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REGIONAL ASPECTS OF THE CIRCULATION ON THE NORTH EUROPEAN SHELF

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Abstract

Estimates of the mean summer and winter circulation of the North European shelf sea are obtained by means of a three-dimensional nonlinear numerical finite difference circulation model. The effects of the tide, stratification and wind are included in the simulations. By a number of systematic model experiments quantitative estimates of the contributions of these three dominant components to the. circulation and of their regional distribution are provided. Further, estimates of the amount of nonlinear interactions between the components are derived from the difference of the flow fields which were obtained by a linear and by a nonlinear superposition of the components, respectively. The model experiments show that the tidal residual flow is allmost everywhere much smaller than the mean flow caused by a mean wind and by stratification. However, the tide appeared to be the dominant mechanism that causes nonlinear interactions between the flow components. Seasonal variations of both, wind and stratification are causing significant spatial changes in the mean flow as well as in the nonlinear interactions. This study was carried out a) to provide insight into the regional aspects of the circulation and b) to provid a basis for an intercomparison of existing models and model estimates of the mean flow, because in principle the model experiments include almost any case which appeared in the literature.

Introduction

The North Sea and adjacent shelf regions are easily accessible for a number of highly industrialized nations which are using the sea as an important source for nutrients and mineral resources and as a dumping site. The increasing awareness of marine environmental problems of the European continental shelf sea initiated ongoing national and international efforts to investigate the state of the eco-system and to determine its anthropogenic hazards.

Besides measurements which are carried out to determine the content of pollutants in the sea and their possible fluxes and interactions within the biomass and the sediments there is a demand for water quality simulations. The latter are, in combination with measurements, an important tool for a description of the processes within the marine environment and for an assessment of a possible marine pollution management. Recent communications within the ICES have drawn attention on the possible and likewise considerable influence of the circulation and its variability on the delicate recruitment process of fish species within the North Sea.

However, the quality of any water quality model crucially depends on the flow field which is used to determine the dispersion of pollutants and/or biomass within the sea. Since the dispersion of matter in the sea covers time scales of the order of weeks to years there seems to be a general agreement that a suitable flow field should mainly consider low frequency variations, as for example monthly, or seasonal, or annual and inter-annual fluctuations.

In a considerable number of publications of the past ten years (mean) flow fields of this kind were presented. They were used to determine parameters like flushing-times, residence times (ICES report no. 123) or the age of water masses within the region of interest, and used also to estimate the dispersion of matter in the sea. The number of model concepts, i.e. the choice of the physical processes that were argued to be relevant to determine the flow is almost as high as the number of publications. In most of the model studies the effects of tides and wind are incorporated. Quite often a homogeneous wind (stress) field is used standing for an actual or for a climatological mean; sometimes a mean wind stress is determined from a mean wind, which constitutes an underestimation of the stress; quite seldom the effects of fluctuations of the wind field are considered. A very large number of studies neglect the effects of stratification, arguing that the waters on a shallow shelf are often well mixed, or that local gradients of the stratification are small. It will be demonstrated in this contribution that these assumptions may be rather misleading.

In view of this variety of arguments and model concepts and their respective results and the conclusions drawn from them the non-expert must be helpless because it is impossible for him to determine which model is the one he can rely upon. Even for an expert an intercomparison of the different model results is rather difficult due to the variety of forcing conditions. The importance of the environmental problem of the North European shelf sea is reason enough to undertake an attempt to clarify this situation. This constitutes a main motivation for this investigation.

One intention of this investigation is to provide a basis for a comparison of existing models and model results with regard to their respective forcing conditions. A comparison of different methods, i.e numerical techniques will not be carried out. We thus assume that for a given forcing condition all methods will (cum grano salis) yield the same result. The main intention, however is to provide a quantitative estimate of both the separate and the combined effect of the tide, the (mean) wind forcing and of the stratification to the mean circulation on the North European continental shelf. A systematic separation of the respective contributions will give insight into the reasons of the spatial variability of the circulation and hence into regional and large scale dynamics of the flow. Simultaneously it constitutes an opportunity to estimate the consequences of different model concepts. As a further result of the determination of both, the separate and the combined, nonlinearily superimposed effect of the three contributions to the flow we obtain an estimate of the regional distribution of their nonlinear interactions. Since both, wind and stratification show an annual signal we are also interested to estimate the mean regional variability of the flow due to the respective seasonal changes of these forcing components and due to their possible interactions.

Model Experiments and Input Data

The above sketched analysis is carried out by means of a series of systematic model experiments using a nonlinear three-dimensional circulation model. Compared to measurements models ofer a great advantage: a model can provide estimates of the separate components of regional flow dynamics. It is quite often impossible or at least very difficult to extract this information from local observations.

The numerical scheme of the three-dimensional nonlinear circulation model used in this investigation is described in detail in a separate publication (Backhaus 1985). Therefore we here mainly consider the observational data which entered the model.

However, in order to provide an impression about the limits of the model results discussed below with regard to the spatial resolution of the model we briefly denote the main features of the approximation of the model domain: the horizontal grid size is 1/5 and 1/3 of a degree in lattitude and longitude, respectively (approx. 20 Km). The vertical resolution on the shelf was chosen according to the oceanographic standard depths and it varies between 7 (winter) and 12 layers (summer) in order to give a reasonable approximation of the vertical stratification. This spatial resolution allows for a decent

approximation of the large scale flow only. Small scale processes like internal tides or eddies with dimensions of the order of the internal Rossby radius of deformation are definitely not resolved by the present model. It should therefore be addressed as a general shelf circulation model (GSCM).
The prescribed mean of the stratification (summer, winter) shows the considerable horizontal density gradient which is present throughout the year because it is mantained by the advection of haline water masses from the Atlantic and by the fresh water run off along the coast lines. This large scale gradient is demonstrated by the climatological mean of the winterly surface salinity for the model domain displayed in figure 1 for the first model-layer.
For the North Sea region the data for temperature and salinity was digitized and interpolated from the charts of climatological monthly means published by Tomczak and Goedecke (1962) and by Goedecke et. al. (1967). For the rest, the western part of the model area the climatological means on a 1x1 degree grid prepared for general ocean circulation models by Levitus (1982) were taken. Substantial spatial interpolation was necessary, due to the coarse grid, in order to obtain a first order approximation of the three-dimensional T,S-fields in this part of the model domain. As a consequence the structure of the baroclinic jet at the continental shelf edge (Gould et. al.1985) is not adequately resolved by the data and hence by the model.
A final dynamical interpolation of the T,S fields was carried out by means of the baroclinic circulation model in order to eliminate inconsistencies caused by the extensive interpolation. In a prognostic model run an approximate geostrophic and hydrostatic balance of the density field was obtained by prescribing the forcing of the M2-tide and of a respective mean of the wind forcing. The resulting baroclinic pressure field derived from the dynamically balanced density distribution was prescribed as a 'frozen', constant forcing in the following model experiments, according to a diagnostic approach.
The only time-dependent forcing component in the model experiments is the periodic M2-tide prescribed at the open boundaries of the model in the eastern Atlantic. A tidal verification of the model results for coastal tide gauges yielded a relative error of about 10 %, which is the usual error marge for tidal models of the present state of the art.
The data that was used to determine the atmospheric forcing for the model simulations was provided by the Norwegian Meteorological Institute. The record of 28 years (1955-1982) of six-hourly sea surface air-pressure distributions on a 150x150 km grid covers the northeastern North-Atlantic Ocean, the adjacent European shelf and some continental margins (fig. 2). The air-pressure fields were used to estimate the wind stress from the geostrophic wind by means of the nonlinear relationship developed by Luthardt and Hasse (1981, 1983). A climatological seasonal mean (summer, winter) of these parameters (air-pressure and wind stress) constitutes the atmospheric forcing for the experiments. An atlas of these atmospheric

fields and of their temporal and spatial variability was published by Backhaus et.al. (1985).

For the description and discussion of the model experiments we introduce the following abbreviating nomenclature:
W,T,S = circulation due to Wind, Tide, Stratification resp.
(W,T) = circulation due to nonlinear superposition of W and T
W+T = circulation due to linear superposition of W and T
N(W,T) = estimate of nonlinear interaction between W and T
Adopting this nomenclature enables us to write simple symbolic bulk formulae, as for example:

$$(W,T) = W + T + N(W,T)$$

This expression means: the nonlinear superposition of wind and tide can be described (decomposed) by the result of a linear superposition of these components plus a possible residuum N(W,T), which is a measure for the amount of nonlinear interaction. In this context a linear superposition is simply the sum of two (or three) flow fields of isolated simulated components, whereas for example (W,T) means that both components are incorporated in the model and hence possible interactions are included in the resulting flow field. We should further note that the above symbols stand for time-independent flow fields, which implies that T stands for the (Lagrangian) tidal residual flow induced by the M2-tide. In a superposition run that incorporates the tide the resulting quasi-stationary time-dependent flow field will be averaged over a tidal cycle in order to obtain the desired stationary (residual) flow field.
Since most of the available models of the North Sea and adjacent areas are vertically integrated and since the properties of the depth mean large scale flow are sufficient to visualize regional differences of the circulation we shall here only consider the depth mean flow, derived from the three-dimensional model output. With regard to stratification the presented results cannot be reproduced by means of a depth-integrated model.

Discussion of the Model Experiments

In our experiments we have considered the following cases for both seasons (summer, winter):

A: single components; W,T,S
B: superpositions (W,T); (S,T), (W,S) and (W,T,S)
C: nonlinear interactions N(W,T), N(S,T), N(W,S) and N(W,T,S)

For the convenience of a comprehensive display we introduce a simple scalar quantity, the 'pseudo' Kinetic Energy of the Mean Flow (KEMF) in units of cm^2/s^2. The mass distribution was neclected in order to avoid the description of spatial variances of the kinetic energy which are only caused by varying water dephts. Thus,no vector field (especially the directional pattern) will be presented. For further information on circulation patterns obtained with the model we therefore refer to a current atlas, recently published by Hainbucher et.al. (1986).

Applying our bulk formula on the resulting scalar KEMF-fields we obtain the estimates for the amount of nonlinear interactions by a simple computation. For example:

$$N(W,T,S) = (W,T,S) - (W + T + S),$$

which is essentially the difference of the KEMF of two flow fields, where the first has been obtained by a nonlinear, the second by a linear superposition of the components. This difference might be negative. In this case we conclude that due to the nonlinear interaction between the considered flow components the KEMF of the resulting flow is reduced. We shall realize from the results presented that this will be the case almost everywhere for all superpositions including the tide.

Insight into the regional distribution and the dominance of the considered components is given by the display of the respective superpositions and their nonlinear interactions. The results of the experiments are presented in the plates 1-3 (summer) and 4-6 (winter) for the cases A to C, respectively. We leave a detailed inspection and interpretation of specific local features to the reader who might have in mind his own region of interest. Instead we comment on some general features.

In the plates 1 and 4 the distributions of the KEMF are given for the single flow components (summer, winter). The possibly most striking feature are the low KEMF values for the tidal residual flow compared to the solely wind and solely stratification induced flow. The display is almost white, except for some regions where high tidal currents induce tidal residuals of some magnitude. However, the white regions do not mean that there the tidal residual flow is zero but that the KEMF value is smaller than the minimum value of 2 cm^2/s^2 chosen for this display. From these results one might conclude that the tidal residuals are almost negligible compared to the other components. However, from the below discussed superpositions (plates 2 and 5) we deduce that the tide has a considerable influence via nonlinear interactions. With regard to this finding we presume that the numerous 'tidal residuals' extracted from current measurements are likely to represent not solely the effect of the tide...

A comparison of the plates 1 and 4 (summer against winter) with regard to the influence of wind and stratification reveals that the solely wind induced circulation has its highest KEMF-values in the shallow southern and eastern North Sea, along the continental coast line; further, a remarkable difference between summer and winter is obtained. This is a result of the pronounced annual cycle of the wind forcing over the model domain, documented and quantified by the respective climatological seasonal means in the meteorological atlas (Backhaus et. al. 1985). The patterns due to stratification clearly show the main inflow routes of the Atlantic water masses merging with the coastal less haline water. They indicate the regions where the baroclinic flow caused by the large scale and essentially haline density gradient has its maximum values. This basin-wide feature obviously need to be incorporated in order to obtain a realistic description of the baroclinic flow. It explains why attempts to describe local dynamics by the local density gradients, which might be rather small, have failed. A typical example of which is the southern Bight. For this region our results yield KEMF values for the baroclinic flow that are higher than those of the tidal residuals. Seasonal differences in the KEMF patterns due to stratification are much less pronounced compared to the purely wind induced flow. However, it is noteworthy and in accordance with observations (H.Dooley, pers. com.) that for the baroclinic flow in the northern North Sea the maximum values are obtained for the summer season.

Referring to the plates 2 and 5 (superpositions for summer and winter) we note that whenever a constant flow component (W or S) is combined with the time-dependent periodic tide a considerable reduction of the resulting residual flow is obtained. The KEMF residuum N in our bulk formula will then have a negative sign. We explain this process by the presence of a much higher energy dissipation due to bottom friction when the actual tide is included, compared to the linear superposition of constant residual flow fields (which have much smaller magnitudes than the tidal currents). By a simple estimate of the magnitude of single terms in the equations of motion we can argue that the bottom friction in a shallow shelf sea plays a key-role for the nonlinear interactions. We conclude that the concept of a linear superposition including tidal dynamics yields highly unrealistic results. This remark is further supported and visualized by the display of the spatial distribution of nonlinear interactions (plates 3 and 6) where regions with negative interactions (residuum N) are indicated by shading.

The nonlinear superposition (plates 2 and 5) of the constant components due to wind and stratification yields, with only some few exceptions, an enhancement of the flow compared to the linear superposition. Hence, the nonlinear interactions will then have a positive sign, which is indicated in the 'interaction-plates' 3 and 6 by plus-symbols. Obviously in this case, contrary to the tidal interactions, less energy is dissipated at the sea bed compared to the linear superposition.

For both seasons considered here we state that the nonlinear combination of all three components (W,T,S) in the plates 2 and 5, which of coarse is the case closest to reality, cannot be obtained from any of the pair-wise superpositions. This is a consequence of the nonlinear interactions which in some regions act in an opposite way as can be seen from an inspection of the plates 3 and 6. The most conspicious seasonal difference in the nonlinear interactions is caused by the annual changes of the wind forcing. In some North Sea regions zones with positive and negative interactions are closely spaced. We expect that possible variations (stratification and/or wind forcing anomalies, spring/neap changes of the tide etc.) of the flow components, which are not considered here, may have a considerable influence on the variability of the large scale flow especially in these regions.

Conclusions

The above presented model experiments are to a certain degree highly unrealistic; for example the tidal signal will (hopefully) not cease in nature. However, we feel that the somewhat academic separation of single flow components in combination with their systematic superposition provide insight into the processes that are causing regional and seasonal differences of the large scale circulation. In this sense the model was applied as a useful tool in the field of regional oceanography. It is obvious that none of the three circulation components considered here can be neglected. Linear superpositions/model concepts in a shallow shelf sea, where bottom friction plays an essential role, are likely to yield unrealistic results. With regard to other models we leave the decision about their respective realism to the reader. However the presented results might enable him to localize those regions where certain model concepts/ assumptions/ results may need revision.

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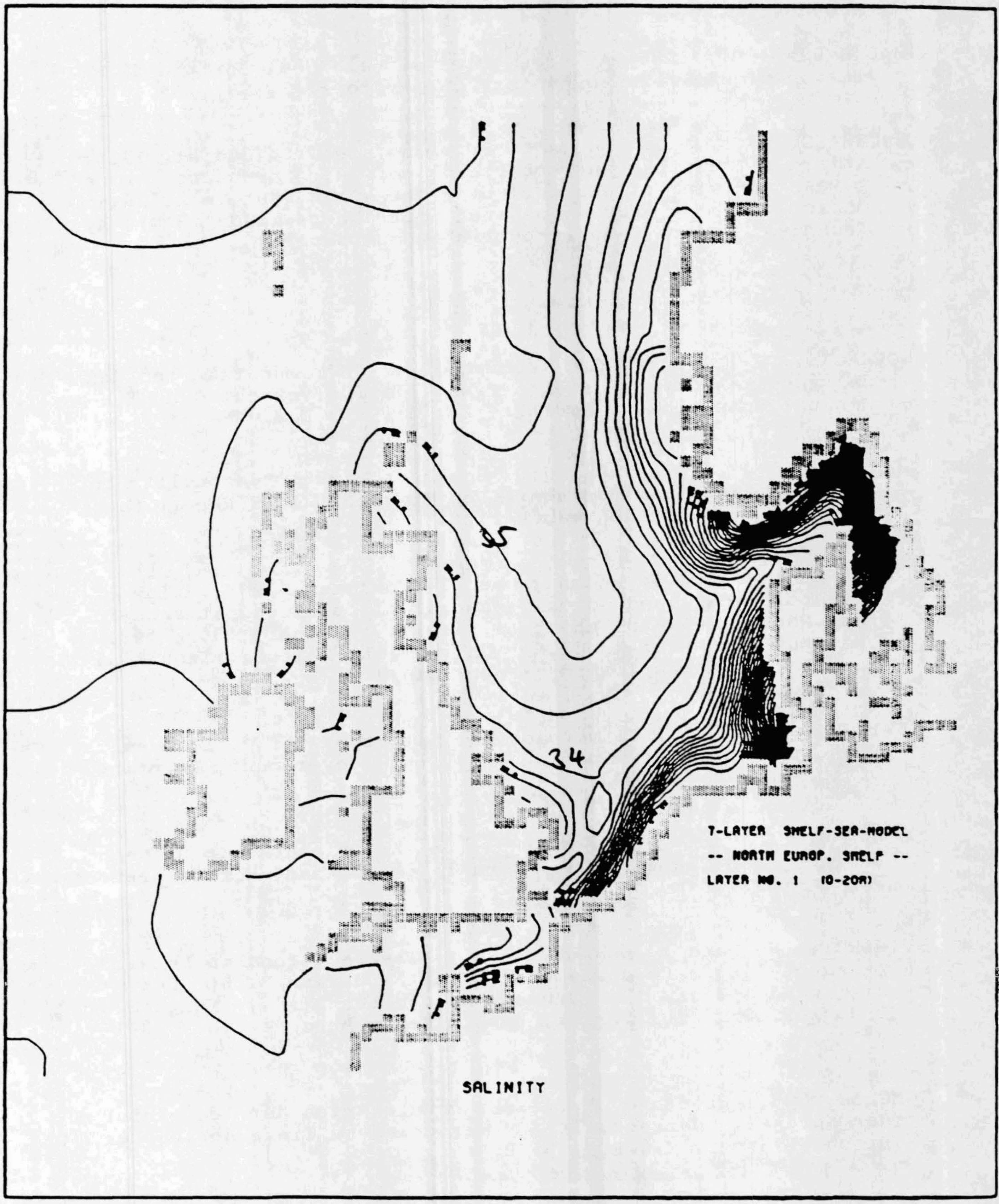

Figure 1
Interpolated surface salinity distribution (winter)

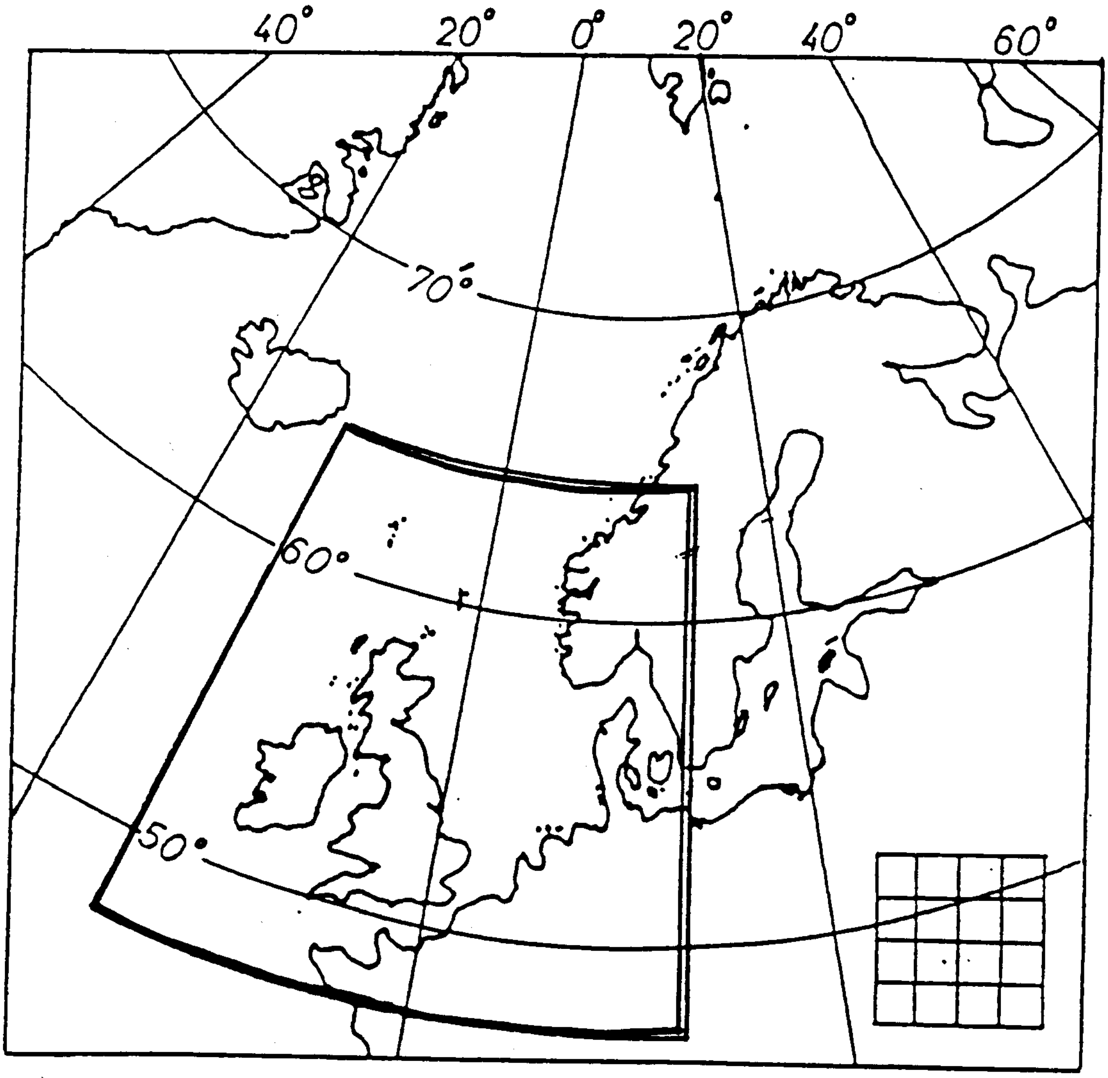

Figure 2
Area of atmospheric forcing (grid-size: 150 km as indicated).
Domain of North European shelf model indicated.

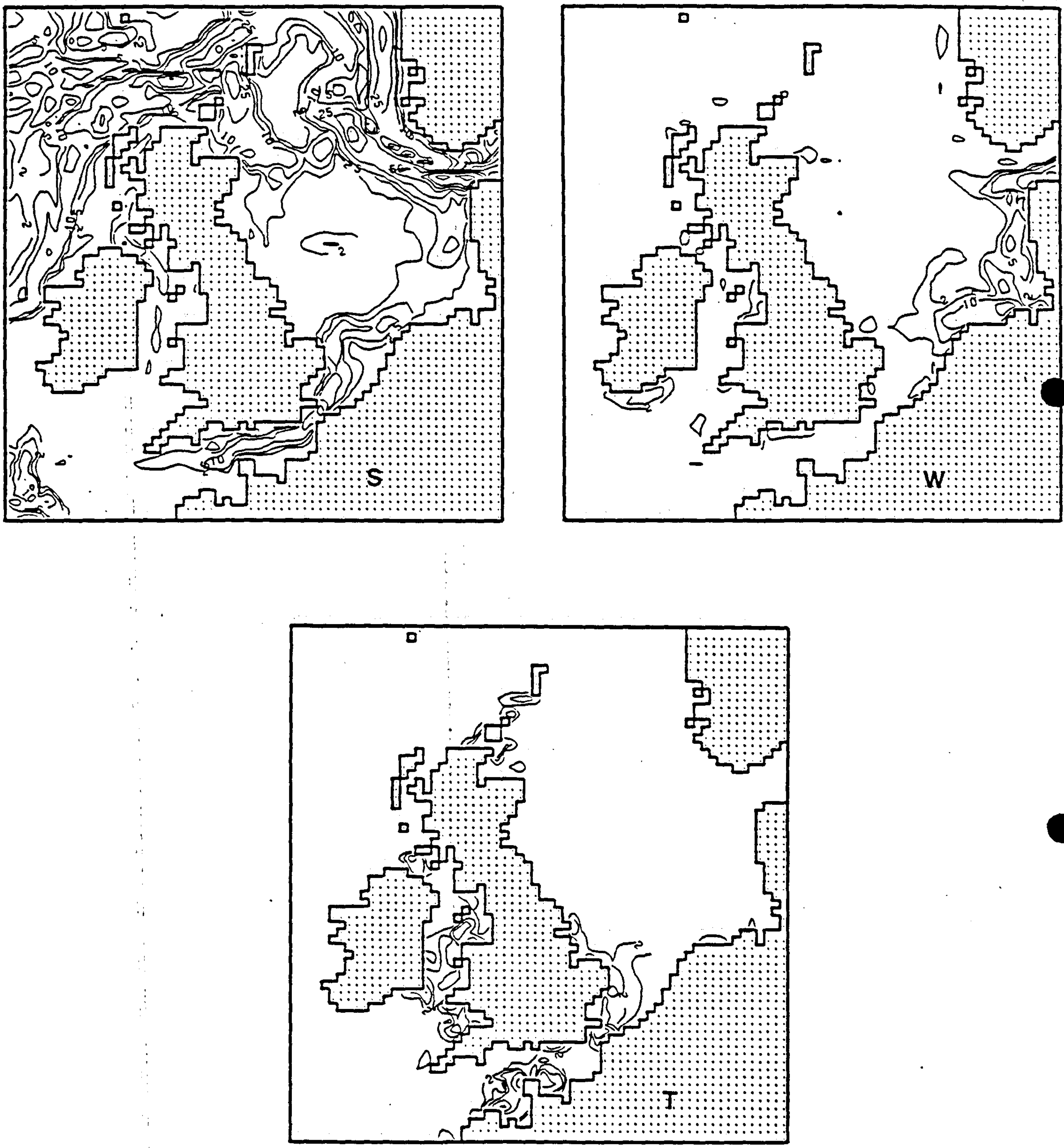

Plate 1
Summer: Kinetic Energy of the Mean Flow (KEMF) for the three single flow components $(cm/s)^2$.
T: tide; S: stratification; W: wind.

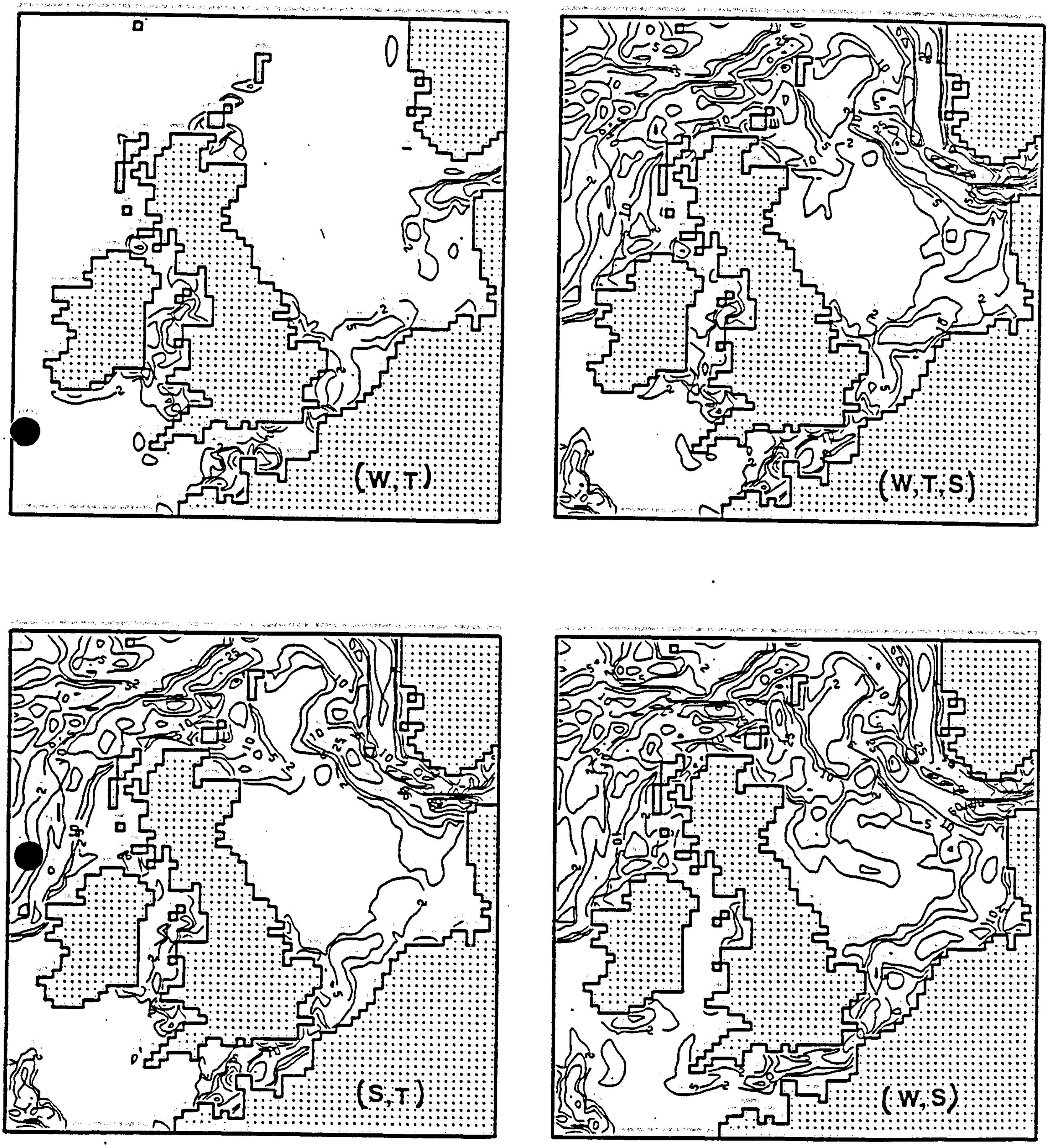

Plate 2
Summer: Nonlinear superpositions for different combinations of the three flow components in KEMF units $(cm/s)^2$.
(W,T): wind and tide; (S,T): stratification and tide;
(W,S): wind and stratification; (W,T,S): all together.

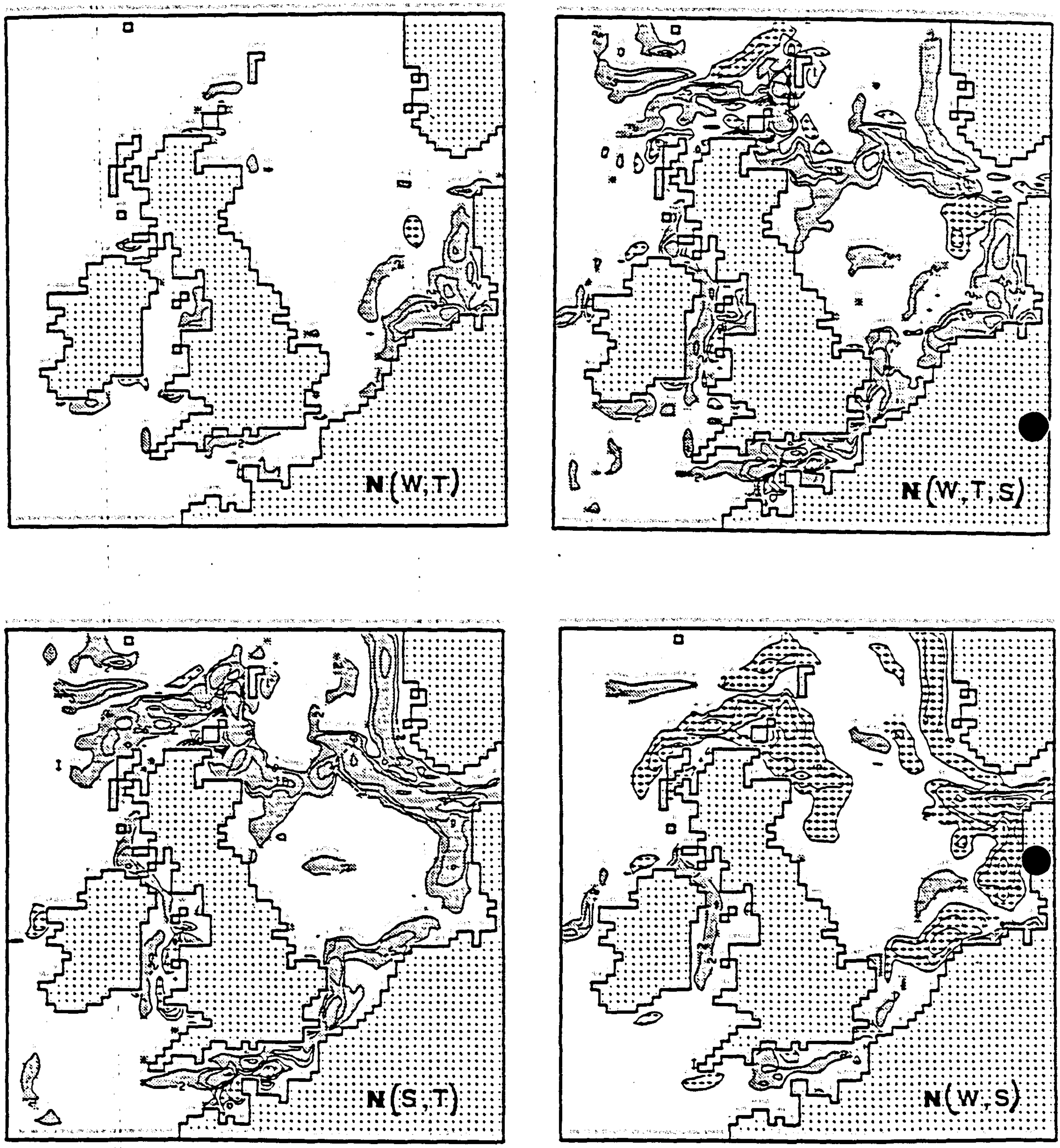

Plate 3
Summer: Nonlinear interactions for different combinations of the three flow components in KEMF units $(cm/s)^2$.
(W,T): wind and tide; (S,T): stratification and tide;
(W,S): wind and stratification; (W,T,S): all together.

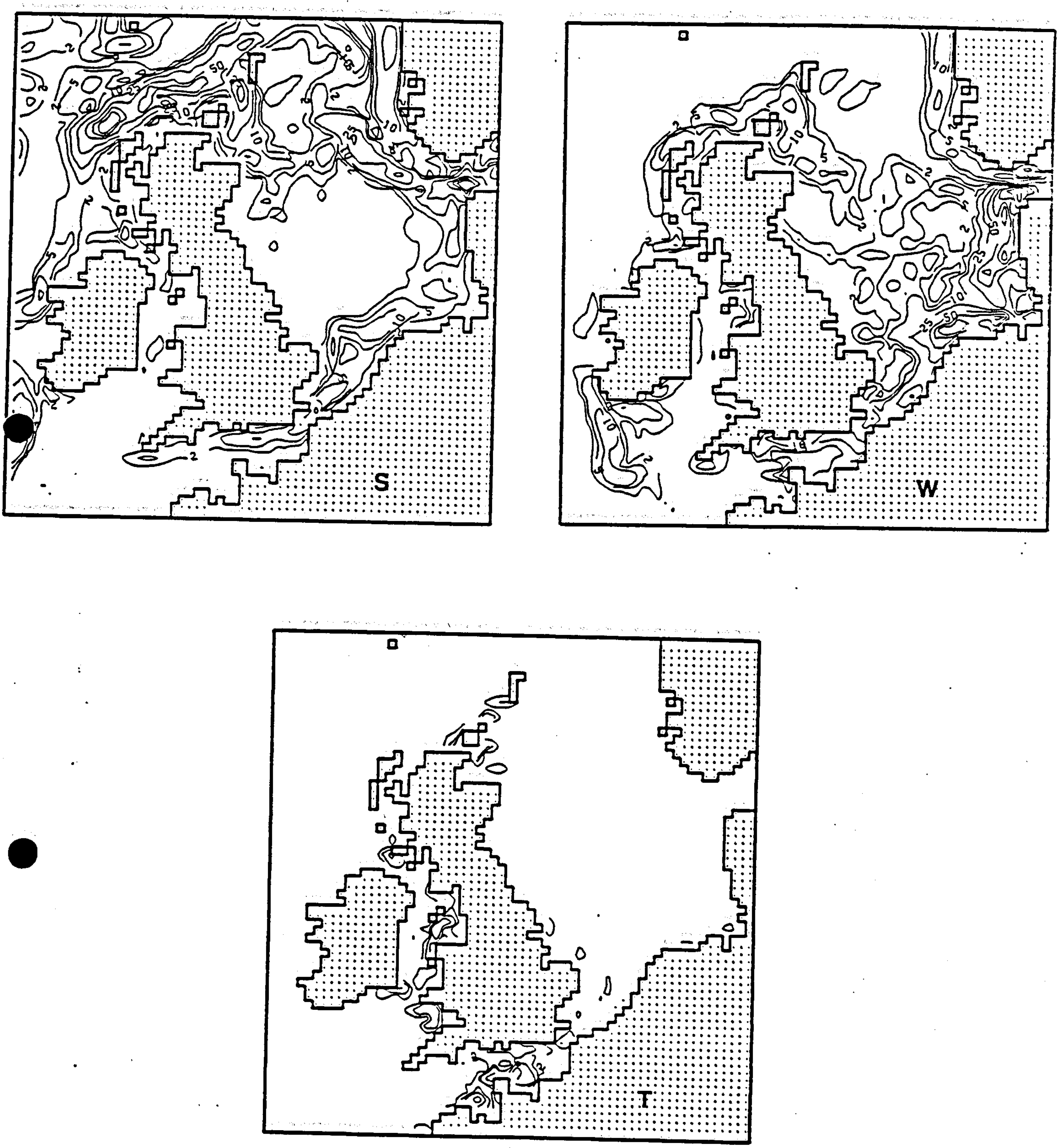

Plate 4
Winter: Kinetic Energy of the Mean Flow (KEMF) for single flow components (cm /s)^2.
T: tide; S: stratification; W: wind.

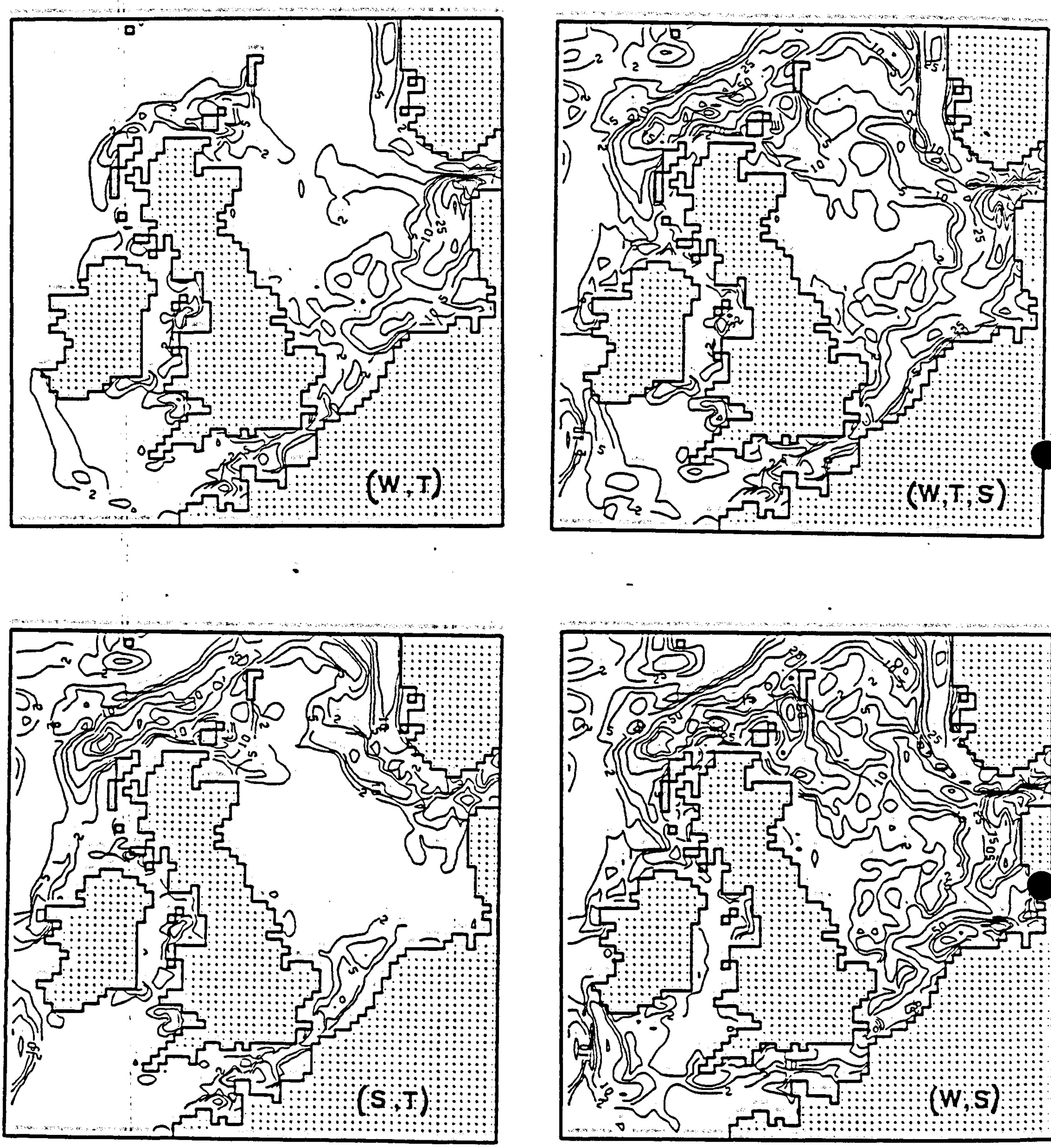

Plate 5
Winter: Nonlinear superpositions for different combinations of the three flow components in KEMF units (cm /s)^{2}.
(W,T): wind and tide; (S,T): stratification and tide;
(W,S): wind and stratification; (W,T,S): all together.

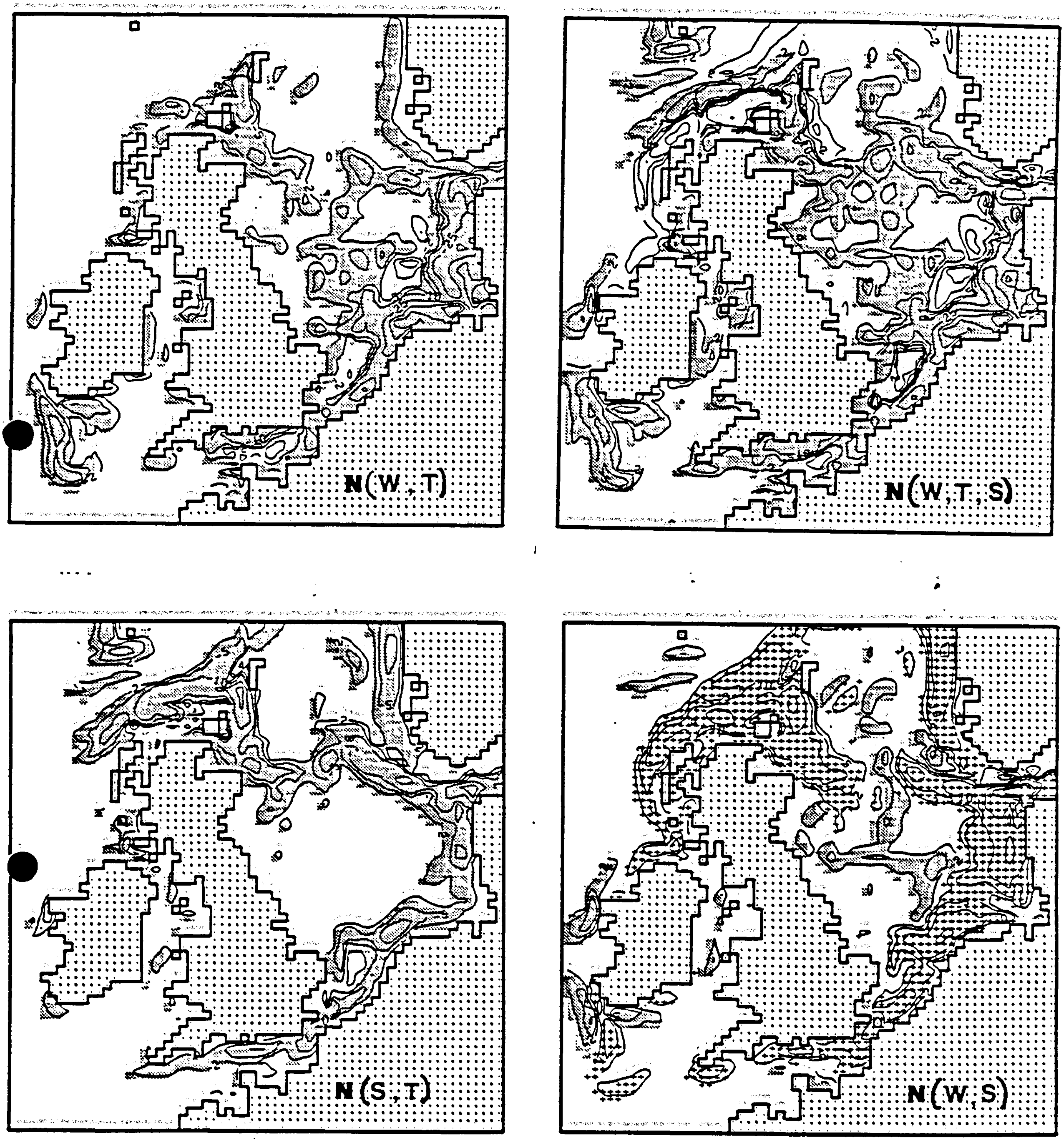

Plate 6
Winter: Nonlinear interactions for different combinations of the three flow components in KEMF units $(cm/s)^2$.
(W,T): wind and tide; (S,T): stratification and tide;
(W,S): wind and stratification; (W,T,S): all together.