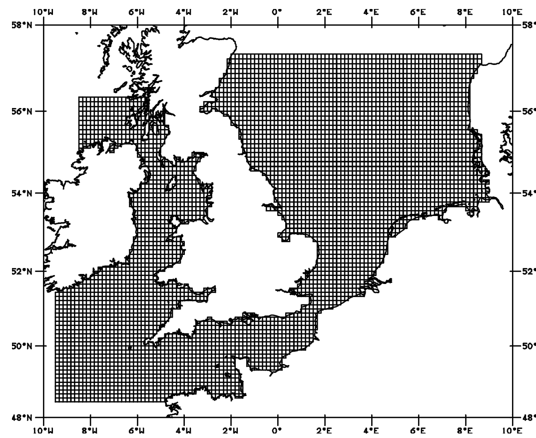


Figure 6.1. NEAC model grid (~35 km resolution) with ECHAM4, T106 data points (left) and NISE model grid (~12 km resolution) (right).

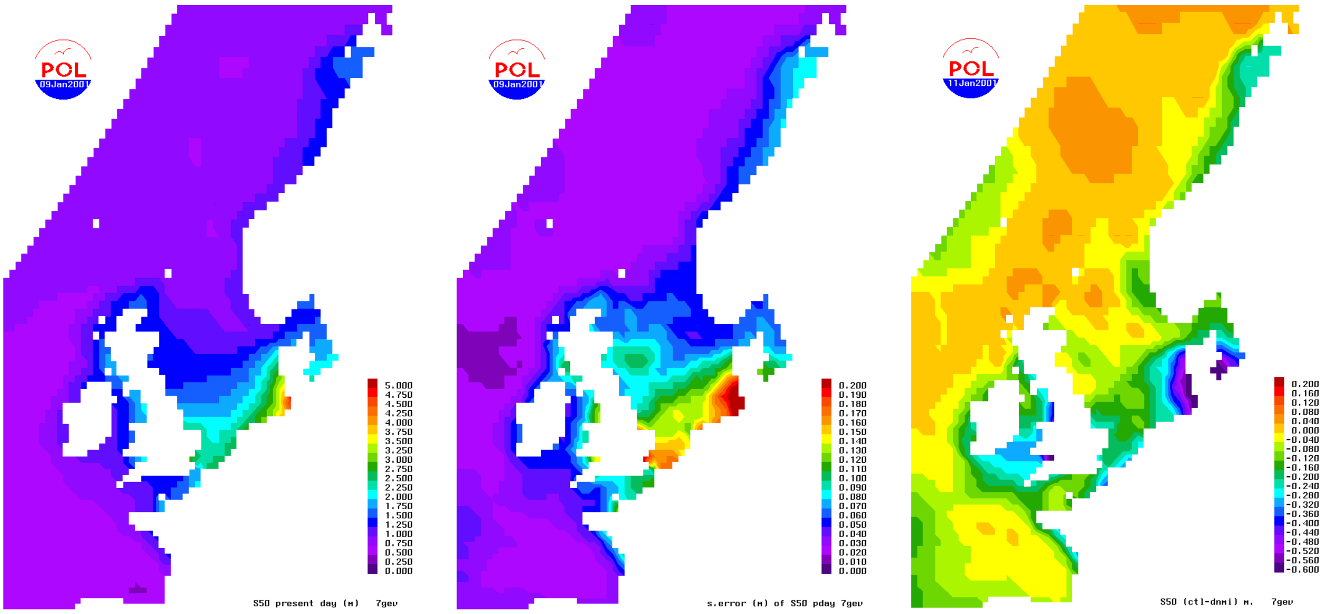


Figure 6.2. Computed distribution of 50 year surge elevation (m), left, from the NEAC model with DNMI forcing for (1955-1997), representing "hindcast" conditions and the standard error in the estimate, middle, and difference (m) defined as ("present day" minus "hindcast". All plots were made from results using the GEV distribution with r = 7.

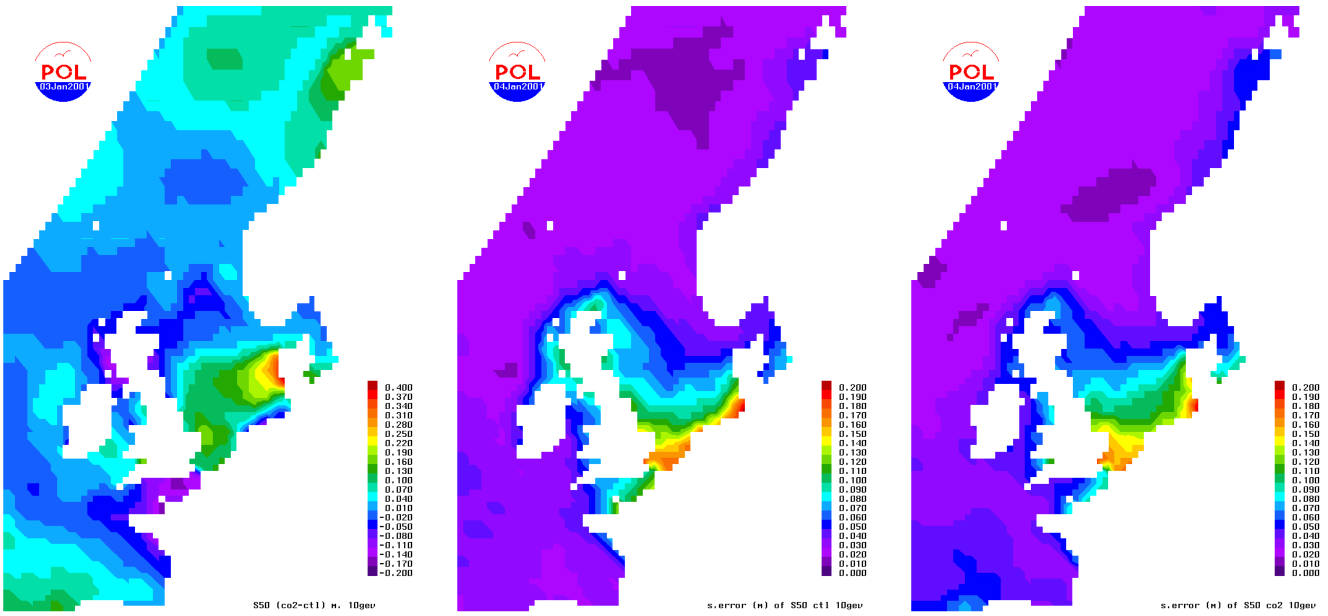


Figure 6.3. Left: difference (m), defined as ("2×CO_2" – "present day"), in 50 year return surge elevation. The middle and right panels show the standard errors of the fits to the GEV distribution for the "present day" run and the "2×CO_2" scenario run, respectively. All plots were made using the GEV distribution with r = 10.

6.3 Comparison of *GHG* and *PRD*.

Fig. 6.3 shows the difference in 50 year return surge between the *GHG* and the *PRD* simulation. The procedure for calculating the return value was the same as in Fig. 6.2 except that an r value of 10 instead of 7 was used (for the GEV distribution this has very little influence on the results). It can be seen from the figure, that the changes in extreme surges from the *PRD* to the *GHG* simulation are relatively small with maximum values up to about 40 cm (i.e. about 10% increase) along the west coast of Jutland in Denmark. It should be noted, that these findings are sensitive to choice of distribution function used for the extreme value analysis. This is further discussed and analysed in the partner contribution from POL.

The changes in surge include a small (2-3 cm) increase in the average water level along the Danish, Swedish and Norwegian coasts, due to the increased average westerly wind forcing in the *GHG*.

It is complicated to evaluate if the change in Fig. 6.3 is both significant and due to the increased greenhouse gas forcing. A simple measure of significance can be obtained by considering the level of standard error (middle and right panel). Based on these considerations the change along the

Jutland west coast and in West Fjorden in northern Norway are significantly larger than 0. But even significant differences between *GHG* and *PRD* is no guarantee that the difference in 50 year return surge is due to greenhouse gas forcing. This is because natural variability on time scales longer than 30 years may mask the results. In other words several independent 30 year realisations of both the *PRD* and the *GHG* simulations are needed. Unfortunately we only have one atmospheric time slice and therefore other measures of the natural variability are needed. One data set that may give a hint (see the partner contribution from POL) is the 43 year surge hindcast obtained during WASA (WASA, 1998), although this data set does not include several independent 30 year periods. Another possibility is to look at inter 30 year variability of other parameters that have been observed or simulated for much longer periods and which are related statistically to storm activity. One set of such parameters is sea level pressure fields. Section 2 (above) describes a simple methodology comparing a 300 year control simulation with ECHAM4/OPYC3 in T42 resolution. The conclusions are that the overall zonalization (enhanced westerlies) of the flow in the 30 year *GHG* time slice relative to the *PRD* is likely to exceed inter 30 year period variability. However, many details at more regional scale may be an artefact of natural variability. In this way our surge conclusions become rather uncertain: there seems to be some eastward shift in the driving storm activity, but we cannot conclude much regarding regional details, e.g. if it is in the southern or northern part of the North Sea we should expect the future increases in large surges.

7. Surge statistics based on 30 year T106 time slices: The Adriatic Sea (Task 6)

The Venetian littoral, the flat northern coast of the Adriatic Sea, is particular vulnerable to extreme marine events. Intensification or a change of the regimes of storm surges and waves would require the reorganization of the coastal defenses for the protection of an economically important area and a unique historical heritage.

To investigate future changes in the wave heights (task 10) and surges simulations using the wave model WAM and a shallow water coastal circulation model were performed. The models should be driven by the wind and sea level pressure (SLP) from the *PRD* and the *GHG* run with the ECHAM4 model at T106 horizontal resolution. However, the resolution of the T106 model is inadequate for reproduction of realistic surface wind fields in the Adriatic Sea. When transferred to a lat-lon grid, the whole wind field in the Adriatic Sea is only represented by ten grid points and there is a poor reproduction of the deformation of the wind flow due to the mountain ridges surrounding the basin. Therefore downscaling of the ECHAM4 model winds had to be performed using wind-output from the BOLAM atmospheric regional model.

The downscaling relates SLP fields at T106 to wind fields at the higher horizontal resolution of BOLAM (25 km). To train the downscaling, simulation(s) with BOLAM are required as the first step. BOLAM is in this case forced with 6 hourly lateral boundary conditions from either ERA (ECMWF Re-analysis at T106 horizontal resolution) or from ECHAM4. The next step is to pre-filter the T106 pressure fields and the corresponding BOLAM wind fields using principal component analysis with 14 components for SLP and 20 components for the wind field. For computational reasons the procedure is based on a number of individual training cases rather than on the entire ERA period or the entire 30 year time slice periods of ECHAM4. The correlation coefficients and the canonical maps relating the fields were then obtained using CCA and this was used to build a regression model (the downscaling) with near surface winds as predictands and pressure maps at T106 resolution as

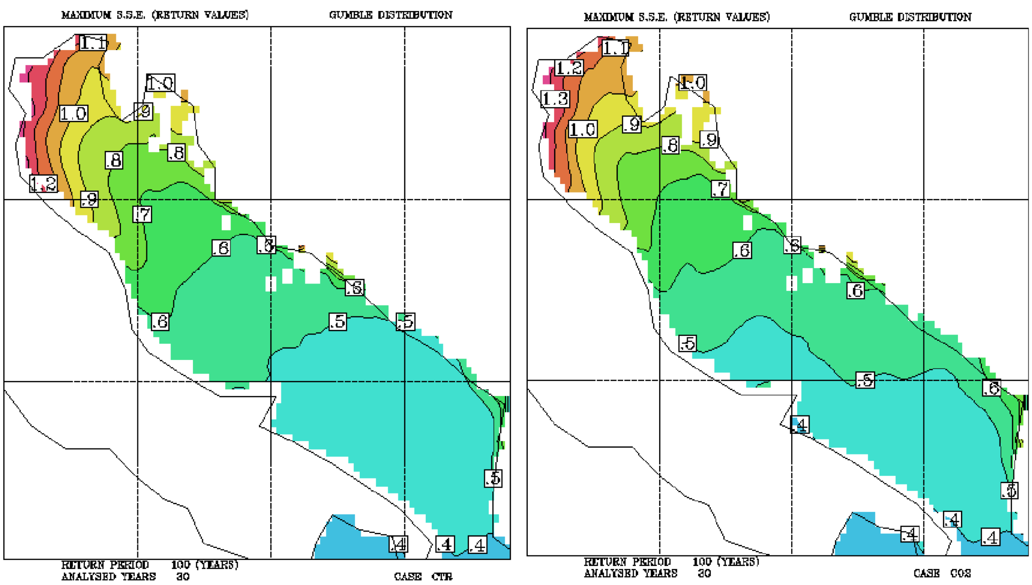


Figure 7.1. The 100 year surge level in the Adriatic Sea estimated from the CTR (left) and CO_2 (right) time slice experiments (left).

predictors. Once set up, the regression model was used to calculate a multiyear sequence of regional wind fields using the SLP predictor maps from the T106 data as input. These wind fields were finally used to drive the WAM model and the shallow water coastal circulation model. The SLP fields from the T106 data were used unmodified in the surge model.

The downscaling process is crucial for the simulation of extreme surges and waves and it was therefore evaluated by comparing the dynamical simulations, using ERA SLP-data as input, with in situ observations of sea surface elevation and significant wave heights in the Adriatic Sea. The downscaling was trained on 7 moderate to intense storms in the Adriatic Sea. Two types of simulations were done, one forced with the down scaled winds and one with the ERA T106 winds. The downscaling achieved a huge improvement with respect to the T106 forcing, but it still underestimates the observed waves and surges and it misses a few events.

For the climate change studies the CCA analysis was performed on the basis of 10 storms from the *PRD* and 10 storms from the *GHG* run. Using the T106 SLP and the downscaled winds the surges and waves were finally simulated using the WAM and shallow water coastal models. Two 30-years simulations were performed, one for the *PRD* simulation and one for the *GHG* simulation.

By fitting the results to a Gumbel distribution the maximum surge expected in 100 years was calculated for the *PRD* and *GHG* periods, respectively (Fig. 7.1). The surge reach its maximum level in the northern shallow part of the Adriatic. The *GHG* shows a very small, not significant, reduction in these high surge events.

8. Downscaling of surge statistics to estimate local variations. (Task 7)

To investigate how climatic changes will influence surges along the coast and in shallow estuaries very high resolution models are needed. This can be achieved by using either statistical or dynamical downscaling. In task 7 surges in the Irish Sea and in the Dutch Wadden Sea in a changed climate were investigated.

A fine grid (1.2 km) model of the eastern Irish Sea (EIS) was run for the period 2065-2069 using meteorological forcing from ECHAM4 and surge boundary input from the corresponding runs of the NISE (12 km) model. Corresponding tide-only runs were carried out and hourly model surge arrays calculated and analysed using Generalised Extreme Value (GEV) distribution with r = 10. The 10-year return period surge, S10, was considered a reasonable extrapolation from the 5-year data set. Comparing S10 distributions, EIS values were generally smaller than those from NISE, but taking the standard errors in the estimates into account, the differences may not be significant. Percentiles were also computed, and gave similar results with EIS values about 10% smaller than NISE equivalents. The reasons for this were not clear.

To investigate surges in the Wadden Sea a combined dynamical/statistical downscaling technique was planned, but during the project it became feasible to run the full *PRD* and *GHG* period with a high resolution model, the most ideal reproduction of the storm surge climate. To handle this the following restrictions were made: boundary conditions from POL's NEAC model and selection of winter half year periods only. The model used is the Southern North Sea Model from RIKZ. It is a curvilinear model which covers the area of the Southern North Sea from Aberdeen to Cherbourg with a varying grid size. The model was evaluated successfully (together with other models) by simulating a storm period (December 28, 1994 - January 12, 1995) and comparing the

a

b

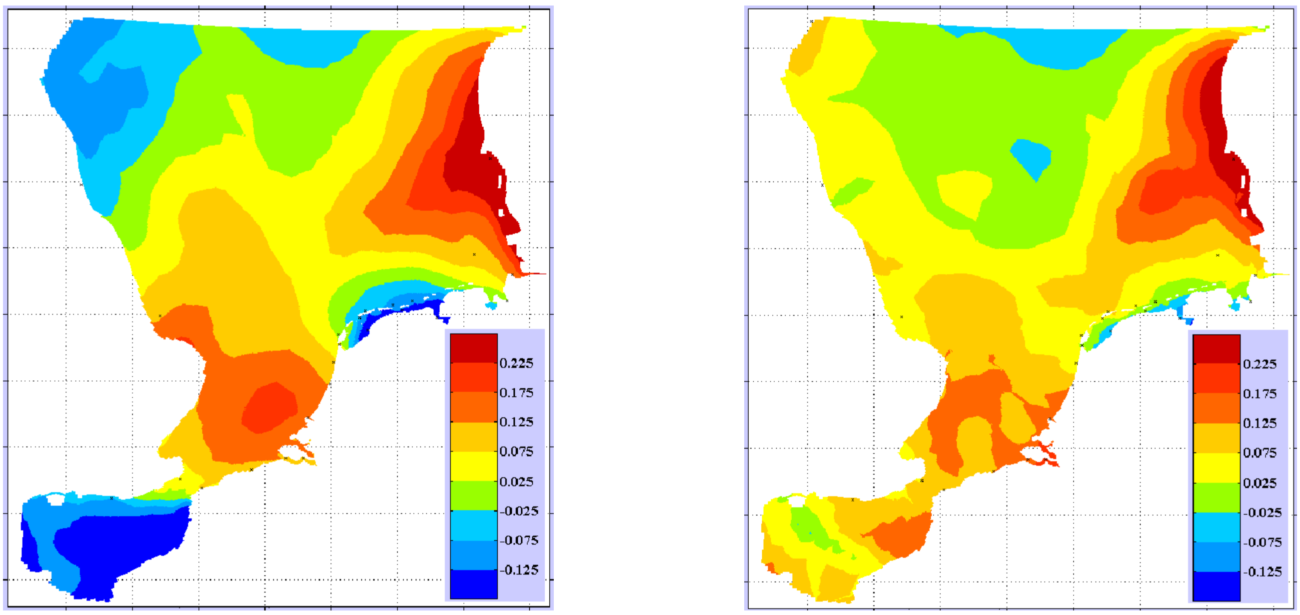


Figure 8.1. Differences between 50 year water levels [m] of scenario and control simulations with the "Southern North Sea model from RIKZ for the surge only (panel a) and the combined surge and tide (panel b) simulations.

results of sea level with observations.

With the Southern North Sea Model computations including tide and surge, as well as surge only, were performed for both the *PRD* and *GHG* periods (29 winter seasons each).

Statistical analyses of the simulations were carried out for both 10 minute values and for hourly values. For the 10 minute values the sea level maxima for 61 selected locations were fitted to exponential and Gumble distributions both for *PRD* and *GHG* runs. In the *GHG* run the 50 year surge for the west North Sea coast of The Netherlands shows an increase of 1 or 2 decimetres, a decrease of 1 or 4 decimetres for the Dutch Wadden Sea area, and an increase up to 4 or 6 decimetres for the Danish Wadden area near Esbjerg, as compared to the *PRD* run. For the one hour output the 50 year sea level maxima were calculated for each grid point by fitting the data to an exponential distribution. The results (only differences) of this are shown in Fig. 8.1 for surge alone and for tide and surge. The figure confirms the main feature from the results based on the selected 10 minute data. In Fig. 8.1a (surge only) three areas show a decrease of the 50 year surge level in the *GHG* situation relative to the *PRD* situation: the English Channel (up to 10 or 20 cm decrease), the Dutch Wadden Sea (up to 10 or 20 cm decrease) and the east coast of Scotland (about 10 cm decrease). An increase is found for the southern North Sea coast of The Netherlands and the English coast of Norfolk and Suffolk (about 15 cm) and also for the Danish coast (about 25 cm). The differences between the 50 year water levels of the *GHG* and the *PRD* situation are less clear in the case of combined surge and tide simulations (Fig. 8.1b). A shift of the tidal phase relative to the atmospheric forcing might influence this result.

The statistical significance of the changes in maximum sea level for the individual stations were calculated by dividing the time series of 29 storm seasons into subsets of 14.5 storm seasons. The maximum sea levels were fitted to a Weibull distribution. The results show that the increase in the 50 year surge level between the *PRD* and the *GHG* runs for Esbjerg is significant but this is not the case for the decrease at Delfzijl. The above results are broadly consistent with those from Task 5.

9. Influence of resolution of atmospheric forcing on surge statistics: North-western European shelf seas. (Task 8)

The aims in Task 8 were to quantify the impact on surges of the resolution (in space and time) of the atmospheric forcing and of the ocean model resolution. For this, simulations with NISE and three fine grid (~1.2km) tide surge models with different geographical coverage were carried out. Six surge events; three from the *PRD* and three from the *GHG* were selected, with one from *PRD* and one from *GHG* for each of the fine grid models. The HIRHAM

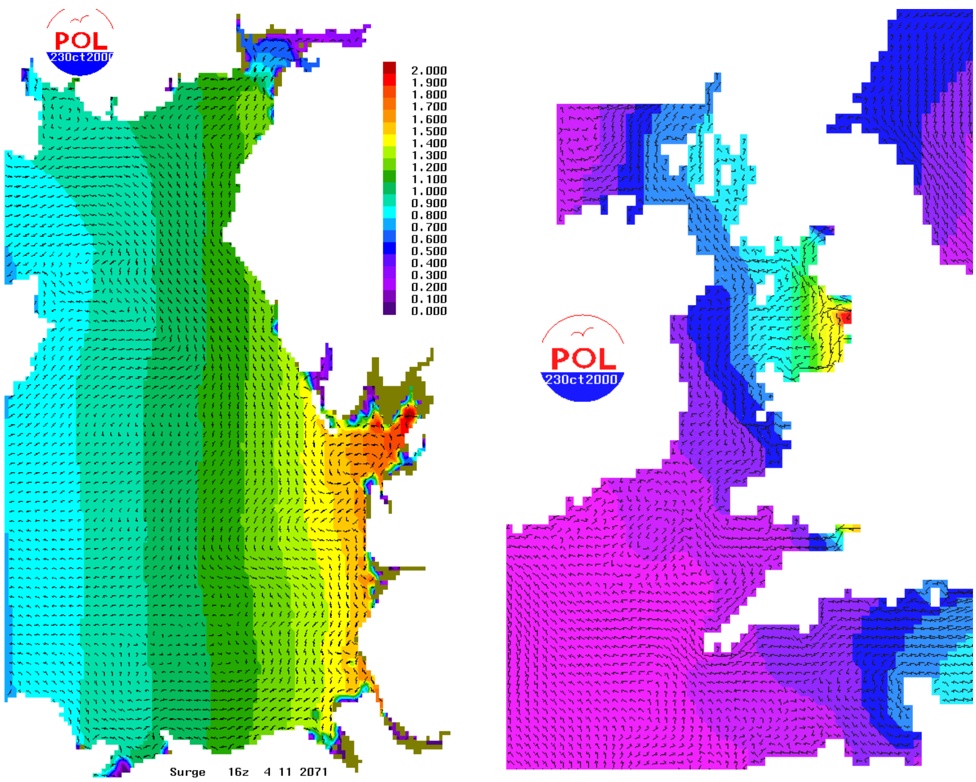


Fig. 9.1. Surge elevation (m) and currents at 1600GMT 4/11/2071 from the 1.2 km Eastern Irish Sea model (left) and the 12 km NISE (right) models.

model was run for 5-day periods by DMI to provide high resolution meteorological data (hourly and 30km) for each event.

To examine the impact of the resolution of the atmospheric forcing, NISE was run for all events forced by ECHAM4 (6-hourly, T106), HIRHAM (hourly, 30km), and HIRHAM (6-hourly, 30km). Spatial distributions and time series of surge elevation at representative locations were extracted and plotted. Comparing time series using ECHAM and HIRHAM with 6-hourly forcing, there are substantial (O(50cm)) differences in surge elevation at times for some locations. Spatial plots of the difference also showed significant differences, which propagate like the surges themselves. The differences may be due to the different spatial resolutions of the forcing, but could also result from different evolution of a storm in ECHAM and HIRHAM, i.e., non-linear error growth in the HIRHAM 5-day runs.

To examine the impact of ocean model resolution, the three fine grid models were run with HIRHAM forcing (both hourly and 6-hourly) and input of open boundary surges provided from equivalent runs of the NISE model. Spatial distributions of surge from fine grid models and NISE are very similar, see for example Fig. 9.1. Time series were also compared, taking from the fine grid models either the surge at the same location as the NISE grid point, or at the fine model grid point closest to the actual point of interest, e.g. a tide gauge, which could be a few km away. Differences are generally small on open coasts, but can be large in estuaries and shallow water. The fine models do, however, represent coastal features more realistically so comparing results at the model point closest e.g. to a tide gauge, gives further small differences.

The overall conclusion is that there is a relatively small impact from increased horizontal resolution of the surge model except in shallow estuaries and embayments. For impact studies it may be important to have high resolution to provide details of these local variations.

10. Case studies: The Adriatic Sea (Task 9)

An investigation has been carried out for comparing the results of the statistical and the dynamical downscaling. The wind fields of the 20 storms used for the CCA has been simulated with the tri-modular model MIAO, which includes BOLAM (the meteorological BOlogna Limited Area Model), WAM (WAve Model) and POM (Princeton Ocean Model). The resolution used was 0.25 degrees for BOLAM, 1/6 for WAM and 1/12 for POM, that is WAM and POM adopted the same resolution that was used in the 30-year long *PRD* and *GHG* experiments. The differences between these case studies and the corresponding results of the *PRD* and *GHG* experiments are due to the different forcing fields and to the different treatment of the southern open boundary of the Adriatic. In the case studies the sea level at the open boundary could vary according to the dynamics of the whole Mediterranean Sea and waves generated in the Ionian sea could propagate inside the Adriatic. In the *PRD* and *GHG* experiments only a small fraction of the Ionian Sea was included resulting in a strong reduction in the variability of the sea level at the southern exit of the Adriatic and in the amount of waves propagating across it. Actually, since the same set of storms was used for the CCA analysis, one would expect that the wind field used for the forcing is equivalent to the results of the LAM. This would imply, neglecting the effect of the boundary conditions, a relatively small difference in the resulting significant wave height (see next section) and surge level. This consideration is correct, but because the time resolution of forcing fields is much longer for the statistical than for the dynamical downscaling (6 hours versus 1 hour) and because the statistical downscaling tends to damp the wind the dynamical downscaling resulted in systematically higher surge and waves.

11. Wave simulations in The Mediterranean (Task 10)

The analysis of the climate change in wave heights has been focused in the Adriatic Sea, where the wave heights were simulated using the wave model WAM. The model was forced by wind fields that were downscaled from the sea level pressure (SLP) fields of the T106 simulations. See section 7 (Task 6) for a description of the downscaling procedure.

Results from the 30 year *PRD* run and the 30 year *GHG* run with the WAM model are summarised in Fig. 11.1 which shows the 100 year return significant wave height (SWH) according to a statistical model based on a fit to a Gumbel distribution. The *PRD* run shows two maxima of SWH, one at the northern part of the Adriatic Sea where the fetch is longest and one at the southern end where the strongest winds occur. For the wave field the greenhouse gas forcing generally results in a diminished expected maximum SWH in this region.

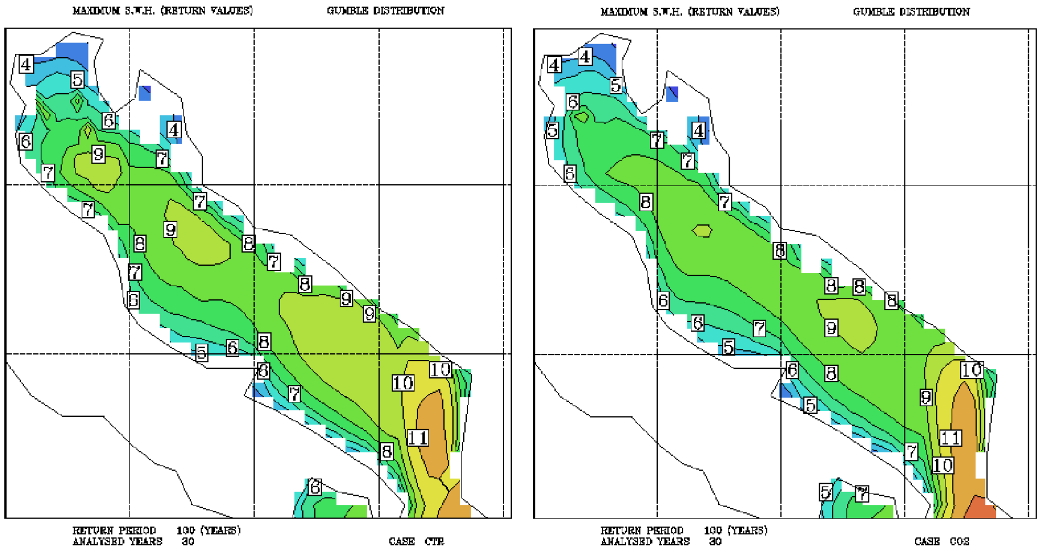


Figure 11.1. 100-year swh in the Adriatic Sea estimated from the CTR (left) and CO_2 (right) time slice experiments (left).

12. The northern seas (Task 11)

A climate change in waves that leads to e.g. a 10 % increase of the highest waves may have a rather important impact both on safety of existing structures and on the regularity of marine operations. To study possible changes in the wave climate the wave model WAM has been run for two times 30 years with wind input from the *PRD* and *GHG* runs with the ECHAM4 at T106 horizontal resolution. Average significant wave height is fairly well modelled in the *PRD* run compared to observations and hindcast data. The high wave heights seem to be slightly overestimated by the model.

The average significant wave height increases in the North Sea and the Norwegian Sea and the area north and north-west of the British Isles in the *GHG* simulation relative to *PRD*. The increase is largest in the autumn with about 10 % increase in the Norwegian Sea near the Norwegian coast. In the summer season there is no increase in average heights. For the extreme wave heights (see Fig. 12.1) the conclusions are not so clear, but there is a tendency to increasing extreme

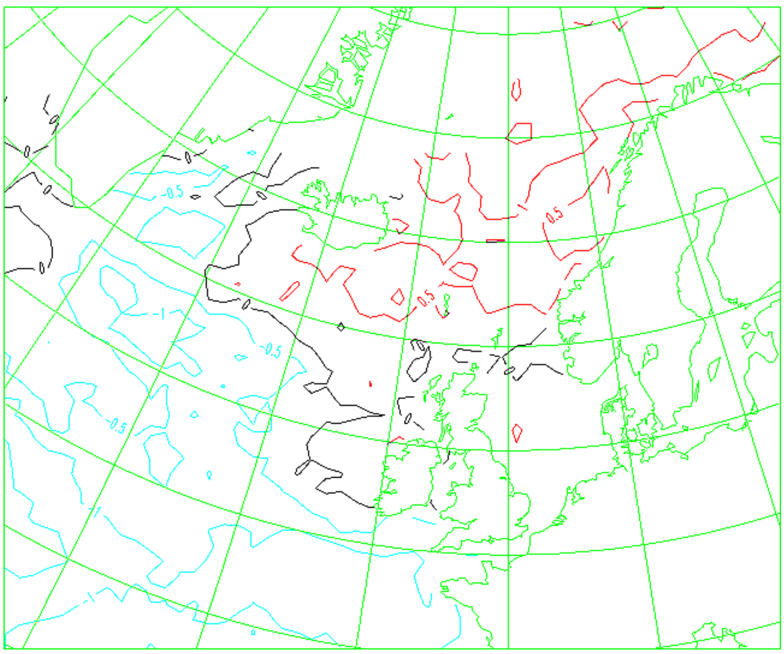


Fig. 12.1. The difference between the 99.9 percentile of significant wave height from the $2XCO_2$ run and the control run.

wave heights in the North Sea, the Norwegian Sea and the Barents Sea. In the north-western part of the Norwegian Sea and into the Barents Sea there are increases of 1 to 1.5 m's correspond to about 10%. Both average and extreme wave heights are decreasing in the western and south-western part of the model area.

13. Ocean wave generator (Task 12)

As an important link towards practical utilisation of the results obtained in the project a local wave "weather" generator, conditioned on changes in the large-scale state of the troposphere due to increasing greenhouse gas concentrations, has been developed and applied. This type of model is most valuable for planning purposes of off-shore structures and operations and for economic cost-benefit analyses of expected climate change.

The wave generator provides 3-hourly wave heights and direction conditioned on the monthly mean air pressure state. It consists of three main steps:

1. In the first step the varying monthly distributions (percentiles) for wave heights in the meridional and zonal directions are modelled using a statistical downscaling technique, redundancy analysis (RDA). As predictor for the wave climate the monthly mean SLP fields were chosen. The predictands, i.e. the monthly wave statistics, are characterised by the levels of 11 different percentiles of the wave distribution for both the zonal and meriodional directions. The RDA model was fitted with data from 1955 to 1964, and validated with data from the 1965-94 period. The input wave data for training was taken from a 40-year wave hindcast (see WASA, 1998). Figure 13.1 illustrates the performance of the model for a grid-point close to oil platform Ekofisk in the Norwegian Sea. It can be seen that model is able to reconstruct the typical variations in percentiles in the zonal direction. For all percentiles the mean correlation is 0.78 in the verification period 1965-94.
2. The second step is the generation of 3-hourly wave heights for each direction. This is modeled using an autoregressive second-order process. The wave generator was validated successfully against hindcasted wave statistics from an independent period.
3. The third step consists of a first order autoregressive model which generates synthetic input to the wave generator in terms of the RDA coefficients. I.e., the component mimics the variations in monthly wave statistics due to monthly SLP variability and change. This autoregressive model is conditioned on the seasonal cycle and on the greenhouse gas concentration (via a projection of the RDA values obtained in step 1 onto the long term mean SLP difference between the *GHG* and *PRD* simulations). This third step can be omitted if specific SLP patterns are used directly to the model (step 1).

The complete statistical model (both with and without the third step) was validated by comparing the mean wave height and percentiles with output from the dynamical wave model (WAM).

The results for the northern North Sea in the *GHG* are shown Fig. 13.2 in terms of changes in the different percentiles for waves in the zonal and meridional direction. There is a minor increase in the height of south- and northward waves (because the lowest percentiles representing the largest southward propagating, i.e. negative, waves are shifted to even more negative values and the highest percentiles representing the larger northward waves are shifted even further up. In the zonal direction there are fewer and decreased extreme values for the westward waves and more waves and increased extreme values for eastward waves.

For an approach of a zero-order economic-climate model the wave data near the coast were transformed in such a specific manner enabling estimation of the future development of the wave height and energy in front of the dikes or at risky erosion areas.

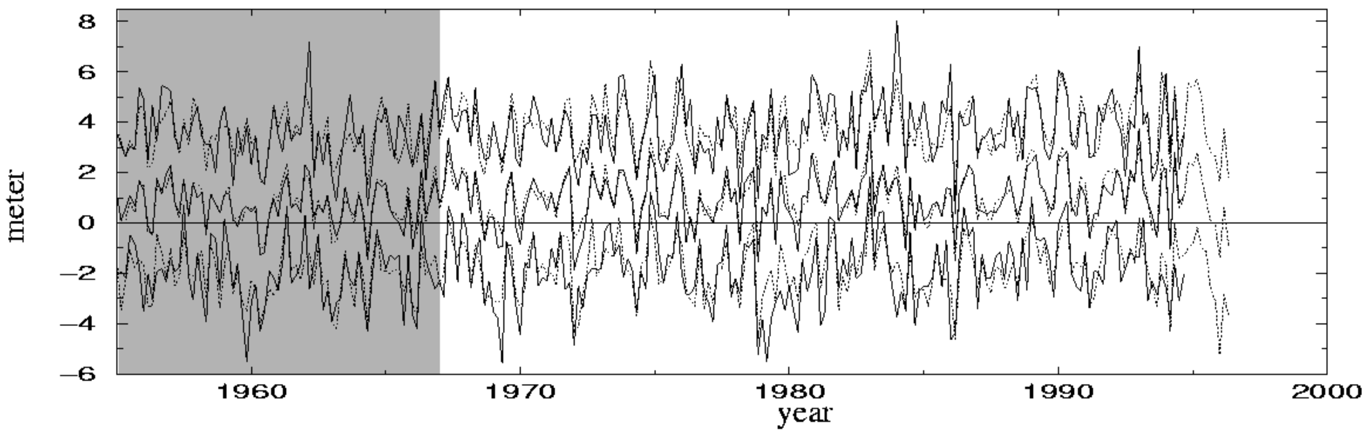


Fig. 13.1. Time-series of the 5th, 50th and 95th percentile of the monthly waves in zonal direction, as derived from hindcasted (solid) and estimated from the monthly mean air-pressure field (dotted). The fitting period is shaded. The plot is valid for a grid box in the central northern North Sea.

Although not part of the original work plan the work also included detection of recent anthropogenic influence on the wave climate. This was examined by investigating the frequency of intra-monthly wave direction in the central North Sea. The wave climate from 1900 to 1996 was reconstructed using the observed monthly SLP over North Atlantic and Western Europe. By comparing this to the characteristics of the results from a 260 years GCM transient run it was concluded that the most recent rising 30 year trend in the reconstructed wave climate seems inconsistent with natural variability. A detailed description can be found in Pfizenmayer and von Storch (2001).

14. Conclusions

On the basis of the individual partner contributions and on the discussions above the following general conclusions have been obtained from the STOWASUS-2100 project.

The atmosphere:

The main change concerning storms and wind in the winter season in the T106 simulations is a moderate shift/extension towards Northeast of the North Atlantic storm track and an overall zonalization (i.e., enhanced westerlies) of the mean flow between 50 and 70N with decreased surface air-pressure in the arctic region. Since this feature is simulated by most modern coupled atmosphere-ocean models (see e.g. IPCC, 2001), it is considered a fairly robust climate change signal. The large scale change generally leads to slightly increased extreme wind speed statistics (e.g. to increasing .1 percentiles of the 10 m wind) along the north western European coasts. However, due to the relatively short simulated periods of 2 times 30 years the T106 change in extreme wind statistics is highly patchy and generally it is not statistically significant at individual locations. We consider most of the local/regional features as artefacts of natural variability. Therefore our conclusions become rather vague: there seems to be some eastward shift in the storm activity with an overall moderate worsening of the storm climate in the north-eastern Atlantic / northern European region, but we cannot conclude much regarding regional details. Longer or more simulations are needed to judge, e.g., to what extend the simulated increase in extreme winds from westerly and south westerly directions in the North Sea (see e.g. Figs. 2.4 and 2.5) is due to the greenhouse gas forcing or, alternatively, a simple consequence of inter-decadal natural climate variability.

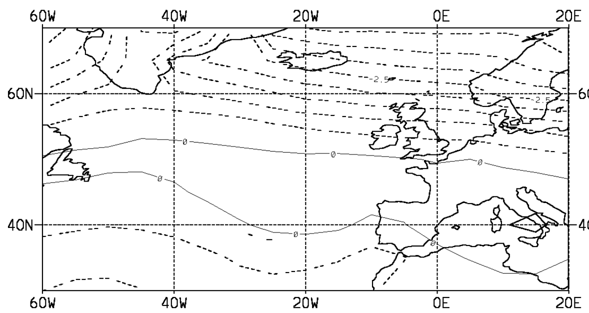
There are no indications that regional grid point models at horizontal resolution 30-50 km simulate a worsening of the extreme storms in a warmer climate relative to what is seen in the T106 time slice. This statement is based on many case studies with the BOLAM model and the HIRLAM model and it regards both baroclinic developments, polar lows and Mediterranean lows which are strongly influenced by latent heat release. The potential threat that Mediterranean systems may develop into tropical hurricanes in the warmer climate with higher sea surface temperatures is not supported by the experiments carried out in STOWASUS-2100. If anything, there seems to be a small decrease of the extreme wind speed in these systems although the central pressure of the most intensive systems is somewhat deeper in the *GHG* case. We note, however, that these conclusions regarding the influence of latent heat release on intensive low pressure systems could be model dependent.

Surges:

Different surge models have been run with atmospheric pressure and wind forcing taken from the T106 simulations. However, an intermediate downscaling of the T106 simulated sea level pressure (to regional wind) was needed for ocean modelling in the Adriatic due to complicated regional topography. In general the output from the surge models is consistent with the simulated change in atmospheric conditions:

The simulated surge climate in the Northern Adriatic presents no significant difference between present and the warmer climate. Regarding the cultural and economic values in the Venice area, this means that changes in storm surge activity constitutes no additional threat on top of the general threat due to global sea level rise.

In the North Sea there are both small increases and decreases in the 50 year return surge but the results are quite dependent on the choice of distribution function to which the data are fitted and to the number of extreme value data chosen in the fit. The increase is seen most clearly along the Jutland coast where it is statistically significant when the high surge data are fitted to a GEV distribution. The increase in terms of height is locally close to 10%. The surge simulations show no significant changes in the high surge events further



per	5	10	20	30	40	50	60	70	80	90	95
zonal	42	43	41	39	38	38	36	36	37	37	38
meridional	-8	-6	-2	0	2	4	7	10	13	15	17

Fig. 13.2. Mean SLP difference (top) between the control and $2\times CO_2$ run for the winter (ONDJFM) and the connected change of the percentiles of the wave distributions at a location close to oil platform Ekofisk in the northern North Sea (bottom).

south-west along the Dutch part of the Wadden Sea or in the Irish Sea. There are moderate (up to ~10%) increases in the high surges in the Vestfjorden area in northern Norway. The mean change in wind forcing produces a small (2-3 cm) long term average pile up of water along the Danish, Swedish and Norwegian coasts.

Although the rise in surge along the Jutland west-coast is statistically significant it is uncertain if it is due to the greenhouse gas forcing or - at least to some extent - due to interdecadal natural variability. This is because this rise is related to the regional rise in extreme west and south-westerly winds which - as discussed above - may or may not be due to greenhouse gas forcing. Longer simulations would be needed to investigate this problem.

Waves:

The change in wave climate follows the wind forcing closely. The average significant wave height increases by about 5% in North Sea in the *GHG* relative to *PRD*, and by almost 10% in the Norwegian Sea in autumn. For extreme waves (e.g. the 99.9 percentile) the increase is only seen clearly in Norwegian Sea where it reaches 10%.

The highest wave in the Adriatic have been simulated to decrease about 10% in the *GHG*.

The project also included the construction of a wave generator. This is a statistical model based on an auto-regressive second-order process which - via the variations in the sea level pressure patterns - is conditioned on the greenhouse gas concentration. The model can generate long local synthetic time-series for planning purposes of off-shore structures and operations and for economic cost-benefit analyses of expected climate change.

Choice of model resolution:

Relative to the T106 global time slice simulations there is little - if any - added ”value” provided by the regional atmospheric models regarding the magnitude of the change in strong extra-tropical storms.

Similarly for surge models, it also appears that very high resolution does not add significant new information regarding the climatic change.

In both cases, however, added value will often be provided by the very high resolution atmosphere and surge models when subsequent impact studies are in the focus. This is because such models are able to resolve smaller scales and therefore they can provide more local details of the storms and surges.

15. Deviations from the work programme

There has not been any severe deviations from the original work programme. However, certain tasks have been modified slightly as described under the partner contributions.

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Appendix: Deliverables

Scientific, oral

The project was presented at meetings, symposia, workshops and conferences. It is important to note that some of the presentations were given at meetings with representatives from the industry (mainly re-insurance):

Dilling, Douwe: “Do the Wadden profit from a by CO2 changed climate (in Dutch: Hebben de Wadden baat bij een door CO2 veranderd klimaat?)”. Presented at a meeting in the “*werkgroep Waterstanden, Stromingen en Transporten*” of the “*Raad van Overleg voor het Fysisch Oceanografisch onderzoek van de Noordzee*”, at the KNMI, October 11, 2000.

Flather, Roger A: “Climate scenarios for water-related and coastal impact” ECLAT-2 workshop, Den Dolder, Holland, 11 May 2000.

Flather, Roger A: "Climate change effects on storm surges". Presented at 26th General Assembly of the European Geophysical Society in Nice, France, 25-30 March 2001 in session G4.02: Causes and consequences of sea level change.

Kaas, Eigil, Uffe Andersen, Roger Flather, Jane Smith, Piero Lionello, Piero Malguzzi, Arnt Pfizenmayer, Reiner Schnur, John de Ronde, Marc Philippart, Stephanie Holterman, Magnar Reistad and Knut Helge Midtbø. 2000: Regional Storm, Wave and Surge Scenarios for the 21st Century. Presented at the European Climate Science Conference, Vienna, 19-23 October 1998 (contribution).

Kaas, Eigil and Uffe Andersen: "Scenarios for Extra-Tropical Storm and Wave Activity: Methodologies and Results", ECLAT-2 workshop, Den Dolder, Holland, 11 May 2000.

Kaas, Eigil: "Future Changes in Extreme Wind Storm Statistics". Workshop on Extreme European Wind Storms and Floods, The RISK prediction Initiative, Bermuda, 23 May 2000.

Kaas, Eigil: "Hvad kan vi vente os af fremtidens storme" ("*What can we expect from the storms in the future*"), Talk to delegates from the company "Østifterne" at "SØRUP Herregård", 23 Nov. 2000.

Kaas, Eigil: "Historiske variationer i stormaktivitet i Nordvesteuropa samt et kig ind i fremtiden". Talk to representatives from the Danish/European Re-insurance industry at Forsikringshøjskolen in Rungsted (Invited by Cologne Re) 27 Jan. 2000.

Kaas, Eigil: "European scenarios for extra-tropical storm and wave and surge activity". Presented at 26th General Assembly of the European Geophysical Society in Nice, France, 25-30 March 2001 in session, NH2.0: Meteorological and hydrological hazards: Diagnosis, modelling and forecasting extreme rainfall events and storms.

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Pfizenmayer, Arnt:"Signature of changing wave climate in the North Sea." 15th Conference on Propability and Statistics in the Atmospheric Sciences, American Meteorological Society. Ashville, North Carolina. 8-11 May 2000.

Scientific, written

The following list only includes articles and reports which have been published or submitted, or are close to submission. More articles are in preparation:

Andersen, U. J., E. Kaas, and W. May, 2001: "Changes in the storm climate in the North Atlantic / European region as simulated by GCM time-slice experiments at high resolution". *Danish Climate Centre report*, **No 01-1**, ISSN: 1399-1957 (Online), 15 pp.

Dillingh, M.E. Philippart and J.G. de Ronde: A CO_2 scenario and the storm surge climate in the southern North Sea and Wadden Sea, *report RIKZ*/**2001.002**, Den Haag. January 2001.

Flather R.A. and Williams, J.A. 2000. Climate change effects on storm surges: methodologies and results. pp. 66-78 in Beersma, J., Agnew, M., Viner, D. and Hulme. M. (eds.) *Climate scenarios for water-related and coastal impact*. ECLAT-2 Workshop Report No. 3, KNMI, the Netherlands, 10-12 May 2000

Hacket, B., 2001: Surge climate scenarios in the northern North Sea and along the Norwegian coast. Norwegian Meteorological Institute *Research Report No. 123*. ISSN 0332-9879.

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Kaas, Eigil, Uffe Andersen, Roger Flather, Jane Smith, Piero Lionello, Piero Malguzzi, Arnt Pfizenmayer, Reiner Schnur, John de Ronde, Marc Philippart, Stephanie Holterman, Magnar Reistad and Knut Helge Midtbø. 2000: Regional Storm, Wave and Surge Scenarios for the 21st Century. Article #166 in European Climate Science Conference, Vienna, 19-23 October 1998 (contribution).

P.Lionello, A.Nizzero, E.Elvini (2001) Ocean waves and storm surges in the Adriatic Sea: intercomparison between the present and doubled CO2 climate scenarios. Submitted to *Climate Research*.

P.Lionello, F.Dalan, E.Elvini, 2001: Cyclones in the Mediterranean Region: the present and the doubled CO_2 climate scenarios. Submitted to *Climate Research*

Malguzzi P., D'Isidoro M., and Uboldi F., 2000: Changes in the Statistical Properties of Mediterranean Lows in the 21st Century Climate. In preparation.

Pfizenmayer A. and H. von Storch, 2001: Anthropogenic climate change shown by local wave conditions in the North Sea. *Climate Res.* (in press).

Reistad, M, B. Hackett and K.H. Midtbø, 2001: Søkelys på bølger, stormflo og polare lavtrykk i STOWASUS-2100-klimascenariene. Submitted to *CICERONE*. Center for International Climate and Environmental Research, Oslo.

Popular

The severe storms that hit Europe in December 1999 have attracted considerable public interest in the subject of a possible changing storm climate. The STOWASUS-2100 and some of its basic results concerning changes in storm activity have been presented by the co-ordinator in a 25 minute long, direct TV broadcast (prime time) on the Danish public TV. (DR-1, "Profilen", 7/12 1999), and it has been mentioned in many Danish newspapers articles.

Furthermore the following oral series of presentations have been given:

Uffe Andersen: "Byder fremtiden på kraftigere storme". A series of oral presentations to the Danish public on possible changing storm activity ("Naturvidenskabsfestival") on 25th, 26th, 27th and 28th September 2000.

In Italy the project results has been referred in a newspaper article by Piero Lionello in "LA STAMPA" (a major Italian newspaper) on January 17th 2001: "Ecco le tempeste nel 2100 -- simulato un raddoppio di gas serra ", i.e.,:" The storms in 2100 -- simulated doubling of greenhouse gas"

The Danish Climate Centre

The Danish Climate Centre was established at the Danish Meteorological Institute in 1998. The main objective is to project climate into the 21 st century for studies of impacts of climate change on various sectors and ecosystems in Denmark, Greenland and the Faroes.

The Climate Centre activities include development of new and improved methods for satellite based climate monitoring, studies of climate processes (including sun-climate relations, greenhouse effect, the role of ozone, and air/sea/sea-ice interactions), development of global and regional climate models, seasonal prediction, and preparation of global and regional climate scenarios for impact studies.

The Danish Climate Centre is organised with a secretariat in the Research and Development Department, and it is co-ordinated by the Director of the Department. It has activities also in the Weather Service Department and the Observation Department, and it is supported by the Data Processing Department.

The Danish Climate Centre has established the Danish Climate Forum for researchers in climate and climate related issues and for others having an interest in the Danish Climate Centre activities. The Centre issues a bi-annual newsletter "KlimaNyt" (in Danish).

DMI has been doing climate monitoring and research since its foundation in 1872, and establishment of the Danish Climate Centre has strengthened both the climate research at DMI and the national and international research collaboration.

Previous reports from the Danish Climate Centre:

- Dansk Klimaforum 29.-30. april 1998. (Opening of Danish Climate Centre and abstracts and reports from Danish Climate Forum workshop). *Climate Centre Report 98-1* (in Danish).
- Danish Climate Day 1999. *Climate Centre Report 99-1*.
- Dansk Klimaforum 12. april 1999. Workshop: Klimatisk variabilitet i Nordatlanten på tids-skalaer fra årtier til århundreder. *Climate Centre Report 99-2* (in Danish).
- Luftfart og den globale atmosfære, Danmarks Meteorologiske Instituts oversættelse af IPPC's særrapport "Aviation and the Global Atmosphere, Summary for Policymakers". *Climate Centre Report 99-3* (in Danish).
- Forskning og Samarbejde 1998-1999. *Climate Centre Report 00-1* (in Danish).
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- Metoder mødes: Geofysik og emner af samfundsmæssig interesse. Dansk Klimaforums Workshop 15.-16. maj 2000. *Climate Centre Report 00-4* (in Danish).

- A time-slice experiment with the ECHAM4 A-GCM at high resolution: The simulation of tropical storms for the present-day and of their change for the future climate. *Climate Centre Report 00-5*.
- The climate of the 21 st century: Transient simulations with a coupled atmosphere-ocean general circulation model. *Climate Centre Report 00-6*.
- Changes in the storm climate in the North Atlantic / European region as simulated by GCM time-slice experiments at high resolution. *Climate Centre Report 01-1*.
- Klimadag 26 april 2001, Klimaændringer og deres virkninger. *Climate Centre Report 01-2*.
- Synthesis of the STOWASUS-2100 project: Regional storm, wave and surge scenarios for the 2100 century. *Climate Centre Report 01-3*.