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Oxygen In the Deep Basins of the Baltic Sea: The influence of winter mixing.

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Abstract:

Variations in oxygen conditions below the permanent halocline influences the Baltic ecosystem through a number of mechanisms. Principle among these are fluctuations in the availability of benthic habitat suitable for Baltic cod (the top predator in the Baltic ecosystem). Variations in the volume of deep oxygenated water influences directly the potential feeding habitat and volume of water suitable for spawning. Recent research has identified the importance of inflows of saline, oxygen rich North Sea water into the Baltic sea on the recruitment success of Baltic cod. These inflows increase the volume of water with suitable oxygen and salinity conditions for the development and survival of cod eggs (termed spawning volume). Increases in the "spawning volume" have occurred with out the occurrence of a major inflow from the North Sea (e.g. 1958-59; 1966-67). Other candidate processes suggested to potentially increase the "spawning volume" include variations in timing and volume of terrestrial runoff, advection of water from the Arkona Basin, convective overturning of the water column due to surface cooling as well as wind mixing down to the halocline. In order to examine the latter three mechanisms, we have performed model simulations utilizing the Baltic Sea Model (Lehmann, 1995). Three-dimensional fields of temperature and salinity were obtained from field studies in July 1995 and interpolated onto the model grid, atmospheric forcing data was obtained from EUROPA-Model. The Baltic Sea model was then run from the period from July 24 to December 31, 1995. To test the effects of increased wind energy and surface cooling on oxygen conditions below the permanent halocline variations in the oxygen conditions were examined utilizing the following experiment conditions;

a) a reduction of SST by 5 °C over the entire simulation period thereby increasing vertical convection.
b) an increase of surface wind energy over the modeled period by 15%.
c) two high energy winter storms

The results of these simulations and the possible implications of the effects of these processes on the reproductive environment of Baltic cod will be discussed.

Key Words: Baltic Sea, cod spawning volume, oxygen, 3-D modeling, convection, wind mixing.

Introduction

The Baltic Sea is a large estuary with shallow connections to the ocean, principle of these being the Danish Belt Sea. Fresh water inputs into the Baltic, on the order of 15000 $m^3.s^{-1}$ (Bergström & Carlsson, 1994), create a low salinity (~ 7 ‰) layer typically of 60-65 m in thickness (70 % total volume of the Baltic Sea). Below this layer exists a 10 m termed the upper deep water pycnocline (25% of the Baltic volume; residence time circa 3 years) which overlies the deep saline waters of the Baltic (10-13 ‰; 5% total volume; residence time varies due to intermittent renew by inflows). Salinities and stratification vary significantly horizontally with salinities being lower to the north and east (e.g. Bothnian Bay) and higher to the west and south (e.g. Arkona Basin). A seasonal thermocline develops in the spring due to surface heating and is maintained due to solar inputs until the autumn. Between the summer thermocline and the halocline exists a cold intermediate layer termed the "winter water". The summer thermocline deepens in the autumn due to the combined effects of heat loss due to surface cooling and wind induced entrainment eventually coalescing with the remnants of the previous winters cold intermediate water resulting in a relatively homogeneous surface mixed layer down to the halocline. (for more detailed descriptions see Kullenburg & Jacobsen, 1981; t & Wulff, 1987).

The unique oceanographic conditions of the Baltic Sea, the resultant residence times of the various layers coupled with the sedimentation of organic materials from terrestrial sources and surface euphotic layers results in a build up in organic materials in the deep layer (e.g. Wulff et al., 1990). These organic materials are degraded by bacteria utilizing oxygen in the process. This depletion of oxygen in the deep layers results in periods of stagnation between inflows of oxygen rich saline waters from the North Sea (e.g. Matthaus, 1995; MacKenzie et al., 1996), hence, influencing the spawning habitat and egg survival of Baltic cod, the top predator in the Baltic ecosystem (Nissling et al., 1994; Weiland et al., 1994). Variations in the volume of water with oxygen and salinity conditions favorable for the development and survival of cod eggs ("reproductive volume") coupled with estimates of spawning stock biomass have been utilized to explain a significant amount of the variability in recruitment success of Baltic cod (e.g. Plikshs et al., 1993).

The principle mechanism influencing the replenishment of oxygen in the deep Basins of the Baltic is the inflow of saline oxygen rich waters from the North Sea (e.g. Matthaus & Franck 1992) However, the "reproductive volume" for Baltic cod can be seen to vary considerably independent of inflow of North Sea water (e.g. Fig, 1; and MacKenzie et al., 1996). A number of processes have been suggested to influence oxygen levels in the halocline and deep layers of the Baltic these include;

- normal advection, which entails the inflow of water masses originating from the Arkona Basin into the Bornholm Basin (e.g. Stigebrandt 1987). A process which is not a result of extreme westerly winds which have been identified to generate major inflows (e.g. Matthaus & Franck, 1992).
- winter convection, which results in an improvement of the oxygen conditions by cooling the surface water to the density maximum resulting in unstable vertical stratification and overturn of the water column (Schulz et al.,1992). This process potentially forces a redistribution of temperature and oxygen (to lesser extent also salinity) by vertical convection. Oxygen saturation at the surface is a function of temperature and salinity with concentrations in this region typically 100 % saturation or more. Winter convection then potentially mixes oxygen saturated surface water with unsaturated water masses of lesser density occurring at the interface and in the halocline.

- vertical turbulent mixing, which results in the entrainment of oxygen from the surface mixed layer into the halocline as well as the erosion and expansion of the halocline. This process is typically the result mechanical stirring induced by high wind speeds (e.g. Stigebrandt & Wulff, 1987; Matthaus, 1995).

Typically, examination of the effects of mixing processes such as convection and wind mixing in the Baltic Sea have been examined synoptically during field programmes or through the utilization of 1-dimensional physical oceanographic models (e.g. Stigebrandt 1987; Matthaus 1990). These methods have proved extremely valuable in understanding the dynamics of the Baltic Sea, however, in order to quantify the influences of individual mixing events on the oxygen content in the region of neutral buoyancy of Baltic cod eggs we have chosen to utilize a 3-D modeling approach. Employment of this modeling technique will allow, through the variation of input values, a comparison of the effects of specific simulated physical scenarios on the "spawning volume" of Baltic cod. Our approach is to first simulate, using existing environmental data, the break down of the summer thermocline and transition to winter conditions. Secondly, we will change the intensity of the environmental forcing during specific periods and compare the results to those utilizing the actual environmental forcing to describe the influences of specific mechanisms on the oxygen concentrations in the Bornholm Basin. The Bornholm Basin is at present of particular interest as this is the primary present day spawning ground for the Eastern Baltic Cod stock (e.g. MacKenzie et al., 1996).

Methods:

For the investigation of convective and wind mixing on the oxygen conditions in the halocline and deep layers of the Bornholm Basin the Baltic Sea model, a three-dimensional eddy-resolving numerical model was employed in this study (Lehmann, 1995). The model is based on the free surface Bryan-Cox-Semtner model (Killworth et al., 1991) which is a special version of the Cox numerical ocean general circulation model (Bryan, 1969; Semtner, 1974; Cox, 1984), adapted to include the free surface. Special modifications necessary for modeling the Baltic Sea are described in Lehmann (1995). Figure 2, illustrates a subcomponent of the model domain as well as the reference transect utilized to depict changes in oxygen, salinity and temperature due to manipulation of the forcing parameters (i.e. wind velocity and temperature).

Initialization and Forcing:

Three-dimensional fields of temperature and salinity were initialized utilizing a data set representing the three-dimensional distribution of temperature and salinity for summer conditions compiled during a hydrographic survey in the Bornholm Basin in summer 1995. Salinity, temperature and oxygen fields were created by interpolating field observations of these variables onto the three-dimensional model grid employing objective analysis. The simulation commenced on 24 July, 1995 and lasted to the end of December. For time t=0 (24-July-1995) the velocity components were set to zero and the surface elevation was taken from the restart file. Forcing was switched on and the model allowed to equilibrate to the prescribed mass field over a period of a few days. Atmospheric forcing for the simulations were obtained from the EUROPA-Model of the German Weather Service (Deutscher Wetterdienst in Offenbach), namely 2-d wind field, dew point temperature (2m height), air temperature (2m) and precipitation. The heat budget was calculated from incoming short and longwave radiation, outgoing longwave radiation and from latent and sensible heat fluxes. Figure 3 illustrates the wind velocities, sea surface temperature, air temperature and mixed layer incremental temperature over the period of the simulation. In order to account for uncertainties in the calculated heat fluxes as well as for the unknown heat content of the oceanic mixed layer, the surface temperature of the ocean was relaxed to observed SST's taken from infrared satellite images. These images were processed at the BSH (Bundesamt fuer Seeschiffahrt und Hydrograpie, Hamburg). Infrared data from satellite overpasses for one week were combined in order to achieve a nearly or almost cloud free estimation of the Baltic Sea surface temperatures.

Simulations:

The influence of potential mixing processes were examined by modifying the physical forcing parameters during December 1995 and comparison with the modeled distributions utilizing "real" environmental forcing was performed. In order to do so data from the simulation from July 24 to December 31, 1995 were extracted (6 hr times steps) and these data served as a reference for following experiments;

a) Convective mixing: for this simulation atmospheric heat inputs were switched off and the SST's (from infrared satellite images) were reduced by 5 °C to initiate strong vertical convection.

b) Increased total wind energy: For this experiment the wind forcing was increased by 15%, hence initiating stronger turbulent mixing.

c) Storm Effects: The intensity of two storm events occurring in December 1995 were intensified by a factor of 1.8 resulting in storms with wind velocities of 18 $m.s^{-1}$ and >20 $m.s^{-1}$ respectively.

Results:

Simulation Utilizing Realistic Forcing

Figure 3 illustrates the weather evolution in December 1995. The maximum t wind speeds (daily mean average of in Bornholm Basin) reached 12 m/s during 2-12 and 23-28 December, 1995 with air temperatures during this period range between -6.0 to 3.0 °C, with the lowest values found at the end of December. The SST as obtained from satellite estimates dropped from 7-8 °C to 3-4.5 °C at the end of December producing a situation was suitable for winter convection. However, the temperature required to generate of the maximum density of surface water in the Bornholm Basin (S ~ 7 ‰ Temp max=2.5 °C) was not reached.

Evolution of the Salinity distribution:

Figure 4 illustrates the salinity distribution at the conclusion of the simulation utilizing realist forcing. During the simulation period surface salinities in the Arkona Basin ranged from 8-7.5 ‰. In the western part of the basin salinity increased from 9 ‰ at 15 m to 13 ‰ at the bottom. In the Bornholm Gat the salinity was vertically homogeneous down to 30 m, this was also true for the Bornholm Basin. The permanent halocline was separated by an intrusion of a relatively warm water mass (11 °C) at a depth of about 55m. So the permanent halocline was bifurcated in the western part of the Bornholm Basin, one branch

8-10 ‰ (40-50 m) and the other 11-16 ‰ (60-75 m). At the bottom of the Bornholm Basin the salinity reached 17 ‰.

Evolution of the Temperature distribution:

Figure 5 illustrates the temperature distribution at the conclusion of the simulation utilizing realist forcing The surface temperatures during the simulation ranged from 4.5 to 5 °C. The temperature was almost vertically homogeneous down to the permanent halocline, or it is better to say down to the 8.5 ‰ isohaline. A thermocline separated Baltic Sea water masses from higher saline waters. It's vertical position is found in the western Arkona Basin at 15 m, in the Bornholm Gat at 35 m and in the Bornholm Basin at 40-45 m. In the Bornholm Basin, below the thermocline, at a depth between 50-70 m a region of 11 °C water was observed C). This homogeneous temperature layer was separated from the relatively cold bottom layer (5 and 6°C) at 75 m by a sharp second thermocline (lower branch of the permanent halocline).

Evolution of the Oxygen distribution:

Figure 6 illustrates the oxygen distribution at the conclusion of the simulation utilizing realist forcing The vertical oxygen distribution resembled strongly the temperature field. The gradient zones in oxygen were connected to the thermoclines. Within the intermediate layer of homogenous temperature , a tongue of higher oxygen values (6.-6.5 ml/l) was found. Similar oxygen values were found in the lower layer of the Arkona Basin suggesting that this water mass was advected from the Arkona Basin.
Note: Oxygen values are somewhat artificial as uptake rates as well as initial conditions require further examination. However, as the goal is to describe potential changes in O_2 relative to entrainment of oxygen rich water these can be utilized as relative.

Convection Simulation:

In this simulation there was only a change in the surface boundary condition for temperature, hence the no strong deviations in the vertical salinity distribution were observed. Figure 7 illustrates the potential change in oxygen content due to convective mixing relative to the simulation utilizing realistic forcing. Variations in temperature occurred in the surface mixed layer as expected however no significant changes were found in or below the permanent halocline. Strong cooling at the surface provided an increased heat loss from the ocean, but water masses which were taking part in advection were not influenced by vertical convection hence changes in the oxygen distribution were also confined to the mixed layer.

Simulation of Increased Mean Wind Stress:

The situation for this set of experiments is the same as in the convection experiment , with one exception, namely there is a slight increase in oxygen (0.2 ml/l) within the permanent halocline to a depth of 60 meters. Figure 8 illustrates the change in oxygen content due to increased wind energy relative to the simulation utilizing realistic forcing. The increased oxygen content observed in this experiment is the result of a change in the advection pattern due to the increased wind forcing which has two effects. The distribution of salinity observed in Figure 9 supports the hypothesis of advection from the Arkona Basin into the Bornholm Basin. The first, due to the increased wind stirring the mixed layer depth is slightly increased, which means water masses which were being advected were modified, and second, the increased wind forcing led to an increased circulation and transport from the Arkona Basin.

Simulation of Storm Effects:

The effects of the two storms (18 $m.s^{-1}$ and >20$m.s^{-1}$) were observed in this simulation to alter the oxygen content below the permanent halocline to a depth of greater then 80 meters. Figure 10 and 11 illustrates the change in oxygen content due to the first and second simulated storm events respectively. The first storm event was observed to increase oxygen content by up to 0.5 $ml.l^{-1}$ with the second event further increasing levels to 2$ml.l^{-1}$ relative to the simulation utilizing realistic forcing. It is apparent from these simulations that the increased wind energy was sufficient to influence the oxygen conditions in halocline and in fact into the deep layers of the Bornholm Basin.

Summary:

The utility of 3-D physical oceangraphic models for characterizing variations in the physical environment which potentially influence biological processes in the marine and coastal environment has clearly been presented in the Baltic as in other systems (e.g. St. John et al., 1992). 3-D model simulations allow a characterization of the environment and the testing of specific physical hypotheses impossible using synoptic or 1-D models as 3-D models allow estimates of potential fluxes unobtainable with other approaches. However, care must be utilized in the interpretation of results (i.e. fluxes and transport rates) obtained by this method. Characterization of the physical processes involved may be quite variable due to the variations in paramterization of specific processes (i.e. entrainment rates, the effects of topographic steering, efficiency of transfer of energy from the atmosphere to the ocean surface, sub-grid scale processes). However, taking into account that actual rates may vary these models can be utilized as a diagnostic tool to create an index of importance and variability of effects of specific forcing. Hence, identifying areas for future more detailed examination as well as providing an index to compare potential variations in biological regimes or processes.

In this study we have clearly identified the potential importance of surface wind stress on mixing at and below the halocline in the Bornholm Basin as presented by Matthaus (1990). Historic variations in the cod "spawning" volume may in part be the result of wind mixing as well as resultant coastal upwelling and downwelling(e.g. Matthaus, 1990) and the breaking of internal waves in open water (Krauss, 1981)in regions where the halocline approaches the bottom(e.g. Schaffer, 1979). The effects of winter convective mixing examined here on oxygen levels in the halocline seems however to be limited although any process reducing the stratification intensity will allow a more efficient transfer of wind energy to depth. Hence, warm winters have the potential to have a reduced influence of wind mixing on oxygen levels in the halocline as well as increased biological rates and oxygen utilization (e.g. MacKenzie et al., 1996)

A key process identified during this exercise requiring future examination is the influence of advection of saline oxygen rich water into the Bornholm Basin from the Arkona Basin. This process has the potential to dramatically influence the salinity and

oxygen conditions influencing Baltic cod spawning success. Future research will quantify the effects of these processes (winter wind mixing and advection) on the spawning volume of Baltic cod. The end goal of this effort being to develop an index of intra annual variability of the effects of these processes on the spawning environment of Baltic cod.

Acknowledgments:

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Figure Captions:

Figure 1: Time series of the changes in reproductive volume (km^3) in May and the intensity of inflow (Q_t) from the North Sea in the previous winter . Data kindly provided by M. Pliksh and W. Matthaus respectively.

Figure 2: Contour plot of a sub component the Baltic Sea model domain including the Bornholm Basin, Bornholm Gat illustrating the depth distribution and orientation of the transect chosen to represent simulated conditions in the Bornholm Basin.

3) Daily time series of wind speed (m.s-1), air temperature (above the sea surface), sea surface temperature (as obtained from satellite imagery) as well as temperature of the mixed layer in the Bornholm Basin in December 1995.

4) Contour plot of salinity conditions (‰)on December 31, 1995 along the transect (shown in figure 2) as simulated by the Baltic Sea model.

5) Contour plot of temperature (°C) conditions on December 31, 1995 along the transect (shown in figure 2) as simulated by the Baltic Sea model.

6) Contour plot of relative oxygen distribution ($ml.l^{-1}$) on December 31, 1995 along the transect (shown in figure 2) as simulated by the Baltic Sea model.
Note: these are not intended to represent the actual conditions in the Bornholm Basin due to deviations between modeled and actual in oxygen utilization rates. These are intended as values to be utilized to examine the relative change in O_2 content due to physical forcing.
7) Convection Experiment: Contour plot of changes in relative oxygen content ($ml.l^{-1}$) due to a simulated 5 °C decrease in surface temperature over the period from 1st to 31, December 1995, along the transect (shown in figure 2) as simulated by the Baltic Sea

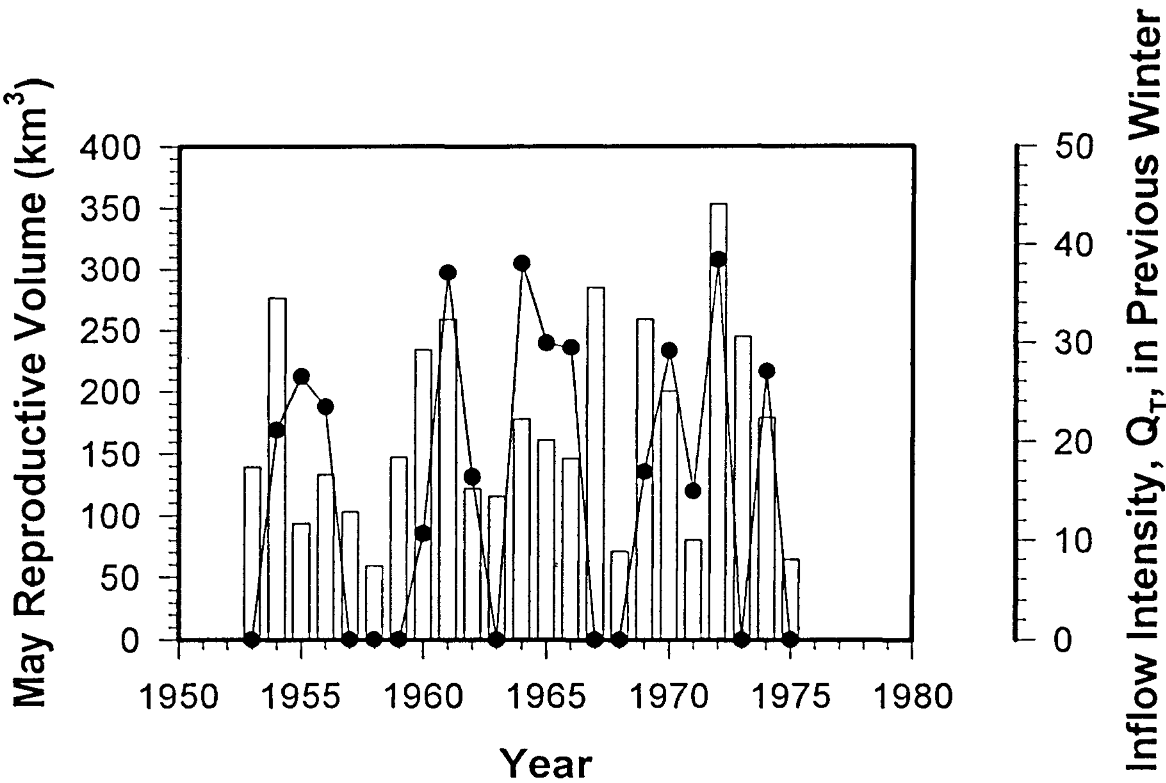
model. Delta O2 is calculated as the change in oxygen content between the simulation utilizing realistic conditions for the Bornholm Basin and the experimental condition.

8) Increased Wind Stress Simulation: Contour plot of changes in relative oxygen content ($ml.l^{-1}$) due to a simulated 15% increase of wind energy over the period from 1st to 31, December 1995, along the transect (shown in figure 2) as simulated by the Baltic Sea model. Delta O2 is calculated as the change in oxygen content between the simulation utilizing realistic conditions for the Bornholm Basin and the experimental condition.

9) Increased Wind Stress Simulation: Contour plot of changes in salinity (‰)due to a simulated 15% increase of wind energy over the period from 1st to 31, December 1995, along the transect (shown in figure 2) as simulated by the Baltic Sea model. Delta salinity is calculated as the change in salinity (‰) between the simulation utilizing realistic conditions for the Bornholm Basin and the experimental condition.

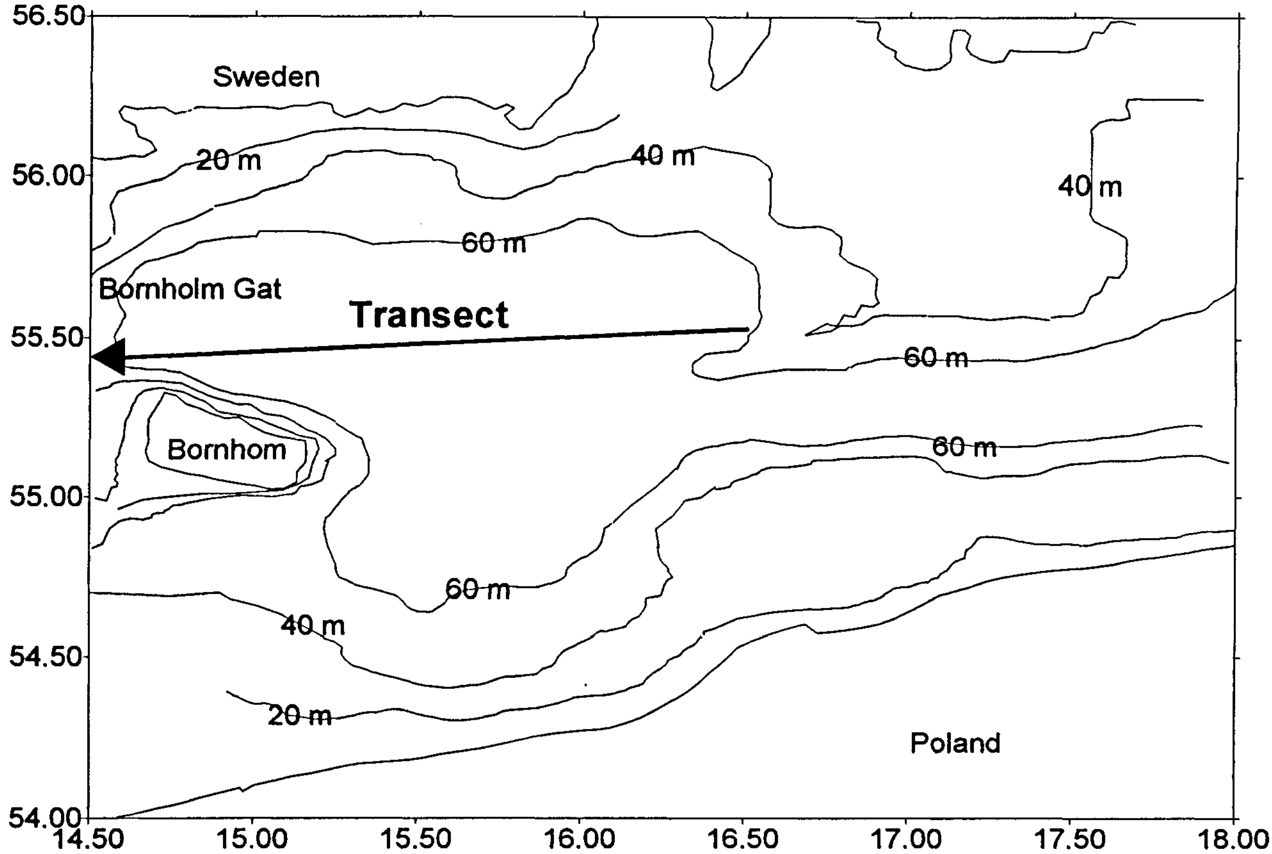
10) Storm Experiment 1: Contour plot of changes in relative oxygen content ($ml.l^{-1}$) due to a simulated 1.8 % increase of wind energy over the period from 3rd to 6th, December 1995, along the transect (shown in figure 2) as simulated by the Baltic Sea model. Peak wind speed in experimental condition is 18 $m.s^{-1}$ Delta O_2 is calculated as the change in oxygen content between the simulation utilizing realistic conditions for the Bornholm Basin immediately after the storm and the experimental condition immediately after the storm.

11) Storm Experiment 1 : Contour plot of changes in relative oxygen content ($ml.l^{-1}$) due to a simulated 1.8 % increase of wind energy over the period from 3rd to 6th, December 1995, along the transect (shown in figure 2) as simulated by the Baltic Sea model. Peak wind speed in experimental condition is in excess of 20 $m.s^{-1}$. Delta O_2 is calculated as the change in oxygen content between the simulation utilizing realistic conditions for the Bornholm Basin immediately after the storm and the experimental condition immediately after the storm.



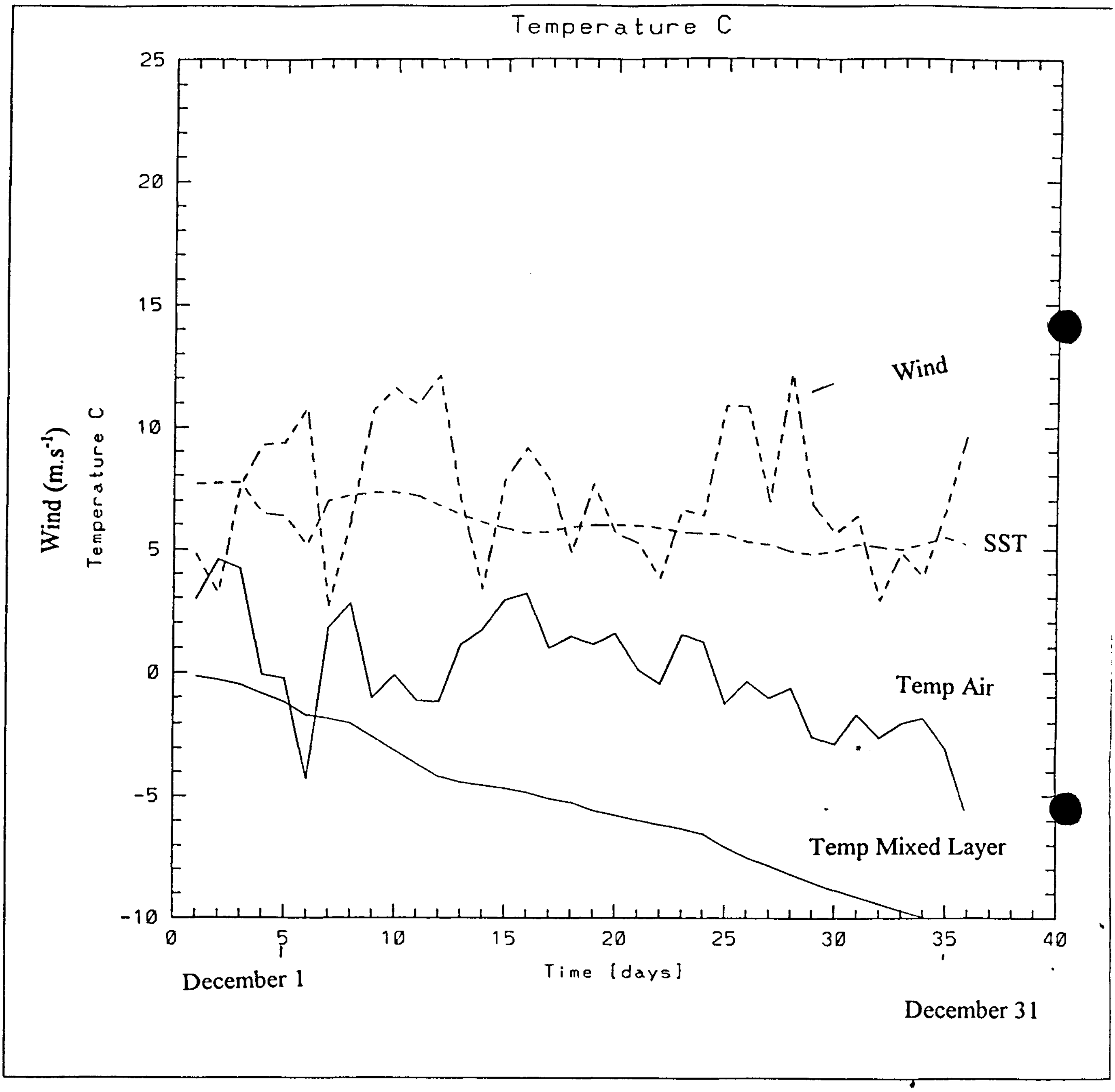
May Reproductive Volume (km3)
400
350
300
250
200
150
100
50
0
1950
1955
1960
1965
1970
1975
1980
Year
50
40
30
20
10
0
Inflow Intensity, QT, in Previous Winter

Figure 1



56.50
56.00
55.50
55.00
54.50
54.00
14.50
15.00
15.50
16.00
16.50
17.00
17.50
18.00
Sweden
20 m
40 m
40 m
60 m
Bornholm Gat
Transect
60 m
Bornhom
60 m
60 m
40 m
20 m
Poland

Figure 2



Temperature C
25
20
15
10
5
0
-5
-10
0
5
10
15
20
25
30
35
40
Wind (m.s-1)
Temperature C
Time [days]
Wind
SST
Temp Air
Temp Mixed Layer
December 1
December 31

Fig 3

13°09.5 E
54°80.3 N

Realistic Conditions

16°47.0 E
55°30.7 N

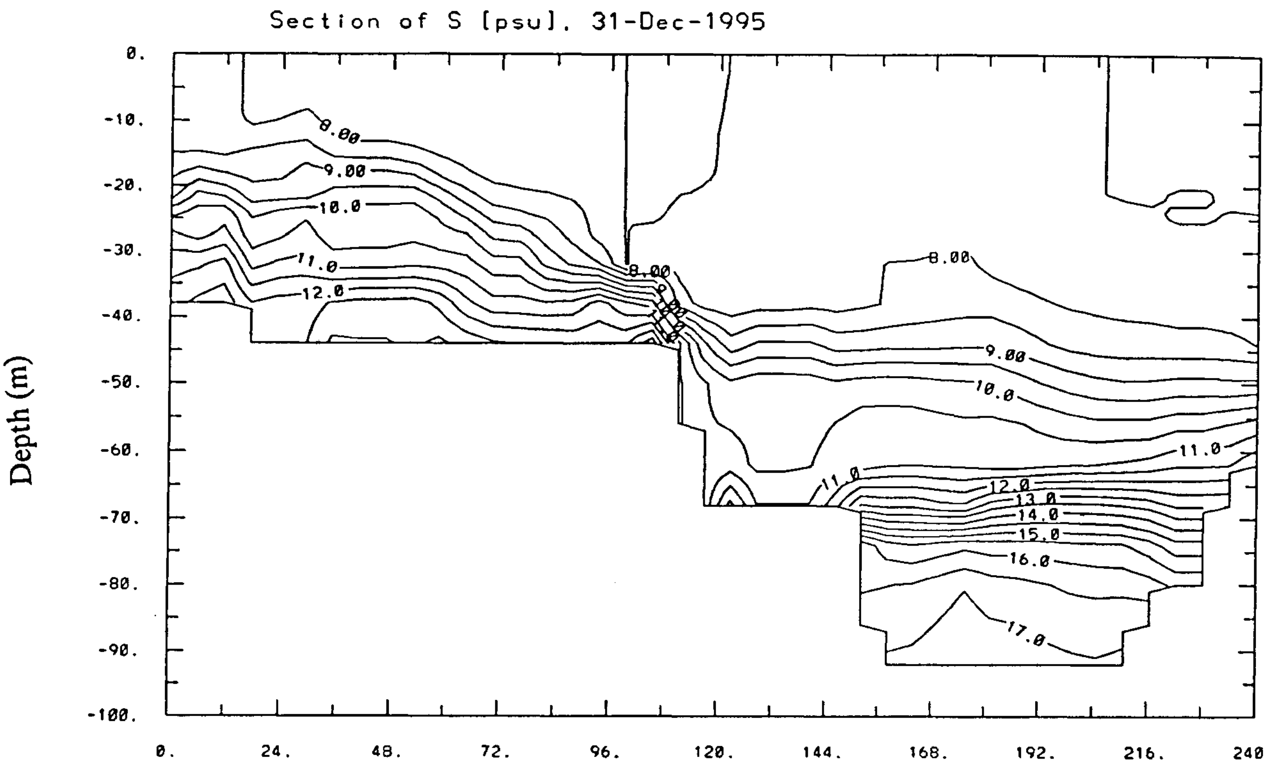


Fig4

Realistic Conditions

13°09.5 E
54°80.3 N

16°47.0 E
55°30.7 N

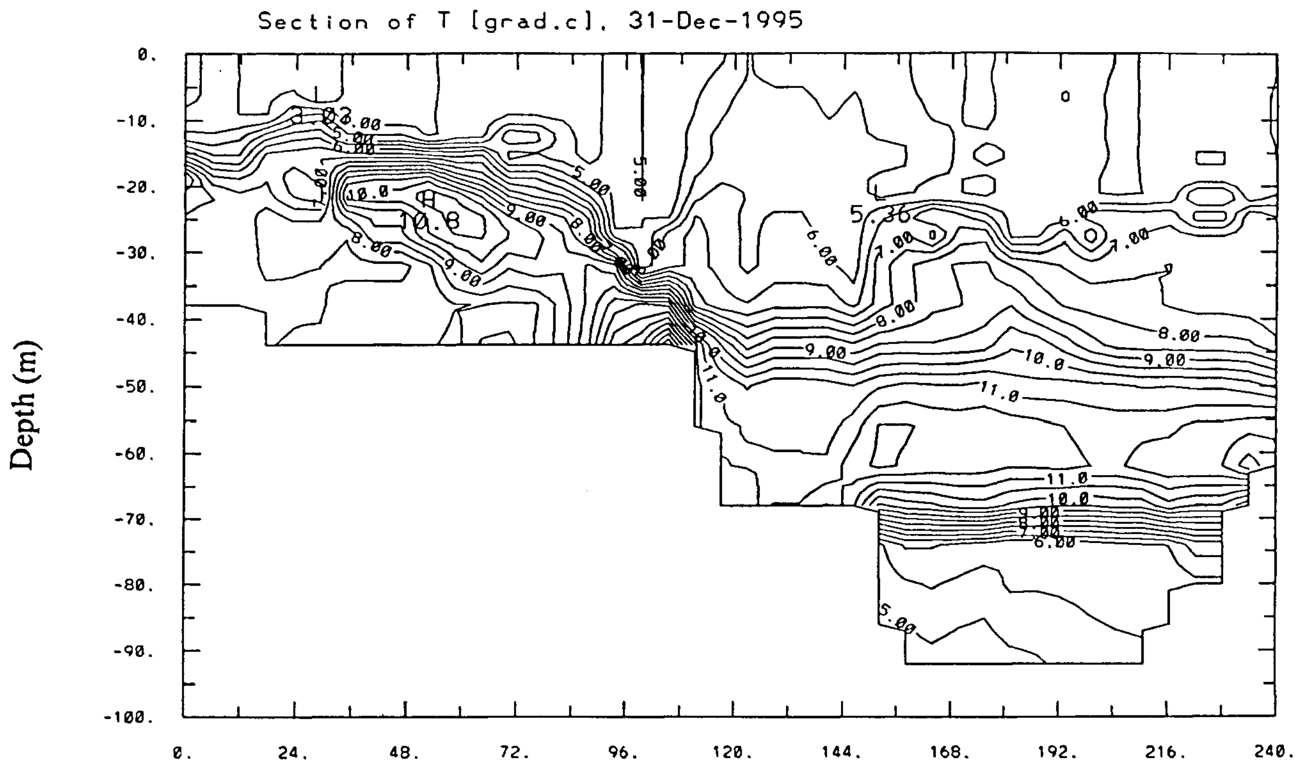


Fig 5

Realistic Conditions

13°09.5 E
54°80.3 N

16°47.0 E
55°30.7 N

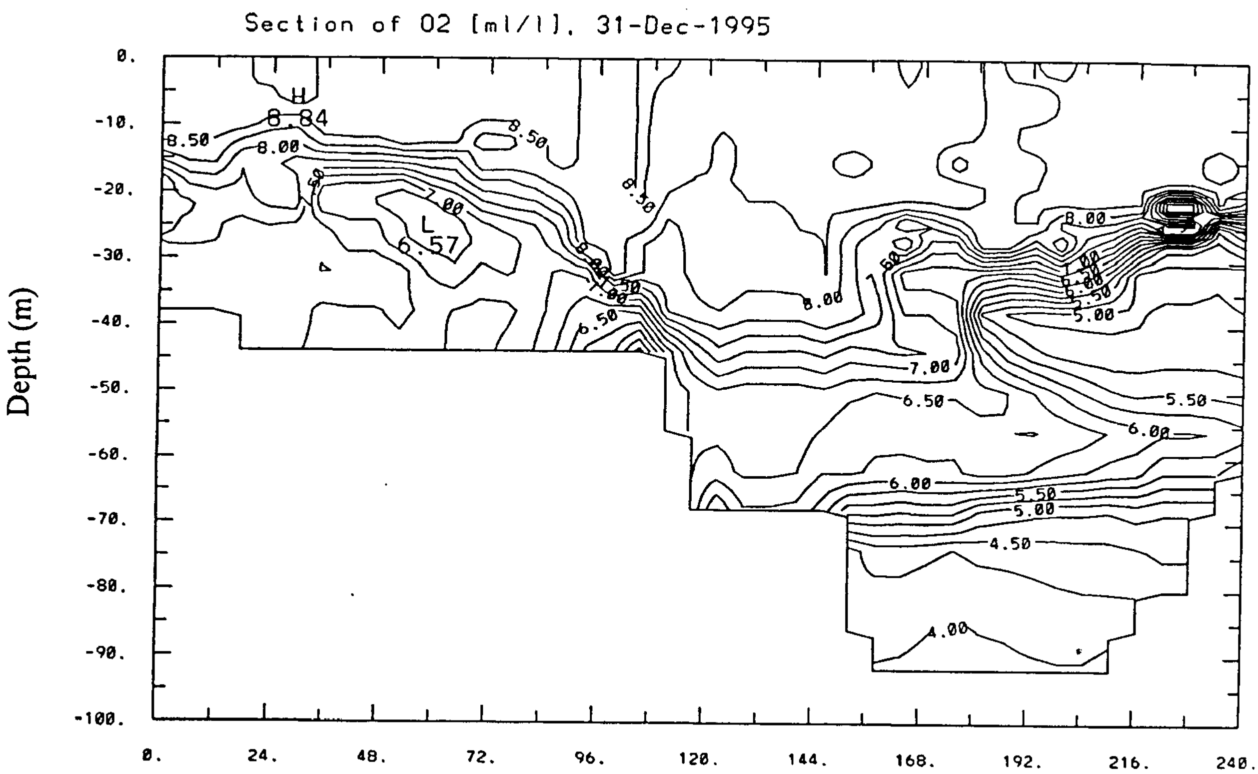


Fig 6

Thermal Convection

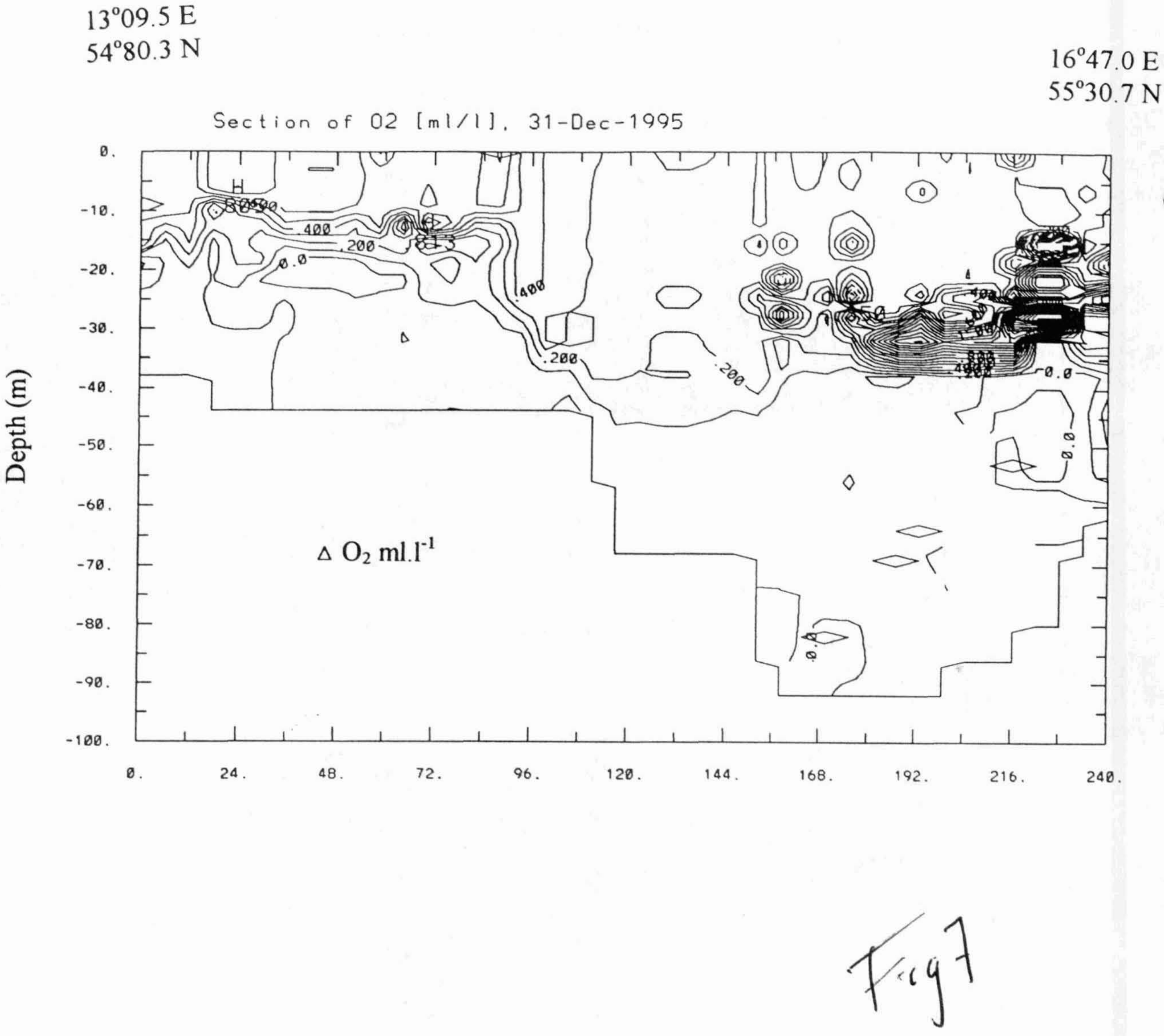


Fig 7

13°09.5 E
54°80.3 N

Simulation with Increased Wind Stress

16°47.0 E
55°30.7 N

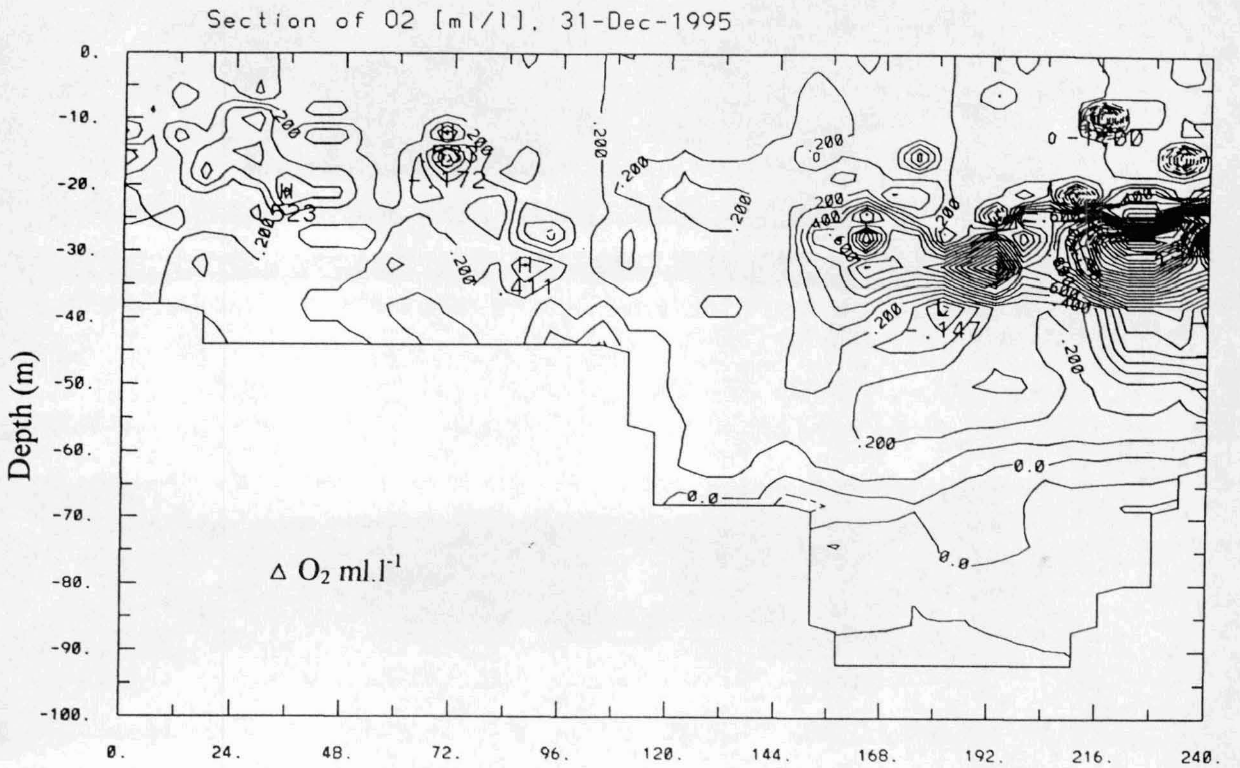


Fig 8

Simulation with Increased Wind Stress

13°09.5 E
54°80.3 N

16°47.0 E
55°30.7 N

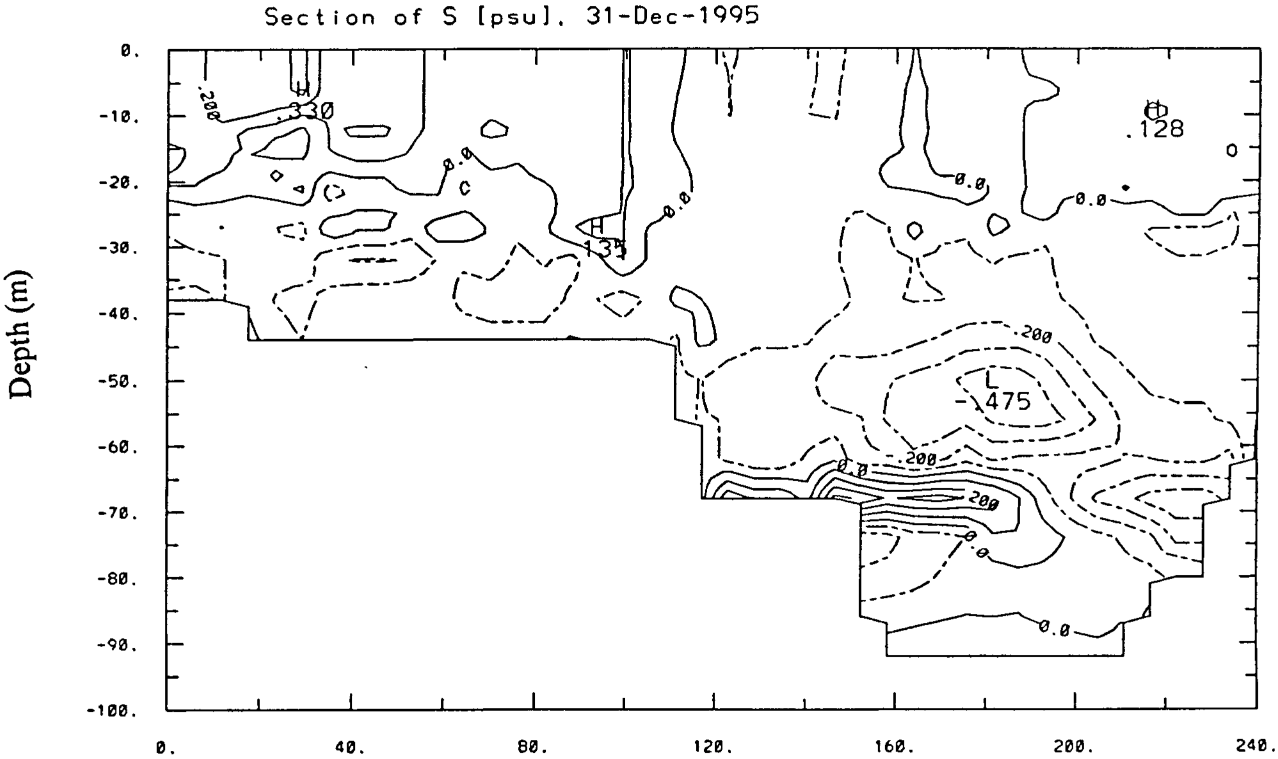


Fig 9

Storm Simulation 1 (18 m.s^{-1})

13°09.5 E
54°80.3 N

16°47.0 E
55°30.7 N

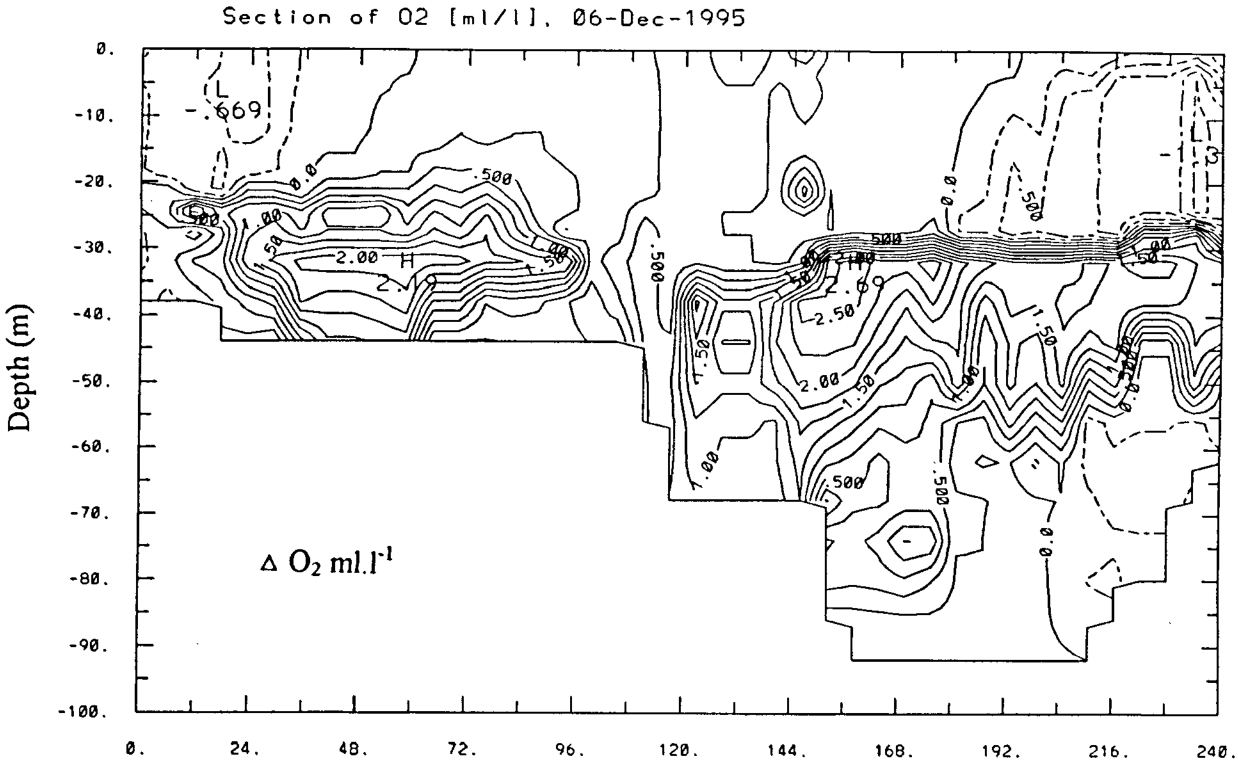


Fig 10

13°09.5 E
54°80.3 N

Storm Simulation 2 (>20 $m.s^{-1}$)

16°47.0 E
55°30.7 N

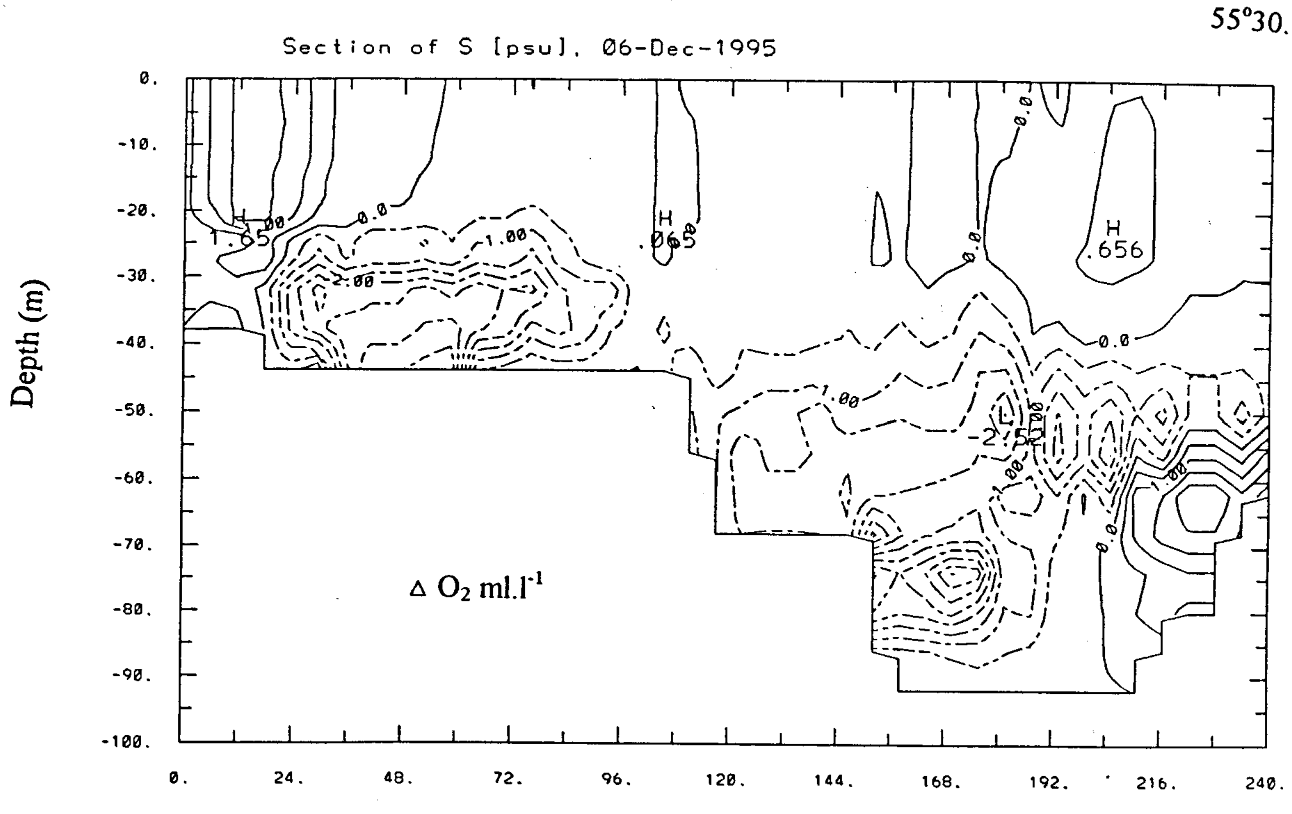


Fig 11