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Analysis of frequently repeated XBT lines in the Indian Ocean

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2 INTRODUCTION

CSIRO developed an Expendable Bathythermograph (XBT) network under the auspices of the international Tropical Ocean Global Atmosphere (TOGA) program, starting in 1983, and the World Ocean Circulation Experiment (WOCE), starting in 1990. The CSIRO network (Figure 1) is a contribution to the international TOGA/WOCE network (Figures 2a, 2b, 2c).

Four frequently repeated XBT lines in the Indian Ocean are analysed in this report: IX-1, IX-12, IX-22 and PX-2. The lines, which are part of the CSIRO XBT network , are presented in Figure 3. The analysis covers various statistics of sampling and variability, and describes the seasonal and interannual variation in thermal structure, along each line, for the period 1983 to 1996. On the website (see below) the time series have been updated to 1998, inclusive.

The main sections of the report are :

- DATA DESCRIPTION
- MEAN AND VARIANCE
- CLIMATOLOGY
- INTERANNUAL VARIATION.

The data description illustrates data coverage in space and time, as well as the bins used for gridding. The mean and variance are displayed as temperature/depth sections. The climatology and interannual variation are shown as Hovmoller diagrams.

Earlier publications on the thermal structure of the Indian Ocean include: CSIRO Australia Oceanographical Cruise Reports (1959 - 1966), Hamon (1967), National Oceanographic Data Centre (NODC - 1967), Highley (1968), Colborn (1971), Wyrtki (1971), Andrews (1976, 1977), Edwards (1977), Cresswell et al (1978), Greig (1986), Greig et al (1986).

An extended and more comprehensive analysis of the XBT profiles is available on the web, at the following address : http://www.marine.csiro.au/research.html . On the web, the XBT analysis results can be viewed 'by line', as well as 'in parallel'. When viewed 'by line', the results for each line are presented separately. When viewed 'in parallel', one can look at different lines simultaneously and compare the results. In addition to the above sections, the web report has a chapter on Empirical Orthogonal Functions (EOF) analysis of the interannual anomalies .

All of the original XBT data used in this report and the analytical results, are available from L.Pigot at Lidia.Pigot@marine.csiro.au .

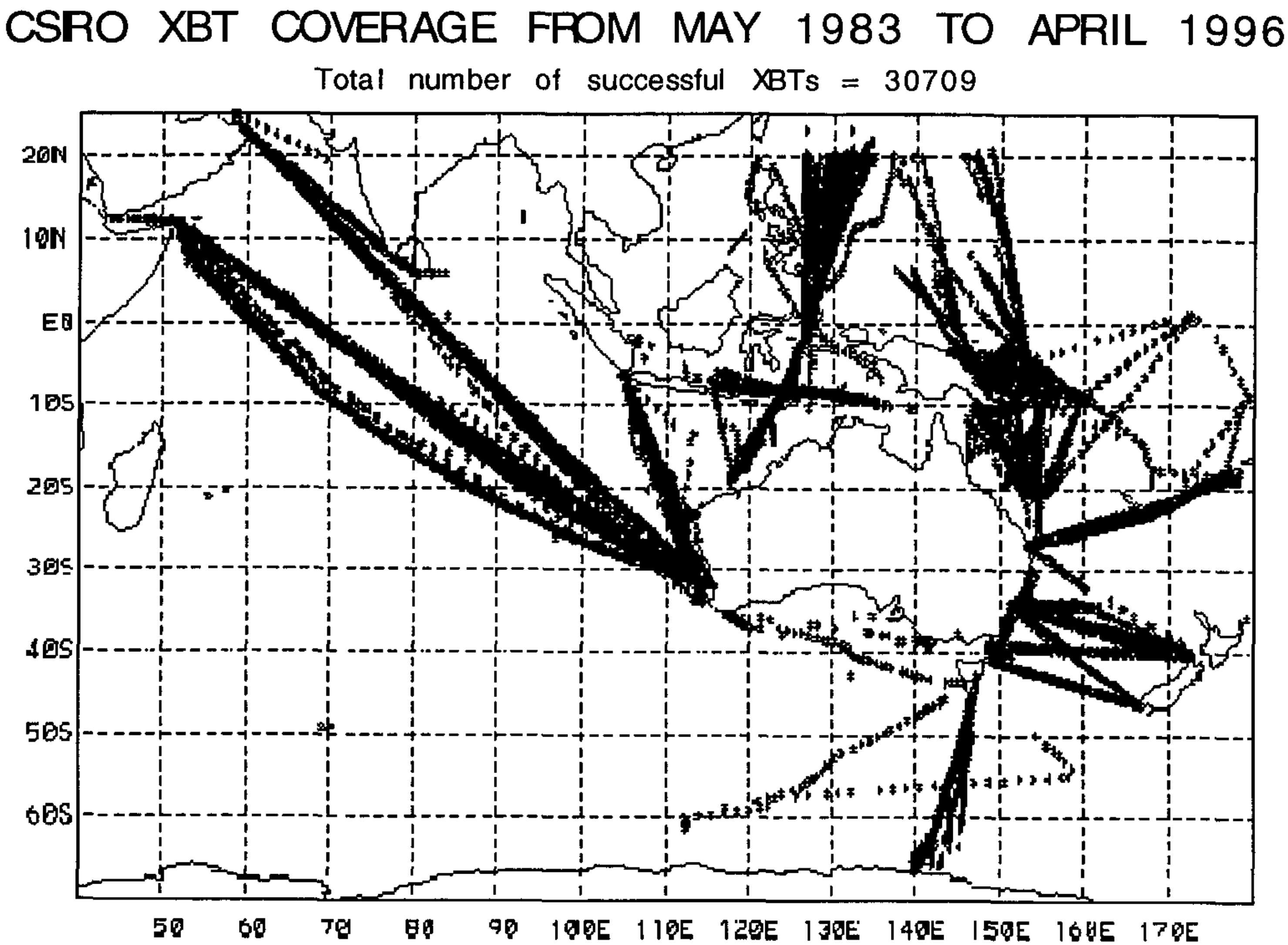


Figure 1
CSIRO XBT network

ATLANTIC OCEAN

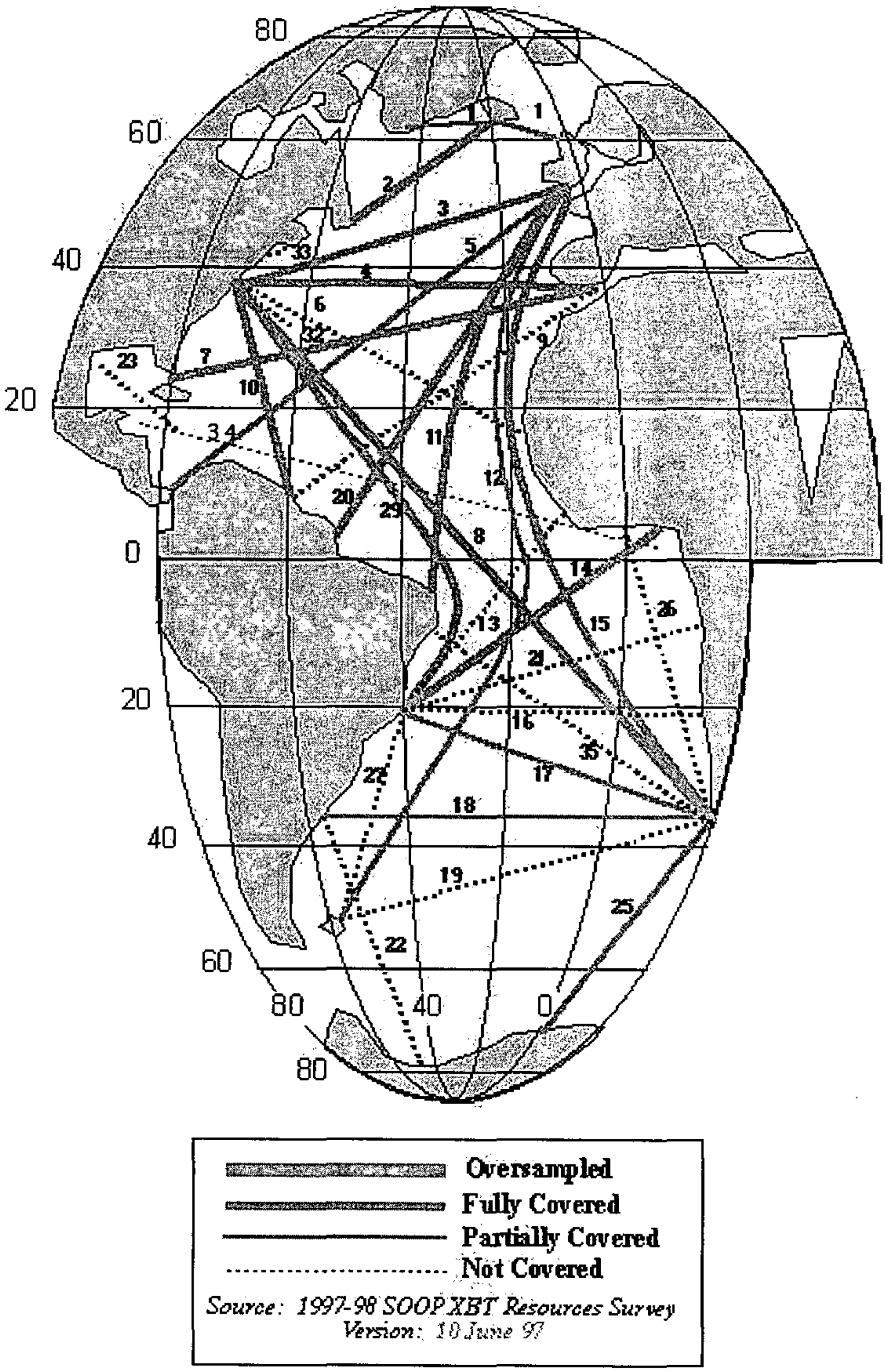


Figure 2(a)
TOGA/WOCE/IGOSS XBT network

INDIAN OCEAN

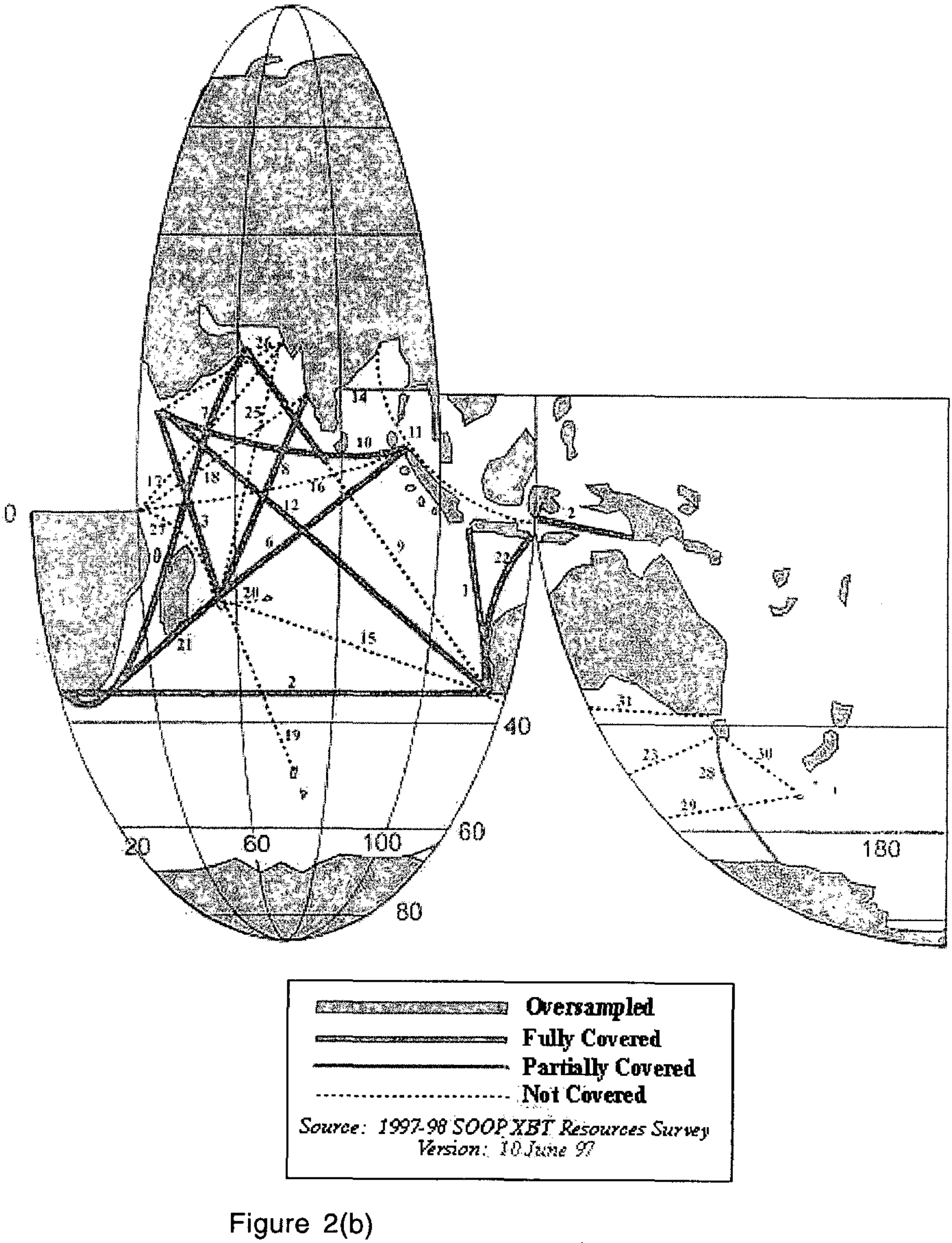


Figure 2(b)
TOGA/WOCE/IGOSS XBT network

PACIFIC OCEAN

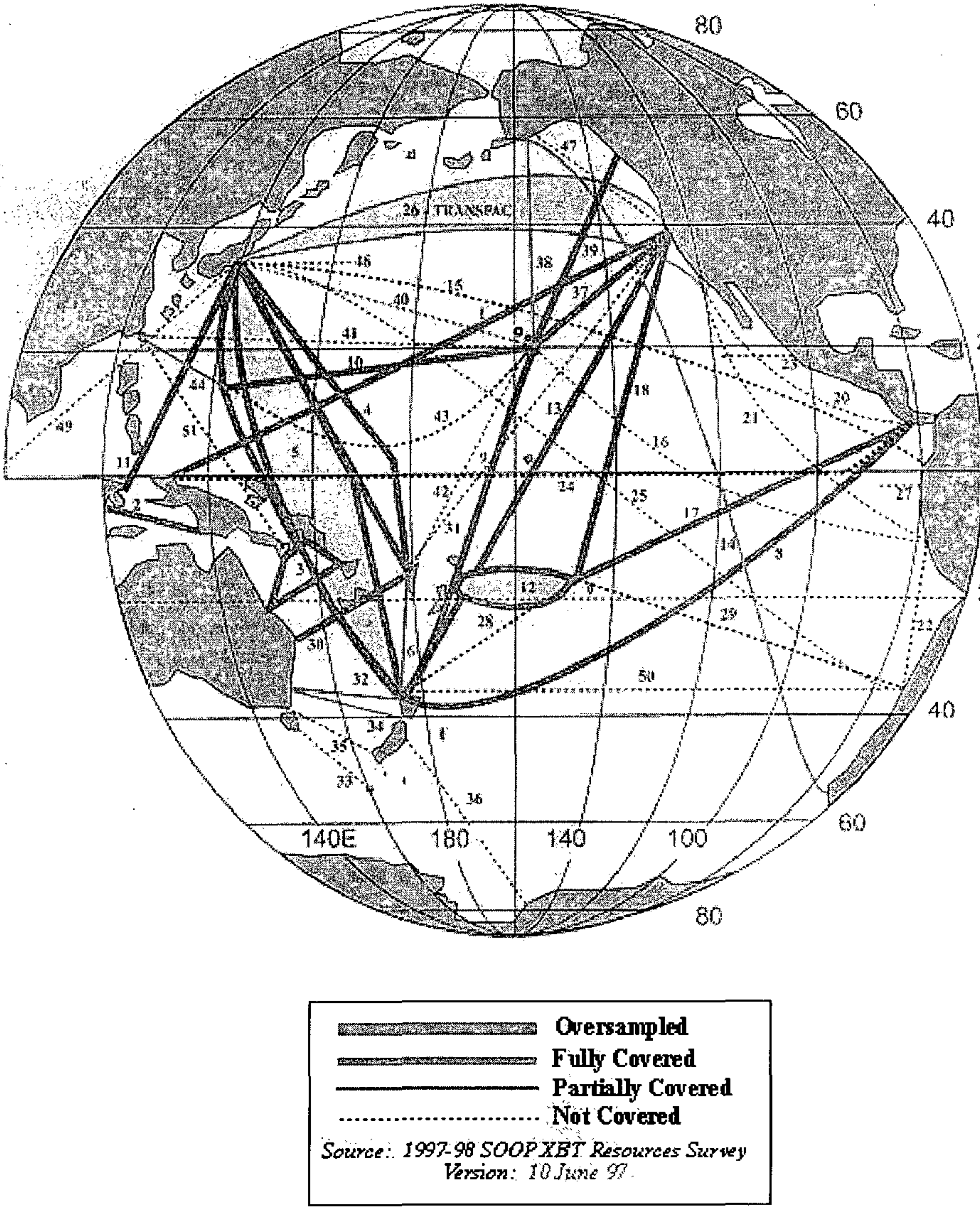


Figure 2(c)
TOGA/WOCE/IGOSS XBT network

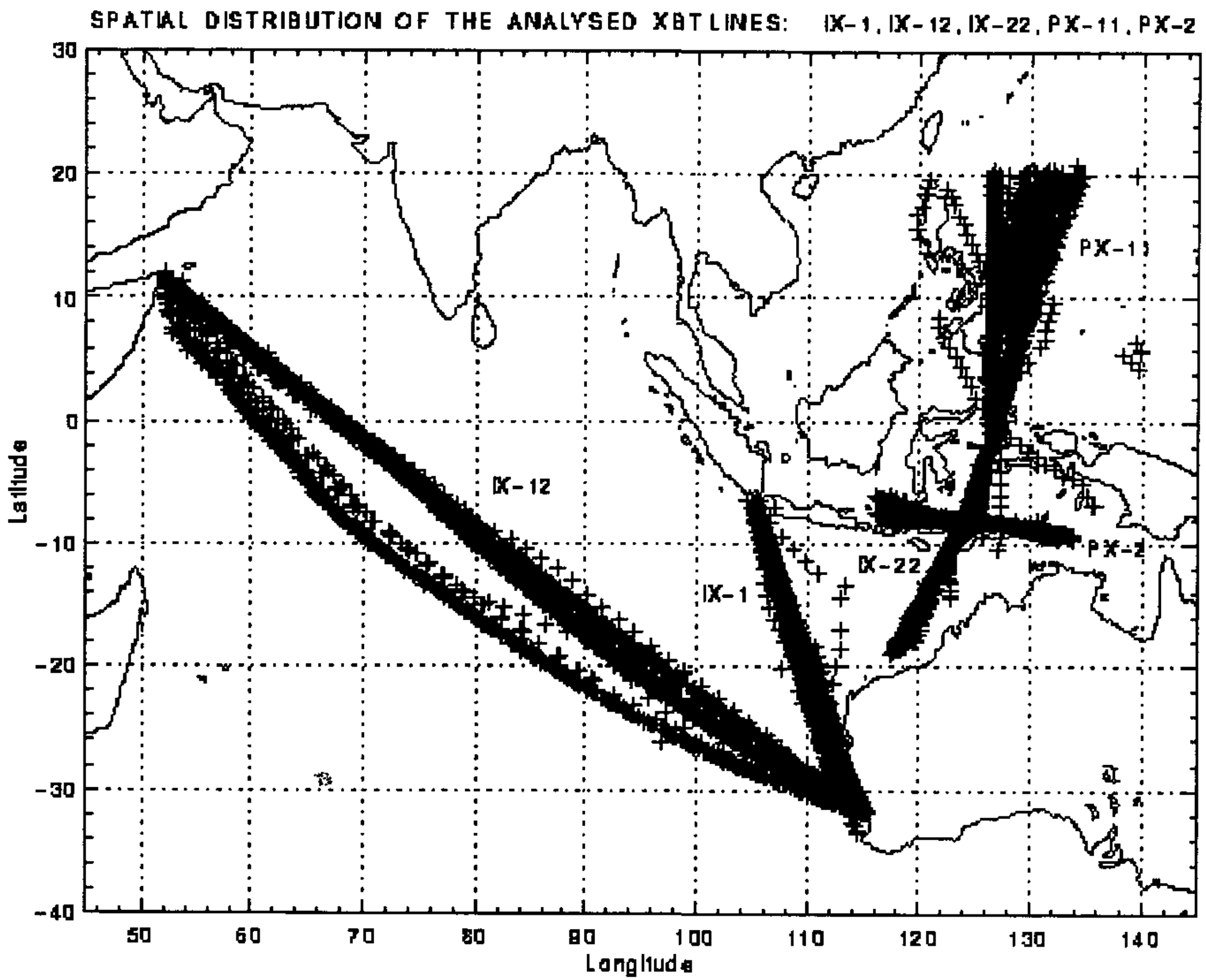


Figure 3
Analysed XBT lines

3 DATA DESCRIPTION

Expendable Bathythermographs (XBTs) are devices to measure the temperature of the upper ocean. They are deployed from moving vessels, which enables wide coverage of the world's oceans, mostly between 30 degrees North and 30 degrees South, and up to a depth of 800 m. The temperature/depth data set thus obtained provides the best data to document long-term variability of the upper ocean on the scale of ocean basins.

The XBT data were collected through an extensive SOOP (Ship of Opportunity) network, covered by volunteer merchant ships. The SOOP/XBT network around Australia was established by the CSIRO Division of Marine Research as a national contribution to the Tropical Ocean Global Atmosphere (TOGA) and the World Ocean Circulation Experiment (WOCE) international programs. In 1997, most of the XBT network was transferred to the Australian Bureau of Meteorology, and continues as an operational Australian contribution to the Global Ocean Observing System (GOOS). Some XBT lines continue as research activities of the CSIRO Marine Research / Bureau of Meteorology Research Centre joint facility for the Australian Ocean Observing System (AOOS).

The goals of XBT sampling under TOGA and WOCE were :

- to obtain a ten year time series and description of the large scale thermal structure of the tropical upper oceans
- to collect subsurface data for testing and validating tropical ocean models
- to provide observational data for assimilation into general ocean circulation models, as part of a climate prediction system.

Three approaches to sampling were used :

- broadscale mapping
- frequently repeated line
- high-density

The broadscale mapping approach attempts to map the temperature fields horizontally throughout the basin. The sampling strategy is to cover each line in the TOGA/WOCE/IGOSS XBT Network once a month, with an XBT drop every 6 hours (or 150 km). This mode of sampling is sometimes called "low density". Broadscale mapping is done by Neville Smith at the Bureau of Meteorology Research Centre (see http://www.BoM.GOV.AU/bmrc/mrlr/nrs/nrs.htm).

Under the frequently repeated line approach, ships sail repeatedly along nearly the same route, in order to resolve the low-frequency detail of temporal variability of the temperature sections. Ideally, the sampling strategy is 18 voyages a year, and 6 observations a day. The sampling rates are based on the method of optimal interpolation (Meyers et al. 1989, Phillips et al. 1990, Sprintall and Meyers 1991, Meyers et al. 1991, Smith et al. 1991).

The high-density sampling approach attempts to cover 4 seasonal sections a year at a higher rate of spatial sampling (16-20 observations a day) in order to obtain eddy statistics of temperature and geostrophic shear and transport fields.

This analysis is focused on the frequently repeated XBT lines, comprising initially the CSIRO network (Figure 1). Only lines with good temporal coverage (12-18 sections a year) have been selected. Later, the analysis will be extended (in a subsequent report) to additional lines in the TOGA/WOCE/IGOSS XBT network : IX-3, IX-9, PX-5, PX-31, PX-18, PX-17 (Figure 2).

All the XBT data have been quality controlled by A. Gronell and R. Bailey, according to the methods developed by Bailey et al. (1994) for processing delayed mode XBT data. Only `top' and `good' quality XBT temperatures are used in this study. The XBT temperature sections are displayed in the catalogues produced by A. Gronell, Ann.Gronell@marine.csiro.au.

None of the XBT profiles analysed in this report is depth corrected (Hanawa et al. 1995). This is to avoid mixing `depth-corrected' data after 1996 with `not depth-corrected' data before 1996. The XBT temperatures are binned and analysed by the methods described below. The bins are 1 degree in latitude, in general, with the exception of the bins near the continental slope, which were adjusted on some lines to represent coastal currents. Line PX-2 is an exception, because it runs east-west across the Banda Sea. Overlapping 1 degree longitude bins, with half degree spacing, were used in this case, to partly resolve the thermal structure associated with the gaps between islands of the Indonesian archipelago.

For each line, the data distribution in space, as well as the bins, are shown in Figure 4 the distribution in time is shown in Figure 5 and the bins are described in Table 1.

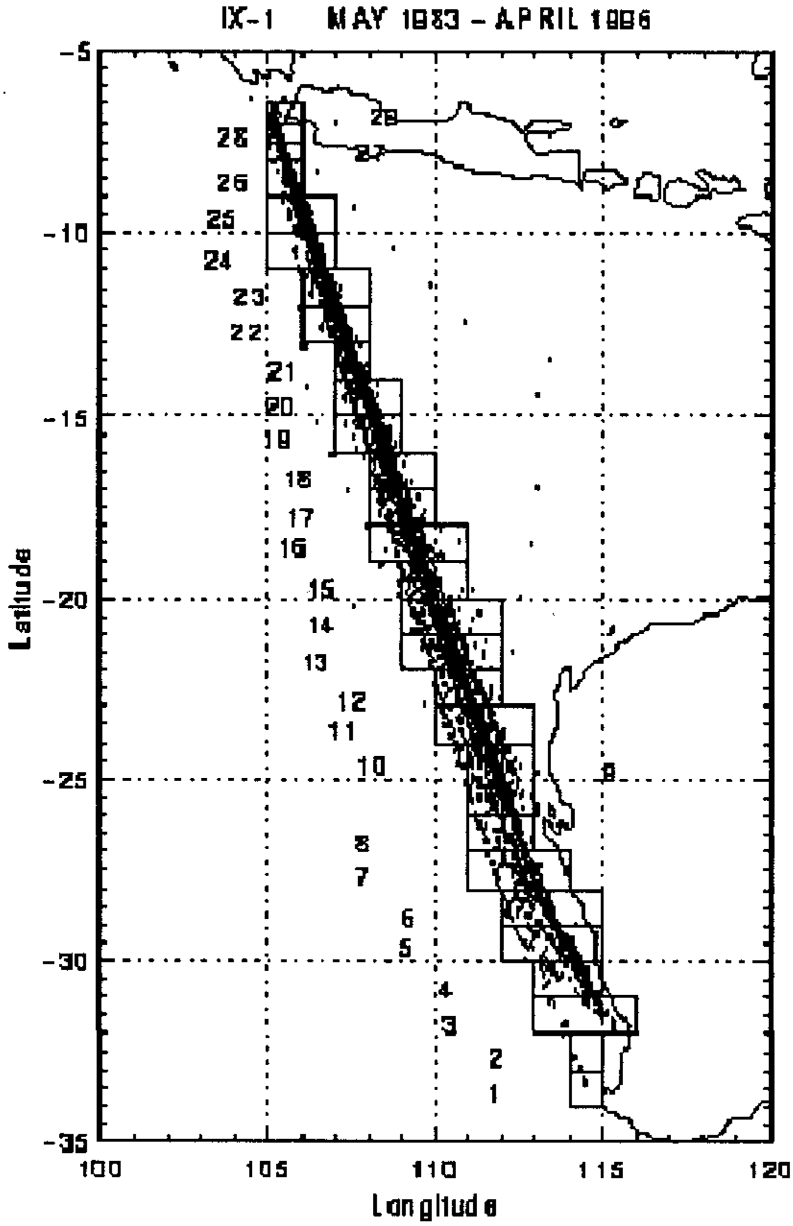


Figure 4 (a)
Data location and gridding for IX-1

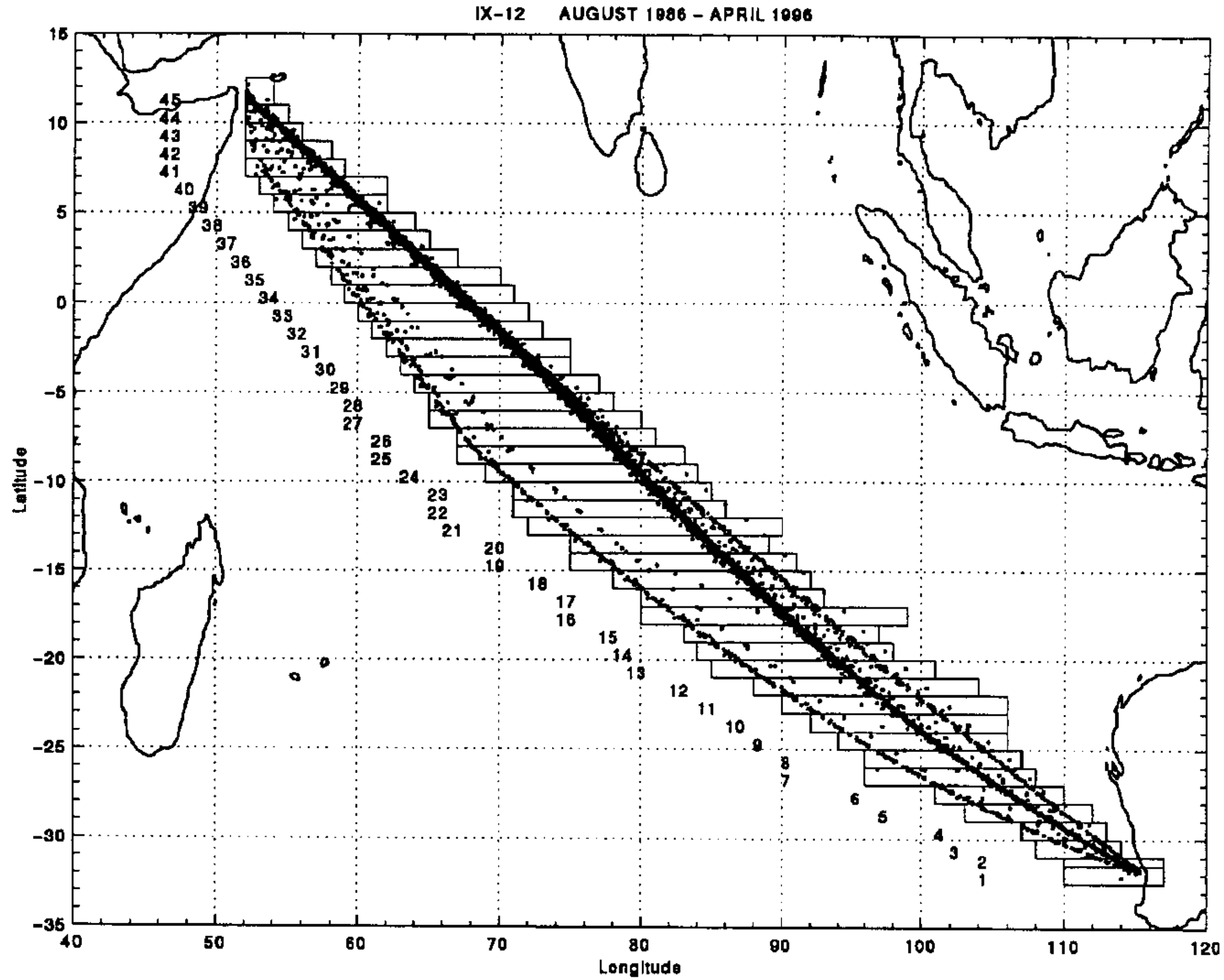


Figure 4 (b)
Data location and gridding for IX-12

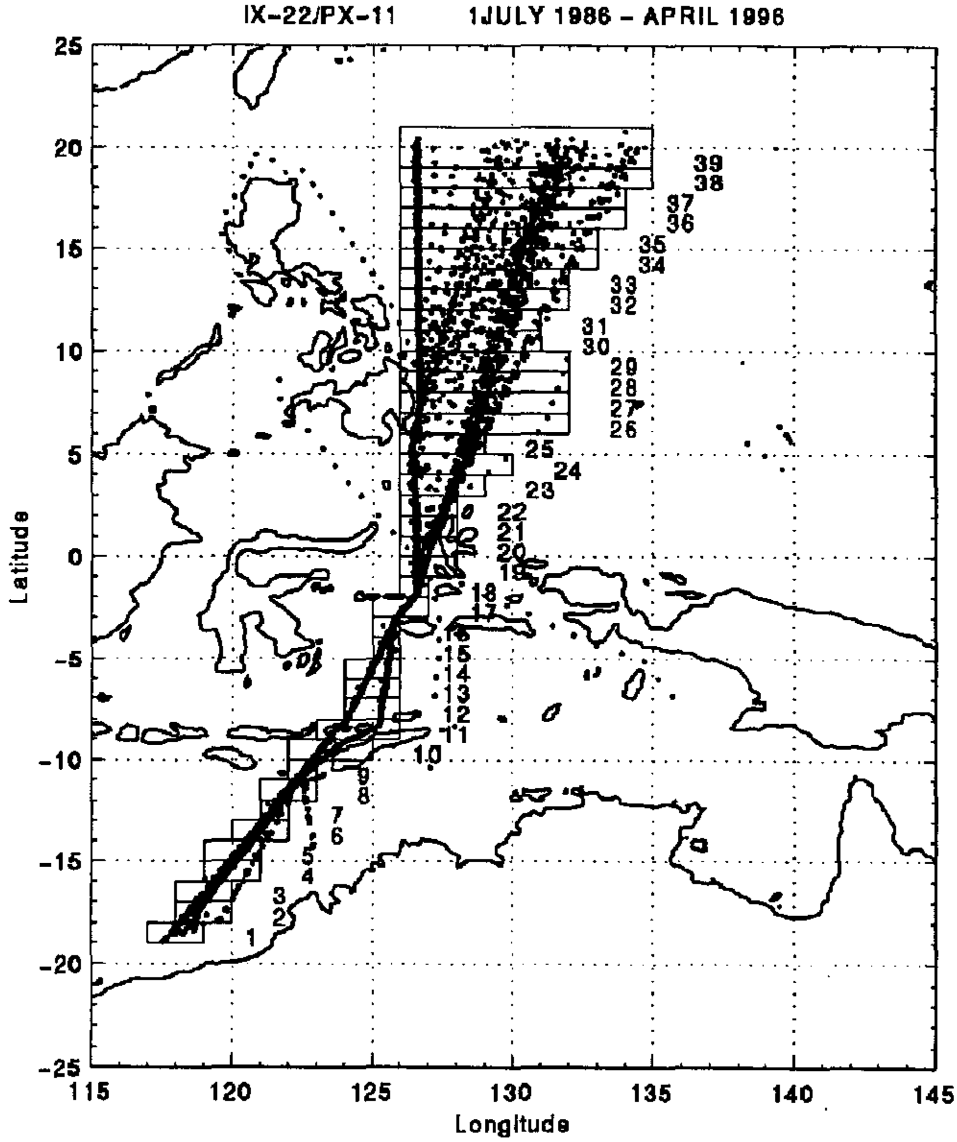


Figure 4 (c)
Data location and gridding for IX-22/PX-11

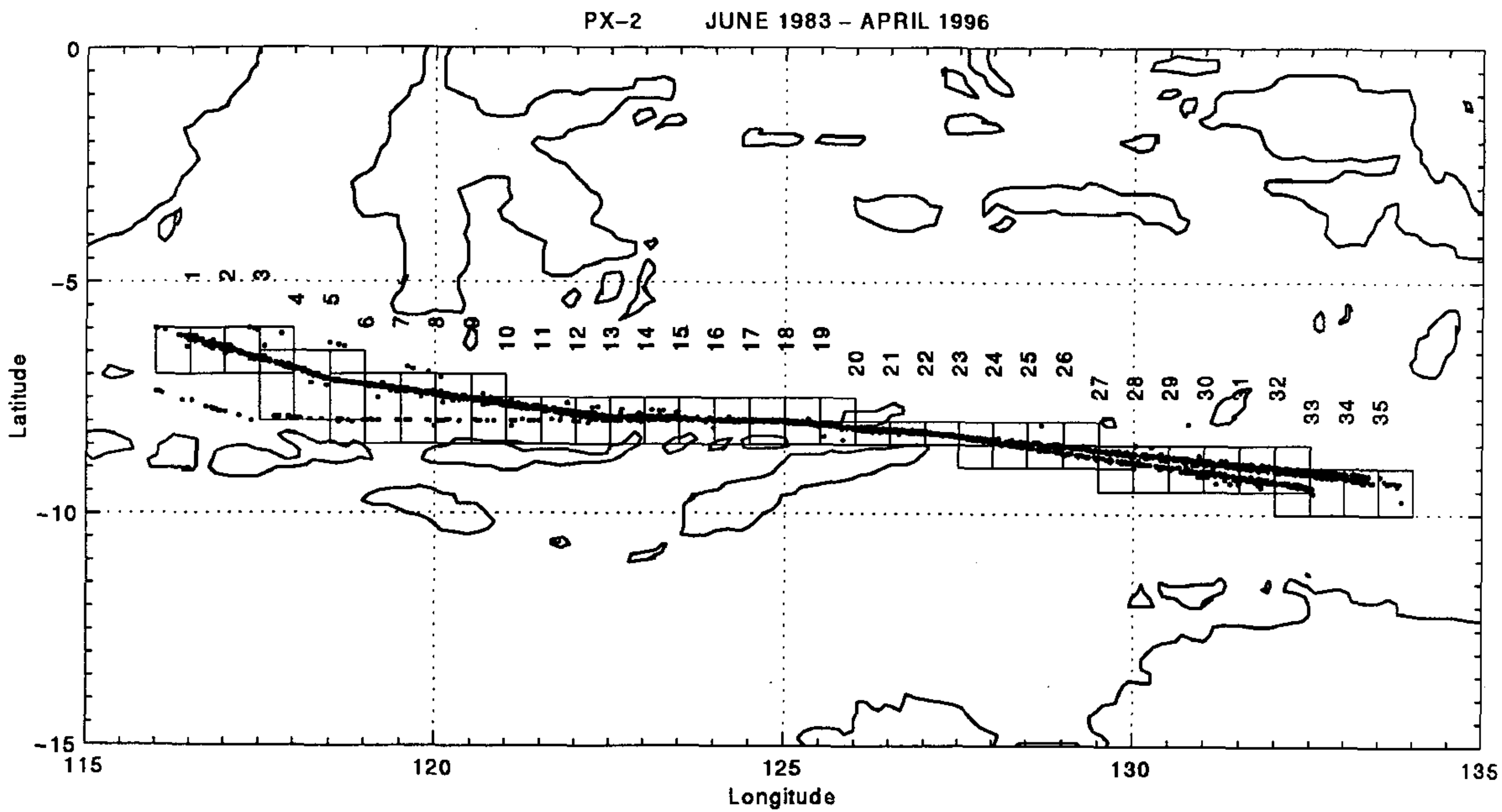


Figure 4 (d)
Data location and gridding for PX-2

LINE : IX-1 FREMANTLE - SHARK BAY - SUNDA STRAIT

PERIOD : MAY 1983 - APRIL 1996

263 SECTIONS

Grid Number	Min. Latitude	Max. Latitude	Min. Longitude	Max. Longitude	XBTs per bin	Depth of no motion	Mean Latitude	Mean Longitude	XBTs at >= 400m	XBTs at >= 700m
29	-7.0	-6.5	105.0	106.0	173	200	-6.79	105.17	83	29
28	-7.5	-7.0	105.0	106.0	156	400	-7.26	105.29	150	127
27	-8.0	-7.5	105.0	106.0	79	400	-7.77	105.46	69	53
26	-9.0	-8.0	105.0	106.0	202	400	-8.48	105.70	190	158
25	-10.0	-9.0	105.0	107.0	214	400	-9.52	106.07	197	154
24	-11.0	-10.0	105.0	107.0	204	400	-10.48	106.40	188	156
23	-12.0	-11.0	106.0	108.0	222	400	-11.49	106.78	211	168
22	-13.0	-12.0	106.0	108.0	219	400	-12.53	107.15	207	167
21	-14.0	-13.0	107.0	108.0	197	400	-13.49	107.50	183	154
20	-15.0	-14.0	107.0	109.0	216	400	-14.49	107.88	205	169
19	-16.0	-15.0	107.0	109.0	221	400	-15.48	108.25	211	170
18	-17.0	-16.0	108.0	110.0	218	400	-16.51	108.64	209	179
17	-18.0	-17.0	108.0	110.0	220	400	-17.50	109.01	205	166
16	-19.0	-18.0	108.0	111.0	226	400	-18.51	109.40	209	165
15	-20.0	-19.0	109.0	111.0	197	400	-19.55	109.79	184	158
14	-21.0	-20.0	109.0	112.0	225	400	-20.53	110.15	213	170
13	-22.0	-21.0	109.0	112.0	214	400	-21.53	110.54	204	161
12	-23.0	-22.0	110.0	112.0	222	400	-22.52	110.94	207	168
11	-24.0	-23.0	110.0	113.0	230	400	-23.54	111.31	217	168
10	-26.0	-24.0	111.0	112.0	235	400	-24.80	111.65	210	140
9	-26.0	-24.0	112.0	113.0	194	360	-25.25	112.19	72	6
8	-27.0	-26.0	111.0	113.0	117	***	-26.50	112.24	77	31
7	-28.0	-27.0	111.0	114.0	121	***	-27.55	112.68	72	33
6	-29.0	-28.0	112.0	115.0	142	***	-28.52	113.17	89	53
5	-30.0	-29.0	112.0	115.0	133	***	-29.51	113.70	121	87
4	-31.0	-30.0	113.0	115.0	157	***	-30.45	114.35	107	82
3	-32.0	-31.0	113.0	116.0	82	***	-31.32	114.84	19	12
2	-33.0	-32.0	114.0	115.0	3	***	-32.72	114.21	3	1
1	-34.0	-33.0	114.0	115.0	5	***	-33.32	114.48	0	0
Total XBTs:					5044 (out of 5098)				4312	3285

*** Depth was defined only for the grid boxes for which transport was calculated.

Table 1(a)
Data Gridding for IX-1

LINE : IX-12 FREMANTLE - RED SEA

PERIOD : AUGUST 1986 - APRIL 1996

155 SECTIONS

Grid Number	Min. Latitude	Max. Latitude	Min. Longitude	Max. Longitude	XBTs per bin	Depth of no motion	Mean Latitude	Mean Longitude	XBTs at >= 400m	XBTs at >= 700m
45	11.0	12.5	52.0	54.0	90	800	11.31	52.32	66	25
44	10.0	11.0	52.0	55.0	143	800	10.45	53.36	101	29
43	9.0	10.0	52.0	56.0	146	800	9.43	54.69	90	27
42	8.0	9.0	52.0	58.0	136	800	8.47	55.87	103	33
41	7.0	8.0	52.0	59.0	147	800	7.48	57.02	108	31
40	6.0	7.0	53.0	62.0	141	800	6.47	58.30	113	35
39	5.0	6.0	54.0	62.0	143	800	5.53	59.65	104	32
38	4.0	5.0	55.0	64.0	148	800	4.50	60.79	120	33
37	3.0	4.0	56.0	65.0	141	800	3.50	62.38	115	34
36	2.0	3.0	57.0	67.0	143	800	2.51	63.59	117	31
35	1.0	2.0	58.0	70.0	140	800	1.48	65.00	118	38
34	0.0	1.0	59.0	71.0	140	800	0.49	66.38	121	32
33	-1.0	0.0	60.0	72.0	145	800	-0.52	67.67	123	35
32	-2.0	-1.0	61.0	73.0	135	800	-1.53	68.94	117	36
31	-3.0	-2.0	62.0	75.0	139	800	-2.52	70.29	120	34
30	-4.0	-3.0	63.0	75.0	126	800	-3.47	71.59	110	33
29	-5.0	-4.0	64.0	77.0	149	800	-4.48	72.45	129	37
28	-6.0	-5.0	65.0	78.0	123	800	-5.53	74.19	108	32
27	-7.0	-6.0	65.0	80.0	140	800	-6.53	75.11	117	34
26	-8.0	-7.0	67.0	81.0	128	800	-7.54	76.33	103	28
25	-9.0	-8.0	67.0	83.0	132	800	-8.48	77.32	110	31
24	-10.0	-9.0	69.0	84.0	128	800	-9.46	78.56	112	27
23	-11.0	-10.0	71.0	85.0	141	800	-10.47	79.85	122	31
22	-12.0	-11.0	71.0	86.0	136	800	-11.49	81.29	123	36
21	-13.0	-12.0	72.0	90.0	147	800	-12.51	82.59	127	38
20	-14.0	-13.0	75.0	89.0	145	800	-13.56	83.90	129	34
19	-15.0	-14.0	75.0	91.0	150	800	-14.52	85.16	133	36
18	-16.0	-15.0	78.0	92.0	151	800	-15.52	86.99	137	35
17	-17.0	-16.0	80.0	93.0	144	800	-16.53	88.05	129	35
16	-18.0	-17.0	80.0	99.0	142	800	-17.51	89.58	126	33
15	-19.0	-18.0	83.0	97.0	142	800	-18.51	91.14	126	35
14	-20.0	-19.0	84.0	98.0	144	800	-19.52	92.58	127	34
13	-21.0	-20.0	85.0	101.0	124	800	-20.52	94.03	111	34
12	-22.0	-21.0	88.0	104.0	113	800	-21.53	95.28	105	37
11	-23.0	-22.0	90.0	106.0	102	800	-22.56	97.20	98	32
10	-24.0	-23.0	92.0	106.0	106	800	-23.54	99.07	96	36
9	-25.0	-24.0	94.0	106.0	107	800	-24.53	100.65	99	35
8	-26.0	-25.0	96.0	107.0	106	800	-25.51	102.22	94	31
7	-27.0	-26.0	96.0	108.0	110	800	-26.48	103.66	102	38
6	-28.0	-27.0	101.0	110.0	110	800	-27.46	105.82	102	36
5	-29.0	-28.0	103.0	112.0	114	800	-28.46	107.79	106	38
4	-30.0	-29.0	107.0	113.0	120	800	-29.51	109.93	112	41
3	-31.0	-30.0	108.0	114.0	122	800	-30.51	112.09	119	39
2	-31.5	-31.0	110.0	117.0	87	800	-31.31	114.12	76	29
1	-32.5	-31.5	110.0	117.0	94	460	-31.67	114.91	33	4
Total XBTs:					5860 (out of 5860)				4957	1484

Table 1(b)
Data Gridding for IX-12

LINE : IX-22 / PX-11 PORT HEDLAND - JAPAN

PERIOD : JULY 1986 - APRIL 1996

111 SECTIONS

Grid Number	Min. Latitude	Max. Latitude	Min. Longitude	Max. Longitude	XBTs per bin	Depth of no motion	Mean Latitude	Mean Longitude	XBTs at >= 400m	XBTs at >= 700m
39	9.0	21.0	126.0	135.0	150	800	19.63	130.05	138	106
38	18.0	19.0	126.0	135.0	104	800	18.47	129.91	94	72
37	17.0	18.0	126.0	134.0	110	800	17.47	129.87	102	70
36	16.0	17.0	126.0	134.0	101	800	16.46	129.32	94	68
35	15.0	16.0	126.0	133.0	107	800	15.46	129.38	94	66
34	14.0	15.0	126.0	133.0	115	800	14.48	129.02	103	75
33	13.0	14.0	126.0	132.0	110	800	13.47	128.84	101	70
32	12.0	13.0	126.0	132.0	110	800	12.45	128.74	98	69
31	11.0	12.0	126.0	131.0	98	800	11.50	128.44	86	64
30	10.0	11.0	126.0	131.0	110	800	10.51	128.26	96	74
29	9.0	10.0	126.0	132.0	114	800	9.49	128.13	102	71
28	8.0	9.0	126.0	132.0	102	800	8.48	128.09	92	63
27	7.0	8.0	126.0	132.0	106	800	7.48	127.89	90	66
26	6.0	7.0	126.0	132.0	106	800	6.45	127.54	90	67
25	5.0	6.0	126.0	129.0	110	800	5.47	127.41	95	71
24	4.0	5.0	126.0	130.0	113	800	4.49	127.29	96	74
23	3.0	4.0	126.0	129.0	119	800	3.47	127.15	107	80
22	2.0	3.0	126.0	128.0	105	800	2.48	127.02	93	73
21	1.0	2.0	126.0	128.0	104	800	1.51	126.89	97	71
20	0.0	1.0	126.0	128.0	115	800	0.54	126.76	106	70
19	-1.0	-0.0	126.0	128.0	115	800	-0.48	126.67	99	67
18	-2.0	-1.0	126.0	127.0	102	800	-1.52	126.61	93	59
17	-3.0	-2.0	125.0	127.0	129	800	-2.48	126.21	118	83
16	-4.0	-3.0	125.0	126.0	109	800	-3.48	125.72	108	78
15	-5.0	-4.0	125.0	126.0	118	800	-4.52	125.44	106	78
14	-6.0	-5.0	124.0	126.0	112	800	-5.52	125.17	101	75
13	-7.0	-6.0	124.0	126.0	113	800	-6.54	124.88	103	68
12	-8.0	-7.0	124.0	126.0	108	800	-7.49	124.65	96	73
11	-9.0	-8.0	123.0	126.0	163	800	-8.52	124.15	128	79
10	-10.0	-9.0	122.0	125.0	124	800	-9.49	123.33	114	87
9	-11.0	-10.0	122.0	123.0	119	800	-10.55	122.62	91	52
8	-12.0	-11.0	121.0	123.0	117	800	-11.52	122.09	103	72
7	-13.0	-12.0	121.0	122.0	104	800	-12.50	121.49	94	70
6	-14.0	-13.0	120.0	122.0	112	800	-13.50	120.98	103	79
5	-15.0	-14.0	119.0	121.0	111	800	-14.52	120.38	98	72
4	-16.0	-15.0	119.0	121.0	110	800	-15.52	119.82	103	72
3	-17.0	-16.0	118.0	120.0	105	800	-16.51	119.22	99	67
2	-18.0	-17.0	118.0	120.0	129	400	-17.58	118.76	66	17
1	-19.0	-18.0	117.0	119.0	71	200	-18.35	118.35	3	1
Total XBTs:					4380 (out of 4475)				3800	2689

Table 1(c)
Data Gridding for IX-22/PX-11

LINE : PX-2 BANDA SEA

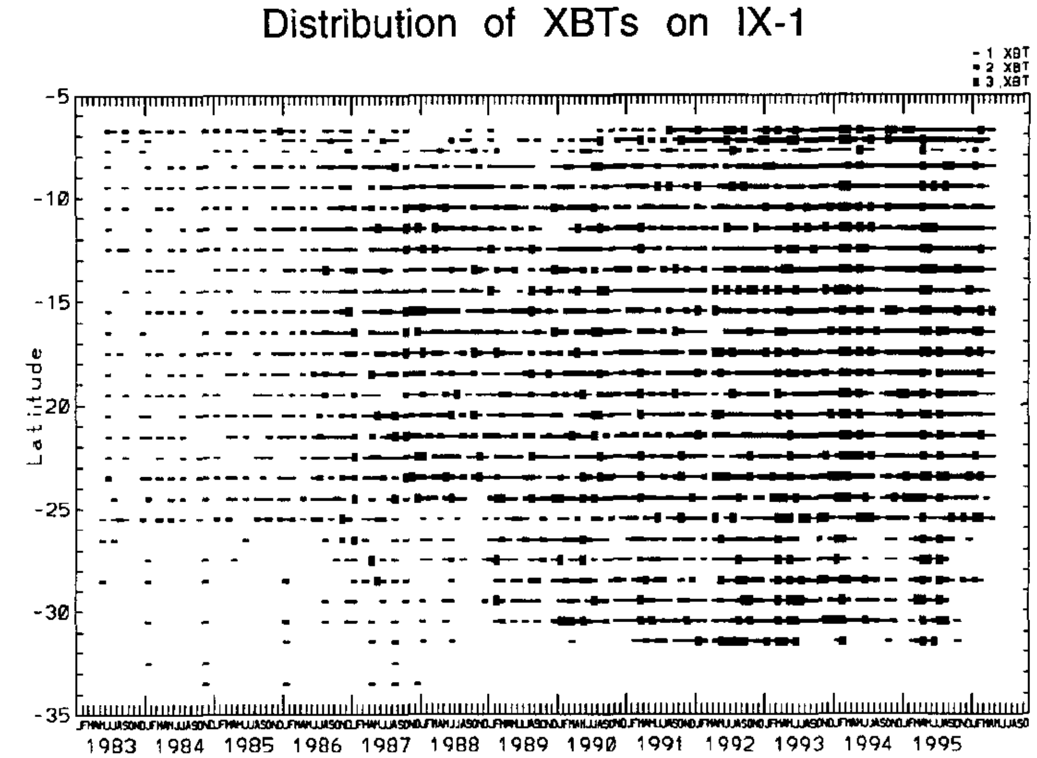
PERIOD : JUNE 1983 - APRIL 1996

190 SECTIONS

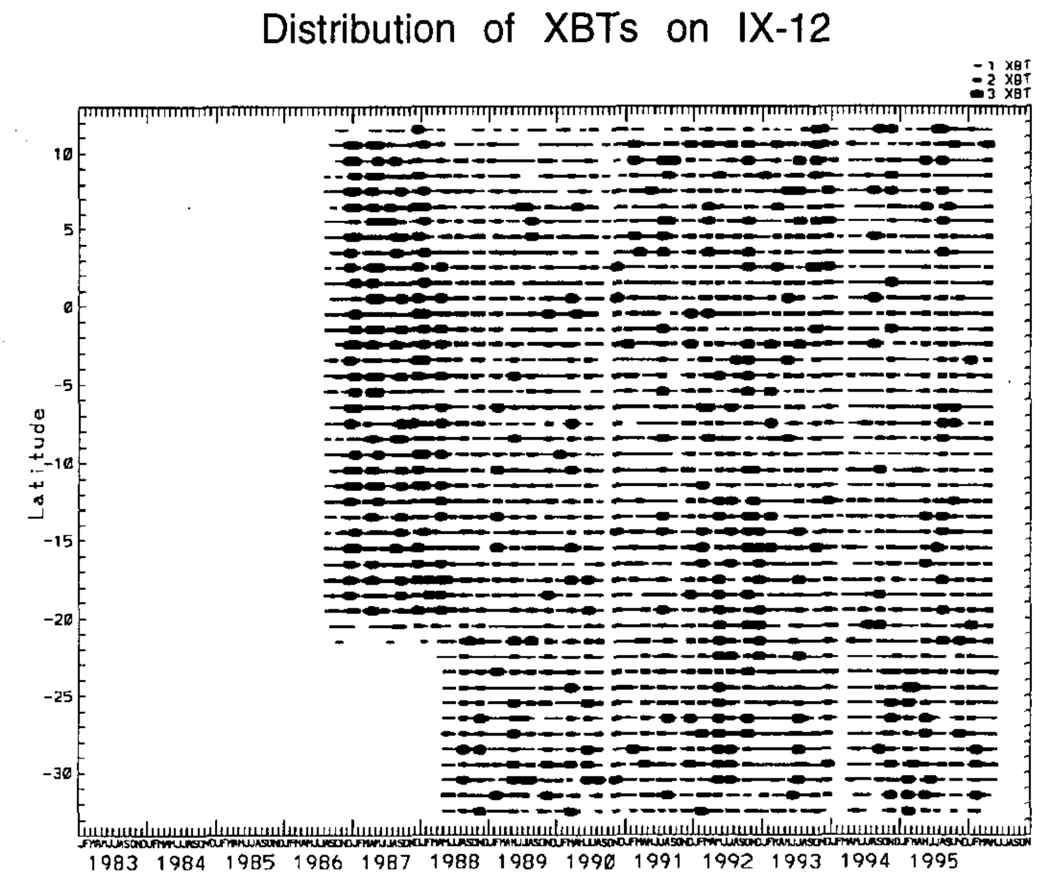
Grid Number	Min. Latitude	Max. Latitude	Min. Longitude	Max. Longitude	XBTs per bin	Depth of no motion	Mean Latitude	Mean Longitude	XBTs at >= 400m	XBTs at >= 700m
1	-6.0	-7.0	116.0	117.0	261	200	-6.29	116.64	26	0
2	-6.0	-7.0	116.5	117.5	238	360	-6.40	116.91	29	0
3	-6.0	-7.0	117.0	118.0	155	360	-6.63	117.46	37	0
4	-6.5	-8.0	117.5	118.5	160	420	-6.98	118.02	106	11
5	-6.5	-8.0	118.0	119.0	143	540	-7.13	118.43	115	23
6	-7.0	-8.5	118.5	119.5	128	800	-7.31	118.98	110	70
7	-7.0	-8.5	119.0	120.0	145	800	-7.39	119.48	129	105
8	-7.0	-8.5	119.5	120.5	149	800	-7.48	119.95	131	107
9	-7.0	-8.5	120.0	121.0	134	800	-7.58	120.45	118	100
10	-7.5	-8.5	120.5	121.5	147	800	-7.70	121.03	137	104
11	-7.5	-8.5	121.0	122.0	151	800	-7.77	121.46	138	106
12	-7.5	-8.5	121.5	122.5	132	800	-7.85	121.99	110	90
13	-7.5	-8.5	122.0	123.0	134	800	-7.91	122.49	110	81
14	-7.5	-8.5	122.5	123.5	160	800	-7.93	123.04	143	113
15	-7.5	-8.5	123.0	124.0	146	800	-7.95	123.44	137	120
16	-7.5	-8.5	123.5	124.5	132	800	-7.98	124.07	123	107
17	-7.5	-8.5	124.0	125.0	149	800	-7.99	124.49	136	110
18	-7.5	-8.5	124.5	125.5	147	800	-8.02	125.02	126	105
19	-7.5	-8.5	125.0	126.0	139	800	-8.07	125.47	115	100
20	-8.0	-8.5	125.5	126.5	145	800	-8.15	126.03	120	102
21	-8.0	-8.5	126.0	127.0	154	800	-8.19	126.49	127	107
22	-8.0	-8.5	126.5	127.5	149	800	-8.25	127.00	123	99
23	-8.0	-8.5	127.0	128.0	141	800	-8.31	127.46	120	93
24	-8.0	-9.0	127.5	128.5	140	800	-8.41	128.00	126	104
25	-8.0	-9.0	128.0	129.0	158	800	-8.49	128.49	142	121
26	-8.0	-9.0	128.5	129.5	150	800	-8.58	128.98	128	109
27	-8.5	-9.0	129.0	130.0	151	800	-8.69	129.55	124	107
28	-8.5	-9.5	129.5	130.5	158	800	-8.77	130.01	132	107
29	-8.5	-9.5	130.0	131.0	150	800	-8.86	130.51	121	78
30	-8.5	-9.5	130.5	131.5	161	540	-8.96	131.02	90	32
31	-8.5	-9.5	131.0	132.0	210	320	-9.08	131.54	33	3
32	-8.5	-9.5	131.5	132.5	261	240	-9.17	132.03	0	0
33	-9.0	-10.0	132.0	133.0	234	200	-9.19	132.51	0	0
34	-9.0	-10.0	132.5	133.5	210	200	-9.16	132.95	0	0
35	-9.0	-10.0	133.0	134.0	109	180	-9.21	133.26	0	0
Total XBTs:					5631 (out of 2921)				3462	2514

***NOTE: Since the bins overlap, some of the XBTs in each bin are double counted.

Table 1(d)
Data Gridding for PX-2

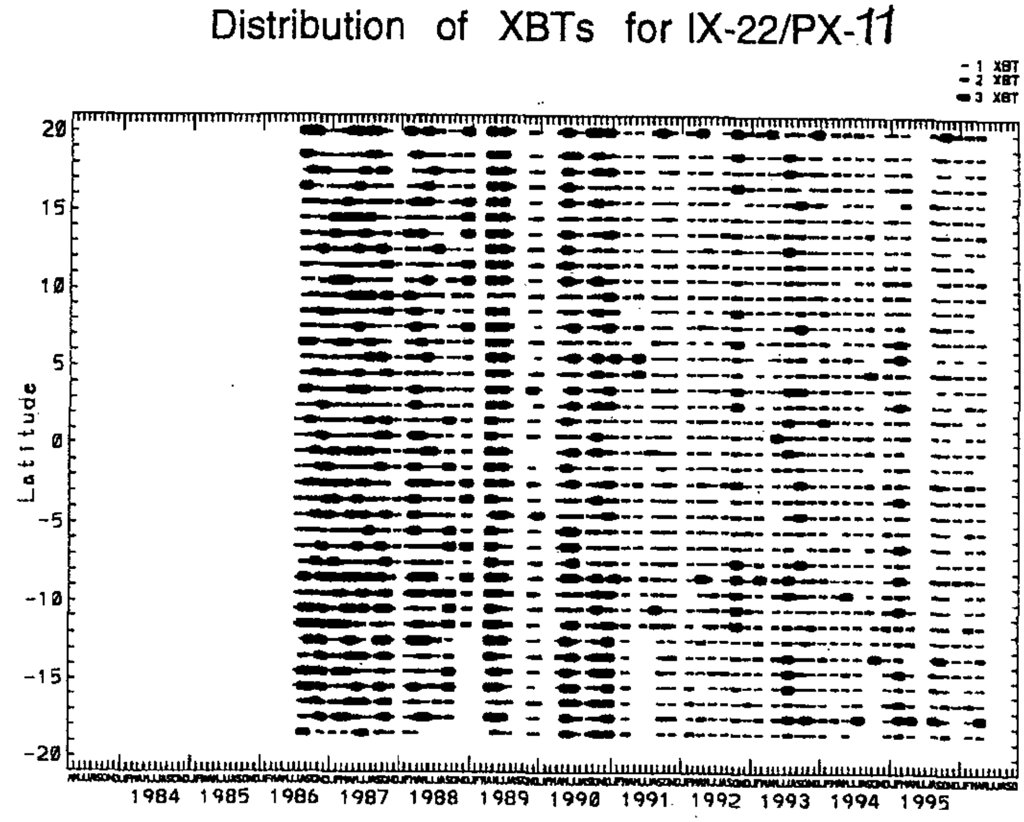


(a)

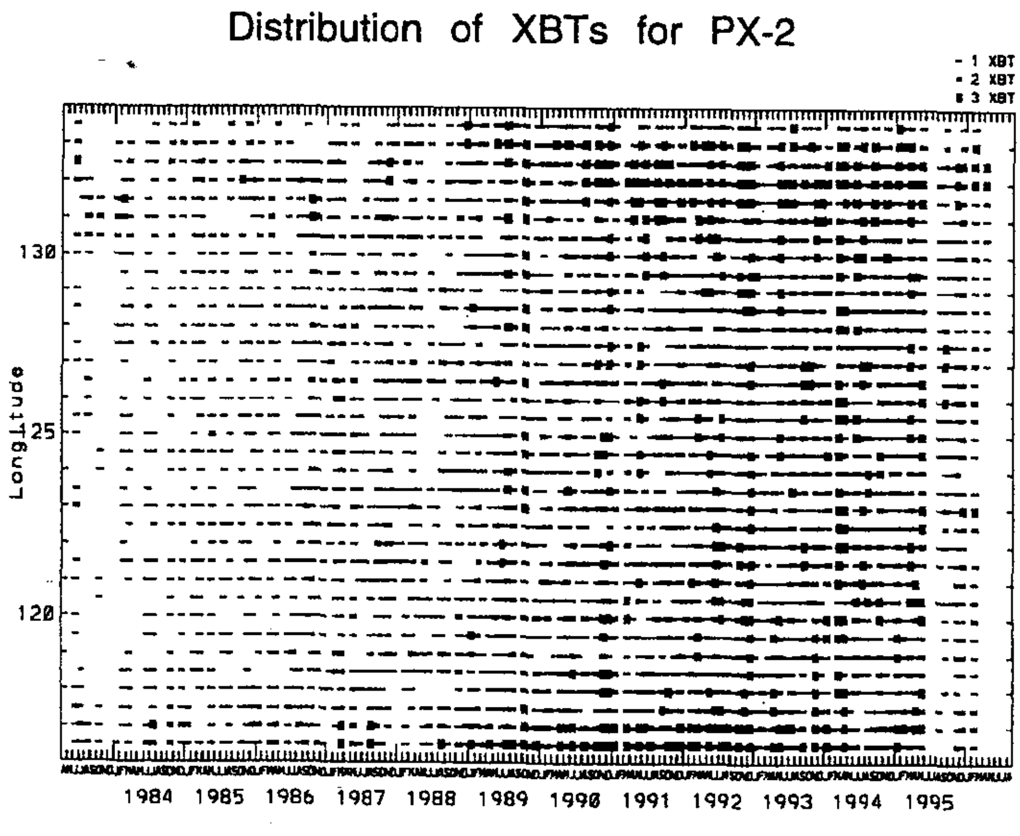


(b)

Figure 5 (a,b)
Data distribution in time for IX-1 and IX-12



(c)



(d)

Figure 5 (c,d)
Data distribution in time for IX-22/PX-11and PX-2

4 MEAN AND VARIANCE

The annual mean temperature for each line is calculated from the raw XBT data collected for the whole period of this study, in latitude/longitude bins (Table 1) and decimated every 20 m in depth. Figure 6 illustrates the total mean temperature sections .

The following Standard Deviations of the temperature section were also calculated :

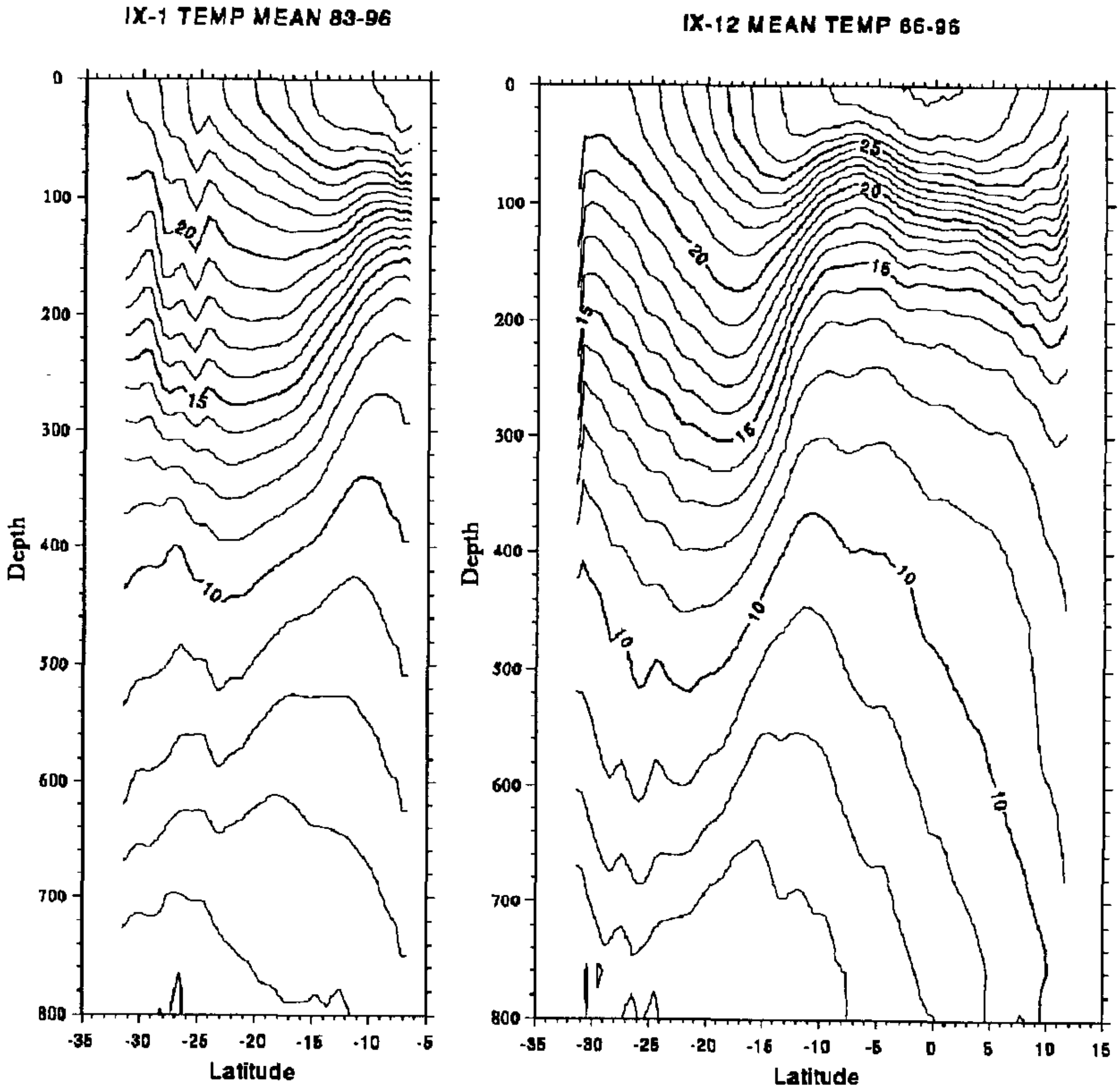
- Standard Deviation of all the raw XBT temperatures collected during the period
- Standard Deviation of the seasonal cycle
- Standard Deviation of the interannual temperature anomalies.

The Standard Deviation results are illustrated in Figures 7 to 9 .

In addition to the above, the report on the web, includes :

- ratio of seasonal, to interannual Standard Deviation
- noise Standard Deviation
- ratio of noise to signal Standard Deviation
- two-monthly mean temperature sections
- annual and two-monthly mean salinity values.

The long-term annual mean temperature sections at certain locations on IX-1, IX-22 and PX-2 have been published (Meyers et al. 1995) to show the horizontal gradients associated with baroclinic currents at these locations.



(a)

(b)

Figure 6 (a,b)
Mean temperature sections for IX-1 and IX-12

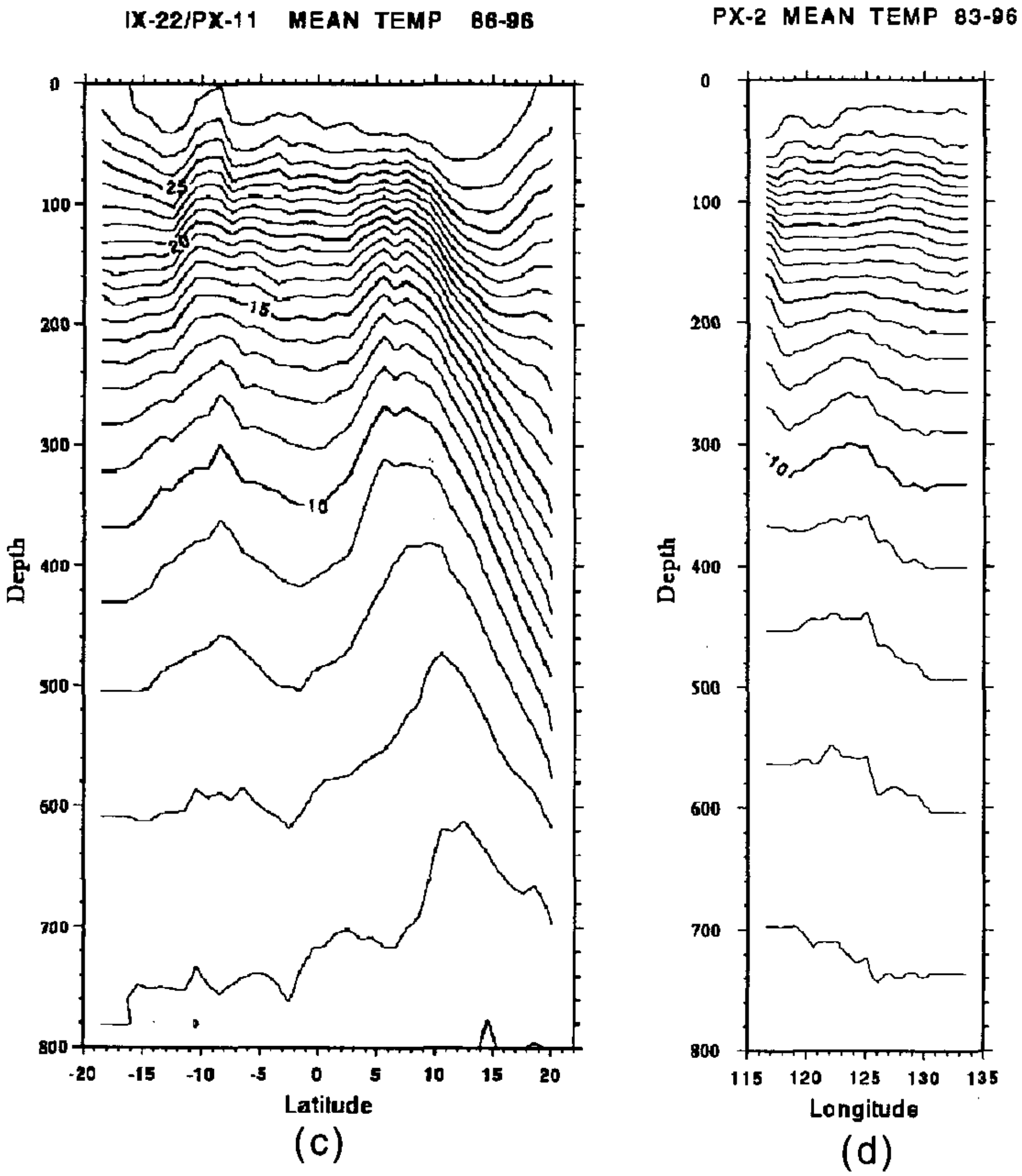


Figure 6 (c,d)
Mean temperature sections for IX-22/PX-11and PX-2

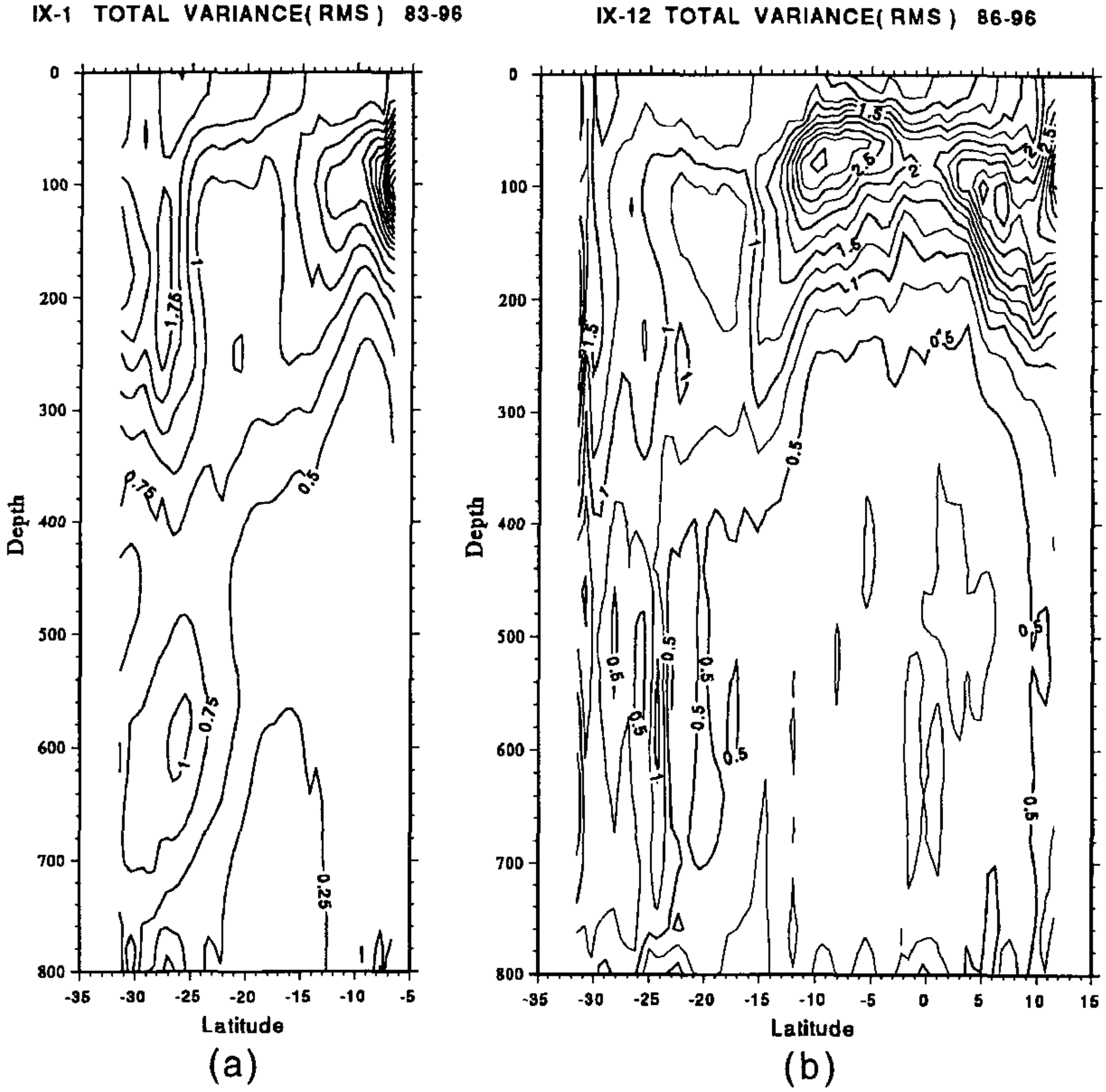
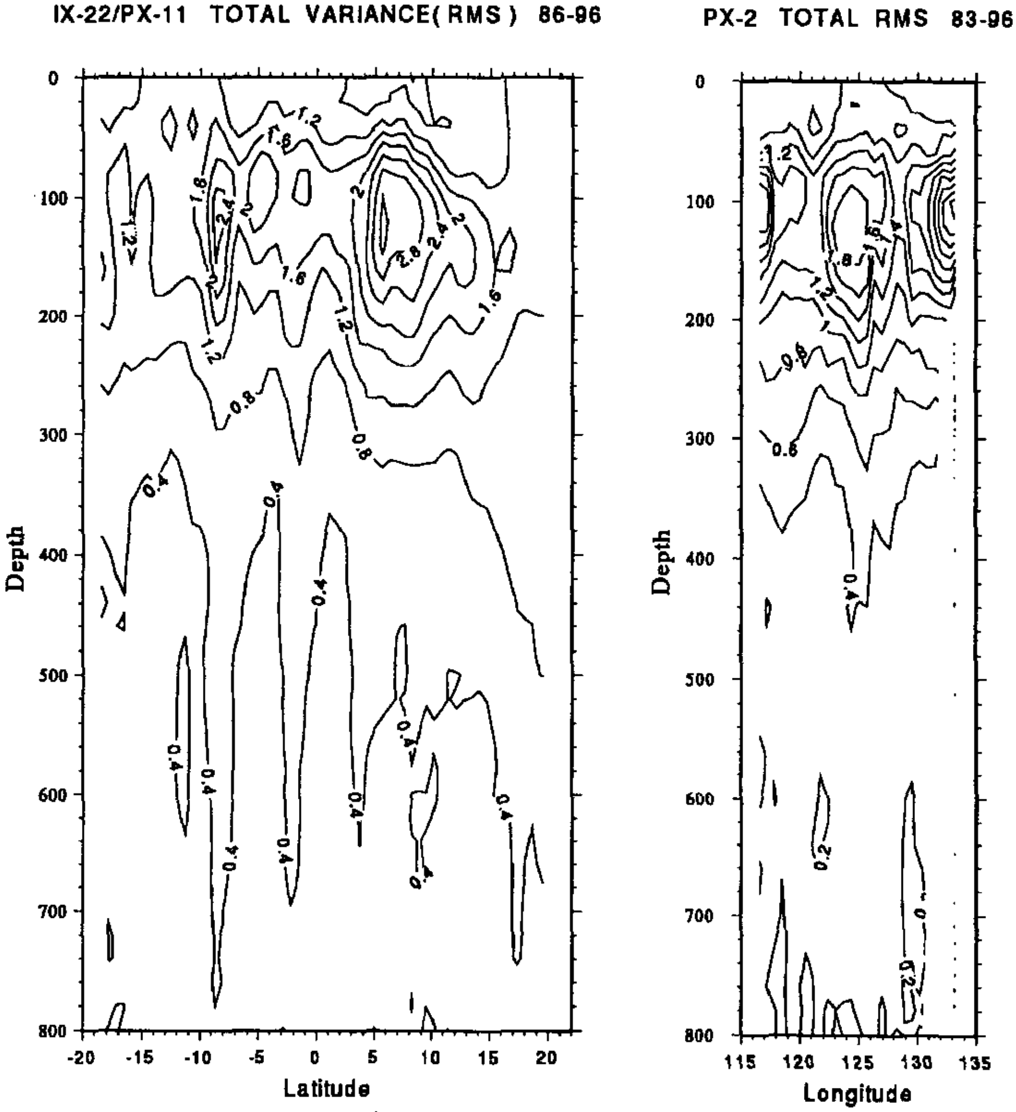
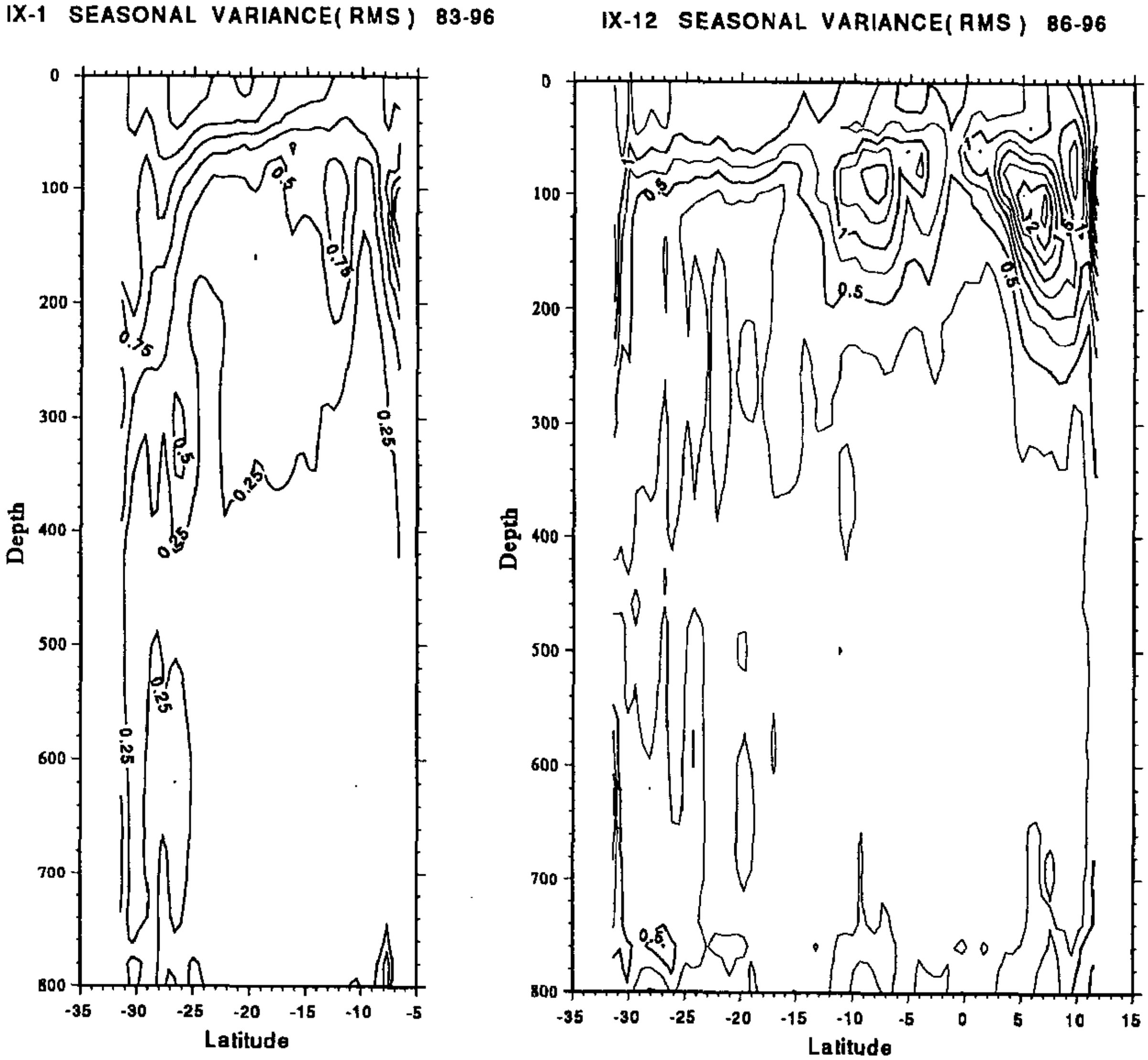


Figure 7 (a,b)
Total Standard Deviation for IX-1 and IX-12



(c) (d)

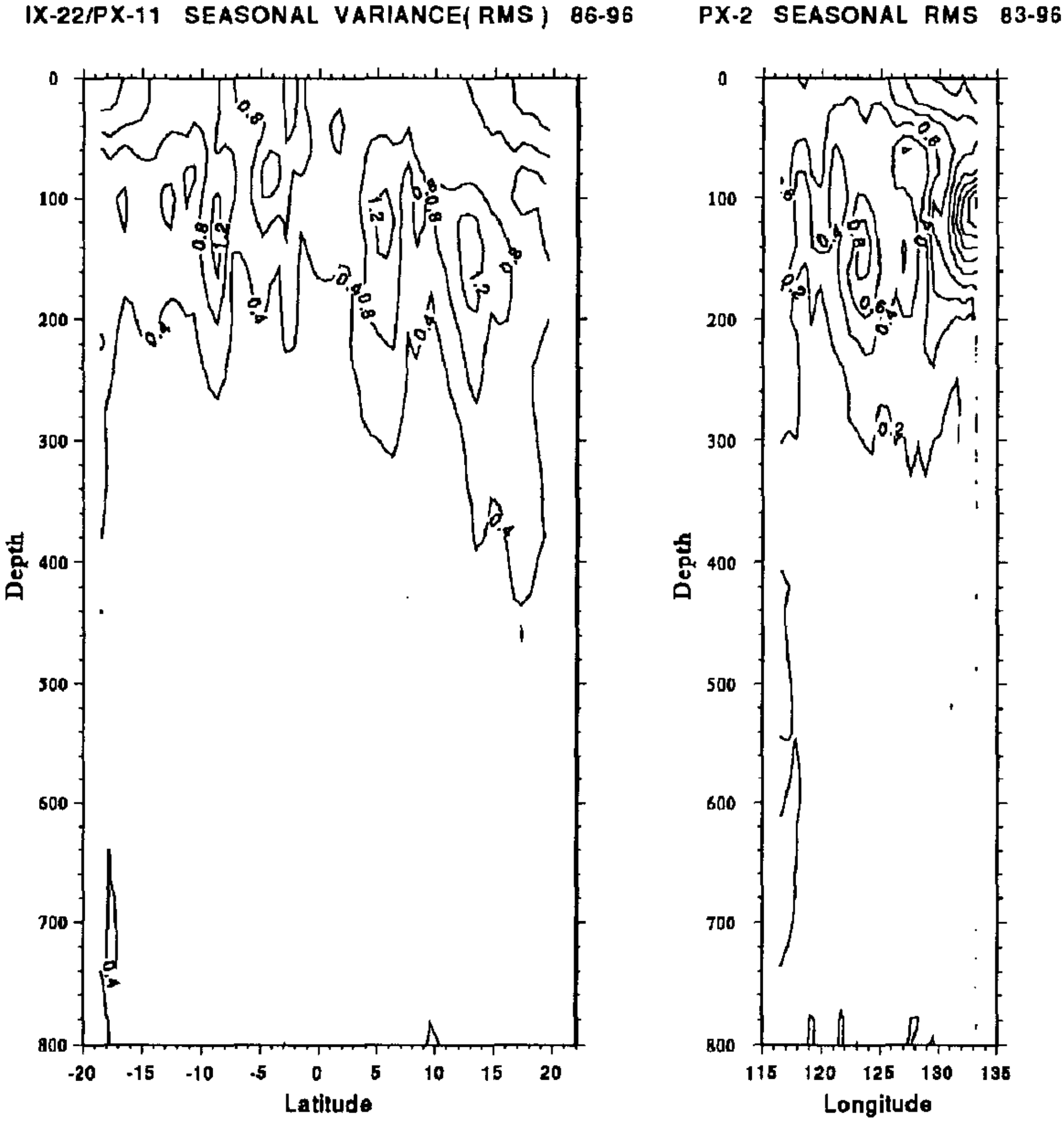
Figure 7 (c,d)
Total Standard Deviation for IX-22/PX-11 and PX-2



(a)

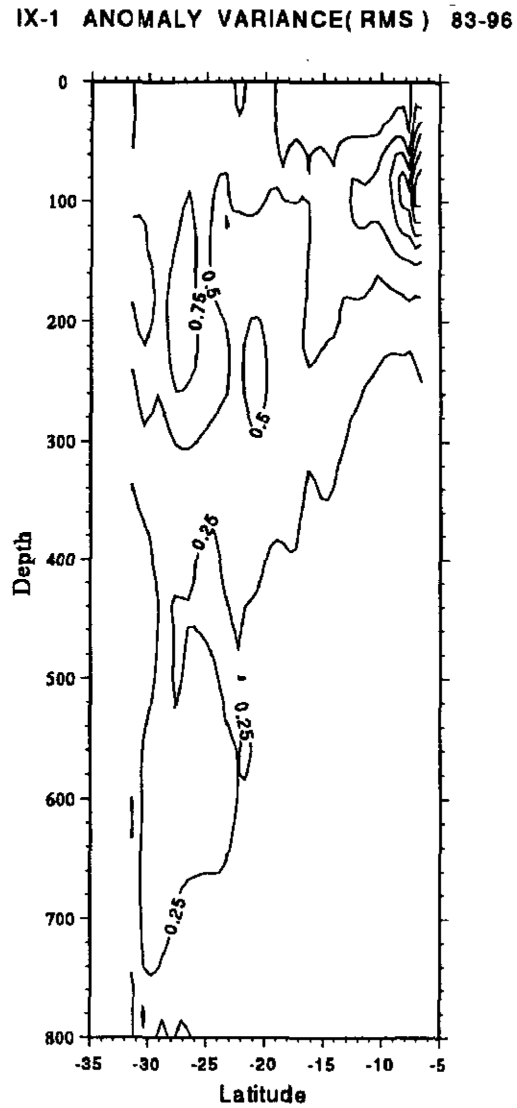
(b)

Figure 8 (a,b)
Seasonal Standard Deviation for IX-1 and IX-12

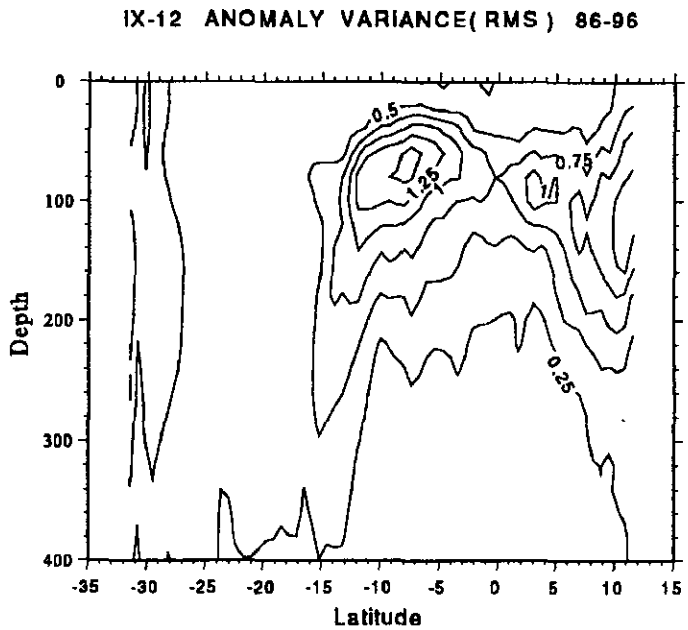


(c) (d)

Figure 8 (c,d)
Seasonal Standard Deviation for IX-22/PX-11and PX-2

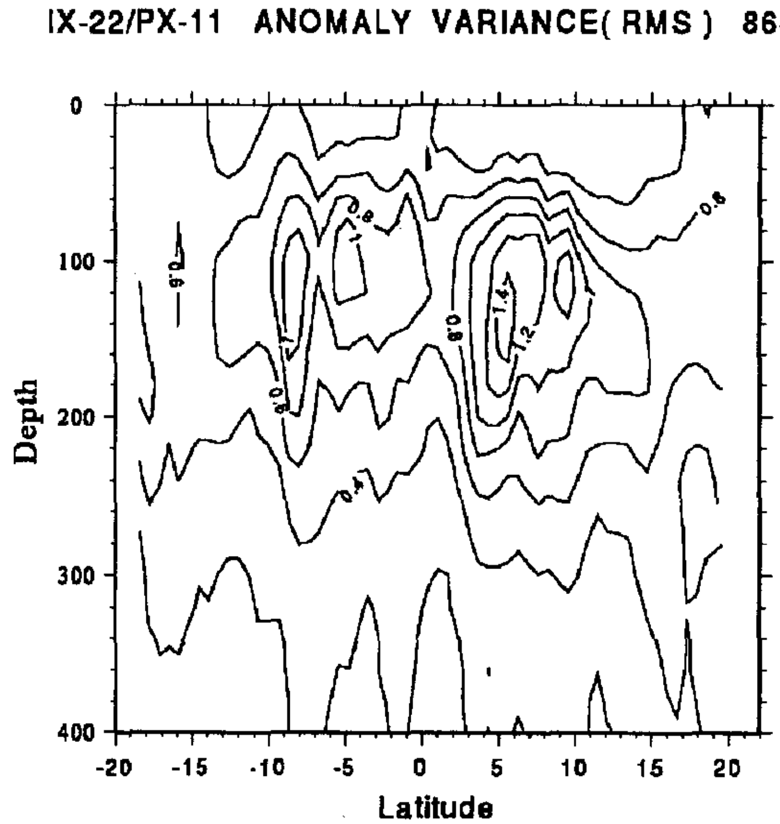


(a)

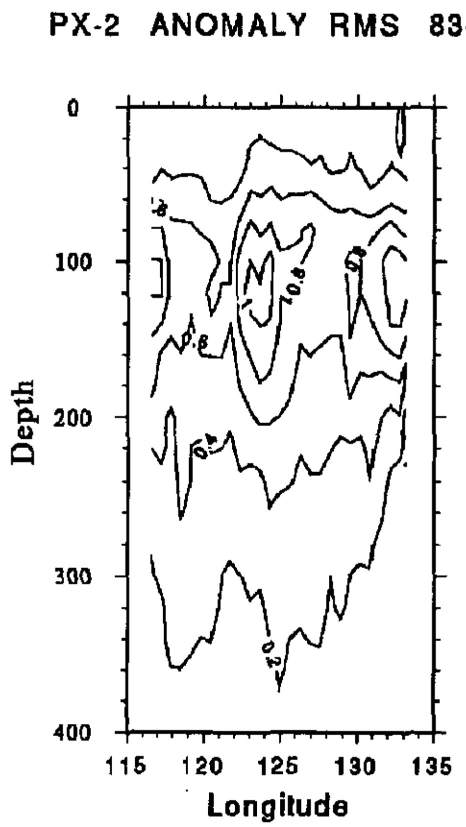


(b)

Figure 9 (a,b)
Interannual Standard Deviation for IX-1 and IX-12



(c)



(d)

Figure 9 (c,d)
Interannual Standard Deviation for IX-22/PX-11 and PX-2

5 CLIMATOLOGY - MEAN SEASONAL CYCLE

The bimonthly mean of the following indices of the thermal structure were calculated:

- the Sea Surface Temperature (SST), in degrees Celsius
- the Depth of the 20 degrees Isotherm (D20), in meters
- the Dynamic Height 0/400 (DHT), in Dynamic Centimeters.

The results are presented as Hovmoller diagrams in Figures 10 to 12 . In the diagrams, the bimonthly values are centered on the first day of the second month (e.g. on the 1 February for J/F).

The salinity values used to calculate dynamic height are obtained from the bimonthly mean XBT temperatures and from the Levitus annual mean T/S relationship (Levitus,1982), using linear interpolation in depth.

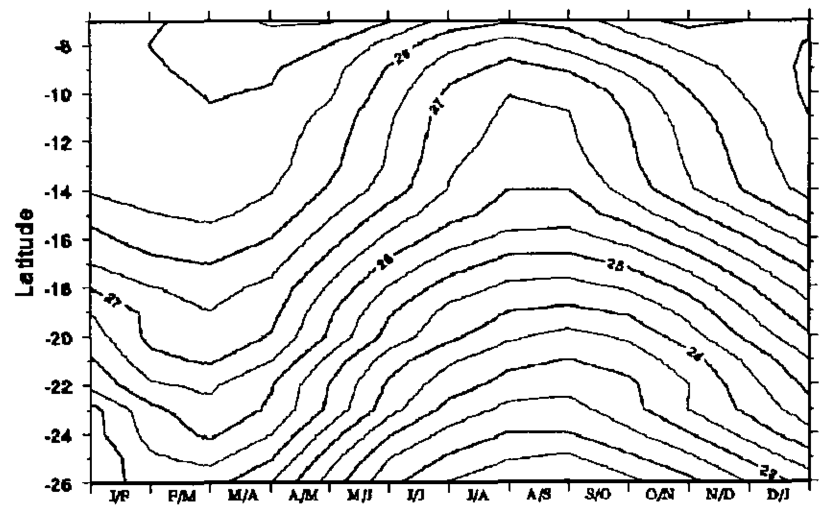
If the range of Levitus temperature values is smaller then the range of XBT temperature values in a particular bin, the interpolation (at either end of the T/S relation) cannot be performed. In this case, the last Levitus salinity value, at either end of the TS relationship, is used to extrapolate to the highest or lowest XBT temperature.

Dynamic height was calculated by modifying the 'geopotential anomaly' function ('sw_gpan'), in Morgan's SEAWATER matlab library, (Morgan, 1994). When calculating dynamic height close to the continental shelf, the bottom topography was taken into account by replacing the temperature and salinity values below the bottom depth, and above the reference depth, with the temperature and salinity values in the nearest adjacent water at each level. This gives a horizontal density gradient and vertical shear of zero, at depths greater than the bottom.

In addition to the above, the Dynamic Height (0/700), the Transport Function (0/400) and (0/700) and the Total Transport (0/400) and (0/700) were also calculated. The results are presented on the web.

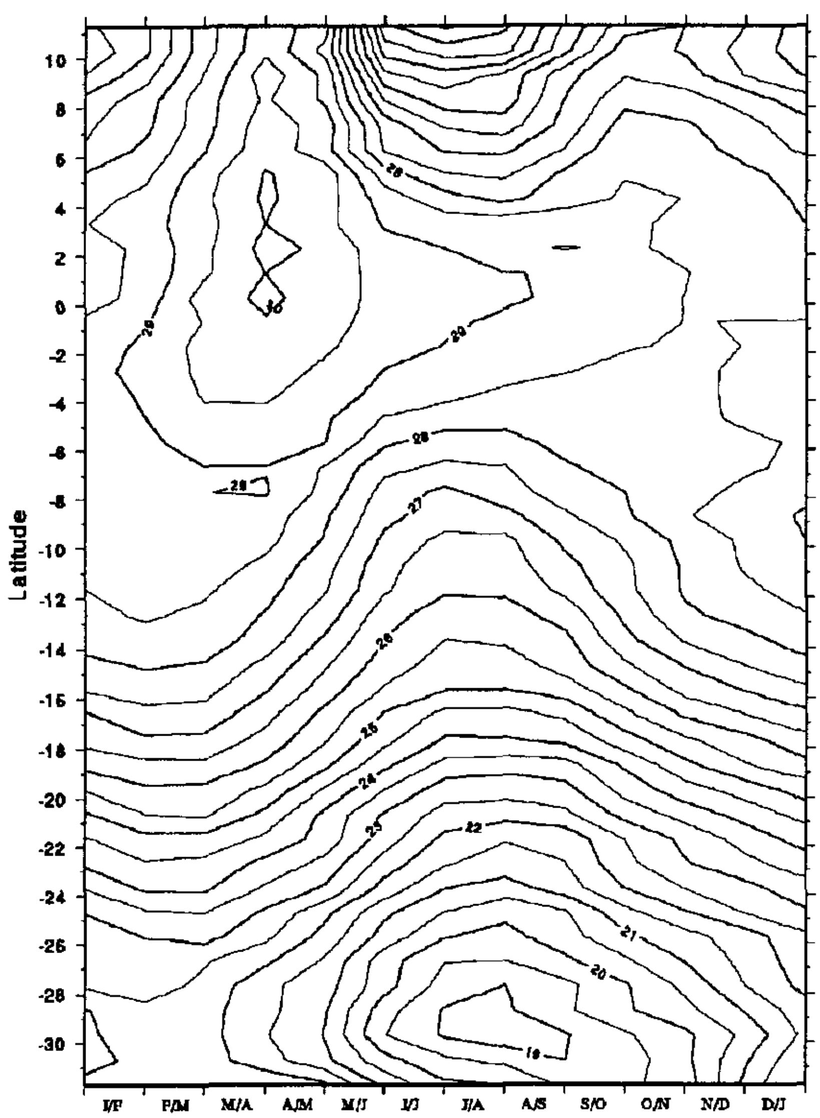
From the vertically integrated DHT(0/400), the long-term bimonthly mean transports were calculated along IX-1, IX-22 and PX-2 to document the geostrophic transport of the Indonesian throughflow (Meyers et al. 1995). Seasonal variations of DHT and transports (0/400) along IX-12, IX-9 and IX-3 have also been computed, in order to study the distribution of currents in the western tropical Indian Ocean (Donguy et al. 1995).

IX-1 SST CLIMATOLOGY



(a)

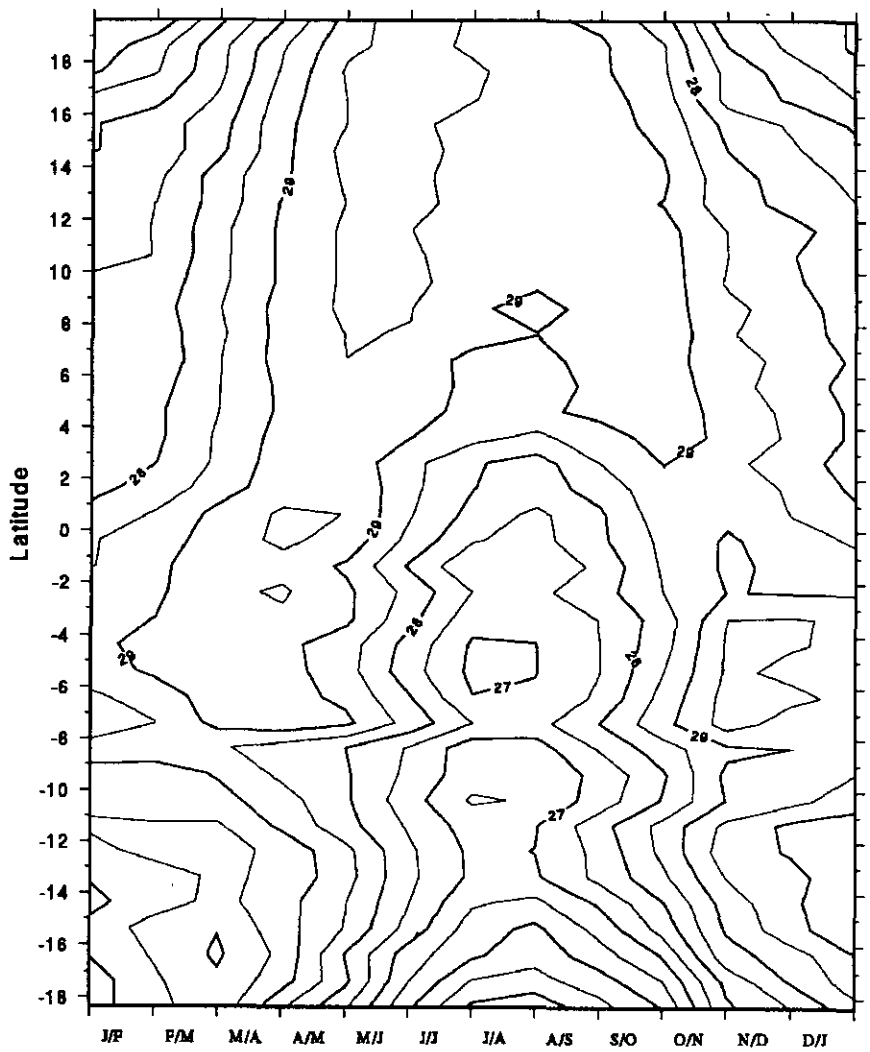
IX-12 SST CLIMATOLOGY



(b)

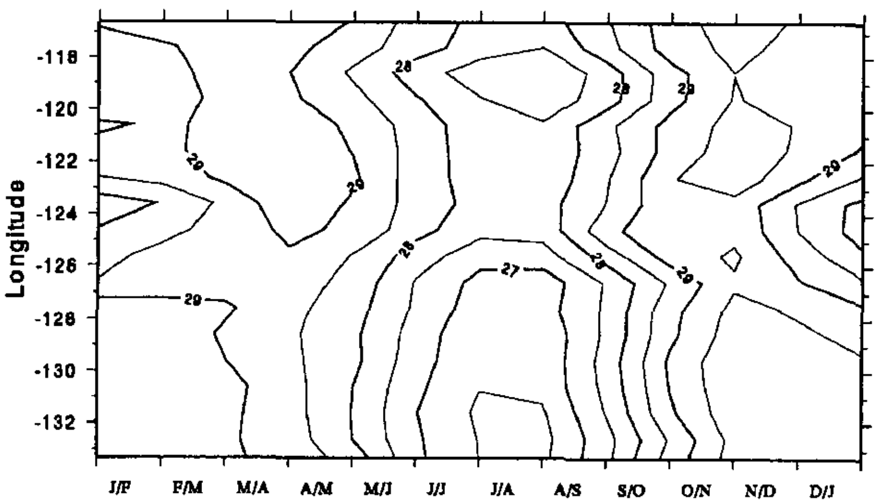
Figure 10 (a,b)

IX-22/PX-11 SST CLIMATOLOGY



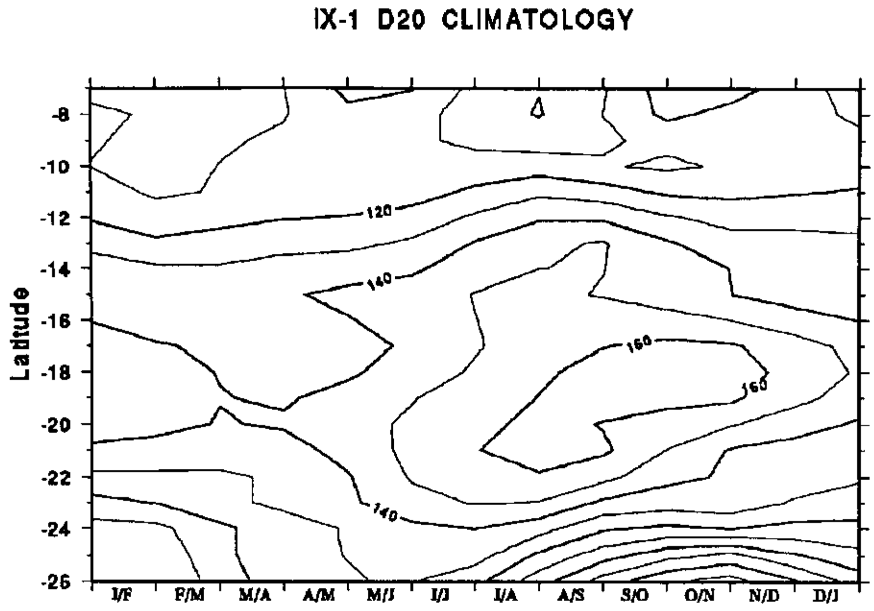
(c)

PX-2 SST CLIMATOLOGY

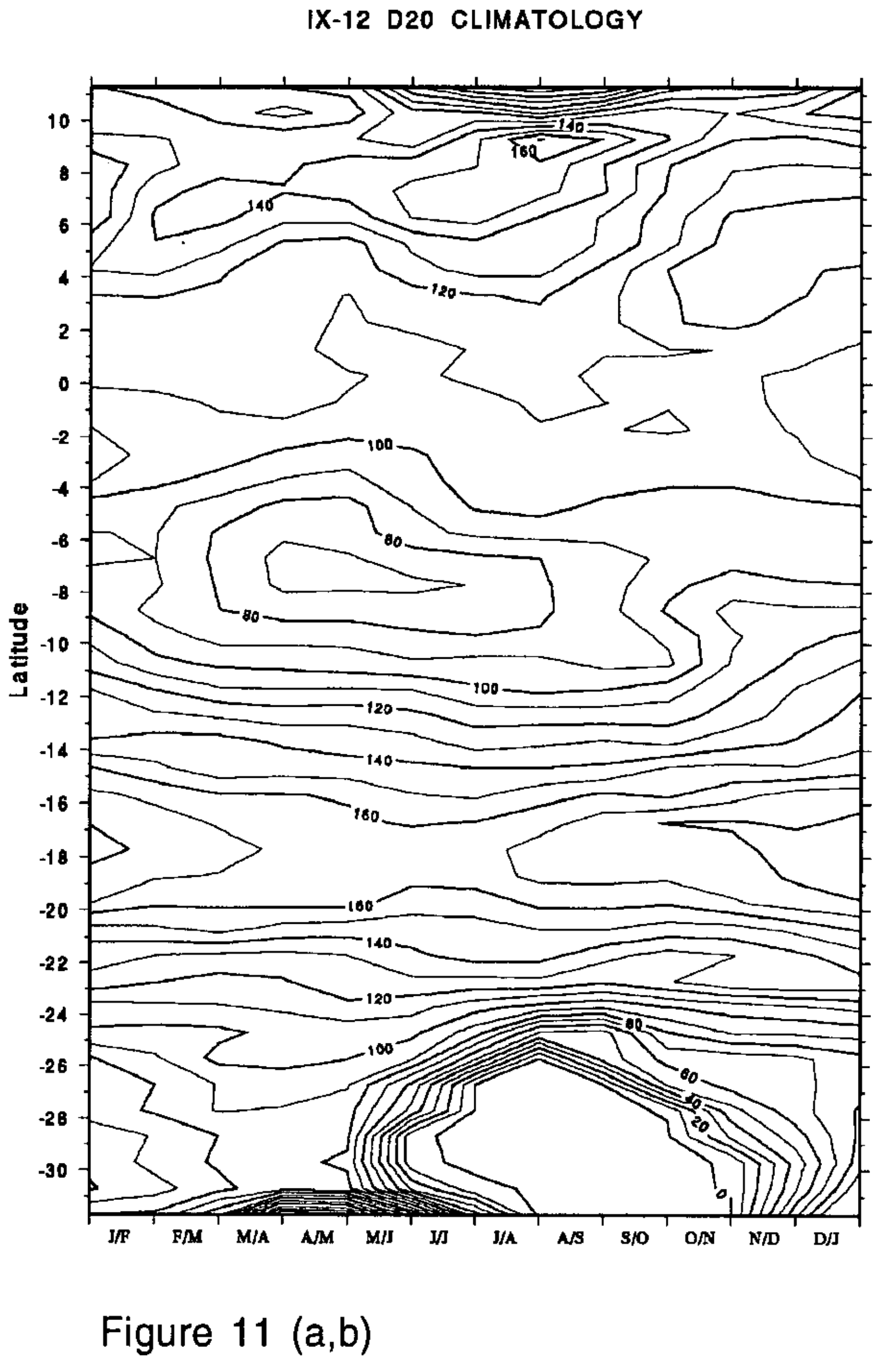


(d)

Figure 10 (c,d)



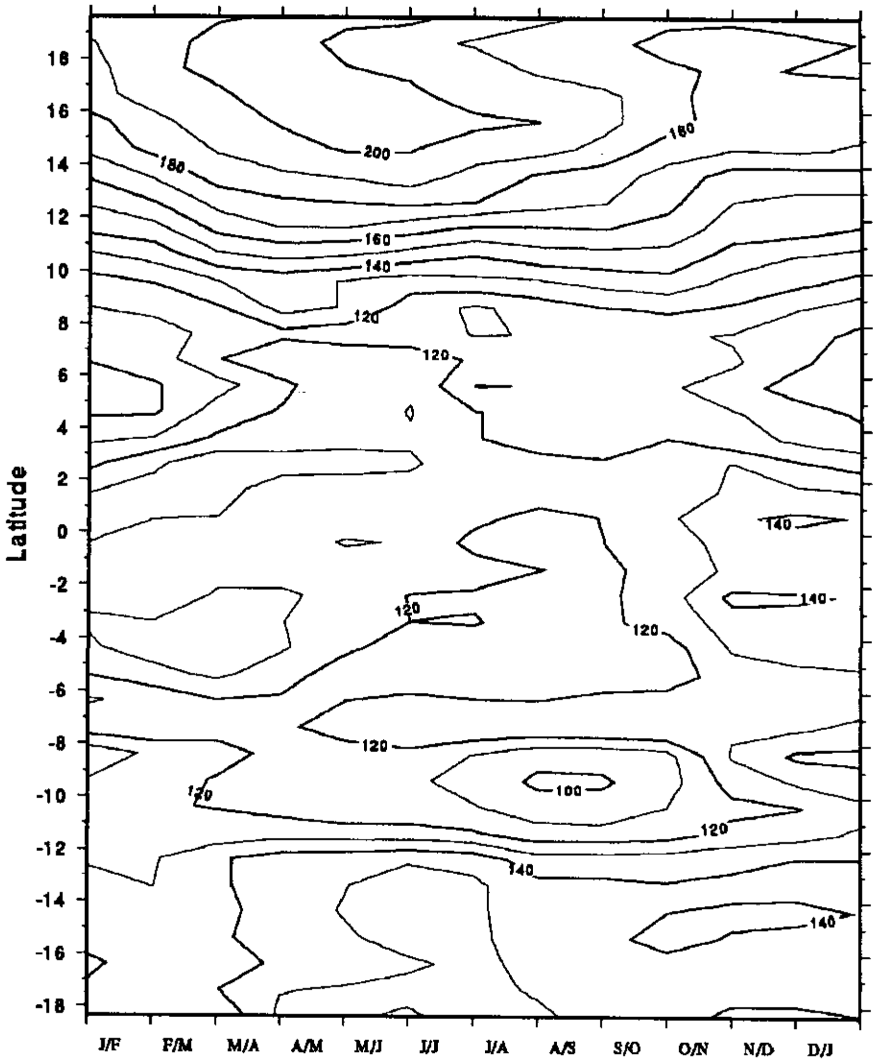
(a)



(b)

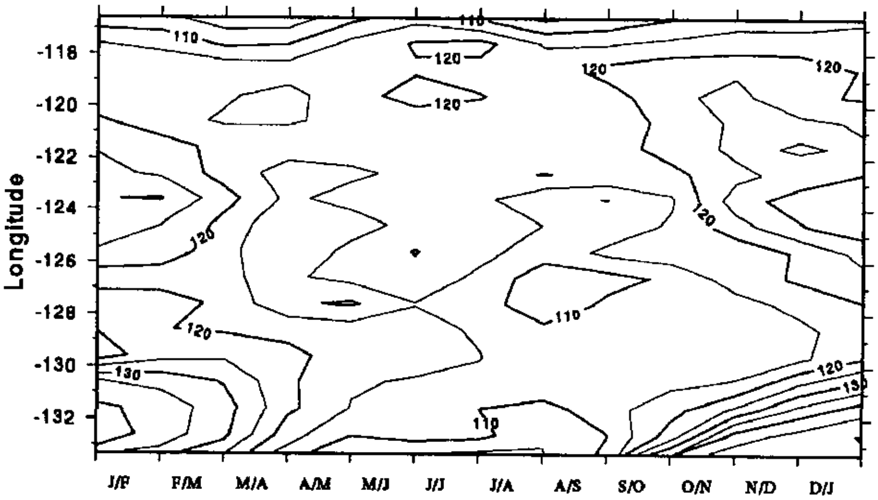
Figure 11 (a,b)

IX-22/PX-11 D20 CLIMATOLOGY



(c)

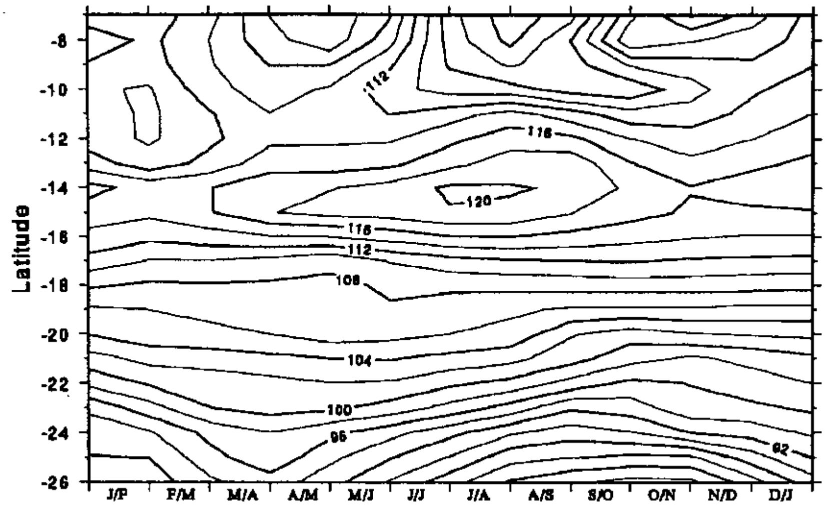
PX-2 D20 CLIMATOLOGY



(d)

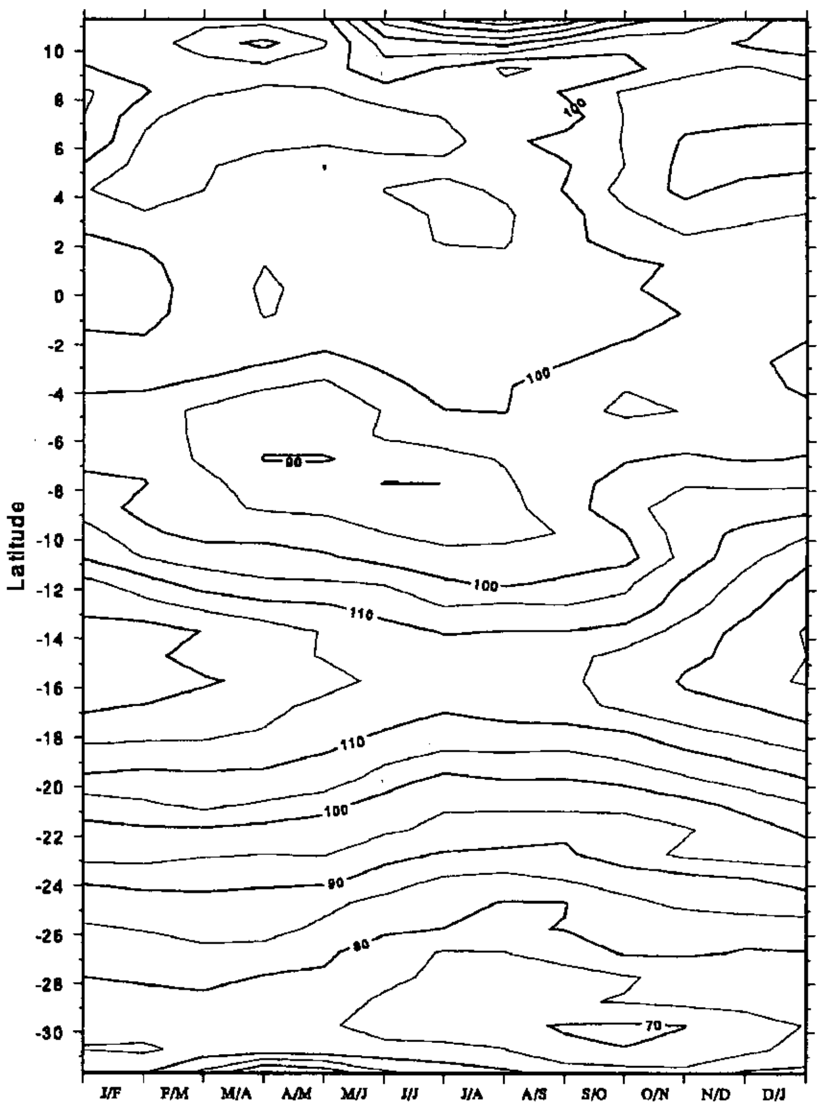
Figure 11 (c,d)

IX-1 DYNAMIC HEIGHT(0/400) CLIMATOLOGY



(a)

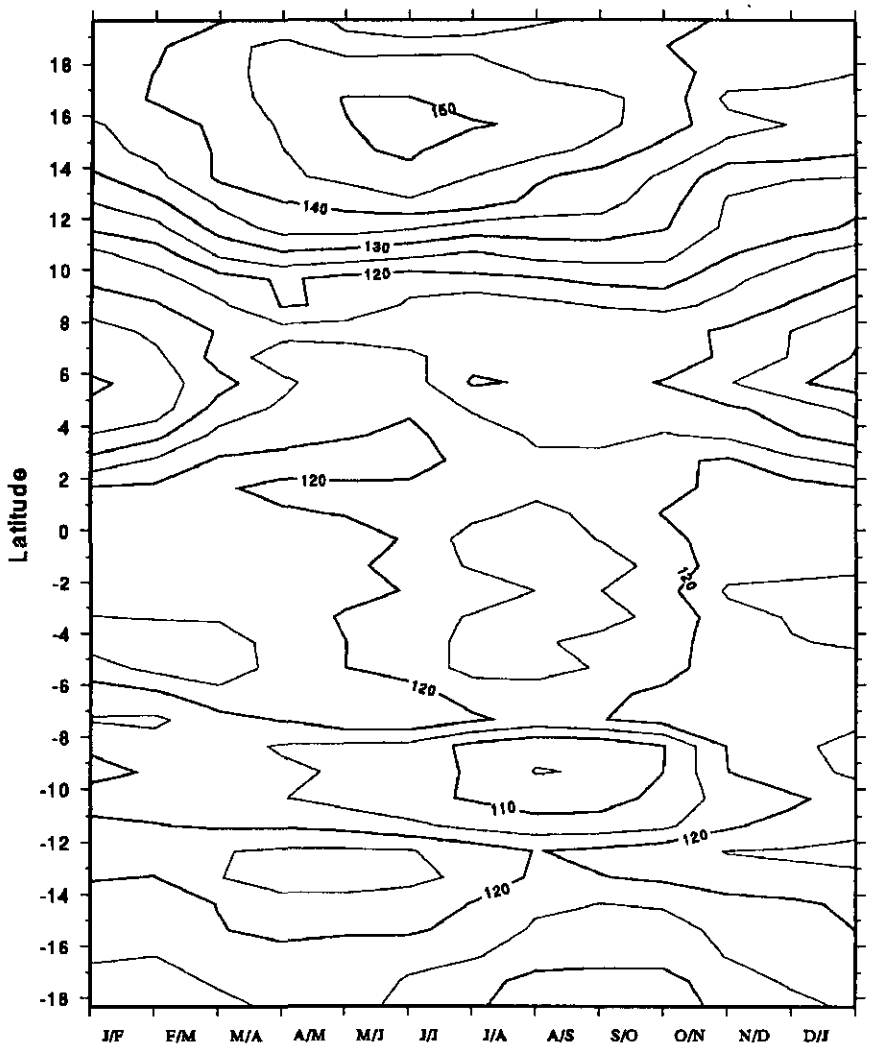
IX-12 DYNAMIC HEIGHT(0/400) CLIMATOLOGY



(b)

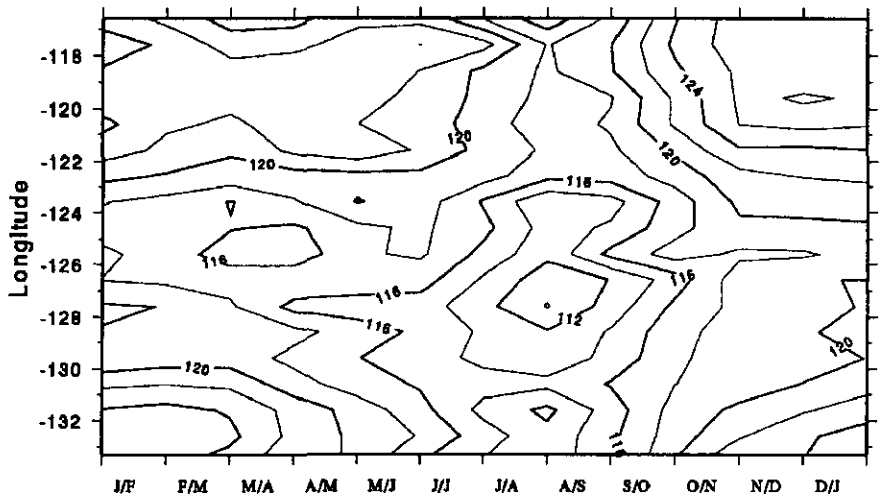
Figure 12 (a,b)

IX-22/PX-11 DYNAMIC HEIGHT(0/400) CLIMATOLOGY



(c)

PX-2 DYNAMIC HEIGHT(0/400) CLIMATOLOGY



(d)

Figure 12 (c,d)

6 INTERANNUAL VARIATION

The XBT profiles are irregularly sampled in time. To minimise the analysis error and obtain an interannual time series of bimonthly averages, an optimal estimation method is used. The theory of optimal interpolation as applied in meteorology (initially by Gandin 1963), is also used to analyse oceanographic data. The method used in this study (temporal optimal averaging - OA) was developed by Chelton and Schlax (Chelton et al. 1991).

The temperature data we used in the OA analysis has the all data mean removed. After the Optimal Averaging, the mean is then added back to the OA temperature deviations. From the OA temperatures thus obtained, the bimonthly anomaly is calculated by removing the mean seasonal cycle. The final temperatures are then reconstructed by adding the seasonal bimonthly mean calculated from measured XBTs, to the interannual bimonthly anomaly.

To calculate the optimal averages, the following parameters are used :

- an AVERAGING PERIOD of 2 months, centred at the beginning of the second month, e.g., 1 January refers to the averaging period of December/January
- a DECORRELATION TIME SCALE of 2 months
- a SIGNAL-TO-NOISE VARIANCE RATIO of 1
- a DATA WINDOW of 6 months, i.e., 3 months on either side of the estimation time.

The statistical structure parameters are further documented in Meyers et al. 1989, Phillips et al. 1990, Meyers et al. 1991 .

Examples of the optimally averaged (OA) temperatures at 100m depth (between 1988 and 1996) are compared in Figures 13(a to d), to the raw XBT data sampled at that depth. The comparison shows that the OA temperatures underestimate the peaks and overestimate the troughs. The OA results improve substantially with better sampling (compare Figures 13a and 13c), but still underestimate the maxima and overestimate the minima. This is due to a signal-to-noise ratio equal to 1. Where there are no XBT data, or very few, the OA gives a temperature value closer to the mean. This happens because the OA weights were not constrained to be unity in this study. Also, in some regions, the signal-to-noise ratio should be greater than 1 (Phillips et al., 1990). Since the OA statistics and the sampling rate vary over the years and along the XBT routes, the best compromise was thought to be a signal-to-noise ratio equal to one, throughout the study region.

OA time series of temperature sections are calculated for all lines, as described above. OA time series of SST, D20 and Dynamic Height (0/400)db are calculated next. The time series are illustrated on the web. Hovmoller diagrams are used to visualise the interannual anomaly of SST, D20 and Dynamic Height (Figures 14 to 16). The Dynamic Height was calculated by modifying the 'geopotential anomaly' function ('sw_gpan') in Morgan's SEAWATER matlab library (Morgan 1994).

The 1983 to 1994 time series of SST, D20 anomalies, the joint Empirical Orthogonal Functions (EOFs) of SST, D20 and Dynamic Height (0/400) anomalies and the geostrophic transports through IX-1 were analysed and related to the field of wind stress, in order to study the variation of the Indonesian throughflow and the El Nino Southern Oscillation (Meyers 1996).

NOTE : For lines IX-1 and IX-12, the interannual anomaly of D20 has the range of values reduced to the limits : -40 to 40, by replacing all anomalies greater than 40 with 40, and all anomalies less than -40 with -40. In doing so, a better contrast between the positive and negative anomalies is achieved. See Figure 18 for lines IX-1 and IX-12. The reduction is done for illustration only. The D20 anomaly data set is not changed.

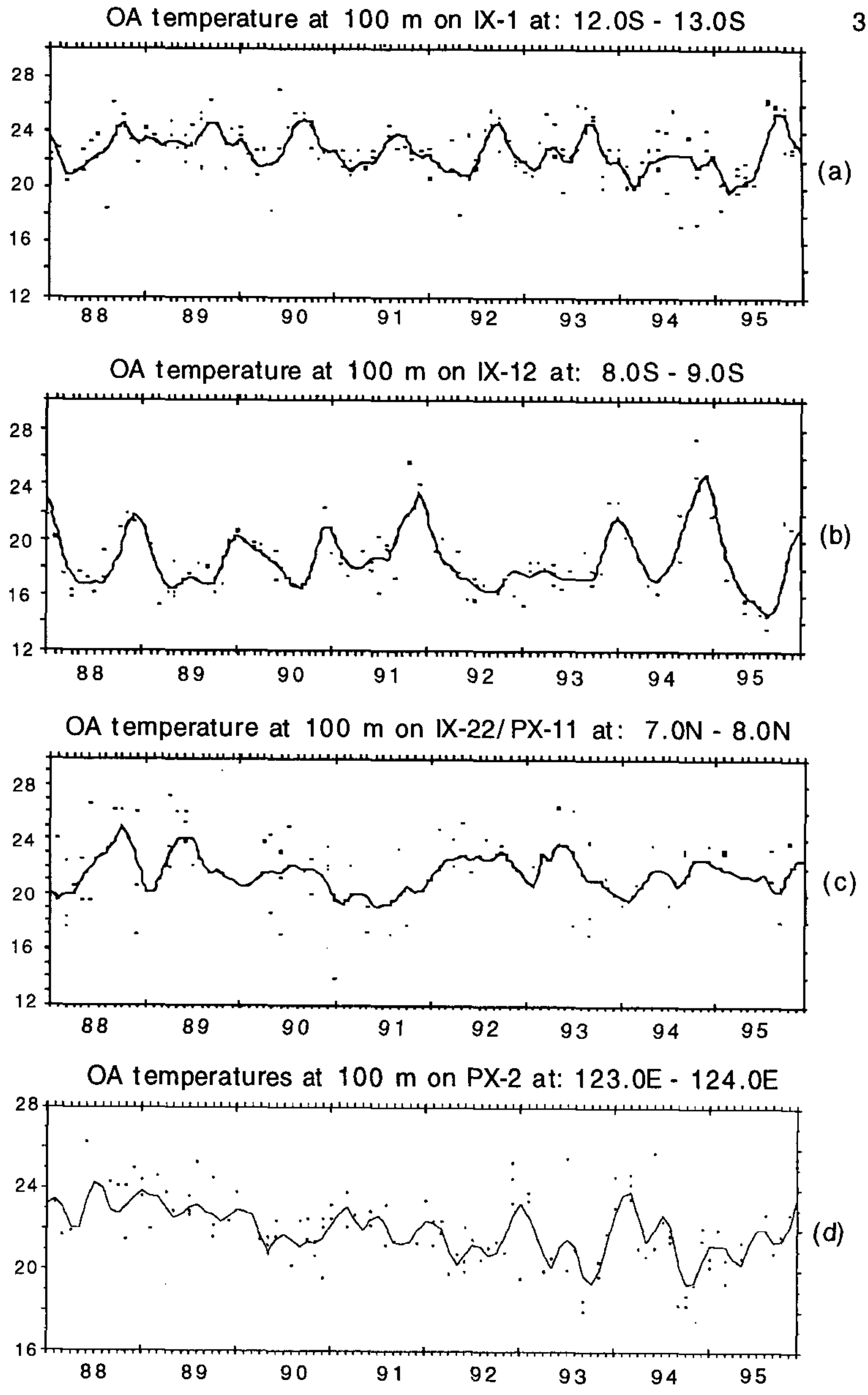


Figure 13 (a,b,c,d)
Optimally averaged temperatures (solid lines) against measured temperatures (dotted lines) .

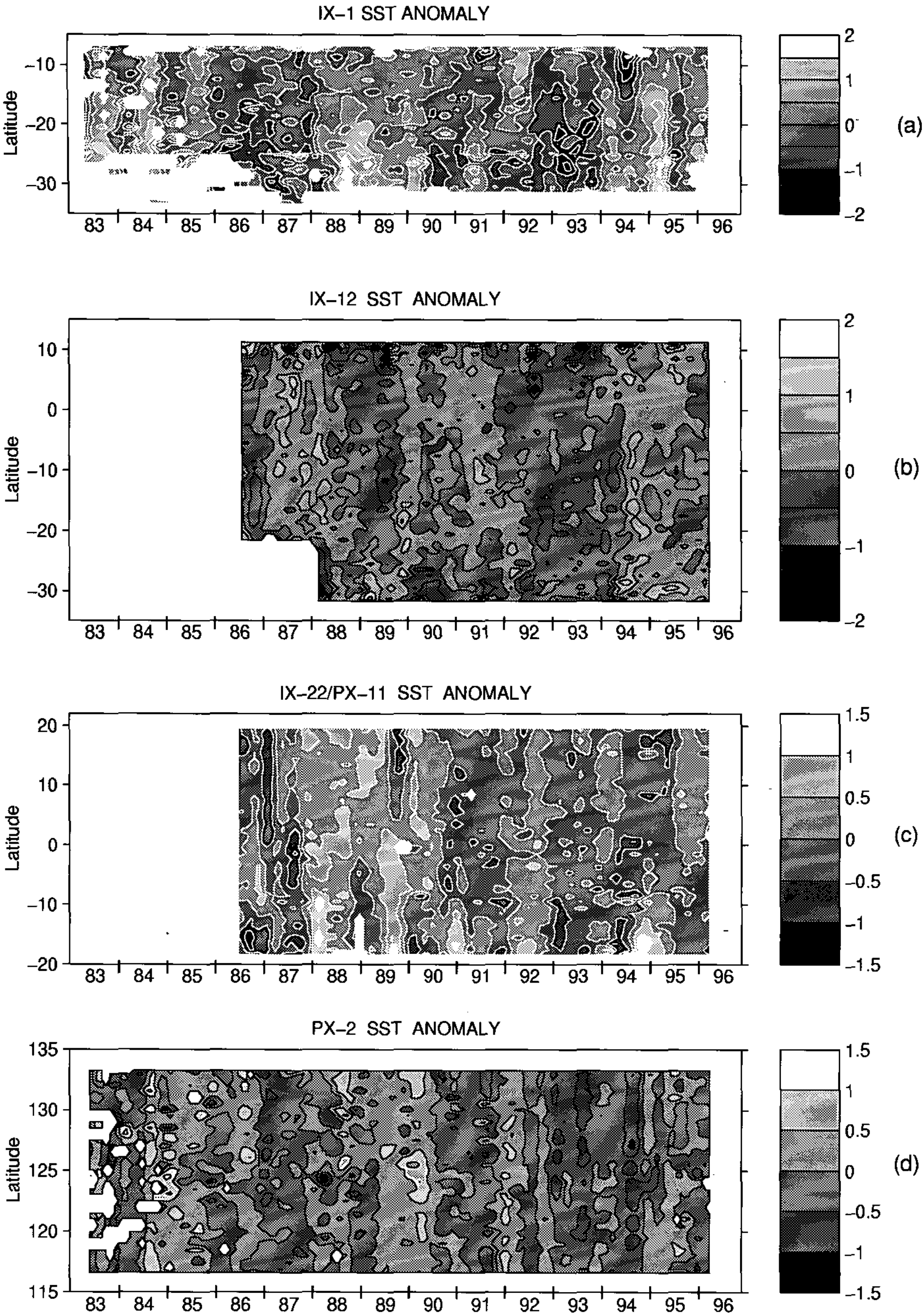


Figure 14 (a,b,c,d)

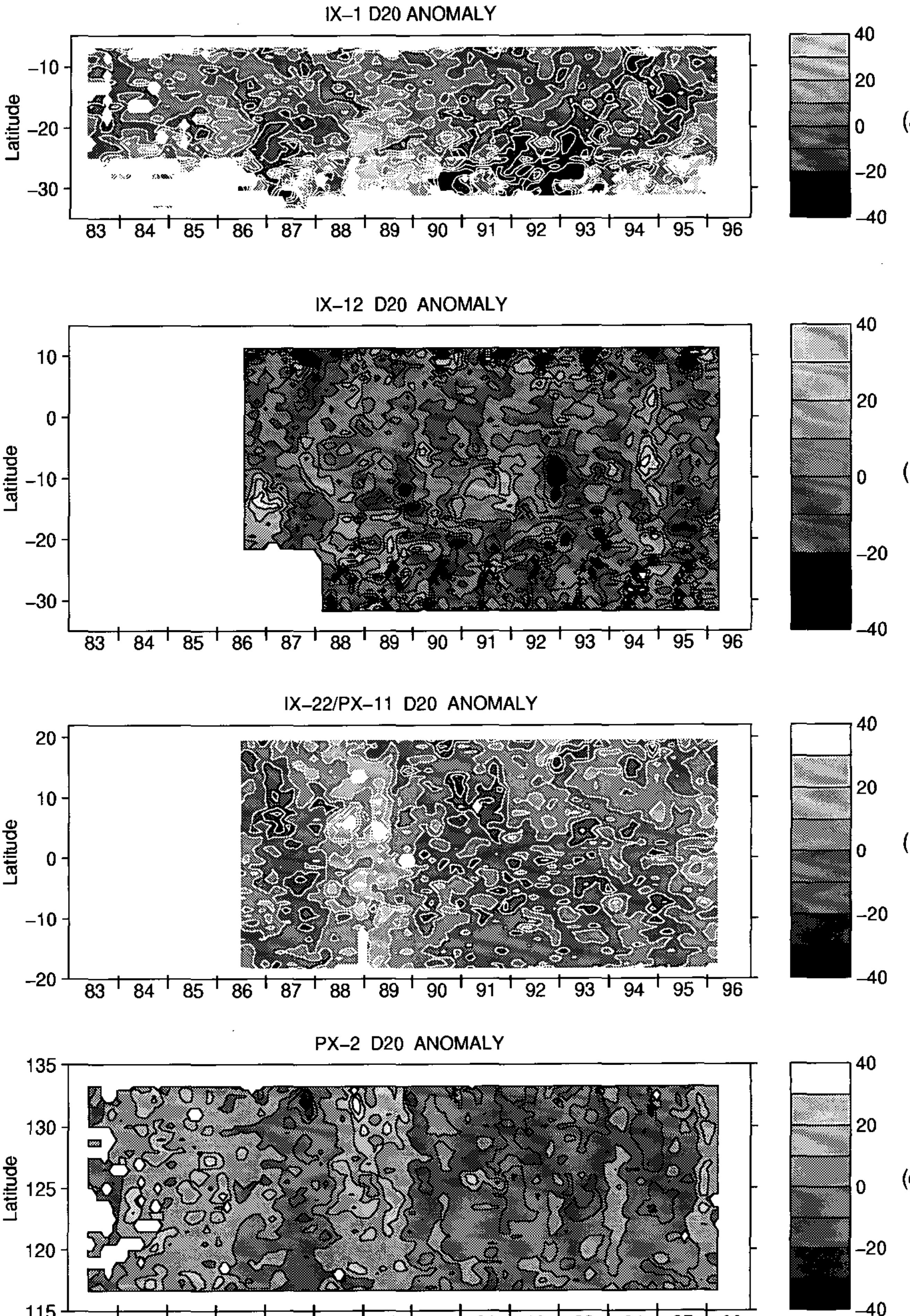


Figure 15 (a,b,c,d)

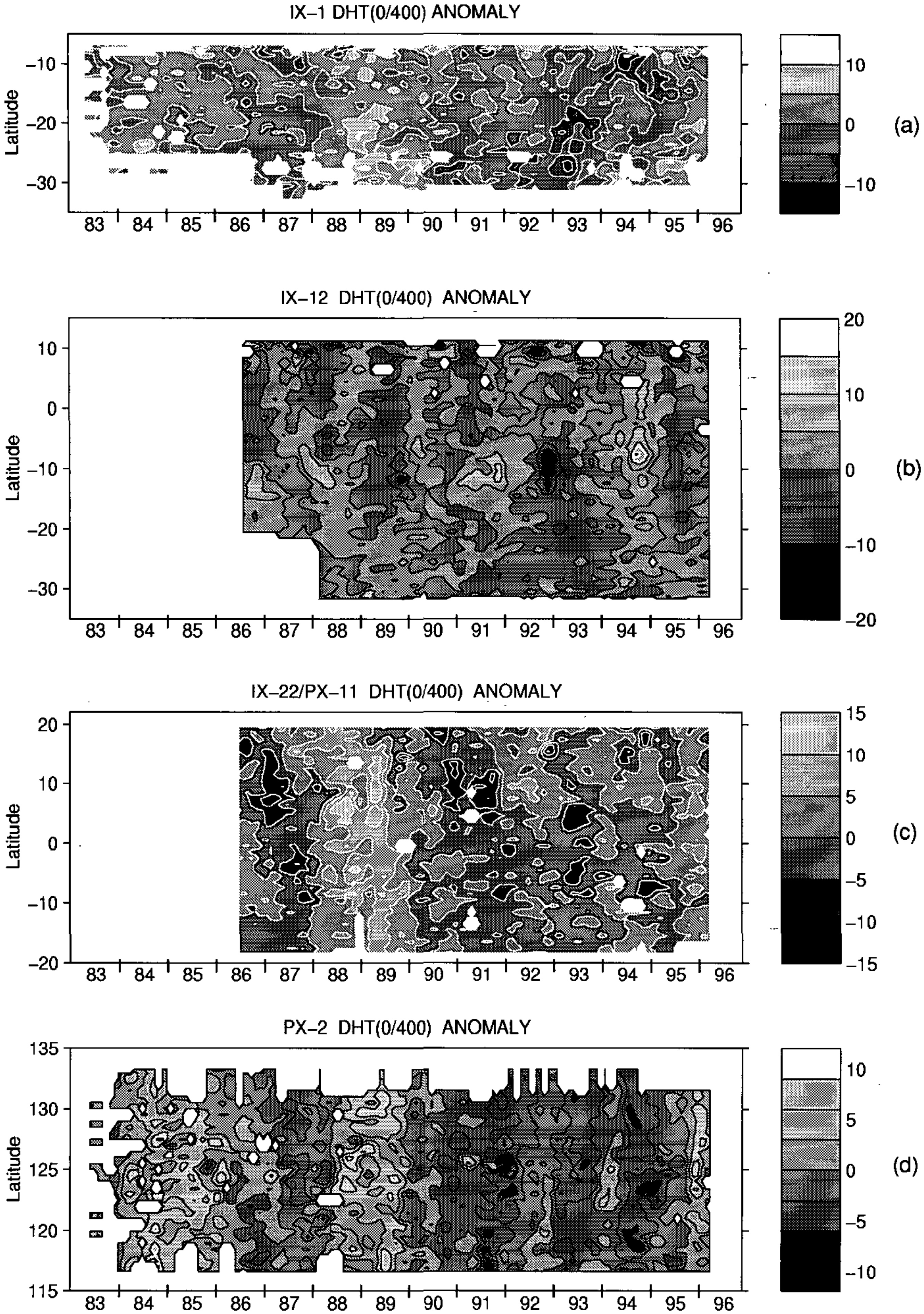


Figure 16 (a,b,c,d)

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Also, thanks to the Computer Support group and especially to Peter Campbell.

8 REFERENCES

Andrews, J.C. (1976)

'The bathythermograph as a tool in gathering synoptic thermohaline data.'

Australian Journal of Marine and Freshwater Research 27, 405-415.

Bailey R., A. Gronell, H. Phillips, E. Tanner and G. Meyers (1994)

'Quality Control Cookbook for XBT Data',

CSIRO Marine Laboratories Report 221, 84 pp.

Chelton D.B., M.G. Schlax (1991)

'Estimation of time averages from irregularly spaced observations, with application to Coastal Zone Scanner Estimates of Chlorophyll Concentration'

Journal of Geophysical Research 96, 14669-92 .

Colborn, J.G. (1971)

'The thermal structure of the Indian Ocean. International Indian Ocean Expedition'

Oceanographic Monograph, 2, University Press of Hawaii.

Creswell, G.R., T.J. Golding, F.M. Boland (1978).

'A buoy and ship examination of the Subtropical convergence south of Western Australia'

Journal of Physical Oceanography 8, 315-320

CSIRO Australia Oceanographical Cruise Reports (1959-1966),

Oceanographical observations in the Indian Ocean from 1959 to 1966.

Report numbers 1-4, 7, 9, 11, 14, 15-18, 20, 21, 23-25, 30, 33, 36, 38, 40, 49, 51, 53.

Donguy J.R., G. Meyers (1995)

'Observations of geostrophic transport variability in the western tropical Indian Ocean'

Deep-Sea Research 42, No. 6, 1007-28

Edwards, R.J., (1977)

'Hydrological investigations of R.V. Sprightly, April 1974 - April 1975 '

CSIRO Australia Division of Fisheries and Oceanography Report 73, 5 pp. + 40 figs.

Gandin, L.S. (1963)

'Objective Analysis of Meteorological Fields',

Gidrometeorologicheskoe Izvdatel'stvo, Leningrad, USSR, 286 pp.

Greig, M.A., K.R. Ridgway, D.J. Vaudrey and J.S. Godfrey (1986)

'M/V ANRO Australia Sections : Thermal Profiles in the Eastern Indian Ocean, May 1983 to July 1984'

CSIRO Marine Laboratories Report 174, 29 pp.

Greig, M.A. (1986)

'The Warreen Sections; Temperatures, Salinities, Densities and Steric Heights in the Leeuwin Current, Western Australia, 1947-1950'

CSIRO Marine Laboratories Report 175, 22 pp.

Hamon, B.V. (1967)

'Medium-scale temperature and salinity structure in the upper 1500 m in the Indian Ocean'

Deep-Sea Research 14, 169-181

Hanawa K., P.Rual, R.Bailey, A. Sy and M. Szabados (1995)

'A new depth-time equation for Sippican or TSK T-7,T-6 and T-4 expendable bathythermographs (XBT)'

Deep-Sea Research 42, No. 8, 1423-51

Highley, E. (1968)

'The International Indian Ocean Expedition: Australia's contribution.'

CSIRO Australia Division of Fisheries and Oceanography Technical Paper 28, 42 pp.

Levitus, S. (1982) :

'Climatological Atlas of the World Ocean',

NOAA Professional Paper 13, Rochville, MD, 173 pp.

Meyers G., J. Sprintall, H. Phillips, J. Peterson, T. Fonseca (1989)

'Design of an Ocean Temperature Observing Network in the Seas North of Australia. Part 1 - Tropical Pacific Ocean Statistics.'

CSIRO Marine Laboratories Report 204, 50 pp.

Meyers G., H. Phillips, N. Smith, J. Sprintall (1991)

'Space and time scales for optimal interpolation of temperature - Tropical Pacific Ocean',

Progress in Oceanography 28, 189-218

Meyers G., R.J. Bailey, and A.P. Worby (1995)

'Geostrophic transport of Indonesian throughflow'

Deep Sea Research 42, No. 7, pp. 1163-74

Meyers G. (1996)

'Variation of Indonesian throughflow and the El Nino - Southern Oscillation'

J Geophys Res 101, No. C5, pp. 12255-63

Morgan, P. P.(1994)

'SEAWATER: A Library of MATLAB Computational Routines for the Properties of Sea Water',

CSIRO Marine Laboratories Report 222, 29pp.

National Oceanographic Data Centre (NODC - 1967)

'Indian Ocean Atlas. Interpolated values of depth, salinity and temperature on selected sigma-t surfaces.'

NODC, General Series, Publication G-12, 61 pp.

Phillips H., R. Bailey, G. Meyers (1990)

'Design of an Ocean Temperature Observing Network in the Seas North of Australia. Part 2 - Tropical Indian Ocean Statistics'

CSIRO Marine Laboratories Report 211, 58 pp.

Sprintall J. and G. Meyers (1991)

'An optimal XBT sampling network for the Eastern Pacific Ocean'

J Geophys Res 96, 10539-52

Smith N., J.E. Blomely, G. Meyers (1991)

'A univariate statistical interpolation scheme for subsurface thermal analyses in the tropical oceans.'

Prog Oceanog 28, 219-250

Wyrtki, K., E.B. Bennett, D.J. Rochford (1971)

'Oceanographic Atlas of the International Indian Ocean Expedition'

National Science Foundation, Washington 531

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