Forecasting Research

Short Range Forecasting Division

Scientific Paper No. 9

The Use of ERS-1 Products in Operational Meteorology

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August 1992

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S Division Scientific Paper No 9

August 1992

This paper has been prepared for:

Committee on Space Research (COSPAR)
WORLD SPACE CONGRESS
WASHINGTON, DC
28 AUGUST - 5 SEPTEMBER 1992

Symposium A.5-M: Satellite Observations of the Ocean and Air/Sea Interface with Emphasis on New Results from ERS-1

Invited Paper I.D. No: A.5-M.1.04

It will be submitted for publication in the *Advances in Space Research* volume dedicated to the conference.

THE USE OF ERS-1 PRODUCTS IN OPERATIONAL METEOROLOGY

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ABSTRACT

The Meteorological Office processes ERS-1 fast-delivery products from the scatterometer, the altimeter, and the Along-Track Scanning Radiometer. Wind vectors, wind speed, wave height, and sea-surface temperature data are all validated against the operational atmospheric, wave, and sea-surface temperature analyses. Summary statistics from these validations are presented. The ERS-1 data appear to have smaller errors than the ship data currently used.

Surface winds from the scatterometer should both improve the atmospheric analyses and forecasts, and improve the fluxes from the atmospheric analyses used to drive wave and ocean models. The wave data have made it worthwhile for the first time to develop a wave assimilation, rather than deducing the wave field solely from the history of atmospheric forcing. Results from preliminary parallel tests measuring the impact of these data sources are presented. Further work developing the model assimilation schemes is needed, before they give the full improvement hoped for.

1 INTRODUCTION

The ERS-1 satellite was launched in July 1991. The Meteorological Office contributed to the in situ calibration and validation campaigns /1,2/. This paper describes the activities preparing for the use of the data in the Meteorological Office's operational systems. Although the prime purpose of these systems is forecasting, archives from the system are useful for other purposes. With every observation (O) processed, the prior model estimate (background B) and the assimilation's fitted value (analysis A) are stored. These archives can be classified and analysed as desired to give information on O-B and O-A biases. In the operational NWP environment, data from several observing systems are available; intercomparison can indicate whether the bias is due to the observations, the model, or both. The rapid provision of this information to those calibrating the instruments and algorithms has greatly helped in the development of quality products from ERS-1. In addition to their forecasting use, the analyses are archived for climate-related research /3/. It is important therefore that biases should be well understood.

The European Space Agency (ESA) produces a fast-delivery data stream, including the UWI scatterometer (wind) data, and URA altimeter (wave height and wind speed) products used at the Meteorological Office. The data are encoded in the international BUFR code, and sent from Rome to Bracknell, and on to other users. Most of the data are received in Bracknell in less than three hours from the time of observation. The Meteorological Office contributed to the design and construction of the Along-Track Scanning Radiometer (ATSR) instrument. As the ATSR is not an ESA instrument, its data are processed and sent to Bracknell each day, as part of a special project. The Meteorological Office has played an important role in setting up and monitoring these communications links.

The remaining sections of this paper are devoted to the accuracy, and use, of the wind, wave, and sea-surface temperature data in turn. The data are a considerable advance on that available previously (from ships). But further work is needed before full use can be made of them in operational systems. It is hoped that good progress will be made with this in the coming months, so that data from ERS-1, and its planned successor ERS-2, can be demonstrated to be useful for operational meteorology.

2 SCATTEROMETER (WINDS)

Processing

Calculation of wind vectors from the scatterometer data is a rather complicated process. First an engineering calibration is needed to convert the observed signal into backscatter cross section σ_0, for each of the three antennae. Then an empirical relationship relating these σ_0 to the surface wind stress has to be inverted. Because the σ_0 seen looking up- or down-wind are very similar, two antennae give a vector wind with a four-fold ambiguity in direction. A third usually reduces this to a two-fold ambiguity. Before launch, it was hoped that the differences in up-wind and down-wind σ_0s, and the comparison of adjacent fields of view, would be sufficient to resolve this ambiguity, and produce a unique vector wind. However this has turned out not to be so. Figure 1 (left) shows that the vector winds produced by ESA have an 180° ambiguity; almost 50% differ from the model background's direction by about 180°. A data assimilation scheme is capable of providing the information to resolve the ambiguity. The fact that there are few O-B directions near $\pm 90^\circ$ shows that the background directions are accurate; if they were not, one would expect the differences to be more evenly distributed. So at the Meteorological Office we reprocess the σ_0 data, using the background wind information. This does not mean that the background direction is always retained; if the antennae look angles are such that the information in the observation, or surrounding observations, make another direction more likely, it is chosen. An example of this can be seen in figure 3. (In this case **most** of the ESA winds had the wrong direction.) Having control of the processing system allows us to make a rapid response to changes in the instrument calibration, or improvements in the σ_0-wind relationship, so the wind speed statistics for our winds do not precisely match those for ESA's. Figure 1 (right) shows that the speeds for the winds from both systems were biased low compared with the model (which is itself suspected of a low bias). However the Met Office system was better calibrated. All the results shown below are for the winds processed by the Met Office system.

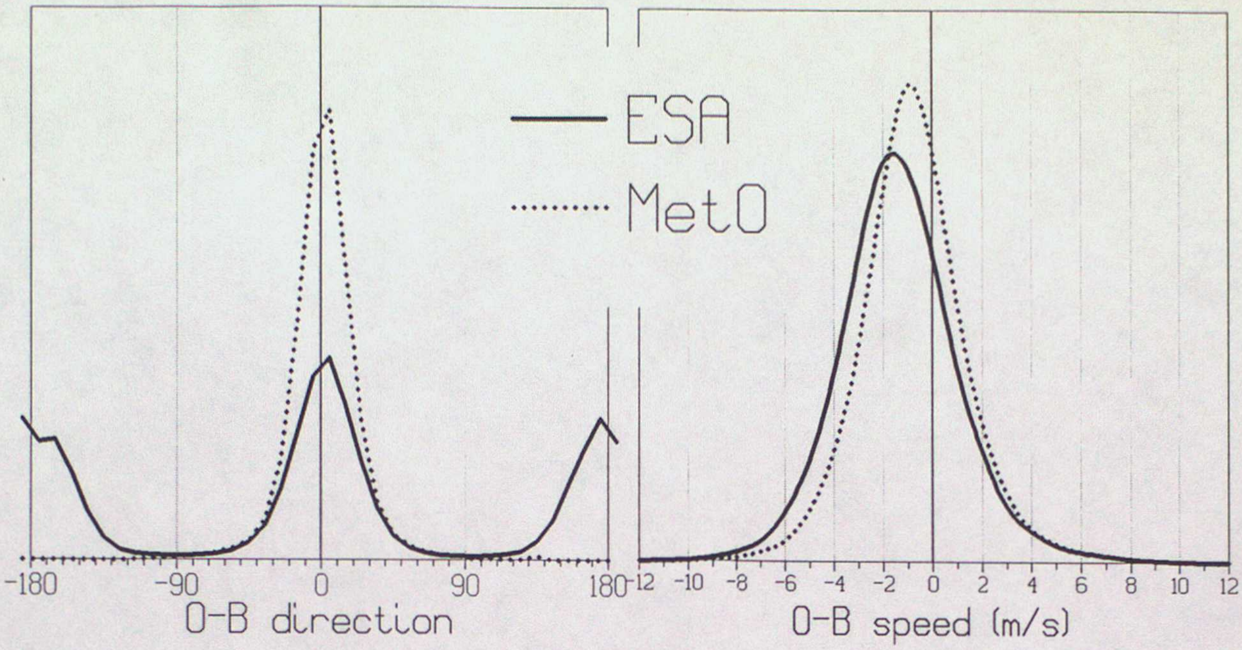

Figure 1: Histograms of ESA's and Met Office's observation minus background (O-B) differences, for observations for which the speed satisfies 5 < (O+B)/2 < 15 m/s, for March 1992. *Left:* direction (degrees). *Right:* speed (m/s).

Monitoring Results

Tables 1 and 2 shows some results from monitoring the Met Office processed winds for March 1992 /4/. Excluded from the statistics are reports which might be bad: less than 3 beams used, instrument arcing, close to sea ice or land, the Met Office retrieval process failed to resolve the ambiguity in wind direction, ESA or Met Office winds missing (which for example occurs when the speed is less than 4 metres per second), ESA or Met Office O-B vector wind difference exceed 25 metres per second. The statistics for ERS-1 winds can be compared with those for 'reliable' ships. (A ship is 'reliable' if its monthly rms vector O-B is less than or equal to the mean for all ships in the 10° box in which it falls). Out of 75645 ship wind reports, 30272 (40%) were from the 'reliable' ships.

The final calibrations for the processing were not available in March 1992. Table 1 show a negative O-B bias for the ERS-1 winds, which is more significant because the ships seem to indicate that the model winds are too weak (ships' observed wind speeds may however be overestimates of the 10m wind). Overall the impression gained from both tables is that the ERS-1 winds are somewhat more accurate than the ships'. Table 1 shows that O-B differences for both observing systems are larger in the southern hemisphere. This is indicative of the background being less accurate there.

Table 1. Statistics on the differences between Met Office processed ERS-1 winds, and the background provided by the Met Office global model, for March 1992, classified by latitude band. Comparison statistics for reliable ships are also given. Units are m/sec and degrees.

	30-90°S	30°S-30°N	30-90°N	Global
	ERS-1 scatterometer winds processed at UKMO			
No. of observations	800905	505873	187457	1494235
Mean obs. speed	8.9	7.1	9.1	8.2
Mean O-B speed	-0.6	-0.4	-0.5	-0.5
Mean O-B direction	2.5	-1.0	-1.1	0.9
SD O-B speed	2.8	1.8	2.3	2.4
SD O-B direction	25.5	19.0	21.2	23.1
RMS O-B vector	4.6	2.8	3.8	3.9
	Reliable ships			
No. of observations	2404	11611	16167	30182
Mean obs. speed	8.8	6.5	9.0	8.0
Mean O-B speed	1.5	0.9	1.2	1.1
Mean O-B direction	3.3	-0.8	-2.2	-1.2
SD O-B speed	3.2	2.3	2.8	2.7
SD O-B direction	41.8	33.4	34.0	34.5
RMS O-B vector	5.6	3.8	4.9	4.6

Table 2, as table 1, classified by the mean of observed and background speeds.

(O+B)/2 speed	0-5	5-10	10-15	15-20	20-25	>25
	ERS-1 scatterometer winds processed at UKMO					
No. of obs	49050	1199252	393748	32011	903	4
Mean obs speed	4.9	7.2	11.4	16.8	21.9	
Mean O-B speed	2.7	-0.7	-0.7	1.1	2.8	
Mean O-B dirn.	-0.9	0.5	1.8	-1.0	-5.1	
SD O-B speed	1.9	2.1	2.9	3.0	2.6	
SD O-B dirn.	47.5	23.0	18.7	15.6	12.0	
RMS O-B vector	4.4	3.6	4.7	5.4	6.5	
	Reliable ships					
No. of obs	7931	15918	5267	989	74	3
Mean obs speed	3.7	7.8	13.0	18.2	24.5	
Mean O-B speed	0.2	1.1	1.9	3.2	6.2	
Mean O-B dirn.	-0.2	-1.2	-2.0	-1.5	1.8	
SD O-B speed	2.1	2.5	3.1	3.5	3.3	
SD O-B dirn.	53.7	32.4	22.5	17.5	20.1	
RMS O-B vector	3.5	4.4	5.6	6.8	10.2	

Impact

Maps of the UKMO de-aliased winds have been made available to the Central Forecast Office since Autumn 1991 and have been received enthusiastically; the quality is good and de-aliasing problems are few. Small scale low pressure systems (both extra tropical and tropical) and trough lines (e.g. fronts) have been identified with considerable extra detail compared with model background plots. The forecasters have also been happy with the wind strengths in the high wind regimes.

The Met Office σ_0 to wind processing implicitly includes some quality control, against the background used and the surrounding data. Prior to the data assimilation, the observation processing system includes a check against a new background field, made using more recently received observations. Additional constraints on the observed divergence are being considered to filter out some of the incorrect aliases. The observations at the inner edge of the swath have been found to be unreliable (e.g. the most westerly winds in figure 3) and are rejected. The assimilation was performed using the Met Office's operational Analysis Correction scheme /5/.

The characteristics of the scatterometer wind observations differ significantly from conventional sources of surface wind data. Apart from the obvious geographical distribution difference (with the satellite data having a uniformly high data density within the swath), the retrieval algorithms have been tuned to give winds at a nominal 10m (the heights of ships' winds are not clearly defined) and the directions are considered more unreliable than ships in light wind regimes. Revisions to the operational data assimilation system have been introduced to account for these different characteristics. The increments at the observation position are calculated using a modelled 10m wind (obtained from the boundary layer parametrisation). Below a threshold (4m/s) the assimilation takes speed information but not direction from the report. Additional flexibility has been built into the assimilation to enable parameter tuning to be more observation specific, thus capturing information from the scatterometer observations whilst still making best use of ship reports. Some further revision of parameters is in progress, to enable the assimilation to capture some of the small-scale detail present in the data. A more efficient algorithm to spread information horizontally has been developed using a recursive filter to cope with the high density of data. Improved coupling of wind and pressure information is being developed.

Preliminary assimilation tests were run during March 1992, whilst the processing algorithms were still being tuned. There were substantial gaps in the data coverage in the North Atlantic sector where the SAR instrument was regularly switched on in preference to the scatterometer. However, despite this there were an average of 160000 reports/day used by the assimilation during a 10-day period from 2nd March. Assimilation and forecasts with the global model (resolution 90 km) were compared with those made operationally not using ERS-1 data.

The first tests showed a disappointingly small impact on the analyses in the Tropics and Northern Hemisphere, but in the Southern Oceans the control and test assimilations diverged substantially. There were surface pressure differences of up to 8mb in the vicinity of the major low pressure systems (figure 2) and more detail in the 10m wind analyses. The impact was retained in the southern hemisphere during a 72 hour forecast. From a global perspective, there was a small shift towards weaker 10m winds, reflecting the apparent biases in the scatterometer data.

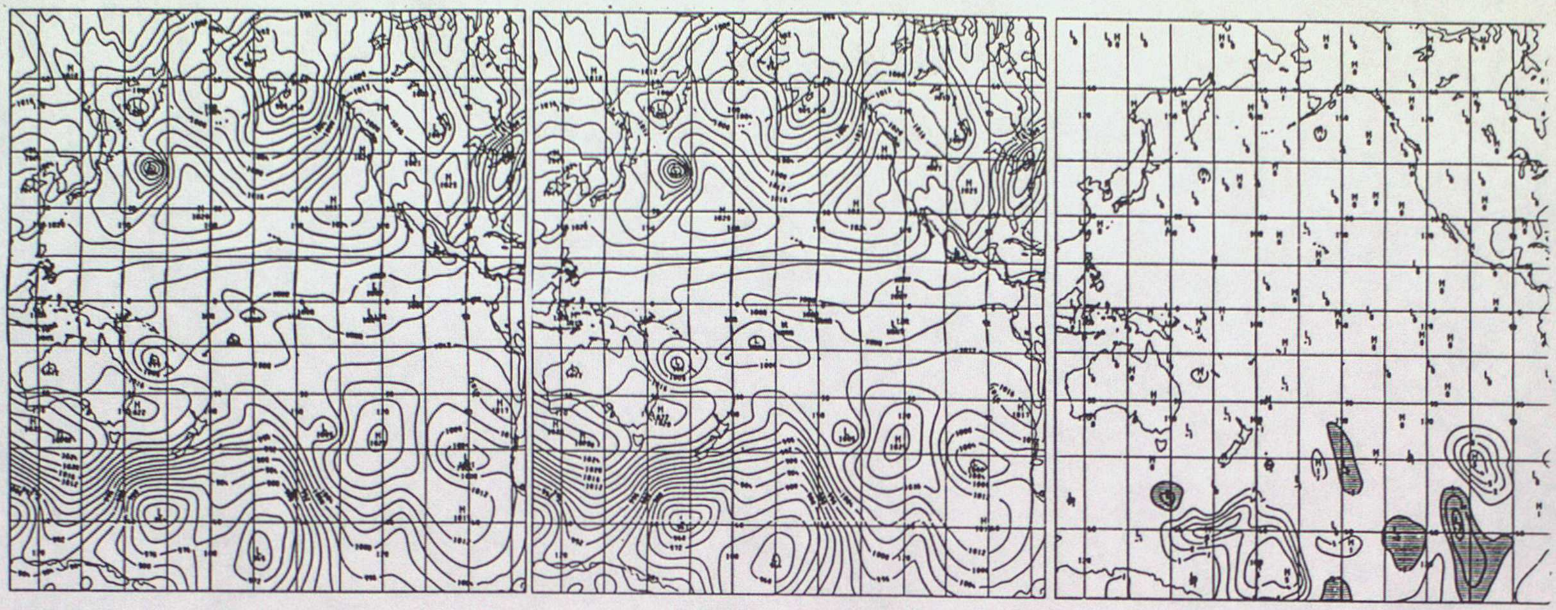

Figure 2: Surface pressure analysis for the Pacific on 11th March 1992,
Left: from the assimilation using the ERS-1 winds (contour interval 4mb),
Middle: corresponding analysis not using ERS-1 data,
Right: Difference (contour interval 1mb, <-1mb shaded, zero suppressed).

It is emphasised that these preliminary runs were not optimised for the assimilation of scatterometer data. For the larger scales, geostrophic adjustment theory indicated that pressure data are more effective than winds; an inverse balance coupling between wind increments is being developed, but was not available for these experiments. As noted by the operational forecasters, the data contains much apparently useful small scale information. We are still learning how best to capture and retain such detail in the assimilation. Some of the information is diagnostic, for instance a development at the surface is driven by the upper flow pattern. It it difficult to invert this and deduce the upper pattern given the surface flow. A simpler problem is that the global assimilation is tuned to extract information with scale of several grid-lengths, while the detail in a swath of data often has smaller scales. In this context some 40 km resolution limited area assimilation experiments have been run to examine a low pressure system near the UK which was not identified well by model forecasts or conventional data sources. On the 11th March a cold air ‘polar’ low moved rapidly southward across northeast Scotland causing increased shower activity and a short period of storm force winds over the North Sea oil rigs. The reruns of this case using scatterometer data (figure 3) with higher weighting and decreased horizontal correlation scale gave analyses with a more clearly identified troughing in the wind field (figure 4) and matching changes to the pressure (figure 5).The effect of these changes was seen in the short period forecast which followed (not shown); in a slightly sharper trough, and heavier convection.

In summary, we have seen clear potential in this new data source and we are beginning to learn how to realise that potential.

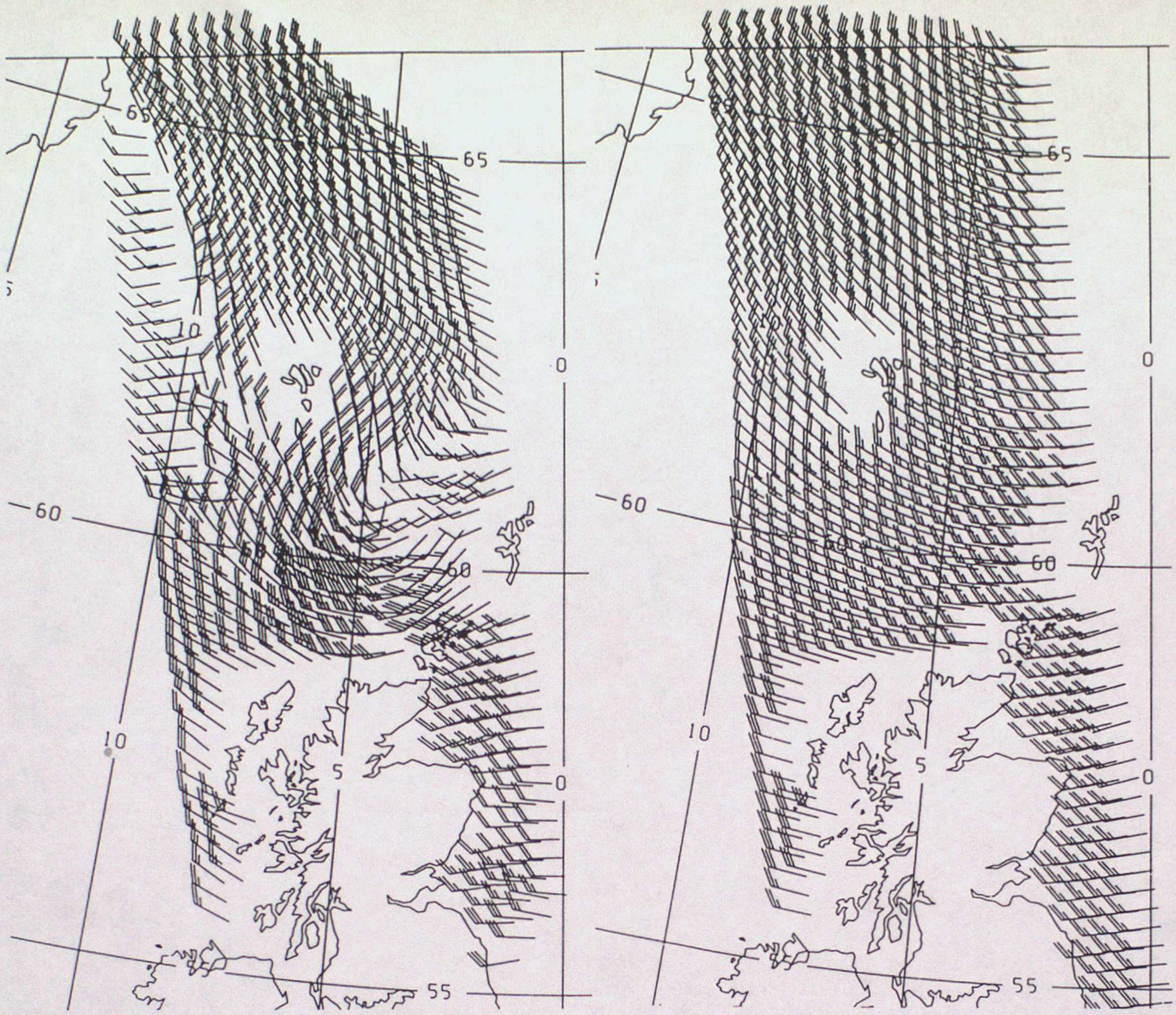

Figure 3: *Left:* ERS-1 winds, processed at the Met Office, 11th March 1992, for a swath north of the UK. *Right:* background winds used in the processing.

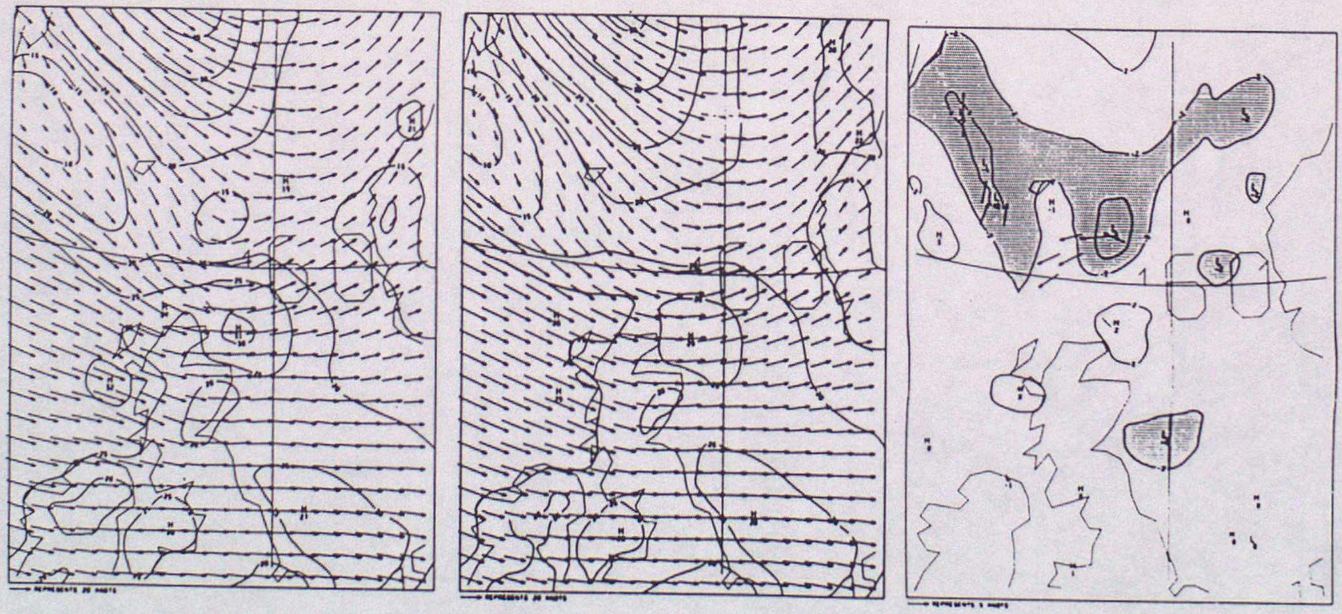

Figure 4: 10m winds north of the UK on 11th March 1992,
Left: from the assimilation using the ERS-1 winds (contour interval 5 knots),
Middle: corresponding analysis not using ERS-1 data,
Right: Difference in speed (contour interval 0.2knots, <-0.2knots shaded, zero contour suppressed), and vectors (for vector differences > 5 knots).

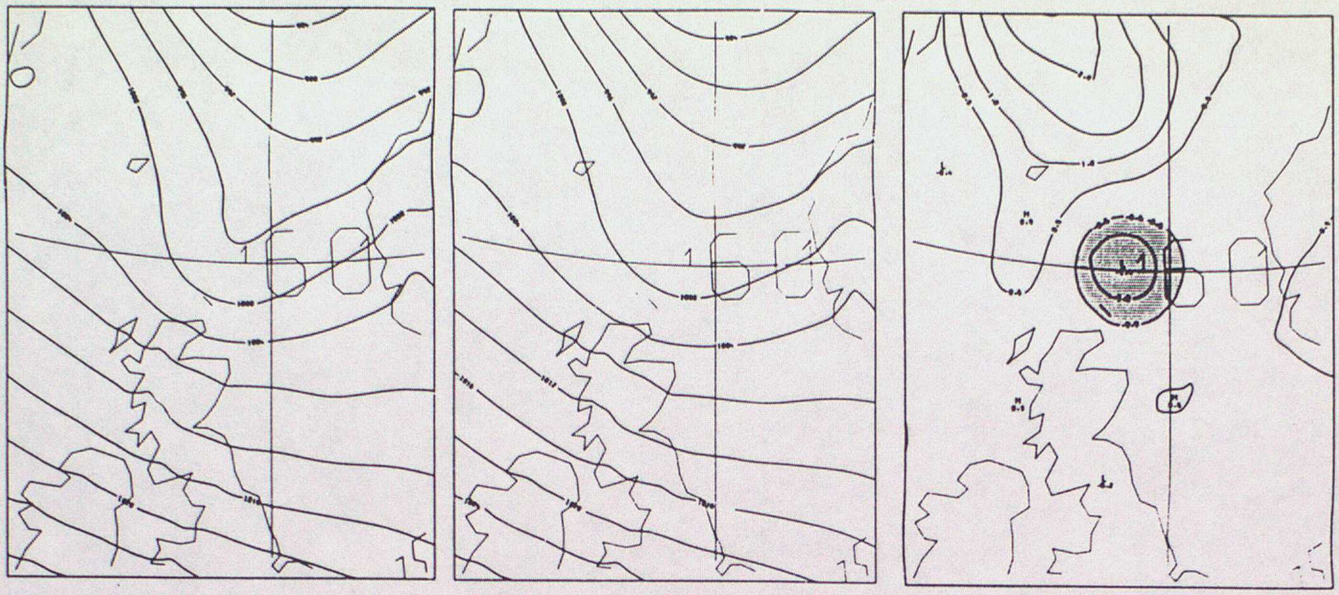

Figure 5: Surface pressure analysis north of the UK on 11th March 1992, *Left:* from the assimilation using the ERS-1 winds (contour interval 4mb), *Middle:* corresponding analysis not using ERS-1 data, *Right:* Difference (contour interval 0.5mb, <-.5mb shaded, zero contour suppressed).

3 ALTIMETER (WAVE HEIGHT & WIND SPEED)

ERS-1 carries a radar altimeter. This measures three quantities of interest to oceanographers: the height of the satellite above the ocean surface, the surface wind speed, and the significant wave height. Of these, the last two measurements have been studied at the Met Office. Since August 1991, altimeter data have been delivered in real time and processed by the wave modelling group. Accuracy of the altimeter wind and wave data has been assessed by comparing the ERS-1 estimates with those from the atmosphere and wave models. A typical weekly summary is shown in table 3 for the wind speeds, which may be compared with table 2. Only observations over sea were included, but nevertheless there is some contamination because of the time delay for the altimeter to adjust from land to sea tracking mode. This, and also physical saturation of the signal, makes the altimeter winds unreliable for speeds > 20 m/s. Table 4 shows a similar summary for the significant wave heights, and a comparison with buoys, to give an indication of the model bias, although care must be taken as the buoys give a small sample not collocated with ERS-1 observations. ERS-1 estimates of the wave heights are similar to those of buoys at low wave heights; both have a large bias (comparable to the SD), indicating that the model values are too low. At higher wave heights the ERS-1 heights are greater than those of the buoys.

<u>Table 3</u>, as table 2, for altimeter winds 14-21 February 1992. (units m/s)

(O+B)/2 speed	0-5	5-10	10-15	15-20	>20
		ERS-1 radar altimeter wind speeds			
No. of obs	61854	110336	30573	3792	32
Mean O-B speed	-0.4	0.4	0.9	1.9	9.7
SD O-B speed	2.3	2.2	2.8	3.3	8.8

Table 4. Statistics on differences between ERS-1 altimeter wave heights (O)and the Met Office global wave model (B), for 14-21 February 1992. Data from a few moored buoys are included for comparison. (units m)

	ERS-1 radar altimeter wave heights			
(O+B)/2 height	0-3	3-6	6-9	>9
No. of obs	168552	37026	1949	60
Mean O-B	0.8	0.7	6.1	4.3
SD O-B	0.6	1.6	5.9	3.3
	Moored buoys wave heights			
O height	0-3	3-6	6-9	
No of obs	457	163	7	
Mean O-B	0.5	1.1	2.9	
SD O-B	0.7	1.3	3.0	

The Met Office's operational wave forecasts come from a model driven by the atmospheric model's winds. A continuous "hindcast" using analysed winds gives fairly realistic wave fields, which are initial conditions for a forecast using forecast winds. No wave observations are used. Starting in mid-November, ERS-1 wave and wind speed data were used in an experimental assimilation scheme /6/ for the wave model. This finished at the end of January. The use of the altimeter data improved verification statistics for the model against buoys (buoy data were not used in the assimilation). The bias was reduced by 0.3 m. The impact can be seen in figure 6, which shows 12 hours' data, and the difference between assimilation and control at the end of the period. Practically all of this difference was positive, with areas of 1 m under the recent satellite track (peak value 2 m). The pattern of changes clearly reflects the satellite orbits shown, and there is some residual impact from earlier orbits. Synoptically, the most obvious improvement was in the treatment of swell in the tropics. It was possible to track differences in swell arising from the assimilation across ocean basins.

An important spin-off from these experiments was the characterisation of systematic errors due to deficiencies in the wave model; the main impact of the wave data was the reduction of the bias caused by these. Work on an improved model is well advanced. When it is complete, we will repeat the above experiment, and also assess the (probably equally important) impact of the scatterometer winds, via the atmospheric assimilation, on the wave model.

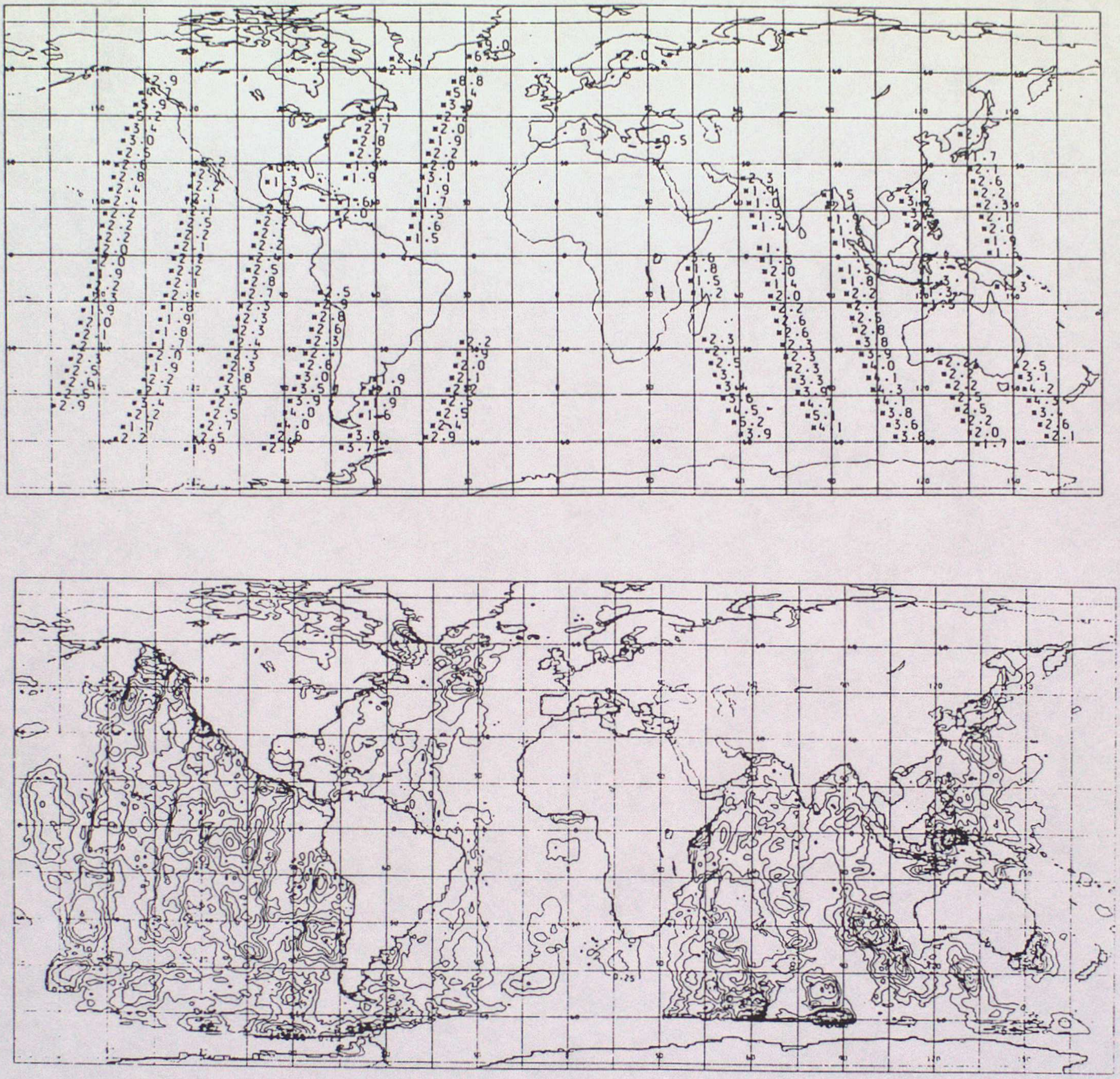

Figure 6: ERS-1 altimeter wave height observations, averaged along the track, for the 12 hours before 00Z 13 November 1992. Wave assimilation minus operational (no ERS-1 data) wave heights (contour interval 0.25m).

4 ATSR (SEA-SURFACE TEMPERATURE)

Previous satellite observations of sea-surface temperature (SST) have used infra-red (IR) radiances affected to an unknown extent by atmospheric effects, especially from aerosol. Empirical calibration against in situ observations has to be used. The ATSR instrument uses a conical scanning technique: the instrument sweeps out a cone of half angle 23.45° to produce a nadir and a forward swath, each 500km wide. This results in two views of the same point at short time intervals through different atmospheric path lengths. This, and careful absolute calibration of the instrument, give the capability in principle of a direct physical derivation of the sea-surface temperature. The ATSR data processing system produces several products including high resolution 512x512Km brightness temperature and SST images and half degree average sea surface temperatures (ASSTs). The ASSTs are processed and transmitted from the satellite receiving station in Tromsø, Norway to the UK Met Office in near real time. It is this product which is being assessed in order to determine its suitability for use in the Met Office's SST analysis.

IR radiometers measure the radiative temperature of the oceans skin, which is representative of only the top few micrometers, since water is a strong absorber and emitter of IR radiation. Ships' and buoys' SST sensors are located at depths ranging from several centimetres to several metres below the sea surface. The radiative skin temperature is generally less than the temperature immediately below by approximately 0.2-0.5K, as a result of vertical heat fluxes through the air-sea interface. The magnitude of this differences varies with several factors including surface wind stress, solar insolation and cloud cover. It is the bulk temperature which is required for meteorological uses, since it is more stable. It will be necessary to parametrize the skin effect if the ATSR physically derived data are to be used. In the first instance we are just validating the observations, with the aim of using them with an empirical correction.

Table 5 shows validation statistics against an analysis made using in situ data only. The global mean bias of the dual-path ASSTs is slightly less than 1K. This is somewhat larger than the skin effect measured from research ships /7/, indicating that more work is needed before the data can be used as direct absolute measurements to the accuracy needed for climate change detection (~0.2K). The standard deviation of the differences between ASSTs and the analysis is approximately 0.7K. The other satellite SSTs are produced using algorithms empirically calibrated against in situ data; they are estimates of bulk SST. They have smaller biases, but comparable standard deviations. The ATSR ASSTs have a considerably lower s.d. than ship data. This indicates the potential utility of the data when the skin effect and bias problems have been sorted out.

Table 5. O-A STATISTICS FOR SST OBSERVATION TYPES (MARCH 1992)

Observation type	Used in analysis?	n	mean O-A	s.d. O-A
Ships	yes	57597	0.12	1.06
Drifting buoys	yes	38544	-0.04	0.33
Fixed buoys	yes	34758	0.02	0.46
Bathys	yes	4201	0.08	0.51
Trackobs	yes	659	0.08	0.65
NOAA-11 (AVHRR)	no	100211	-0.37	0.73
Meteosat	no	67898	-0.41	0.74
GMS (Japan)	no	21232	-0.76	1.08
ATSR (dual)	no	125293	-0.86	0.69

The ATSR, being an IR instrument, is affected by cloud in the field of view. Algorithms for detecting cloud-free fields of view are still under development; some versions give very few data for high latitudes. This is apparent in table 6. The quality of the ASST products has proved to be highly sensitive to these cloud tests. When one view is not cloud free, single view data may be returned. The single view algorithm is intrinsically less accurate in correcting for atmospheric effects. Also, the single view data used in the table come from cloudier areas, another source of error. Not surprisingly, dual view ASSTs show significantly better agreement with the UKMO analysis than the single view.

Table 6. Comparison of ATSR data and the UKMO SST Analysis - March 1992

	Number		Mean O-A		s.d. O-A	
	Single	Dual	Single	Dual	Single	Dual
60-90N	2		1.95		0.00	
30-60N	8425	5478	-1.67	-1.04	0.69	0.64
0-30N	21304	45767	-1.75	-0.84	0.63	0.59
0-30S	29227	44304	-1.65	-0.90	0.62	0.65
30-60S	32228	29626	-1.18	-0.82	0.91	0.90
60-90S	3335	64	-1.10	-0.69	0.63	0.49
ALL	94521	125293	-1.49	-0.86	0.73	0.69

Experiments have been performed using the dual view ASSTs in the global analysis program. (Because of the poor data availability, they are of little use for local UK mesoscale use). The bias seen in table 5 is manifest in the difference between this and the in situ data analysis.

SUMMARY

The Met Office has been assessing wind wave and SST data from ERS-1. Comparison of the observations from ERS-1 with model fields has shown the data to be useful, and in many cases to be better than existing sources of data. The data analysis systems are being modified and developed to take full advantage of this new data source.

REFERENCES

1. Offiler, D. 1992 "Wind measurements from the MRF C-130 and the Derivation of Analyses from RENE-91 Winds" ESA Proceedings of ERS-1 Geophysical Validation Workshop, France, April 1992.

2. Offiler, D. 1992 "Validation and comparison of alternative wind scatterometer models" ESA Proceedings of ERS-1 Geophysical Validation Workshop, France, April 1992.

3. Lorenc, Andrew C. 1992 "Assimilation of Satellite Data in Models for Energy and Water Cycle Research". Met.O(S) Scientific Paper 8. presented at the COSPAR World Space Congress, Washington D.C., September 1992. to be submitted for publication in *Adv. Space Res.*

4. Smith S.G., and Waters S.R., 1992 "Statistics of ERS-1 scatterometer winds for March 1992 including a comparison with ship observations" Met.O(CF) Monitoring Note 9.

5. Lorenc,A.C., Bell,R.S., and Macpherson,B. 1991 "The Meteorological Office Analysis Correction data assimilation scheme".*Quart.J.Roy.Met.Soc.*, **117**, 59-89

6. Stratton R.A., Harrison D.L., and Bromley R.A., 1990 "The assimilation of altimeter observations into a global wave model." AMS 5th Conference on Satellite Meteorology and Oceanography. London 1990. 108-109

7. Schluessel P., Emery W.J., Grassl H., and Mammen T., 1990 "On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperatures". *J.Geophys.Res.*, **95**, 13341-13356

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