A final comment. It was disappointing to find no real mention of Bayesian methods in this report. There is some irony here, since a number of commonly used methods (kriging, for example) have a strong Bayesian flavor. In any case, whatever their predilections, statisticians must recognize that there have been enormous advances in practical Bayesian methods. Some of us actually use them!

Comment

Hans von Storch

1. GENERAL

Being in the process of preparing a monograph on "statistical analysis in climate research," I was intrigued by the title of the report of the National Research Council on the present use and future need of statistics in physical oceanography. But after having gone through it I became rather disappointed—apparently these people had a "physical oceanography" in mind which had hardly any overlap with the type of problems which I meet in my own research. Relevant topics were not mentioned, such as the variability of the thermohaline circulation (note that the deep ocean was excluded in Figure 2.1 of the report) and its implications for the global climate. Influential names, such as Frankignoul, did not appear. Fundamental papers, such as that of Hasselmann (1976) on stochastic climate models, were not cited. The data assimilation issue related to preoperational predictions of the oceans were not sufficiently taken into account (see Derber and Rosati, 1989, or Mellor and Ezer, 1991). I could not even identify the members of the committee who supposedly represent the community of physical oceanographers.

The solution to this inconsistency is likely that neither the committee nor I—and my colleagues whom I have contacted in this matter—represent the full spectrum of statistical thinking in what is called physical oceanography. I have to admit that I am in touch with only a narrow window of the spectrum, namely, that part with relevance for the dynamics of climate and for the concept of climate change. In the following I will go through a number of examples of statistical thinking in our field. These examples have been encountered by the Climate Dynamics and Oceanography division of the Max-Planck-Institut für Meteorologie in Hamburg, in the past.

2. THE IDENTIFICATION OF DYNAMICAL SUBSYSTEMS

The dynamics of the ocean operate on a large phase space with spatial and temporal scales spanning a wide range. The sheer amount of information, representing the state of the ocean during any well-documented interval of time, inhibits any complete description of the oceanic dynamics—independently if we work with observed or simulated data. Therefore it is advisable, or even required, to split the full phase space into a "signal" subspace and a "noise" subspace. The definition of the two subspaces depends, of course, strongly on the considered problem: The physically significant part of the dynamics span the "signal" subspace whereas the "noise" subspace comprises those processes which contribute to the dynamics only through their overall statistics and not through their details. The identification of such dynamical subsystems represents a major challenge for ocean sciences.

2.1 Stochastic Climate Models

In the "stochastic climate model" approach (Hasselmann, 1976) the separation into signal and noise subspaces is done by means of time scales. The "high-frequency" part is considered as "noise" whereas the "low-frequency" part is understood as being the dynamical response to the "noise." To keep the system stationary, negative feedback must prevail in the "signal" subspace.

This concept has been applied to modeling the dynamics of sea-ice variability (Lemke, 1977) and of sea-surface temperature variability (Frankignoul and Hasselmann, 1977; Ortiz Bévia and Ruiz de Elvira, 1985; Herterich and Hasselmann, 1987). More recently the concept has been used in a "stochastically forced" ocean general circulation model experiment (Mikolajewciz and Maier-Reimer, 1990). In this run the ocean model was forced with climatological conditions without any temporal vari-

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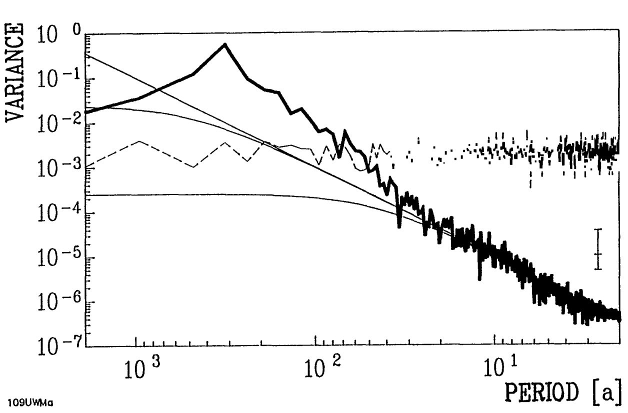

FIG. 1. *Results from a "stochastically driven" ocean general circulation model experiment over several thousand years; variance spectra of the following: (heavy line) the mass transport through the Drake Passage (the "signal"); (dashed line) the freshwater flux into the Southern Ocean (the "noise"); and first-order autoregressive models with a linear negative feedback term with characteristic times of* 50 *years or* 500 *years and without feedback. (From Mikolajewicz and Maier-Reimer,* 1990.)

ations apart from the annual cycle. Additionally a time-variable freshwater flux was imposed which was "white" in time (a time step of one month) and slightly correlated in space. The ocean (including its deep part) responded to this stochastic forcing with marked low-frequency variations. Figure 1 shows the variance spectra of the freshwater flux into the Southern Ocean and of the transport through the Drake Passage. For comparison also the spectra of fitted red-noise processes are added. The "slow" ocean dynamics seemingly integrate the "noise" into low-frequency variations. Apart from the general accumulation of energy at low frequencies there is a preference for a quasi-cyclic behaviour at a time scale of 300–400 years. It is likely that these spectral peaks represent an eigenmode of the Atlantic Ocean.

2.2 PIP's and POP's

A general formalism for the identification of dynamical subspaces has been proposed by Hasselmann (1988) by his "principal interaction patterns" (PIP's) approach. The idea is to postulate that the "signal" subspace is spanned by a specified number of (yet unspecified) coordinates. Within this space the dynamics are controlled by a set of rules. These rules are specified in their functional form but unknown with respect to a finite set of parameters. Then, the coordinates and the parameters are chosen such that they explain the temporal evolution of the data field in an optimal way.

A simplified, easily implemented version of the PIP's are the "principal oscillation patterns" (POP's, von Storch et al., 1988). POP's are designed to identify two- and one-dimensional subspaces in which the temporal evolution of the coordinates are represented by bivariate or univariate autoregressive processes of first order. This POP technique is now widely used in oceanic and atmospheric sciences [for a review, see von Storch et al. (1994); examples of POP analyses of oceanic variability are provided by, among others, Xu (1993) and Weisse, Mikolajewicz and Maier-Reiner (1993)]. An interesting application has been presented by Mikolajewicz (1990) when analysing the "stochastically forced" ocean general circulation model experiment mentioned above. To isolate the dynamics of the spectral peak, the POP analysis of a two-dimensional latitude-depth cross section through the Atlantic Ocean revealed a two-dimensional subspace within which the system generates stochastic oscillations with a "period" of about 360 years. The two patterns $\vec{p}_1$ and $\vec{p}_2$ which span the two-dimensional "signal"-subspace are depicted in Figure 2. The system tends to create sequences of the type $\cdots \to \vec{p}_1 \to \vec{p}_2 \to -\vec{p}_1 \to \cdots$.

The POP technique has been generalized in two ways. In the "cyclostationary" POP analysis (Blumenthal, 1991) the data are no longer considered to be stationary. Instead the moments may vary with an external deterministic cycle (such as the annual cycle or the diurnal cycle). In the "complex" POP analysis (Bürger, 1993) the (real-valued) vector data are augmented with an imaginary component being the Hilbert transform of the data field. In this way not only the "location" but also, in some general sense, its "momentum" are made available for the analysis.

3. CLIMATE CHANGE

A climate change, with a general warming of the ocean and the atmosphere, is expected by the majority of climate researchers to evolve as a response to the increasing concentrations of greenhouse gases in the troposphere (Houghton, Jenkins and Ephraums, 1990; Haughton, Callander and Varney, 1992). For physical oceanography several important problems arise—apart from the ocean's role in the carbon cycle.

3.1 The Detection Problem

One of the problems is the unequivocal detection of the warming signal which is competing with intermittent slow warmings stemming from natural variations within the climate system. The detection takes the form of a statistical test with the null hypotheses "the present warming is due to internal dynamics." To have sufficient power, it is preferable to test this null hypothesis not in the full high-dimensional phase space but in a low-dimensional subspace. This subspace should have a favourable

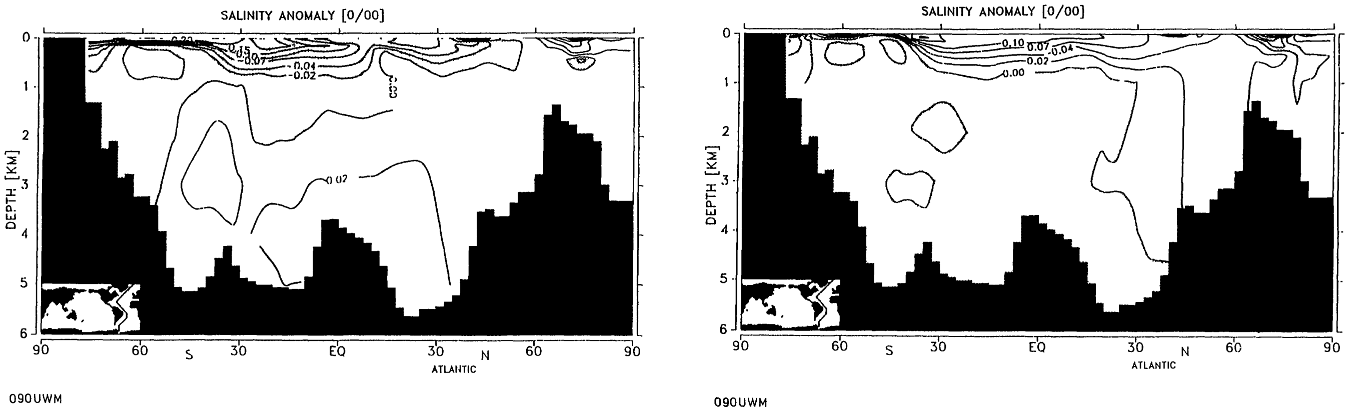

FIG. 2. *Results from a "stochastically driven" ocean general circulation model experiment: patterns $\vec{p}_1$ (left) and $\vec{p}_2$ (right) in the latitude–depth field of Atlantic Ocean salinities anomalies (deviations from the climatological mean). The two patterns span the two-dimensional "signal"-subspace in which the spectral peak at* 360 *years (see Figure* 1) *is generated. The system creates trajectories which rotate around the origin with a mean period of* 360 *years.* (*From Mikolajewicz,* 1990.)

"signal-to-noise" ratio. Thus, not the strength of the signal matters for the detection problem but its "visibility" in the "sea of noise."

Therefore it is very reasonable to attempt to detect man-made climate change in the ocean, where the absolute signal might be small but where, at the same time, the noise is small also. This idea has been pursued in Munk and Forbes' (1989) proposal of an array of long-range acoustic transmissions from the southern Indian Ocean. The speed of the sound waves depends on the temperature. Therefore an increase of temperature should be reflected in a decrease of the travel time of sound waves. Monitoring global-scale travel paths, say, extending from the Indian Ocean to the United States west coast, should reduce the noise in the data considerably.

This idea has been tested in a model experiment by Mikolajewicz, Maier-Reimer and Barnett (1993), who used model-based estimates of the natural variability and of the expected climate change signal to assess the chances for the proposed project to be successful. They found that the chances to detect climate change within the next 10 years would be low if just one acoustic receiver would be installed. If, however, the locations of a set of receivers were chosen carefully, such that the expected "signal-to-noise" ratio is optimized, the method could well achieve the detection within a 10-year observational period.

The general idea of preparing an experimental strategy, by augmenting observed data with model output and by optimising the a priori chances to assess the statistical significance of a signal, has been put forward by Hasselmann (1979, 1993).

3.2 Downscaling

The other climate change problem in physical oceanography is the specification of the expected change of the state of regional oceans, of estuaries and other "small" units. User communities, such as coastal engineers or marine ecologists, ask for information on spatial scales of 100 km, 10 km and even less. All information on the expected climate change, on the other hand, stems from global climate models which include fully coupled atmosphere and ocean general circulation models. Such models produce an output with a typical nominal horizontal resolution of 500 km. Whether the information on this nominal scale is useful is open to discussion, but certainly sub-grid-scale information cannot be produced by simply interpolating in space.

What can be done instead is to derive dynamical or statistical models which relate the (potentially) reliably simulated large-scale change to a regional scale change. Such statistical models are fitted to historical observations of the large-scale state and of the regional scale data. When fed with the large-scale output of climate change experiments such postprocessing models deliver estimates on the desired regional or local scales. This procedure is named "downscaling" (von Storch, Zorita and Cubasch, 1993). A first oceanographic example, on the coastal sea level in Japan, has been presented by Cui, von Storch and Zorita (1994).

4. EL NIÑO/SOUTHERN OSCILLATION

The El Niño/Southern Oscillation (ENSO) is the strongest climate signal on time scales of one to several years, with enormous implications for the socioeconomic well-being of various countries (such as Peru, Australia and even the United States). The phenomenon must be understood as the result of an interaction between the tropical Pacific and the atmosphere, but the active part of the dynamics seems to reside in the ocean whereas the atmosphere seems to play the role of an amplifier during a certain part of the evolution.

The ENSO has been monitored carefully for a couple of decades so that good observations are available, at least for surface properties. Also much effort has been put into the development of coupled atmosphere-ocean models of different complexity. In all such models the dynamics of the ocean are described in some detail, whereas the atmospheric component has been treated in many different ways. The most complex approach is to use full atmospheric general circulation models. The most economic approach is to use simple (so far almost always linear) statistical models, in which the state of the atmosphere, and in particular the low-level wind field, is modelled as being in an equilibrium with the sea-surface temperature. [For an overview see the review paper by Latif et al. (1994).]

The potential of an operational predictive capability of these ENSO models is another major challenge for the ocean sciences. These various ENSO models are used in experimental, or semioperational, forecast setups with good successes for lead times of 6, 12 and even more months. The objective evaluation of these forecasts, in terms of accuracy and value, is an important task in the future.

5. AIR-SEA INTERACTION

When dealing with the ocean as a part of the climate system, an important aspect is the large-scale air–sea interaction. I will briefly present two examples of statistical approaches in this context.

5.1 Identifications of Characteristic Patterns

What is the impact of anomalous sea-surface temperature on the atmospheric circulation, and what is the oceanic response to anomalous atmospheric circulation? For the extra tropics the answer is not obvious from theoretical reasoning. One way of dealing with this problem is to analyse simultaneously monthly mean fields of sea-surface temperature (SST) and of sea-level air pressure (SLP, as a representative of the atmospheric circulation). Zorita, Kharin and von Storch (1992) considered time series of such paired fields for the area of the northern North Atlantic during winter. With the help of a "canonical correlation analysis" (Hotelling, 1936; or, for instance, Zorita, Kharin and von Storch, 1992) they identified characteristic pairs of patterns. An expansion of the full fields into these patterns yields pairs of time-coefficients which are optimally correlated—indicating that the respective patterns of SST and SLP tend to occur at the same time. Such a pair of simultaneously occurring SST and SLP patterns are shown in Figure 3. A physical argument leads to the conclusion that the anomalous atmospheric circulation is creating (in winter) the SST anomalies and not vice versa.

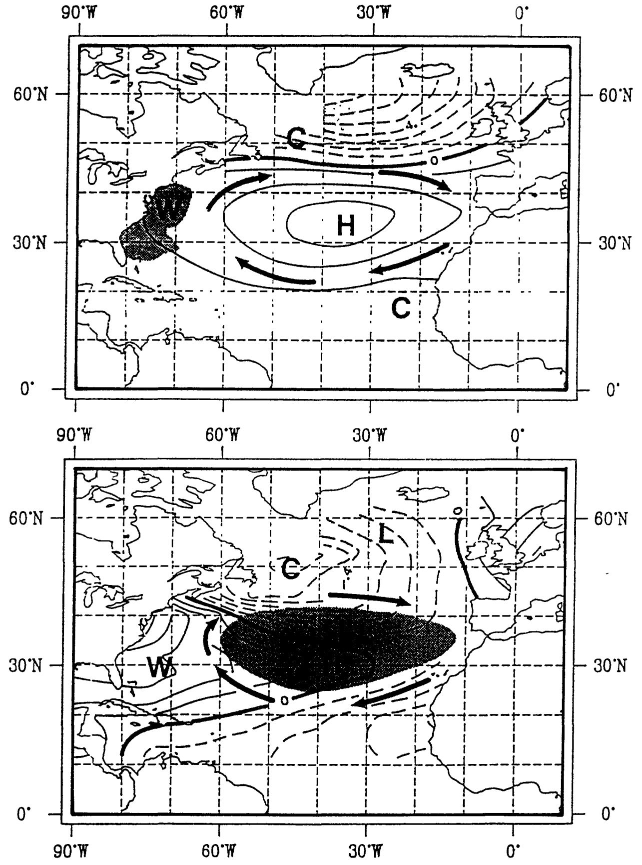

FIG. 3. *A pair of characteristic anomaly patterns of sea-surface temperature (SST, bottom) and sea-level air-pressure (SLP, top) in the northern North Atlantic: the time-coefficients of the two patterns are maximally correlated. A physical argument unveils that the SLP anomalies create the SST anomalies. The major structures from the SST pattern are depicted as shading in the SLP map and vice versa. (From Zorita, Kharin and von Storch,* 1992.)

5.2 Measuring Statistical and Physical Significance

To assess the importance of anomalous ocean-related boundary conditions, such as sea-surface temperature or surface roughness, for the state of the atmosphere, paired experiments with atmospheric general circulation experiments are conducted. In one run, the "control experiment," the boundary conditions are specified as normal. The other experiment, that is, the "anomaly experiment," is identical to the control experiment except for a deliberate and controlled modification of the boundary conditions. The effect of this treatment is expected to show up in the difference fields from any variable of interest in the two experiments.

The two runs are extended over a long time (tens of months). From the full time series, sets of, at least ideally, statistically independent chunks are formed. From these chunks independent and identically distributed (monthly) mean values are calculated. These means are considered as samples representing the "control" and the "anomaly" climate. In the last step the null hypothesis that the two ensembles are identical, or, as in most practical cases, that the expectations of the two ensembles are equal, is tested with an appropriate statistical test.

The problem with this approach is that the chances of the wanted rejection of the null hypotheses increase with the number of available samples—which is limited only by the computational resources of the researcher. Therefore the *statistical significance does not necessarily imply physical significance*. One way to evaluate the physical significance is the measurement of the degree of overlap of the two random variables "control" and "anomaly" climate. Von Storch and Zwiers (1988) and Zwiers and von Storch (1989) have introduced for that purpose a concept named "recurrence analysis" which is conceptually based on multiple discriminant analysis.

Figure 4 shows the evaluation of an experiment on the effect of the enhanced ocean surface roughness connected with the process of growing wind-sea (Ulbrich et al., 1993). To assess the possible impact of this effect on the state of the atmosphere, the surface roughness was (unrealistically) increased tenfold in the Southern Hemisphere stormtrack. The analysis on the effect of this treatment was done in a "hierarchical manner" (Barnett et al., 1981): the full signal "mean anomaly minus mean control" is projected on a set of a priori specified patterns, and the analysis is done in the subspace spanned by the first k patterns. For each k the level of recurrence (the degree of nonoverlap between the control and anomaly ensemble), the risk of erroneously rejecting the null hypothesis of equal expectations and the percentage of variance of the full signal explained in the k-subspace are calculated and displayed in Figure 4. The treatment is identified as being statistically and physically significant.

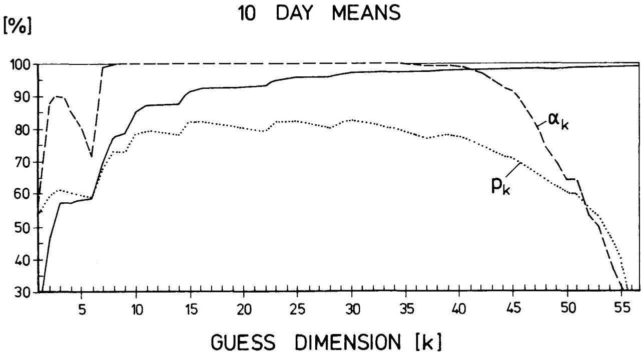

FIG. 4. *Assessment of the physical and statistical significance of* 10-*folding the surface roughness in an atmospheric general circulation model experiment: the physical significance is measured by the "level of recurrence"* p_k *(estimated degree of nonoverlap of the control and anomaly ensemble), and the statistical significance* α_k *is given as "*1 *minus the risk" of rejecting erroneously the null hypothesis of equal expectations. The third (continuous) curve describes the rate of variance of the full signal accounted for by the subspace of dimension k. The test is done in a hierarchical mode in a sequence of subspaces spanned by the first k patterns of a set of a priori specified patterns.* (*From Ulbrich et al.* 1993.)

In a follow-up experiment (Weber et al., 1993), in which the effect of growing wind-sea was modelled realistically in terms of distributions and strength by using a full ocean wave model, the effect was found to be negligible.

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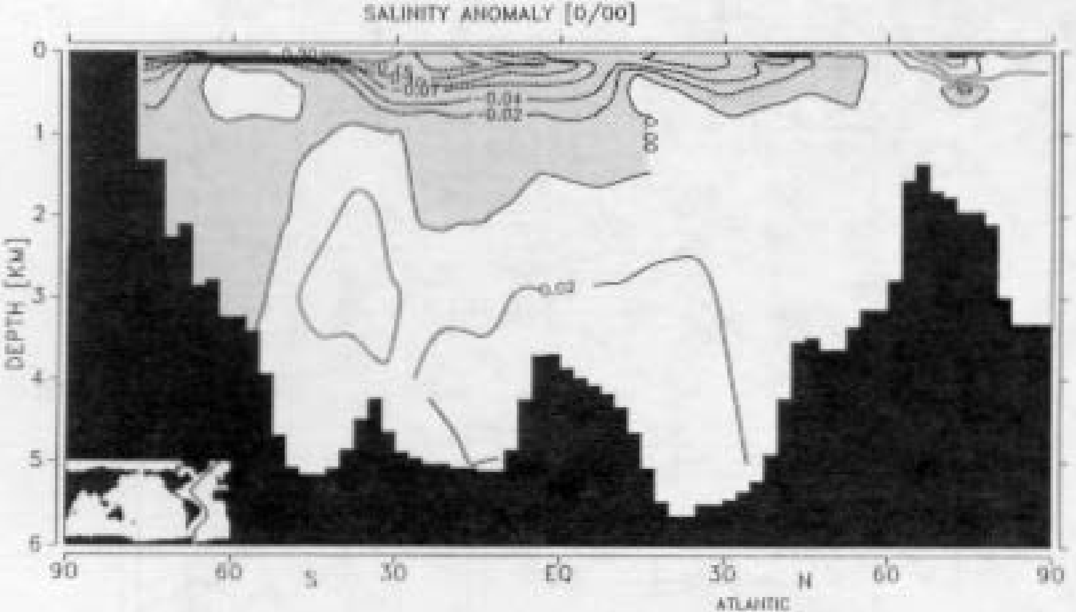

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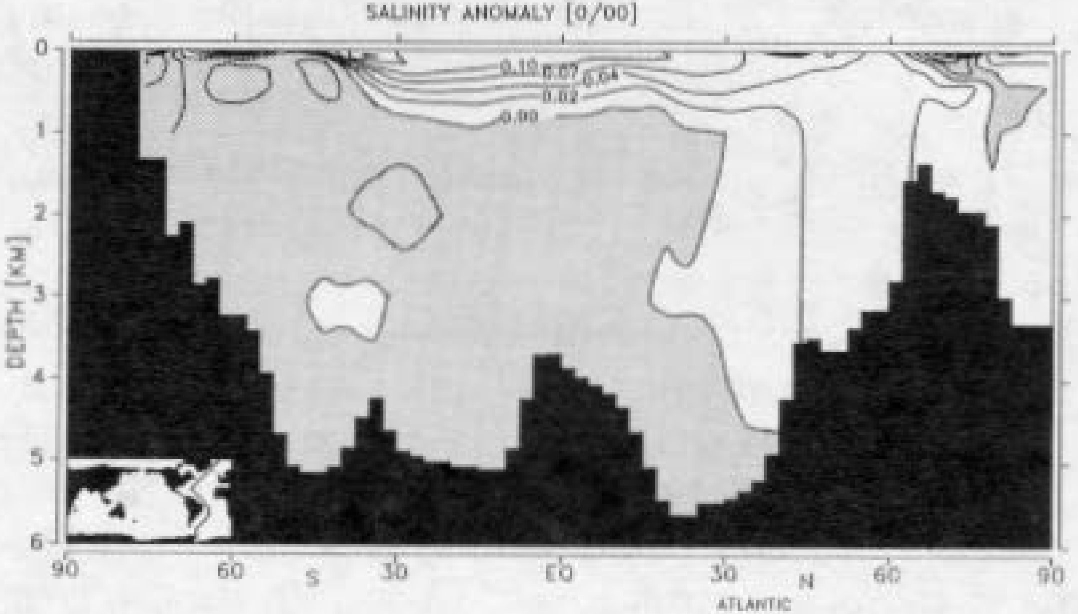

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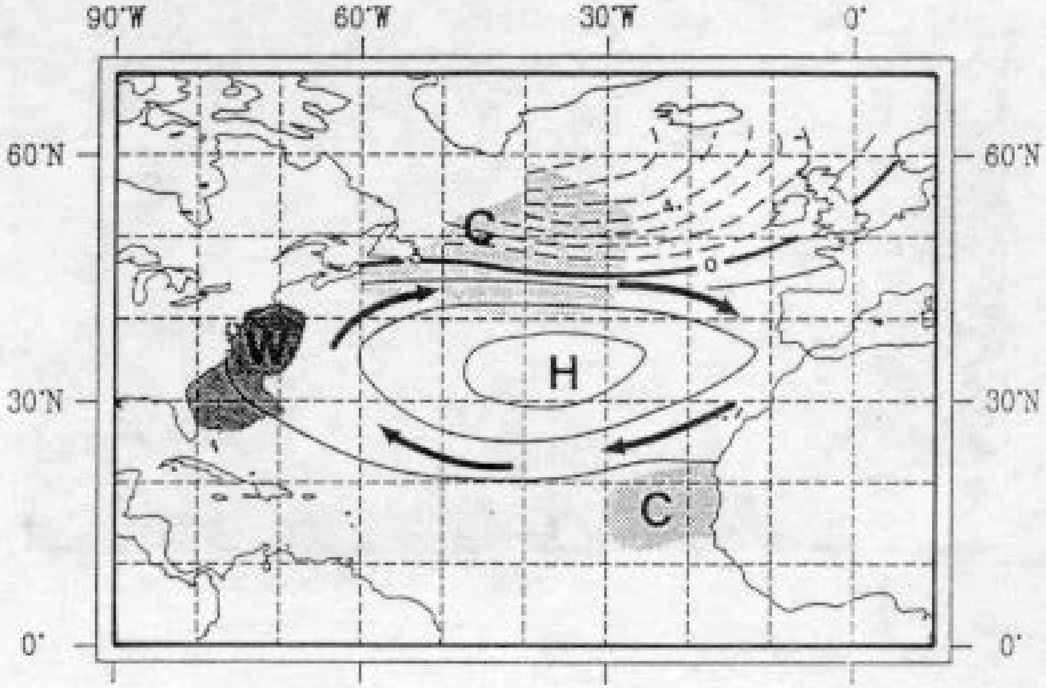
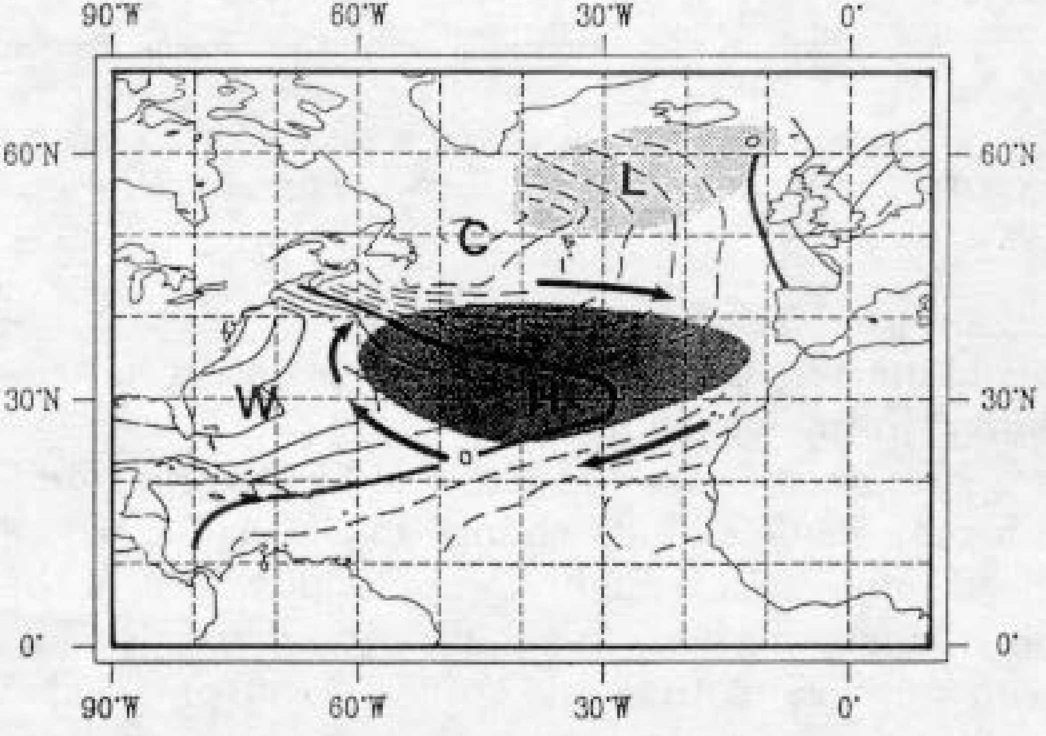

90°W
60°W
30°W
0°
60°N
30°N
0°
C
0
W
H
C


90°W
60°W
30°W
0°
60°N
30°N
0°
L
0
C
W
H
0