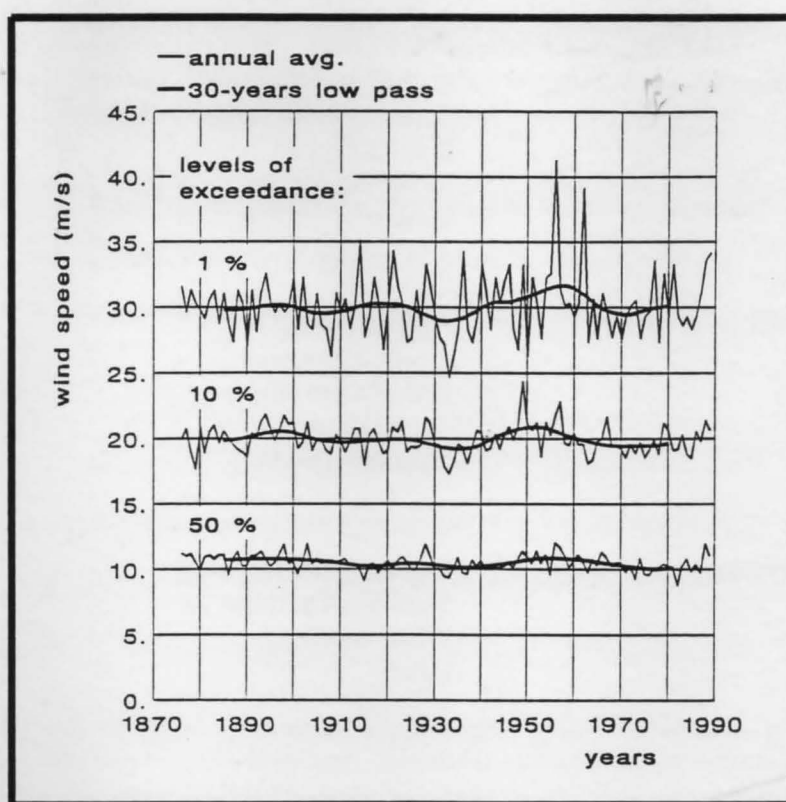# Max-Planck-Institut
für Meteorologie

REPORT No. 116

CHANGING STATISTICS OF STORMS
IN THE NORTH ATLANTIC ?

by

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Changing Statistics of Storms in the North Atlantic?

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Abstract

Problems in the present discussion about increasing storminess in the North Atlantic area are discussed. Observational data so far available do not indicate a change in the storm statistics. Output from climate models points to an intensified storm track in the North Atlantic, but because of the limited skill of present-day climate models in simulating high-frequency variability and regional details any such "forecast" has to be considered with caution.

A downscaling procedure which relates large-scale time-mean aspects of the state of the atmosphere and ocean to the local statistics of storms is proposed to reconstruct past variations of high-frequency variability in the atmosphere (storminess) and in the sea state (wave statistics). First results are presented.

1 Introduction

In December 1992 and in March 1993 Havmiljø - Overvåkning og Varsling, a subdivision of Det norske meteorologiske institutt, organized two stimulating workshops, "Climatological Trends and Future Offshore Design & Operation Criteria" in Bergen and Reykjavik. These meetings were motivated by recent alarming observations about increasing wave heights in the North Sea. An obvious candidate who might serve to explain these apparent news is a change of the statistics of storminess in the North Atlantic. During the workshops this hypothesis was discussed. No systematic overall study was at hand but several people could contribute with bits and pieces from various parts of Northwestern Europe. Interestingly nobody could report any sound evidence in favor of an increased storminess; instead there is no evidence of such a change based on data collected from fixed platforms.

In the following we summarize the discussions from Bergen and Reykjavik. First we identifiy the scientific consensus in Section 2 and review the public response in Section 3. The various bits and pieces of information on the temporal evolution of the storm statistics are the subject of Section 4. In Section 5 we discuss the perspective offered by climate model experiments conducted with the ECHAM/LSG model of the Max-Planck-Institut für Meteorologie. In Section 6 we deal with an alternative approach to derive scenarios for changing storminess: The "downscaling" technique relates statistically large-scale time-mean features, which are potentially reliably simulated by climate models, to statistical moments of the storm-related distribution, which are not well simulated by such models.

2 Scientific Consensus

Within the scientific community the discussion on climate change is no longer a discussion on the existence but merely on the strength and the pattern of the expected change. The Intergovernmental Panel on Climate Change (IPCC) represents a highly valued international body which is widely considered as representing the "scientific consensus" among the scientific community. This consensus has been presented in the two reports of the IPCC in 1990 and 1992 (Houghton et al., 1990, 1992).

The main conclusions to be drawn so far are:

- Climate Change is real. Climate change is due to internal dynamics (e.g. Little Ice Age) and, very likely, to man-made modifications of the composition of the atmosphere.

- An *upward* trend in the overall, time-mean sea level and in the overall time-mean temperature of the troposphere and of the ocean is expected. Such a general increase has been identified in the observations of the last 100 years but this signal has *not* yet unambigously been attributed to the man-made emissions of greenhouse gases and the subsequent increase of greenhouse gas concentrations in the atmosphere. There is optimism that this attribution will be possible in the upcoming decade of years.

- A change in the time-mean distribution of temperature and other fields will be associated with changes in the extratropical storm statistics. The scientific community does *not* agree on the patterns or on the sign of this change.

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3 The Public Response

There is an enhanced awareness on climate change in the public. Unfortunately this awareness goes along with a misconception of extreme events. Severe storms are no longer understood as being "normal" in the full spectrum of weather events. Instead severe storms are taken as "marks on the wall" of upcoming climate change. This public misunderstanding is intensified by some scientists who deliver information to the public on the basis of inadequate analysis. Typical errors are

- the uncritical use of time series which have undergone significant variations in quality and biases (an example is the study by Schinke, 1992). In the past 100 years the procedures to observe, report and analyse data have changed markedly so that great care is required for any analysis of historical data. Some data are almost free of such inhomogeneities (e.g., pressure readings from stations), some data sets have been or are presently corrected (e.g., global distributions of sea surface temperature) and some data sets are so strongly affected that they can hardly be used for climate change studies (e.g., minima in daily weather maps).

- the use of too short time series. Since there is considerable low-frequency variability on time scale of decades of years in the climate system these natural variations appear as *trends* if the analysis period is limited to 10 or 20 years. To do a proper diagnosis as to whether climate statistics are changing data sets of at least 40 years are required.

4 What Do We Know About Changing Storm Statistics In The Last 100 Years?

Little effort has been put in the systematic study of trends in the storminess in the North Atlantic or the North Sea. Since the increase in greenhouse gas concentration in the atmosphere is gradual, the expected climate response is a slowly evolving trend. All serious results, which we know of, indicate no such systematic change in either the frequency or the severity of storms in the past 100 years. However, the evidence available to us is far from being comprehensive:

- Daily air pressure readings from three stations surrounding the German Bight in the North Sea (Borkum, Hamburg and Fanø) allow for the calculation of homogeneous time series of geostrophic winds and, for each year from 1876 to 1989, annual distributions of the strength of the geostrophic winds. The plot of the 1%, 10% and 50% quantiles shows no trend whatsoever (Figure 1). More details of the analysis are described in Schmidt and von Storch (1993).

- The annual frequency of "severe storm days" on *Iceland* has been established on the basis of local wind observations. Since storms are quite common in Iceland rather than being an exception and the vegetation is sparse leaving most of the observing stations rather exposed, Iceland is a particularly rewarding location to study the temporal evolution of storminess in the North Atlantic.

  Wind observations, based on an observer assessment made on the Beaufort scale (0 - 12), have been available from a changing

Figure 1: *Time series of the 1%, 10% and 50% quantiles derived from annual distributions of daily geostrophic wind speeds in the German Bight (Southeast North Sea).*
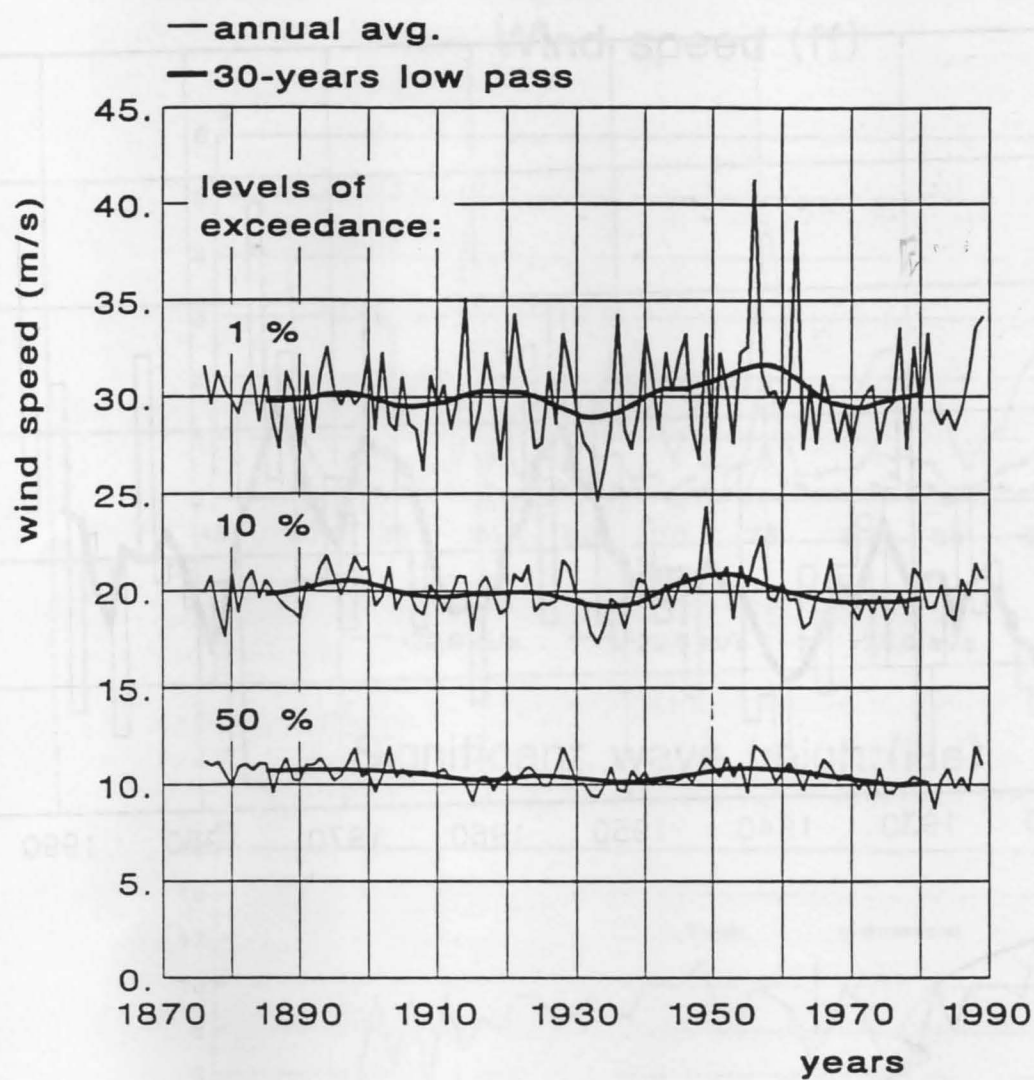
Figure 2: *Number of severe storm days in Iceland per year (July through June). In 1949 the observation practice was changed so that the present plot exhibits an inhomogeneity in that year. After (before) that year the time series are (almost) homogeneous.*
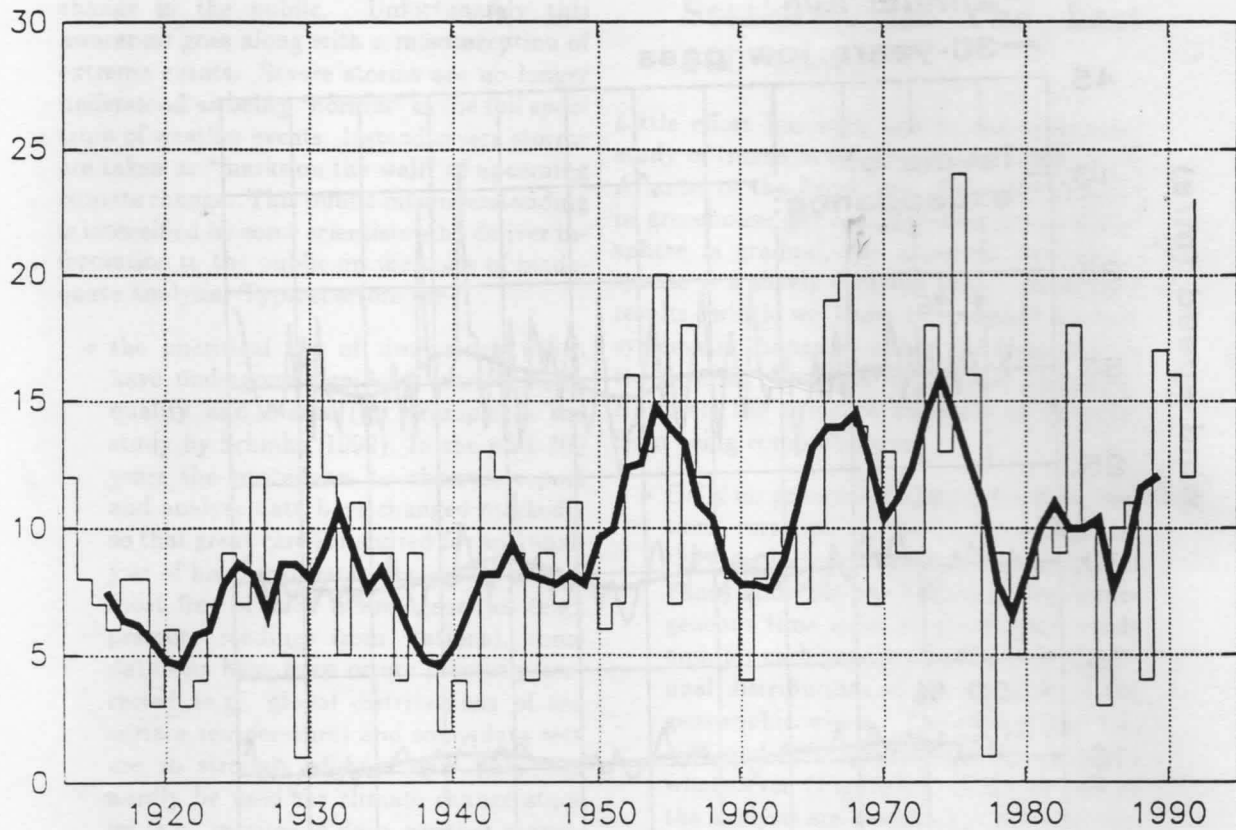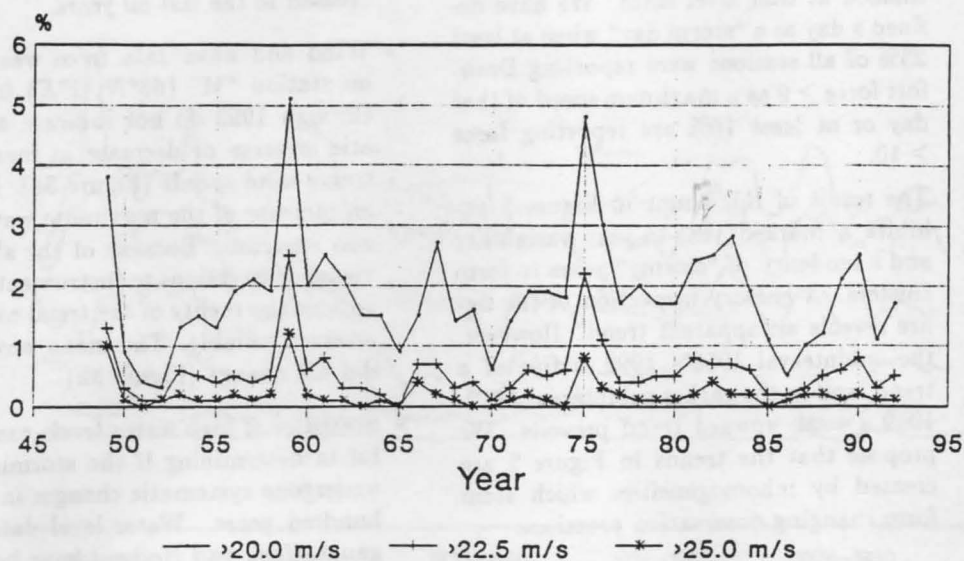
Figure 3: *Time series of annual wind and wave statistics derived from observations made on board of weatherships on station "M" (66°N, 2°E). a) Frequency of winds above some thresholds. b) Maximum and mean wave height within a year. Note the discontinuity in 1979 from visual to instrumental observation.*

Wind speed (ff)

— >20.0 m/s   —+— >22.5 m/s   —*— >25.0 m/s

Significant wave height(Hs)

— Max Hs   —+— Mean Hs
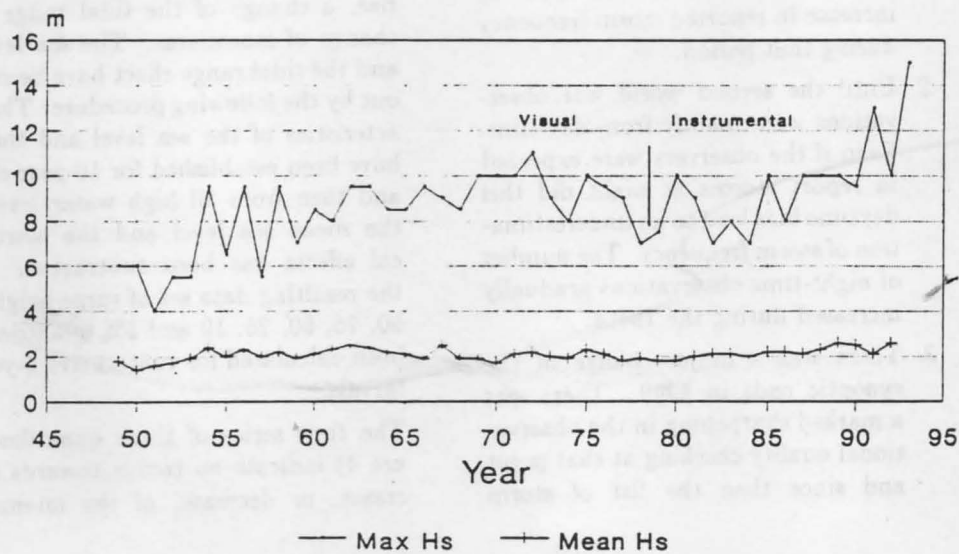
numbers of stations from 1912 to 1992. The number of stations reporting wind was 12-20 before 1920, then steadily growing in numbers until the early 1960s when the number reached about 80 and has remained at that level since. We have defined a day as a "storm day" when at least 25% of all stations were reporting Beaufort force ≥ 9 as a maximum speed of that day or at least 10% are reporting force ≥ 10.

The result of this count in Figure 2 exhibits a marked year-to-year variability and a tendency of "stormy" years to form clusters. A cursory inspection of the figure reveals an apparent trend. However, the subinterval 1950 - 1992 is free of a trend, and in the earlier subinterval 1912-1949 a weak upward trend prevails. We propose that the trends in Figure 2 are created by inhomogeneities which stem form changing observation practises:

1. There is a marked difference in storm frequencies at coastal and inland stations. Arround 1930 the number of coastal stations increased disproportionately. This leads to an apparent increase in reported storm frequency during that period.

2. Until the second world war observations were mainly from day-time. Even if the observers were expected to report storms at night did this daytime bias lead to an underestimation of storm frequency. The number of night-time observations gradually increased during the 1940s.

3. There was a major change in the synoptic code in 1949. There was a marked sharpening in the observational quality checking at that point and since then the list of storm
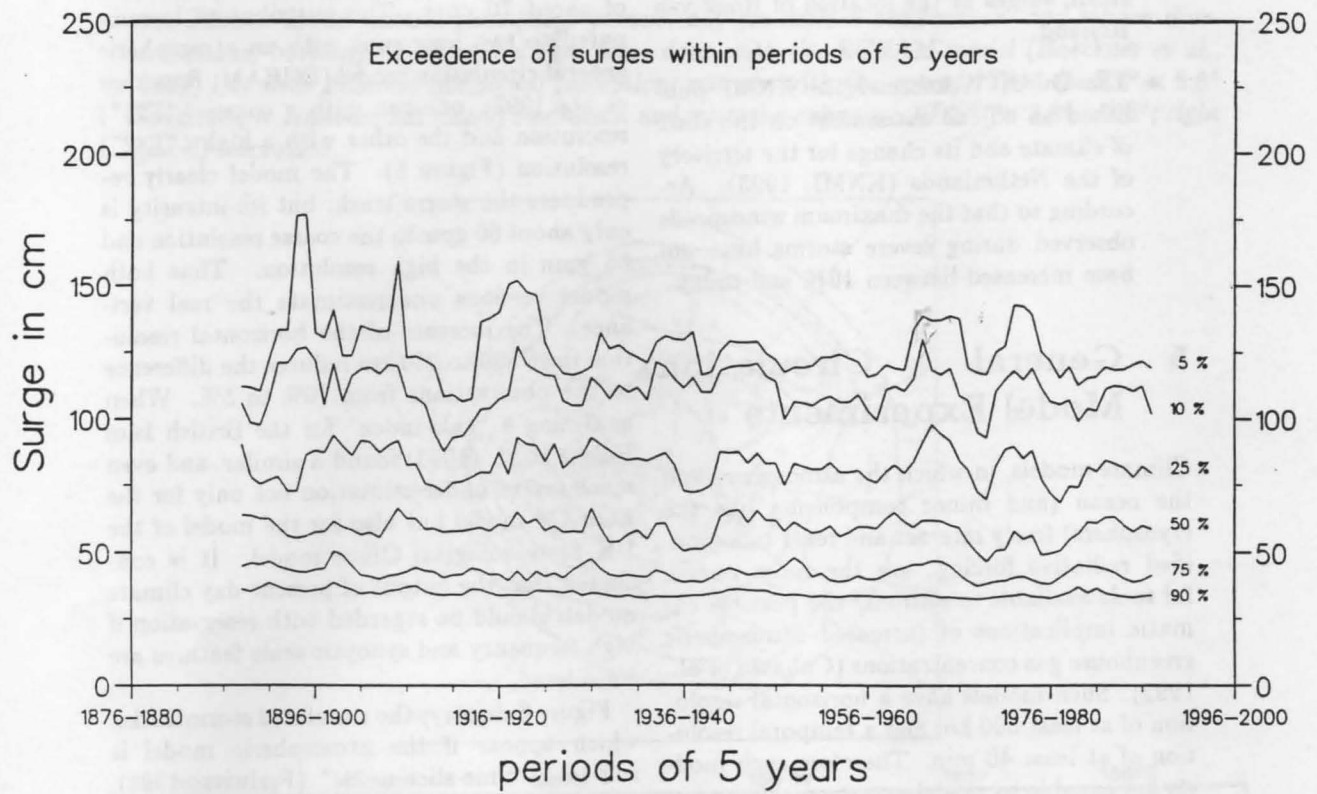
events is probably more or less homogeneous.

We conclude that the frequency of storms on Iceland has not systematically increased in the last 80 years.

• Wind and wave data from weatherships on station "M" ($66^{\circ}N$, $2^{\circ}E$) from 1949 through 1992 do not indicate a systematic increase or decrease in mean or extreme wind speeds (Figure 3a). However, an increase of the maximum wave height was reported. Because of the shift from visual observations to instrumental observations the reality of the trend can not be assessed reliably. The mean wave height did not change (Figure 3b).

• Statistics of high water levels can be useful in determining if the storminess has undergone systematic changes in the last hundred years. Water level data of the gauge *Hoek van Holland* have been analyzed in this respect.

In the raw water level data there are, at least, three different processes which might create a long-term trend: a sea level rise, a change of the tidal range and a change of storminess. The sea level rise and the tidal range effect have been taken out by the following procedure: The characteristics of the sea level and the tides have been established for 10-year chunks, and then from all high water level data the mean sea level and the astronomical effects has been subtracted. From the resulting data set of surge heights the 90, 75, 50, 25, 10 and 5% quantiles have been calculated for consecutive 5-year intervals.

The time series of these quantiles (Figure 4) indicate no trends towards an increase, or decrease, of the intensity of

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Figure 4: *Quantiles of distributions of surge heights at Hoek van Holland.*

Surge in cm

Exceedence of surges within periods of 5 years

5 %
10 %
25 %
50 %
75 %
90 %

1876–1880   1896–1900   1916–1920   1936–1940   1956–1960   1976–1980   1996–2000

periods of 5 years

storm surges at the location of Hoek van Holland.

- The Durch Weatherservice KNMI published an official assessment on the state of climate and its change for the territory of the Netherlands (KNMI, 1993). According to that the maximum windspeeds observed during severe storms have not been increased between 1910 and today.

5 General Circulation Model Experiments

Climate models, in which the atmosphere and the ocean (and minor components like the cryosphere) freely interact and react to a modified radiative forcing, are the most powerful tools available to estimate the possible climatic implications of increased atmospheric greenhouse gas concentrations (Cubasch et al., 1992). Such models have a horizontal resolution of at least 500 km and a temporal resolution of at least 40 min. Therefore such models are capable to model extratropical storms. However, because of the relatively small scale of storms, typically of the order of a couple of thousand kilometers. climate models are not considered as particularly skillful in the simulation of stormtracks and of individual storms.

A good way to represent the stormtracks is to compute the standard deviation of the bandpass filtered variability of the 500 hPa height field. Typical settings for the band pass filter are to retain all variability between 2.5 and 6 days so that the characteristic times of cyclones are well captured but all variability due to low frequency events. like blockings. are taken out. For the present climate. the bandpass filtered standard deviation. obtained from routine daily analysis, are shown in Figure 5 (from Metz and Lu, 1990). The North Atlantic storm track is clearly visible with a maximum

of about 70 gpm. This distribution is compared to two long runs with an atmospheric general circulation model (ECHAM; Roeckner et al., 1992), one run with a coarse ("T21") resolution and the other with a high ("T42") resolution (Figure 5). The model clearly reproduces the storm track, but its intensity is only about 60 gpm in the coarse resolution and 65 gpm in the high resolution. Thus both model versions underestimate the real variance. The increase of the horizontal resolution from 500 to 250 km reduces the difference to the observations from 10% to 5%. When analysing a "gale index" for the British Isles Hulme et al. (1993) found a similar, and even more severe underestimation not only for the ECHAM model but also for the model of the UK Meteorological Office model. It is concluded that the output of present day climate models should be regarded with reservation if high-frequency and synoptic scale features are considered.

Figure 6 displays the simulated stormtracks, which appear if the atmospheric model is run in a "time-slice mode" (Perlwitz, 1994). Sea-surface temperature anomalies and sea-ice distributions, which have been obtained in a climate change experiment with the coupled ECHAM/LSG atmosphere-ocean model (Cubasch et al., 1992), are specified as boundary conditions in these atmosphere-only experiments. Mean conditions from the last decade ("2076-2085") in an IPCC scenario A "business as usual" ($\approx 1\%/year$) climate change experiment are used. The radiative forcing is specified according to situation envisaged by the IPCC scenario during the decade "2075-2085". In both resolutions the model responds to the changed boundary conditions with an intensified storm track, with a maximum of 60 gpm in the coarse resolution and 70 gpm in the high resolution. The simulated response to the modified radiative forcing is thus comparable to the model error found earlier.

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Figure 5: *Bandpass (2.5 - 6 days) filtered variance of 500 hPha height during winter (December-January-February) derived from operational analyses (top, from Metz and Lu, 1990) and from two climate model control runs (both present day sea-surface temperature and sea-ice diustributions; bottom). Both model runs were done with the ECHAM-model (Roeckner et al., 1992) but with different horizontal resolution, namely with the coarse "T21" (≈ 5.6° × 5.6° longitude × latitude; left panel) resolution and with the enhanced "T42" (≈ 2.8° × 2.8°; right panel) resolution.*
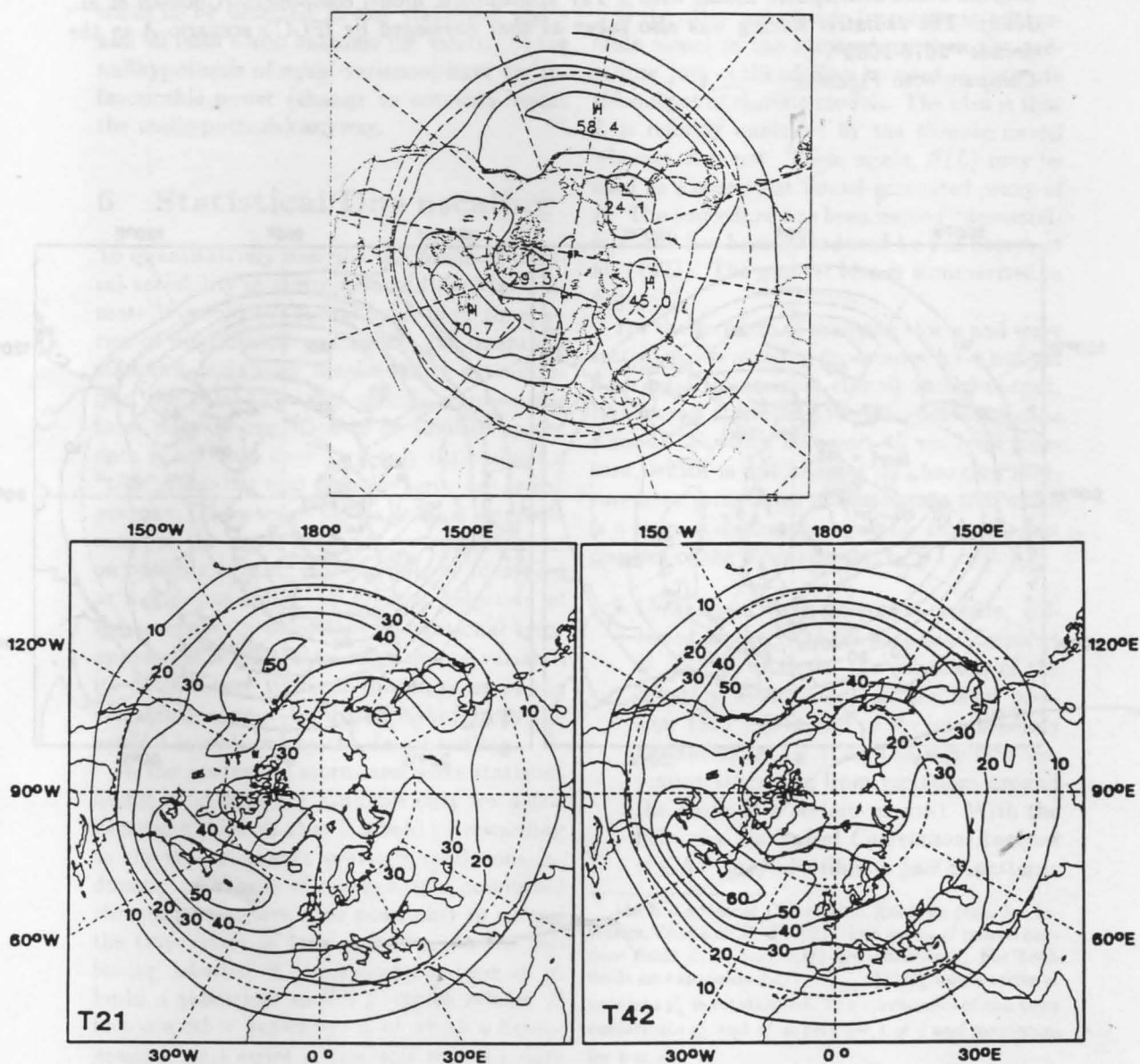

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Figure 6: *Bandpass (2.5 - 6 days) filtered variance of 500 hPha height during winter (December-January-February) from two climate model runs forced with anomalous sea-surface temperature, sea-ice conditions and radiative conditions. Both runs were made with the same model, namely ECHAM (Roeckner et al., 1992) but with different resolutions: "T21" ($\approx 5.6° \times 5.6°$ longitude $\times$ latitude; left panel) and "T42" ($\approx 2.8° \times 2.8°$; right panel). The sea-surface temperature and sea-ice distribution was specified according to the state which was simulated in the decade "2075-2085" in an "IPCC Scenario A" climate change experiment with a fully coupled ocean-atmosphere model with a T21 atmospheric model component (Cubasch et al., 1992). The radiative forcing was also taken as that envisaged by IPCC's scenario A in the decade "2075-2085".*

Compare with Figure 5.
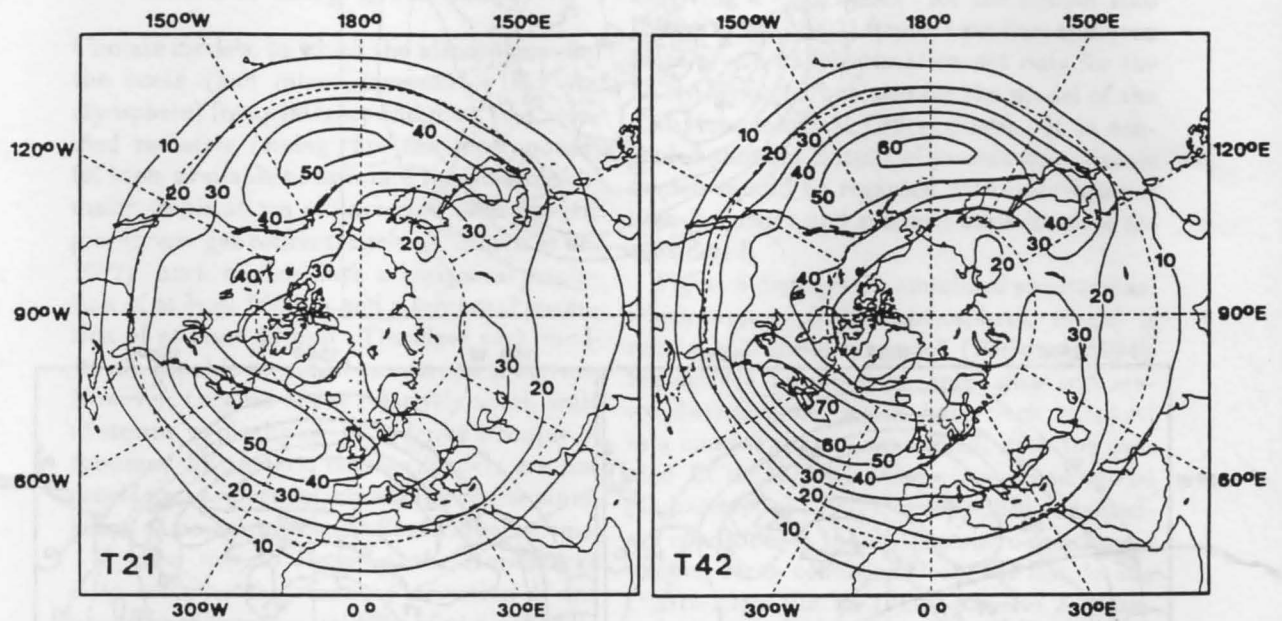
The increase in the storm-related standard deviation in the "T42" resolution model is 5 gpm, which is about 8% of the value in the control run. An increase by 8% in 100 years would limit the increase in the first decades to less than 1%. Such a value is much too small to be detected in any statistical test - and all tests which examine the validity of the nullhypothesis of equal variances have an unfavourable power (change to correctly reject the nullhypothesis) anyway.

6 Statistical Downscaling

To quantitatively describe the limits of natural variability in storminess and the wave climate it would be desirable to have time series of distribution parameters (as quantiles, standard deviations, means) which extend far into the past. For this specific purpose the most relevant condition to be fulfilled by the data is not that they vary only little about a "true" value but that the time series are *homogeneous*. There must be no gradual improvement of the data, because any improvement on possibly existing biases would be identified as a spurious trend. A gradual reduction of the uncertainty or of the observational error appears as a systematic reduction of variability so that any trend in the mean or in the variability cannot be distinguished from the artifact introduced by the data handling.

In the context of storm and wave statistics useful local data are available only for a few decades at best so that it would be rewarding to try to reconstruct previous conditions indirectly by means of other, better monitored climate parameters. One possibility to extend the time series of local statistics, in the following labelled R, backwards in time is to build a statistical model $\mathcal{F}$ which relates R to some other parameter L of which a homogeneous time series is available over a longer time. Then the longer time series of L may be used to estimate R by $\tilde{R} = \mathcal{F}(L)$. The result is a homogeneous time series of an estimate $\tilde{R}$ of the local parameter R which hopefully does not vary too strongly around the true R - but which might do so.
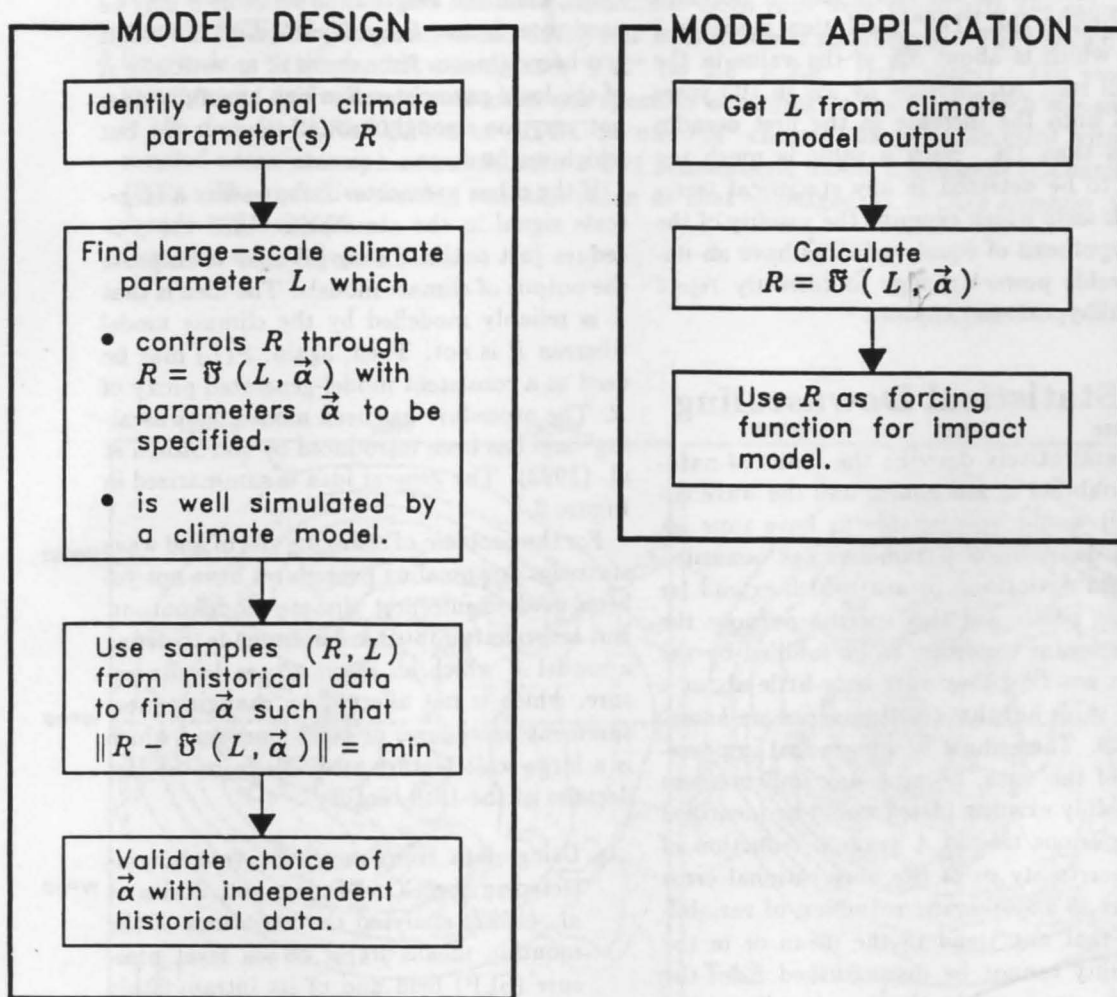
If the other parameter L represents a large-scale signal in the atmosphere then the procedure just outlined may be used to improve the output of climate models. The idea is that L is reliably modelled by the climate model whereas R is not. Then, again, $\mathcal{F}(L)$ may be used as a consistent model-generated proxy of R. The procedure has been named "downscaling" and has been introduced by von Storch et al. (1993). The general idea is summarized in Figure 6.

For the problem of changing storm and wave statistics downscaling procedures have not yet been used to interpret climate model output. But several attempts have been made to define a model $\mathcal{F}$ which all resort to sea level pressure, which is not affected by changing measurement procedures or techniques and which is a large-scale feature available from the last decades of the 19th century.

- Using data from merchant vessels, collected in the COADS data set, Zorita et al. (1992) analysed the variations of the monthly means μ_{SLP} of sea level pressure (SLP) field and of its intramonthly variability σ_{SLP} (i.e., the standard deviation stemming from variations around the mean of a certain month). With the help of a *Canonical Correlation Analysis* (CCA)[1] they identified a pair of patterns

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[1] In a Canonical Correlation Analysis (see, for instance, Zorita et al., (1992)) time series of paired random fields $\vec{x}_1(t)$ and $\vec{x}_2(t)$ are considered. For both fields an expansion $\vec{x}_i(t) = \sum_k z_k^i(t)\vec{p}_k^i$ into a series of patterns $\vec{p}_k^i$ is established. The correlation of two time coefficients z_k^1 and z_j^2 is zero for $k \neq j$ and maximum for $k = j$.

Figure 7: *Concept of downscaling procedure.*

MODEL DESIGN

Identify regional climate
parameter(s) R

Find large-scale climate
parameter L which

- controls R through
  $R = \mathfrak{F}(L, \vec{\alpha})$ with
  parameters $\vec{\alpha}$ to be
  specified.

- is well simulated by
  a climate model.

Use samples (R, L)
from historical data
to find $\vec{\alpha}$ such that
$\| R - \mathfrak{F}(L, \vec{\alpha}) \| = \min$

Validate choice of
$\vec{\alpha}$ with independent
historical data.

MODEL APPLICATION

Get L from climate
model output

Calculate
$R = \mathfrak{F}(L, \vec{\alpha})$

Use R as forcing
function for impact
model.

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$\bar{P}$ of μ_{SLP} and $\bar{Q}$ of σ_{SLP}. The projection of the mean SLP field $\mu_{SLP}(t)$ of any winter (December-January-February) on the pattern $\bar{P}$ yields a coefficient $L(t)$. Likewise the projection of the standard deviation $\sigma_{SLP}(t)$ of a winter on the pattern $\bar{Q}$ yields a coefficient $R(t)$. The CCA has been designed such that the correlation of the two coefficients $R(t)$ and $L(t)$ is maximum. In the downscaling context the L-parameter represents the better documented variable whereas the less well known variable is the intramonthly standard deviation R. The correlation between the two coefficients defines the statistical model $\mathcal{F}$. The two optimally correlated patterns $\bar{P}$ and $\bar{Q}$ are shown in Figure 8. Note that the patterns describe anomalies around the long term means of μ_{SLP} and σ_{SLP}.

- A generalization of the Zorita et al. approach is the following. The mean North Atlantic circulation in winter is represented by the winter mean SLP field μ_{SLP}. As local parameter which is less known the distribution of daily pressure values at some location, in this case at $60°N$ and $0°E$, is chosen. Using gridded data from 1955 through 1985 a CCA is made to identify the two patterns $\bar{P}$ and $\bar{Q}$ in the two vector time series, which are made up of spatially distributed winter mean SLP values and of the distribution function of daily SLP values within the considered winter. The two patterns, which both represent anomalies around the mean state, are shown in Figure 9. A mean circulation, represented by a low slightly southwest of $60°N$, $0°E$ is connected with a general lowering of the air pressure at that location and adds, on an average, a wide tail towards small pressure values to the distribution. The ar-

gument is linear so that an anomalous high over Scotland goes with an overall increase of local daily SLP. Again $R(t)$ is the coefficient of the distribution-pattern $\bar{Q}$ and $L(t)$ is the coefficient of the circulation pattern $\bar{P}$. The correlation of 0.9 between R and L establishes the statistical linear model $\mathcal{F}$.

Then, $\mathcal{F}(L(t))$ is an estimate of a distribution of daily pressure values from which 10% and 90% quantiles may be derived. Smoothed time series, from 1900 to 1990, of these estimated quantiles as well as of the time series derived from the raw daily data are shown in Figure 10. On the year-to-year time scale the two curves deviate a bit but on the low-frequency time scale the similarity of the two curves is good. Apparently the downscaling procedure yields useful results not only for the "fitting" period but also prior to 1955.

- Regular and reliable measurements of the ocean wave field have been carried out only during the last 20 to 30 years. To get an estimate of the long term evolution of the wave climate it is therefore required to apply indirect methods. In the present example analyses of mean sealevel air pressure for the years 1881 - 1992 have been used to establish time series of monthly mean significant wave height for selected positions. This downscaling approach was done in several steps.

  - High quality air pressure fields (on a 75 km grid; every 6 hours), have been analysed by Det norske meteorologiske institutt (DNMI) for the years 1955 - 1992. From these pressure analyses 6 hourly winds 10 m above sea level have been computed on the same grid. With this set of wind data a numerical wave model

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Figure 8: *Canonical Correlation Patterns* $\vec{\mathbf{P}}$ *and* $\vec{\mathbf{Q}}$ *of the winter (December-January-February) mean sea level pressure field* μ_{SLP} *(top) and of the intramonthly variance* σ_{SLP} *(bottom). Both patterns represent anomalies around the long-term mean fields and share a maximum correlation of their coefficients. The shading represents maximum values in the other diagram. (from Zorita et al., 1992)*
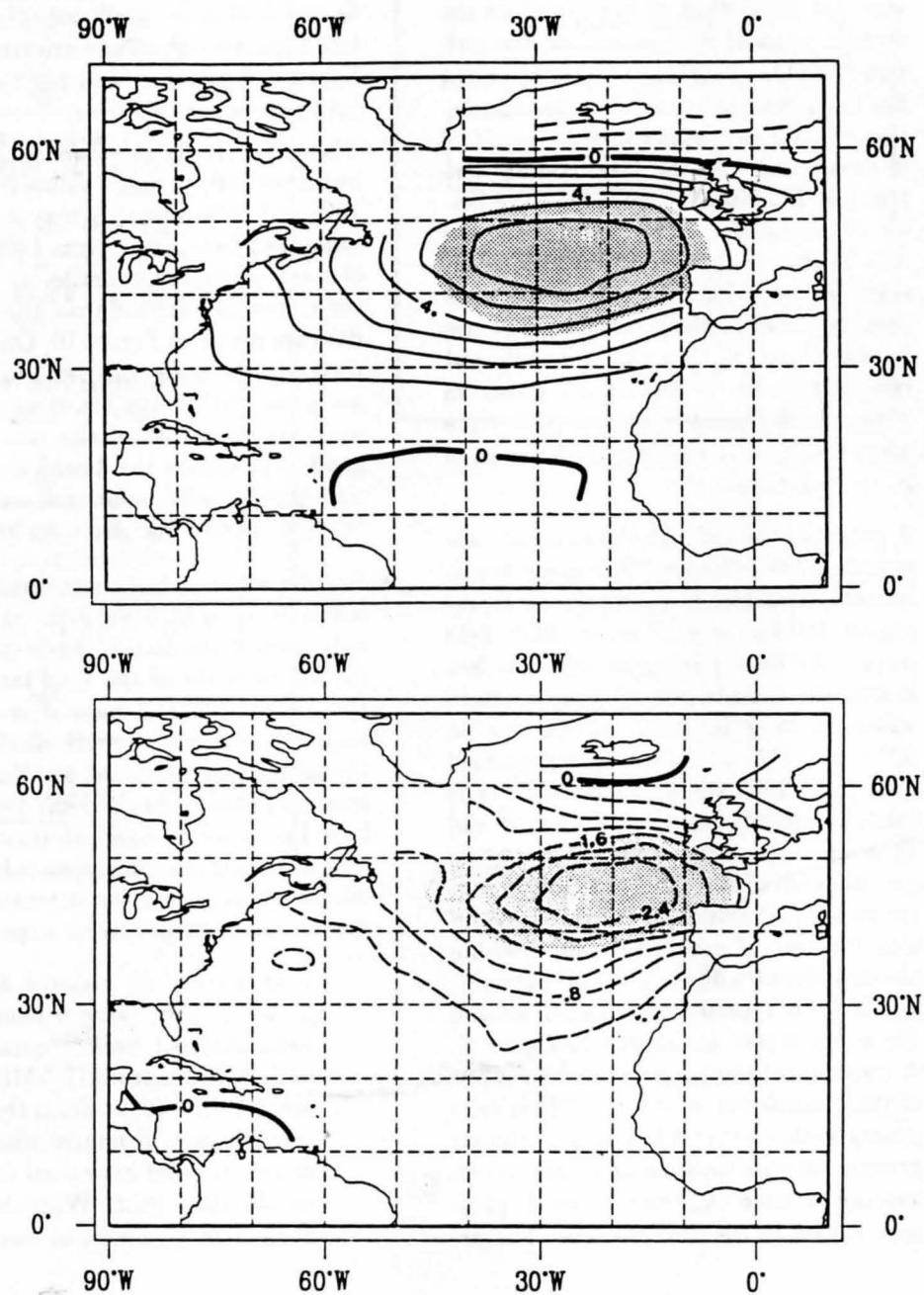
Figure 9: *Canonical Correlation Patterns* $\vec{P}$ *and* $\vec{Q}$ *of the winter (December-January-February) mean sea level pressure field* μ_{SLP} *and of the frequency distribution of daily air pressure at* $60^{\circ}N$, $0^{\circ}E$. *Both patterns represent anomalies around the long-term mean fields and share a maximum correlation (0.9) of their coefficients.*
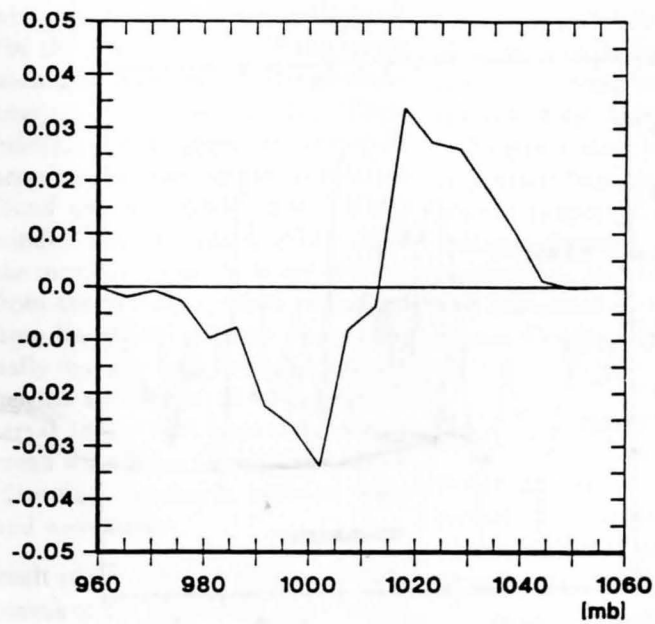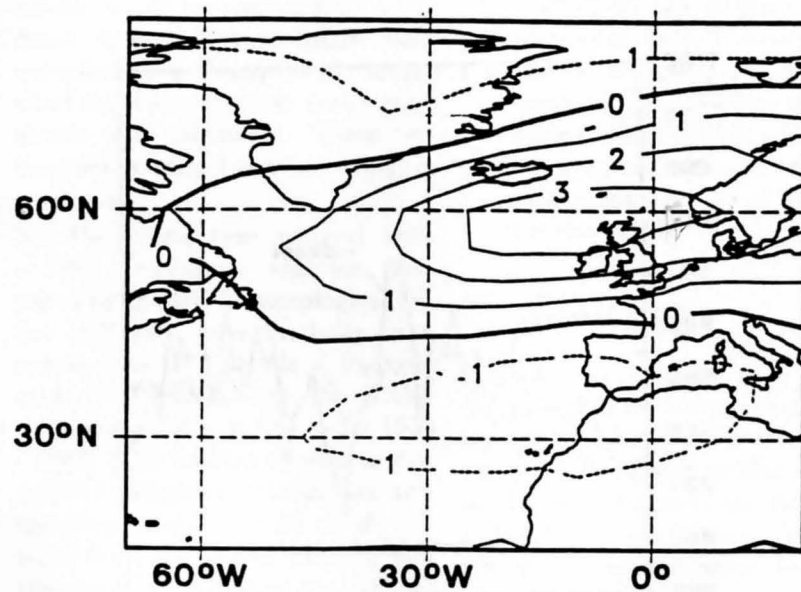
Figure 10: *10% and 90% quantiles of the distributions of daily sea level pressure during winters (December-January-February) at $60°N$, $0°E$ from 1900 through 1990. The solid line represents the quantiles derived from the raw local data and the dashed curves stems from the estimated distributions, as given trough the CCA model $\mathcal{F}$ defined by Figure 9. The series have been subjected to a 5-year running mean filter.*
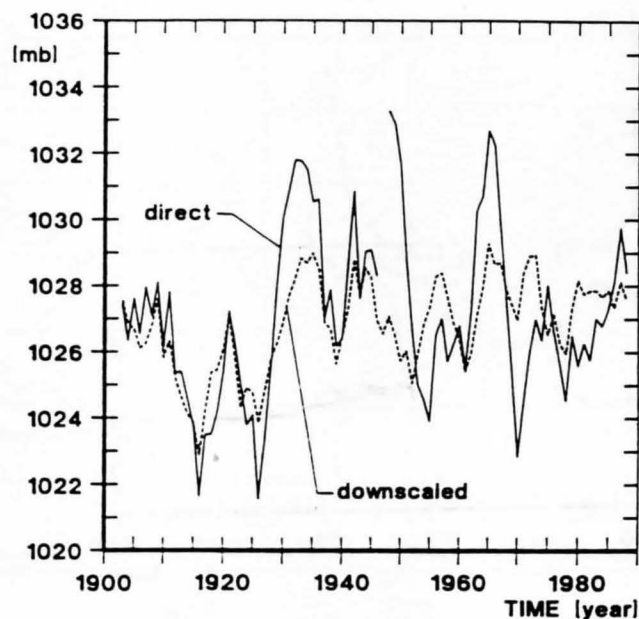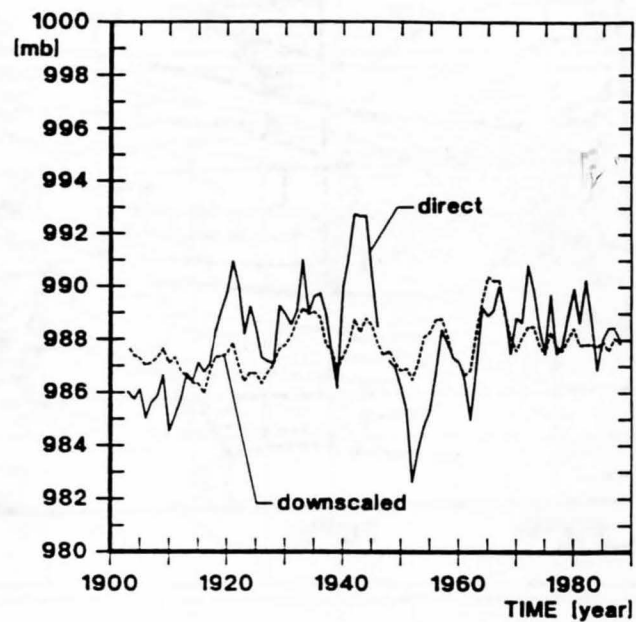
has been run so that best estimates of the wave field were available for the interval 1955 - 1992. From the model output time series of monthly mean significant wave height were extracted and from the 6 hourly wind fields the monthly mean wind speeds were calculated. These two time series turned out to be highly correlated.

- For the longer time interval 1881 - 1982 air-pressure analyses, prepared by the UK Meteorological Office (UKMO), were available on a coarse $5° \times 10°$ latitude $\times$ logitude grid. The UKMO and the DNMI data sets overlap in the years 1955 - 1982. This overlap is used to calculate an empirical relation between the (supposedly better) winds derived from the DNMI product and the winds derived from the UKMO product.

- In the last step the monthly mean wind speeds have been estimated. For the years 1881 - 1954 the winds computed from the UKMO pressure analyses have been used. These monthly wind speeds are corrected according to the empirical relation found between DNMI and UKMO winds. For the years 1955 - 1992 the monthly mean winds are derived from the 6 hourly winds computed from the DNMI pressure maps. Finally monthly mean significant wave heights are calculated for the full interval 1881 - 1992 from the monthly mean wind fields through the earlier identified correlation between wind and wave height.

The result of this exercise is shown for annual means of the significant wave height at one location ($61°N$, $2°E$) in Figure 11. In the last 5 years, or so, the annual mean wave heights have been larger than in the last 90 years. This recent development does, however, not appear as part of a general, possibly accelerating, trend; also the absolute values are comparable to those of 1880 - 1900 (even if these early estimates should be considered with reservation because of the quality of the pressure analyses).

7 Epilogue

Motivated by the concerns in the insurance industry and in the European offshore oil industry about an increase of storminess, we have reviewed our present understanding about the temporal evolution of the statistics of storms in the Northeast Atlantic. This knowledge is not at all comprehensive, but it is made up of samples from various sources derived from meteorological stations along the Northwest European coasts. This information, even if it represents just bits and pieces of a more complete picture, indicates the absence of a systematic increase or decrease of storminess in the Northeast Atlantic area.

To give a more comprehensive answer more systematic studies are required. A joint project supported by institutions from Great Britain, Norway, Sweden, Denmark, The Netherlands and Germany has been prepared and submitted to the Commission of the European Community for funding.

8 Acknowledgements

Figure 11: *Annual mean significant wave height (in m) for 61°N, 2°E as estimated from sea level pressure data. The height is given as anomaly from the mean (2.88 m).*
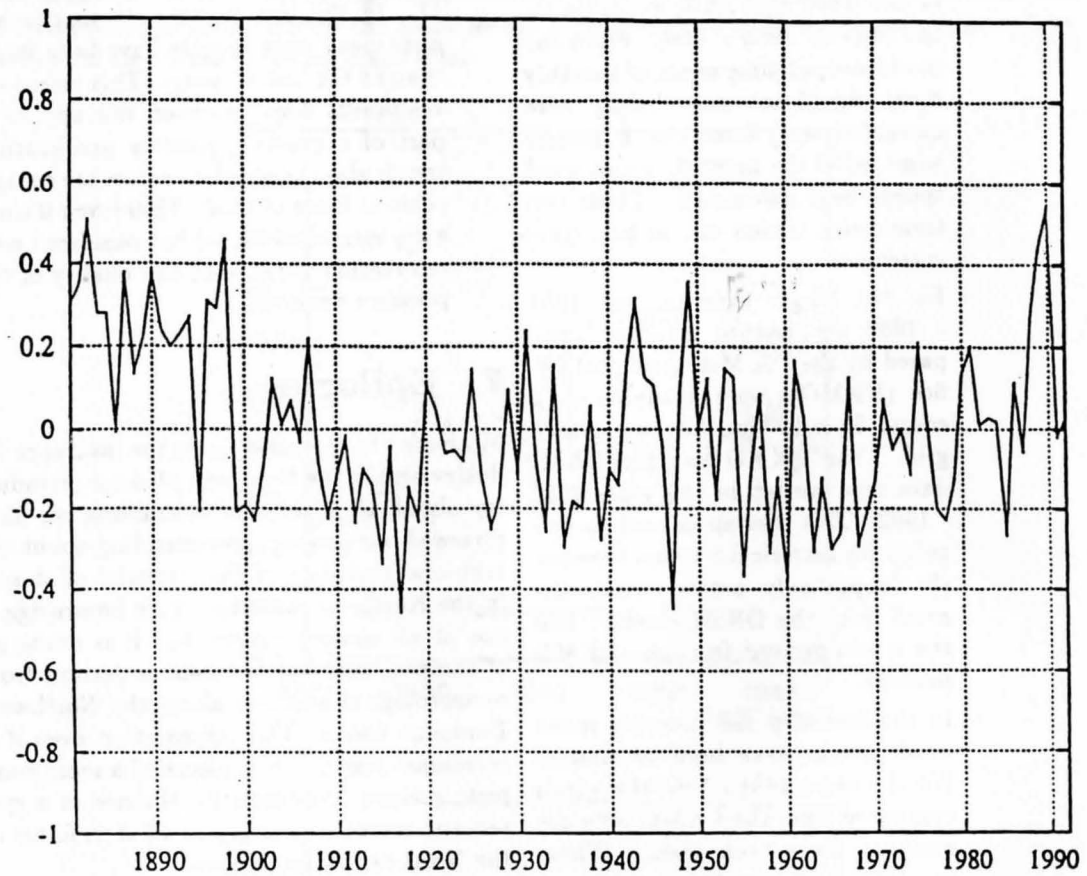
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