MAUSAM, **53**, 2 (April 2002), 153-164

551.501

Impact of ERS-2 Scatterometer wind data on Global Analysis-Forecast system

M. DAS GUPTA, S. R. H. RIZVI and A. K. MITRA

National Centre for Medium Range Weather Forecasting (NCMRWF)

Mausam Bhawan, New Delhi –110003, India

(*Received 7 September 1999, Modified 28 December 2001*)

सार - राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र (एन.सी.एम.आर.डब्ल्यू.एफ.) में फरवरी 1997 से वास्तविक समय आधार पर यूरोपीय अंतरिक्ष अभिकरण (ई.एस.ए.) के यूरोपीय सुदूर संवेदी उपग्रह ई.आर.एस.-2 से निकटवर्ती धरातल की स्कैटरोमीटर पवन के आँकड़ें उपलब्ध हो रहे हैं। इन आँकड़ों के उष्णकटिबंधीय क्षेत्रों में किए गए विशलेषणों और मध्यम अवधि मौसम पूर्वानुमान पर पड़ने वाले इनके प्रभावों का अध्ययन करने हेतु एन.सी.एम.आर.डब्ल्यू.एफ. में आरंभ की गई भूमंडलीय आँकड़ों समीकरण प्रणाली (जी.डी.ए.एस.)के समुचित गुणता नियंत्रण के पश्चात् इनसे प्राप्त किए गए आँकडों को एकत्रित करने का प्रयास किया गया है। इस उद्देश्य के लिए जी.डी.ए.एस. में 15 दिनों (27 मई से 10 जून 1998) तक कार्य किया गया। इस पर पड़ने वाले प्रभाव की परिसंचरण अभिलक्षणों तथा विभिन्न वस्तुपरक स्कोरों के माध्यम से जाँच की गई है। इस अध्ययन से यह पता चला है कि समुचित गुणवत्ता नियंत्रण से वास्तविक समय पर आधारित स्कैटरोमीटर पवन आँकड़ों को एकत्रित किया जा सकता है जिसके परिणामस्वरूप विश्लेषण पूर्वानुमान प्रणाली के कार्य निष्पादन में पूर्णरूपेण सुधार हो जाएगा।

ABSTRACT. The near surface scatterometer wind data from the European remote sensing satellite ERS-2 of European space agency(ESA) became available at NCMRWF on real time basis since February 1997. An attempt has been made to assimilate this data in the global data assimilation system(GDAS) operational at NCMRWF after proper quality control to study its impact on the analysis as well as on medium range weather forecast over the tropics. For this purpose the GDAS was run for 15 days (27 May to 10 June 1998). The impact has been examined through circulation characteristics and various objective scores. The study revealed that with proper quality control the scatterometer wind data can be assimilated in real time basis, resulting in an overall improvement in performance of the analysis-forecast system.

Key words – European remote sensing satellite, ERS, Scatterometer wind, Global data assimilation, Quality control, Data impact, Numerical weather prediction , Medium range weather forecast, Tropical cyclone, Anomaly correlation.

1. Introduction

Data scarcity over the oceanic region is one of the major problems of the Numerical Weather Prediction (NWP) over tropics. To overcome this, an increasing trend of utilization of non-conventional data in NWP system is seen all over the operational NWP centres. At NCMRWF continuous efforts have been made to enhance the database using various types of satellite data. The scatterometer data from ERS-2 satellite is one of such data sets which gives an opportunity to reveal the surface flow characteristic over the tropical ocean. Since, this data have its own limitations, hence before utilizing this data for studying its impact, proper quality control needs to be developed.

The European Space Agency's (ESA) remote sensing satellite, ERS-1, launched on 17 July, 1991 has already proved to be a valuable source of high quality near surface wind data, mainly over the oceanic region. The beneficial impact of assimilating the scatterometer wind data in the global analysis and its impact on medium range weather forecast have already been established by several studies *e.g.* Stofflen *et al.*(1991, 1997), Hoffman (1993), Anderson *et al.*(1991). Efforts have also been made (Joshi *et al.*, 1996, 1998 and Bansal *et al*. 1994, Rao *et al.*, 1998) in India, to study the impact of ERS-1 scatterometer data on medium range weather forecasting of cyclones and monsoon using NCMRWF's Global Data Assimilation System (GDAS). Various other studies have been carried out to asses the impact of satellite derived temperature profile data (Prasad *et al.*, 1998) and cloud motion vectors on data assimilation system, which reveal that the impact of this kind of data over data sparse oceanic region is different from that over conventional data rich mid latitudes.

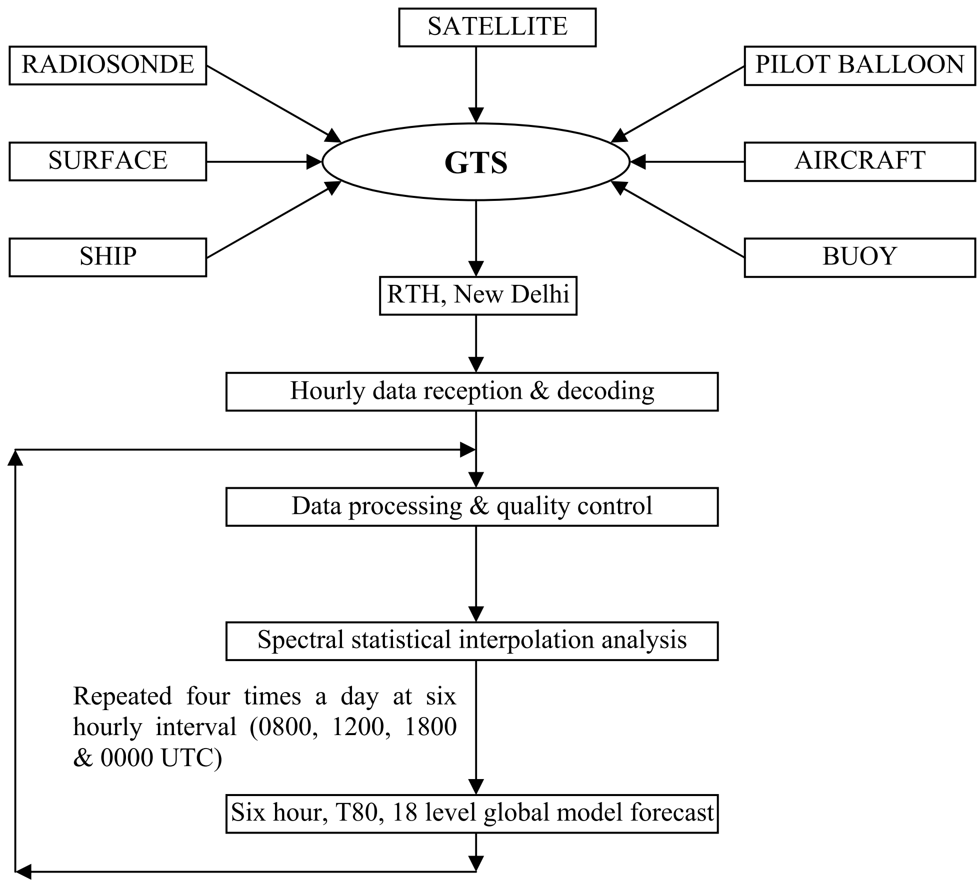


Fig. 1. Global data assimilation system at NCMRWF

The next satellite in this series, ERS-2, was launched in 1994 and the processed scatterometer wind data by ESA is being disseminated on Global Telecommunication System (GTS). The ERS-2 data, which is available at present on real time at NCMRWF *via* Global Telecommunication system (GTS) ranges from 30° S to 30° N and 0° E to 180° E. This study aimed to utilize the above data in NCMRWF's operational GDAS system to examine the quality of the data as well as to study its impact on the analysis and medium range weather forecast, specially over tropics. Thus following this, in section 2, GDAS and the forecast model used, is briefly described, section 3 deals with the quality control procedure followed for ERS-2 data utilization and section 4 describes about the numerical experiment carried out for this study. Results of the study are discussed in section 5 and the conclusions are summarized in the last section.

2. Global data assimilation system (GDAS) and forecast model

A global data assimilation and forecast system to provide medium range weather forecast for agro-meteorological advisory services over India has been made operational since 1 June, 1994. The NCMRWF's GDAS is an intermittent six hourly assimilation system. It consists of data processing and quality control, analysis scheme and forecast model as its main components (Fig.1) and the same are briefly described below.

The decoded data is passed through comprehensive hydrostatic quality control (CHQC) checks (Collins and Gandin, 1990) which comprises of Multivariate Optimum Interpolation for *u*, *v* and thickness, baseline check for surface pressure element and hydrostatic checks. Based

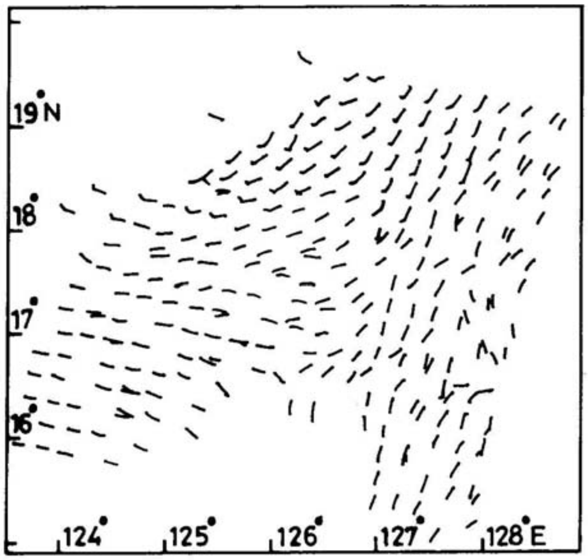


Fig 2. ERS-2 (FDA) from ESA showing directional ambiguities giving rise to incoherent flow pattern

on the results of these checks a decision making algorithm (DMA) is invoked to assign the final quality flag to each meteorological element.

The analysis scheme used for preparing the initial condition is the spectral statistical interpolation (SSI) technique, which is an adapted version of the analysis scheme described by Parrish and Derber, 1992 and its details can be seen in Bansal and Rizvi (1993) and Rizvi and Parrish (1995). The analysis is done in spectral space on the sigma levels of the forecast model, the analysis variables are the sigma level spectral coefficients of the amplitudes of the empirical orthogonal functions (EOF's) of vorticity, mixing ratio, unbalanced part of divergence, temperature and log of surface pressure. The balanced part of the various fields are being computed using a quasi-geostrophic linear balance relationship (Haltiner and Willium, 1979) in which the contribution of only first six EOF's of vorticity are taken into account.

The forecast model, adapted from the National Centre for Environmental Prediction (NCEP) is based on the primitive equations of vorticity, divergence, virtual temperature, log of surface pressure and specific humidity. The model uses the spectral method of horizontal representation with resolution of 80 waves triangular truncation (T 80). In the vertical, it has 18 unequally spaced levels on sigma co-ordinate system. The Physics is computed on Gaussian grid (128×256), which corresponds roughly to 160 km. Further details of various aspects of the model can be seen in Sela (1980), Kanamitsu (1989) and Paliwal *et al*. (1999).

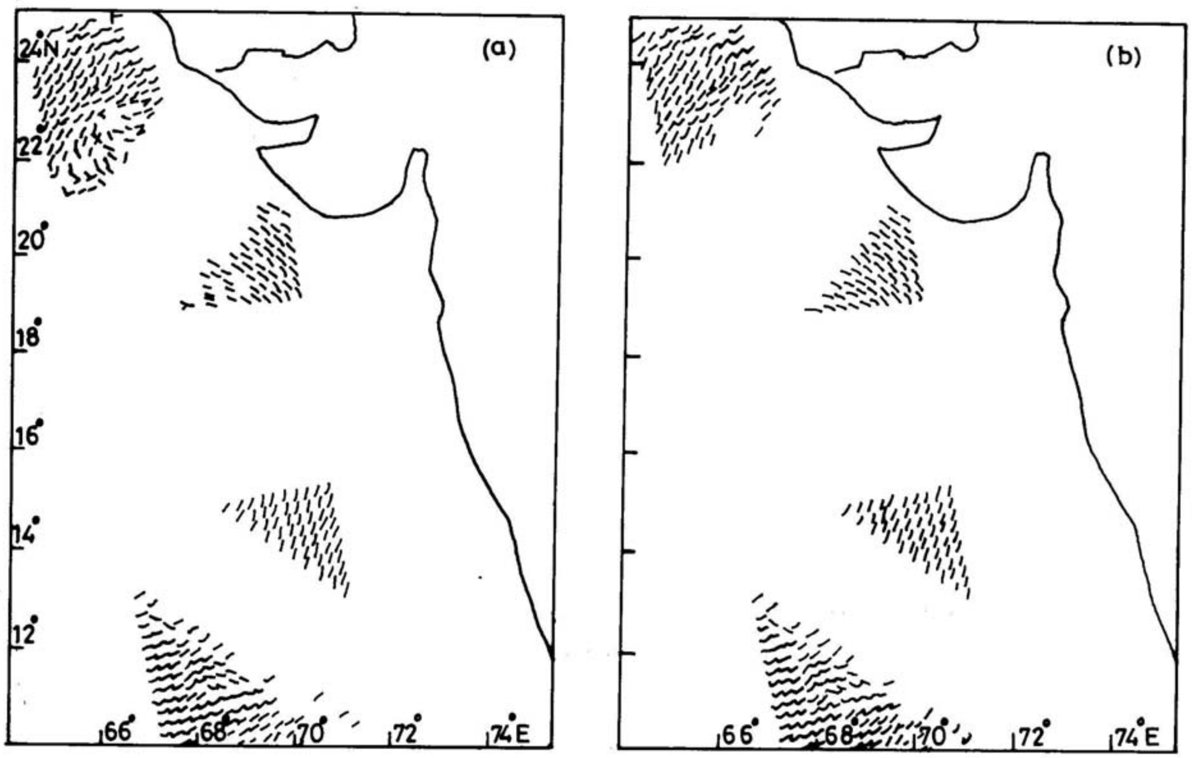
At present data used in the operational assimilation are, (a) surface observations both from land and ship stations (wind speed and direction, temperature, moisture, surface pressure and mean sea level pressure), (b) upper air data profiles from Radiosonde and Pilot Balloon observation (wind speed and direction, temperature specific humidity), (c) aircraft data (wind speed and direction temperature), (d) buoy data (wind speed and direction, temperature, surface pressure), (e) CMV's from the INSAT, METEOSAT, GMS GOES satellites both at the lower and the upper levels, (f) temperature profiles and total precipitable water content from NOAA series of satellites .

3. Quality control procedure for ERS-2 data

NCMRWF has been receiving the ERS-2 scatterometer data since February, 1997 in the form of fast delivery product (FDP) from ESA. The FDP includes three measurement of back-scattered power (σ_0) at each measurement location (cell), along with wind direction and speed computed by ESA. NCMRWF receives this data in BUFR (FM-94) code (WMO Manual on Codes No. 306) through GTS *via* RTH, New Delhi. The data is being received in packets (one frame) each containing 19 × 19 data points (cell). In every packet each data points is separated by a distance of 25 km in the direction across and along the sub-satellite track. The width of the swath is 500 km, with 19 cells across the satellite track. The polar orbital period is roughly about 100 minutes yielding 14 orbits per day. It may be mentioned here that, due to transmission and coding related problems, it is not always possible to retrieve the entire data, thus generating in between data gaps. Approximately the additional wind vector from ERS-2 assimilated in this study is about 25% of the total grid at T 80 resolution.

A suitable BUFR decoder has been developed to decode this data at NCMRWF. After decoding, the data is sorted out for each day in four data files, each corresponding to 0000, 0600, 1200 and 1800 UTC main synoptic hours. These four data files contain the data reported within (±3 hours of the respective main synoptic hours and are being used in the corresponding hour assimilation.

Though the accuracy of the scatterometer wind speed and direction are supposed to be 2 ms^{-1} and $\pm$20° respectively, several deficiencies of FDP of ESA has been observed and the same are also discussed by Gemmill *et al*. (1994). The directional ambiguity of the wind vector is one of them, for *e.g.* in some region winds blowing at 180° opposite to each other at adjacent points are commonly observed. Problems are also observed in



Figs. 3(a&b). (a) ERS-2 scatterometer wind data as received at NCMRWF (pass over Arabian sea) Date : 1800 UTC, 7 June 1998, (b) ERS-2 scatterometer wind data after quality control (pass over Arabian sea) Date :1800 UTC, 7 June 1998

regions of light winds, sometimes giving rise to incoherent flow pattern (Fig.2).

To overcome the directional ambiguity problem of ERS-2 wind data and to minimise the unnecessary processing of poor quality data, a quality control procedure has been developed at NCMRWF. First guess (six hourly forecast) of zonal (u) and meridinal (v) wind components at 10 mts height at 1.5 × 1.5 latitude/longitude grid is computed. These are then interpolated to the observation locations (ERS-2 data cell), from which the first guess wind direction (d_g) is computed. The observed wind direction (d_0) is checked against d_g as well as the neighbouring observed wind direction. Depending on the result of this check, a quality flag ranging from 0 to 5 is assigned to each observation. The same is described briefly as below :

Step 1: Quality flag 6 is assigned to all the data with wind speed below 2.5 ms^{-1} as well as above 25 ms^{-1}, as it is known to be erroneous.

Step 2: If the difference between the observed and the first guess wind direction (d_o - d_g) is within $\pm$30° range, quality flag 0 is attached assuming that there is no directional ambiguity, otherwise flag 5 is attached (suspected wind direction).

Step 3: All the wind direction with quality flag 5 are checked against co-located first guess wind direction after adding $\pm$180° with the suspected wind observation. If the corrected wind direction (d_0 $\pm$180°) falls within $\pm$30° range as well as it matches with the neighbouring wind directions, with quality flag < 6, then its flag is changed to 1 and the correction is being retained.

Step 4: Wind direction with quality flag 5 is checked against the neighbouring observations, and if more than 50% observation matches (within ±30°) with the wind direction then its flag is changed to 0. Finally, only the data points with quality flag 0,1,2 have been utilized by the assimilation system

4. Numerical experiment

Quality controlled ERS-2 data was assimilated along with other operational data input in the GDAS starting from 0000 UTC of 27th May 1998 to 0000 UTC of 10

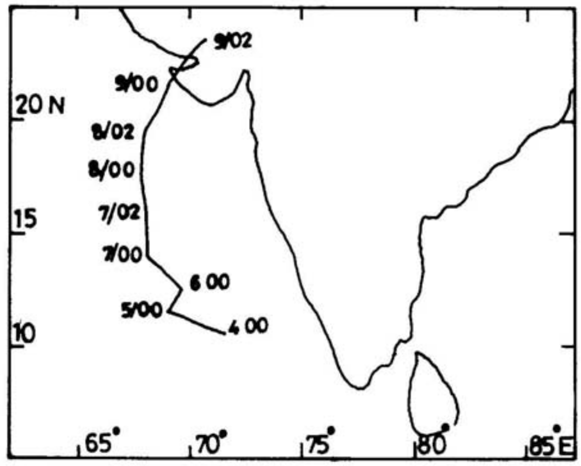


Fig. 4(a). Track of cyclonic storm over Arabian sea (0000 UTC, 4 June 1998 to 1200 UTC, 9 June 1998)

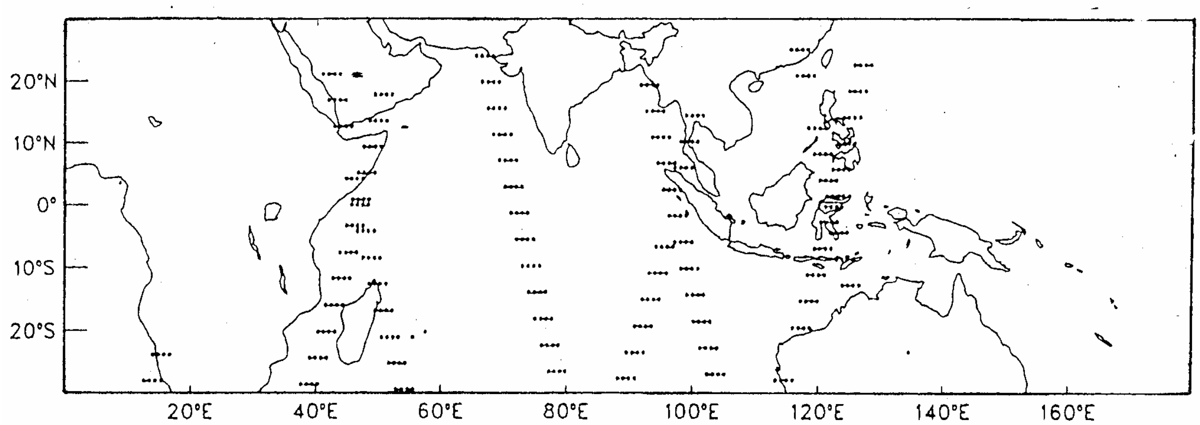


Fig. 4(b). Availability of ERS-2 wind data at NCMRWF (along the satellite track) Date : 7 June 1998

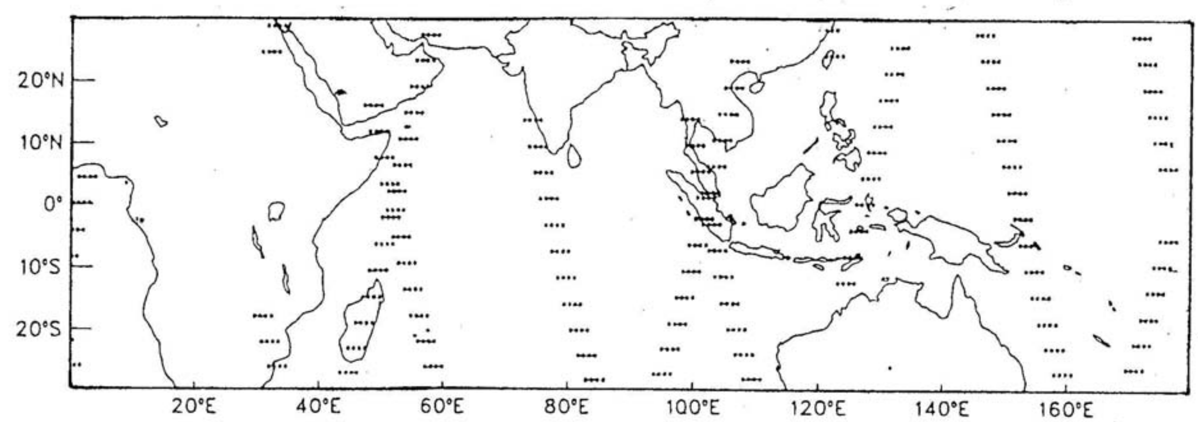


Fig. 4(c). Availability of ERS-2 wind data at NCMRWF (along the satellite track) Date : 8 June 1998

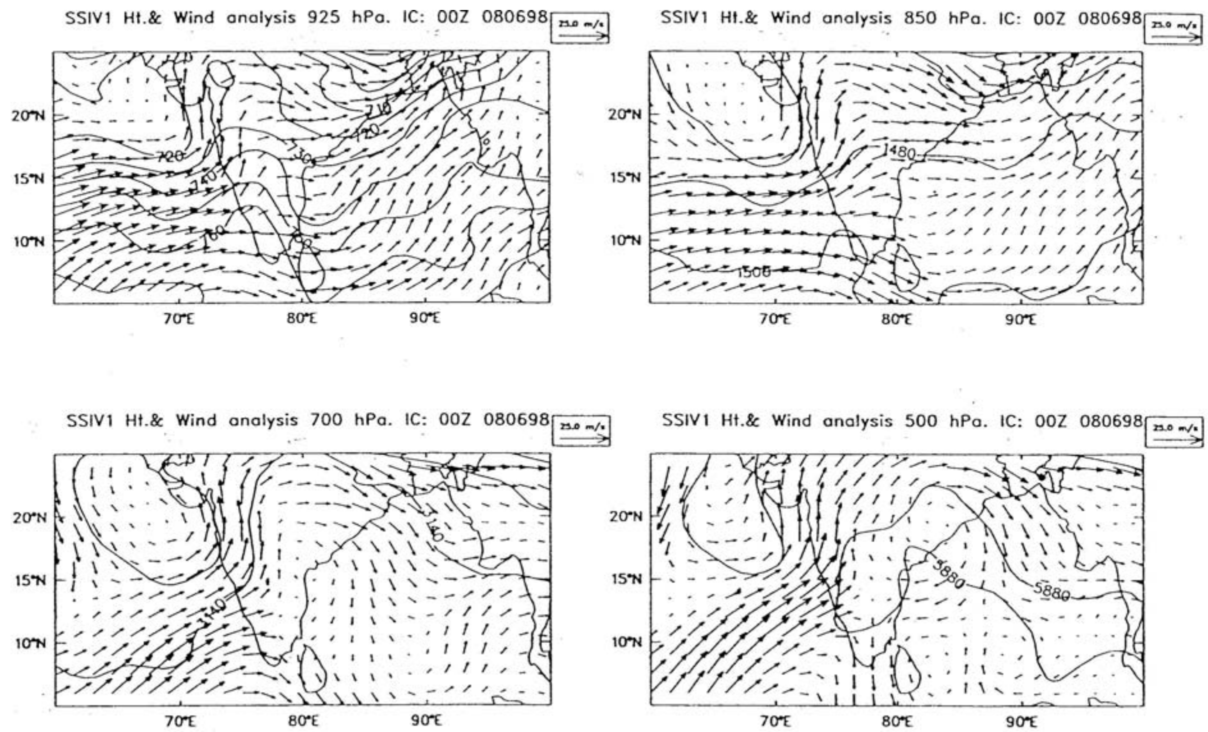


Fig . 5(a). Analyzed (wind and height) field of the operational run (SSIV1) at 925, 850 ,700 and 500 hPa. IC: 0000 UTC, 8 June 1998

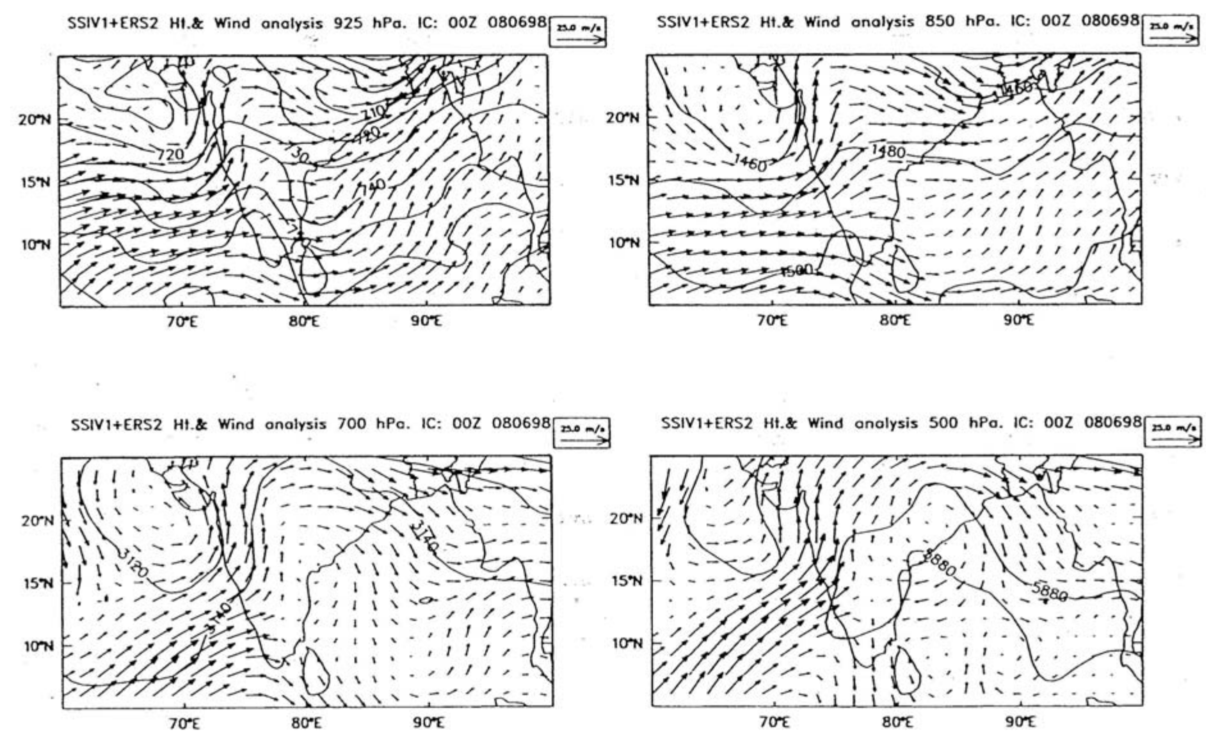


Fig . 5(b). Analyzed (wind and height) field of the experimental run (ERS2) at 925, 850 , 700 and 500 hPa. IC: 0000 UTC 8 June 1998

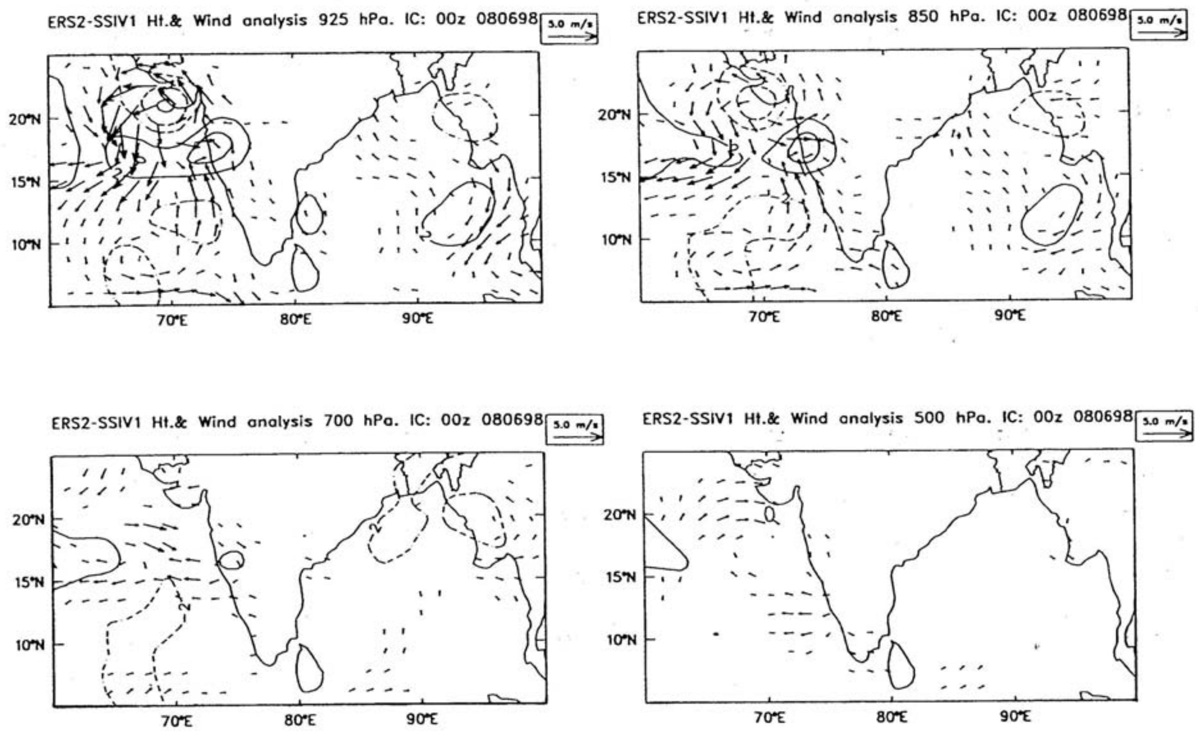


Fig . 5(c). Difference of the analyzed wind and height field (ERS2-SSIV1) at 925, 850 ,700 and 500 hPa. IC: 0000 UTC 8 June 1998

June 1998 . This period was selected keeping in view that monsoon 1998 onset took place over Kerala in the first week of June and a tropical cyclone was observed in the Arabian sea between 7th -10th June, 1998. Thus after assimilation run, based on 0000 UTC initial condition for each day, five day forecasts have been made. Experimental analysis and forecast fields were compared with the corresponding operational run (without ERS) to see the impact of ERS-2 data on assimilation and forecast system. For this purpose circulation characteristics and objective scores like anomaly correlation coefficient (ACC), root mean square error (RMSE) statistics etc. were compared for the two runs over the tropical region (30° S to 30° N and 0° E to 180° E).

5. Results and discussion

During the period of 27 May to 10 June 1998, on an average there were about 23000 ERS-2 wind reports per day. After quality control it was found that 60% of the data was of good quality and it matched well with the first guess field. In all about 18% of the data got rejected due to directional ambiguity. 4% of the data could not be utilized due to low/high wind speed. Quality control procedure could correct 6 % of the data for directional ambiguity. Results of quality control procedure are shown in Figs. 3(a&b) where the wind direction and speed are shown before and after the quality control respectively for a typical pass during this period over the Arabian Sea region.

The track of cyclonic storm over the Arabian sea from 7 June to 10 June, 1998 is shown in Figs. 4(a-c) depict the track of the ERS-2 during 7 and 8 June 1998 respectively. During this period one ERS-2 pass (1800 UTC 7 June 1998) was received passing very close to the storm position (16.5° N and 68° E) and the same is shown in Fig. 2(a). The impact of which was seen in the analysis of 0000 UTC of 8 June 1998. Figs. 5(a&b) are the analyzed height and wind field of 0000 UTC 8 June 1998 for operational (SSIV1) and experimental (ERS2) run respectively. It can be seen that in the experimental run Fig. 5(b), at 925 hPa the circulation (20° N, 68° E) has been clearly brought out where as it was seen only as a trough in the operational run [Fig. 5(a)]. Fig 5(c) is the difference plot of the experimental and operational analysis of 0000 UTC 8 June 1998, showing the strengthening of the system in the experimental run, specially in the lower tropospheric region (up to 850 hPa). As expected, the impact was seen mainly over the oceanic region. There is very little impact above 500 hPa. However, no major difference is seen in the forecast field giving rise to more or less the same track of the system.

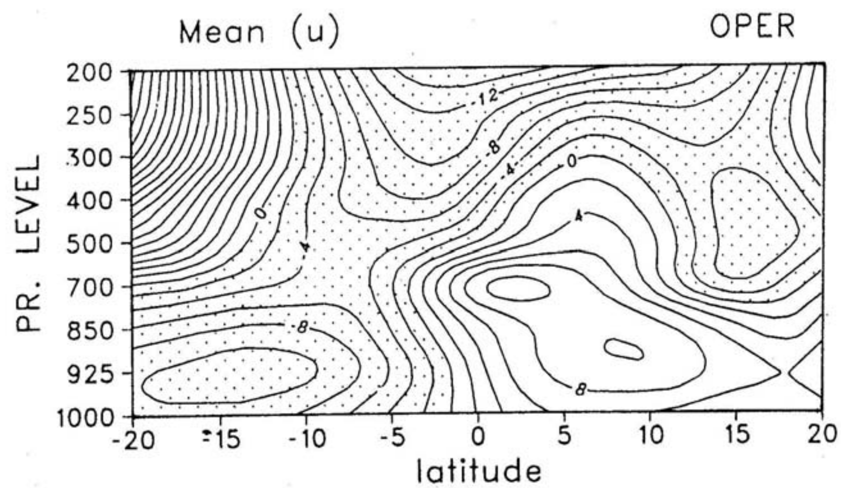


Fig . 6(a). Average (27 May - 10 June , 1998) pressure-latitude cross section of zonal wind analysis sectoral mean (60° E to 80° E) of the operational run

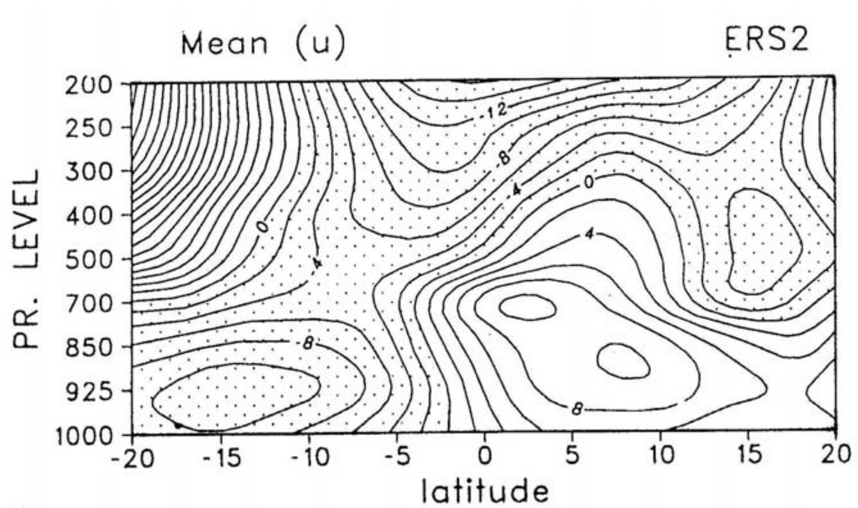


Fig. 6(b). Average (27 May - 10 June, 1998) pressure-latitude cross section of zonal wind analysis sectoral mean (60° E to 80° E) of the experimental run

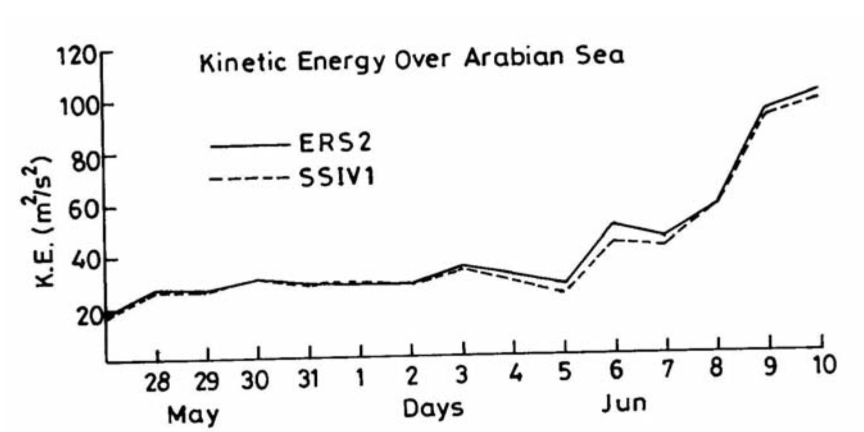


Fig. 7. Kinetic energy over Arabian sea during 27 May to 10 June, 1998 for operational (SSIV1) and experimental run (ERS2)

TABLE 1

RMSE of first guess field and analyzed field from observation

Pressure level (hPa)		Observation - Guess				Observation-Analysis			
		Global		Tropical		Global		Tropical	
		SSIV1	ERS2	SSIV1	ERS2	SSIV1	ERS2	SSIV1	ERS2
1000		3.2	3.2	2.8	2.7	2.3	2.3	1.9	1.8
850	(*u*)	3.4	3.3	3.5	3.4	2.6	2.6	2.6	2.5
700	(m/s)	3.5	3.5	3.5	3.5	2.6	2.4	2.5	2.6
500		3.7	3.7	3.7	3.7	2.6	2.6	2.6	2.6
200		4.9	4.9	5.2	5.2	3.1	3.1	3.1	3.1
1000		3.1	3.0	2.8	2.7	2.3	2.2	2.1	2.0
850	(*v*)	3.5	3.5	3.4	3.5	2.7	2.7	2.6	2.5
700	(m/s)	3.4	3.5	3.4	3.5	2.6	2.6	2.5	2.5
500		3.8	3.7	3.5	3.4	2.7	2.7	2.6	2.6
200		4.8	4.8	5.2	5.2	3.3	3.3	3.5	3.5
1000		13.8	13.6	11.9	11.6	10.5	10.5	8.8	8.8
850	(*z*)	15.0	14.8	14.6	14.4	11.0	10.9	11.0	10.8
700	(gpm)	17.9	17.7	20.1	19.9	12.4	12.2	14.6	14.5
500		25.1	24.9	29.0	28.7	17.0	17.0	22.0	22.0
200		44.9	44.3	56.0	55.3	30.5	30.8	43.1	43.1
1000		2.5	2.5	1.6	1.6	1.9	1.9	1.4	1.3
850	(*t*)	1.8	1.9	1.6	1.7	1.3	1.2	1.2	1.1
700	(^{0}C)	1.5	1.5	1.5	1.5	1.1	1.1	1.0	1.0
500		1.4	1.4	1.3	1.3	0.9	0.9	1.0	1.0
200		1.9	1.9	1.7	1.7	1.4	1.2	1.3	1.3
1000		1.7	1.7	2.2	2.1	1.5	1.4	2.0	1.9
850	(*q*)	1.7	1.7	2.3	2.2	1.4	1.4	2.0	1.9
700	(g/kg)	1.5	1.4	1.9	1.9	1.2	1.1	1.6	1.5
500		0.7	0.7	1.1	1.1	0.6	0.6	1.0	1.0

Figs. 6(a&b) are the average (27 May – 10 June 1998) pressure-latitude cross section of zonal wind analysis sectoral mean (60° E to 80° E) of operational and experimental run respectively. The mean kinetic energy (analyzed) over the region (0° to 19.5° N and 55.5° E to 75° E) at 850 hPa level is also computed and shown in Fig. 7. There is no major difference in the zonal wind sectoral mean of the two runs. However a slight strengthening of low level westerlies was observed between equator to 10° N. The same is reflected in the higher kinetic energy field observed over the Arabian Sea in the experimental run with ERS-2 data.

Root mean square error (RMSE) of the first guess and the analysis field from the observations for wind, height, temperature and specific humidity at various

TABLE 2

RMSE of geopotential height(*z*), zonal(*u*) and meridinal(*v*) comp. of wind at different vertical levels of the experimental(ERS2) and operational (SSIV1) run (average for 1-10 June 1998) computed for N.H. and over tropical region

Pressure level (hPa)		Forecast days Day 1 SSIV1	Day 1 ERS2	Day 3 SSIV1	Day 3 ERS2	Day 5 SSIV1	Day 5 ERS2
				(Northern Hemisphere)			
1000		14.61	14.22	31.16	31.10	45.27	44.69
850		12.88	12.61	28.71	28.83	43.77	43.52
700	(*z*)	13.37	13.13	30.57	30.72	48.39	50.56
500	(gpm)	17.26	16.85	40.59	40.77	64.59	67.22
200		27.56	27.01	58.34	57.81	91.94	91.97
1000		1.93	1.90	3.69	3.61	4.67	4.57
850	(*u*)	2.20	2.16	4.34	4.33	5.68	5.71
700	(m/s)	2.25	2.20	4.42	4.45	6.14	6.30
500		2.87	2.82	5.66	5.57	8.11	8.32
200		3.84	3.79	7.38	7.33	10.71	10.31
1000		1.99	1.95	3.97	3.91	4.87	4.96
850	(*v*)	2.14	2.09	4.30	4.32	5.29	5.28
700	(m/s)	2.20	2.12	4.46	4.43	5.70	5.82
500		2.85	2.79	5.81	5.76	7.71	7.90
200		3.88	3.83	7.77	7.88	10.78	10.16
				(Tropical Region)			
1000		9.65	9.24	17.01	16.64	18.83	17.99
850	(*z*)	9.82	9.46	18.17	17.80	20.45	19.80
700	(gpm)	12.00	11.53	21.84	21.41	25.30	25.05
500		15.02	14.34	27.00	26.59	33.61	33.84
200		24.13	23.33	46.09	46.23	64.21	65.73
1000		1.74	1.65	2.53	2.47	2.82	2.81
850	(*u*)	2.21	2.07	3.49	3.43	3.92	3.91
700	(m/s)	2.29	2.13	3.71	3.70	4.24	4.22
500		2.76	2.57	4.24	4.19	4.99	4.99
200		3.87	3.59	4.91	5.21	7.97	7.98
1000		1.62	1.51	2.27	2.26	2.64	2.62
850	(*v*)	1.86	1.73	2.67	2.65	3.06	3.03
700	(m/s)	2.00	1.80	2.88	2.85	3.27	3.25
500		2.37	2.14	3.42	3.35	4.01	4.00
200		3.76	3.51	5.89	5.92	6.98	6.98

standard isobaric pressure level (1000, 850, 700, 500, 200 hPa) are computed over global and tropical region(19.5° S to 19.5° N) for the entire 15 days assimilation period and the same is given in Table 1. On an average, the RMSE of experimental run is slightly less than the operational run RMSE. Forecast RMSE of height and wind at different

TABLE 3

ACC of zonal(*u*) and meridinal(*v*) comp. of wind at different vertical levels of the experimental(ERS2) and operational (SSIV1) run (average for 1-10 June 1998) computed for N.H. and tropical region

Pressure		Day 1		Day 3		Day 5	
level (hPa)		SSIV1	ERS2	SSIV1	ERS2	SSIV1	ERS2
				(Northern Hemisphere)			
1000		0.91	0.92	0.66	0.66	0.45	0.46
850	(*u*)	0.92	0.92	0.68	0.68	0.45	0.46
700		0.93	0.94	0.74	0.74	0.50	0.48
500		0.95	0.95	0.78	0.78	0.55	0.54
200		0.95	0.96	0.82	0.82	0.62	0.62
1000		0.90	0.91	0.62	0.61	0.40	0.39
850	(*v*)	0.91	0.91	0.64	0.64	0.42	0.43
700		0.92	0.93	0.69	0.69	0.46	0.46
500		0.93	0.93	0.72	0.72	0.49	0.48
200		0.94	0.94	0.76	0.75	0.51	0.50
				(Tropical Region)			
1000		0.76	0.79	0.52	0.55	0.38	0.39
850	(*u*)	0.82	0.84	0.56	0.60	0.40	0.42
700		0.85	0.87	0.60	0.61	0.44	0.44
500		0.84	0.86	0.62	0.63	0.44	0.44
200		0.90	0.92	0.72	0.73	0.57	0.58
1000		0.77	0.80	0.57	0.58	0.41	0.42
850	(*v*)	0.75	0.79	0.49	0.50	0.33	0.34
700		0.73	0.78	0.44	0.45	0.28	0.30
500		0.76	0.80	0.45	0.48	0.22	0.22
200		0.80	0.83	0.47	0.48	0.27	0.28

vertical levels over the Northern hemisphere (North of 19.5° N) and tropical region (19.5° S to 19.5° N) are computed for 1-10 June 1998 and the same is presented in Table 2. Forecast anomaly correlation coefficient (ACC) of zonal and meridinal component of winds is presented in Table 3. It is seen that experimental run RMSE and ACC computed over the tropical region have shown improvement up to day 5.

6. Conclusions

It has been found that ERS-2 (FDP of ESA) data has lot of directional ambiguities, therefore as such it can not be utilized directly. In the present study about 80% of the ERS-2 data could be utilized in the NCMRWF Global data assimilation system after passing it through a suitable quality control procedure developed at NCMRWF. The amount of data available is important for the improvement of the analysis. Since the ERS-2 data comprises of winds at 10 mts height, the maximum impact on analysis is mainly seen in the lower level of the atmosphere. The study has shown that the ERS-2 data has the potential to define the position as well as the structure of the tropical system in the lower troposphere, provided there is a satellite pass in the vicinity of the system. Regarding the impact of this data on the medium range weather forecast, the present study revels that there is a marginal improvement in the forecast RMSE and anomaly correlation score up to day 5, however not much of impact is seen on the track prediction of this cyclonic system. It is expected that more impact on the forecast will be possible if this data is used along with other satellite data, specially form future Indian satellites with microwave sensors giving moisture and surface wind information over the data sparse oceanic region.

Acknowledgements

The authors are extremely grateful to Dr. R. K. Paliwal and Shri R. K. Bansal for their valuable suggestion and guidance. Authors are thankful for many useful discussions with NCMRWF colleagues specially Dr. K. Bhattacharya and Dr. V.S. Prasad. The encouragement given by Head, NCMRWF to carry out this study is gratefully acknowledged.

References

Anderson, D.L.T., Hollingsworth, A., Uppala, S. and Woiceshyn, P.M., 1991, "A study of the use of scatterometer data in the ECMWF operational analysis-forecast model. Part -II : Data Impact", *J. Geophys. Res*., **96**, 2635-2647.

Bansal, R. K. and Rizvi, S.R.H., 1993, "A new approach to analysis problem, Proceeding Seminar Meteorology and National Development", TROPMET-93.

Bansal, R. K., Krishnan, R., Kishtwal, C. M., Simon, B., Joshi, P. C. and Narayanan, M.S., 1994, "Impact of ERS-1 scatterometer data on the analysis and prediction of a storm in the Bay of Bengal", *Vayu Mandal*, **24**, 3-4, 59-66.

Collins, W. and Gandin, L., 1990, "Comprehensive hydrostatic quality control at the National Meteorological Centre", *Mon. Wea. Rev*., **118**, 2752 - 2767.

Gemmill, W.H., Woiceshyn, P., Peters, C.A. and Gerald, V.M., 1994, "A Preliminary Evaluation of Scatterometer Wind Transfer Functions for ERS-1 Data", NMC/OPC Technical Note, September 1994. Ocean Products Center, NMC,Camp Springs, MD 20746.

Haltiner, G. J. and Williams, R. T. 1979, "Numerical and Dynamic Meteorology", 2nd ed. John Wiley & Sons, Inc.

Hoffman, R. N., 1993, "A preliminary study of the impact of C-band scatterometer wind data on global-scale numerical weather prediction", *J. Geophys. Res*.,**98**,(C6), 10233-10244.

Joshi, P.C., Simon, B., Narayanan, M.S., Rizvi, S. R. H. and Bansal, R. K., 1996, "Impact of ERS-1 surface wind data in the analysis for medium range weather forecasting", Proceeding National Symposium on Advances in Tropical Meteorology and National Development, (TROPMET-93), 17-19 March, 1993, New Delhi, India, 85-91

Joshi, P. C., Kishtawal, C. M., Simon., B., Narayanan, M .S., . Rizvi., S. R. H and Bansal, R. K., 1998, "Impact of ERS-1 scatterometer data in medium range weather forecasting (Cyclone and Monsoon)", Scientific Report, ISRO-SAC-SR-43-98.

Kanamitsu, M., 1989, "Description of the NMC global data assimilation and forecast system", Weather Forecasting, **4**, 335-342.

Paliwal, R. K., Begum, Z. N. Ramesh, K. J. and Gupta, Akhilesh, 1999, "Evolution and maintenance of the summer monsoon -1998 by the global data assimilation-forecast system of India", Department of Science and Technology, Scientific Report - April 1999, p120.

Parrish, D. F. and Derber, J. C., 1992, "The National Meteorological Center's Spectral Statistical Interpolation analysis system", *Mon. Wea. Rev*., **120**, 1747-1763.

Prasad, V. S., Ramesh, K. J., Bohra, A. K. and Bhatia, R.C., 1998, *Meteorol. Atmos. Phys*., **68**, 197-212.

Rao, U. R., Desai, P. S., Joshi, P. C., Pandey, P. C., Gohil, B. S. and Simon, B., 1998, "Early prediction of onset of southwest monsoon from ERS-1 scatterometer winds", *Proceeding Indian Acad. Sci. (earth Planet Sci.)*, **107**, 1, 33-43.

Rizvi, S.R.H. and Parrish, D. F., 1995, "Documentation of the Spectral Statistical Interpolation (SSI) Scheme", NCMRWF, Technical Report. 1/1995.

Sela, J. G., 1980, "Spectral modelling at NMC", *Mon. Wea. Rev*.,**108**, 1279-1763.

Stofflen, A. C. M. and Cats, G. J., 1991, "The impact of SEASAT-A scatterometer data on high resolution analysis and forecasts, The development of the QEII storm", *Mon. Wea. Rev*., **119**, 2794-2802.

Stofflen, A. C. M. and Anderson, D., 1997, "Ambiguity removal and assimilation of scatterometer data", *Q. J. R. Meteo. Soc*., **123**, 491-518.