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Spatial and Temporal Extent of Hydrocarbon Contamination in Marine Species of Bristol Bay

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Spatial and Temporal Extent of Hydrocarbon Contamination in Marine Species of Bristol Bay

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INTRODUCTION

The potential biological contamination resulting from a hypothetical Bering Sea oil spill, and the effect of fish migrations on the distribution of the contamination, are simulated by BIOS (Biological Impact of an Oil Spill), a multispecies biomass-based ecosystem model. BIOS was developed at the request of the Outer Continental Shelf Environmental Assessment Program (OCSEAP) as part of their eastern Bering Sea oil impact study (Swan 1984, Gallagher 1984). Uptake of oil contaminants, from exposure to contaminated water and sediments as well as from consumption of contaminated food, is simulated for 16 fish species groups (Table 1). Two oil spill scenarios (Table 2) were modelled at each of three locations in Bristol Bay: offshore of Cape Newenham, Port Heiden, and Port Moller (Figure 1). Gridded values of hydrocarbon concentrations dissolved or in suspension in the water column (referred to here as the water soluble fraction, WSF) were provided by Rand Corporation in conjunction with Science Applications, Inc. (see Laevastu and Fukuhara 1984a). The fraction of oil reaching the bottom and entering the sediments (referred to here as TARS) was calculated with a simulation model developed by Laevastu and Fukuhara (1984b).

The simulation techniques for hydrocarbon uptake and depuration are described in Gallagher and Pola (1984) and will not be discussed in detail here. The concentrations of hydrocarbons within the fish (referred to here as contamination) are calculated in parts per million (ppm; mg hydrocarbon per kg biomass). This report examines the magnitude and spatial extent of contamination over the model grid simulated with and without fish migrations of various speeds and directions. In addition, the contamination of migrating fish beyond the bounds of the model grid is traced until depuration

Table 1.--Species groups in the BIOS model.

No.	Species
1	Herring juveniles
2	Herring adults
3	Pollock juveniles
4	Pollock adults
5	Pacific cod juvenile
6	Halibut juveniles
7	Yellowfin sole juveniles
8	Other flatfish juveniles
9	Yellowfin sole adults
10	Other flatfish adults
11	Pacific cod adults
12	King and Bairdi crab juveniles
13	King and Bairdi crab adults
14	Mobile epifauna
15	Sessile epifauna
16	Infauna

Table 2.--Hypothetical oil-spill scenarios.

Scenario	Oil type	Volume	Duration	Grid size
Blowout	Prudhoe Bay crude	20,000 bbl/day	15 days	50 x 50
Accident	Automotive diesel	200,000 bbl	10 days	32 x 34

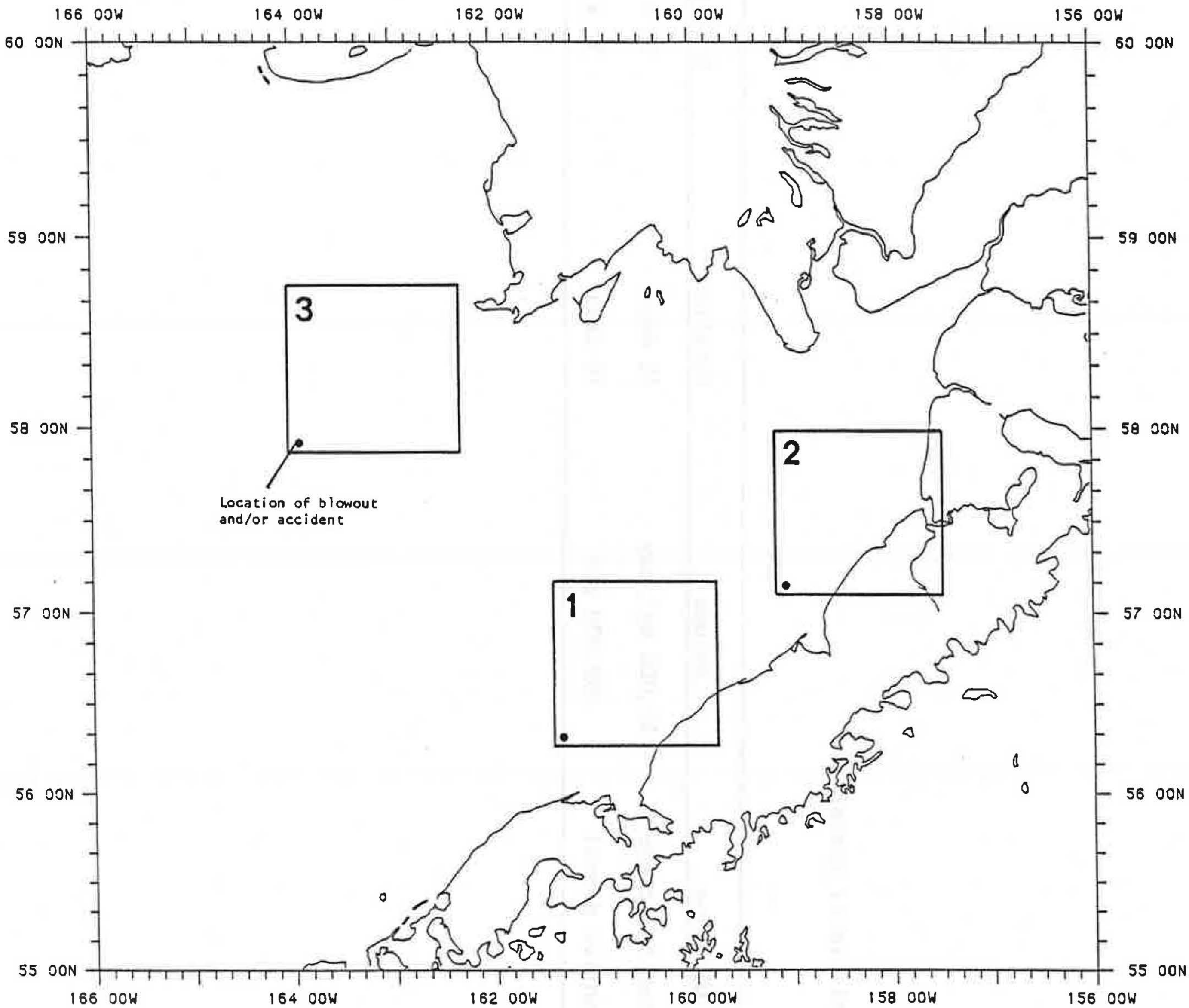

Figure 1.--Locations of hypothetical oil spill scenarios.

below detectable levels of contamination (defined as <5 ppm) is complete. The model does not allow avoidance of oil by fish, in an attempt to maximize the biological impact of the hypothetical oil spills.

METHODS

Model Formulations

The amount of contamination in a fish species (C_f) at any time step (t_d) is computed in the BIOS model as:

$$C_f(t_d) = \frac{k_1 C_o(t_d)}{k_2} (1-\exp(-k_2)) + C_f(t_d-1)\exp(-k_2) \quad (1)$$

where C_o is the external oil concentration, k_1 is the uptake rate, and k_2 is the depuration rate. Equation 1 is a finite-difference approximation to the single compartment model discussed by Wilson (1975) and Moriarty (1975), and reviewed by Connell and Miller (1981). Uptake of contaminants is assumed to be equally divided between uptake from exposure to oil in the water or sediments and uptake from consumption of contaminated food (Teal, 1977). C_f refers to the total amount of hydrocarbons in the fish; no attempt has been made to partition the contamination within the fish (gut, liver, muscle, etc.), and no information was provided by Rand Corporation as to the chemical composition of the oil at each time step.

Equation 1 can be rewritten as:

$$C_f(t_d) = C_U + C_D \quad (1a)$$

where C_U is the amount of contamination taken up by a fish species at simulation time step t_d and C_D is the amount accumulated over previous time steps, after depuration. The external oil concentration includes both oil in the water column (WSF) and in the sediments (TARS); the relative effect of each component is determined by the proportion of pelagic or demersal food in the species' diet. The uptake of contamination is computed in the model as:

$$C_U = (F_p B_p C_{WSF} + F_d B_d C_{TARS})\ (1-\exp(-k_2)) \tag{2}$$

where F_p and F_d are the fractions of pelagic and demersal food, respectively, in a species' diet, B_p and B_d are the pelagic and demersal bioconcentration factors, and C_{WSF} and C_{TARS} are the napthalene fractions of the oil concentrations in the water column and in the sediments, respectively. A detailed discussion of assumptions and parameters in equations 1 and 2 is given in Gallagher and Pola (1984).

The BIOS model functions include optional fish migration. The biomass of each species group is assumed constant over all gridpoints (see the following section); migrations are therefore simulated in the model by the advection of contamination through the grid. The amount of contamination leaving gridpoint (n,m) in the x-direction is:

$$R_{x,n,m} = (G_x t|U|)/L \tag{3}$$

and in the y-direction is:

$$R_{y,n,m} = (G_y t|V|)/L \tag{4}$$

where t is the migration time step, L is the grid spacing, U and V are the migration velocity components, and G_x and G_y are contamination gradients:

$$G_x = [C(t)_{n,m+j} - C(t)_{n,m}] \tag{5}$$

$$G_y = [C(t)_{n+i,m} - C(t)_{n,m}] \tag{6}$$

The subscripts i and j are defined as:

$$i = \begin{cases} 1 , & V < 0 \\ 0 , & V = 0 \\ -1 , & V > 0 \end{cases}$$

$$j = \begin{cases} -1, & U < 0 \\ 0, & U = 0 \\ 1, & U > 0 \end{cases}$$

such that the gradients G_x and G_y are taken in the "upstream" direction. The contamination is then redistributed over the grid:

$$C(t+1)_{n,m} = C(t)_{n,m} - R_{x,n,m} - R_{y,n,m} \tag{7}$$

$$C(t+1)_{n,m+j} = C(t)_{n,m+j} + R_{x,n,m} \tag{8}$$

$$C(t+1)_{n+i,m} = C(t)_{n+i,m} + R_{y,n,m} \tag{9}$$

The migration time step, t, is restricted by the stability criterion:

$$t|U^*| < L \tag{10}$$

where U* is the maximum migration speed in km/day. That is, for a migration speed of 15 km/day and grid spacing of 2 km, t < .13 days. In the present analysis, a migration time step of .0625 days was used, and migrations were performed 16 times during each daily model time step.

Any contamination leaving the grid is saved on disk to be used as input to the submodel OUTMIG, which traces the spatial extent of contamination until depuration to less than 5 ppm, the level used as the threshold for the detection of tainting in fish. The OUTMIG submodel uses a grid with twice the dimensions of the BIOS grid (e.g., for the accident scenario, a grid size of 64 x 68 is used). The BIOS model grid occupies one quadrant of the OUTMIG grid; the specific quadrant is dependent upon the migration direction (Figure 2). As contamination leaves the BIOS grid, it enters the first adjacent row and column of the OUTMIG grid. Migrations in OUTMIG are calculated as in the main BIOS model (i.e., using equations 3 - 9); however, since the oil spill is restricted to the area of the BIOS model grid, there is no uptake of contaminants (equation 2) in the OUTMIG submodel.

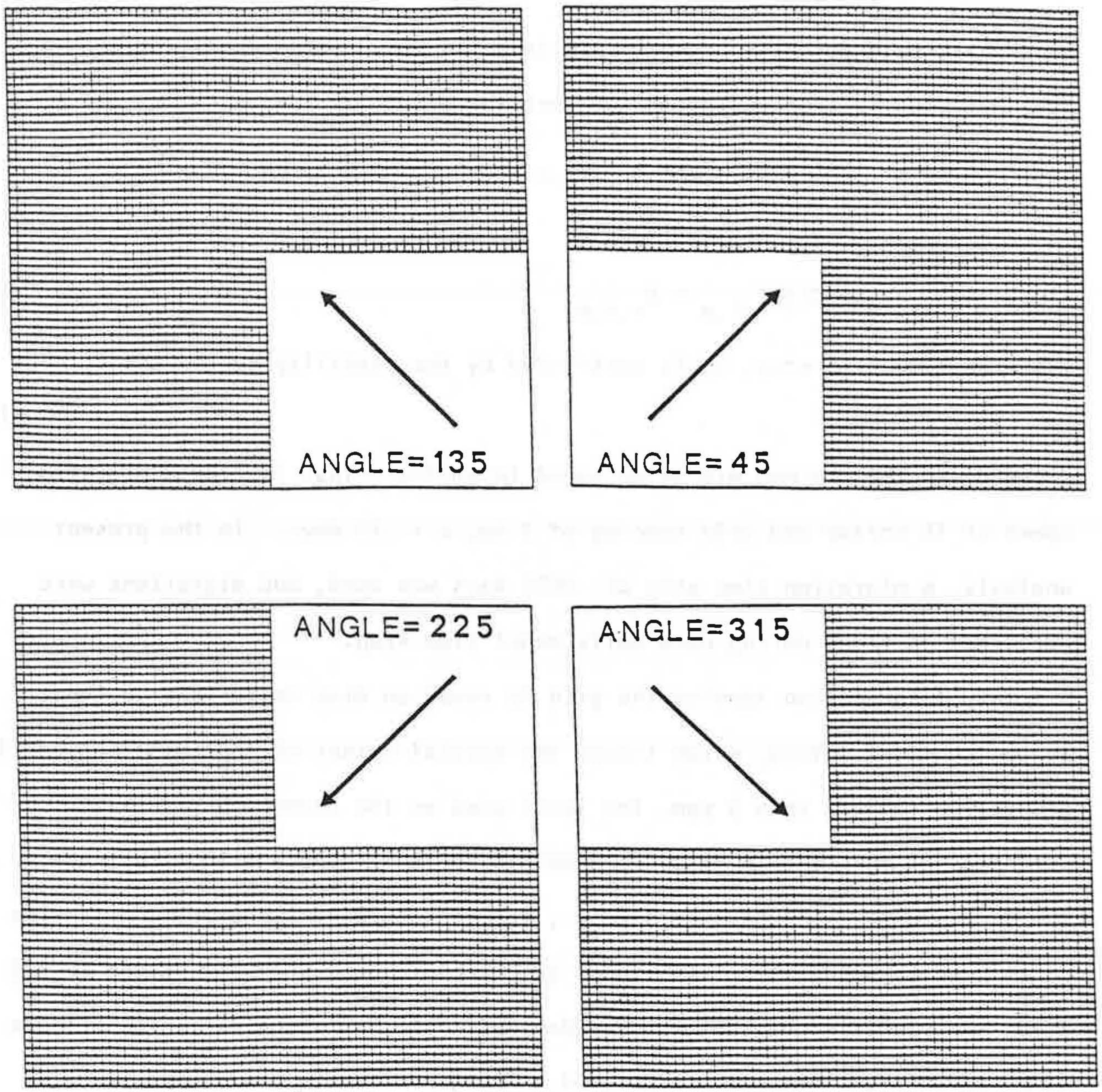

Figure 2.--Migration directions and corresponding grids used in the OUTMIG submodel.

Both the BIOS model and the OUTMIG submodel were run for 50 days. The oil concentrations provided by Rand Coporation were computed for 10 days in the accident scenario and for 15 days in the blowout scenario (Table 2). At model time steps greater than those limits, the oil concentrations in the water column were decayed at a constant rate:

$$WSF(t_d)_{n,m} = WSF(t_d - 1)_{n,m} e^{-k} \qquad (11)$$

where a decay rate (k) of 0.3 was estimated from the Rand data.

Model Parameterization

Model calculations are performed at each model gridpoint during each daily time step. Grid size for the accident scenario is 32 x 34 and for the blowout scenario is 50 x 50 (Table 2); grid spacing for each scenario is 2 km. Since 1975 (in some cases, since 1972), survey data have been collected at regular intervals at consistent locations in the Bering Sea. Station spacing for survey cruises is 20 n mi (34.04 km). The biological data cannot be adequately resolved to the 2 km model grid spacing; therefore, the biomass for each species group is assumed constant over all gridpoints. Biomass values (kg/km^2) used for each location are shown in Table 3 (see Table 1 in Gallagher and Pola (1984) for a description of assumptions used in the biomass calculations). When the migration option is selected in the model, it is assumed that fish (i.e., contamination) leaving the model grid are replaced by the equivalent biomass (at zero contamination) entering the grid at the opposite ("upstream") side.

Species-specific migration speeds and directions are input to the BIOS model. Most available literature on migrations of fish stocks in the Bering

Table 3.--Species biomass (kg/km^2) at each simulation location.

Species number	Location: Port Moller	Port Heiden	Cape Newenham
1	1409	521	1551
2	1121	414	1234
3	3708	2322	3261
4	11007	6893	9679
5	424	279	307
6	730	330	240
7	722	482	711
8	2004	1472	1650
9	800	534	789
10	2004	1472	1650
11	861	461	681
12	664	222	432
13	1654	553	1078
14	5970	4995	6075
15	13930	11655	14175
16	19150	13750	19250

Sea are based on seasonal distribution patterns (Thorsteinson and Thorsteinson 1984; Pereyra et al. 1976; Bakkala and Smith 1978); minimum migration speeds are computed as the mean distance between seasonal locations divided by the time between seasons. Information on migration speeds from tagging-recapture studies is contradictory. Harden Jones (1968) gives a value of 3 body lengths per second (bl/s) as the maximum sustainable speed for fish between 10 and 100 cm length (i.e., maximum sustainable speeds are 25.9 - 259.2 km/day). Walker et al. (1978) calculated average ground speeds for plaice that moved more than 15 km in the duration of their tracking experiment; values were between 16 and 40 km/day (mean 24.39 km/day). Arnold (1981), in another tagging-recapture study of plaice, calculated a mean ground speed of 0.3 km/h (7.2 km/day), and Harden Jones (1981) in the same publication listed plaice speeds of between 38 and 95 cm/sec (33 - 82 km/day). Table 4 (adapted from Harden Jones 1977) summarizes results from several tagging-recapture studies. Migration speeds range from 1 - 185 km/day and no direct relationship between fish length and migration speed is evident from these data. In the present study various migration speeds and directions were used and differences in the resulting contamination fields were examined. The oil slick moved toward the northeast at approximately 3 km/day. Migration speeds of 5, 10, and 15 km/day were input into the model. Migration directions used were 45° (i.e., moving approximately in the same direction as the oil spill), 135° (moving across the spill toward the northwest), 225° (moving toward the source of the spill), and 315° (moving across the spill to the southeast); all angles are measured relative to due east (see Figure 2). The effects of beaching of oil were not addressed; therefore, in the present analysis, all grid boundaries are open.

Species	Mean length (cm)	Speed		Author
		km/day	bl/sec	
Sole	30	7-16	0.28 - 0.53	Anon. (1965)
Plaice	35	1-7	0.06 - 0.23	Bannister (unpub.)
Herring	25	4-30	0.20 - 1.40	Bolster (1955)
Mackerel	35	16-23	0.54 - 0.77	Bolster (1974)
Sockeye salmon	70	9-22	0.15 - 0.36	Harden Jones (1968)
Cod	80	6-28	0.09 - 0.40	Trout (unpub.)
Albacore	77	26-44	0.39 - 0.66	Clemens (1961)
Bluefin	250	93-185	0.43 - 0.86	Mather et al. (1977)

Table 4.--Migration speeds calculated from tagging-recapture studies.

Conflicting values for the minimum detectable level of contamination (threshold level of tainting) are also given in the literature. Howgate et al. (1977) give a threshold value of 10 l/kg (between 8 and 10 ppm, depending on the density of the oil); Rice (1981) states that "experienced tasters can detect 10-30 ppm crude oil in cooked or raw fish fillets". However, a literature review by Solomon and Mills (1982) gives a value of 0.4-0.5 ppm as the lowest detectable level of oil in fish. In a study by Brandal et al. (1976), a panel of experienced tasters found tainting in Atlantic salmon, *Salmo salar*, with a contamination level of 0.5 ppm. In the latter example however, only the aromatic hydrocarbons (primarily benzene and napthalene) were measured; in addition, the 0.5 ppm refers to the contamination within the muscle tissue only, rather than the level of contamination within the entire organism (as computed by the BIOS model). The threshold of 5 ppm used in the present study, therefore, is considered reasonable and slightly conservative.

RESULTS

Oil Concentrations

Gridded subsurface oil concentrations (WSF) for two hypothetical oil-spill scenarios at three locations in the Bering Sea (Figure 1; Table 2) were provided by Rand Coporation. Maximum WSF concentrations (ppm) for all six simulated oil spills are given in Table 5. Maxima are the same order of magnitude at the 3 locations for each scenario; however, maxima differ by an order of magnitude between scenarios. The similarity of contoured WSF concentrations among locations is illustrated in Figures 3 (Port Moller and Cape Newenham) and 4 (Port Heiden) five, ten, twenty, and thirty days after the onset of the

Table 5.--Maximum subsurface oil concentrations for each simulated oil spill.

	Maximum WSF (ppm)		
Scenario	Pt. Moller	Pt. Heiden	Cape Newenham
Accident	9.04	8.98	9.58
Blowout	0.34	0.30	0.29

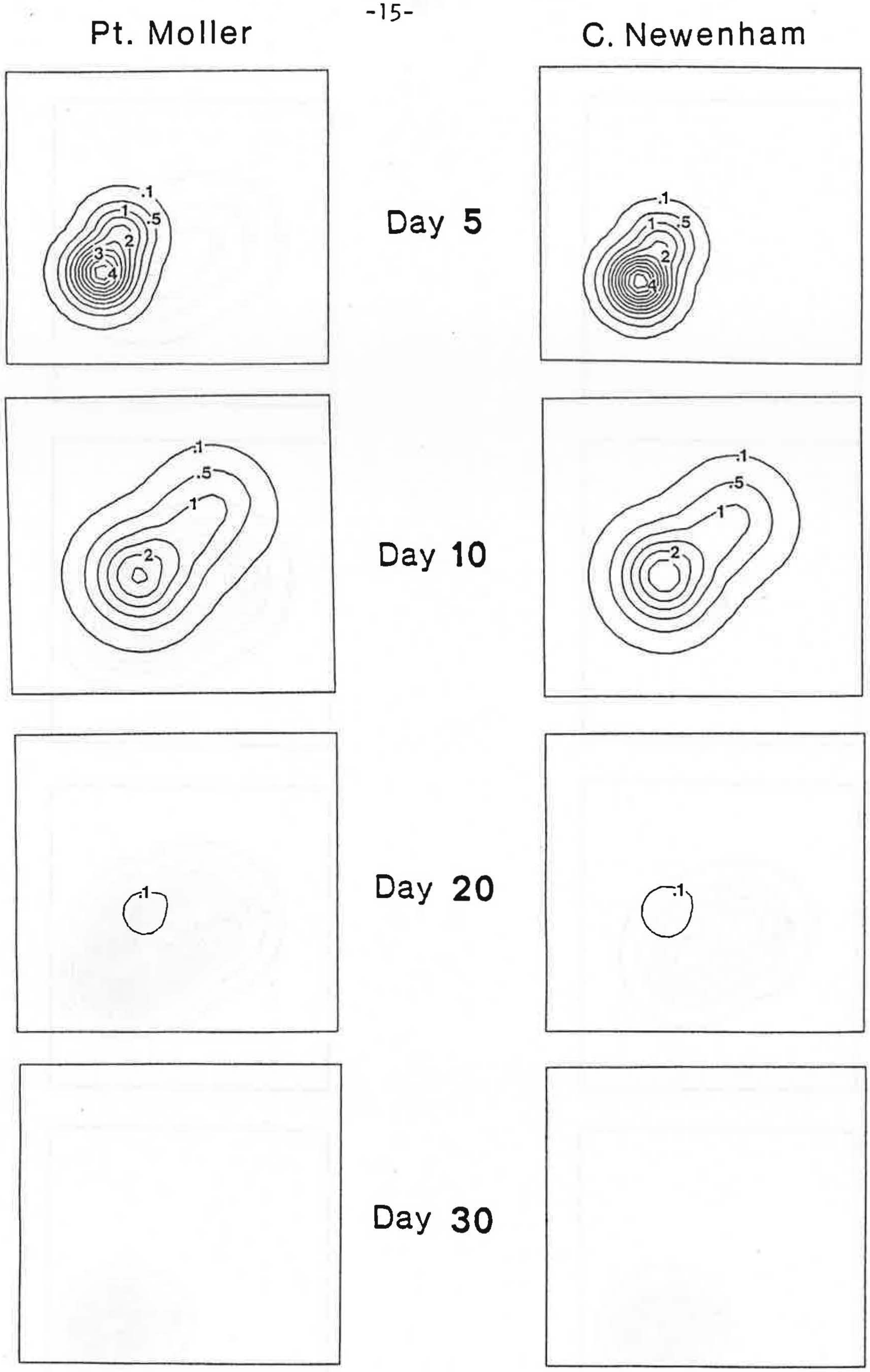

Figure 3.--Concentrations of oil in the water column (WSF) at Port Moller and at Cape Newenham. Contour interval is 0.5 ppm and the 0.1 ppm contour is included.

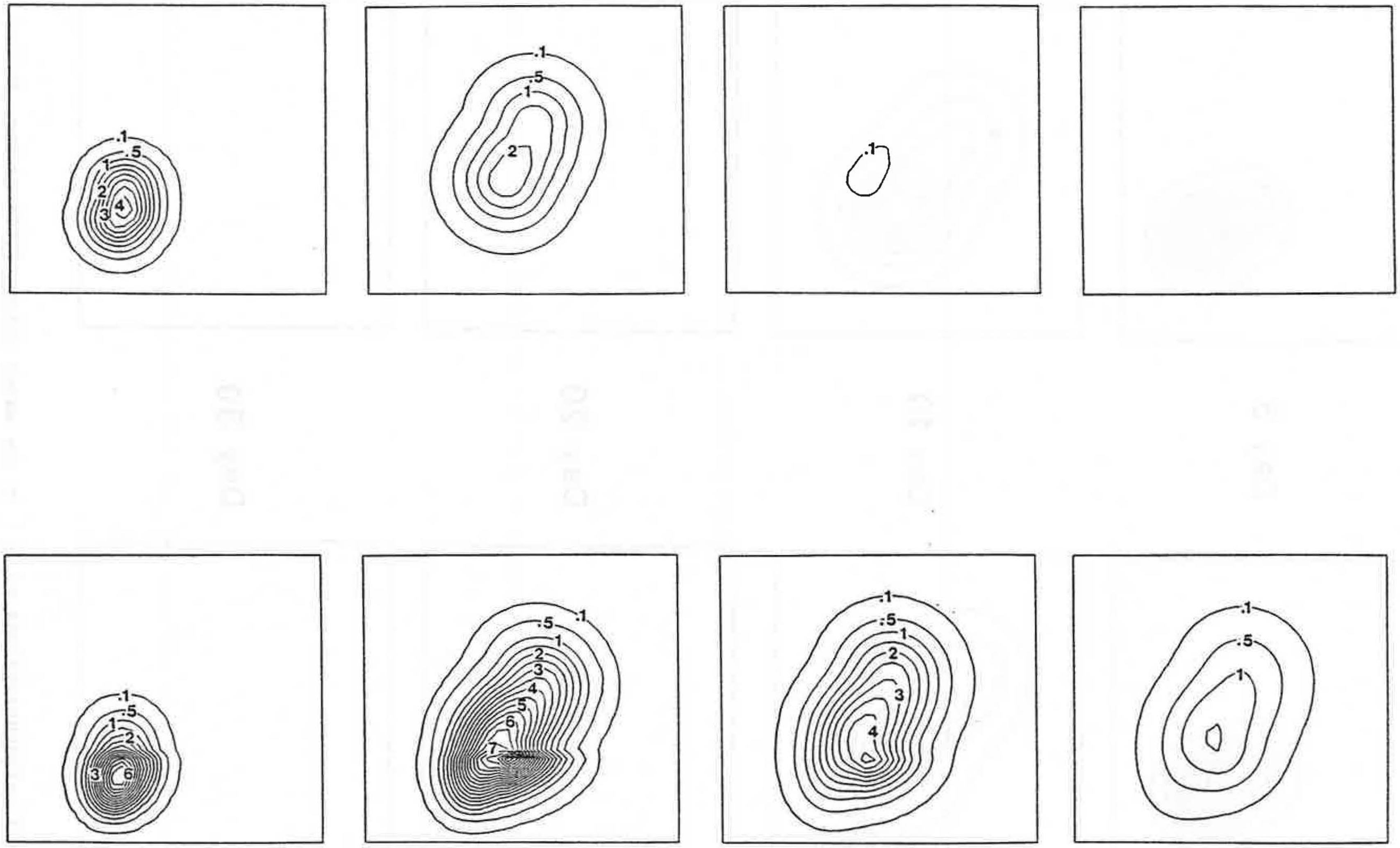

Figure 4.--Concentrations of oil in the water column (WSF) and in the sediments (TARS) at Port Heiden. Contour interval is 0.5 ppm and the 0.1 ppm contour is included.

oil spills (accident scenario). Concentrations are less than 1.5 ppm at all locations after 20 days; after 30 days, concentrations are everywhere less than 0.001 ppm (1.0 ppb). To avoid unnecessary repetition of results, therefore, only Port Heiden will be discussed. Concentrations of oil in the sediments (TARS), which are computed by the model of Laevastu and Fukuhara (1984b) using WSF concentrations as input, are also shown for the Port Heiden accident scenario in Figure 4. TARS reach a maximum of 10.1 ppm by day 10, and remain at levels above 1.5 ppm 30 days after the onset of the simulation.

Contours for the blowout scenario are not shown, since WSF concentrations are everywhere below 0.5 ppm (Table 5). Spatial coverage of oil in the blowout scenario is also much less than in the accident scenario. Time series of total area (km^2) covered by oil concentrations greater than 1.0 ppm, 0.1 ppm, 0.01 ppm, and 0.001 ppm (1.0 ppb) are shown in Figure 5 for both the accident (upper panel) and blowout (lower panel) scenarios. Maximum area covered and the duration of coverage for each concentration level are summarized in Table 6. In the blowout scenario, the maximum areal extent of oil concentrations, even at levels as low as 0.001 ppm, is less than 700 km^2, while in the accident scenario, over 300 km^2 are covered by concentrations above 1.0 ppm. This disparity is in part a result of the different types of oil spills simulated: the diesel fuel of the accident scenario is more water soluble than the Prudhoe Bay crude oil of the blowout scenario. In addition, at our request, winds, tides, and temperatures for the accident scenario were selected so as to maximize the amount of oil in the water column. Approximately 32,000 tonnes of oil (at 0.89 g/cm^3 density) were released in the blowout scenario and 20,000 tonnes (at 0.83 g/cm^3 density) were released in the accident

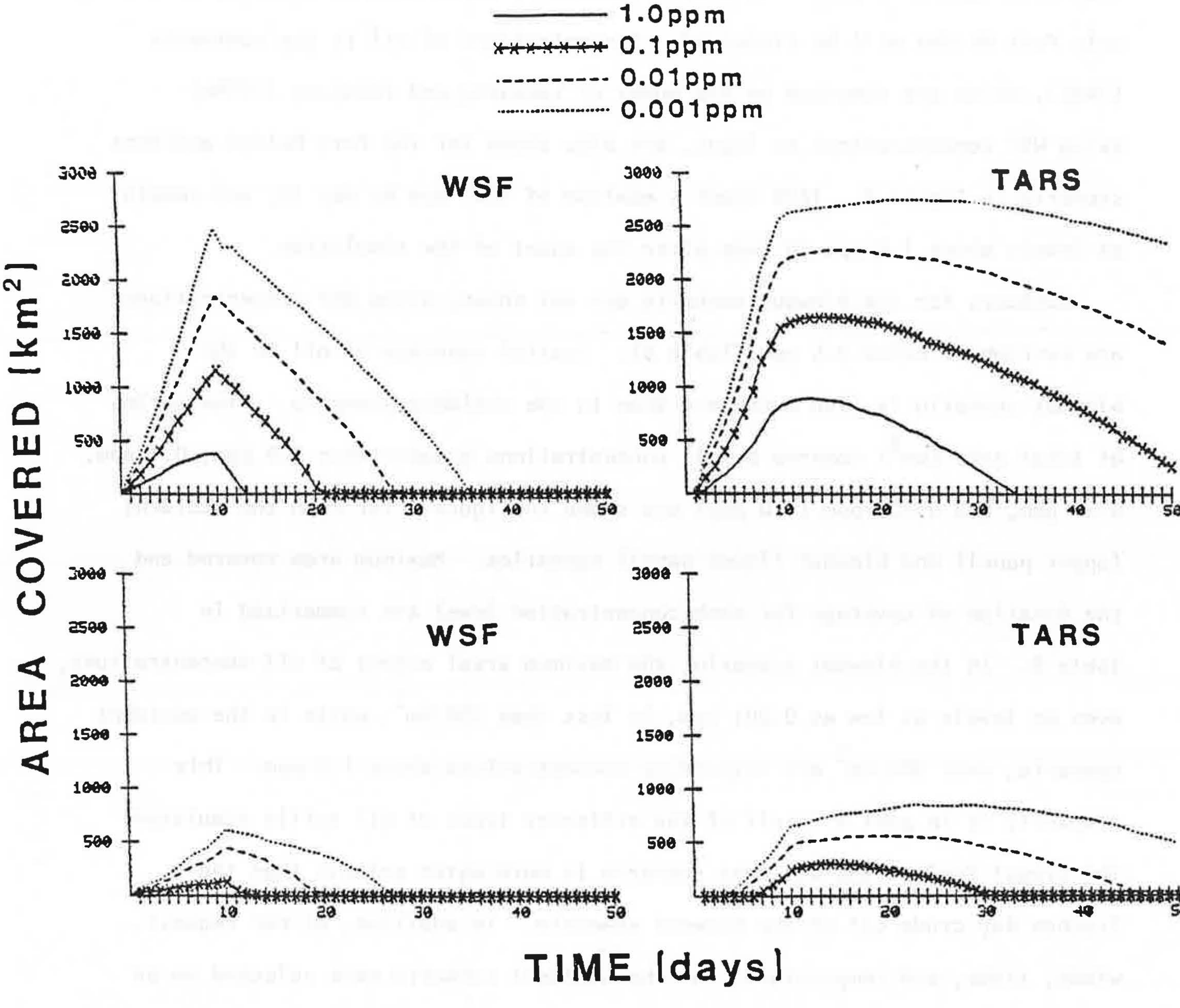

Figure 5.--Time series of total area covered (km^2) by WSF and by TARS at concentrations greater than 1.0 ppm, 0.1 ppm, 0.01 ppm, and 0.001 ppm for the accident (upper) and blowout (lower) scenarios.

Table 6.--Maximum spatial coverage (km^2) and maximum duration (days) of various levels of subsurface (WSF) and bottom (TARS) oil concentrations at Port Heiden.

Oil conc. (ppm)	Accident				Blowout			
	WSF		TARS		WSF		TARS	
	area	duration	area	duration	area	duration	area	duration
>1.0	380	13	752	33	0	0	0	0
>0.1	1160	21	1548	>50	132	12	248	24
>0.01	1844	28	2140	>50	444	20	460	43
>0.001	2480	36	2560	>50	616	27	652	>50

scenario. Of these totals, 81% of the fuel oil, but less than 1% of the crude oil, entered the water column as WSF. Figure 6, from Gallagher and Pola (1984), shows the percent of biomass contaminated (as simulated by BIOS) for selected species in the accident and blowout scenarios. Most species are untainted in the blowout scenario and tainting, when it occurs, affects less than 4% of the Port Heiden biomass (e.g., less than 0.01% of the Bering Sea adult herring biomass; see Table 7). Subsequent results on fish contamination and migrations will therefore only be presented for the accident scenario.

Fish Contamination

The relative effect of either WSF or TARS on each fish species in the BIOS model is proportional to the fraction of pelagic or demersal food in the species' diet (F_p and F_d in equation 2) and dependent upon the toxicity of either oil type. Oil toxicity is primarily due to napthalenes; the WSF concentrations from the diesel accident were estimated to be 50% napthalene and TARS were estimated to be 10% napthalene (Gallagher and Pola 1984). This difference is reflected in the contrast between contamination of a pelagic species (Species 1, juvenile herring; F_p = 1.00) and a demersal species (Species 13, adult crabs; F_p = 0.10, F_d = 0.90) from a model run with no migrations shown in Figure 7. Contours of 5, 10, 50, and 100 ppm are drawn; results are shown 5, 10, 20, and 30 days after the oil spill. The area covered by WSF (for Species 1) or TARS (for Species 13) greater than 1.0 ppm is shaded in each figure. Totals of area (km^2) covered by each level of contamination for 50 daily model time steps are given in Table 8. The pelagic species is more quickly contaminated and reaches higher levels of contamination than the demersal species, even though concentrations of TARS reach higher levels than

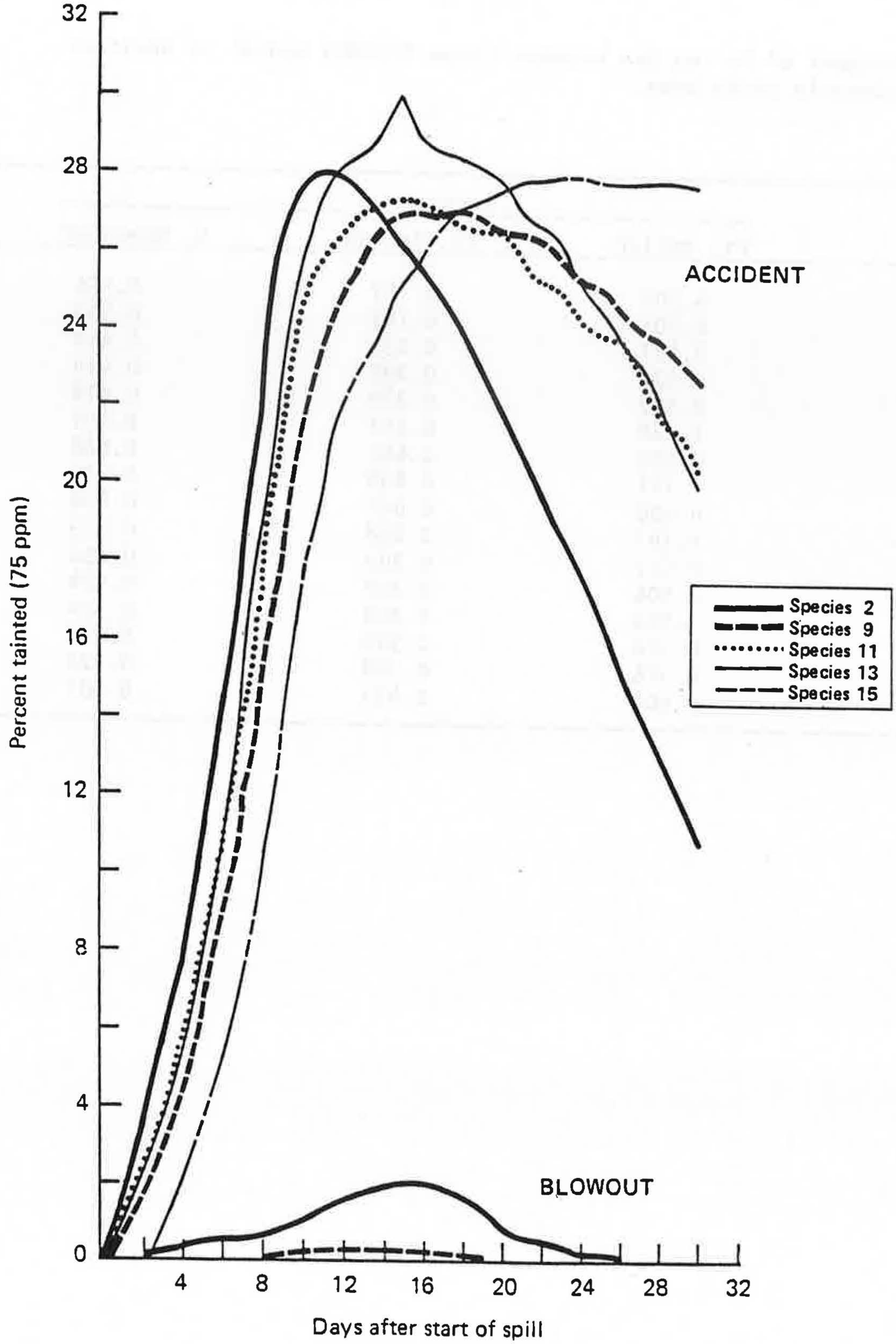

Figure 6.--Percent of biomass within the BIOS model grid contaminated in the accident and blowout scenarios (from Gallager and Pola 1984).

Table 7.--Percent of Bering Sea biomass (from DYNUMES model) in accident scenario study area.

Species number	Location		
	Pt. Moller	Pt. Heiden	C. Newenham
1	0.505	0.187	0.556
2	0.505	0.187	0.556
3	0.471	0.295	0.414
4	0.471	0.295	0.414
5	0.577	0.379	0.418
6	1.220	0.551	0.401
7	0.902	0.602	0.888
8	1.141	0.838	0.939
9	0.900	0.601	0.888
10	1.141	0.838	0.939
11	0.577	0.309	0.456
12	0.806	0.269	0.524
13	0.804	0.268	0.524
14	0.416	0.348	0.424
15	0.416	0.348	0.424
16	0.604	0.433	0.607

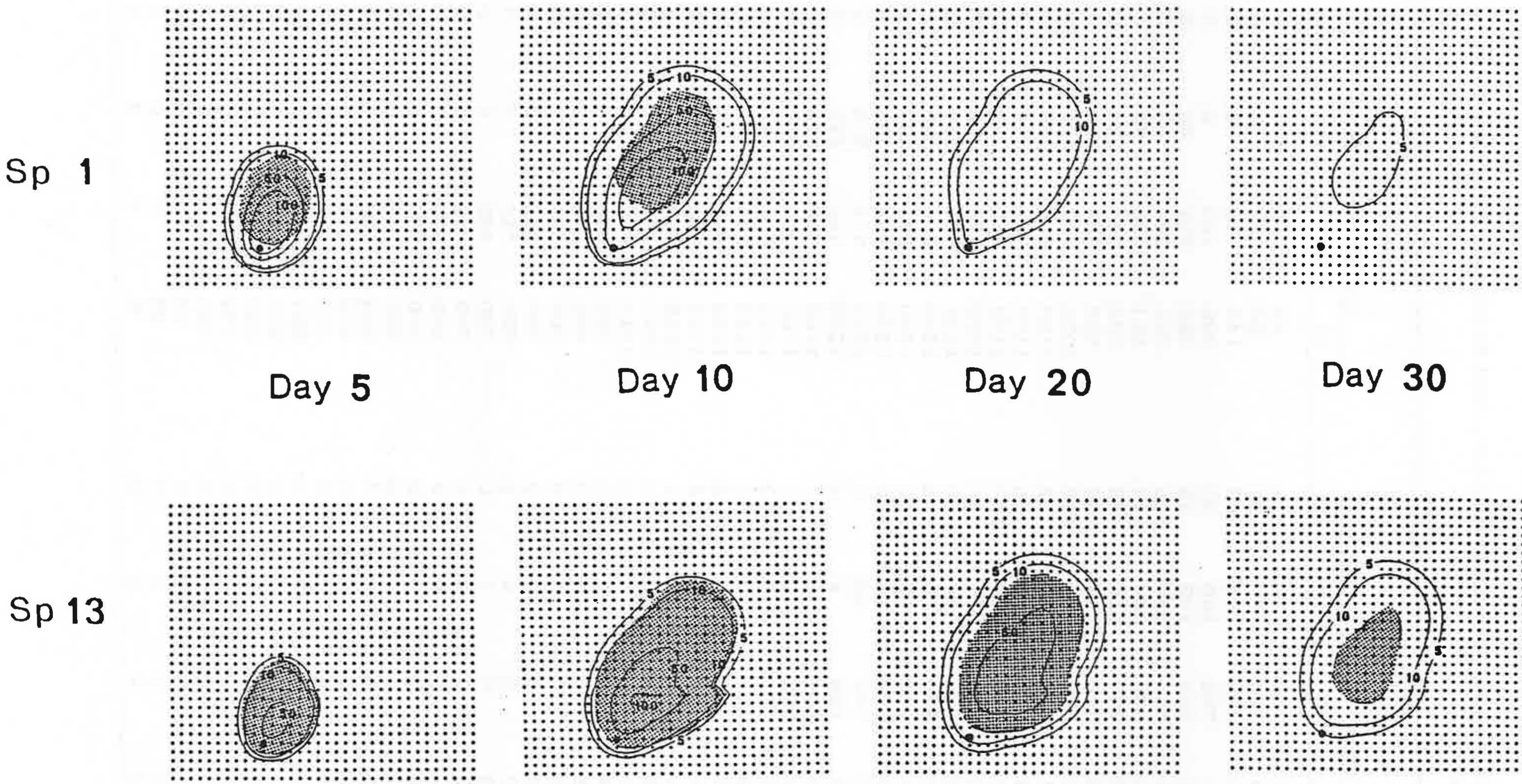

Figure 7.--Contamination of a pelagic (Species 1) and a demersal (Species 13) species group from a model run with no migrations. Contours of 5, 10, 50, and 100 ppm are drawn.

Table 8.--Area covered (km^2) by contamination, Port Heiden accident scenario, no migration.

	Species 1				Species 13			
	Contamination (ppm)				Contamination (ppm)			
Day	>5	>10	>50	>100	>5	>10	>50	>100
1	72	56	24	4	24	8	0	0
2	144	120	60	32	80	52	0	0
3	240	208	96	48	144	96	0	0
4	356	292	140	80	228	160	8	0
5	468	392	192	96	320	232	40	0
6	616	512	248	116	424	324	68	0
7	764	632	304	144	564	428	92	0
8	968	792	360	148	736	544	124	0
9	1080	900	412	152	904	684	156	4
10	1212	988	452	168	1020	788	216	20
11	1224	1020	472	152	1108	868	268	24
12	1232	1036	452	136	1144	920	292	32
13	1216	1012	424	104	1192	960	328	32
14	1188	976	376	56	1228	976	356	32
15	1152	936	328	20	1236	1000	364	28
16	1100	880	268	0	1240	1008	368	20
17	1068	856	192	0	1240	1004	352	16
18	1036	792	116	0	1244	996	336	12
19	972	744	52	0	1240	976	320	8
20	924	684	4	0	1220	960	292	4
21	868	604	0	0	1188	952	272	0
22	820	552	0	0	1168	932	220	0
23	744	476	0	0	1152	916	196	0
24	688	400	0	0	1148	884	156	0
25	604	340	0	0	1128	860	112	0
26	540	248	0	0	1104	832	80	0
27	472	152	0	0	1068	784	24	0
28	388	76	0	0	1040	760	0	0
29	324	8	0	0	1016	732	0	0
30	224	0	0	0	968	696	0	0
31	128	0	0	0	940	640	0	0
32	48	0	0	0	904	592	0	0
33	0	0	0	0	864	568	0	0
34	0	0	0	0	824	516	0	0
35	0	0	0	0	780	448	0	0
36	0	0	0	0	748	412	0	0
37	0	0	0	0	692	372	0	0
38	0	0	0	0	648	304	0	0
39	0	0	0	0	588	248	0	0
40	0	0	0	0	548	180	0	0
41	0	0	0	0	488	116	0	0
42	0	0	0	0	440	64	0	0
43	0	0	0	0	384	16	0	0
44	0	0	0	0	324	0	0	0
45	0	0	0	0	268	0	0	0
46	0	0	0	0	192	0	0	0
47	0	0	0	0	136	0	0	0
48	0	0	0	0	92	0	0	0
49	0	0	0	0	28	0	0	0
50	0	0	0	0	0	0	0	0

concentrations of WSF (Figure 4). The maximum daily contamination of the two species are shown in Figure 8 along with the maximum daily concentrations of WSF and TARS. The largest WSF concentration, 9.0 ppm, occurs on the first day; the largest TARS concentration, 10.1 ppm, occurs on day 10. The greatest contamination of the pelagic species is on day 5 and that of the demersal species is on day 14 (i.e., maximum uptake lags maximum oil in each case by 4 days). Although the pelagic species reaches contamination levels almost twice that of the demersal species (208.1 ppm vs 129.7 ppm), tainting of the demersal species (contamination >5 ppm) continues 17 days after the pelagic species has depurated below detectable levels, due to the longer residence time for TARS than for WSF.

Effects of Migrations

The effects of fish migrations on the level of contamination within the fish and on the spatial extent of contaminated fish were examined. The area covered by tainted fish (contamination >5 ppm) for each migration speed and direction, as well as for the case of no migration, is shown for Species 1 (juvenile herring; pelagic) and Species 13 (adult crabs; demersal) in Figures 9 and 10, respectively. In all cases, migration reduced the total area covered by tainted fish. Coverage for both species groups was least, but the duration of tainting was longest, at the slowest migration speed (5 km/day). Tainting lasted 5 to 8 days longer for the 5 km/day migrations than for the case of no migration.

The duration (in days) of fish contamination at levels above 5, 10, 50 and 100 ppm is given in Table 9 for the pelagic (upper) and demersal (lower) species. Contamination at all levels remains for the longest period of time for migrations of 5 km/day. Migration (at all speeds and directions) increases

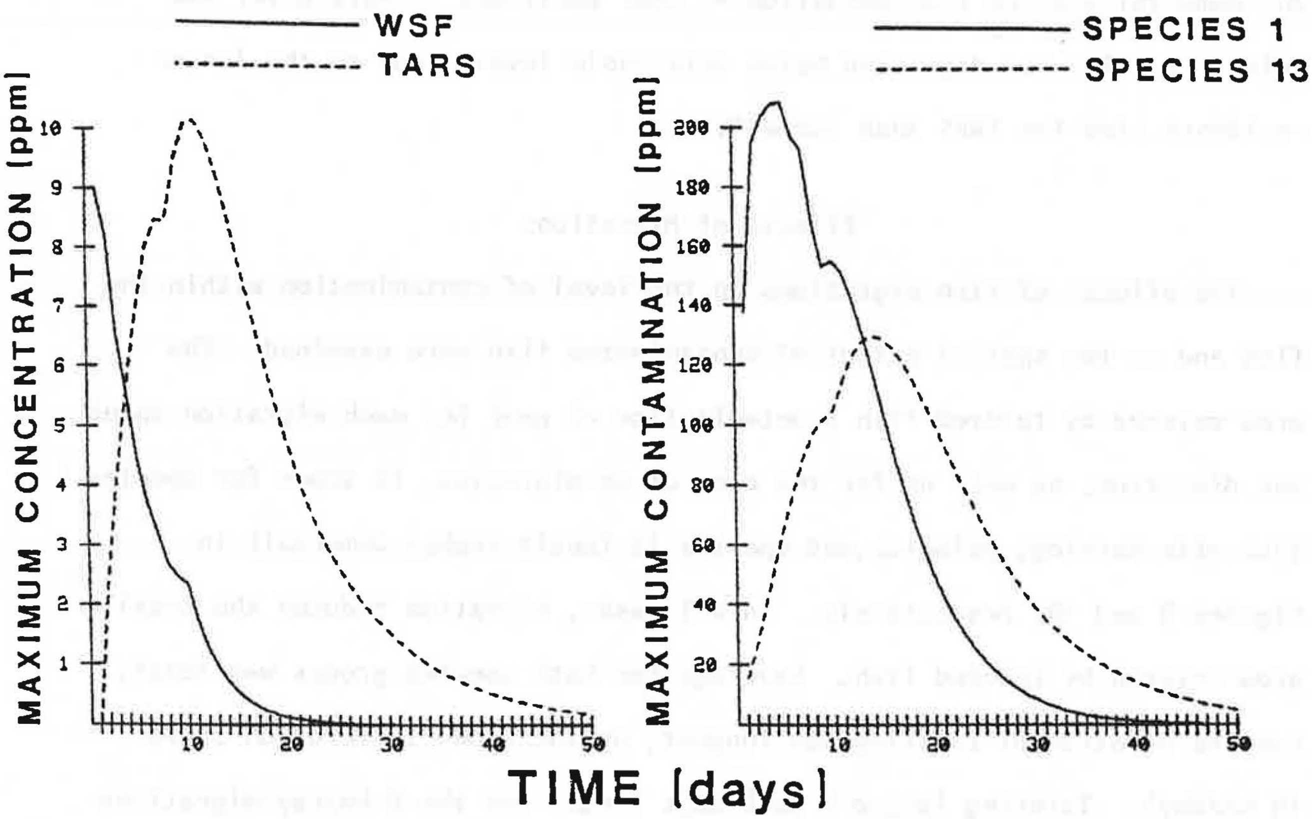

Figure 8.--Maximum concentrations of WSF and TARS and maximum contamination of Species 1 (pelagic) and Species 13 (demersal) each daily model time step.

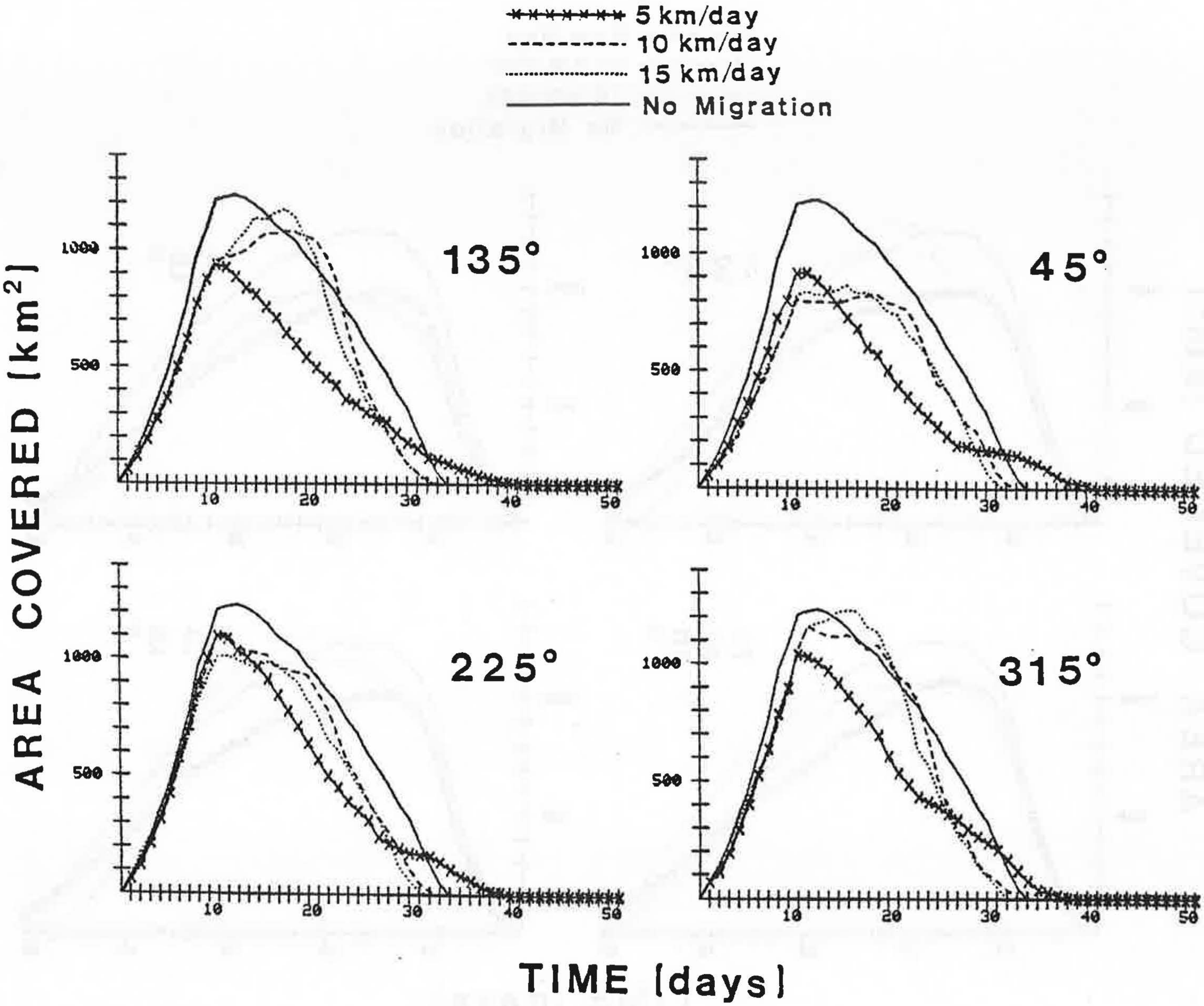

Figure 9.--Area covered by tainting (contamination >5 ppm) of a pelagic fish species from a model run with no migrations (solid line) and with migrations of 5, 10, and 15 km/day. Migration directions are as in Figure 2.

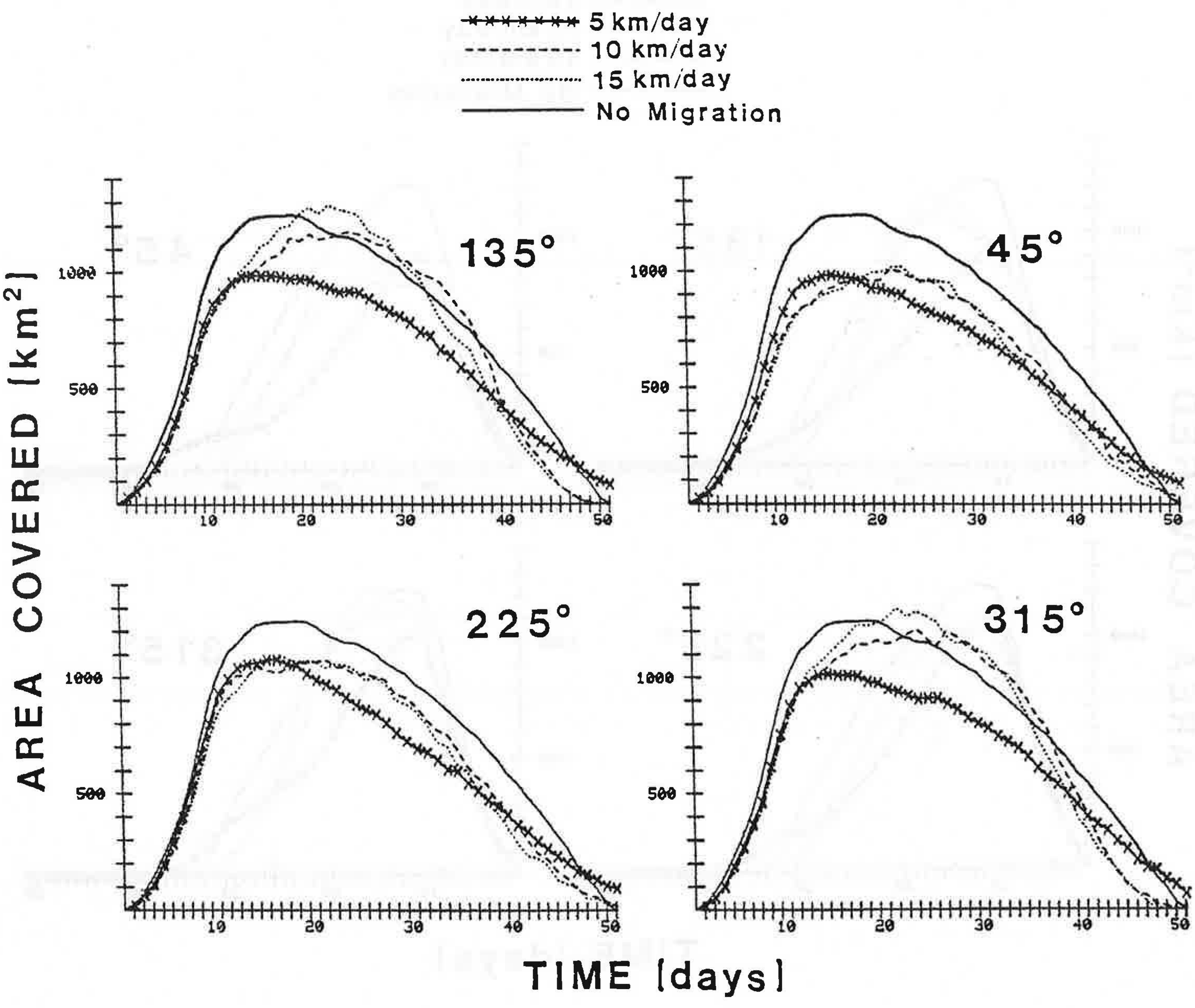

Figure 10.--Area covered by tainting (contamination >5 ppm) of a demersal fish species from a model run with no migrations (solid line) and with migrations of 5, 10, and 15 km/day. Migration directions are as in Figure 2.

Speed	Angle	Contamination Level >5	>10	>50	>100
No Migration		32	29	20	15
5	135	40	38	28	25
	45	39	36	28	25
	225	38	35	27	23
	315	37	35	26	22
10	135	31	30	21	19
	45	32	30	23	21
	225	31	29	22	20
	315	32	30	24	18
15	135	31	29	23	19
	45	30	29	22	20
	225	30	28	22	20
	315	31	28	23	18

Speed	Angle	>5	>10	>50	>100
No Migration		49	43	24	12
5	135	56	52	35	26
	45	54	50	35	26
	225	54	50	33	25
	315	54	48	33	24
10	135	49	43	28	20
	45	51	47	34	25
	225	51	46	33	22
	315	48	42	28	21
15	135	48	43	29	21
	45	51	48	35	27
	225	51	47	34	25
	315	47	42	28	21

Table 9.--Duration (days) of various levels of contamination for Species 1 (upper) and Species 13 (lower), with and without migrations.

the duration of the higher (>50 and >100) levels of contamination.

The effect of migration of the pelagic species is illustrated in Figure 11, where contours of 5, 10, 50, and 100 ppm contamination are shown for day 10 in the case of no migration and with migrations of 5 km/day in four directions (angles are relative to due east). The initial source of the oil is marked by a solid dot in each figure and the area covered by WSF greater than 1.0 ppm is shaded. The contamination field in each case is extended in the direction of migration. When migrating in the direction of the movement of the oil (~45°), fish take up contamination, but can then depurate as they leave the oil-spill area. On the other hand, fish migrating toward the original source of the oil (225°) are exposed to more oil over a longer period of time.

It was shown in Figure 10 that the total area covered by tainted fish was actually reduced by migrations. The distortion of the contamination field caused by migrations, however, can increase the affected fishing area. This is illustrated in the results for Species 1 from the OUTMIG submodel shown in Figures 12 through 14. In each figure, grid points with tainted fish (contamination >5 ppm) are marked. Results shown for days 5, 10, 20, and 30 with migrations of 5 and 10 km/day at 45° (Figure 12) and 225° (Figure 13) can be compared with results with no migration (Figure 14). As the contaminated fish migrate through the grid and beyond, the length of the area of tainting increases. For example, in the case of migration at 10 km/day at an angle of 225° (Figure 13), tainted fish occupy a strip extending 76 km to the southwest of the original source of the oil by day 20. A circle of this radius has an area of over 18,000 km^2, whereas the area of tainting on day 20 in the case of no migrations can be contained in a circle with a

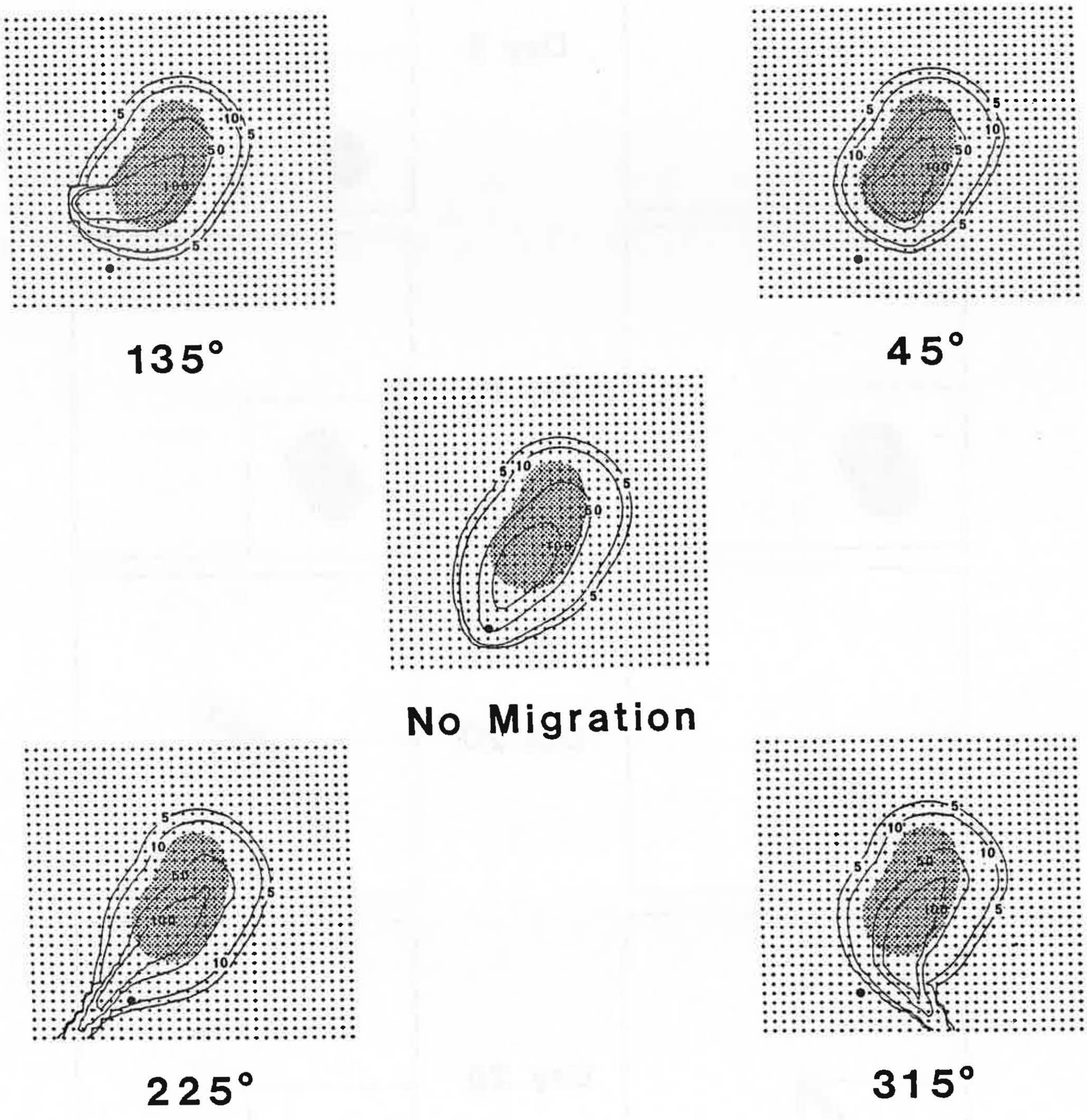

Figure 11.--Contamination of a pelagic fish (Species 1) at day 10 from model runs with no migrations and with migrations of 5 km/day. Contours of 5, 10, 50, and 100 ppm are drawn. Original source of the oil is marked "●" and area covered by 1.0 ppm WSF at day 10 is shaded.

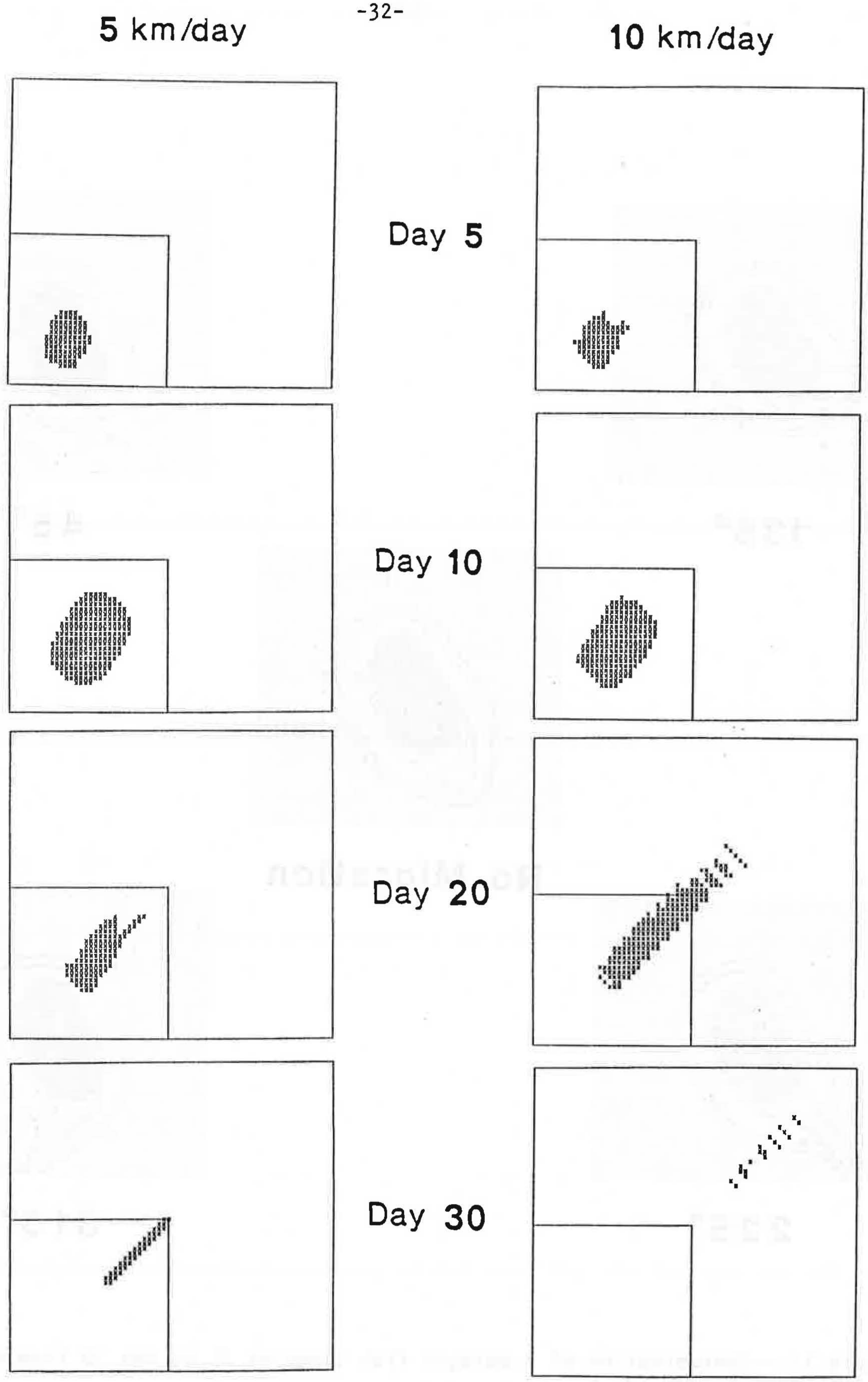

Figure 12.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 45° (in the direction of the oil movement).

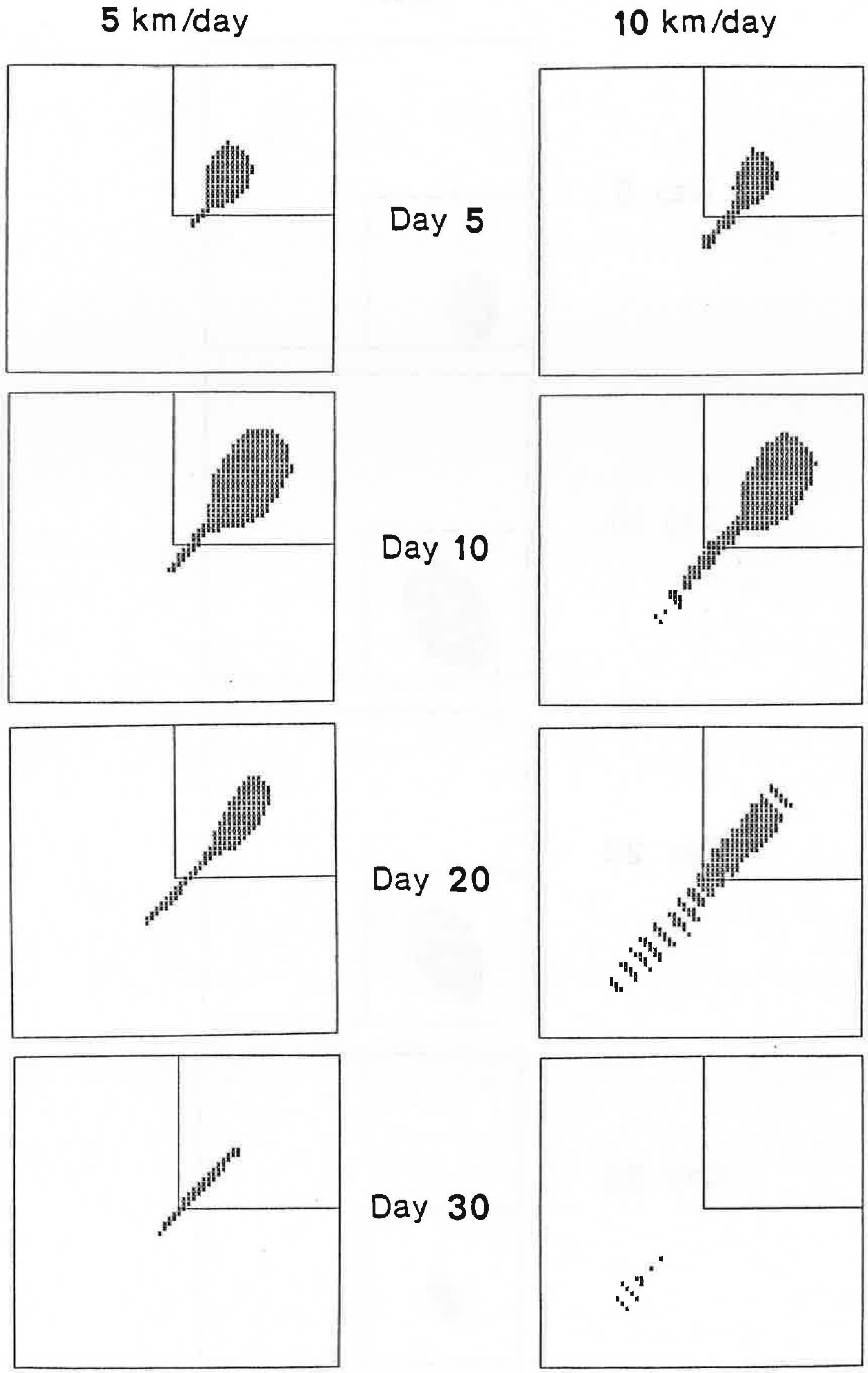

Figure 13.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid for migrations of 5 and 10 km/day and migration angle of 225° (in the opposite direction of the oil movement).

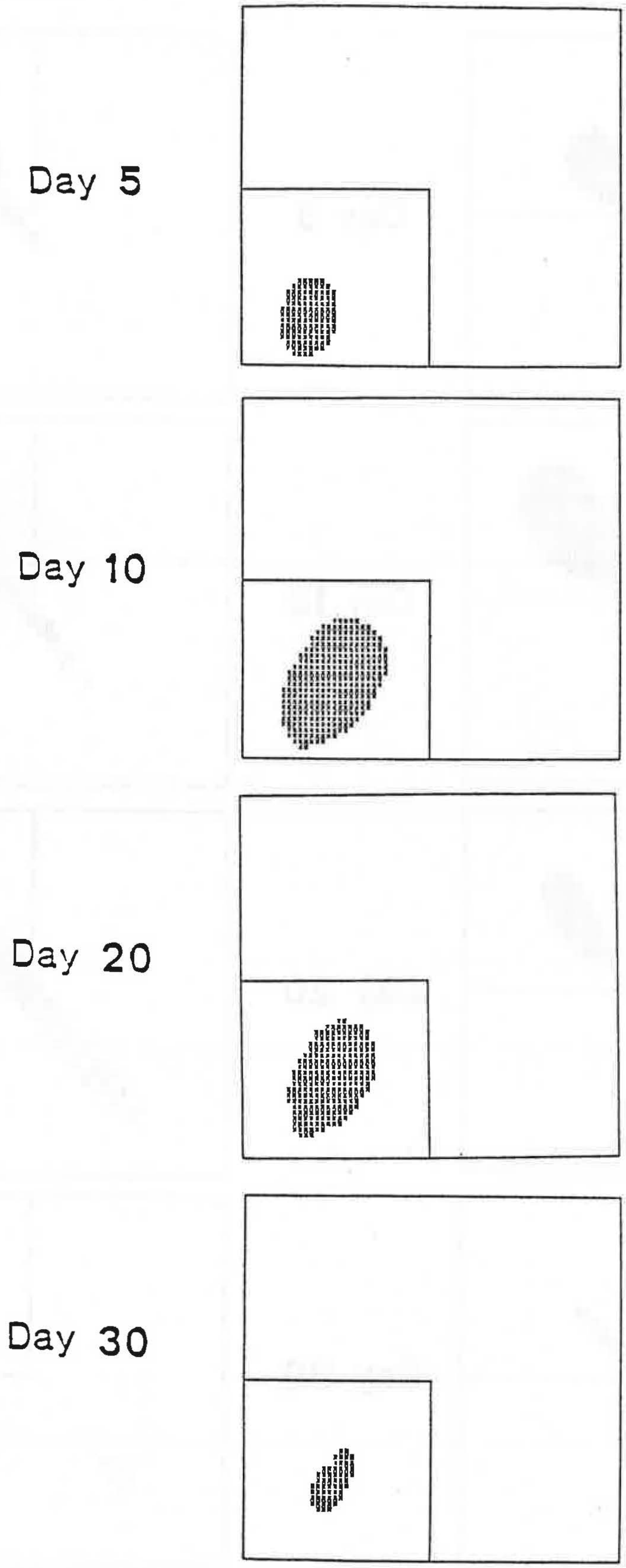

Figure 14.--Tainting of Species 1 (pelagic) over the OUTMIG submodel grid with no migrations.

radius of 25 km (i.e., less than 2,000 km^2). This is not to suggest that 18,000 km^2 of the Bering Sea should be closed to fishing in the event of an oil spill. It does demonstrate, however, that tainted fish migrating through an oil spill area can travel well beyond the bounds of the oil before depurating.

SUMMARY AND DISCUSSION

The BIOS model was developed to evaluate potential effects of an oil spill on the eastern Bering Sea ecosystem. Due to a lack of accurate quantitative data on many of the processes involved in an oil spill, the model was kept as simple and generic as possible. Biological contamination was simulated as a combined function of uptake and depuration. Uptake of contaminants was assumed to be equally divided between uptake from the water or sediments and uptake from contaminated food. The latter was simulated as a function of the relative pelagic or demersal species in a fish's diet. Migration of fish was simulated by the advection of contamination through the model grid and beyond.

Concentrations of oil in the water column (WSF) for the well blowout scenario were everywhere below 0.5 ppm and had a minimal simulated effect on the ecosystem. WSF concentrations for the accident scenario were an order of magnitude larger (maximum 9.0 ppm). Computed concentrations of oil in the sediments (TARS) reached a maximum of 10.1 ppm and remained in the area up to 50 days.

Results for a pelagic-feeding species (juvenile herring) and a demersal-feeding species group (adult crabs) were presented. Maximum contamination of both species occurred 4 days after the corresponding maximum oil concentrations.

Contamination of the pelagic species reached a maximum of 208.1 ppm (approximately twice the maximum of the demersal species). Maximum area covered by tainted fish in the simulation with no migrations was less than 2,000 km^2.

Migrations of 5, 10, and 15 km/day were simulated in each of four directions: moving with the oil (45°), moving toward the source of the oil (225°), or northwest (135°). Migrations increased the duration of higher levels of contamination (>50 and >100 ppm), due to the movement of already contaminated fish through higher concentrations of oil. In addition, migrations extended the distance from the source of the oil at which tainted fish could be found.

The assumptions and simplifications of the model could be improved with more accurate data on rates of uptake and depuration of oil, transfer of contamination through feeding, detectable levels of contamination, and avoidance of oil by fish. Laboratory and field studies using realistic oil concentrations could be designed to address many of these problems. Until more accurate quantitative data is available, however, the qualitative results of a model such as BIOS can provide insights to many of the interactive processes involved in an oil spill.

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