Indian Ocean Analyses

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Abstract

The background and goals of Indian Ocean thermal sampling are discussed from the perspective of a national project which has research goals relevant to variation of climate in Australia. The critical areas of SST variation are identified. The first goal of thermal sampling at this stage is to develop a climatology of thermal structure in the areas and a description of the annual variation of major currents. The sampling strategy is reviewed. Dense XBT sampling is required to achieve accurate, monthly maps of isotherm-depth because of the high level of noise in the measurements caused by aliasing of small scale variation. In the Indian Ocean ship routes dictate where adequate sampling can be achieved. An efficient sampling rate on available routes is determined based on objective analysis. The statistical structure required for objective analysis is described and compared at 95 locations in the tropical Pacific and 107 in the tropical Indian Oceans. XBT data management and quality control methods at CSIRO are reviewed. Results on the mean and annual variation of temperature and baroclinic structure in the South Equatorial Current and Pacific/Indian Ocean Throughflow are presented for the region between northwest Australia and Java-Timor The mean relative geostrophic transport (0/400 db) of Throughflow is approximately 5 x 106 m3/sec. A nearly equal volume transport is associated with the reference velocity at 400 db. The Throughflow feeds the South Equatorial Current, which has maximum westward flow in August/September, at the end of the southeasterly Monsoon season. A strong semiannual oscillation in the South Java Current is documented. The results are in good agreement with the Semtner and Chervin (1988) ocean general circulation model. The talk concludes with comments on data inadequacies (insufficient coverage, timeliness) particular to the Indian Ocean and suggestions on the future role that can be played by Data Centers, particularly with regard to quality control.of data as research bodies are replaced by operational bodies in the Global Ocean Observing System.

Background and Goals

Indian Ocean thermal analyses will be discussed from the perspective of a project which has research goals relevant to variation of climate in Australia. The goals of Australian XBT sampling are motivated by studies showing that variation of climate in Australia depends significantly on sea surface temperature (SST) patterns in the Indian Ocean (Nicholls, 1981; Meehl, 1987). The XBT sampling has consequently been concentrated in the regions where the significant SST anoma-

lies develop. It is worth noting that variation of climate in Asia and Africa also depends on SST patterns in the Indian Ocean (Gadgil et al., 1984; Cadet, 1987, Rocha, 1992).

More than half of the winter rainfall variance in Australia can be represented by two rotated principal components (Nicholls, 1989). The first pattern (Fig. 1) is a broad band stretching from the northwest to the southeast corners of the continent and it is associated with SST anomalies in the Indonesian region and the central Indian Ocean. The second pattern (not shown) is centered on the eastern third of the country and is associated with ENSO. Experiments with atmospheric general circulation models have shown that continental scale rainfall anomalies are most sensitive to SST in the Indian Ocean (Simmonds, 1990). A better understanding of the general oceanography of the Indian Ocean, and in particular the mechanisms that cause the SST anomalies, is required before really useful models for prediction of climate variation in Australia can be developed.

One of the goals of CSIRO XBT sampling is to obtain a ten-year description of the large scale thermal structure and currents in the areas that are critical for Australian climate. Very little historical, subsurface data was available for a climatology, so at this stage we are concentrating on documentation of the mean and annual variation of thermal structure and currents. The thermal features that can be described by XBT observations are the heat storage in the mixed layer and the geostrophic transports of the major currents, as demonstrated in many studies of the Pacific Ocean (Meyers and Donguy, 1984; White et al., 1985,1989; Meyers et al., 1986; Donguy, 1987, Kessler and Taft, 1987, Harrison et al., 1989; Taft and Kessler, 1991, Picaut and Tournier, 1991). Another goal is to collect the observational data required for testing and verification of Indian Ocean models. A third goal is to provide timely data for assimilation into ocean general circulation models and for initialization of a forward run of coupled models for prediction of climate variations.

Sampling Strategy

Aliasing of small scale variations is a major problem in designing a large scale sampling strategy. The above goals require at least monthly coverage. Features such as eddies, fronts and coastal boundary currents cannot be resolved by VOS XBT sampling on this time scale, and they consequently appear as a high level of noise in the large scale measurements. The question is: How dense should the sampling be in order to minimize the large scale mapping errors, without resolving the small scale features?

Another consideration is that ship routes dictate where dense XBT sampling can be achieved in the Indian Ocean (Fig 2). Our approach was to concentrate the XBT sampling on "tracklines" where merchant ships tend to sail repeatedly along nearly the same route, permitting sampling which is dense in both space and time. Setting the sampling strategy requires specifying the distance between XBT

profiles along the routes and how frequently each route will be repeated. We also need to specify how accurately the large scale, thermal features on the section can be mapped for the chosen sampling rates.

Sampling efficiency curves (Fig. 3) can be calculated from the theory of optimal interpolation to show the relationship of the normalized, squared mapping error (E2/S2) to sampling density (Meyers et al., 1991; Meyers and Phillips, 1992). E2/S2 is mapping error variance normalized by variance of signal. The sampling density is the number of XBT stations per decorrelation scale in an array, which can be distributed two-dimensionally in time and distance along a trackline or horizontally in latitude and longitude. The curves are given for a range of signal to noise ratios (S/N) from 0.5 to 3.0. (Note that the curves represent a very large range of variance ratios, S2/N2, from 0.25 to 9.0.) Most of the sampling efficiency curves (Fig. 3) show at first a rapid decrease in error with increasing sampling density, then they become nearly flat at the nondimensional sampling density of 3.0. Thus 3.0 is a cost effective sampling density in the sense that further reduction of the sampling error will require a lot of additional resources for only a small improvement in the mapping error.

For tracklines, this sampling density corresponds to one XBT station each degree of latitude (on nearly meridional sections) and repeat cruises 18 times per year (using the scales in the next paragraph). For a ship traveling at 15 knots a drop every four hours is required, which is usually possible for volunteer observers on ships of opportunity. The accuracy for maps of isotherm depth along the section and in time will be 6.3 m for this sampling density.

The statistical structure required for objective analysis and determination of mapping errors has now been estimated at 95 locations in the tropical Pacific and 107 locations in the tropical Indian Oceans (Meyers et al., 1991; Sprintall and Meyers, 1991; Phillips et al., 1990). Histograms for the depth of the 20°C isotherm show that the statistical structure of the two oceans is remarkably similar (Fig. 4). The space and time scales used for designing a sampling strategy are 3° latitude, 15° longitude and 2 months, and a signal to noise ratio of 0.75. (While a longer time scale might be used in some parts of the Indian Ocean, other areas have a dominant semiannual oscillation which will be undersampled if a longer time scale is used.)

XBT Data Management and Quality Control

Quality control (QC) of the ship of opportunity data at the delayed mode stage is closely supervised by research oceanographers at the Division of Oceanography (Bailey, 1992). A flow chart of the QC procedures is shown in Figure 5. The vertical profiles are checked on a voyage basis for common malfunctions, regional oceanographic features, drop-to-drop consistency along the ship track, and duplicate drops of unusual features (which we encourage our observers to take.) The data are checked against a climatology based on data collected by ships participating in

the CSIRO XBT program. An archive of profiles with unusual features observed along the different lines is used in the QC process. The features are checked with CTD data as opportunities arise.

An interactive editing routine has been set up on the in-house mainframe computer (Silicon Graphics) to edit the data. QC decisions on common malfunctions and real oceanographic features are flagged on the data set (see the Appendix for a list and description of the flags.) The data are further classed (1-4) by depth according to the type of flag associated with the data. Class 1 data is good data. Class 2 data has unusual features, but they are considered to be probably real. Class 3 has features considered to be most likely the result of instrument malfunctions and not real features. Class 4 data are obviously erroneous data.

The data is stored in three archives. The first archive contains the unedited, full resolution, raw data as collected from the merchant ships. The second archive consists of the edited, full resolution data (Class 4 removed). The third data archive has the data condensed to a two meter format (Class 3 removed). This third archive is used for Divisional research, and for the transfer of data to other organisations.

Quality control of the data is considered to start by providing the voluntary observers with continual feedback on why they are collecting the data as well as the results obtained. The two-way communication between observers and researchers inevitably leads to a more carefully collected and generally higher quality data set.

One of my main concerns about data management is that the close connection between researchers and observers will break down as operational agencies replace researchers in the Global Ocean Observing System, and that the quality of the data for research purposes will be decreased. We have already seen this happen in the meteorological community and only recently has the trend been reversed by combining research, operational analysis, modelling, data management and direction of the observing network under one roof at major centers. Perhaps the oceanographic community needs a network of National (or International) Ocean Observatories where all of the work relevant to ocean data and research can be carried out in a coordinated way.

Results on the South Equatorial Current and Throughflow

The XBT tracklines between the Australian northwest shelf and the Indonesian Archipelago provide transects across the headwaters of the South Equatorial Current in the eastern Indian Ocean and the Pacific to Indian Ocean Throughflow. We have prepared a climatology of thermal structure and geostrophic transports on these sections using data collected since 1983 on three tracklines.

Table 1 Number of Transects

	1983	'84	'85	'86	'87	'88	'89	Total
Shark Bay-Sunda Strait	5	6	8	13	22	27	24	105
Djakarta-Torres Strait	5	6	8	11	14	16	21	95
Port Hedland-Japan	0	0	0	10	21	15	10	56

The long-term annual mean temperature sections (Fig 6, A to C) show the baroclinic structure. The individual observations were mapped to a uniform grid by averaging in one degree latitude bins, except near continental boundaries where bins reflected the topography. The thermocline slopes upward from Shark Bay to Sunda Strait indicating net transport toward the west, while the shallow isotherms indicate a shear toward the east . North of Port Hedland, a ridge in the thermocline at 8.5 deg S indicates eastward flow on the northern side of the Indonesian Archipelago and westward flow on the southern side. The zonal section across the Banda Sea indicates southward flow in the Makassar Strait, and southward flow again between Alor Strait and the Arafura Shelf. The relative geostrophic transport (0/400 db) was calculated for these sections using the mean temperature/salinity (T/S) curves from the global ocean climatology of Levitus (1982). The net transport function (i.e., net in the sense that it shows transport between one end and each other grid points along the track) is also shown with the temperature sections. The transport of significant currents was calculated between the peaks and troughs of the net transport functions, and plotted on a map (Fig. 7). The map suggests a net relative Throughflow of about 5 . (1 Sv = 1x106 m3/sec) feeding the eastern end of the South Equatorial Current. These results are in excellent agreement with the estimates of Throughflow by Godfrey (1989) based on historical T/S data and a model.

An important application of routine XBT sampling is to study time variation of temperature and baroclinic structure. The temperature sections and transports were calculated for long-term mean bimonths (January/February, February/ March, etc.). The transports (Figs. 8 and 9) showed that the South Java Current reversed direction twice a year, with a strong eastward flow developing during March-June and a secondary one during October-December. The flow in the South Java Current balances the South Equatorial Current in these seasons so that the net westward relative transport on the Shark Bay-Sunda Strait track is reduced to essentially zero. The maximum relative westward transport occurs during July-October when the Southeasterly Monsoon accelerates the South Equatorial Current. The net southward relative transport across the Djakarta-Torres Strait line is maximum in May-June. The difference between the net westward (Sunda-out) and net southward (Banda-in) transports in fig. 9 shows a distinctive seasonal cycle. During the seasonal cycle, the triangular region of the eastern Indian Ocean bounded by the Indonesian Archipelago, the Arafura Shelf and the northwest coast of Australia acts as a buffer between the Throughflow and the South Equatorial Current, accumulating the warm water during April to June and feeding it into the Indian Ocean during most of the rest of the year.

The mean temperature section and annual variation of relative geostrophic transports on the Shark Bay-Sunda Strait line have been compared to the results of the eddy resolving, global general circulation model of Semtner and Chervin (1988) by T. Qu (Personal communication, 1992). The temperature section (Fig 10) is in very good agreement, except that the model temperature has a deeper and weaker vertical temperature gradient presumably due to the strong vertical diffusivity in the upper water of the model. The annual mean of relative transport across the trackline is 10.8 Sv in the model, in comparison to 5.3 Sv calculated geostrophically from the XBT data and 3.8 Sv in Ekman transports calculated from wind stress. The annual variation of relative transports in the model is in fair agreement with the observed geostrophic transports (Fig. 11), with the model showing the two minima in net westward transport during the Monsoon transitions.

Studies of the surface layer heat budget are usually not possible with observations alone because all of the necessary data are not ordinarily available. One way to study the mechanisms that control the heat budget is to validate models and then investigate the heat budget of the model. A heat budget for the Semtner and Chervin model for the area between the northwest coast of Australia and 13 deg S (Qu, Personal communication, 1992) indicates that the primary control on annual variation of SST is the surface heat flux. However almost half of the fluxes are balanced by advection of oceanic currents (Fig. 12). This suggests that circulation could play a role in the generation of the SST anomalies in some of the critical areas for Australian climate variation found by Nicholls (1989).

Mapping, Modelling and Data Assimilation

At present modelling and data assimilation for the Indian Ocean is being developed at three organisations (to my knowledge).

Table 2: Modelling and data assimilation for the Indian Ocean

Organisation & PI's	Model	Period	Comment
BMRC	GCM-GFDL	1985 to	XBT to be assimilated
R Gardiner-Garden	MOM-Code	1990	Model includes salinity
N Smith	20 levels		
A Moore	2 x 1/2 deg (approx.)		
UKMO	GCM-GFDL	Not yet	XBT to be assimilated
D Carrington	Cox code	started	Model includes fluxes
D Anderson	16 levels		Model comparisons to
		1 x 1/3 deg (approx.)	Geosat
LODYC	Shallow	1985 to	Comparison to Geosat
P Delecluse	water-	1989	Assimilation planned
C Perigaud	One layer		

Modelling and data assimilation for the Indian Ocean probably will require broad scale mapping throughout the basin. The bimonthly, horizontal distribution of XBT stations which is available through the normal TOGA and WOCE channels is too sparsely distributed for this purpose (Pazan and White, 1991). Mapping errors less than 0.7 standard deviations are achieved only along the TOGA/WOCE XBT tracklines (Fig. 13). Recently, new data sets are available which will substantially improve horizontal coverage. Declassified XBT data from the US Navy provides good coverage of the Arabian Sea and the area off the west coast of Australia. The Japan Far Seas Fisheries Agency has provided BT coverage of the Indonesian and north Australian waters since 1967. These data are extremely valuable for modeling and assimilation and the availability should be more timely.

Data centers could do a great service for the research community if they could assist in providing scientific quality control for these and other data collected by operational (non-research) agencies. The quality control procedure that I described earlier is labor intensive, and the staff in research institutes who are capable of this kind of work are usually fully committed to the processing of data collected by their own research projects. In most countries, research funding and resources cannot be directed toward operational and archiving activities. I recommend that data centers work closely with research institutes to provide scientific quality control, even to the extent of stationing center personnel at institutes for long periods of time to expedite the transfer of expertise required for really good control.

Questions

Q. A number of questions on what other countries are supplying XBT data.
A. Data from Japan and France are obtained through the TOGA Subsurface Center. Also the U.S. Navy clarified one question regarding data from other navies. The U.S. Navy has released data as referred to in the talk for U.S. vessels only.

Q. Is the sampling adequate for the type of analyses desired?A. Only where we are doing 18 per year is it really adequate.

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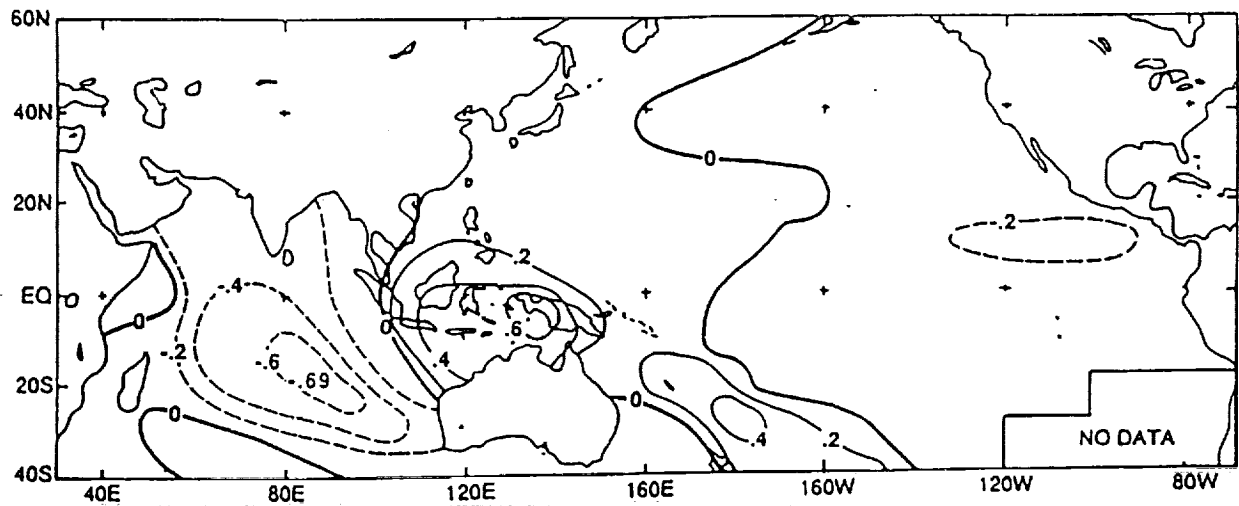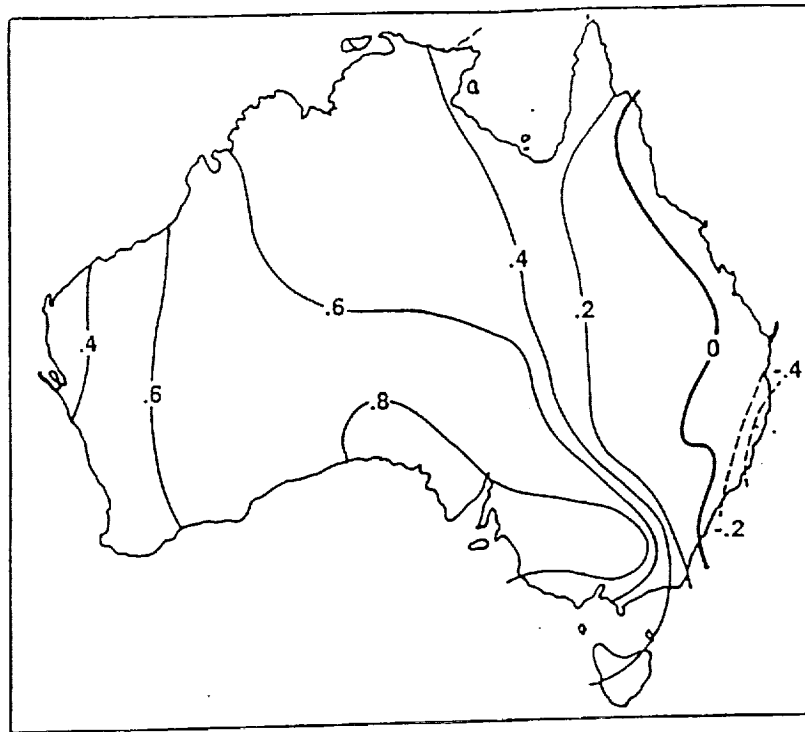
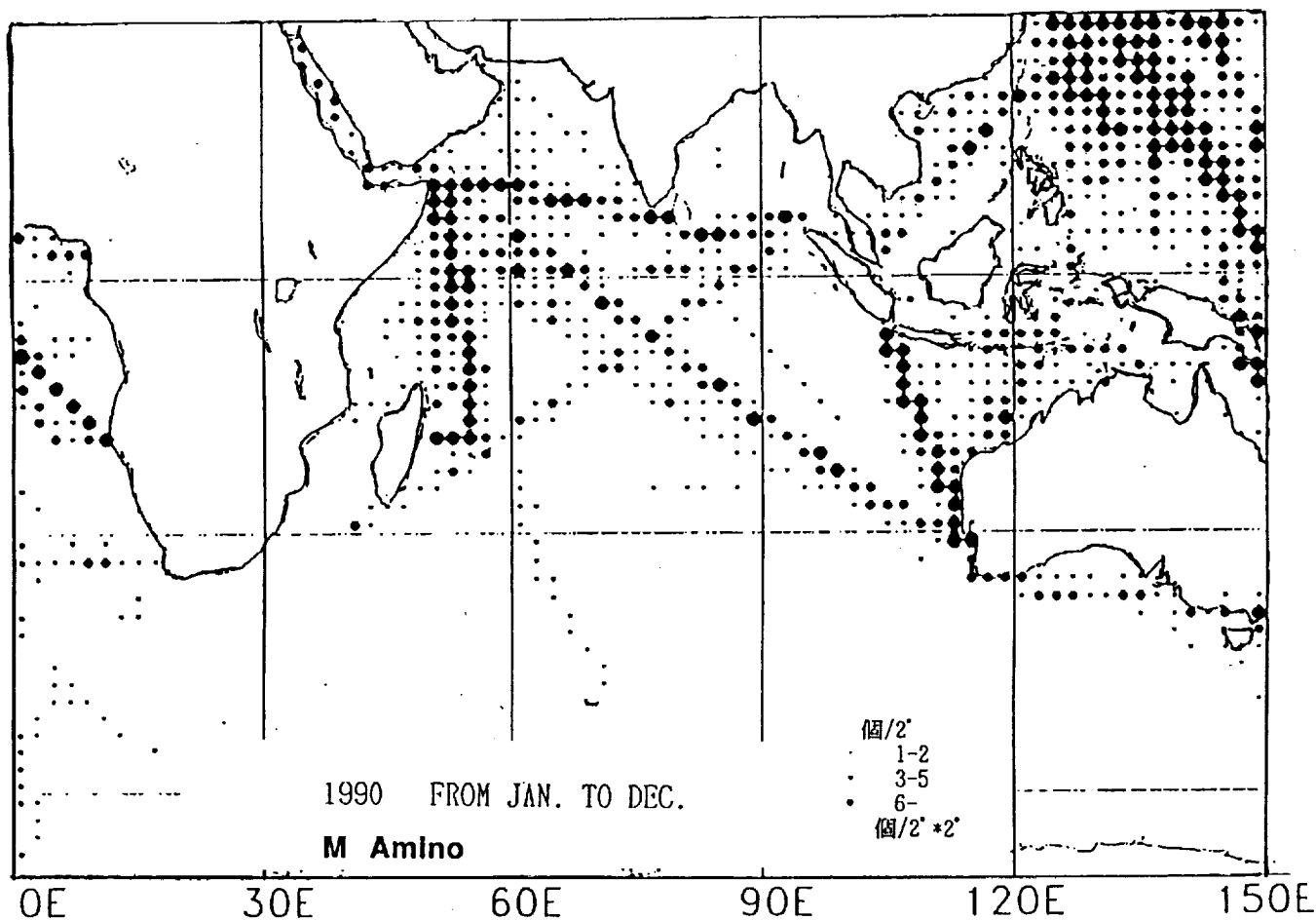*Figure 1. Correlations of district rainfall (top) and sea surface temperature (bottom) with the principal component of Australian winter rainfall (from Nicholls, 1989).*

Figure 2. XBT tracklines in the Indian Ocean during 1990. Number of observations per 2° x 2° square: Large dot >6; Medium dot 3-5; Small dot 1-2. (Prepared by Masaaki Amino at the Japan Meteorological Agency from real time data on the Global Telecommunication System.)

Number of samples per decorrelation scale
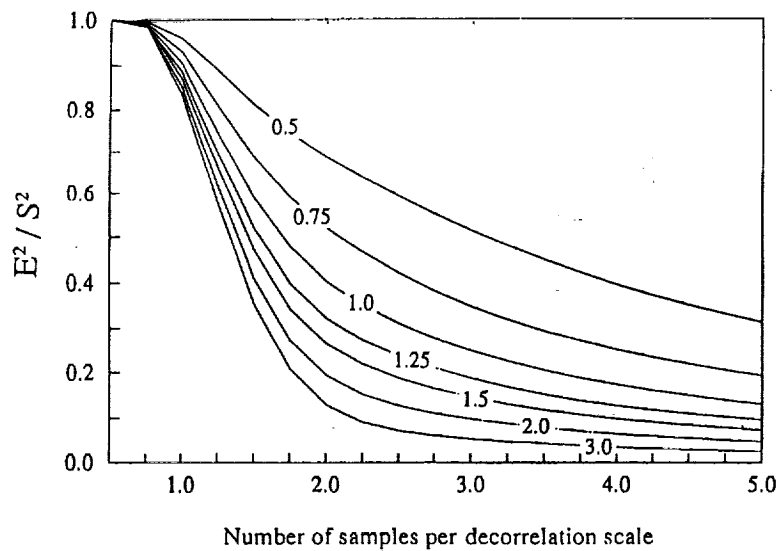
Figure 3. Sampling efficiency curves for a station array which is two dimensional in time and distance along the ship track or in latitude/longitude. The ratio of squared mapping error variance (E2) to signal variance (S2) is a function of sampling density expressed as the number of samples per decorrelation scale. The curves are labeled with signal to noise ratio (S/N, where S and N are standard deviation of the signal and noise variations.)
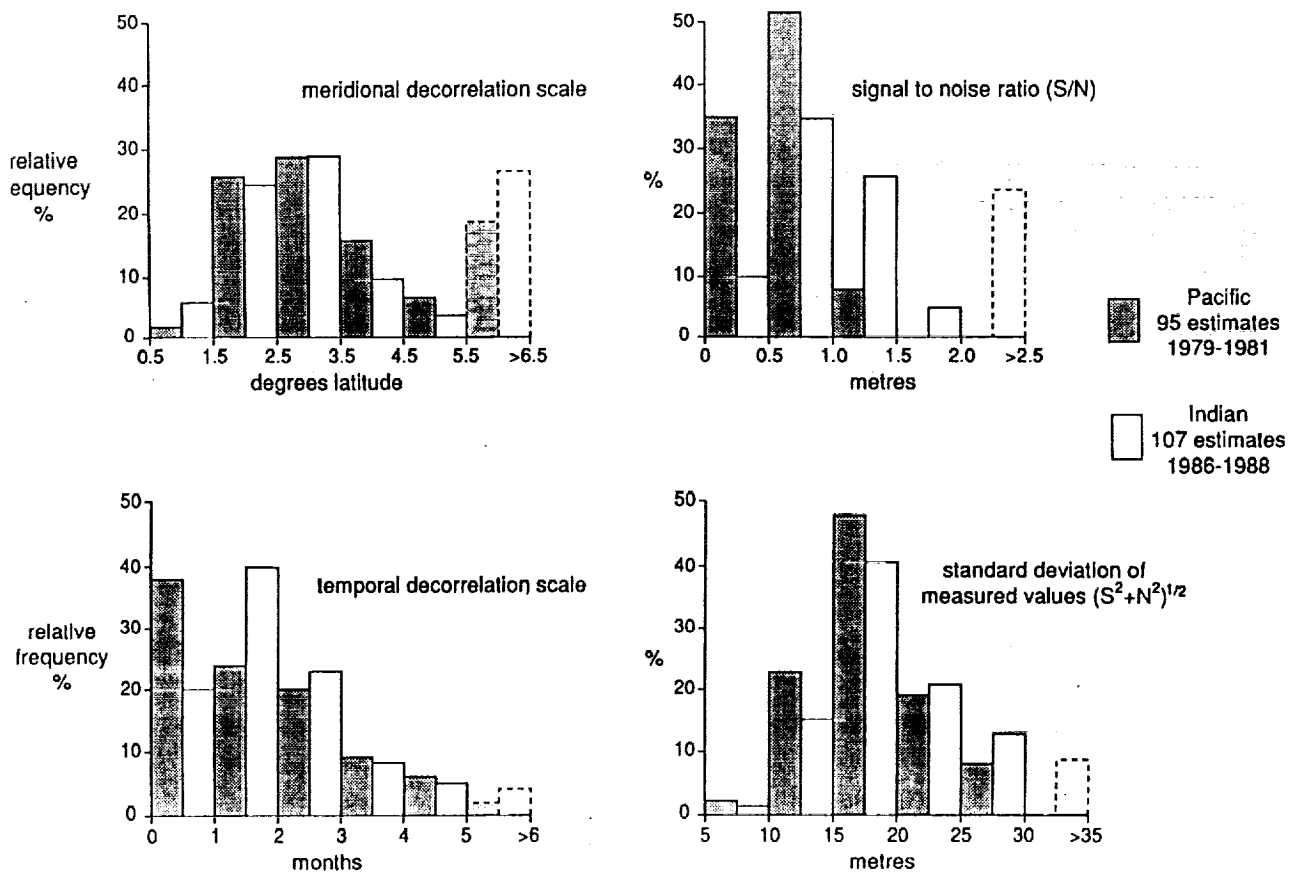
Figure 4. Histograms of the decorrelation scales and variance statistics for optimal interpolation of the depth of the 20°C isotherm for the tropical Pacific and Indian Oceans.

XBT Data Processing
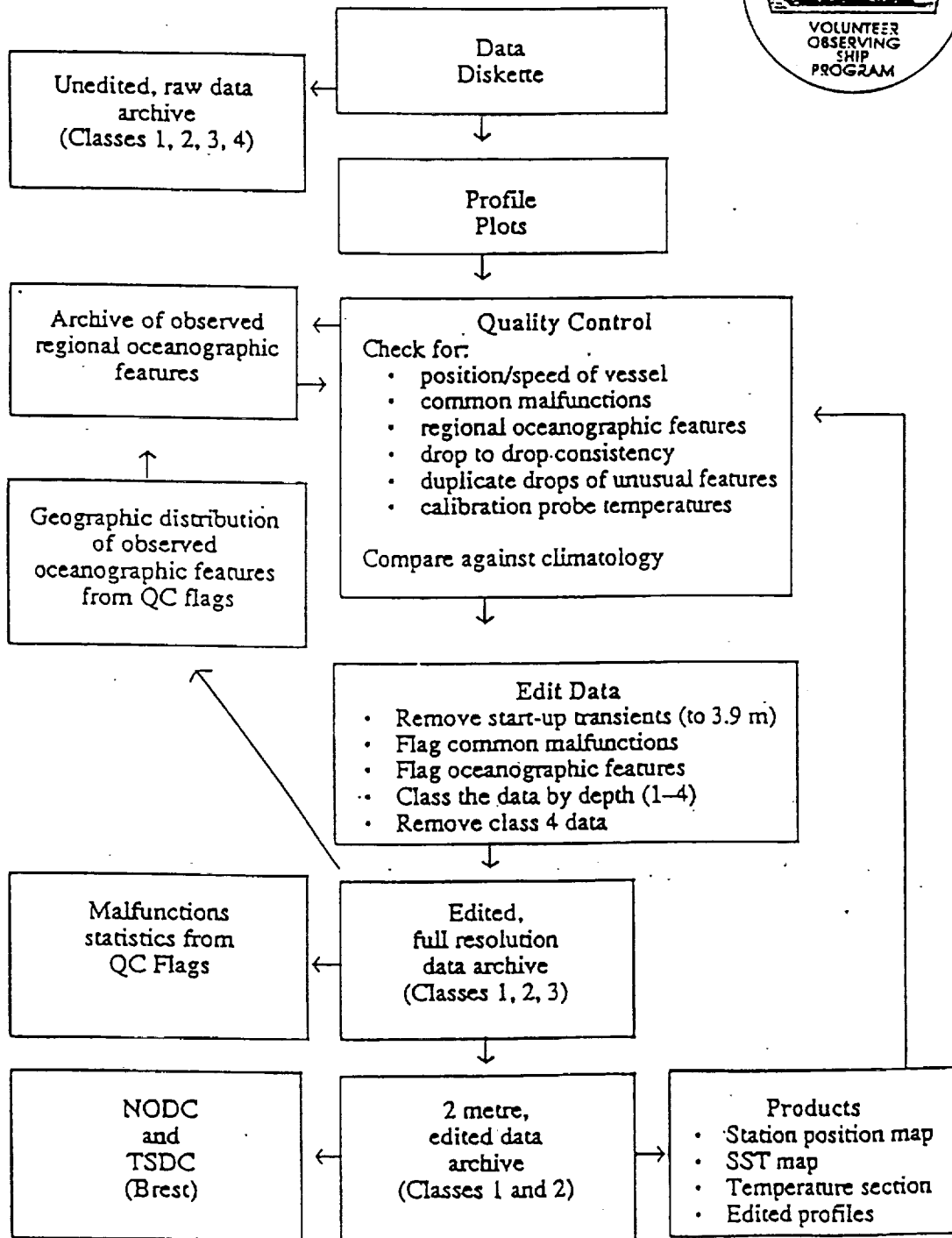
Figure 5. Flow chart for XBT data processing at CSIRO Division of Oceanography (R. Bailey, personal communication)

FREMANTLE - SUNDA STRAIT

MEAN TEMPERATURE

MAY 1983 - OCT 1989   XBTs
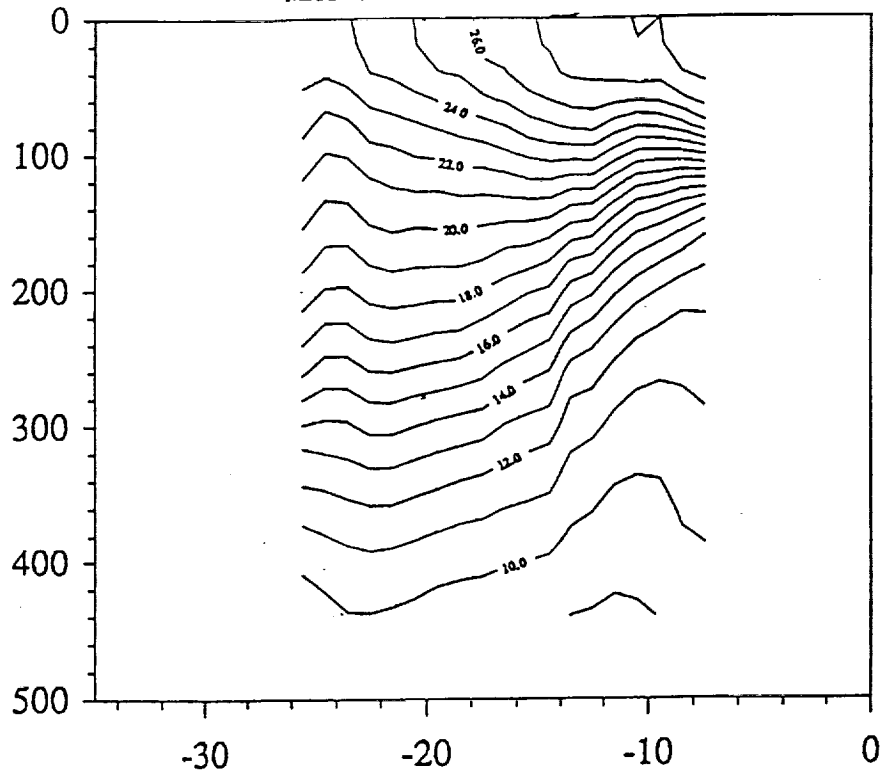
SVERDRUPS
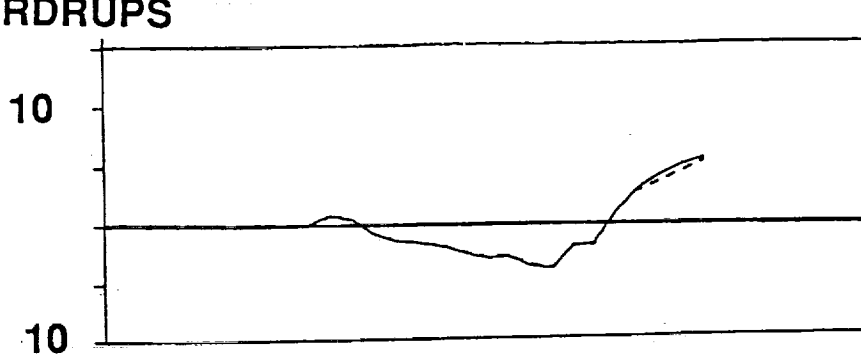
RELATIVE TRANSPORT (0/400 DB)

Figure 6A. Long-term mean temperature section from Shark Bay (25.5°S) to Sunda Strait (7°S). The relative transport function (0/400 db) gives the net transport in 106 m3/s (Sverdrups) between Shark Bay and each point along the section.

BANDA SEA

MEAN TEMPERATURE

JUN 1983 - OCT 1989
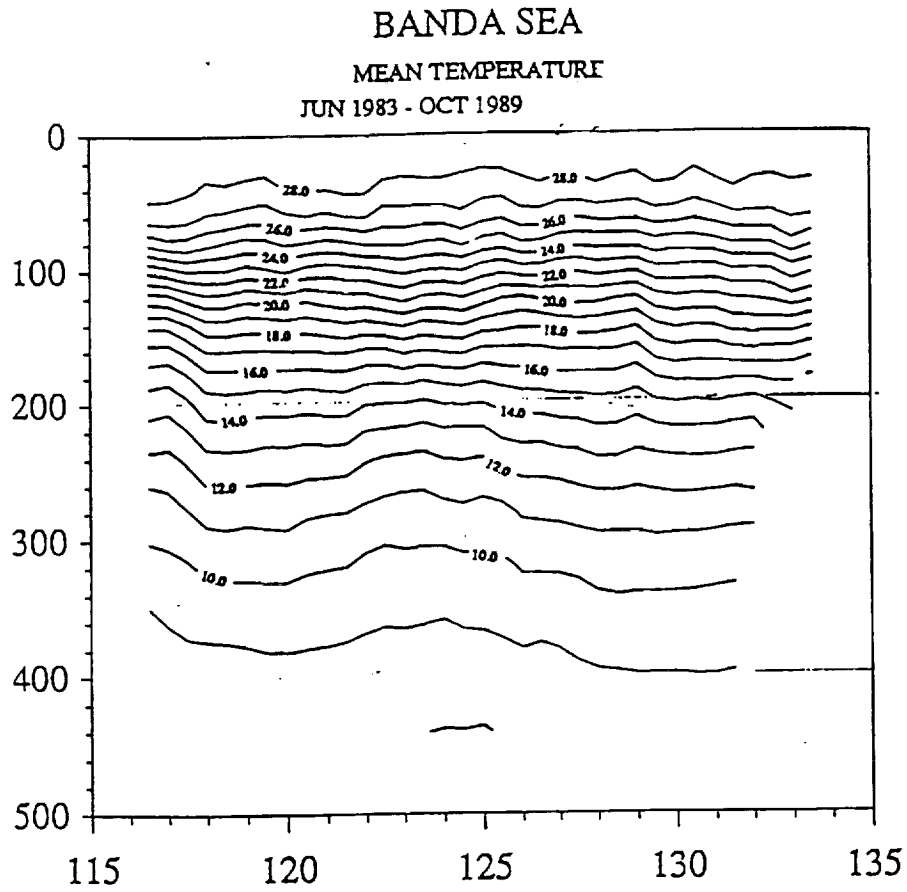
SVERDRUPS
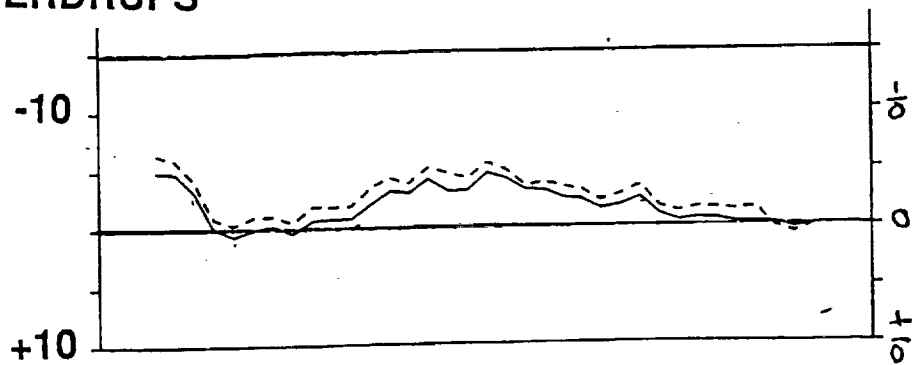
RELATIVE TRANSPORT (0/400 DB)

Figure 6B. As in Fig. 6A for the route from Djakarta to Torres Strait (Note that water depth is less than 100 m west of 116°E and east of 134°E).

PT. HEADLAND - HALMAHERA - MINDANAO

MEAN TEMPERATURE
JUL 1986 - JUL 1989   1190 PROFILES
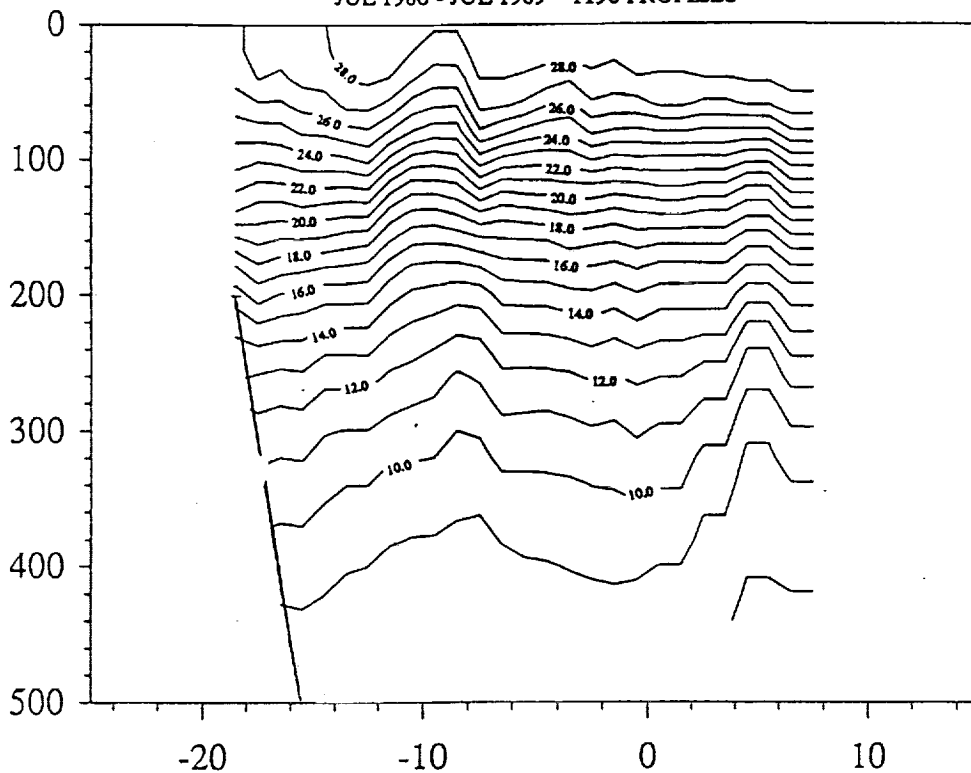
SVERDRUPS
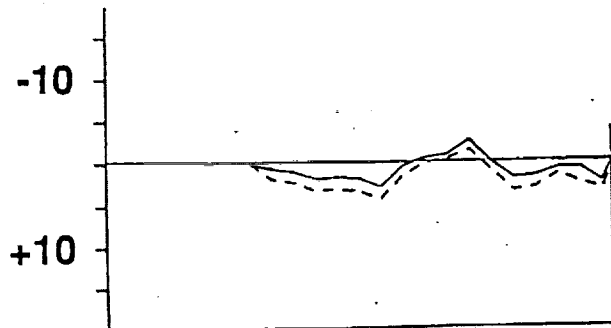
RELATIVE TRANSPORT (0/400 DB)

Fig.ure 6C. As in Fig. 6A for the route Port Hedland to Japan.
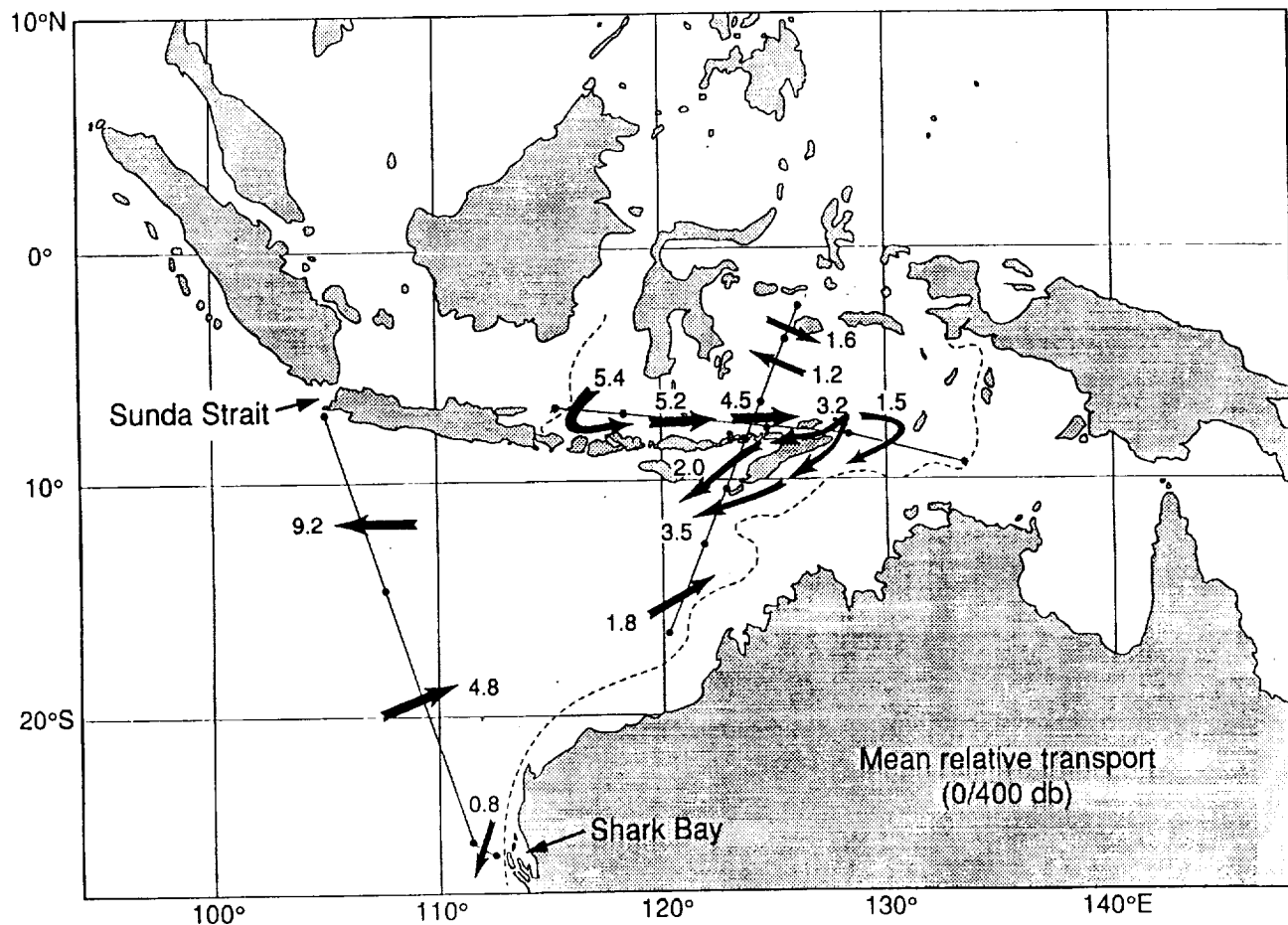
Figure 7. Long-term mean relative transport (0/400 db) in Sverdrups (106 m3/s) estimated from the transport functions in Fig. 6. The boundaries of significant currents are marked by dots.
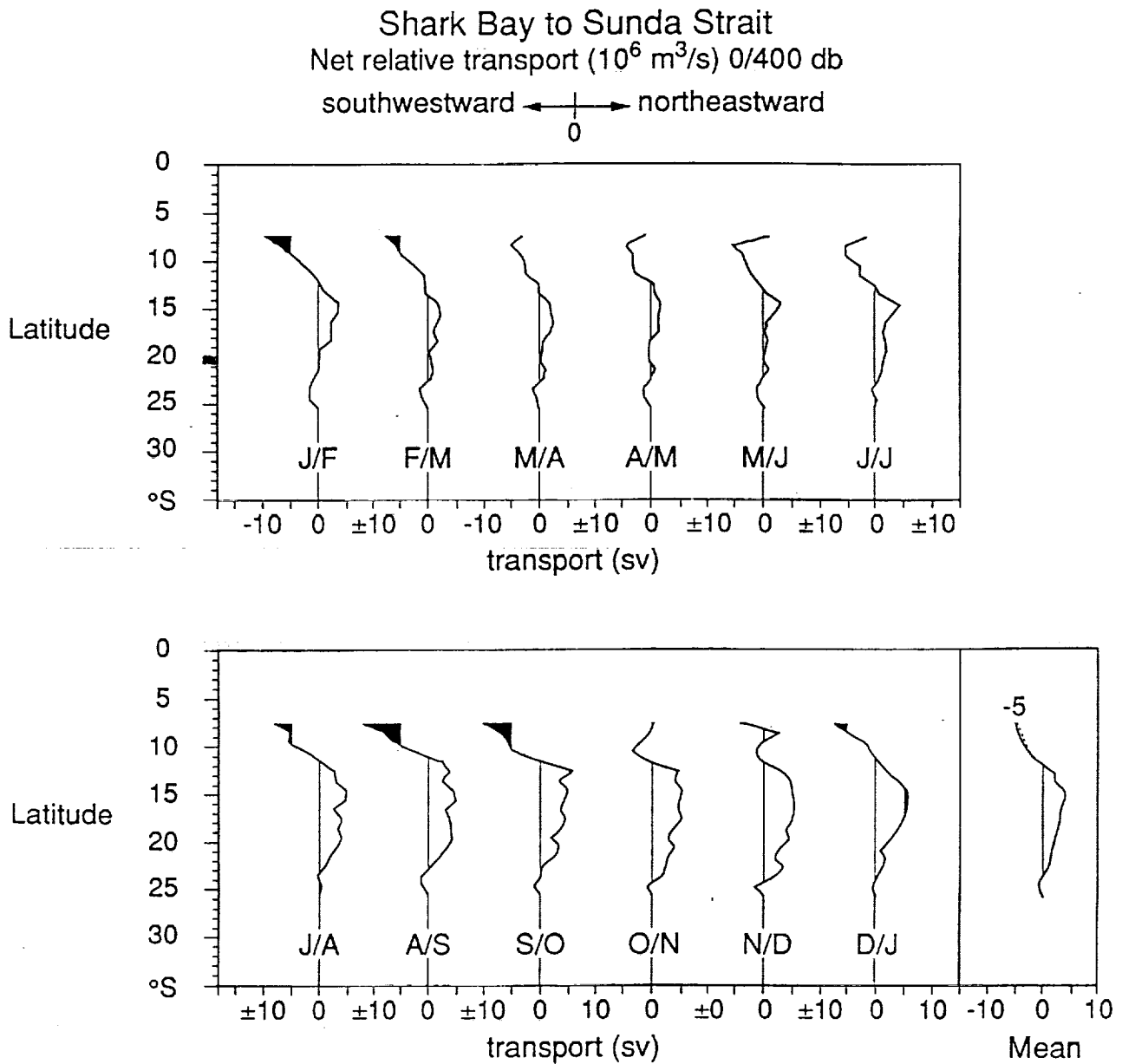
Figure 8. Annual variation of the net relative transport function on the section from Shark Bay to Sunda Strait.
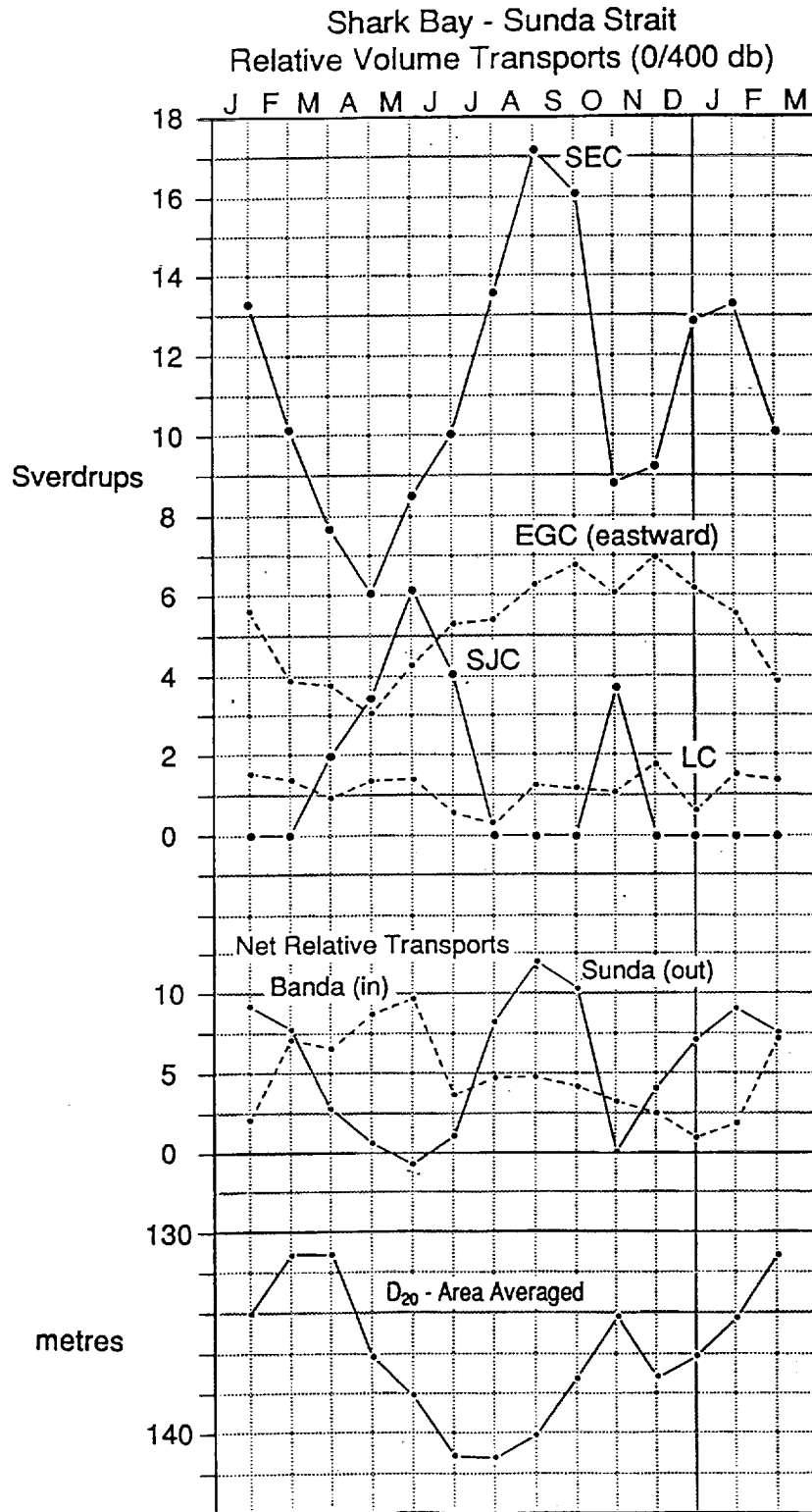
Figure 9. (Top) Annual variation of transport of major currents on the section from Shark Bay to Sunda Strait. South Equatorial Current (SEC); South Java Current (SJC); Eastward Gyre Current (EGC); Leuuwin Current (LC). (MIDDLE) Net relative transport westward on the Shark Bay to Sunda Strait section (solid line labeled Sunda-out), and southward on the Djakarta to Torres Strait section (dashed line labeled Banda-in). (Bottom) Depth of the 20°C isotherm averaged by linear interpolation in the area between Java, Timor and northwest Australia.
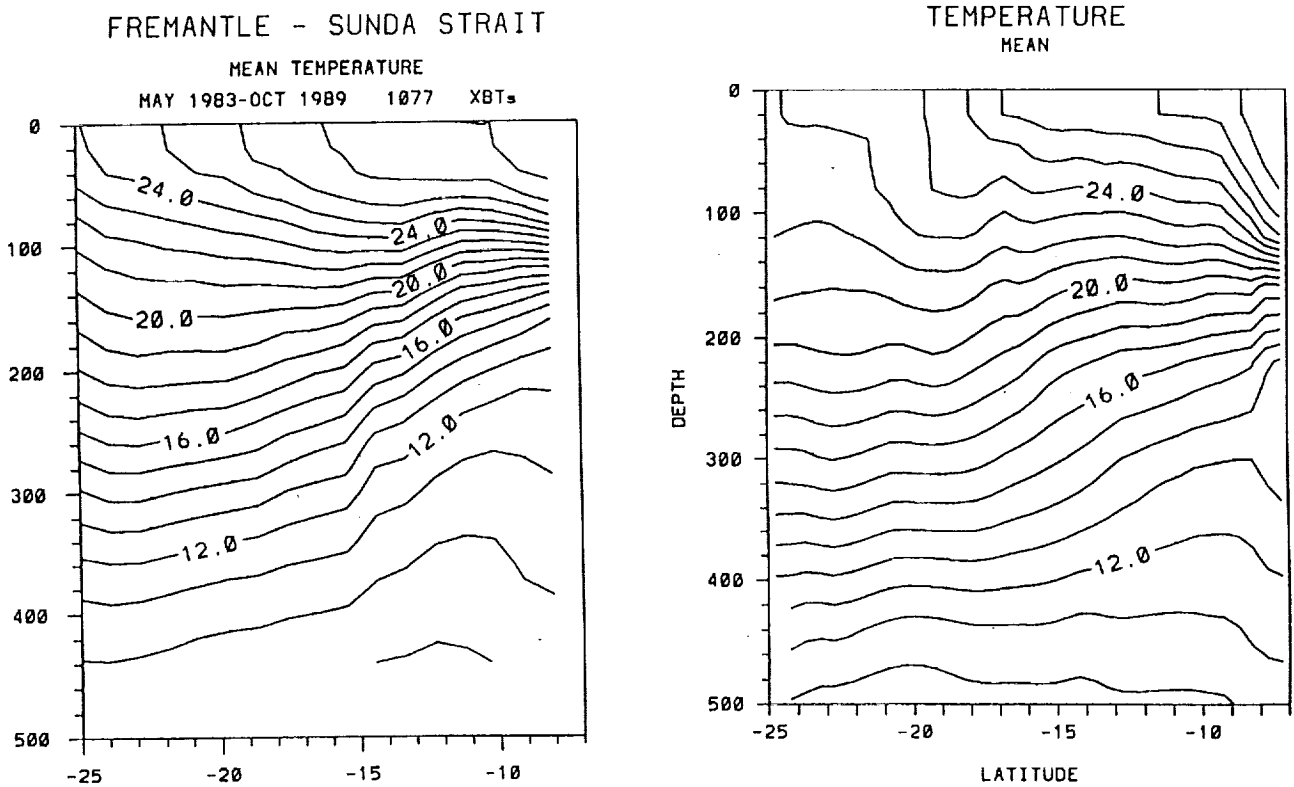
Figure 10. Comparison of the temperature sections from Shark Bay to Sunda Strait from the XBT observations (left) and from the ocean general circulation model (right) by Semtner and Chervin (1988).
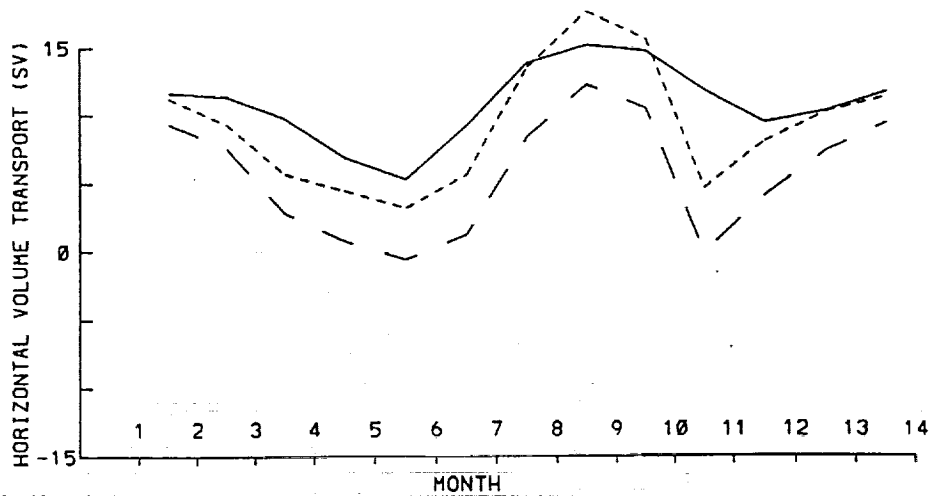

Figure 11. Comparison of transports on the Shark Bay to Sunda Strait section from the XBT observations (long dashed line) and the ocean general circulation model (solid line) by Semtner and Chervin (1988). The XBT transport plus the directly calculated Ekman transport is given by the short dashed line (from T. Qu, personal communication.)
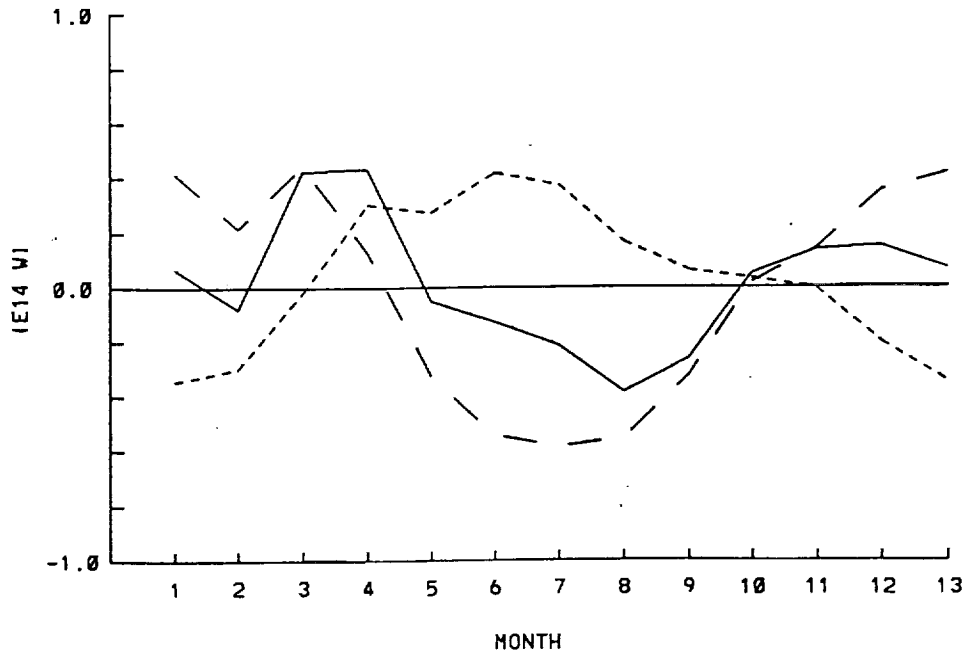
Figure 12. Surface layer (0-50 m) heat budget (in 1014 W) over the area between northwest Australia, 13°S and the Shark Bay to Sunda Strait section. Surface heat flux (long dashed line); heat content change (solid line) and horizontal advection (short dashed line) (from T. Qu, personal communication).
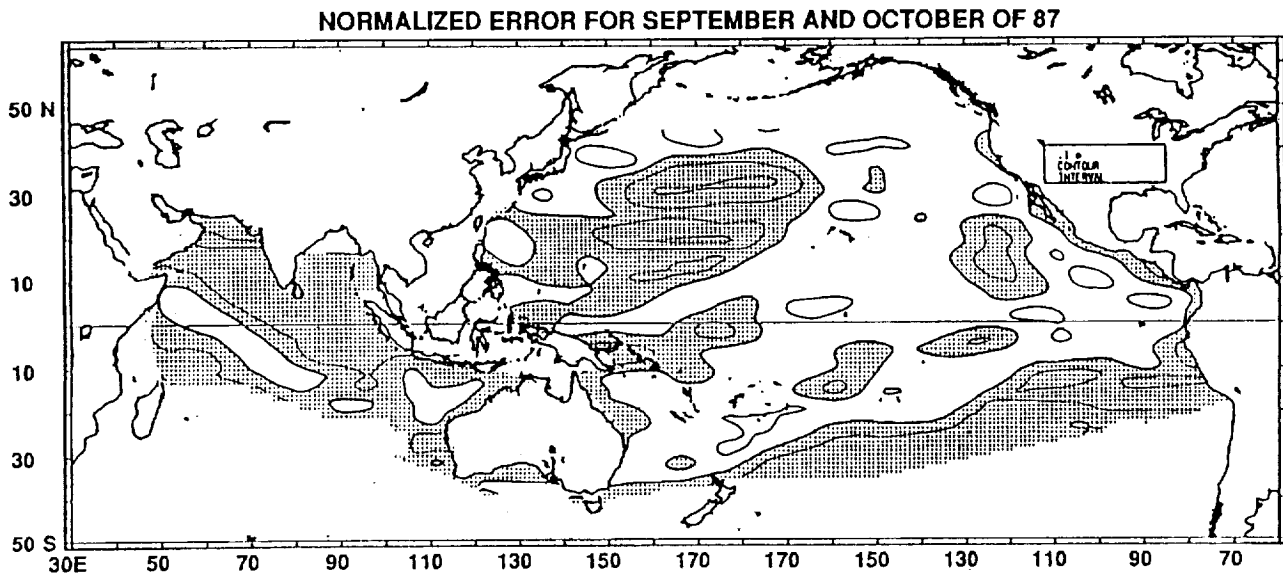

Figure 13. Normalized mapping error for the 400 m vertically averaged temperature anomaly, in standard deviations of the anomaly signal. Errors greater than 0.7 standard deviations are shaded. (from Pazan and White, 1991)