ISSN 0252-1075
Research Report No. RR-095

Contribution from
Indian Institute of Tropical Meteorology

REAL TIME SIMULATIONS OF SURFACE CIRCULATIONS BY A SIMPLE OCEAN MODEL

by

P. RAHUL CHAND REDDY,
P.S. SALVEKAR, D.W. GANER
and
A.A. DEO

PUNE – 411 008
INDIA

JANUARY 2003

Contents

		Page No.
	Abstract	ii
1.	**Introduction**	1
2.	**Model details**	1
3.	**Data and Methodology**	4
4.	**Results and Discussion**	5
	4.a Validations of model simulations.	5
	4.b Validations of Mesoscale gyres.	7
5.	**Conclusions**	7
	Acknowledgments	7
	References	8
	List of Figures	9-17

Real Time Simulations of Surface Circulations by a Simple Ocean Model

P.Rahul Chand Reddy, P.S.Salvekar, D.W.Ganer and A.A.Deo

Indian Institute Of Tropical Meteorology, Pune 411008, India.

Abstract

Ocean models will be fully proved to be well formulated once they reproduce simulations that are totally consistent with the observed circulations. We present here the Simple Reduced Gravity Ocean model, which simulates daily upper layer circulations of TIO† over the region 35E to 115E and 24S to 23N. Model simulated surface currents are obtained by using daily NCEP surface forcings. These computed currents are validated over 19 different positions of TIO viz. over Somali region, west equatorial region, central tropical region, east equatorial region and south bay of Bengal. For this purpose observations of WOCE (World Ocean Circulation Experiment) from six cruise (Research Vessels Knorr and Meteor) during January to October 1995 are used. It is found that model simulated currents are in qualitative agreement with observations but the magnitudes of model currents are 30% under estimated which is mainly because observed currents are about 25-35 meter depth and model simulated currents are depth averaged upper layer (100 mtr) currents. Also, a mesoscale double gyre structure in a diffusive stage simulated by the model during the 1st week of August 1995 is validated with the WOCE observations. The study clearly indicates that model simulated surface currents are a first – order estimate in the data sparse regions.

Keywords: Daily surface circulation, Reduced gravity model, Slice modeling, Twin Gyres, Tropical Indian Ocean.

† --- Tropical Indian Ocean

1.Introduction

The ocean is now well recognized to play a dominant role in climate system. Wind driven upper circulation gives rise to massive, near surface flows such as the Gulf Stream and Kuroshio and Antarctic circumpolar currents. Actual circulation is much more subtle and interesting according to Carlwunsch (2000), yet the ocean has been very much undermeasured for most of the history of ocean science. An unparalleled, united and the first truly global scientific undertaking attempt to understand (and eventually predict) the role played by the oceans in the earth's climate is the World Ocean Circulation Experiment (WOCE) designed by the WCRP (World Climate Research Program multinational research effort established in the 1970's). WOCE has undoubtedly proved that the ocean is turbulent and highly variable Quadfasel (2002). Adequate observations are a prerequisite to test, accept and refute hypothesis, theories and models. Ocean numerical models have become quite realistic as recognized by Semnter (1995) in simulating the seasonal and interannual large-scale circulations.

The basin scale Reduced Gravity 1½ layer ocean model has been proven to simulate realistic circulations on both monthly and seasonal scales as seen by Behera et al (1996, 1998) and Potemera et al (1991). We found that this model does exceptionally well in simulating the surface circulations of the TIO, with the interannual daily NCEP winds, as verified with the observational ADCP (Acoustic Doppler Current Profiler) results of WOCE (e.g.R/V Meteor, Knorr etc.) for a period January-October 1995. It is interesting to note from the daily climatologically simulated currents that there exist westward moving Twin Mesoscale gyres on either side of the equator near central equatorial Indian Ocean during midmonsoon months. WOCE observations are found to be very useful to validate the dissipating stage of such gyres during the 1st week of August 1995. It is now being realized that very simple models, which can be run on relatively inexpensive computers, can provide results different from, but just as useful as those produced by high resolution simulations, Triendl (2002).

It is also a fact that regional and simple models provide insights into understanding minute phenomena when daily forcings are taken into consideration. In the present study model details, data & methodology in brief and validation of model simulated surface currents are discussed. Finally along with the conclusions we suggest a simple method of "slice modeling" that would help to use our model on a global scale.

2.The model details

The model used in this study has one active layer, overlying a deep motionless inactive layer, i.e., zero pressure gradient in the lower layer that effectively filters the fast barotropic mode. The model equations are based on vertically integrated shallow water equations over a layer, assuming no vertical shear in horizontal fields.

The model equations in Cartesian co-ordinate are:

$$U_t + (UU/H)_x + (UV/H)_y - fV + (g'/2)(H^2)_x = A_H \nabla^2 (U) + \tau_{xz} / \rho_1 \qquad (1)$$

$$V_t + (UV/H)_x + (VV/H)_y + fU + (g'/2)(H^2)_y = A_H \nabla^2 (V) + \tau_{yz} / \rho_1 \qquad (2)$$

$$H_t + U_x + V_y = We \qquad (3)$$

Where U and V are zonal and meridional components of transport obtained from vertically integrating upper layer velocity field, f is the Coriolis parameter. H is the upper layer thickness, $g' = g\,(\rho_2 - \rho_1)/\rho_2$ is the reduced gravity. A_H is the horizontal eddy viscosity coefficient and 'τ_{xz} ' ' τ_{yz}' are the components of the wind stress applied as a body force. w_e is a source term representing entrainment from deep motionless layer to the upper active layer. This entrainment is introduced only to prevent the interface from surfacing that happens when a small initial upper layer thickness is considered. This term is positive for upper layer when the layer thickness becomes less than a pre-set minimum depth *Hmin.* The term is determined through a simple function as suggested by McCreary and Kundu (1988). The effect of this entrainment on the upper layer density, momentum and kinetic energy balance has been neglected. It is assumed that the entrained water engulfed into the upper layer, has zero velocity and is instantaneously adjusted to the density ρ_1. The values of various parameters and constants used in this study are listed in the Table 1.

Parameters	Symbol	Value
Reduced gravity	g'	0.03ms $^{-2}$
Initial upper layer thickness	Ho	100 m
Minimum upper layer thickness	Hmin	75 m
Grid length	ΔX and ΔY	28 km
Time step	Δt	30 min
Density (air)	ρ_a	1.2 kg m $^{-3}$
Density(water)	ρ_1	1026 kg m $^{-3}$
Drag coefficient	C_D	1.25*10 $^{-3}$
Initial phase speed	Co= (g'Ho) $^{1/2}$	2.45 ms $^{-1}$
Entrainment time	τ_e	8 hr
Eddy viscosity coefficient	A_H	2250 m ^{2} s $^{-1}$

Table 1.Parameters used in the model.

The model equations are solved numerically on a finite difference mesh staggered in space (Arakawa C-grid) and integrated with respect to time using leapfrog finite-difference scheme. An Euler scheme is applied at every 49th step to eliminate the spurious growth that usually arises due to time splitting in leapfrog scheme. The horizontal domain used in the model extends from 35°E to 115°E and from 24°S to 23°N (Fig.1). Boundary conditions are no slip *(U = V =0)* at land boundaries and modified radiation boundary condition by Camerlengo and O'Brien (1980) and Jensen (1990) is applied at the open boundaries. The reduced gravity model has realistically simulated most of the circulation features in the Indian Ocean as referred by Luther *et al.* (1985), Simmons *et al.* (1988), Luther and O'Brien (1989).

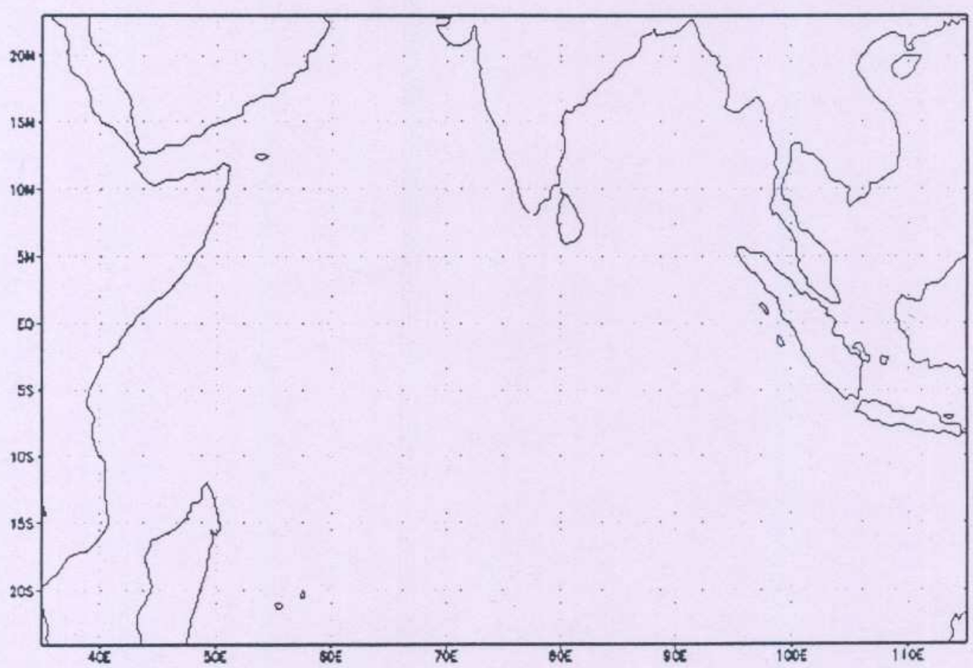


Fig.1. The Tropical Indian Ocean Model geometry.

3.Data and Methodology

The model is integrated by using daily climatology of NCEP winds from 1992-1998 and the spin up time to reach the steady state is 10 years. Model is further integrated from Jan 1992 to Dec1998 using daily interannual surface forcings. WOCE had deployed R/V to record the various parameters (of which surface circulations was one) over the tropical Indian Ocean during Jan to October 1995,hence the model simulations for the year 1995 have been considered for validation. Observations over19 different positions viz. over Somali region, west equatorial region, central tropical region, east equatorial region and south bay of Bengal are used to validate the model simulations. The cruise details like the Cruise name, start date, End date, Longitude range and Latitude range are given in the table below.

Case No.	Cruise Name (R/V)*	Start Date	End Date	Longitude Range	Latitude Range
Case 1	KNORR	1995/01/24	1995/03/05	079.67E-115.75E	32.05S-19.76N
Case 2	KNORR	1995/03/12	1995/04/14	079.99E-115.37E	34.01S-02.85N
Case 3	METEOR	1995/06/08	1995/07/10	050.00E-059.49E	04.54S-16.93N
Case 4	KNORR	1995/07/15	1995/08/23	051.42E-065.54E	20.12S-26.42N
Case 5	METEOR	1995/09/22	1995/10/27	058.53E-068.63E	10.46S-23.85N
Case 6	KNORR	1995/09/30	1995/10/13	079.62E-097.55E	04.50N-09.99N

Table 2. The cruise details of the WOCE ships.
***R/V-Research vessel**

4.Results and discussion

4(a) Validation of Model simulations.

We begin with the validation results. The observed currents from all the WOCE cruises considered here, are 25 to 35m depth. Model simulated currents are compared with three positions of all six cases of cruises. The tracks of 6 cruises are shown in Fig.2, the locations are marked from a to r. The detailed comparison is provided below.

Case 1 as seen in fig.3: from 24/01/1995 to 5/3/1995 (East Indian Ocean)

(a) Around 1st march at 9N-88E a westward movement of the surface currents on the eastern side of the Sri Lankan island is noticed in both the model simulations and WOCE results.
(b) Around 24th Feb at 3N - 95E a North Eastward movement is recorded as well as simulated near Kepulanuan Banyak.
(c) Around 9th Feb. 1995 between Eq-5N and at 92E the surface currents show a strong North of Northwest movement and are perfectly matching with simulations.

Case 2 in fig.4: from 12/3/1995 to 14/4/1995(Mid South Indian Ocean)

(d) Around the 16th March 1995 at 1S and 80E the WOCE results show a Westward movement of the surface currents and model simulations suggest the same.
(e) On the 21st March 1995 at 10S-81E westward movement of the surface currents with lesser magnitudes is recorded as well as simulated.
(f) On 26th March 1995 near 20S –80E Southwest movement of the surface currents with low magnitudes is recorded. The simulated currents agree not only with directions but also with magnitudes.

Case 3 in fig.5: from 8/6/1995 to10/7/1995 (Somalian Gyres)

(g) Around 4th June1995 at 3S-58E Eastward currents are observed just above Seychelles and in this case the model currents are exactly simulated.
(h) Around 9th June 1995 at 1S-53E Southeast surface currents detected in the Owen fracture zone and similar currents are seen in the model currents.
(i) Around 14th June 1995 at 4N-52E strong southwest currents are simulated in the model results and are matching exactly with the WOCE observations.

Case 4 in fig.6: from 15/7/1995 to 23/8/1995(Somalian Region)

(j) Around 14th July 1995 at 20S-55E southwest currents with low magnitudes are detected along Mauritius trench and simulations are in good agreement.

(k) Around 13th August 1995 at 9N-64E South East currents with low magnitudes are detected in the south Arabian basin / west equatorial Indian Ocean as seen in both the results.
(l) Around 18th August 1995 at 17N-61E South East currents with low magnitudes are observed in the Gulf of Masira and the simulated current has low magnitude in this case.

<u>Case 5</u> in fig.7: from 22/9/1995 to 27/10/1995 (Somalian Region)

(m) Around on 17th Oct 1995 at 8N-64E Southwestward turning currents with very low magnitudes are noticed both in the observations and in the model results, along the Carlsberg ridge.
(n) Between22nd and 23rd Oct 1995 Eq-3N along 62.5E very strong South Eastward currents simulated by the model are in total agreement with the observed currents.
(o) Around 0n 27th Oct 1995 at 10S-59E Southwest currents are detected and simulated, by WOCE and by the model respectively.

<u>Case 6</u> in fig.8: from 30/9/1995 to 13/10/1995(South Bay Of Bengal)

(p) Around 2nd Oct 1995 at 10N, 90E WOCE results show currents moving off the Dondra Head North of North Eastwards rather with higher magnitudes. This is well simulated by the model.
(q) On 7th Oct 1995 at 10N-88E we see strong northeast currents in the Andaman Sea both in the observations and model results.
(r) On 12th Oct 1995 at 5N-82E Northeast currents are detected by WOCE and are again well simulated by the model.

From the above discussions it can be said that the model does simulate the observed currents with a reasonably good accuracy, except near the coast. Even though the directions of the surface currents tally completely, the magnitudes (as seen in the figure: at the bottom of each panel) of the simulated currents are found to be 30% less than the observed currents. This is easily seen from the case 5(a) in which the model currents have a magnitude of 10cm/s where as the observations show 30 to 40cm/s, as denoted by the magnitudes scales. Same is found for all the other validations. This is expected since the WOCE observations are taken at depth of 25-35m where as the model currents are upper layer depth averaged.

4. (b) Validation of Mesoscale gyres.

Qualitative features of a mesoscale double gyre structure in the model simulations also tally with the WOCE observations. The observations of R/V Malcom Baldridge in the TIO near 64E-70E,Eq-5N for 3/08/1995(Fig 9(a)) presented with the zoomed figure for the same region Fig.9 (b) support the model simulated currents for the same day using NCEP forcing (Fig 9(c)).

5.Conclusions

Comparison of the model simulated daily currents and WOCE observations clearly indicate that the model performs extremely well over tropical Indian Ocean. The model simulations match qualitatively with the WOCE results in the sense that the directions are consistent but the model underestimates the magnitudes by 30%. This is expected because the model currents are depth averaged where as the WOCE currents are recorded between 25 to 35m.The model is also able to simulate the observed mesoscale phenomena like the twin gyres that are found to occur in the TIO during the midmonsoon months. In view of these results it can be said that if one wishes to study the surface circulations over the data sparse regions (in the open ocean), this model could be used with confidence for qualitative understanding. Further, this simple model can be used to study surface circulations over the other parts of the globe by changing the boundary conditions. It is well known that Tropical Meteorology is different from Extra tropical Meteorology and to understand air sea interactions for the study of Tropical climate, observations over the Tropical Ocean are very much essential, with this point of consideration it may be useful to consider a "slice modeling" technique, in which the global ocean can be sliced into smaller regions and this model can be separately applied over them. To obtain the upper layer circulation over the entire globe over certain time period, the model-simulated circulation over different small regions, which can cover entire globe, can be analyzed. With this type of experiment one can study the global ocean circulation with reasonably good accuracy using simple ocean model that requires less computer time and memory as compared to the use of GCM's. The resolution of the model can be made finer to simulate small scale features, as the influence of meso-scale process on large-scale processes is just beginning to emerge, but may lead to a radical change in ocean modeling as proposed by Quadfasel (2002).

Acknowledgements

The first author is thankful to the Director IITM, Dr.G.B.Pant, for allowing me to work the Research work respectively.

Corresponding author:
Dr. (Mrs.). P.S.Salvekar,
Email: pss@tropmet.res.in

References:

Behera S K., Salvekar, P S, 1996: Development of Simple reduced gravity ocean model for the study of upper North Indian Ocean.*IITM Research Report* – 072.

Behera S K., Salvekar P S, 1998: Numerical investigation of Coastal Circulation around India.*Mausam* 49: 345 – 360.

Carlwunsch, 2000: Moon, Tides and climate, *Nature* 405:743-744.

Camerlengo and O'Brien, 1980: Open boundary conditions in rotating fluid, *J.Comp.Phys* 35:12-35

Jensen T D, 1990: A numerical study of the seasonal variability of the Somali current, PhD dissertation, and Florida state university pp: 21.

Luther and O'Brien. 1989: Morphology of the Somali current system during southwest monsoon: couples ocean – atmosphere models, Ed.J.C.J. Nihoul, Elsevier Science publication.

Luther et.al, 1985: Modeling the variability in Somali current, Meso scale /synoptic coherent structure in Geophysical turbulence: Ed.J.C.J, Nihoul and B.M.Jamart, Elsevier Science publication.

McCreary and Kundu, 1988: A numerical investigation of the Somali current during southwest monsoon, *J.Mareine Res* 46:25-28

Potemera et.al, 1991: The seasonal circulation of the Upper Ocean in the Bay of Bengal. *J.Geophy.Res.***96:** 12667 – 12683

Triendl R, 2002: Our virtual planet, *Nature* 416:579-580.

Quadfasel, 2002: Ocean circulation & Climate :Observing and modeling the global ocean, *Nature* 415:20-21

Simmons *et al,* 1988: Verification of a numerical ocean model of the Arabian Sea, *J.Geophys.Res* 96:20,449-20.

Semnter, A J, 1995: Modeling Ocean Circulation. *Science* **269:**1379 – 1385.

List of Figures

Fig.1. The Tropical Indian Ocean Model geometry.

Fig 2. The tracks of the six cruises being considered for validation, the enclosed circles denote the points (a to r) with which the model simulations are compared

Fig.3. Left panel shows the WOCE vector plots of the currents, the Right panel shows the model simulations as a, b and c (case 1).

Fig.4. Same as fig.3 except for the case 2 and for d, e and f.

Fig.5. Same as fig.3 except for the case 3 and for g, h and i.

Fig.6. Same as fig.3 except for the case 4 and for j, k and l.

Fig.7. Same as fig.3 except for the case 5 and for m, n and o.

Fig.8. Same as fig.3 except for the case 6 and for p, q and r.

Fig.9. (a) Is the vector plots of surface circulations (25m to 35m) from the WOCE along 50E-80E, 10S-30N during July – August 1995. (b) A zoomed view (65E-70E,Eq-5N) for 3/08/1995 (c) The model simulated surface currents along 64E-70E,Eq-5N for 3/08/1995.

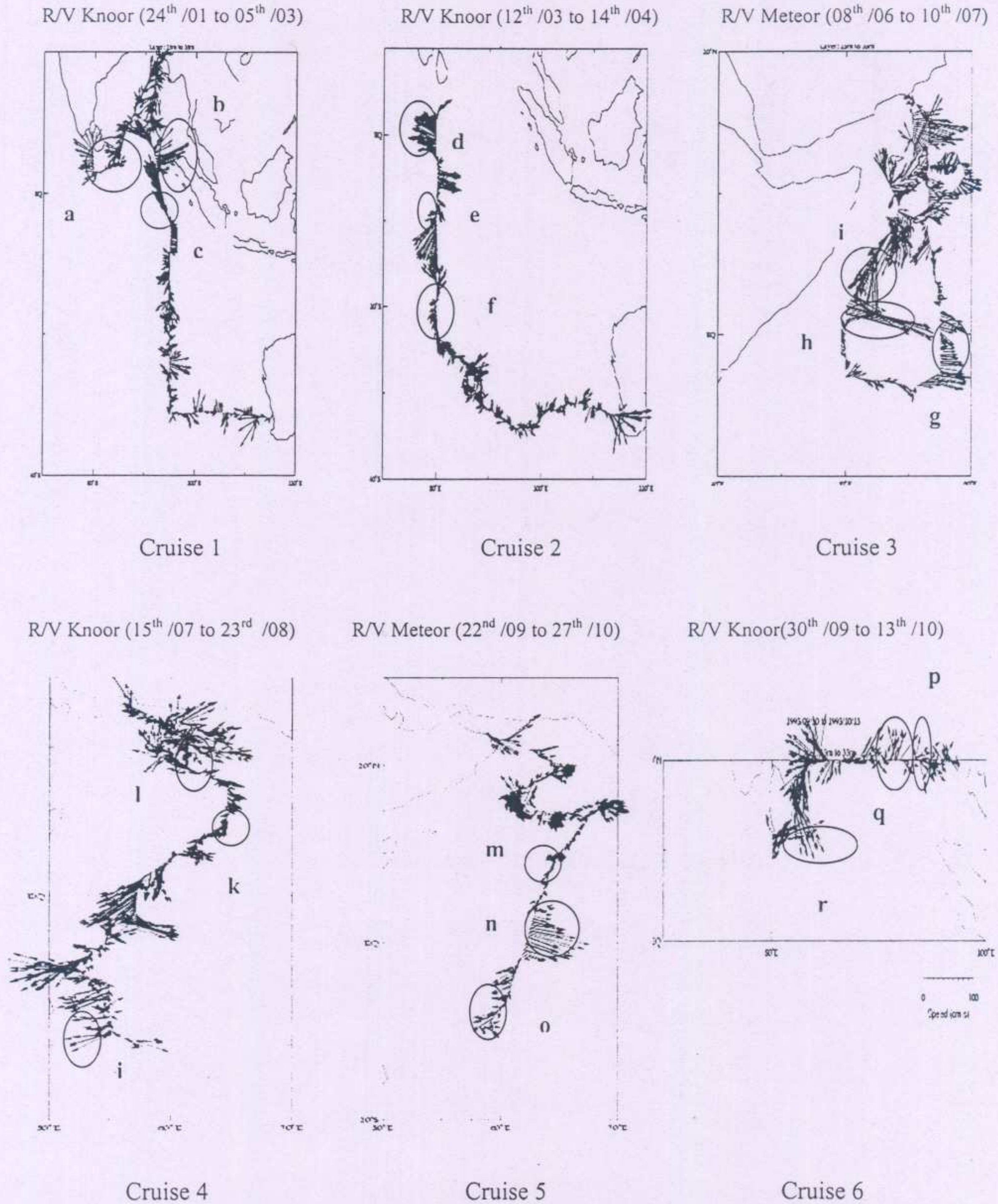


Fig 2. The tracks of the six cruises being considered for validation, the enclosed circles denote the points (a to r) with which the model simulations are compared during the year 1995, the dates are indicated on the top of each panel (for details see Table 2).

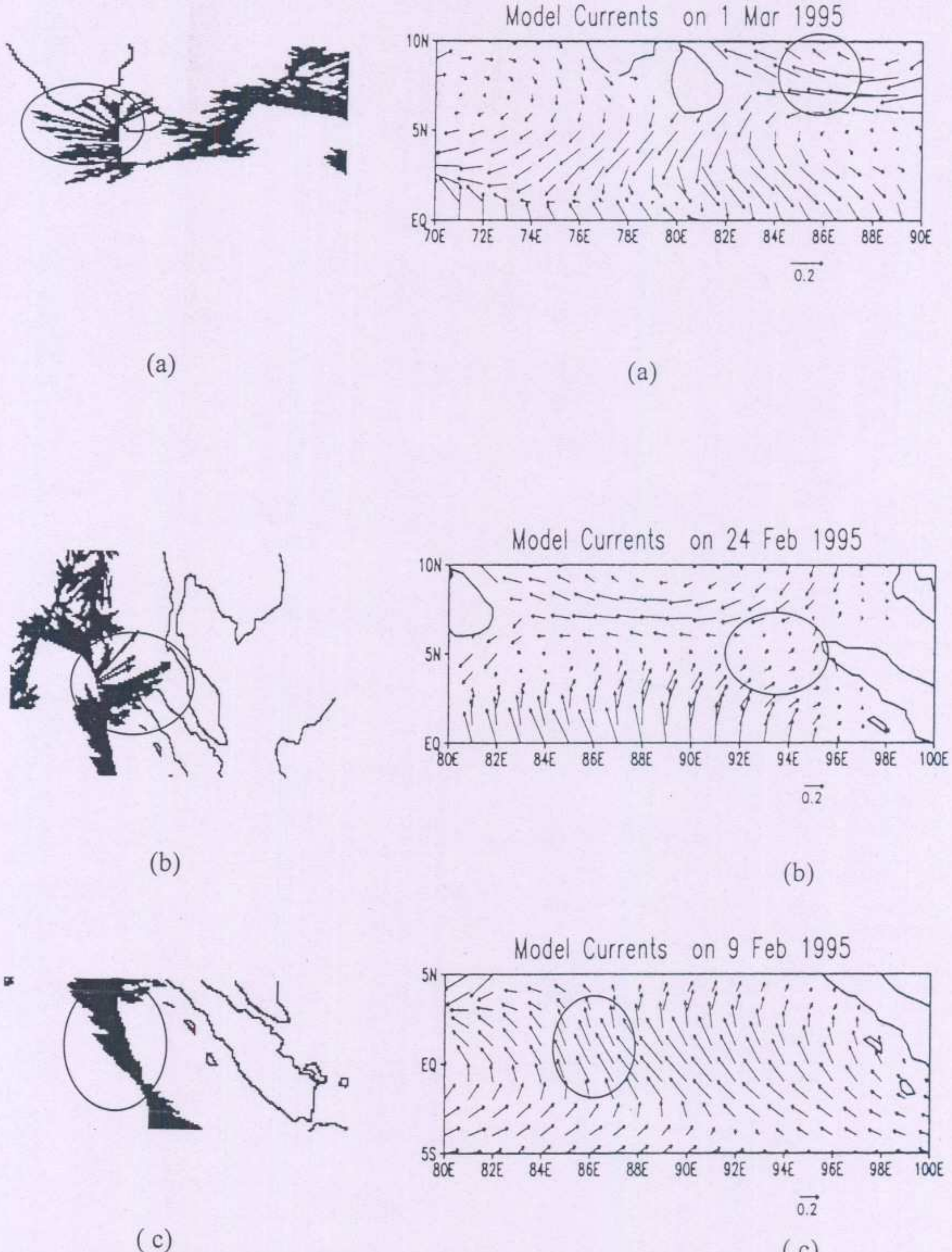
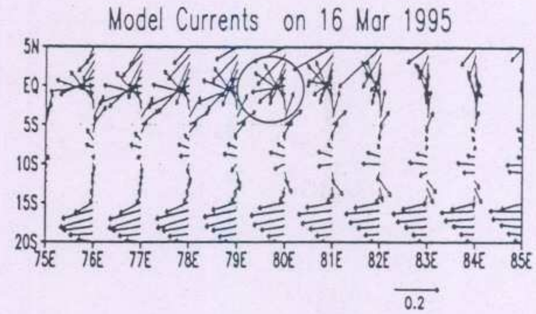
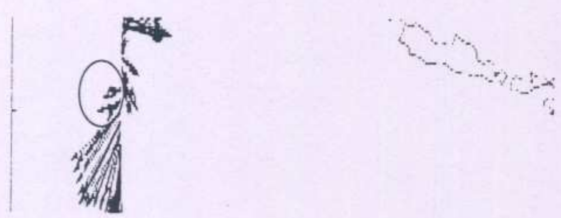
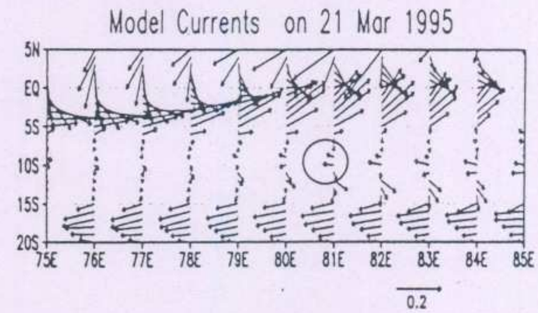


Fig.3. Left panel shows the WOCE vector plots of the currents, the Right panel shows the model simulations as a, b and c (case 1).

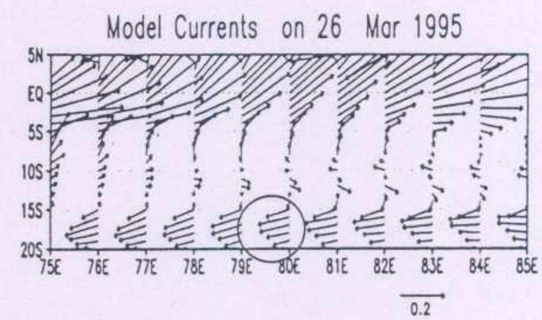


(d) (d)



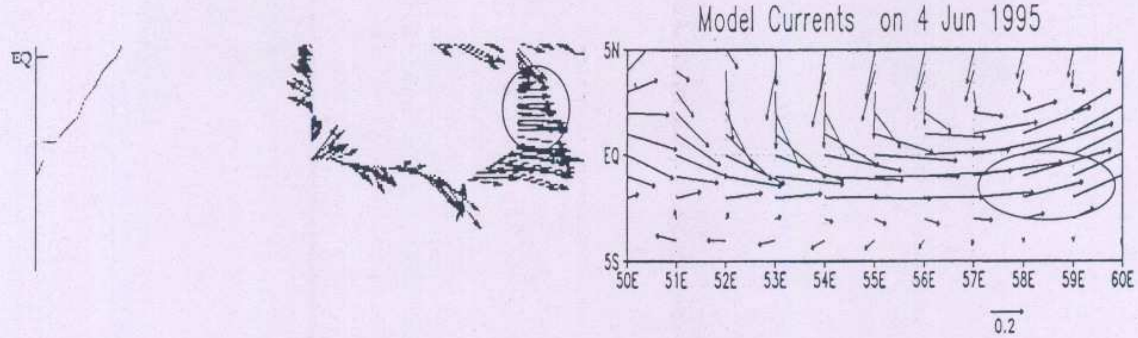


(e) (e)

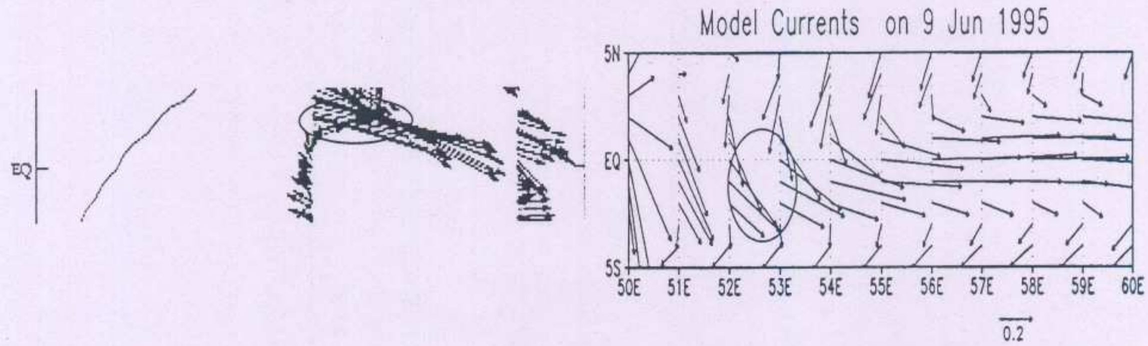


(f) (f)

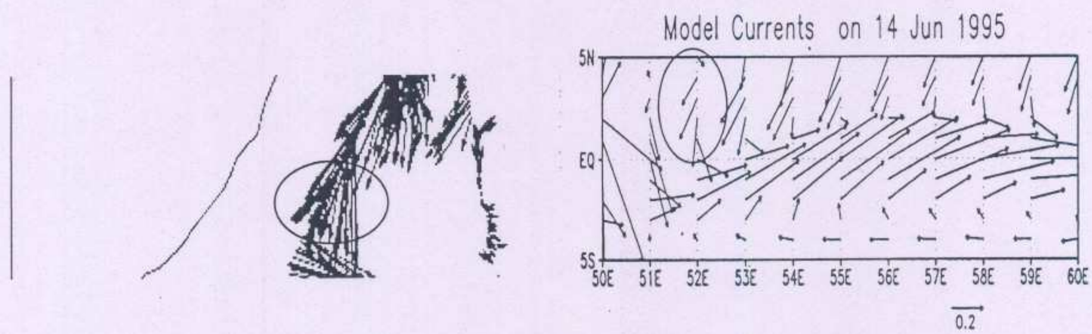
Fig.4. Same as fig.3 except for the case 2 and for d, e and f.



(g) (g)

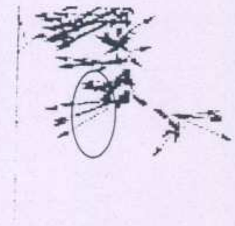


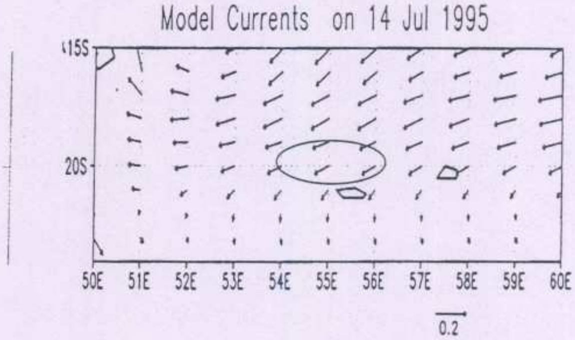
(h) (h)



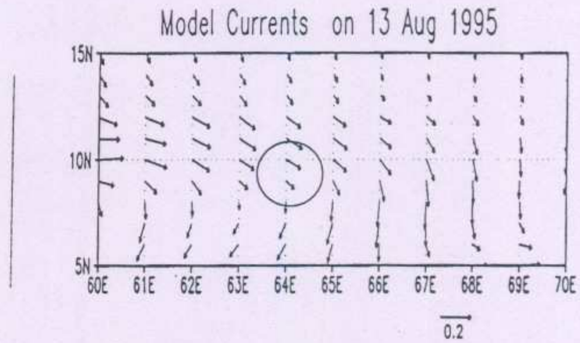
(i) (i)

Fig.5. Same as fig.3 except for the case 3 and for g, h and h.

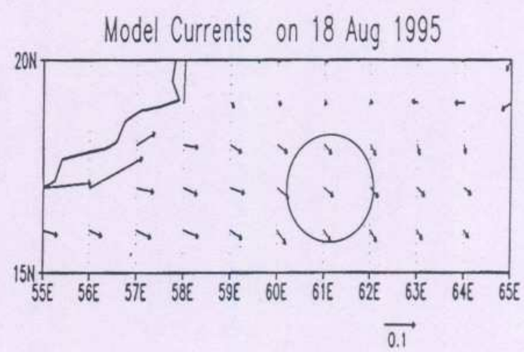




(j) (j)

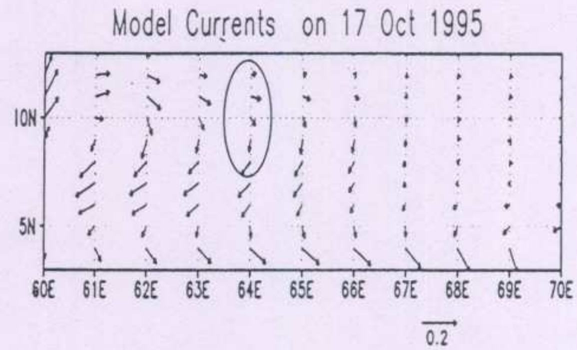


(k) (k)

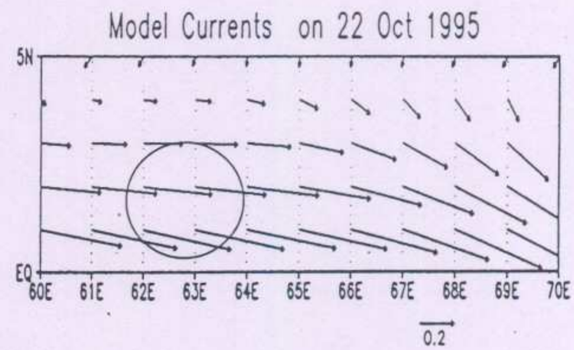


(l) (l)

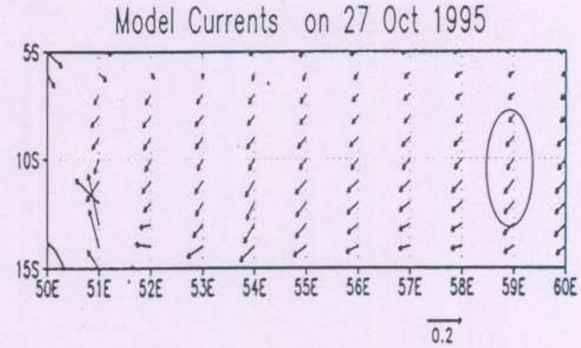
Fig.6. Same as fig.3 except for the case 4 and for j, k and l.



(m) (m)

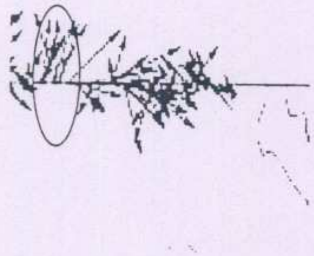


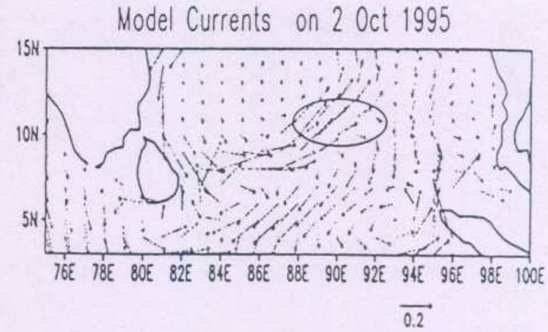
(n) (n)



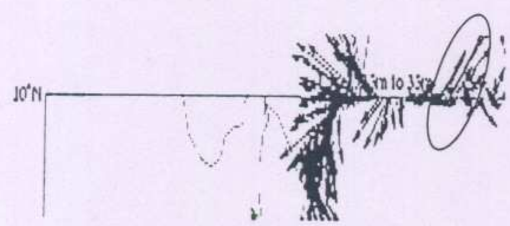
(o) (o)

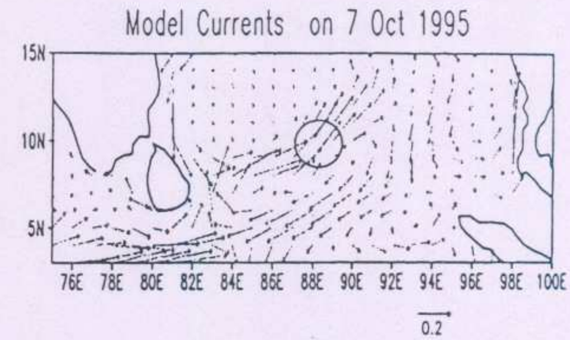
Fig.7. Same as fig.3 except for the case 5 and for m, n and o.



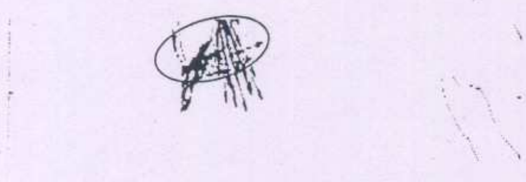


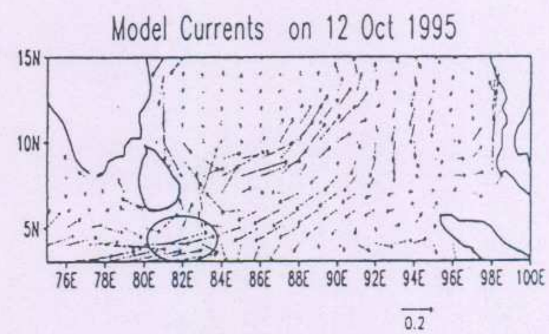
(p) (p)





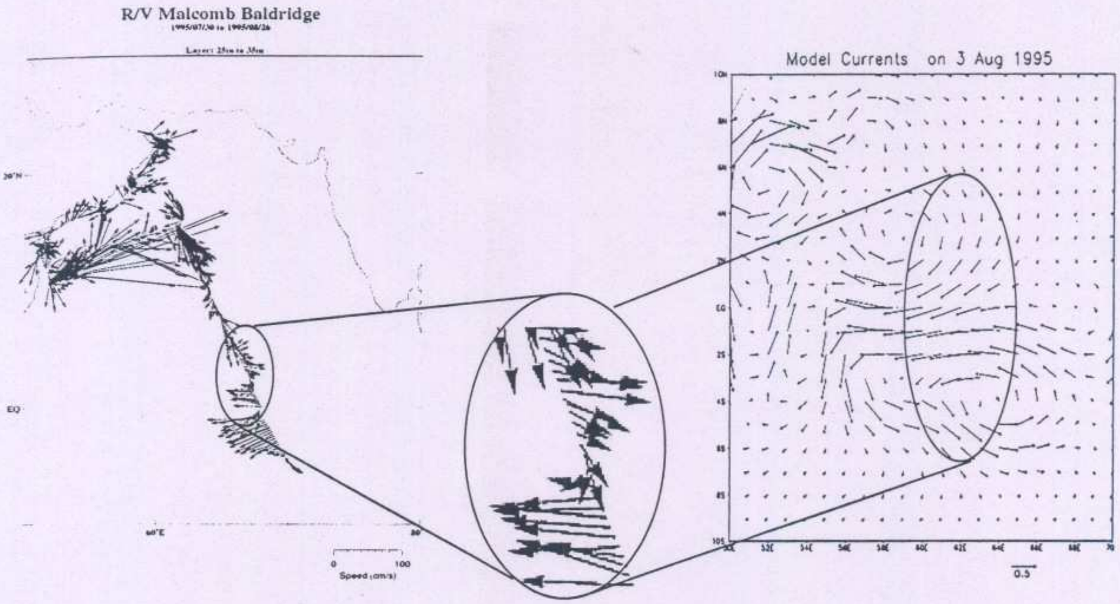
(q) (q)





(r) (r)

Fig.8. Same as fig.3 except for the case 6 and for p, q and r.



(a) (b) (c)

Fig.9. (a) Is the vector plots of surface circulations (25m to 35m) from the WOCE along 50E-80E, 10S-30N during July – August 1995. (b) A zoomed view (65E-70E,Eq-5N) for 3/08/1995 (c) The model simulated surface currents along 64E-70E,Eq-5N for 3/08/1995.

I. I. T. M. RESEARCH REPORTS

- Energetic consistency of truncated models, *Asnani G.C.*, August 1971, RR-001.
- Note on the turbulent fluxes of heat and moisture in the boundary layer over the Arabian Sea, *Sinha S.*, August 1971, RR-002.
- Simulation of the spectral characteristics of the lower atmosphere by a simple electrical model and using it for prediction, *Sinha S.*, September 1971, RR-003.
- Study of potential evapo-transpiration over Andhra Pradesh, *Rakhecha P.R.*, September 1971, RR-004.
- Climatic cycles in India-1: Rainfall, *Jagannathan P. and Parthasarathy B.*, November 1971, RR-005.
- Tibetan anticyclone and tropical easterly jet, *Raghavan K.*, September 1972, RR-006.
- Theoretical study of mountain waves in Assam, *De U.S.*, February 1973, RR-007.
- Local fallout of radioactive debris from nuclear explosion in a monsoon atmosphere, *Saha K.R. and Sinha S.*, December 1972, RR-008.
- Mechanism for growth of tropical disturbances, *Asnani G.C. and Keshavamurty R.N.*, April 1973, RR-009.
- Note on "Applicability of quasi-geostrophic barotropic model in the tropics", *Asnani G.C.*, February 1973, RR-010.
- On the behaviour of the 24-hour pressure tendency oscillations on the surface of the earth, Part-I: Frequency analysis, Part-II: Spectrum analysis for tropical stations, *Misra B.M.*, December 1973, RR-011.
- On the behaviour of the 24 hour pressure tendency oscillations on the surface of the earth, Part-III : Spectrum analysis for the extra-tropical stations, *Misra B.M.*, July 1976, RR-011A.
- Dynamical parameters derived from analytical functions representing Indian monsoon flow, *Awade S.T. and Asnani G.C.*, November 1973, RR-012.
- Meridional circulation in summer monsoon of Southeast Asia, *Asnani G.C.*, November 1973, RR-014.
- Energy conversions during weak monsoon, *Keshavamurty R.N. and Awade S.T.*, August 1974, RR-015.
- Vertical motion in the Indian summer monsoon, *Awade S.T. and Keshavamurty R.N.*, August 1974, RR-016.
- Semi-annual pressure oscillation from sea level to 100mb in the northern hemisphere, *Asnani G.C. and Verma R.K.*, August 1974, RR-017.
- Suitable tables for application of gamma probability model to rainfall, *Mooley D.A.*, November 1974, RR-018.

- Annual and semi-annual thickness oscillation in thenorthern hemisphere, *Asnani G.C. and Verma R.K.*, January 1975, RR-020.

- Spherical harmonic analysis of the normal constant pressure charts in the northern hemisphere, *Awade S.T., Asnani G.C. and Keshavamurty R.N.*, May 1978, RR-021.

- Dynamical parameters derived from analytical function representing normal July zonal flow along 87.5 °E, *Awade S.T. and Asnani G.C.*, May 1978, RR-022.

- Study of trends and periodicities in the seasonal and annual rainfall of India, *Parthasarathy B. and Dhar O.N.*, July 1975, RR-023.

- Southern hemisphere influence on Indian rainfall, *Raghavan K.., Paul D.K. and Upasani P.U.*, February 1976, RR-024.

- Climatic fluctuations over Indian region - Rainfall : A review, *Parthasarathy B. and Dhar O.N.*, May 1978, RR-025.

- Annual variation of meridional flux of sensible heat, *Verma R.K. and Asnani G.C.*, December 1978, RR-026.

- Poisson distribution and years of bad monsoon over India, *Mooley D.A and Parthasarathy B.*, April 1980, RR-027.

- On accelerating the FFT of Cooley and Tukey, *Mishra S.K.*, February 1981, RR-028.

- Wind tunnel for simulation studies of the atmospheric boundary layer, *Sivaramakrishnan S.*, February 1981, RR-029.

- Hundred years of Karnataka rainfall, *Parthasarathy B. and Mooley D.A.*, March 1981, RR-030.

- Study of the anomalous thermal and wind patterns during early summer season of 1979 over the Afro-Asian region in relation to the large-scale performance of the monsoon over India, *Verma R.K. and Sikka D.R.*, March 1981, RR-031.

- Some aspects of oceanic ITCZ and its disturbances during the onset and established phase of summer monsoon studied with Monex-79 data, *Sikka D.R., Paul D.K. and Singh S.V.*, March 1981, RR- 032.

- Modification of Palmer drought index, *Bhalme H.N. and Mooley D.A.*, March 1981, RR-033.

- Meteorological rocket payload for Menaka-II/Rohini 200 and its developmental details, *Vernekar K.G. and Brij Mohan*, April 1981, RR-034.

- Harmonic analysis of normal pentad rainfall of Indian stations, *Anathakrishnan R. and Pathan J.M.*, October 1981, RR-035.

- Pentad rainfall charts and space-time variations of rainfall over India and the adjoining areas, *Anathakrishnan R. and Pathan J.M.*, November 1981, RR-036.

- Dynamic effects of orography on the large scale motion of the atmosphere Part I : Zonal flow and elliptic barrier with maximum height of one km., *Bavadekar S.N. and Khaladkar R.M.*, January 1983, RR-037.

- Limited area five level primitive equation model, *Singh S.S.*, February 1983, RR-038.
- Developmental details of vortex and other aircraft thermometers, *Vernekar K.G., Brij Mohan and Srivastava S.*, November 1983, RR-039.
- Note on the preliminary results of integration of a five level P.E. model with westerly wind and low orography, *Bavadekar S.N., Khaladkar R.M., Bandyopadhyay A. and Seetaramayya P.*, November 1983, RR-040.
- Long-term variability of summer monsoon and climatic change, *Verma R.K., Subramaniam K. and Dugam S.S.*, December 1984, RR-041.
- Project report on multidimensional initialization for NWP models, *Sinha S.*, February 1989, RR-042.
- Numerical experiments with inclusion of orography in five level P.E. Model in pressure-coordinates for interhemispheric region, *Bavadekar S.N. and Khaladkar R.M.*, March 1989, RR-043.
- Application of a quasi-lagrangian regional model for monsoon prediction, *Singh S.S. and Bandyopadhyay A.*, July 1990, RR-044.
- High resolution UV-visible spectrometer for atmospheric studies, *Bose S., Trimbake H.N., Londhe A.L. and Jadhav D.B.*, January 1991, RR-045.
- Fortran-77algorithm for cubic spline interpolation for regular and irregular grids, *Tandon M.K.*, November 1991, RR-046.
- Fortran algorithm for 2-dimensional harmonic analysis, *Tandon M.K.*, November 1991, RR- 047.
- 500 hPa ridge and Indian summer monsoon rainfall : A detailed diagnostic study, *Krishna Kumar K., Rupa Kumar K. and Pant G.B.*, November 1991, RR-048.
- Documentation of the regional six level primitive equation model, *Singh S.S. and Vaidya S.S.*, February 1992, RR-049.
- Utilisation of magnetic tapes on ND-560 computer system, *Kripalani R.H. and Athale S.U.*, July 1992, RR-050.
- Spatial patterns of Indian summer monsoon rainfall for the period 1871-1990, *Kripalani R.H., Kulkarni A.A., Panchawagh N.V. and Singh S.V.*, August 1992, RR-051.
- FORTRAN algorithm for divergent and rotational wind fields, *Tandon M.K.*, November 1992, RR-052.
- Construction and analysis of all-India summer monsoon rainfall series for the longest instrumental period: 1813-1991, *Sontakke N.A., Pant G.B. and Singh N.*, October 1992, RR-053.
- Some aspects of solar radiation, *Tandon M.K.*, February 1993, RR-054.
- Design of a stepper motor driver circuit for use in the moving platform, *Dharmaraj T. and Vernekar K.G.*, July 1993, RR-055.

- Experimental set-up to estimate the heat budget near the land surface interface, *Vernekar K.G., Saxena S., Pillai J.S., Murthy B.S., Dharmaraj T. and Brij Mohan*, July 1993, RR-056.

- Identification of self-organized criticality in atmospheric total ozone variability, *Selvam A.M. and Radhamani M.*, July 1993, RR-057.

- Deterministic chaos and numerical weather prediction, *Selvam A.M.*, February 1994, RR-058.

- Evaluation of a limited area model forecasts, *Singh S.S., Vaidya S.S Bandyopadhyay A., Kulkarni A.A, Bawiskar S.M.,Sanjay J., Trivedi D.K. and Iyer U.*, October 1994, RR-059.

- Signatures of a universal spectrum for atmospheric interannual variability in COADS temperature time series, *Selvam A.M., Joshi R.R. and Vijayakumar R.*, October 1994, RR-060.

- Identification of self-organized criticality in the interannual veriability of global surface temperature, *Selvam A.M. and Radhamani M.*, October 1994, RR-061.

- Identification of a universal spectrum for nonlinear veriability of solar-geophysical parameters, *Selvam A.M., Kulkarni M.K., Pethkar J.S. and Vijayakumar R.*, October 1994, RR-062.

- Universal spectrum for fluxes of energetic charged particles from the earth's magnetosphere, *Selvam A.M. and Radhamani M.*, June 1995, RR-063.

- Estimation of nonlinear kinetic energy exchanges into individual triad interactions in the frequency domain by use of the cross-spectral technique, *Chakraborty D.R.*, August 1995, RR-064.

- Monthly and seasonal rainfall series for all-India homogeneous regions and meteorological subdivisions: 1871-1994, *Parthasarathy B., Munot A.A. and Kothawale D.R.*, August 1995, RR-065.

- Thermodynamics of the mixing processes in the atmospheric boundary layer over Pune during summer monsoon season, *Morwal S.B. and Parasnis S.S.*, March 1996, RR-066.

- Instrumental period rainfall series of the Indian region: A documentation, *Singh N. and Sontakke N.A.*, March 1996, RR-067.

- Some numerical experiments on roundoff-error growth in finite precision numerical computation, *Fadnavis S.*, May 1996, RR-068.

- Fractal nature of MONTBLEX time series data, *Selvam A.M. and Sapre V.V.*, May 1996, RR-069.

- Homogeneous regional summer monsoon rainfall over India: Interannual variability and teleconnections, *Parthasarathy B., Rupa Kumar K. and Munot A.A.*, May 1996, RR-070.

- Universal spectrum for sunspot number variability, *Selvam A.M. and Radhamani M.*, November 1996, RR-071.

- Development of simple reduced gravity ocean model for the study of upper north Indian ocean, *Behera S.K. and Salvekar P.S.*, November 1996, RR-072.

- Study of circadian rhythm and meteorological factors influencing acute myocardial infraction, *Selvam A.M., Sen D. and Mody S.M.S.*, April 1997, RR-073.

- Signatures of universal spectrum for atmospheric gravity waves in southern oscillation index time series, *Selvam A.M., Kulkarni M.K., Pethkar J.S. and Vijayakumar R.*, December 1997, RR-074.

- Some example of X-Y plots on Silicon Graphics, *Selvam A.M., Fadnavis S. and Gharge S.P.*, May 1998, RR-075.

- Simulation of monsoon transient disturbances in a GCM, *Ashok K., Soman M.K. and Satyan V.*,August 1998, RR-076.

- Universal spectrum for intraseasonal variability in TOGA temperature time series, *Selvam A.M., Radhamani M., Fadnavis S. and Tinmaker M.I.R.*, August 1998, RR-077.

- One dimensional model of atmospheric boundary layer, *Parasnis S.S., Kulkarni M.K., Arulraj S. and Vernekar K.G.*, February 1999, RR-078.

- Diagnostic model of the surface boundary layer - A new approach, *Sinha S.*, February 1999, RR-079.

- Computation of thermal properties of surface soil from energy balance equation using force - restore method, *Sinha S.*, February 1999, RR-080.

- Fractal nature of TOGA temperature time series, *Selvam A.M. and Sapre V.V.*, February 1999, RR-081.

- Evolution of convective boundary layer over the Deccan Plateau during summer monsoon, *Parasnis S.S.*, February 1999, RR-082.

- Self-organized criticality in daily incidence of acute myocardial infarction, *Selvam A.M., Sen D., and Mody S.M.S.*, Feburary 1999, RR-083.

- Monsoon simulation of 1991 and 1994 by GCM : Sensitivity to SST distribution, *Ashrit R.G., Mandke S.K. and Soman M.K.*, March 1999, RR-084.

- Numerical investigation on wind induced interannual variability of the north Indian Ocean SST, *Behera S.K., Salvekar P.S. and Ganer D.W.*, April 1999, RR-085.

- On step mountain eta model, *Mukhopadhyay P., Vaidya S.S., Sanjay J. and Singh S.S.*, October 1999, RR-086.

- Land surface processes experiment in the Sabarmati river basin: an overview and early results, *Vernekar K.G., Sinha S., Sadani L.K., Sivaramakrishnan S., Parasnis S.S., Brij Mohan, Saxena S., Dharamraj T., Pillai, J.S., Murthy B.S., Debaje, S.B., Patil, M.N. and Singh A.B.*, November 1999, RR-087.

- Reduction of AGCM systematic error by Artificial Neural Network: A new approach for dynamical seasonal prediction of Indian summer monsoon rainfall, *Sahai A.K. and Satyan V.*, December 2000, RR-088.

- Ensemble GCM simulations of the contrasting Indian summer monsoons of the 1987 and 1988, *Mujumdar M. and Krishnan R.*, February 2001, RR-089.

- Aerosol measurements using lidar and radiometers at Pune during INDOEX field phases, Maheskumar R.S., Devara P.C.S., Raj P.E., Jaya Rao Y.,Pandithurai G., Dani K.K., Saha S.K., Sonbawne S.M. and Tiwari Y.K., December 2001, RR-090.

- Modelling studies of the 2000 Indian summer monsoon and extended analysis, Krishnan R., Mujumdar M., Vaidya V., Ramesh K.V. and Satyan V., December 2001, RR-091.

- Intercomparison of Asian summer monsoon 1997 simulated by atmospheric general circulation models, Mandke S.K., Ramesh K.V. and Satyan V., December 2001, RR-092.

- Prospects of prediction of Indian summer monsoon rainfall using global SST anomalies, Sahai A.K, Grimm A.M., Satyan V. and Pant G.B., April 2002, RR-093.

- Estimation of nonlinear heat and momentum transfer in the frequency domain buy the use of frequency co-spectra and cross-bispectra, Chakraborty D.R. and Biswas M.K., August 2002, RR-094