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THE ACCURACY OF SHIP'S METEOROLOGICAL OBSERVATIONS

RESULTS OF THE VSOP-NA

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THE ACCURACY OF SHIP'S METEOROLOGICAL OBSERVATIONS

RESULTS OF THE VSOP-NA

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P R E F A C E

Meteorological observations made onboard merchant vessels of the WMO voluntary observing ships (VOS) scheme, when transmitted to shore in real-time, are a substantial component of the Global Observing System of the World Weather Watch and are essential to the provision of marine meteorological services, as well as to meteorological analyses and forecasts generally. These observations are also recorded in ships' meteorological logbooks, for later exchange, archival and processing through the WMO Marine Climatological Summaries Scheme, and as such they constitute an equally essential source of data for determining the climatology of the marine atmosphere and ocean surface, and for computing a variety of air-sea fluxes. At the same time, however, it has long been recognized that these observations are subject to errors, both systematic and random. Many of these errors are the result of inadequate or inappropriate instrument siting onboard ship, or through the use of instrumentation or observing techniques which are less than optimal.

The VOS Special Observing Project North Atlantic (VSOP-NA) was therefore initiated, jointly by the WMO Commission for Marine Meteorology (CMM) and the Committee on Climate Changes and the Ocean (CCCO) of IOC/SCOR, on behalf of the WCRP, to try to establish the effects on the quality of VOS data of different ship instrumentation and observing practices.

Six national observing fleets participated - those of Canada, France, Germany, Netherlands, United Kingdom and USA - and ultimately 45 ships supplied data for the project. New logbooks were designed to enable the acquisition of supplementary information to define the detailed instrumentation and practices in use by each ship, so that the effects of these differing methods of data gathering could be quantified. These logbooks were collected by participating Port Meteorological Officers at the end of each voyage, and submitted to the project digitizing centre operated by the Seewetteramt of the German Weather Service in Hamburg. From there, the data were transferred to the United Kingdom Meteorological Office in Bracknell for archival and analysis, jointly by the Meteorological Office and the James Rennell Centre in Southampton. Eventually a total of more than 33,000 observations were collected during the project observation period from May 1988 to September 1990 and these, together with the information on instrument siting and exposure and the meteorological analysis fields from the numerical model of the United Kingdom Meteorological Office, provided the basis for the data analysis.

This particular document, prepared by Ms E. Kent and Dr. P. Taylor of the James Rennell Centre, United Kingdom, and Mr. B. Truscott and Mr. J. Hopkins of the United Kingdom Meteorological Office, gives a summary of the data acquisition, data processing and analysis phases of the project, and describes the results of the analysis. A companion report to this (No. 25 in the same series) contains a catalogue of the VSOP-NA ships, describing in detail the ships' characteristics, routes and meteorological instruments fitted.

There is no doubt that the results of this project are of considerable importance to climate analysis and modelling, in particular in their implications for the computation of air-sea fluxes of heat, momentum and water vapour. They are also likely to have a significant and benefical impact eventually on the operation of the whole of the VOS, with consequent benefits not just for research but also for operational meteorology.

The considerable appreciation of the sponsoring organizations for the project is extended to the authors of these two reports, Ms E. Kent and Dr. P. Taylor of the James Rennell Centre and Mr. B. Bruscott and Mr. J. Hopkins of the United Kingdom Meteorological Office for their substantial and high quality analysis work. Thanks are also due to the Seewetteramt, Hamburg, for undertaking the major task of digitizing the data; to the members of the project Management Committee for their excellent supervision of the project; to the Port Meteorological Offiers of the countries concerned for recruiting and servicing the project ships; and last but by no means least, to the officers and crew of the ships themselves, for their co-operation and support for the project, without which nothing would have been possible. It is hoped that they will eventually see the direct fruit of their efforts in the form of improved meteorological forecast and warning services for mariners.

(J. Rasmussen)
for the Secretary-General of WMO

(G. Kullenberg)
Secretary IOC

Contents

EXECUTIVE SUMMARY

The effect on the quality of Voluntary Observing Ship (VOS) data due to different instrumentation and observing practices has been evaluated during the Voluntary Observing Ships Special Observing Project for the North Atlantic (VSOP-NA). Forty-five VOS ships operating in the North Atlantic were recruited into the VSOP-NA by the participating VOS operators (Canada, France, Germany (FRG), Netherlands, United Kingdom and United States). For these ships, additional information was obtained on the instrumentation carried (Kent and Taylor, 1991, Marine Meteorology and Related Oceanographic Activities, Report No. 25, WMO Geneva) and on the observing practises used (reported on logsheets with each observation).

The output from the analysis phase of the U.K. Meteorological Office Fine Mesh atmospheric forecast model was used as a standard to compare one ship observation with another. Important results include detection of the effects of model characteristics, of biases due to the different types of instrumentation used, and an assessment of the value of the additional data groups reported.

a) Model Characteristics. The VSOP-NA results showed the value of the ship observations for quality controlling model analyses. Compared to the ships, model values of *air temperature* were found to be higher in colder regions and vice versa. Particularly in winter there was a geographical trend with the model temperatures increasing to the northwest compared to the ships. For *humidity* the model values were drier under low humidities but moister for the most often observed humidity values. Model derived surface *wind speeds* were biased low by an estimated 2 knots compared to the ships. *Air pressure* comparisons showed a north-south trend in the model values of about 0.3 mb.

b) Instrument Characteristics. The use of different measuring techniques was found to produce significant differences in the data characteristics. Engine intake derived *sea surface temperature* values were warm by about 0.3°C compared to hull sensor values, and, except in low heat flux, stable conditions, compared to buckets. Psychrometer and screen derived *air temperatures* generally showed similar errors due to solar radiation (of order one or two °C, the effect being modulated by the wind speed); but some screens had particularly poor exposure and correspondingly larger errors. Psychrometer derived *dew point temperatures* were lower (and therefore more likely correct) compared to screen values by between 0.5°C and 1.5°C. Even after allowing for the height of measurement, the fixed *anemometer readings* were greater than Beaufort estimates; furthermore there were many errors in correcting measured winds for the ship velocity. *Pressure* values from digital Precision Aneroid Barometers were less scattered than those from analogue instruments.

c) Augmented Documentation. The major cause of degradation of the data, detected by the additional data groups provided with each observation, was the correction of measured relative winds to true winds. Where more than one method of sea surface temperature measurement is used the measurement method must be known to remove possible biases; this is not presently the case for observations transmitted by radio.

On the basis of these results a series of **recommendations** were formulated by the VSOP-NA Management Committee. These included[1]:

a) **Recommendations to members operating VOS** concerned the need for improved observing practices and equipment, the need to publicise the VSOP-NA results, and the desirability for increased real-time data monitoring. Errors in true wind and dew point calculations should be decreased by the provision of dedicated computer programs or calculators.

b) **Recommendations to WMO** concerned the reporting of sea surface temperature measurement method and of the ships draft or "height of eye"; possibly requiring the implementation of coding changes. A need was identified for improvement of the List of Selected Ships (WMO 47) and also for a reference booklet on observing practices. The importance of the Port Meteorological System to data quality was emphasised. The VSOP-NA results should be considered in re-assessment of the Beaufort Scale, and consideration given to the reporting of relative wind in ships' logbooks.

c) **Recommendations for Climate Research** concerned the use of VOS data to verify model flux determinations, that sea surface temperature data should be processed separately according to observation method, and that support should be given for measures to improve the Port Meteorological Officer system.

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1 For the full text of these recommendations see Section 11 of the report.

1. INTRODUCTION

1.1 VSOP-NA project

The Voluntary Observing Ships Special Observing Project for the North Atlantic (VSOP-NA) (WMO, 1987, 1988) was set up to establish the effect on Voluntary Observing Ship (VOS) data of different instrumentation and observing practices. Six national observing fleets participated - those of Canada, France, Germany (FRG), Netherlands, United Kingdom and United States - and the aim was to recruit about 50 merchant vessels with good observing records to provide extra information to supplement their conventional observations. In the event, 45 vessels supplied data. A catalogue of the VSOP-NA ships (Kent and Taylor, 1991) has been prepared describing in detail the ship characteristics, routes and meteorological instruments fitted.

This document provides a summary of the data acquisition, data processing and analysis phases of the project, and describes the results of the analysis[1].

While many of these errors are likely to be small and perhaps insignificant for operational forecasting, even small biases can have significant effects in air-sea flux estimations. With the increased requirement for longer term forecasting and for climate research and prediction, identification of these errors, through projects such as VSOP-NA is now urgent.

1.2 The need for augmented observations

It has long been recognised that observations made on board merchant vessels are subject to errors, both systematic and random. There are clear difficulties in siting instruments so that they provide measurements which are representative of the 'free' air undisturbed by the presence of the ship itself. Some national services consider that estimates of wind speed, made using the Beaufort Scale, are preferable to measured values which are subject to unquantified calibration, exposure and reading errors. Also, the design and siting of thermometer screens varies widely between national services, and some recommend the use of psychrometers to increase the likelihood of adequate ventilation.

Data submitted by the VOS both in real time and later via logsheets include only very limited information to allow discrimination between different observing practices. A major aim of the VSOP-NA was to acquire supplementary information to define the detailed instrumentation and practices in use by each ship, so that the effects of these differing methods of data-gathering could be quantified.

1.3 Method of analysis

The acquisition and assembly of the VSOP-NA dataset is described in Section 2. To provide a reference against which observations could be compared, archived analysis fields provided by a

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1 Preliminary reports were prepared during the analysis phase by Starkey (1989) and Truscott (1990). In addition, a total of seven newsletters were circulated from the UK archiving centre to keep the participants informed of progress with data collection and early analysis.

Numerical Weather Prediction model were accessed, and each VSOP observation matched against its corresponding model analysis value for the same time and location. Differences (observation minus model) were summarised by ship, by observing practice, and by prevailing conditions, to expose these effects in quantitative terms.

The model analyses, while being subject to various errors due to simplifications and assumptions in the model physics, can be regarded as providing a useful reference datum. Thus, we are not considering the absolute accuracy of the model's performance (although some conclusions can be drawn, see section 10). Rather, using the model, we are seeking to compare ship observations from widely differing areas and times in order to expose relative differences arising from the VSOP ships' differing instrumentation and observing practices. A problem in this approach is that certain of the VOS observations have been used in the model initialisation scheme; this will be considered in Section 3, and in discussion of the affected variables.

A statistical summary of the analysis results is presented in Section 4, followed by a more detailed discussion in Sections 5 - 9. The results show that statistically significant differences exist both between and within national observing fleets; that some observing methods appear more consistent than others, and that certain biases can be linked to inadequate exposure of equipment. It is hoped that these results will assist in establishing the inherent accuracies of the VOS data, for application in such areas as operational weather forecasting, climate change studies and satellite data verification. In the light of these results (summarized in Section 10), some **recommendations** are formulated (Section 11) regarding observational practices on board vessels of the Voluntary Observing Fleets.

2. THE VSOP-NA DATA SET

2.1 Data Acquisition

The identification and recruitment of suitable ships was the first difficult and time-consuming phase of the project. An initial selection was made on the basis of the reporting performance of ships regularly plying the North Atlantic. Actual recruitment was undertaken by Port Meteorological Officers (PMOs), using a presentation package prepared centrally.

Since the additional information on instrumentation and observing practices was crucial for the success of the project, every effort was made to obtain detailed and complete descriptions of instrument types and exposures. The acquisition of this information continued throughout the data collection phase, and ultimately a catalogue was assembled (Kent and Taylor, 1991) containing the following information for most vessels:

i. Methods of observation of wind, temperature, humidity, sea surface temperature and pressure.
ii. Height of all instruments above a nominated reference level.
iii. Ships' plans clearly showing the instrument positions.
iv. Photographs of the instruments showing their exposures.
v. Limited model/manufacturer details for equipment in use.

With each observation, the following supplementary information was requested, to be entered in columns added to the standard logsheet format:

i. Ship's speed.
ii. Ship's heading.
iii. Height of deck cargo above sea level.
iv. Height of nominated reference level above sea level.
v. Method of sea surface temperature measurement.
vi. Location of air temperature measurement.
vii. Relative wind speed.
viii. Relative wind direction.

The first VSOP observations were made (by Dutch recruited vessels) in May 1988, but most German and UK recruited ships started VSOP-NA observations in September of that year, and USA and French ships in the early months of 1989. Table 1a shows the number of observations submitted by each for each month of the project.

Observation sheets were collected by the responsible national meteorological service and forwarded to the data keying centre at Deutscher WetterDienst, Hamburg. The data format used was an extended version of the International Marine Magnetic Tape (IMMT) format, with the supplementary information added at the end of each record. Magnetic tapes were then dispatched to the archiving centre at Bracknell every two to three months. This procedure worked very satisfactorily, although there was often a time lag of several months between data being recorded and received at the archiving centre. The project timetable required that the final analysis be complete by summer 1991, and so the archive was 'frozen' in late 1990 after data for September 1990 were received.

The total number of observations archived in the observation dataset was 33.6k. To allow comparisons to be made with data originating from a smaller vessel manned by professional observers, data from *OWS Cumulus*, when on station LIMA (57°N, 20°W), were collected and added to the archive. About 3.6k observations were obtained from this source. The original aim of acquiring at least a full annual cycle of observations was achieved by 28 of the 45 vessels, with one vessel submitting 25 months of observations and another 24 months. In contrast, 8 vessels submitted data over a period of 6 months or less. Sadly, one vessel, the sole Canadian participant *Irving Forest*, was lost at sea in January 1990; fortunately all hands were safely rescued by a passing ship.

Although the data received fell short of the original plan of at least 12 months of data from 50 ships, recruitment and retention of vessels posed greater problems than had been expected; also, full vessel descriptions and instrumentation details proved difficult to acquire in some cases. However, this report will show that a satisfactory database has been collected to allow meaningful conclusions to be drawn from the analysis.

2.2 Instrument codes

To represent the extra information on instrumentation, special codes had to be defined (Tables 2a - g). Since participating countries use differing codes to denote the method of sea surface temperature measurement, the codes submitted by the ships were converted into a standard code (used for all countries) shown in Table 2c. Codes representing the location of air

Table 1a Calendar showing the number of observations submitted each month by participating ships.

SHIP	88												89												90												
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	
C6DS	0	0	0	0	0	0	0	0	0	0	0	86	27	32	68	49	39	49	19	32	45	39	23	74	28	0	0	0	0	0	0	0	0	0	0	0	610
VSBV3	0	0	0	0	0	0	0	0	62	68	70	78	99	75	55	82	64	65	94	69	70	0	75	59	77	42	56	64	60	69	32	0	0	0	0	0	1485
GJMR	0	0	0	0	0	0	0	0	37	72	96	87	61	83	93	82	70	55	46	47	63	63	79	68	75	72	121	101	109	99	32	0	0	0	0	0	1711
VRAZ	0	0	0	0	0	0	0	7	48	63	70	46	60	37	38	0	56	55	69	76	41	82	76	57	66	73	55	73	66	45	0	0	0	0	0	0	1259
GXES	0	0	0	0	0	0	0	0	0	69	68	72	66	44	70	64	78	72	41	74	54	69	91	52	93	54	59	28	33	8	31	0	0	0	0	0	1290
GJMS	0	0	0	0	0	0	0	0	7	90	72	60	52	39	67	58	56	59	60	50	76	77	73	59	71	61	59	15	74	69	0	0	0	0	0	0	1304
GBVV	0	0	0	0	0	0	0	0	52	38	67	91	54	68	68	51	18	30	43	42	68	84	53	57	76	67	80	58	68	57	72	16	0	0	0	0	1378
GZMM	0	0	0	0	0	0	0	0	10	29	43	47	21	52	50	43	44	56	37	47	14	29	43	32	52	33	44	53	47	37	0	0	0	0	0	0	863
GBSA	0	0	0	0	0	0	0	0	29	64	44	39	43	45	31	35	51	22	8	0	28	8	52	29	29	26	39	69	31	27	0	0	0	0	0	0	749
GBVW	0	0	0	0	0	0	0	0	39	66	50	40	82	93	64	60	64	60	97	72	58	56	49	33	27	4	54	73	83	71	71	0	0	0	0	0	1366
DDLN	0	0	0	0	0	0	0	0	30	73	65	57	53	36	57	62	45	48	56	19	28	52	42	25	12	17	10	0	0	0	0	0	0	0	0	0	787
DDUC	0	0	0	0	0	0	0	0	0	0	34	66	32	46	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	197
DHNE	0	0	0	0	0	0	0	0	49	46	47	56	55	46	41	45	40	42	14	44	46	48	53	61	87	40	54	93	49	0	0	0	0	0	0	0	1056
DNBR	0	0	0	0	0	0	0	0	0	58	81	69	94	86	57	20	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	469
DHRG	0	0	0	0	0	0	0	0	0	2	68	53	48	70	66	42	52	34	3	32	56	56	46	69	66	32	38	17	0	0	0	0	0	0	0	0	850
DIMC	0	0	0	0	0	0	0	0	0	30	53	46	30	51	41	28	10	49	60	43	35	43	55	32	0	70	43	63	31	0	0	0	0	0	0	0	813
DNJR	0	0	0	0	0	0	0	0	24	32	39	36	37	21	42	11	37	37	49	1	53	20	38	31	35	17	29	33	4	0	0	0	0	0	0	0	626
PCEL	0	0	0	0	0	0	0	0	0	0	38	62	76	63	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	263
PGDS	0	0	0	0	0	0	0	0	39	36	40	35	46	26	68	42	59	66	66	42	71	51	43	67	38	54	13	0	0	0	0	0	0	0	0	0	902
PGDG	0	0	0	0	0	0	0	0	0	41	61	17	50	26	63	68	41	54	62	60	72	74	34	64	50	71	32	49	17	0	0	0	0	0	0	0	1006
PELT	0	0	0	0	31	50	36	60	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	206
PELU	0	0	0	0	50	44	40	57	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	217
PGEG	0	0	0	2	31	35	21	61	32	31	29	28	65	18	41	29	28	40	20	59	22	38	24	45	25	41	16	8	0	0	0	0	0	0	0	0	789
PGDW	0	0	0	0	0	0	0	0	0	0	0	18	12	60	19	43	28	30	31	26	61	29	31	48	31	41	30	30	31	0	0	0	0	0	0	0	599
WPWH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	40	51	43	60	48	43	61	48	38	53	0	0	0	0	0	0	0	0	0	0	517
WPVF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	44	57	45	40	56	67	58	37	56	61	39	62	11	0	0	0	0	0	0	0	0	672
KRGJ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	55	41	86	1	35	23	47	53	59	21	33	0	0	0	0	0	0	0	0	0	501
WPFZ	0	0	0	0	0	0	0	0	0	0	60	0	0	0	53	64	43	0	56	55	50	37	57	21	0	0	0	0	0	0	0	0	0	0	0	0	496
WPHZ	0	0	0	0	0	0	0	0	0	0	0	0	0	72	76	67	67	72	66	65	100	70	64	72	94	47	0	0	0	0	0	0	0	0	0	0	932
WMLG	0	0	0	0	0	0	0	0	0	0	0	0	10	41	58	43	35	25	33	22	0	23	20	0	0	0	0	0	0	0	0	0	0	0	0	0	310
OXTZ2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	69	71	73	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	288
OYGK2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	18	16	15	16	13	20	0	0	0	0	0	0	0	0	0	0	0	0	112
WSDG	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	75	39	40	0	22	0	0	0	0	0	0	0	0	0	0	193
KRJL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	81	66	59	51	43	64	38	54	69	8	34	10	49	39	0	0	0	0	0	0	0	665
KRLZ	0	0	0	0	0	0	0	0	0	0	0	0	0	7	48	57	56	36	41	76	77	56	39	49	0	0	0	0	0	0	0	0	0	0	0	0	542
KRJP	0	0	0	0	0	0	0	0	0	0	0	0	0	35	65	52	66	72	60	62	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	426
KRPB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	62	54	34	47	49	49	48	60	58	56	49	20	0	0	0	0	0	0	0	0	0	0	586
FNFD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	111	182	153	180	169	184	192	177	184	193	158	178	180	177	183	178	182	162	0	0	0	3123
FNEF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	34	24	39	53	49	25	35	24	1	67	45	50	60	53	41	39	67	0	0	0	732
FNGS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	17	12	0	0	0	0	11	12	4	0	0	0	0	0	0	0	0	0	0	70
FNGM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	37	41	23	0	0	0	0	0	0	0	0	0	26	28	24	15	0	0	0	0	231
DIDA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	95	69	13	17	82	77	54	29	0	0	0	21	0	6	0	70	94	0	0	0	0	631
FNCZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	65	42	13	0	27	54	70	50	56	53	16	1	65	68	67	0	0	0	0	0	679
FNOY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	119	205	153	66	72	0	0	41	0	0	0	0	0	0	0	0	0	0	0	656
VSBG8	0	0	0	0	0	0	0	0	0	0	0	0	0	43	50	45	65	36	46	29	58	70	46	0	0	0	0	0	0	0	0	0	0	0	0	0	488

OVERALL TOTAL =33645

Table 1b Calendar showing the number of observations submitted each month by participating ships which were matched with model values.

SHIP	88												89												90												
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	
C6DS	0	0	0	0	0	0	0	0	0	0	0	77	27	31	52	45	35	36	3	2	43	37	22	73	28	0	0	0	0	0	0	0	0	0	0	0	511
VSBV3	0	0	0	0	0	0	0	0	61	62	68	78	99	75	51	81	58	57	90	12	70	0	72	51	72	42	56	63	60	66	31	0	0	0	0	0	1375
GJMR	0	0	0	0	0	0	0	0	30	50	78	73	47	65	75	65	48	39	33	8	45	42	49	55	55	52	49	68	69	67	22	0	0	0	0	0	1184
VRAZ	0	0	0	0	0	0	0	7	14	38	35	18	19	16	18	0	25	35	28	8	19	35	41	34	24	32	16	36	37	17	0	0	0	0	0	0	552
GXES	0	0	0	0	0	0	0	0	0	69	66	72	66	44	68	63	75	69	41	7	54	66	87	48	80	54	35	28	27	0	22	0	0	0	0	0	1141
GJMS	0	0	0	0	0	0	0	0	7	62	45	36	37	28	49	40	41	39	42	3	50	60	47	43	53	48	22	2	59	55	0	0	0	0	0	0	868
GBVV	0	0	0	0	0	0	0	0	36	29	48	72	38	54	51	43	13	25	21	13	44	62	42	45	57	44	56	43	51	43	55	16	0	0	0	0	1001
GZMM	0	0	0	0	0	0	0	0	10	29	42	47	21	51	48	43	42	52	37	36	10	27	43	31	50	32	24	50	47	37	0	0	0	0	0	0	809
GBSA	0	0	0	0	0	0	0	0	18	44	12	31	21	32	25	22	31	11	8	0	19	0	36	23	16	20	10	49	1	27	0	0	0	0	0	0	456
GBVW	0	0	0	0	0	0	0	0	28	49	36	30	49	61	53	41	37	46	76	29	45	36	37	25	13	4	31	57	56	55	50	0	0	0	0	0	944
DDLN	0	0	0	0	0	0	0	0	30	73	62	57	53	35	55	61	43	44	55	4	28	50	42	24	12	17	6	0	0	0	0	0	0	0	0	0	751
DDUC	0	0	0	0	0	0	0	0	0	0	23	50	29	27	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	148
DHNE	0	0	0	0	0	0	0	0	48	45	47	56	55	45	38	44	37	42	14	8	45	41	49	59	82	39	54	91	42	0	0	0	0	0	0	0	981
DNBR	0	0	0	0	0	0	0	0	0	56	77	68	94	84	56	20	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	459
DHRG	0	0	0	0	0	0	0	0	0	2	61	47	48	67	61	37	48	32	3	32	54	50	45	54	51	32	31	17	0	0	0	0	0	0	0	0	772
DIMC	0	0	0	0	0	0	0	0	0	28	50	46	29	50	39	28	9	47	54	2	27	36	55	25	0	69	35	62	30	0	0	0	0	0	0	0	721
DNJR	0	0	0	0	0	0	0	0	24	30	36	36	37	20	42	11	33	34	46	1	53	17	36	31	35	16	28	31	2	0	0	0	0	0	0	0	599
PCEL	0	0	0	0	0	0	0	0	0	0	36	62	76	61	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	259
PGDS	0	0	0	0	0	0	0	0	22	15	13	15	17	17	31	23	40	37	37	16	30	0	33	33	22	20	0	0	0	0	0	0	0	0	0	0	421
PGDG	0	0	0	0	0	0	0	0	0	24	39	0	22	7	38	37	17	21	28	28	40	17	17	24	33	38	12	17	13	0	0	0	0	0	0	0	472
PELT	0	0	0	0	19	24	35	46	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	153
PELU	0	0	0	0	39	27	38	45	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	175
PGEG	0	0	0	2	17	10	8	28	23	17	18	21	38	8	29	21	20	30	8	15	15	11	16	24	15	29	7	8	0	0	0	0	0	0	0	0	438
PGDW	0	0	0	0	0	0	0	0	0	0	0	12	0	23	1	22	9	12	12	0	21	0	11	22	0	18	11	10	12	0	0	0	0	0	0	0	196
WPWH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	36	49	34	0	43	38	61	47	37	53	0	0	0	0	0	0	0	0	0	0	427
WPVF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	41	51	41	39	37	65	56	37	54	58	37	35	10	0	0	0	0	0	0	0	0	600
KRGJ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	52	32	75	0	20	5	42	16	56	8	0	0	0	0	0	0	0	0	0	0	349
WPFZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	59	40	0	52	8	49	33	54	21	0	0	0	0	0	0	0	0	0	0	0	0	359
WPHZ	0	0	0	0	0	0	0	0	0	0	0	0	0	63	56	55	45	53	50	37	64	54	49	60	77	46	0	0	0	0	0	0	0	0	0	0	709
WMLG	0	0	0	0	0	0	0	0	0	0	0	0	9	41	57	43	33	21	33	0	0	19	20	0	0	0	0	0	0	0	0	0	0	0	0	0	276
OXTZ2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
OYGK2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WSDG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	28	25	0	11	0	0	0	0	0	0	0	0	0	0	123
KRJL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	65	59	47	42	10	35	35	47	68	3	30	4	37	37	0	0	0	0	0	0	0	539
KRLZ	0	0	0	0	0	0	0	0	0	0	0	0	0	5	45	51	43	33	39	10	56	46	38	48	0	0	0	0	0	0	0	0	0	0	0	0	414
KRJP	0	0	0	0	0	0	0	0	0	0	0	0	0	30	57	41	29	53	52	27	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	300
KRPB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61	52	31	40	48	13	42	56	58	55	46	20	0	0	0	0	0	0	0	0	0	0	522
FNFD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	44	36	34	24	35	52	38	54	48	49	52	43	46	54	51	47	38	0	0	0	766
FNEF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	28	24	38	22	47	21	34	24	1	62	40	45	56	49	39	38	60	0	0	0	653
FNGS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0	0	0	6	0	4	0	0	0	0	0	0	0	0	0	0	16
FNGM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	1	17	11	0	0	0	0	0	0	0	0	0	5	17	5	10	0	0	0	0	81
DIDA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	48	7	6	5	4	30	18	20	0	0	0	5	0	0	0	34	47	0	0	0	0	228
FNCZ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	11	9	2	0	6	9	13	11	13	7	3	1	11	18	16	0	0	0	0	0	133
FNOY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	97	5	71	58	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	271
VSBG8	0	0	0	0	0	0	0	0	0	0	0	0	0	41	45	45	36	35	46	24	56	66	45	0	0	0	0	0	0	0	0	0	0	0	0	0	439

OVERALL TOTAL =22592

Table 2: VSOP CODES

a	Country Codes
00	Netherlands
02	United States of America
03	United Kingdom
04	France
13	Canada
21	Germany (FRG)

b	Method of Wind Speed measurement
0	Estimated
1	Fixed anemometer
2	Handheld anemometer
3	Estimated, but with fixed anemometer fitted

c	Method of Sea Surface Temperature measurement
1	Bucket
2	Engine Room Intake
3	Hull sensor
4	Hull sensor (engine room)
5	Hull sensor (Met O approved)
6	Radiometer
7	Trailing Thermistor
8	XBT

d	Method of Air Temperature measurement
0	Screen
1	Psychrometer

e	Method of Humidity measurement
0	Wet bulb in screen
1	Wet bulb in psychrometer

f	Exposure Codes (higher figures represent better exposures)
0	Airflow fully blocked adjacent to sensor (within 1m)
1	Airflow fully blocked at medium distance (1 to 4m)
2	Airflow fully blocked at larger distance (4 to 10m)
3	Airflow partially blocked adjacent to sensor (within 1m)
4	Airflow partially blocked at medium distance (1 to 4 m)
5	Airflow partially blocked at larger distance (4 to 10 m)
6	Airflow clear with long fetch (> 30m) over ship
7	Airflow clear with fetch 10 to 30m over ship
8	Airflow clear with fetch 1 to 10m over ship
9	Airflow clear with short fetch (<1m) over ship

g	Location of Air Temperature measurement					
Code	Can	Fra	FRG	Neth	UK	USA
1	MS	P	P	S	MO	MO
2	MP	S	S	P	MD	MD
3	MF	-	-	-	MA	MA
4	MA	-	-	-	BO	BO
5	BS	-	-	-	BK	BK
6	BP	-	-	-	BW	BW
7	BF	-	-	-	-	-
8	BA	-	-	-	-	-

KEY:

P - Port
S - Starboard
M - Monkey Island
B - Bridge deck
F - Forward
A - Aft
O - Outboard
D - Amidships
K - Bulkhead
W - Aft of wheelhouse

temperature measurement also differed between participating countries (Table 2g); given the varying degrees of detail submitted, no unified code has been devised in this case.

To allow some quantitative analysis to be made of the exposure of the various sensors in use, an exposure index was devised (Table 2f). Two independent assessments were then made of the index to be applied to each sensor on each vessel, depending on the relative wind direction, using the ship details and photographs supplied. These assessments proved very close in the majority of cases, and a brief discussion achieved consensus in the remaining cases. The resulting Exposure Indices are shown in Table 3. It can be seen that five ships have not had exposure indices estimated, due to lack of information[1].

2.3 Ship Routes

It was intended that vessels recruited to the project should spend a high percentage of their time in the North Atlantic area. In the event, the recruited vessels followed 4 basic types of route (Table 4), some of which took the vessels outside the analysis area which was defined by the coverage of the UKMO Fine Mesh Model (30 - 80°N; 80°W - 40°E).

2.4 Editing of the VSOP-NA data

The question of numerical errors in the data cannot be ignored; for all observations except those provided by FRG, the data have not been subjected to quality control procedures, and so errors in reported variables and incorrect positions will be present in the dataset. There will also be occasions when the model field may not provide an appropriate comparison with observed values for certain variables (for example for ships very close to land). In order that the dataset should be reasonably representative of real-time data disseminated on GTS, it was not considered appropriate to conduct exhaustive quality control checks on the data. Isolated observations which probably contained errors in the reported ship position were deleted from the comparison dataset; such errors may have occurred whilst coding or archiving.

Geographical filtering was applied to avoid inappropriate comparisons with the model fields. It was considered that observations made close to the coast should not be used in the final analysis since they could be subject to local effects which the numerical model would be unable to represent. In such cases, a comparison between the observed and model variables would reflect more on the shortcomings of the model than on the quality of the observation. For this reason, the observations from the areas shown in Figure 2.1 were not included in the Comparison Dataset Further, during analysis of the data at the James Rennell Centre for Ocean Circulation (JRC) it became clear that model air temperatures off the east coast of the USA were anomalously low under certain conditions. A further area of data was therefore excluded from analysis at the JRC; Figure 2.2 shows the distribution of data in the final analysis set.

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1 For a detailed description of the instrument exposure for each ship, and of the ship routes, see the VSOP-NA ship catalogue (Kent and Taylor, 1991).

Table 3 EXPOSURE INDICES

SHIP		Rel wind direction		SCREEN/PSYCHROMETER 315-45	45-135	135-225	225-315	ANEMOMETER 315-45	45-135	135-225	225-315	
C6DS	Atlantic Link	(UK)	S	3	4	6	4	-	-	-	-	
GBSA	Author	(UK)	S	5	5	7	5	9	9	9	9	
GBVV	Geestbay	(UK)	S	8	9	7	9	-	-	-	-	
GBVW	Geestport	(UK)	S	4	7	3	7	-	-	-	-	
GJMR	Geestcape	(UK)	S	4	9	6	9	-	-	-	-	
GJMS	Geesthaven	(UK)	S	4	9	6	9	-	-	-	-	
GXES	CGM Provence	(UK)	S	7	9	9	9	9	9	9	9	
GZMM	Atlantic Conveyor	(UK)	s	7	3	7	6	7	4	4	7	
VRAZ	Nickerie	(UK)	S	4	8	6	8	9	9	9	6	
VSBV3	Canmar Ambassador	(UK)	S	1	9	7	9	6	5	9	9	
DDLN	Independ Endeavor	(FRG)	P	4	8	8	8	-	-	-	-	
DDUC	Euro Texas	(FRG)	P	4	8	8	8	-	-	-	-	
DHNE	Numberg Atlantic	(FRG)	P	4	8	8	8	-	-	-	-	
DHRG	Alemania Express	(FRG)	P	4	8	8	8	-	-	-	-	
DIMC	America Express	(FRG)	P	4	8	8	8	-	-	-	-	
DNBR	Independ Concept	(FRG)	P	8	8	8	8	-	-	-	-	
DNJR	Independ Pursuit	(FRG)	P	8	8	8	8	-	-	-	-	
PCEL	AEL America	(Neth)	P	4	8	8	8	-	-	-	-	
PELT	Gulf Speed	(Neth)	P	4	8	8	8	-	-	-	-	
PELU	Gulf Spirit	(Neth)	P	4	8	8	8	-	-	-	-	
PGDG	Nedlloyd Kingston	(Neth)	P	8	8	8	8	-	-	-	-	
PGDS	Nedlloyd Kyoto	(Neth)	P	8	8	8	8	-	-	-	-	
PGDW	Nedll Zeelandia	(Neth)	P	8	8	8	8	-	-	-	-	
PGEG	Nedll Neerlandia	(Neth)	P	4	8	8	8	4	4	4	4	H
KRGJ	Julius Hammer	(USA)	s	4	8	1	0	-	-	-	-	
KRJL	Margaret Lykes	(USA)	s	3	7	4	7	-	-	-	-	
KRJP	Sheldon Lykes	(USA)	u	-	-	-	-	-	-	-	-	
KRLZ	Sealand Atlantic	(USA)	u	-	-	-	-	-	-	-	-	
KRPB	Sealand Commitmnt	(USA)	u	-	-	-	-	-	-	-	-	
WMLG	Delaware Bay	(USA)	u	-	-	-	-	-	-	-	-	
WPFZ	Adabelle Lykes	(USA)	s	0	3	4	3	-	-	-	-	
WPHZ	Charlotte Lykes	(USA)	u	-	-	-	-	-	-	-	-	
WPVF	Galveston Bay	(USA)	S	1	7	0	7	9	9	9	9	
WPWH	Nedlloyd Hudson	(USA)	S	1	7	0	7	9	9	9	9	
WSDG	Lyra Lykes	(USA)	S	0	3	3	3	9	9	9	9	
OXTZ2	Mercandian Sun	(USA)	P	5	8	9	8	-	-	-	-	
OYGK2	Mercand Continent	(USA)	P	5	8	9	8	-	-	-	-	
DIDA	Ariana	(FR)	s	8	5	9	9	9	7	7	8	
FNCZ	C R Libreville	(FR)	P	4	8	8	8	6	6	8	6	H
FNEF	Atlantic Cartier	(FR)	s	8	7	8	9	9	9	9	6	
FNFD	Edouard LD	(FR)	s	8	9	7	7	9	9	6	9	
FNGM	La Carabie	(FR)	P	4	8	8	8	4	4	4	4	H
FNGS	La Lafayette	(FR)	P	4	8	8	8	4	4	4	4	H
FNOY	Jean Charcot	(FR)	s	5	8	8	7	9	6	9	9	
VSBG8	Irving Forest	(CAN)	S	5	9	8	9	8	4	3	4	

Key -
- P - sling psychrometer
- S - two screens (for this table exposure assessment assumes measurement in the upwind location)
- s - one screen
- u - unknown method of temperature measurement
- H - Hand held anemometer (all other wind exposure assessments for fixed anemometers)

Table 4. Summary of ship routes

Description of Vessel's operation	No. of ships	No. of Obs. used in analysis
Ships spending close to 100% of time within the North Atlantic region of interest.	25	14.3k
Ships from NW Europe leaving area at southern boundary	13	6.9k
Ships operating across Biscay and around Iberian coast	4	1.3k
Ship operating into Mediterranean and also leaving area at southern boundary	1	0.1k
Ships spending 100% of time outside the region	2	0
TOTALS	45	22.6k

The vessel for which these quality control measures had the most impact was FNFD (*Edouard LD*). Due to the likely topographical effects on the windflow close to the Iberian coast, through the straits of Gibraltar and along the North African coast, about 75% of this vessel's observations were excluded as being not representative of 'open sea' conditions. For all other vessels, numbers excluded were very much smaller.

It must be stressed that the total number of observations deleted for the above reasons represent a small percentage of those used for the analysis. The bulk of the observations lost were those made south of 30°N (i.e. out of the Fine Mesh Model area). In total, out of the 33.6k observations archived, 11.0k observations were not included in the Comparison Dataset which was used for the analysis. This left 22.6k observations archived along with model values and special VSOP information, plus a further 3.6k observations and matched model values from *OWS Cumulus*. The Comparison Dataset therefore contains 26,438 observations of which 24,952 fell within the area analysed at the JRC; the calendar of matched observations in the Comparison Dataset is shown in Table 1b.

2.5 Data Archiving

Two basic datasets were assembled at the archiving centre at Bracknell. The first (the Observation Dataset) is a copy of the data sent on the tapes from the keying centre in Germany, reformatted into a slightly more readable layout based on the standard 5-digit codes. The format of this dataset is shown in Table 5a.

The second dataset (the Comparison Dataset) consists of the VSOP observations and all the special VSOP codes, together with matching values of the variables taken from an archive of numerical model analyses. The layout of this dataset is shown in Table 5b (codes used within the dataset were described in Table 2)[1].

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[1] Copies of these datasets have been sent to the World Data Centres A and B. The size of the Observation Dataset is about 4 Mbyte, and that of the Comparison Dataset is 4.28 Mbyte; both are in character format.

TABLE 5a: Format of the VSOP Observation dataset

Column number	Variable
1	Indicator (=3)
2- 3	Year
4- 5	Month
7- 8	Date
9- 10	Time (UTC)
11	Indicator for method of windspeed report (1=estimated in m/s; 2=anemo in m/s; 3=estimated in kts; 4=anemo in kts)
13-14	Indicator (=9N) for Northern Hemisphere
15-17	Latitude in tenths of degree
19	Indicator (=W for Western Hemisphere)
20-23	Longitude in tenths of degree
25	Cloud amount in oktas
26-27	Wind direction (tens of degrees)
28-29	Wind speed
31	Indicator (=1 for dry bulb group)
32	Indicator for sign (0=positive, 1=negative)
33-35	Dry bulb temperature (tenths of degree C)
37	Indicator (=2 for dewpoint group)
38	Indicator for sign (0=positive, 1=negative)
39-41	Dewpoint temperature (tenths of degree C)
43	Indicator (=4 for pressure group)
44-47	Pressure (tenths of mb, omitting thousand digit)
49	Indicator (=7 for weather group)
50-51	Present weather code
52-53	Past weather code
55	Indicator (=0 for sea temperature group)
56	Indicator for sign (0=positive, 1=negative)
57-59	Sea surface temperature (tenths of degree C)
61	Indicator (=2 for wave group)
62-63	Period of sea waves (seconds)
64-65	Height of sea waves (half metres)
67-73	Callsign
75-76	Country code
78-79	Ship's speed (knots)
80-82	Ship's course (degrees true)
84-85	Height of cargo above sea level (metres)
86-88	Height of reference level above sea level (tenths of metres)
90*	Method of sea surface temperature measurement
91*	Location of air temperature measurement
92-94	Relative wind speed (knots)
96-98	Relative wind direction (degrees off bow)

* Single figure codes 0-9 as defined nationally

TABLE 5b: Format of Comparison Dataset

Column Number	Variable
2- 3	Time (UTC)
5- 6	Date
8- 9	Month
11- 14	Year
16- 19	Latitude
21- 25	Longitude (-ve indicates West)
28- 32	Ship Callsign
37- 39	Model Wind Direction (degrees)
44- 45	Model Wind Speed (knots)
48- 51	Model Air Temperature (deg C)
53- 58	Model Mean Sea Level Pressure (mb)
61- 64	Model Sea Surface Temperature (deg C)
68- 70	VSOP Wind direction (degrees)
75- 76	VSOP Wind Speed (knots)
79- 82	VSOP Air Temperature (deg C)
84- 89	VSOP Mean Sea Level Pressure (mb)
92- 95	VSOP Sea Surface Temperature (deg C)
97- 98	Country Code (see Table 2a)
100-101	Ship's speed (knots)
102-104	Ship's course (degrees)
106-107	Cargo Height (metres)
108-110	Height of Reference Level above MSL (tenths of metres)
112-112	Method of Sea Surface Temperature measurement (see Table 2c)
113-113	Location of Air Temperature measurement (see Table 2g)
114-116	Relative Wind Speed (knots)
118-120	Relative Wind Direction (degrees)
123-123	Method of Wind Speed measurement (see Table 2b)
124-125	Height (metres) above MSL of Wind Speed measurement
127-127	Exposure of Wind Speed measurement (see Table 2f)
128-128	Method of Air Temperature measurement (see Table 2d)
129-130	Height above MSL of Air Temperature measurement
131-131	Exposure of Air Temperature measurement (see Table 2f)
132-132	Method of Humidity measurement (see Table 2e)
134-134	Method of Air Pressure measurement (= 0 at present)
135-136	Depth below MSL for Sea Temperatiure measurement (metres)
137-137	Total Cloud cover (oktas)
141-144	VSOP Dew Point Temperature (degrees C)
148-151	Model Dew Point Temperature (degrees C)

3. DESCRIPTION OF THE FORECAST MODEL

3.1 Choice of the Model

Since the forecast model analysis was used as a comparison standard, the method by which the analysed fields are calculated, and the effect of the VSOP-NA observations upon them, must first be considered.

At the UK Meteorological Office (UKMO) there were two archives of numerical model analyses readily available for use as comparison material for the VSOP data: the UKMO Global model and the UKMO Limited-Area (so-called Fine Mesh) model. Although the former has the advantage of no limiting southern boundary (and so all submitted VSOP North Atlantic observations could be compared with model values), the latter has 8 analyses archived per day, against 4 for the former. Also, the spatial resolution of the Fine Mesh model is double that of the Global model and so interpolation errors to an observation point could be expected to be smaller. Thus, on balance, it was considered that the Fine Mesh model would yield better comparison data for VSOP purposes.

The effect of the VSOP-NA data on the model could have been minimised by comparing the observations with a forecast field from, say, 6 hours previously. Unfortunately, not all the required data was available in the archive of "T+6" forecasts. The analysis field was therefore used, even though it was calculated using the VSOP-NA data. Some comparisons were also made with the "T+6" hour forecasts to check the validity of this approach.

3.2 Calculation of the Analysis fields

3.2.1 Introduction

The Fine Mesh model operates on a grid resolution of 0.75° latitude x 0.9375° longitude over an area 30 - 80°N, 80°W - 40°E. The fields of interest to the VSOP-NA are:

Sea Surface Temperature (SST)	10m Wind Speed
1.5m Air Temperature	10m Wind Direction
Relative Humidity (RH)	MSL Pressure

Essentially, each of the above are analysed in a similar manner, by combining observations with a background field to produce a 'best estimate' of conditions on the synoptic scale. For the atmospheric variables, the background field is a forecast field derived from a previous datum time. For sea surface temperature, the background field is simply the previous analysis plus the difference between the current climate field and the climate field for the previous day. Climate fields for a particular date are derived by linear interpolation in time between the monthly fields, defined from UKMO datasets of past ship observations. It is important to note that the model does not make use of all observations in the analysis of the various fields; a summary of the observation types used in the calculation of the model fields of interest can be found in Table 6. For the "SHIP" reports submitted by the VSOP-NA ships, only the pressure, wind, and sea surface temperature are assimilated into the model.

TABLE 6 Data Types Used by the Fine Mesh Model. The VSOP-NA report "ship" messages, the Cumulus is an Ocean Weather Ship (OWS)

Type No.	Description	MSLP	Wind	RH	SST	TEMP
1	Bogus	3	3	3	3	3
2	Temperature Sounding	3		3		3
3	Ship Temp Sounding	3		3		3
4	Drop-sonde	3		3		3
5	Rocket-sonde	3		3		3
6	Ship Rocket-sonde	3		3		3
7	Pilot Balloon					
8	Ship Pilot Balloon		3			
9	SATEM					3
10	SYNOP	3				
11	SYNOP AUTO	3				
12	**Ship**	**3**	**3**		**3**	
13	**Ship auto**	**3**	**3**		**3**	
14	**OWS**	**3**	**3**		**3**	
15	Airep					3
16	Constant level Balloon					
17	Drifting Buoy	3			3	
18	SATOB				3	
19	HERMES					
20	Compressed Code Satem					
21	ASDAR					

For use in the model, the observations are extracted from the UKMO Synoptic Data Bank, which contains all data received via the GTS. After extraction, the data are subjected to quality control procedures which perform validity checks against background field values interpolated to the observation point and also against other observations in the area. After likely erroneous data have been excluded, the remaining observations are incorporated in the analysis using a complex data assimilation scheme during which weights are assigned to each observation so that the type of observation and the observation time (relative to the analysis) can be taken into account. A high weighting indicates observations with high reliability taken close to the time of the analysis; such an observation would have a large influence on the analysis. The weighting can be set to zero so any particular observation type can be ignored by the analysis if so desired.

Bogus observations (observations created by forecasters in real time and based on qualitative evidence, such as satellite pictures) may have been added to the analysis with a relatively high weighting if it was considered at the time that the model was not representing a feature well. The archived analysis may thus contain a small element of subjectively introduced information at times.

3.2.2 Sea Surface Temperature

The sea surface temperature (SST) analysis scheme, which is updated once per day, is based on observations from seven different data sources, a climatological field of SST's, and a background field (essentially persistence). The data are extracted from the UKMO Synoptic Data Bank at approximately 1200 GMT each day for observations between 0001 and 2400 GMT for the previous day.

After a series of validity checks have been applied, the SST at a gridpoint is calculated by combining climate and background fields with valid observations within a defined immediate area. The seven types of observation and their relative weightings in the analysis scheme are:

Ships	1.0	XBTs	1.5
OWS	4.0	Satems	0.0
Drifting buoys	1.0	Satobs	1.0
Fixed buoys	1.5		

Progressively more weight is given to the climate field and less to the background field as the time interval between observations and the previous analysis increases.

3.2.3 Mean Sea Level Pressure, Wind Speed and Wind Direction

The calculation of mean sea level pressure, wind speed and wind direction is more complex than that for sea surface temperature, since the resulting fields of pressure and wind must be themselves consistent, and also consistent with analyses at higher levels. Whilst sea surface temperatures are updated every 24 hours, analysis of these variables is updated at 3 hourly intervals.

As pressure varies reasonably smoothly on the synoptic space scale and a representative measurement can be obtained relatively easily, pressure observations over both land and sea are used by the analysis scheme. However, surface wind speed and direction are more susceptible to localised effects such as shelter and turbulence and so land surface wind reports are not used in the analysis. Wind observations over the sea are generally not subject to such major local effects and so are considered sufficiently representative for inclusion.

The data first pass through the analysis stage which incorporates the automatic quality control procedures and the calculation of weights to reflect the standard errors of each type of observation. The data are then introduced to the model during the assimilation stage, during which the data are used to correct the field at each time step of a 3 hour forecast ending at the analysis time (for more detail see Atkins & Woodage, 1985, or Bell & Dickinson, 1987). Winds from the lowest standard level (approx 25m above sea level) are then extrapolated to 10m above sea level.

3.2.4 Temperature and Humidity

Like the pressure and wind fields, these variables are updated at 3 hourly intervals. No surface observations of temperature or humidity are used by the model as they are considered to be susceptible to local anomalies and thus may be unrepresentative on the synoptic scale. However, temperature and humidity observations at standard levels from radio-sonde ascents are given high weightings by the analysis. The only ships in the VSOP-NA project which launched radiosondes are the *Canmar Ambassador*, VSBV3 (which carries an ASAP system), and the *OWS Cumulus* (which launches 6 hourly radiosonde ascents). Since the first standard level is the surface, this implies that surface temperature and humidity data from these ships, but not other VSOP-NA ships, are used by the analysis.

The data are assimilated into the analysis in the same manner as the pressure and wind observations, and the surface values are extrapolated from the lowest standard level to provide a 1.5m 'surface' value. For ease of comparison with the observations, the model humidity values archived in the VSOP-NA dataset are dew point temperatures calculated from the model relative humidity and dry bulb temperature.

3.3 Model Treatment of the Boundary Layer

Since the model operates using σ-coordinates in the vertical ($\sigma = p/p^*$, where p^* is the local surface pressure), an extrapolation from the lowest σ-level (σ_1) is necessary to produce surface variables for direct comparison with observations. A bulk Richardson number is calculated at each gridpoint to determine the most appropriate profile to use to determine the 'surface' values of wind speed (at 10m) and potential temperature (at 1.5m) from the σ_1 level. The profiles used are derived from Monin-Obukhov similarity theory; more detail is given in Bell & Dickinson (1987) and Devrell et al (1985). The direction of the surface wind is assumed to be that of the wind at the σ_1 level.

4. STATISTICAL SUMMARY OF THE ANALYSIS RESULTS

Following the preparation of the Comparison Dataset by the UKMO the analysis was conducted jointly at the UKMO and the JRC. Table 7, prepared by the UKMO, summarises the mean differences (observation minus model) and standard errors of these means, by variable, by ship and by participating country. The size of the standard errors indicates that, in many instances, differences between and within national fleets are significant. In some cases, it is possible to explain differences by simple consideration of some aspect of instrument exposure, but in others the explanation is not obvious, and further discussion is deferred to sections 6 to 9, where more detailed aspects are discussed for each variable separately. Values discussed below are mean departures from model values.

4.1 Air Temperatures

Over all VSOP observations the average is close to zero (i.e. -0.07°C ±0.01); however, the *OWS Cumulus* shows an average of -0.61°C ±0.02, suggesting that the model displays a positive bias of this order. Only 3 vessels show averages significantly below that of the OWS, suggesting that the majority are subject to warming of air within the ship's boundary layer. Both methods of measurement appear among the highest positive values, suggesting that psychrometers as well as screens can be subject to exposure problems. However a possible geographical trend in the model values (Section 7.3) may have biased some of these statistics.

4.2 Dew Point Temperatures

Over all VSOP observations the average is +0.24°C ±0.02, against an *OWS Cumulus* average of -0.15°C ±0.04. This suggests that positive errors due to inadequate wetting of the wet bulb thermometer are common; ships displaying the largest positive values all use screens rather

TABLE 7 : (OBS-MODEL) STATISTICS BY SHIP AND COUNTRY

Callsign	AIR TEMP (C) No	Mean	SE	DEW POINT(C) No	Mean	SE	SEA TEMP(C) No	Mean	SE	WIND SPEED(kt) No	Mean	SE	WIND DIR'N (Deg) No	Mean	SE	MSL PRESSURE (mb) No	Mean	SE	Callsign
C6DS	508	-0.67	0.08	351	2.50	0.21	471	0.12	0.08	503	0.82	0.36	494	2.69	1.39	511	-0.20	0.06	C6DS
GBSA	455	-0.42	0.06	334	-0.00	0.11	379	0.03	0.06	453	4.03	0.34	449	-1.12	1.50	456	-0.01	0.07	GBSA
GBVV	999	-0.16	0.06	757	0.40	0.09	981	0.11	0.06	980	2.06	0.17	906	-1.36	0.91	1000	-0.21	0.04	GBVV
GBVW	944	-0.11	0.03	676	-0.21	0.08	944	-0.40	0.02	923	0.49	0.13	798	-1.38	0.82	944	-0.20	0.03	GBVW
GJMR	1184	-0.11	0.05	943	0.03	0.07	961	0.35	0.06	1164	1.87	0.14	1080	-1.18	0.90	1184	-0.15	0.04	GJMR
GJMS	868	-0.26	0.04	691	0.31	0.09	663	0.12	0.04	847	1.51	0.18	824	2.17	1.19	868	-0.38	0.04	GJMS
GXES	1141	-0.37	0.04	850	0.91	0.09	1139	0.07	0.04	1133	2.29	0.16	1110	1.26	0.88	1141	-0.16	0.04	GXES
GZMM	808	-0.91	0.07	573	-0.52	0.11	806	-0.11	0.06	795	3.23	0.24	771	2.59	0.89	809	-0.16	0.07	GZMM
VRAZ	550	0.27	0.06	345	0.33	0.11	548	0.44	0.05	546	2.10	0.25	518	-1.71	1.36	552	0.10	0.05	VRAZ
VSBV3	1367	-0.06	0.07	763	0.95	0.09	1362	0.23	0.06	1364	3.16	0.15	1349	-0.79	0.58	1372	0.33	0.03	VSBV3
All UK	8824	-0.31	0.02	8185	0.28	0.03	8254	0.09	0.01	8708	2.21	0.05	8299	-0.25	0.23	8837	-0.05	0.01	All UK
DDLN	751	-0.17	0.05	475	-0.50	0.12	739	-0.15	0.07	749	6.47	0.33	726	-2.25	1.24	750	-0.44	0.05	DDLN
DDUC	148	-0.15	0.10	69	-0.18	0.28	130	-0.30	0.10	147	7.05	0.81	141	-1.10	2.78	148	-1.18	0.16	DDUC
DHNE	974	-0.22	0.06	738	-0.10	0.10	266	-0.16	0.11	973	3.70	0.22	939	0.25	0.99	978	0.19	0.07	DHNE
DHRG	772	-0.60	0.06	557	-0.95	0.11	287	-0.23	0.08	765	2.64	0.22	729	0.25	1.24	772	-0.49	0.06	DHRG
DIMC	721	-0.52	0.06	498	-0.62	0.10	403	0.11	0.07	714	3.02	0.25	684	0.79	1.27	721	-1.63	0.11	DIMC
DNBR	458	-0.50	0.07	222	0.23	0.16	304	-0.10	0.07	457	2.10	0.28	439	1.03	1.54	459	0.48	0.10	DNBR
DNJR	598	-0.39	0.07	463	-0.41	0.10	559	0.24	0.09	590	1.36	0.24	551	-2.54	1.58	565	-0.03	0.13	DNJR
All FRG	4422	-0.37	0.02	3022	-0.43	0.05	2688	-0.04	0.03	4395	3.51	0.11	4209	-0.42	0.51	4393	-0.38	0.04	All FRG
PCEL	258	0.45	0.12	124	0.16	0.23	257	1.14	0.17	258	2.31	0.39	256	1.32	1.66	259	-0.02	0.06	PCEL
PELT	153	0.38	0.14	64	-0.66	0.28	152	2.34	0.24	153	3.82	0.54	151	-2.11	2.56	152	-0.21	0.09	PELT
PELU	175	0.39	0.11	74	-0.46	0.23	175	1.20	0.16	173	4.35	0.50	170	-6.05	2.29	175	0.10	0.59	PELU
PGDG	472	0.44	0.06	318	-0.04	0.14	470	0.09	0.04	457	0.76	0.24	445	-1.79	1.61	472	-0.40	0.06	PGDG
PGDS	420	0.79	0.07	173	-0.43	0.15	392	0.38	0.06	397	1.25	0.36	375	-5.42	1.76	421	-0.45	0.07	PGDS
PGDW	196	0.08	0.08	110	-0.13	0.22	196	-0.21	0.07	191	1.80	0.39	183	-3.29	2.85	196	-0.68	0.10	PGDW
PGEG	438	0.00	0.06	199	-0.60	0.14	355	-0.34	0.06	425	2.18	0.32	409	1.95	1.60	438	-0.62	0.07	PGEG
All Neth	2112	0.38	0.03	1062	-0.26	0.07	1997	0.44	0.04	2054	1.97	0.14	1989	-1.83	0.73	2113	-0.38	0.06	All Neth
KRGJ	346	0.34	0.09	240	0.01	0.15	348	2.12	0.13	322	1.76	0.36	313	4.50	2.55	349	-0.11	0.08	KRGJ
KRJL	539	-0.74	0.10	408	-0.04	0.13	534	-2.37	0.16	525	3.71	0.32	524	-1.48	1.73	539	-1.77	1.69	KRJL
KRJP	298	0.24	0.09	145	0.42	0.19	298	0.19	0.12	298	3.52	0.37	297	-5.40	2.32	298	-0.04	0.11	KRJP
KRLZ	414	0.91	0.15	283	1.02	0.15	2	7.70	10.75	393	3.73	0.34	388	1.11	1.88	414	-0.77	0.12	KRLZ
KRPB	522	0.57	0.10	391	1.05	0.14	476	0.52	0.08	512	2.79	0.26	511	-3.86	1.77	521	-0.30	0.10	KRPB
WMLG	276	-0.06	0.15	149	0.33	0.23	38	1.84	0.51	271	4.65	0.49	268	-1.07	2.26	276	0.28	0.11	WMLG
WPFZ	359	1.11	0.22	247	1.29	0.20	358	1.29	0.14	355	1.65	0.31	356	-3.55	2.43	359	-0.49	0.18	WPFZ
WPHZ	708	0.09	0.07	418	0.52	0.14	704	-0.36	0.12	696	5.21	0.31	691	-0.73	1.56	703	-0.34	0.10	WPHZ
WPVF	600	0.74	0.11	366	1.03	0.14	407	1.16	0.10	599	5.81	0.35	591	-5.58	1.61	600	1.16	0.10	WPVF
WPWH	427	0.33	0.15	326	1.47	0.16	290	-0.12	0.05	420	3.89	0.33	420	0.26	1.74	427	-0.63	0.09	WPWH
WSDG	123	-0.55	0.18	87	0.24	0.27	32	1.09	0.64	123	5.05	0.64	121	1.40	3.26	123	-0.65	0.14	WSDG
All USA	4612	0.31	0.04	3060	0.72	0.05	3487	0.16	0.05	4514	3.91	0.11	4480	-1.67	0.60	4609	-0.49	0.20	All USA
DIDA	228	0.56	0.09	112	0.86	0.27	228	-0.70	0.06	227	2.37	0.32	223	10.62	2.86	228	0.70	0.11	DIDA
FNCZ	133	1.13	0.20	106	0.36	0.28	125	0.32	0.15	132	2.74	0.55	131	4.64	4.04	133	0.91	0.21	FNCZ
FNEF	652	-0.45	0.08	440	0.31	0.12	630	0.11	0.08	643	6.65	0.35	644	0.46	1.64	653	-0.17	0.10	FNEF
FNFD	766	-0.11	0.04	596	0.13	0.09	759	0.31	0.04	756	4.54	0.23	757	-8.73	1.13	766	-0.70	0.06	FNFD
FNGM	81	1.20	0.21	42	0.33	0.43	38	-0.46	0.35	81	3.80	0.66	81	5.07	4.15	81	-0.97	0.33	FNGM
FNGS	16	1.89	0.58	15	-0.26	0.45	15	0.24	0.29	16	0.00	1.26	15	26.07	14.29	16	-0.12	0.30	FNGS
FNOY	271	0.23	0.07	245	-0.63	0.13	268	0.37	0.06	266	2.34	0.27	266	2.31	2.75	271	-0.52	0.07	FNOY
All Fra	2147	0.04	0.03	1556	0.13	0.06	2063	0.13	0.03	2121	4.50	0.15	2117	-0.91	0.85	2148	-0.27	0.04	All Fra
VSBG8	438	-0.02	0.08	290	0.60	0.12	400	-0.36	0.10	435	4.33	0.31	422	7.35	1.69	438	0.21	0.10	VSBG8
All VSOP	22555	-0.07	0.01	15273	0.24	0.02	18889	0.12	0.01	22227	3.03	0.04	21516	-0.52	0.23	22538	-0.29	0.04	All VSOP
OWS Cumulus	3628	-0.61	0.02	1928	-0.15	0.04	3628	0.05	0.01	3611	2.64	0.07	3601	4.76	0.29	3628	0.10	0.01	OWS Cumulus

than psychrometers. There are larger standard errors for dew point than for dry bulb temperature, perhaps indicative of errors introduced during conversion from the observed wet bulb depression.

4.3 Sea Surface Temperatures

The average over all VSOP observations is +0.12°C ±0.01, against an *OWS Cumulus* average of +0.05°C ±0.01. Most of the highest positive values come from ships using a water intake method of measurement; only one vessel, again using an intake method, shows a large negative value.

4.4 Wind Speeds

Over all VSOP observations, the average is +3.03 knots ±0.04, against an *OWS Cumulus* average of +2.64 knots ±0.07. No ship generates a negative mean difference from the model. Each method of measurement gives rise to both high and low averages, and the standard error also varies substantially between ships.

4.5 Wind Directions

Average difference over all VSOP ships is -0.52° ±0.23, against an *OWS Cumulus* average of +4.76° ±0.29. Vessels with large standard errors for wind speed also tend to display large standard errors for wind direction.

4.6 Pressures

Average difference over all VSOP ships is -0.29 mb ±0.04, against an *OWS Cumulus* average of +0.10 mb ±0.01. This negative bias may reflect the prevalence of inadequate height corrections (however see section 9). Precision aneroid barometers seem in general to give rise to smaller mean differences and standard errors.

5. INTRODUCTION TO THE DETAILED ANALYSIS

Detailed results for each variable are discussed in sections 6 to 9. For each variable the distribution of model values represented in the data set is first presented to indicate the range of values for which the results are likely to be valid. The various data comparisons then follow. For a variable, V, the results are normally plotted as the mean difference, ΔV, binned against model values, that is:

$$\Delta V_i = \frac{\Sigma [V_O - V_M]}{N_i} \qquad (1)$$

where V_O is the value observed by the VSOP-NA ship and V_M is the corresponding model value. The summation is over all values of $(V_O - V_M)$ corresponding to V_M values in some range V_{Mi} to $(V_{Mi} + \Delta V_M)$. N_i is the number of observations lying in that range. Where the results are plotted for individual ships, the order of ships shown is in alphabetical order of recruiting country, (Canada, France, Germany, the Netherlands, UK and USA), and, for a given country, in order of the ship call sign. This is the same order as was used by Kent and Taylor (1991).[1].

Where error bars are shown on a plot these represent the standard error of the mean, σ_m, defined by:

$$\sigma_m = \left(\frac{\Sigma [x_i - x_m]^2}{N (N - 1)} \right)^{0.5} \qquad (2)$$

where x_i and x_m are the individual values and the mean value, respectively. N is the number of values. In some cases care must be taken in interpreting the plots, particularly for the extreme values where there are few observations which may only come from one or two ships. In these cases a bias for a particular ship could result in small error bars but a totally unrepresentative mean. Also where there is an artificial limit to the values, this will result in a mean bias in the observations. For example wind speed cannot be reported as less than zero, so observations in light winds are bound to be biased high. It is possible that similar, artificial, limits affect the air and sea temperatures where a separate flag has to be set to report a negative value.

The effect of solar radiation (for example on air temperature measurements) has been represented by calculating the shortwave insolation (in W/m^2) using the local sun time and the ships' observations of cloud cover, as in Smith and Dobson (1985). Night-time values are plotted as a function of the observed cloud cover (in oktas).

Because the data set used for detailed analysis at the JRC excluded values near the east coast of the USA, the results presented in the following section may differ slightly in value to the overall statistics calculated by the UKMO and presented in Table 7; however examination shows that any such differences are not statistically significant.

6. SEA SURFACE TEMPERATURE (SST)

6.1 Range of SST Values Encountered

The range of model SST values which corresponded to VSOP-NA observations is shown in Figure 6.1a. The most likely value lay between 10°C and 15°C with the histogram skewed towards higher temperatures. Few observations existed for model values below 5°C or above 25°C. Figure 6.1b shows the same data but presented for each ship separately. Two ships, DHNE and VSBV3, operated in predominantly colder water, but most ships contributed to the data set over the range 10°C to 25°C.

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[1] Confusion as to the correct call sign for the USA recruited ship, Sealand Atlantic (KRLZ), means that it was listed out of order in the Catalogue of VSOP-NA ships (Kent and Taylor, 1991). The incorrect order has been retained here for consistency with the catalogue.

6.2 Mean SST Differences - Ship by Ship

The mean value of the (observed - model) SST difference, ΔT_S, for each ship is shown in Figure 6.2. The scatter of differences for each ship is shown in Figure 6.3b while Figure 6.3a shows the overall histogram of difference values. Most values for ΔT_S lie within ±0.5°C of the model value, which suggests that for SST the model analysis is a good representation of reality. The mean difference was 0.10°C with a standard deviation of 1.62°C . However the distribution is skewed toward positive difference, that is a tendency for the ships to report values warmer than the model. Ships with the warmest ΔT_S values (Figure 6.2) are those using engine intake measurements. In some cases (e.g. *Gulf Speed*, PELT, *Julius Hammer*, KRGJ) this appears to be a consistent bias since the scatter of observations (Figure 6.3b) is small.

6.3 Variations due to Recruiting Country

The differences by recruiting country evident in Figure 6.2 are mainly caused by the choice between using buckets or hull contact sensors (Germany and the UK) or using engine intake values (France, the Netherlands and the USA). Biases are particularly evident for some ships recruited by the Netherlands (although these values may have been affected by the short data sets available), and some USA ships.

6.4 Variations due to Instrument Type

The variation of ΔT_S according to instrument type is shown in Figure 6.4 both for the observed SST compared to the model values (Figure 6.4a) and for ΔT_S (Figure 6.4b). For the main range of model values the hull sensor values are in close agreement with the model values being about 0.2°C cold relative to the model at 5°C and about equal near 25°C. The bucket values are also close to the model and hull contact values except in the lower SST range where they become relatively warm. The engine intake values are relatively warm over the entire range.

It has been suggested (e.g. Folland and Hsiung, 1986) that, if uninsulated buckets are used, bucket temperatures will be biased low during periods of large heat flux from the sea to the air. Although most of the buckets used by the VSOP-NA ships were insulated, uninsulated buckets may have been used on one or more Netherlands and USA recruited ships (see, for example, Figure 17 of Kent and Taylor, 1991). The values of ΔT_S are plotted in Figure 6.5a as a function of the sum of the sensible and latent heat fluxes (F_H and F_E respectively). These flux values were calculated using the bulk formulae:

$$F_H = \rho\, c_p\, C_H\, (T_a - T_{sm}) \qquad (3)$$

$$F_E = \rho\, L\, C_E\, (q_a - q_{sm}) \qquad (4)$$

where T_a and q_a are the observed air temperature and specific humidity, T_{sm} and q_{sm} are the sea surface values based on the model sea surface temperature. The transfer coefficients C_H and C_E were set to 1.2×10^{-3}; other symbols have their normal meaning[1].

[1] ρ = density of air, c_p = specific heat at constant pressure, L = latent heat of evaporation.

Figure 6.5a shows that, as the sea to air heat flux increased, all the SST measurements became colder relative to the model values Since this may be a feature of the model analysis, the data are replotted in Figure 6.5b using the Hull sensor values as a reference. For heat fluxes in the range 50 W/m^2 to 300 W/m^2 the bucket values agreed within +0.1°C to -0.2°C with the hull sensor value, but with a tendency for the bucket values to become colder with increasing heat flux. However the bucket values were significantly warm for low heat fluxes and stable conditions. The engine intake values behaved similarly but were consistently 0.3°C warm over most of the heat flux range. This engine intake temperature bias is similar to the overall difference found in an extensive comparison of bucket and intake temperatures measured on the same ship by James and Fox (1972). It is not clear whether the colder engine intake temperatures observed at large heat flux values are significant.

Figure 6.6 shows the effect of solar radiation on the SST measurement. All the sensors show warmer values relative to the model under conditions of greater insolation. Compared to the hull sensor the engine intake values are consistently warm both day and night. However, whereas the buckets agree with the hull sensor values during the night, the bucket SST's become warmer with increasing solar radiation. If real, this could be because the buckets become heated on the deck and do not cool to the SST temperature. Alternatively it might be caused by near surface temperature gradients in the ocean.

6.5 Effect of Ship Size

The James and Fox (1972) study found that, on the larger ships, the engine intake temperatures were warmer with respect to buckets compared to smaller ships. The variation of ΔT_S with measurement depth (and hence with ship size) is shown in Figure 6.7. The hull contact sensors are more consistent than the engine intake values with the latter possibly showing a trend toward warmer temperature as the depth of measurement increased.

Figure 6.8 shows, for each measurement type, the ΔT_S value for the 19 ships which were less than 200m in length and the 26 ships which were larger. Few ships contribute to the lower temperatures and the results are probably only significant above 10°. In that range, engine intake temperatures for the larger ships show a tendency to become warmer as the sea temperature increases. For smaller ships, and for buckets, there is the cooling trend with increasing SST. The interpretation of these results is not clear.

6.6 Summary - SST

The use of different SST measurement techniques results in biases in the SST data. Engine intake temperatures are more scattered and exhibit a greater bias (overall mean 0.3°C) compared to buckets or hull sensors. Bucket measurements become relatively warmer for low heat flux conditions, when the air is warmer than the sea, or for periods of greater solar radiation. Intake temperatures increased with sea temperature on the larger ships.

7. AIR TEMPERATURE AND HUMIDITY

7.1 Introduction

Because air temperature and humidity were measured on the VSOP-NA ships using dry and wet bulb thermometers exposed either in a screen or in a handheld psychrometer, the two variables will be treated together. The main measurement errors for the dry bulb temperature are likely to be the "heat island" effect of the ship, the direct effect of solar radiation on the instrument, and insufficient time for a psychrometer, normally kept in the wheelhouse, to reach outside temperature. Most of these errors will increase the observed temperature value. Rarely, a dry bulb may become wet through spray or rain, thus decreasing the observed temperature reading, however a salty dry bulb should still read true. For the wet bulb the main measurement errors are inadequate ventilation or a contaminated or imperfectly wetted wick. Each will result in a decreased wet bulb depression and increased dew point temperature. Thus for both ΔT_a and ΔT_d values which indicate the ship observation being relatively high are more likely to be in error than those which show the ships reading low.

7.2 Range of Values Encountered

Almost all model temperatures were in the range 5°C to 25°C, most values being between 10°C and 20°C (Figure 7.1a). Most ships provided observations over this range (Figure 7.1b). Dew point temperatures peaked in the 10°C to 15°C range (Figure 7.2a) and, as would be expected, the histogram was skewed toward lower values compared to the air temperature. The distribution of dew point temperatures on a ship by ship basis (Figure 7.2b) was similar to that for air temperature. Some ships (e.g. *Nurnberg Atlantic*, DHNE, *CanMar Ambassador*, VSBV3) encountered a colder range of temperatures because they were solely operating on the "Europe to Canada" route.

7.3 Geographical and Seasonal variations

The geographical variation of the (observed minus model) differences for air temperature, ΔT_a and dew point temperature ΔT_d are shown in Figure 7.3. Both variables showed a gradient suggesting that the ship temperatures are colder relative to the model to the north and west compared to the south and east areas. This variation was most marked for ΔT_a in winter (Figure 7.4b) suggesting a temperature dependent relationship. For lower temperatures the ship data appear to be colder relative to the model. Since this means that for higher temperatures the ship data are relatively warmer, solar heating errors in the ship data might be suspected. However Figure 7.4c,d shows the distribution of ΔT_a using nighttime data only (where nighttime was defined by the sun being below the horizon). The northwest to southeast variation in the sign and magnitude of ΔT_a is also present in these nighttime data, ruling out solar radiation errors as the cause. Because the geographical variation of ΔT_a cuts across many of the shipping routes, and also because the *OWS Cumulus* showed similar trends to the VSOP-NA ships (Section 7.5), the variation is believed to be caused, at least in part, by some feature of the model analysis rather than by errors in the ship observations.

These biases also are evident if the ΔT_a values are classified according to season (Figure 7.4e). In the colder temperatures of autumn and winter the ship temperatures are lower than the model values (ignoring the lowest values where few observations exist). In spring the colder ship values values are lower and the warmer values are higher, and in summer the ship values are similar to, or greater than, the model temperatures. Plotted as the mean annual cycle of temperatures (Figure 7.4f), the colder ship values in winter are clearly evident. The differences over the rest of the year appear to be caused by the model lagging the observed temperatures. The cycle of Dew Point Temperature (also shown on Figure 7.4f) shows that the ships report higher humidities in winter, but lower humidities in summer, compared to the model. As for air temperature, the model dew point temperatures lagged the ship observations.

Given that spatial and seasonal variations exist which are believed, at least in part, to be due to the model, it is possible that spurious comparison values will be calculated for ships whose reporting period or area is limited. One such ship is the *OWS Cumulus*. This must be considered when examining the results.

7.4 Variations by Ship and Recruiting Country

7.4.1 Air Temperature

The mean values of ΔT_a and ΔT_d for each ship are shown in Figure 7.5. The ΔT_a values show significant differences which seem to depend more on the recruiting country than the type of instrumentation used. Thus psychrometer values from German recruited ships, and screen values from UK ships were all up to 0.5°C lower than the model values. Psychrometer readings on the Netherlands recruited ships, and screens on the USA ships, were generally warm relative to the model by about 0.5°C . The French and USA ships showed greater variation than those for other countries, with the French ships which used psychrometers giving higher air temperature values than other ships.

Because of the possible geographical variation in the model, there is the possibility that these differences are, at least in part, due to the ships recruited by different countries operating on different routes. Thus the German ships operated on the Europe to North America routes, the Dutch and French ships on the Europe to the Cape or the Straits of Gibraltar. However, Figure 7.5c shows the mean air temperature differences based only on data for the region 45°N to 50°N, 10°W to 20°W, and the period February 1989 to February 1990. This shows similar country to country variations of ΔT_a to those for the whole data set; for example the Netherlands ships' values are warm, the USA ships show a large scatter of values. These characteristics are also evident in the ship by ship distribution of ΔT_a values (Figure 7.6b). Considering the overall distribution of ΔT_a (Figure 7.6a), most values were in the range ±1.5°C suggesting that the biases between the model and the ships became small when averaged over a large area and period. The mean difference was -0.16°C with a standard deviation of 1.73°C.

7.4.2 Dew Point Temperature

In contrast to ΔT_a the mean values for ΔT_d (Figure 7.5b) appear to be more dependent on the instrument method than the country or ship route. The lowest, and therefore probably most reliable values, were obtained using psychrometers and were up to 0.5°C below the model values. Screen values were generally warmer than the model by up to 1.5°C. It is notable that, although the French psychrometer ΔT_a values were biased high, the ΔT_d values were similar to the screen values on other French ships. As for ΔT_a, overall, most ΔT_d values were in the range ±1.5°C but with a skew toward positive values (Figure 7.7a). Most ships contributed to this skewness (Figure 7.7b), however the distributions for the German and UK recruited ships were more sharply peaked than those for the Dutch or USA ships. The mean difference was 0.10°C with a standard deviation of 1.62°C .

7.5 Variations due to Instrument Type

The temperature and humidity instruments used by the VSOP-NA ships were either psychrometers, or screens. The French ships which used the "Pommar" meteorological system, with platinum resistance thermometers in a small "stack of plates" screen, have been treated separately (labelled "PRT" on Figures 7.8 and 7.9). These were the *Edouard LD* (FNFD), *Atlantic Cartier* (FNEF), and the *Jean Charcot* (FNOY).

The values for ΔT_a are plotted as a function of the model temperature in Figure 7.8b. Each of the instruments shows a trend such that the ships values were warmer relative to the model at the higher temperatures. This trend is also shown by the data from the weather ship *Cumulus*, which uses screens, suggesting that the trend is a feature of the model values. On average the psychrometer values are warmest and the PRT values coldest, however the differences are only of order ±0.1°C.

The dew point temperature differences, ΔT_d (Figure 7.9), show both a trend compared to the model, and variations between instrument types. For all instrument types, and for the *OWS Cumulus*, the value of ΔT_d becomes colder relative to the model with increasing temperatures suggesting that compared to the model the ships observe higher humidity at low temperatures and lower humidity at higher temperatures. The psychrometer and PRT values were lower, and therefore more likely to be correct, compared to the screen values. However the *Cumulus* values, based on screen readings, were lower still. There is a possibility that this could be partly a geographic effect, however it suggests that all the VSOP-NA ship data overestimate the humidity values to a greater or lesser extent.

7.6 Effect of Instrument Exposure

The exposure rating of the temperature sensor on each ship (Tables 2f and 3) was assessed for winds within ±45° of the bow, on the beam (45° to 135° and 225° to 315°) and from ±45° of the stern. The histograms of relative wind speeds and directions (Figure 7.10) demonstrate that, since the ships were normally travelling at 16 to 18 knots (Kent and Taylor, 1991), the relative wind is predominantly from the bow (69%, compared to 28% on the beam and 3% from astern). The most important instrument exposure rating is therefore that for winds on the bow. The exposure ratings achieved for the VSOP-NA dataset are shown in Figure 7.11. Psychrometer readings were normally taken on the bridge wing with an exposure rating of 4 or 8. Screen sitings resulted in more varied exposure ratings (see for example the UK ships in Figure 7.11b). On some USA ships the screens were very poorly exposed with low exposure ratings.

The variation of the air temperature difference, ΔT_a, with exposure is shown in Figure 7.12a for good (6 - 9), medium (3 - 5), and poor (0 - 2) exposure ratings. For the night-time values, plotted against cloud cover, the ΔT_a values show little variation with exposure; the poor exposure values may be about 0.2°C warmer, but the difference is hardly significant. Day-time values are plotted against the solar radiation (see section 5.2). The ΔT_a value becomes more positive (ship temperatures warmer) with increasing solar radiation. The effect is greatest for poorly exposed sensors, with medium and well exposed sensors showing relatively smaller biases.

The effect of solar radiation does not seem to depend greatly on whether screens or psychrometers are used (Figure 7.12b). Since at night the psychrometer values are about 0.2°C warmer, and since in the mean the psychrometers are warmer than the screens, it may be that the screens show a greater radiative effect by, at most, about 0.2°C to 0.3°C. There is a marked dependence on the relative wind speed. Stronger values of the relative wind decrease the solar radiation effect considerably (Figure 7.12c).

The ΔT_d values also show exposure related effects (Figure 7.13a). The reason why the poorly exposed sensors should read high under increased solar radiation is not clear, since the dew point temperature should not be altered by sunshine effects. The medium and well exposed sensors both show a different behaviour, with the ship values relatively dry for conditions of low cloud cover (whether by day or by night). The effect occurs for both psychrometer and screen values (Figure 7.13b) although it is more marked in the latter. This suggests that the model overestimates the humidity when the sky is relatively cloud free, and that under cloudy conditions (when the relative humidity is likely to be higher), the screens overestimate the humidity relative to the psychrometers.

7.7 Summary - Air Temperature and Humidity

Geographic trends of order 1°C were detected, particularly in the air temperature comparisons, which are thought to have been due to variations in the model values. The results also suggested significant mean biases in the model values for temperature (biased lower for low temperatures).

Psychrometer measurements of air temperature were similar to, or slightly warmer (by about 0.1°C) compared to those from screens, but the psychrometer humidity values were significantly lower by as much as 1°C (and presumably more accurate) than most of the screen values. However the *OWS Cumulus*, which uses screens, returned dew point temperatures even lower than the psychrometer readings suggesting that all the VSOP ships overestimated the atmospheric humidity.

In general the exposure of psychrometers was better than that for screens. The observed air temperature values were higher for poorly exposed sensors (screens and psychrometers) due to day-time solar heating. This effect decreased with increased wind speed. Under cloudy conditions (when relative humidity was presumably higher). the screen values of dew point were relatively high by about 0.9°C compared to psychrometers. There was also evidence that the model overestimates the relative humidity for periods of light cloud cover.

There were variations which depended on the country which recruited the ship. The "Pomar" type screens on the French ships gave humidity values more nearly comparable to the psychrometer readings. Psychrometer air temperatures on the Dutch ships tended to be warm by about 0.75°C. Instruments on some of the USA recruited ships had poor exposure, and the temperature values from the USA ships showed large biases and scatter.

8. WIND OBSERVATIONS

8.1 Range of Wind Values Encountered

The distribution of model wind speed values corresponding to the VSOP-NA observations (Figure 8.1a) peaks in the range 10 to 15 knots (5 to 7.5 m/s)[1], the most likely values were in the range 5 to 25 knots.with almost all ships reporting wind speed values in that range (Figure 8.1b). The most likely wind direction was about 225° with, as might be expected, significantly more observations of winds from directions from the west than directions from the east (Figure 8.1c).

8.2 Geographical Variations

The ship minus model wind speed differences, Δvv, were positive over the whole area, that is compared to the model the ships reported higher winds. There was a geographical trend with larger values to the north and west compared to the south and east (Figure 8.2) however this was probably related to the distribution of wind speed values (Figure 8.3).

8.3 Wind Speed and Direction - Ship by Ship

8.3.1 Wind speed

The mean value of the ship minus model difference for wind speed, Δvv, and direction, Δddd, are shown in Figure 8.4. The VSOP-NA ships used fixed anemometers, hand-held anemometers, or visual (Beaufort) estimates to determine the wind. The Δvv values were positive for all ships, no matter what instrument type was used. The overall distribution of Δvv was also skewed to positive values (ships reporting higher), the most likely difference being about 1.5 knots compared to the mean difference of 2.9 knots. The standard deviation was about 5 knots. This skewness is evident in the individual ship values of Δvv (Figure 8.5b). It might be caused, at least in part, by miscoding or transmission errors which can impose large positive, but not large negative, wind speed errors.

Hall et al. (1991) compared VOS data to the σ_1 (25m) model wind value for the UKMO model for the period January to June 1990. For data which had been quality controlled they found a near Gaussian distribution for Δvv with a bias of 2.4 knots and a standard deviation of 6.6 knots.

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[1] Ships report winds in either knots or m/s. To simplify comparisons with the ship speeds, this report uses knots. To the accuracy required here, 1 knot = 0.5 m/s.

On the basis of a mean difference of only -0.2 knots between the model and *OWS Cumulus*, they concluded that the VOS ships' observations were too large rather than the model winds being too low. However in these data the *OWS Cumulus* Δvv value, corrected to 10m height, is about 2.6 knots which is a similar to the VSOP-NA mean difference. Thus, overall, these results suggest that the model under-estimates the wind speed by about 2 knots.

The wind reports from the VSOP-NA ships are used by the model in calculating the analysis field. However comparisons using the 6 hour forecast fields from the model were not significantly different to those based on the analysis results.

8.3.2 Wind Direction

The mean Δddd values for almost all ships (Figure 8.4b) were within ±5° of the model value. Six of the ten VSOP-NA ships which used wind vanes were among the 7 ships with mean differences greater than ±5°. Even the *OWS Cumulus*, which uses wind vanes, showed a bias compared to the model of 5°. This probably illustrates the difficulty of aligning a wind vane to the ship's head to better than ±10°. Most Δddd values, whether visual or instrument derived, were within ±10° of the model value (Figure 8.5c). Outside this range, the scatter of Δddd values was similar for the two methods with most ships observing wind values up to 90° from the model value and sometimes more (Figure 8.5d). Some of these differences may have been due to small scale features of the wind field which are not represented in the model. In other cases coding errors may have occurred (see Section 8.6.4).

8.4 Variation with Wind Velocity

The variation of Δvv with wind speed is shown in Figure 8.6. The positive bias of the ship observations compared to the model is evident at all wind speeds. In the most commonly observed range, 5 to 25 knots, the difference increases with wind speed. Both the model and the ships showed a variation of the mean wind speed with wind direction with winds from the west being strongest (Figure 8.6c). This causes an apparent variation of Δvv with wind direction (Figure 8.6d).

8.5 Variation due to Method of Estimation

The variation of Δvv with wind speed was different depending on the estimation method used (Figure 8.7a,b). Visual winds (which dominated in the overall mean relationship shown in Figure 8.6b) were lower than winds from fixed anemometers. The difference was about 2.5 knots for the commonly observed wind speed range. Below 15 knots, winds from hand-held anemometers gave similar Δvv values to visual winds. At higher wind speeds the few observations which were obtained showed large scatter.

These differences were not related to the atmospheric stability (Figure 8.7c). Stable cases were defined as the air temperature being warmer than the sea. Under stable conditions visual winds may have been estimated slightly higher at low wind speeds but there was little significant difference.

8.6 Anemometer Wind Data

8.6.1 Variation with Recruiting Country

The fixed anemometers on French and USA recruited ships (Figure 8.8) showed similar behaviour, both being significantly different to the *OWS Cumulus* anemometer values. This was true whether the model analysis results or the forecast values were used for the *Cumulus* comparison.

8.6.2 Effect of Anemometer Height

For those ships using anemometers, Δvv showed a possible dependence on the anemometer height (Figure 8.9). Also shown on this plot is the required correction to the wind speed to give 10m values assuming neutral stability (Dobson, 1981). Clearly this correction does not explain the difference between the anemometer readings and the model. Even allowing for a model offset, the actual dependence on anemometer height appears to be greater than would be expected from the variation of wind with height. Possibly this is due to increased acceleration of the wind flow over larger ships.

8.6.3 Variation with Instrument Exposure

The exposure rating of the anemometer for those ships carrying fixed anemometers was defined in Tables 2f and 3. In general the anemometers were well exposed with good exposure ratings being achieved both overall (Figure 8.10a) and on an individual ship basis (Figure 8.10b). Most observations (88%) were categorised as having a good exposure rating (6 - 9), relatively few (12%) fell into the medium category (3 - 5), and none were considered poor (0 - 2). In terms of Δvv, there was little statistically significant difference between the good and medium exposure categories (Figure 8.11); the medium exposures perhaps gave lower winds in the 15 to 25 knots range.

8.6.4 Errors in estimating the True Wind

The VOS are requested to report the true wind speed and direction. For those ships using anemometers, the ships' officers must perform the vector subtraction of the ships velocity from the measured relative wind. Given that the typical speed of the VSOP-NA ships was 16 to 18 knots, and that the most likely wind speed was in the range 5 to 20 knots, a large error can result if this calculation is not performed correctly. To determine the likelihood of this error the VSOP-NA ships were requested to report ships speed and head, and the relative wind speed and direction, in addition to the true wind values. Since most VSOP-NA wind data were visual observations, the number of these relative wind observations reported was small (about 2500). Using these data, the relative wind has been calculated from the reported true wind, and compared to the observed relative wind. Figure 8.12a shows that only about 50% of the reported winds corresponded to calculated relative winds within ±2 knots of the observed value. A large fraction of the reports (30%) were more than ±5 knots different. For wind direction only 70% were within ±10°, and 13% were outside ±50°. These are large errors which significantly degrade the dataset of anemometer winds.

8.7 Visual Wind Data

8.7.1 Variation with Recruiting Country

For ships recruited by the Netherlands, UK, and USA, the variation of Δvv with wind speed for visually estimated winds was very similar (Figure 8.13). The German ships produced significantly higher wind values, although these were less than the anemometer derived values discussed above.

8.7.2 Comparison of Day-time and Night-time values.

It might be expected that visual estimation of the wind is more difficult at night than during the day. Figure 8.14a shows the anemometer and visual winds for day-time and night-time periods where night was defined as the sun being below the horizon. The Δvv values for the anemometer winds are not significantly different between the two periods. However with increasing wind speed the Beaufort estimates at night become lower than the day-time values. This suggests that at night the ships' officers underestimate the roughness of the sea and hence the wind speed.

Six of the VSOP-NA ships which returned visual wind reports were also equipped with anemometers. Figure 8.14b shows that, for day-time observations, the Δvv values for these ships were no different to those from other ships returning visual estimates. However at night the Δvv values were similar to those obtained during the day. This suggests that, although the officers on these ships do not rely primarily on the anemometers for wind estimation, the anemometers are used to help estimate the winds at night.

8.7.3 Beaufort Scale Effects

The discrete nature of the Beaufort Scale results in a histogram of visual wind speeds showing peaks at the mid values of each Beaufort Force (Figure 8.15a). This effect, which has been noted before (e.g. Wilkerson, 1986), was noted in the wind reports for most ships (Figure 8.15b). Over many reports the effect should average out. These figures show that few ships report wind force 1.

A number of definitions of the Beaufort Scale are in use. That recommended for use on the VOS ships is known as "Code 1100"; a different definition has been recommended by the Commission for Marine Meteorology as more accurate than Code 1100, but the advantages were not considered sufficient to warrant the introduction of a new code on the VOS (WMO 1970). A further, recent definition has been suggested by Kaufeld (1981). The effect of using these Beaufort Scale definitions is shown in Figure 8.16a. The visual winds are increased at most wind speeds and decreased at the highest wind speeds. For most wind speed observations the difference from the model values is increased. The new scales were defined by comparing visual and anemometer estimates. The difference between the visual winds and the anemometer measurements is shown in Figure 8.16b for each of the Beaufort Code definitions. None of the codes gives good agreement over the whole wind speed range; the new codes produce generally better agreement with the anemometer values than Code 1100 but this does not necessarily mean a closer agreement to true conditions.

8.8 Summary - Wind

The model appears to under-estimate the wind, probably by about 2 knots, compared to the observations. Anemometer estimated winds were about 2.5 knots higher than visual winds. Most anemometers were well exposed and there was little correlation of wind speed differences with exposure. There was a possible correlation between the height of the anemometer and the wind speed "over-estimate" with high anemometers giving stronger winds than would be expected from the variation of wind speed with height. Wind vanes were prone to fixed directional errors which were not present in the Beaufort estimates. The conversion of anemometer measured relative wind velocities to true wind introduced many significant errors into the dataset.

For winds above about 15 knots, visual wind reports underestimated the wind at night compared to day time periods. On those ships reporting visual winds which were also fitted with anemometers, the night-time winds were similar to the day-time visual winds suggesting that the anemometer is being used to help, but not replace the visual estimate. Use of alternative Beaufort Scale definitions produced better agreement between the visual and anemometer winds, but worse agreement with the model. No single scale produced good agreement over the entire wind speed range.

9. PRESSURE

9.1 Range of Pressure Values Encountered

Most of the observations corresponded to model pressure values between 1010 mb and 1030 mb (Figure 9.1a) with most ships contributing data in the range 990 mb to 1040 mb (1 mb = 1hPa).

9.2 Geographical Variations

The (ship - model) pressure differences ΔP show a significant geographical variation with the ships reporting higher pressures with respect to the model to the north, and lower pressures to the south; the variation being of order 0.3 mb. This variation is apparent in Figure 9.3 as a tendency to more negative values of ΔP with increasing values of the air temperature. If this variation was caused by neglecting the effect of temperature in correcting the ships pressure observations to the surface value, then the ships should read **higher** for higher temperature conditions. The opposite trend to that in Figure 9.3. Pending further investigation, the geographical variation of ΔP would appear to be due to the model rather than the ship observations.

9.3 Mean Pressure Differences - by Ship, Country, and Instrument type

The mean values of ΔP for each ship are shown in Figure 9.4. ΔP for the majority of ships was between 0.0 and -0.5 mb. The Dutch and UK ships used digital Precision Aneroid Barometers (PAB's) and generally showed less scatter than ships recruited by the other countries which used analogue aneroid barometers. Large (order 1 mb) but consistent biases occurred in the reports from some of the German and French ships.

The overall histogram of ΔP values (Figure 9.5a) shows that most reports were within ± 0.5 mb of the model value, the mean difference was -0.191 mb with a standard deviation of 1.96 mb. Examination of the scatter of ΔP values (Figure 9.5b) shows that for most ships there were some values which were probably incorrect by 10 mb. Such values would be easily removed by a quality control procedure which would reduce the standard deviation, probably to the 1.6 mb found by Hall et al. (1991). Whereas the ΔP values for many of the ships lay close to the overall mean of -0.2 mb, the *OWS Cumulus* value was +0.1 mb. Given the northerly position of *Cumulus*, this fits the geographical trend in ΔP noted above.

9.4 Variation with Mean Pressure

Figure 9.6 shows the variation of ΔP with the model pressure value. In the most commonly observed pressure range, 990 mb to 1030 mb, the value of ΔP decreases as the pressure increases. That is, when the pressure is high, the ships observe a lower pressure than the model. This variation could be associated with the observed geographical variation of ΔP. A similar variation is not detected in the data for *OWS Cumulus*, which stays in the same position, suggesting that the trend is geographical or temperature related rather than a function of the absolute pressure.

Since pressure is assimilated into the model during the analysis, it might be expected that the model values and the ship values should be in close agreement. The degree to which the ship values influence the analysis can be examined by comparing the ship data to the forecast from 6 hours previously. Figure 9.6c shows that compared to the "T+6" forecast the ship values read low by about 0.5 mb more than the comparison with the analysis would suggest. This contrasts with the values for *OWS Cumulus* which are higher when compared to the forecast (Figure 9.6d). This suggests that the VOS pressures act to decrease the model pressure over much of the region, whereas the *OWS Cumulus* data acts to increase the model pressure. A possible cause of this would be inadequate corrections for barometer height on the VOS ships. This will now be considered in more detail.

9.5 Barometer Height Corrections

On most of the VSOP-NA ships the barometer was situated at between 20m to 30m above sea level. At, say, 15°C this means that the barometer will read low by between 2 mb to 3.5 mb compared to the sea surface pressure. To correct for this, the VOS are expected to apply a correction factor to the observation. Figure 9.7a shows, for each ship, the mean value of ΔP plotted against the height of the temperature sensor (for most ships this will also be the height of the barometer, however on some ships the barometer will be about 3m to 4m higher in which case the plotted point would move higher by up to 0.5 mb). If the ships did not apply a barometer correction the points should lie along the line shown; it would appear that a barometer correction is being applied on all the VSOP-NA ships. This conclusion still holds if the "T+6" forecast data is used instead of the model analysis data (Figure 9.7b).

The barometer correction to be applied should vary as the draft of the ship varies with cargo load etc. The VSOP-NA ships were requested to provide a value for a "reference height" with each observation. Not all ships reported this variable reliably. For those which did, Figure 9.7c shows the value of ΔP (adjusted by the mean pressure bias for that ship) plotted against the variation in reference height. Ships represented by points on the zero line have corrected for changes in draft, ships with points on the sloping line have not. It appears that most ships corrected for changes in the draft which were over 1 metre in magnitude. Smaller changes appear not to have been allowed for.

9.6 Summary - Pressure

Pressure observations from ships using digital Precision Aneroid Barometers appeared to be more accurate than those using analogue instruments. A few instruments had a consistent calibration bias of order 1 mb.

A major cause of mean differences between the ship observations of pressure and the model appeared to be a north to south variation in the model values of order 0.3 mb. In the mean the ship pressures were 0.2 mb lower than the model analysis. Compared to the forecast the ship pressures were lower by about 0.7 mb. These differences were greater under conditions of higher pressure. The lower pressures observed by the ships did not appear to be explained by a failure to correct for the height of, or changes in the height of, the barometer.

10. SUMMARY

10.1 Model Characteristics

During the analysis it became clear that some features of the (ship minus model) differences were probably caused by characteristics of the model analysis. Furthermore that these trends were such that, for example, incorrect conclusions might be drawn concerning the performance of ships which operated in limited geographical areas, or for only part of the project. These features are summarised in Table 10.1.

Table 10.1 Characteristics which can probably be ascribed to the model and which must be allowed for in the analysis.

Variable	Characteristic
SST	Model field appears to be a good representation of reality.
Air Temperature	Model values are warmer under colder conditions, and colder under warm conditions. This leads to a geographical trend; in winter the model values are warm to the northwest compared to the southeast by about 1.5°C. Model values lag the seasonal values of observed temperature.
Humidity	Model values are relatively drier under lower humidities but moister for the most often observed humidities. Model values lag the seasonal values of observed humidity.
Winds	Model values are biased low compared to the ship data (estimated mean bias ≈ 2 knots).
Pressures	North-south trend in the model values of about 0.3 mb.

10.2 Instrument Characteristics

The VSOP-NA results suggest that there are biases and other differences in the data which depend on the measurement method used. These are summarised in Table 10.2.

Table 10.2 Features ascribed to differing methods of observation.

Variable	Method	Characteristic
SST	Hull Sensor	Consistently good.
	Engine Intake	Greater scatter, some large consistent biases. In mean, biased high by about 0.3°C.
	Bucket	Relatively warm (up to 0.5°C) for low heat flux, stable conditions, high solar radiation. Otherwise agreed with hull sensor values.
Air Temperature	Psychrometer	Exposures generally better than screens. Dutch ships' values high (by about 0.75°C ?). Mean solar radiation error of up to 1.5°C which varies with wind speed.
	Screen	Some poorly exposed (particularly USA). Solar radiation error same as psychrometers except poorly exposed screens were worse.
Dew Point	Psychrometer	Values lower than screens by 0.5 to 1.5°C. Values low relative to model particularly under clear sky conditions.
	Screen	Values higher than psychrometers particularly under cloudy (higher relative humidity?) conditions (up to 1°C). Screens on UK ships show least scatter.
Winds	Fixed Anemo.	Speeds were about 2.5 knots greater than visual estimates. Possible dependence on anemometer height even if corrected to 10m. Directions likely to have constant offset. Many errors in conversion to true wind value.
	Hand Anemo.	Speed estimates scattered at wind speeds above 15 knots. Larger scatter for wind direction than other methods.
	Visual	Speeds lower than anemometers. Underestimated for winds above 15 knots at night (unless anemometer on ship). None of Beaufort scale definitions gives perfect agreement with anemometers. Directions generally good.
Pressures	Digital PAB	Digital readings less scattered than analogue. Height corrections seem to be applied properly.
	Analogue Baro.	More scattered, some have offsets of order 1 mb.

10.3 Augmented documentation

A major feature of the VSOP-NA project was the availability of extra information concerning the participating ships. In some cases this information is available from the "List of Selected Ships" (WMO 1990) but in incomplete or inaccurate form. A particular instance is the presence of anemometers on some ships which return visual wind observations. In other cases, such as the type or exposure of some thermometer screens, the information is not available. These examples have been chosen because differences were detectable in the data due to these causes.

The usefulness of the extra codes reported by the VSOP-NA ships is assessed in Table 10.3.

Table 10.3 Value of the Extra Codes reported by the VSOP-NA ships

Extra Information	Assessment
Ship's speed and heading	Needed to convert relative wind observations. The speed and course made good is reported and may be sufficient, but this has not been tested.
Height of deck cargo	Not found useful.
Height of reference level	Could be useful for real time quality control of pressure data; however, misunderstandings caused this variable to be reported unreliably by some ships.
Method of SST measurement.	There is a definite bias between different methods; some ships use more than one method; the method should be reported with each observation.
Location of air temp. measurement.	Not found useful on an observation by observation basis. Needed as part of an overall ship description.
Relative wind speed and direction	For ships with anemometers, the VOS dataset would be significantly improved if this was reported instead of or in addition to true wind, provided an adequate ship's speed and heading were available.

11. RECOMMENDATIONS

A : Recommendations To Members Operating VOS

A1 Observing Practices and Equipment

The results of VSOP-NA demonstrate clearly the value of national observing fleets conforming to recognised standards of instrument exposure and observing practice. Additionally, for some variables, one method of measurement has been shown to be superior to others (eg SST by hull-contact sensor). For other variables, different methods have both advantages and disadvantages; good exposure is often more important than choice of instrument type (see Table 10.2 in this report). It is therefore strongly recommended that Members take note of these findings, and ensure that equipment, exposures and observing practices are chosen and maintained appropriately, with a view to achieving greater accuracy and consistency across the international VOS. Details of hull sensors used by the Netherlands and the UK are included in Kent and Taylor 1991.

A2 Publicity for VSOP-NA Results

It is essential that the results of VSOP-NA be published and made available to all Members, for relevant distribution within their countries. Publications such as Marine Observer, Mariners Weather Log, Wetterlotse, Met Mar and MIM should be used to bring the results in appropriate form to the attention of the VOS. Other methods of publicising the project nationally may also be considered.

A3 Real-Time Data Monitoring

The existing real-time monitoring systems for VOS reports should be extended to cover all variables required for surface flux calculations; specifically VOS databases maintained at each monitoring centre should include more detail for each ship, to facilitate identification of the appropriate corrections. Results of the real-time monitoring should be made available more frequently to Members and PMO's, ideally monthly.

A4 Reduction in Reporting Errors

The results of VSOP-NA show that many errors were made in converting measured relative wind into true wind, and in deriving dewpoint from dry-bulb and wet-bulb temperatures. Members are recommended to provide their VOS with dedicated calculators or computer programs for deriving these quantities, in order to achieve a significant decrease in the number of such errors.

B : Recommendations to WMO

B1 Sea Temperature Measurements

Given the differences resulting from different methods of sea temperature measurement, it is desirable that ships' GTS reports should include an indicator to define the method in use. However in view of the difficulty of devising a suitable code consistent with the logbook (IMMT) procedures and also easily incorporable into the $0s_nT_WT_WT_W$ group of the SHIP code, it is recommended that, before any further action is taken, users concerned with the real-time analysis of SST data should be consulted, in the light of the VSOP-NA results, regarding the value to them of this additional information.

B2 Ship's Draft

Considering the importance of ship's draft/"height of eye" reports for the accurate calculation of sea level pressure, and recognising that this information is at present available only from logbooks, it is recommended that real-time monitoring centres be consulted regarding the value of the inclusion of such reports within each GTS observation.

B3 Code Changes

If a real-time requirement for "method of SST" or "height of eye" information is found to exist (recommendations B1 and B2), then it is recommended that CMM take action to develop and implement appropriate code changes to effect real-time reporting of this information.

B4 Catalogue of Reporting Ships

It is strongly recommended that WMO improve the accuracy and dissemination of the International List of Selected, Supplementary and Auxiliary Ships (WMO No. 47). This could be achieved by requesting Members to update and submit information of a quarterly (rather than an annual) basis, and making the publication available on diskette at similar intervals. Urgent progress should also be made towards providing the information to Members through an on-line database. As a longer-term goal, the expansion of the list to include further information on types and locations of sensors should be studied. In this context, the value of CD-ROM as a medium for the storage of drawings, photographs and sketches of ships should be considered. The VSOP-NA catalogue (ref) might be seen as a model for this type of presentation.

B5 Observing Practices

With the aim of standardising practices between national observing fleets, it is recommended that a reference booklet be prepared to provide concise step-by-step guidance on observing procedures to vessels of the VOS. Material in the Guide to Marine Meteorological Services (WMO No 471) could be used as a starting point.

B6 Port Meteorological Officer System

The results of the VSOP-NA study demonstrate that an efficient Port Meteorological Officer system can have significant impact on the overall quality of data submitted by individual national fleets. It is recommended that appropriate funding and resources be made available to improve the organization, training and operation of the Port Meteorological Officer systems of Member countries. Members with existing, well-established and effective PMO systems should be encouraged to to offer training and assistance facilities to other Members to enable them to upgrade their own PMO services.

B7 Beaufort Scale

The results of the VSOP-NA analysis of wind data suggest that further consideration be given to the wind speed equivalents of the Beaufort scale. It is recommended that CMM initiate/co-ordinate further action in this respect, and the results of VSOP-NA be considered when any proposals are formulated.

B8 Delayed-mode Anemometer Winds

Recognising that the results of VSOP-NA have demonstrated that substantial numbers of errors occur in the calculation and reporting of true wind speed and direction, both in real-time (see also recommendation A4) and in delayed mode, it is recommended that CMM re-examine the procedures for delayed-mode reporting of anemometer winds, with a view to reducing these errors in the archived data through inclusion of relative wind speed and direction in the logbook reports.

C : Recommendations for Climate Research

C1 Noting that model-derived ocean surface flux values will be increasingly used for forcing ocean models, and recognising that the VSOP-NA project has shown that biases exist in model-derived data such that significant errors would exist in the predicted flux values, it is recommended that increased use be made of the VOS ship observation to verify model flux determinations.

C2 It is recommended that, where VOS observations are used to construct sea surface temperature data sets, the observation should be classified according to measurement type and that greatest weight should be given to 1) hull contact sensors, 2) bucket measurements, 3) condenser or engine intake instruments, in that order. In particular it should be noted that there is evidence that intake measurements are of poorer quality and likely to be biased warm compared to the other methods (see also recommendations A1 and B1).

C3 Recognising that ships' observation transmitted over the GTS at present contain a significant number of errors due to the incorrect calculation of true wind velocity and dew point, and that these errors can be reduced by the use of logbook data, the use of delayed-mode logbook-derived data for climate research is recommended (see also recommendation B8).

C4 Noting that the greatest accuracy requirements for VOS data are for the calculation of flux fields for climate research, and recognising that the VSOP-NA project has demonstrated that the quality of ships' data depends on the efficiency of the PMO system, it is recommended that the climate research community supports measures designed to improve the PMO system.

12. ACKNOWLEDGEMENTS

We would like to acknowledge the following without whose contribution this report could not have been assembled: the Owners, Masters and Officers of the VSOP-NA ships; the Port Meteorological Officers, members of the VSOP-NA Management Committee, and staff of the Atmospheric Environment Service (Canada), Direction de la Météorologie Nationale (France), Deutscher Wetterdienst Seewetteramt (Germany), Royal Netherlands Meteorological Institute (KNMI, Netherlands), Meteorological Office (UK), National Weather Service / NOAA (USA); and the World Weather Watch and World Climate Research Programme (WMO) and the the Committee on Climate Changes and the Ocean (IOC/SCOR).

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Figure 2.1. Areas which were excluded from the analysis. Observations from the cross-hatched areas were excluded from the Comparison Dataset. In addition, observations in the dotted area were excluded from the analysis at the James Rennell Centre (JRC).

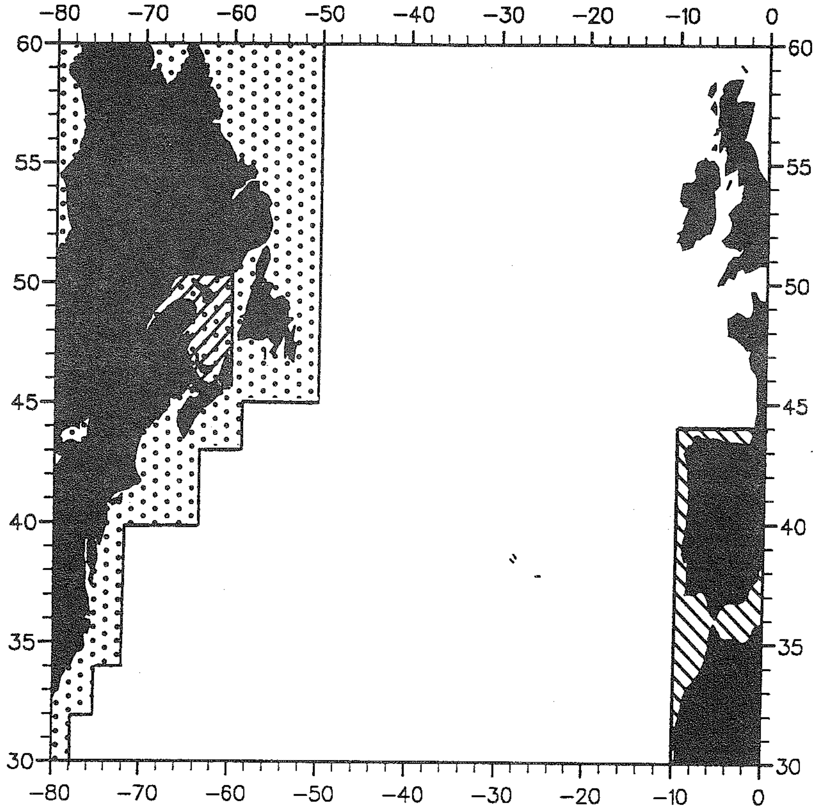
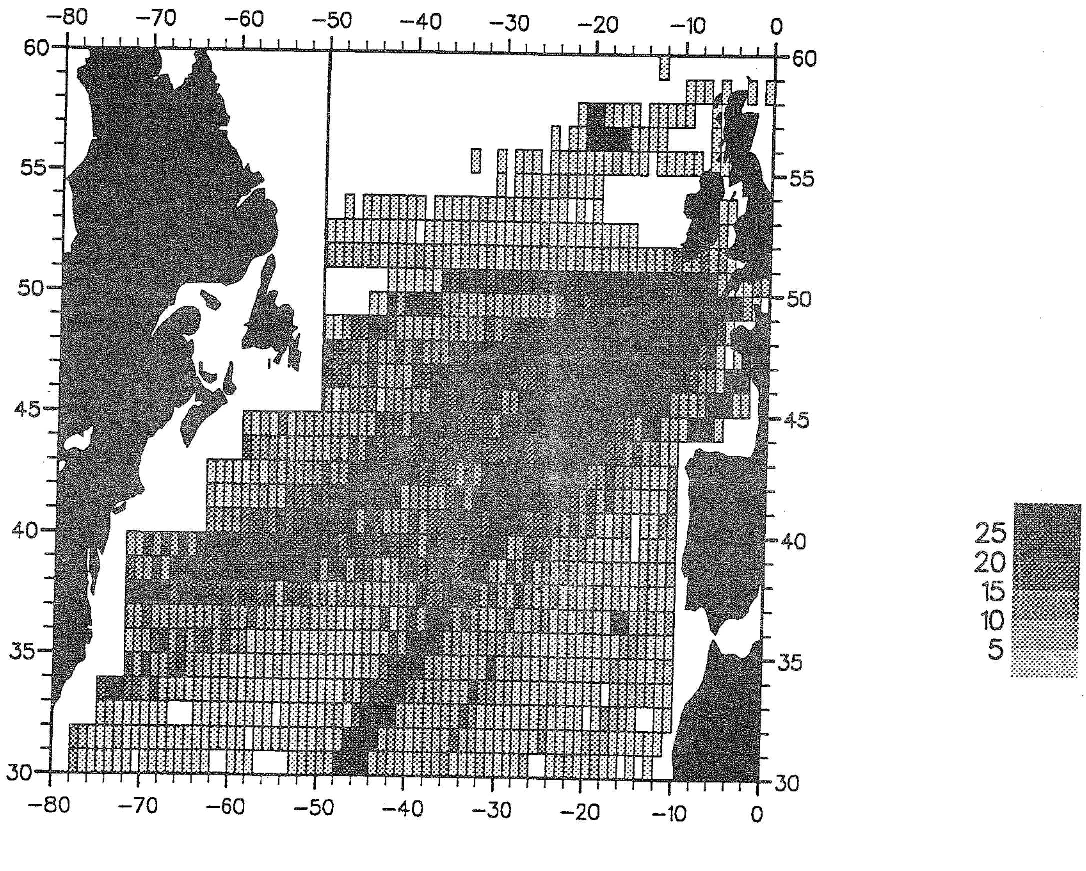
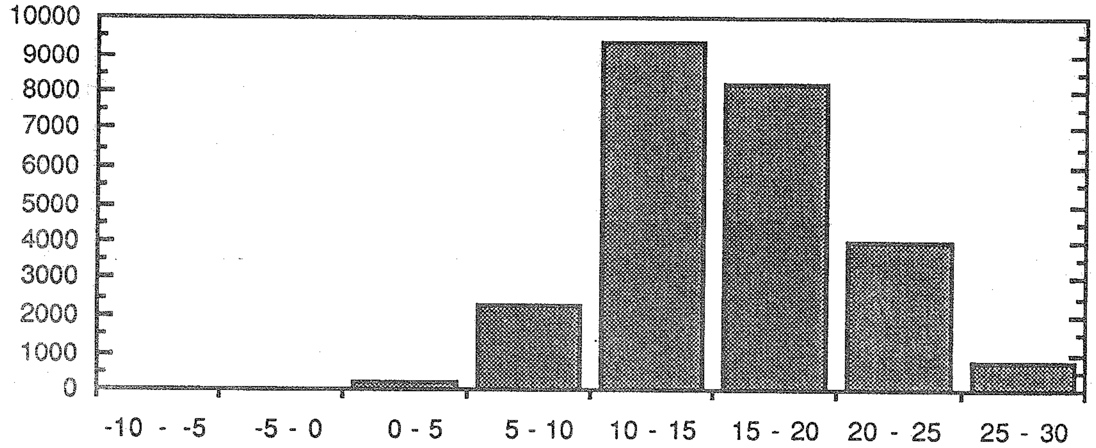


Figure 2.2 Distribution of observations for the Comparison Dataset as analysed at the JRC. The scale is in number of reports per one degree square.





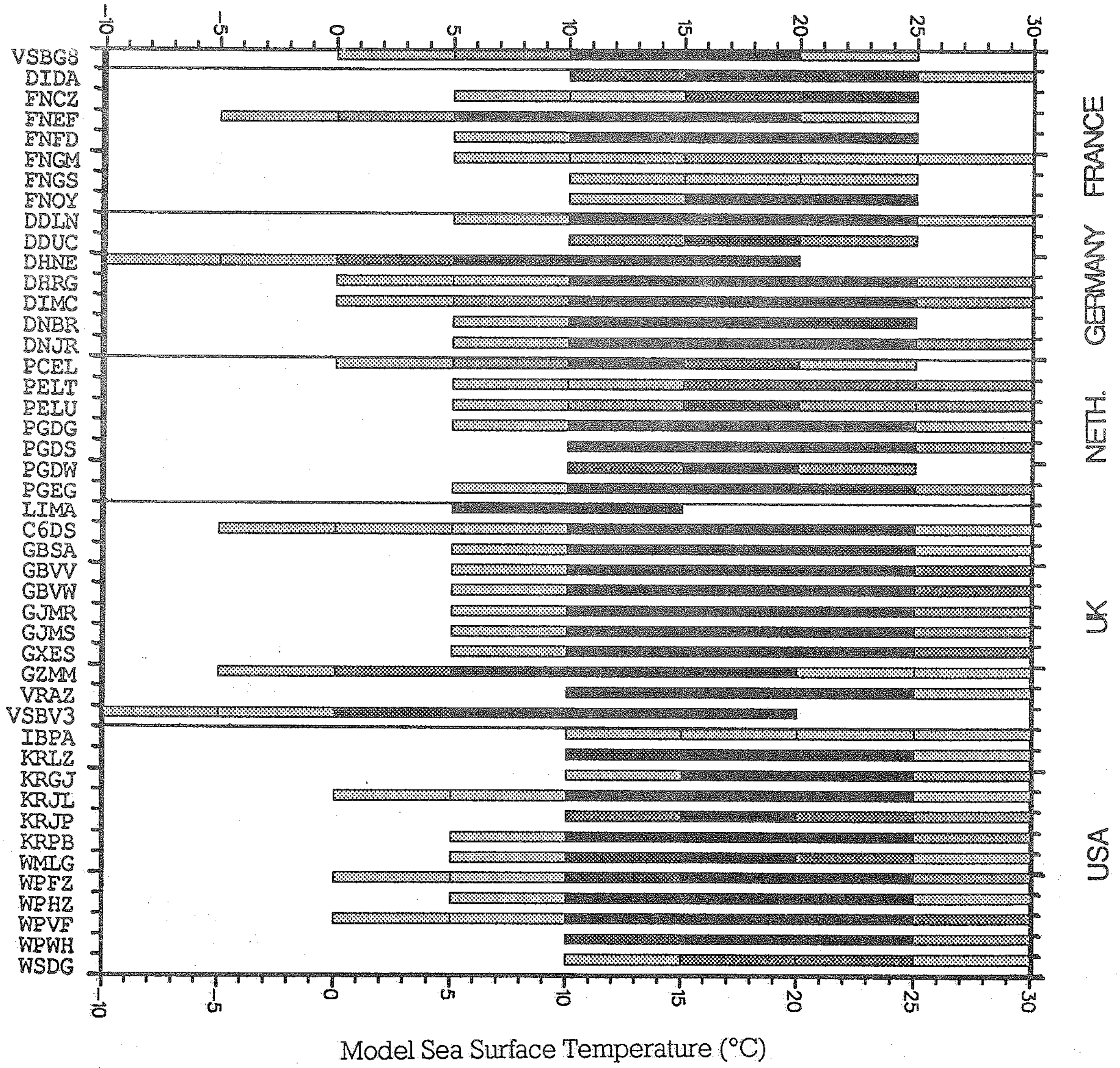


Figure 6.1a (top) - Histogram showing number of VSOP observations for model sea surface temperature ranging from -10 to 30 °C

Figure 6.1b (bottom) - Numbers of VSOP observations by ship for model sea surface temperature ranging from -10 to 30 °C. Shading indicates numbers of observations per 5°C range.

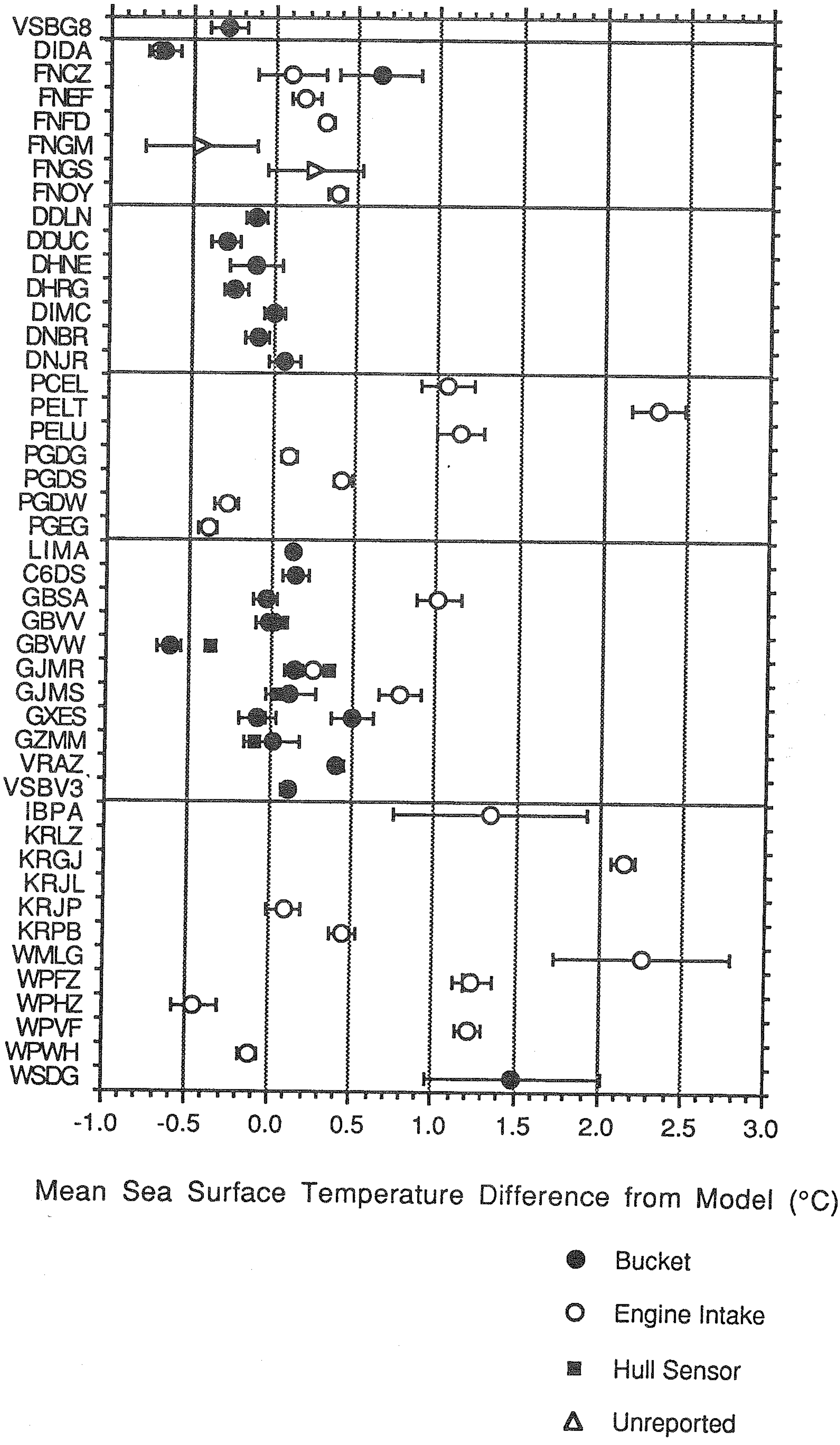


Figure 6.2 - Mean sea surface temperature difference from model (°C) by method (bucket, engine intake,hull sensor or unreported) by ship callsign. If more than one method was used on a ship the values are shown separately

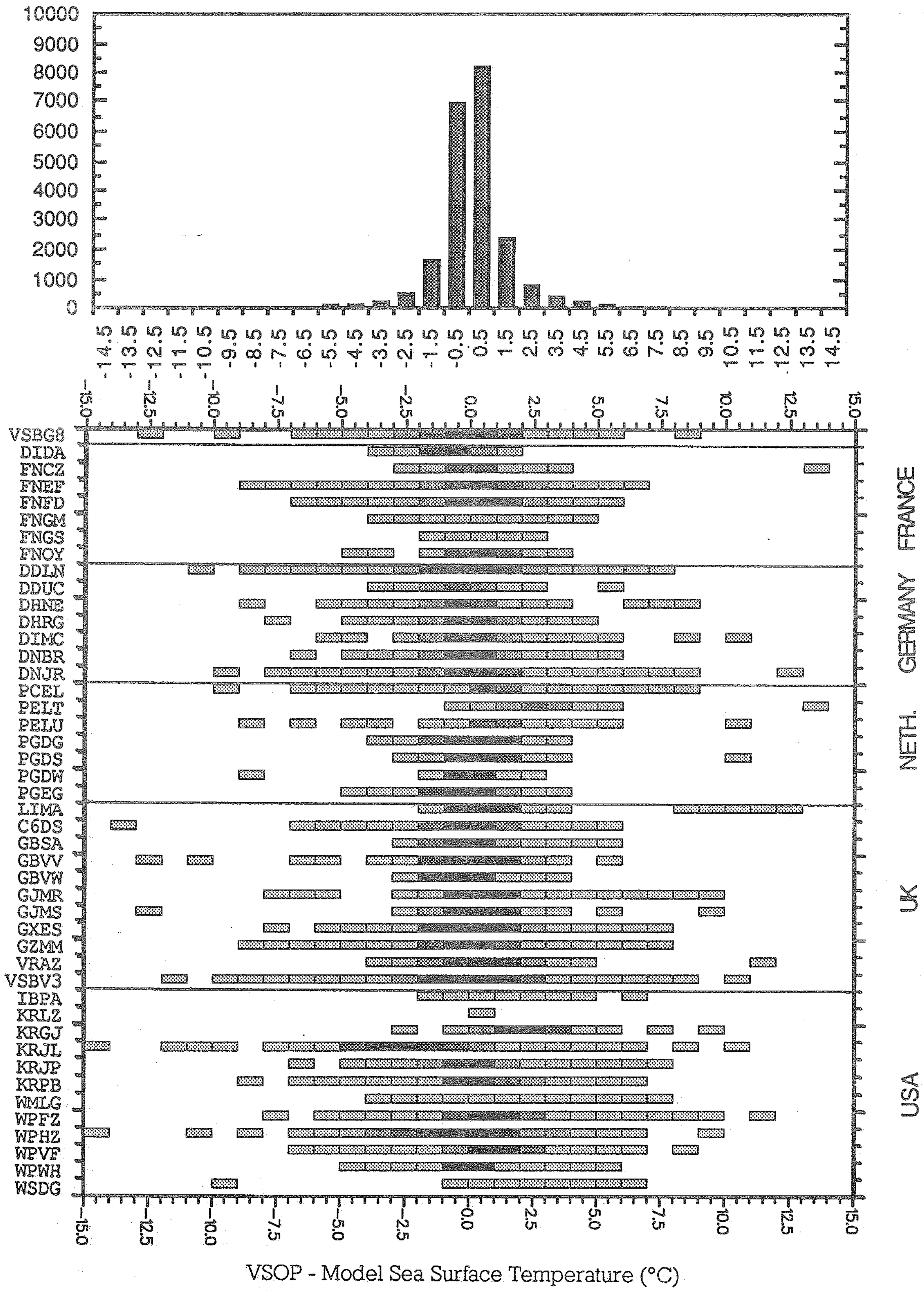
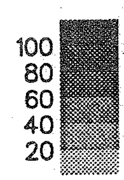
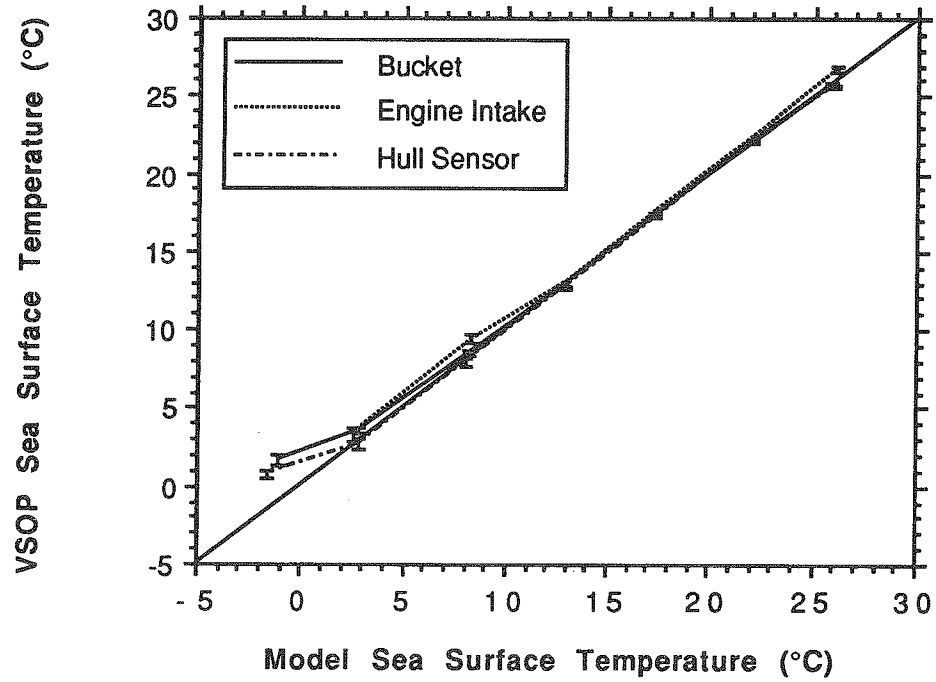


Figure 6.3a (top) - Histogram showing number of VSOP observations differing from model sea surface temperatures ranging from -15 to 15 °C

Figure 6.3b (bottom) - Numbers of VSOP observations differing from model sea surface temperatures by ship for temperature differences ranging from -15 to 15 °C. Shading indicates numbers of observations per 1°C range.





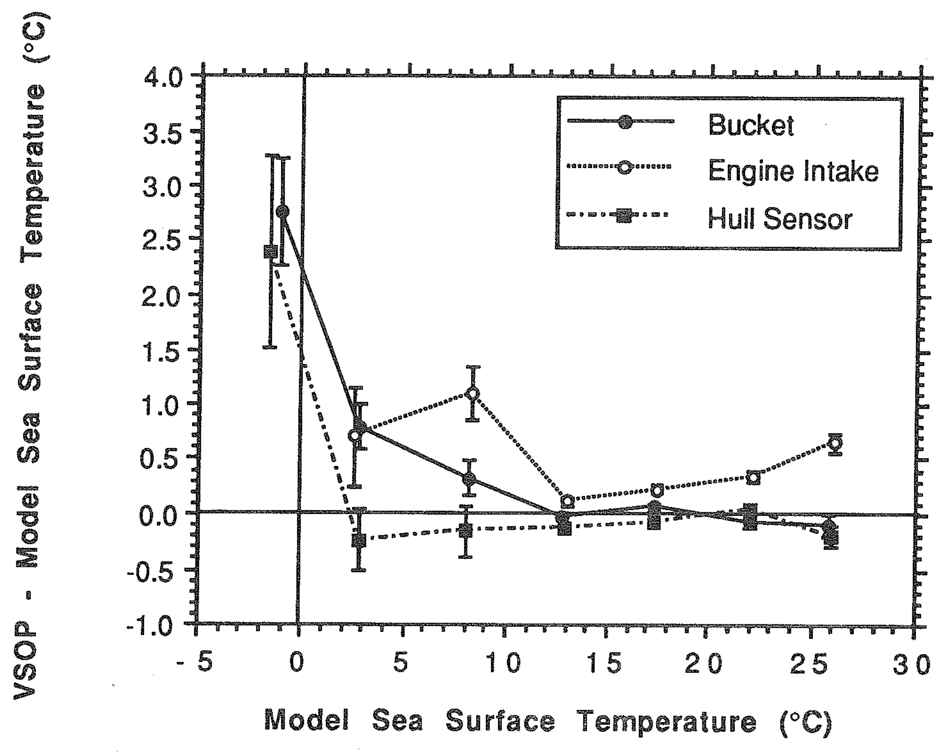
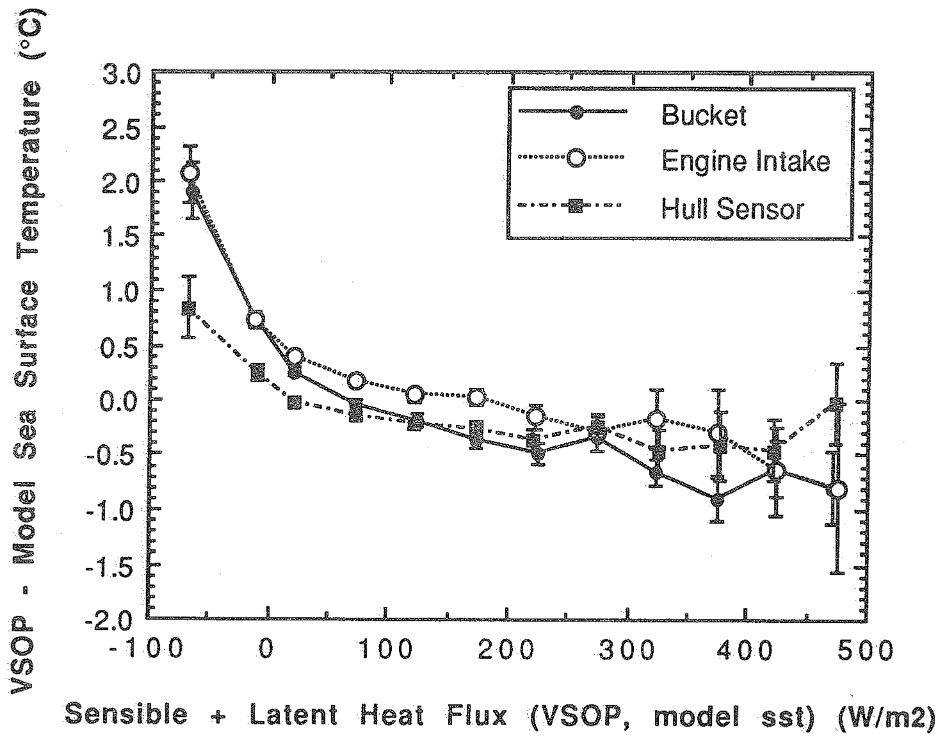


Figure 6.4 a (top) VSOP measured sea surface temperature binned on model sea surface temperature separately for temperatures measured by bucket, engine intake and hull sensors

Figure 6.4 b (bottom) Differences in VSOP measured sea surface from model values binned on model sea surface temperature separately for temperatures measured by bucket, engine intake and hull sensors



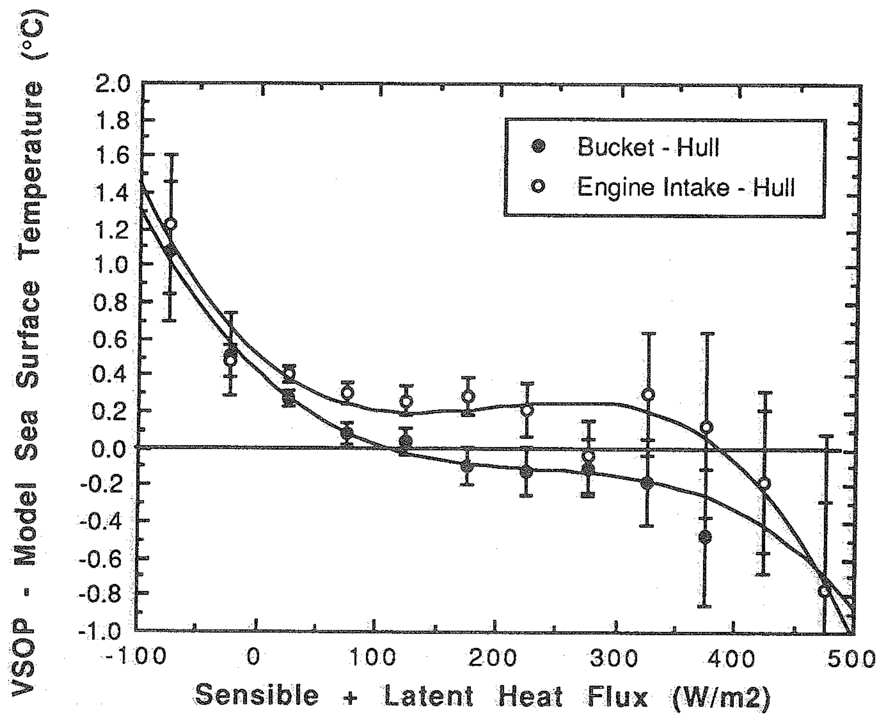


Figure 6.5 a (top) - VSOP measured sea surface temperature binned on sensible + latent heat flux (calculated from bulk formulae using VSOP parameters except for model sea surface temperature) separately for temperatures measured by bucket, engine intake and hull sensors

Figure 6.5 b (bottom) - Differences in bucket and engine intake measured sea surface temperature from hull sensor values, binned on sensible + latent heat flux calculated as in 6.5a

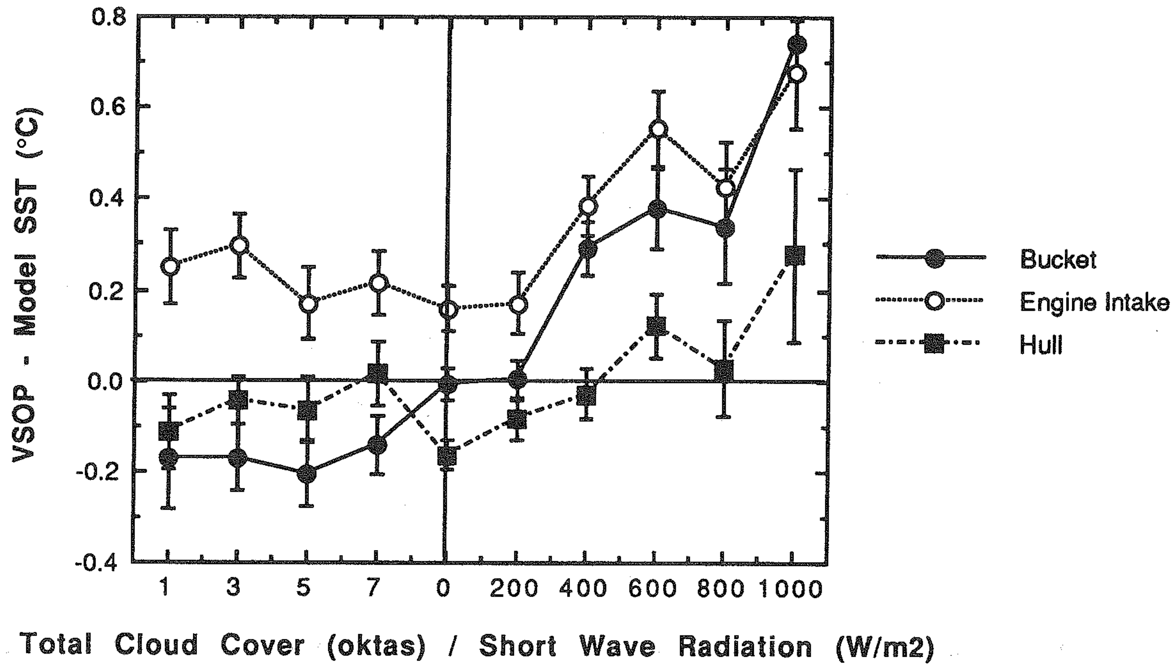


Figure 6.6 - VSOP measured sea surface temperature binned on short wave radiation for daytime measurements, and total cloud cover for nighttime measurements, separately for temperatures measured by bucket, engine intake and hull sensors

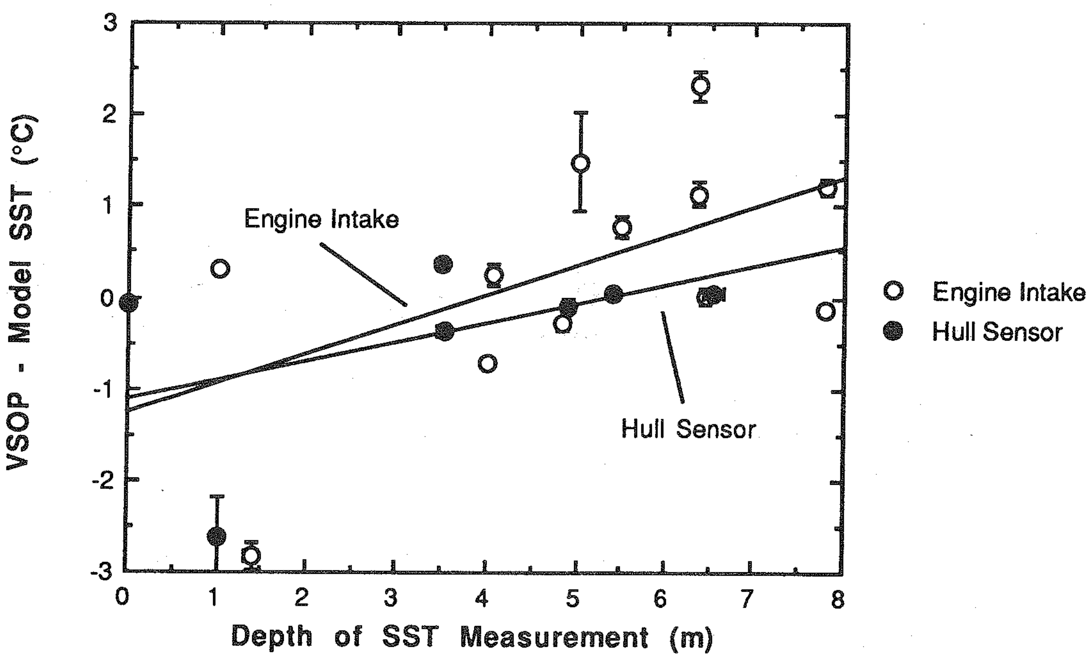
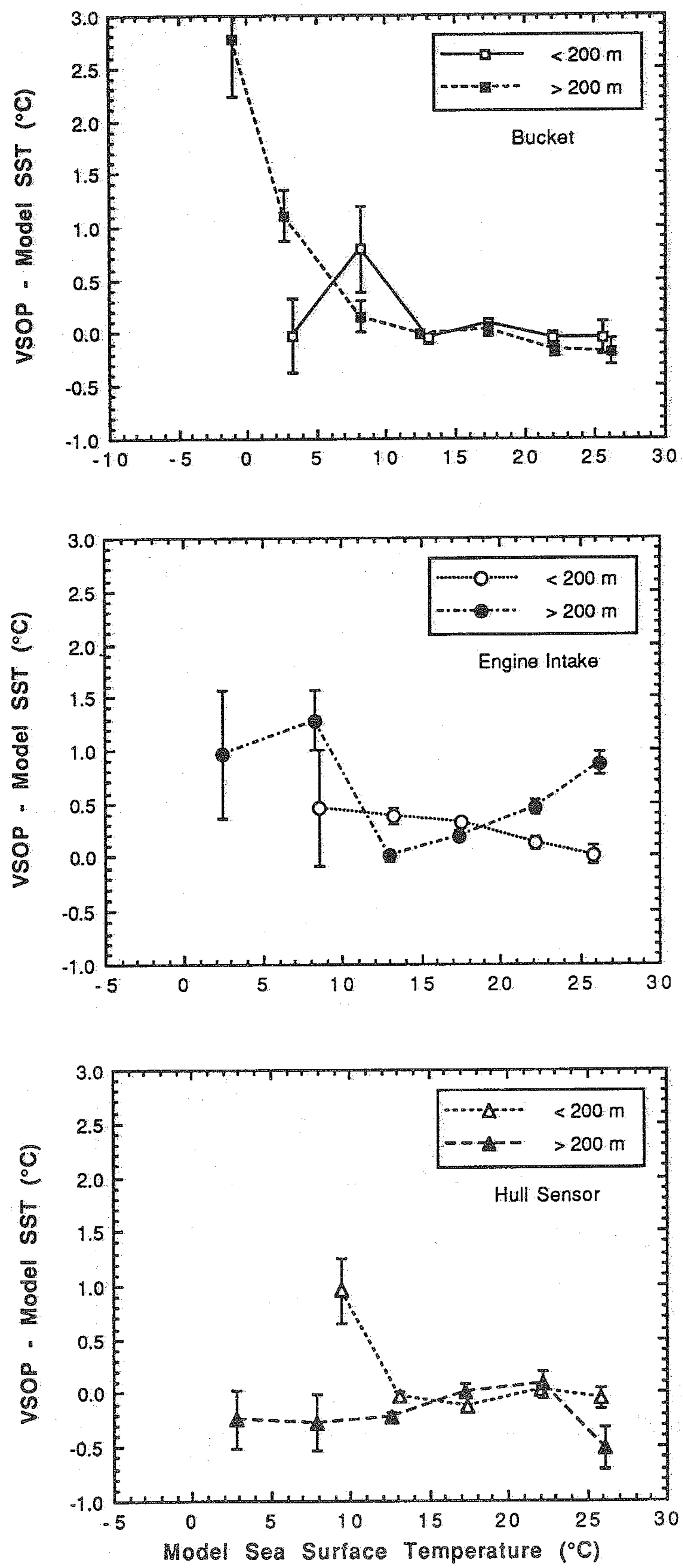
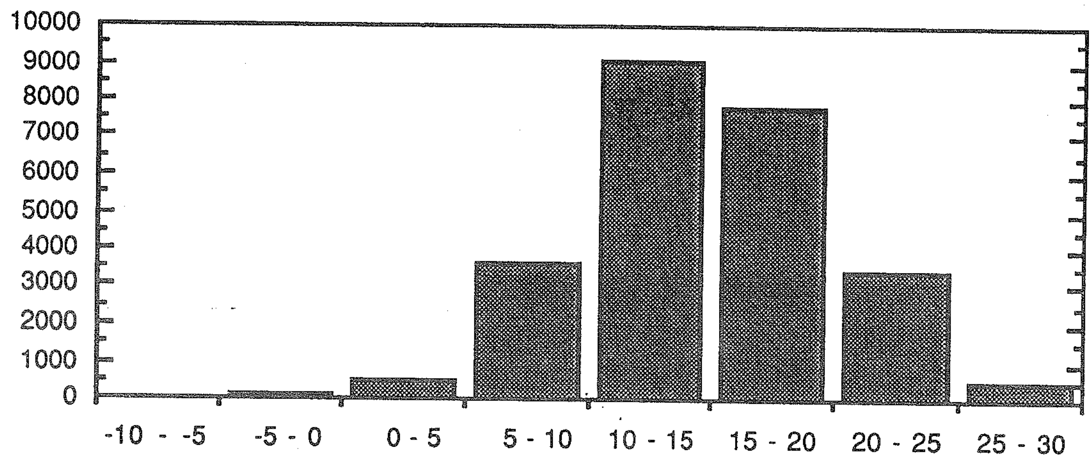


Figure 6.7 - Mean differences in VSOP measured sea surface temperature from model values plotted against mean sensor depth for engine intake and hull sensor measured data



Figures 6.8 a, b, c - Sea surface temperature difference from model (°C) by method (bucket, figure 6.8a top, engine intake, figure 6.8b centre and hull sensor, figure 6.8c bottom) for ships greater than and less than 200 m length



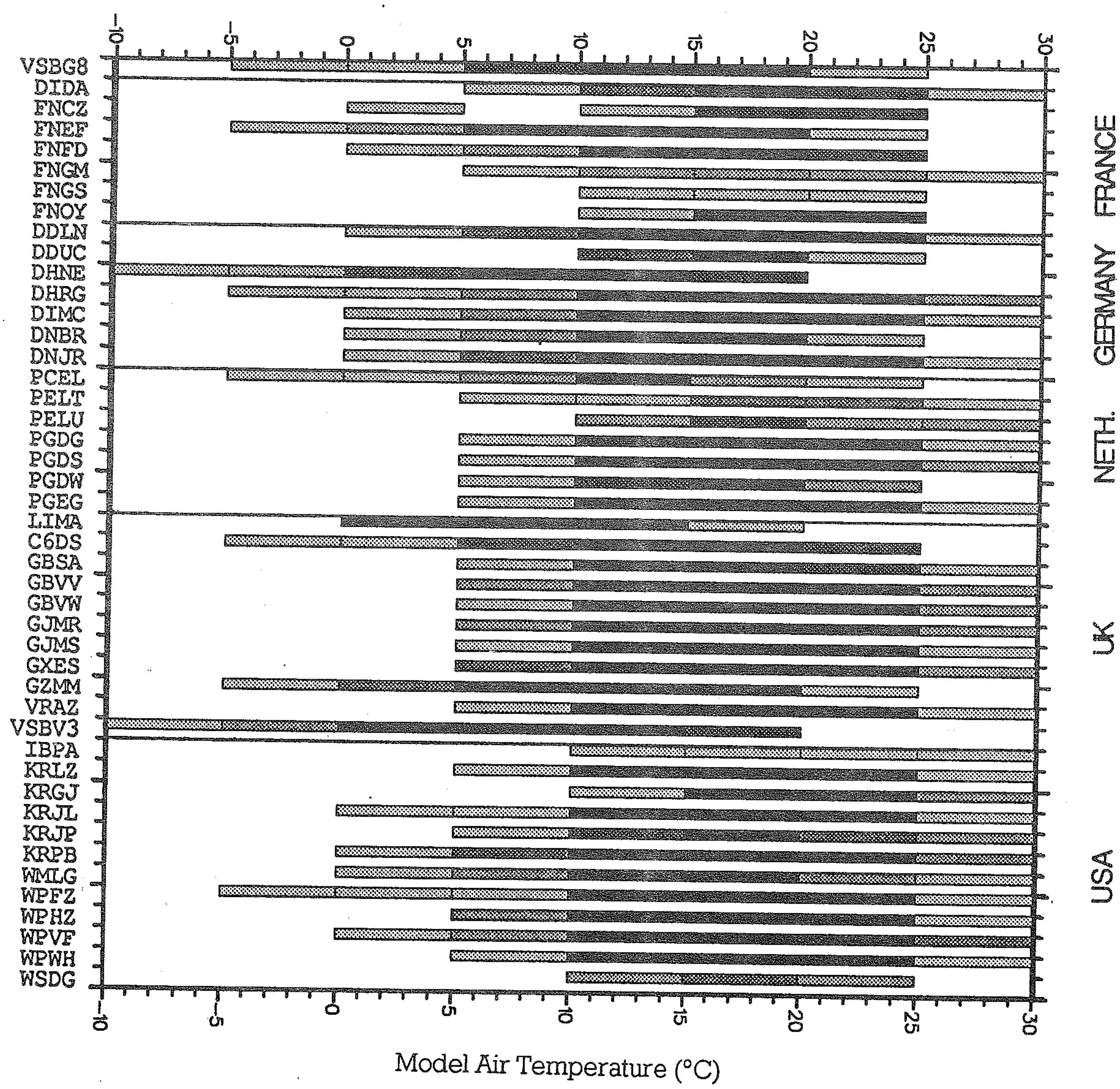


Figure 7.1a (top) - Histogram showing number of VSOP observations for model air temperatures ranging from -10 to 30 °C

Figure 7.1b (bottom) - Numbers of VSOP observations by ship for model sea surface temperature ranging from -10 to 30 °C. Shading indicates numbers of observations per 5°C range.

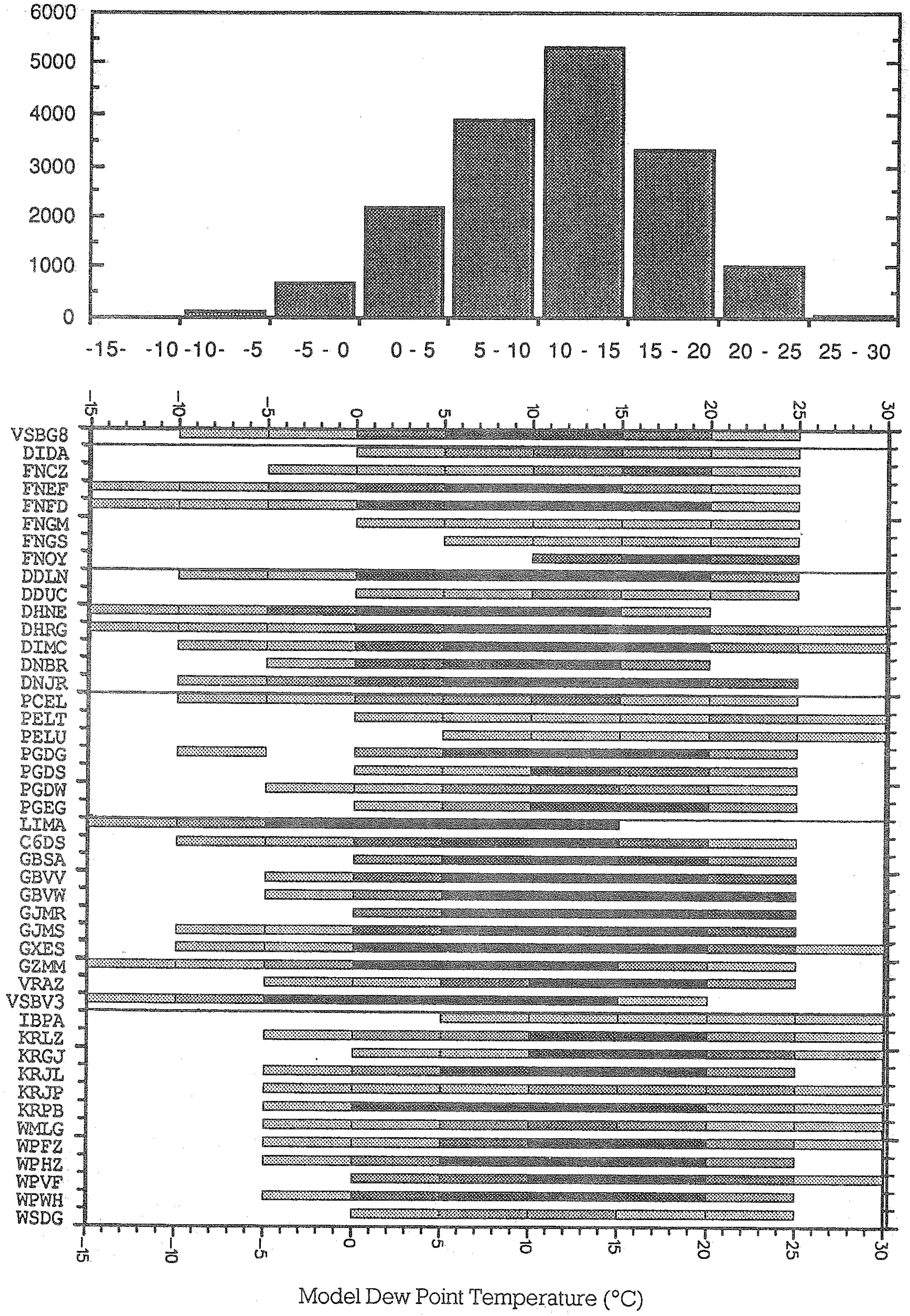
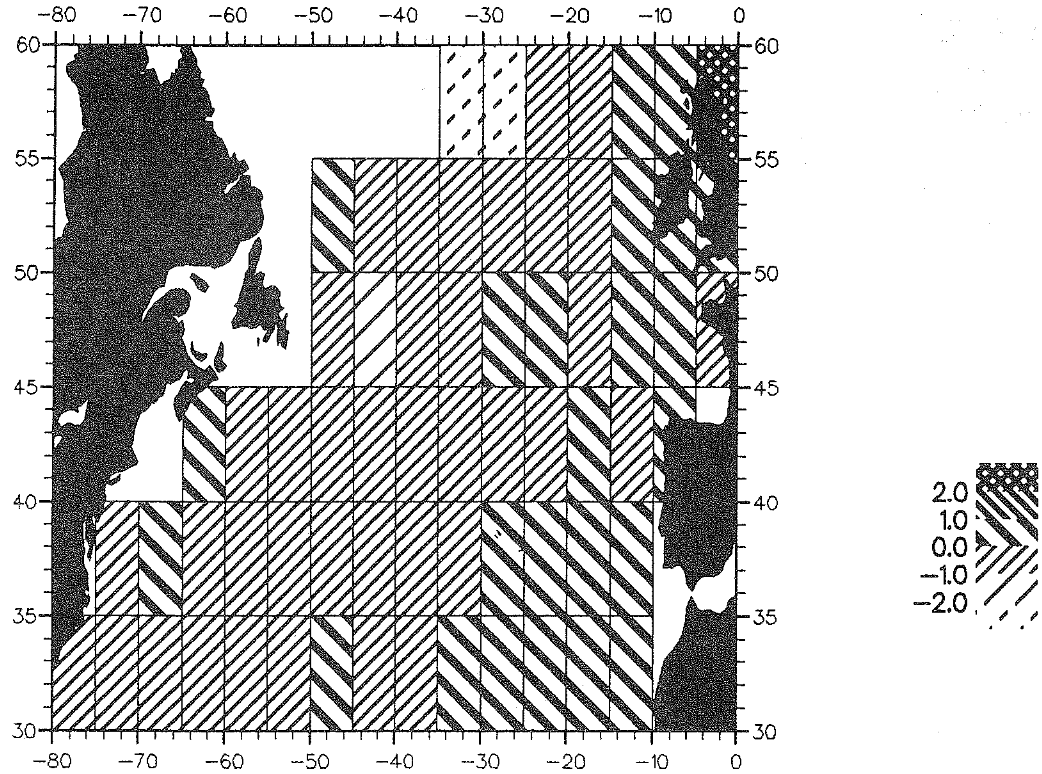


Figure 7.2a (top) - Histogram showing number of VSOP observations for model dew point temperature ranging from -15 to 30 °C

Figure 7.2b (bottom) - Numbers of VSOP observations by ship for model dew point temperature ranging from -15 to 30 °C. Shading indicates numbers of observations per 5°C range.



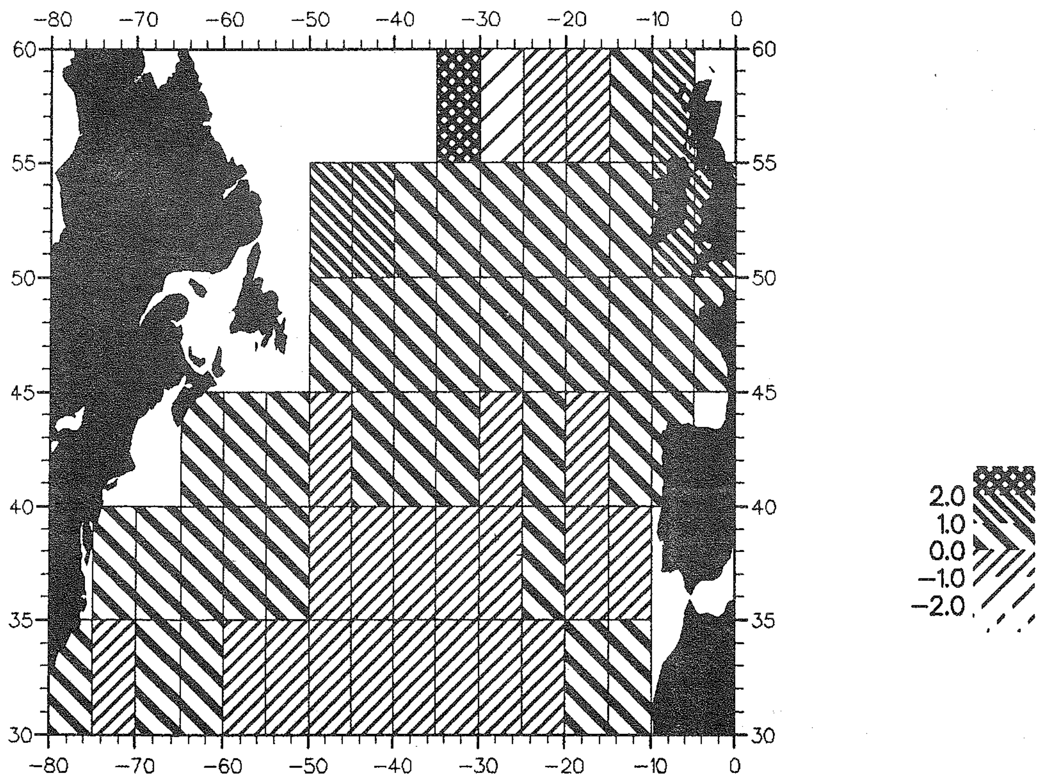
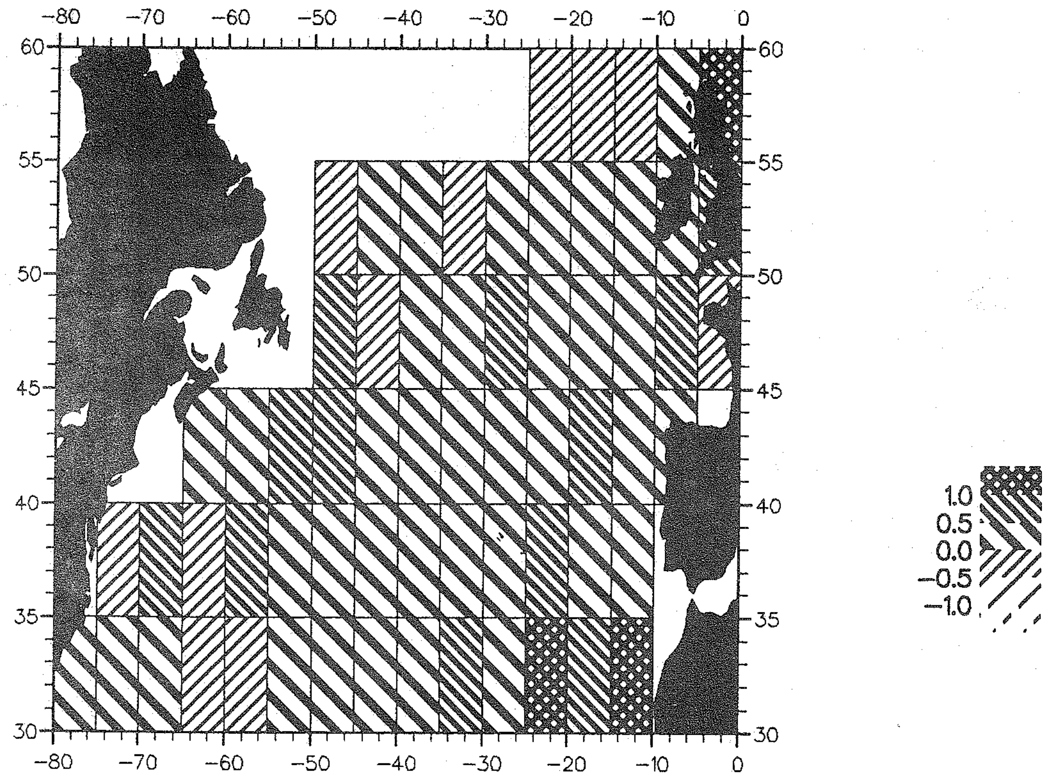


Figure 7.3a (top) - Air temperature difference from model (°C) averaged in 5° squares over the North Atlantic.

Figure 7.3b (bottom) - Dew point temperature difference from model (°C) averaged in 5° squares over the North Atlantic.



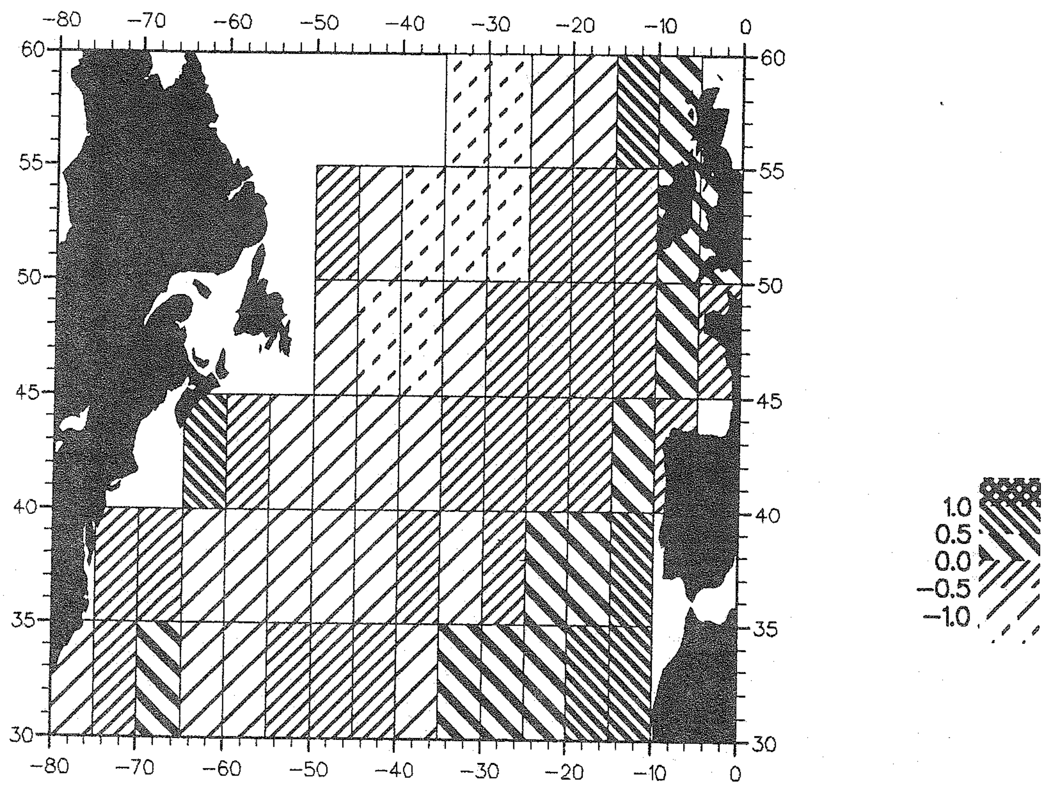
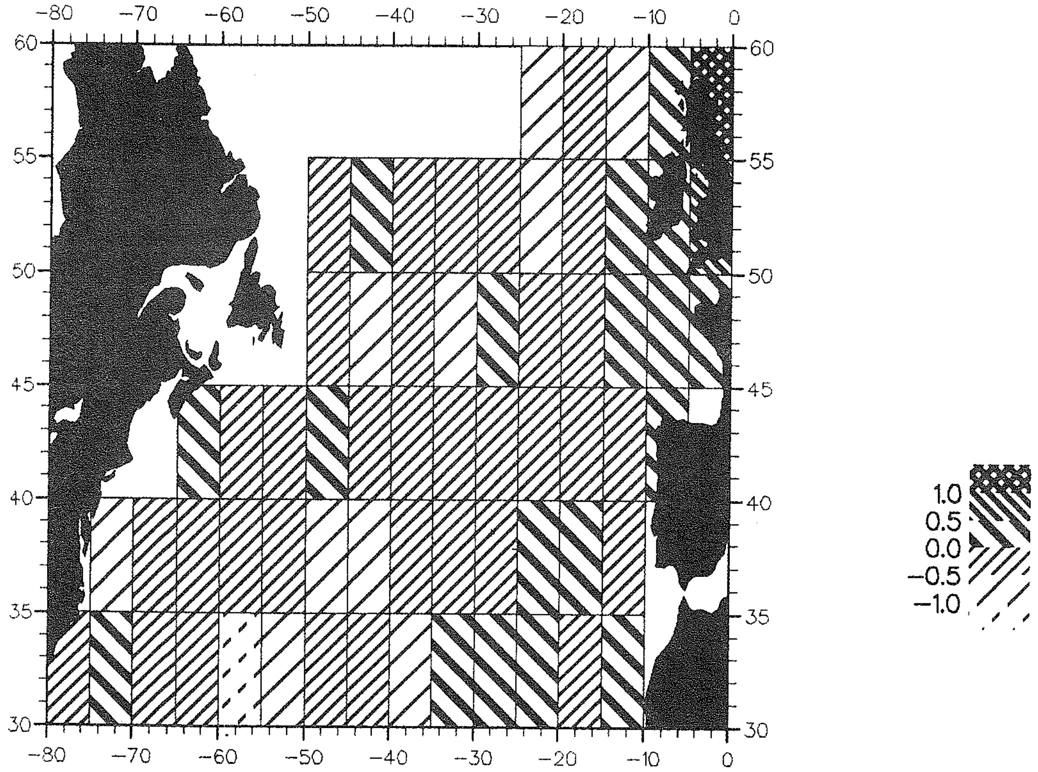


Figure 7.4a (top) - Summer (May to September inclusive) air temperature difference from model (°C) averaged in 5° squares over the North Atlantic.

Figure 7.4b (bottom) - Winter (November to March inclusive) air temperature difference from model (°C) averaged in 5° squares over the North Atlantic.



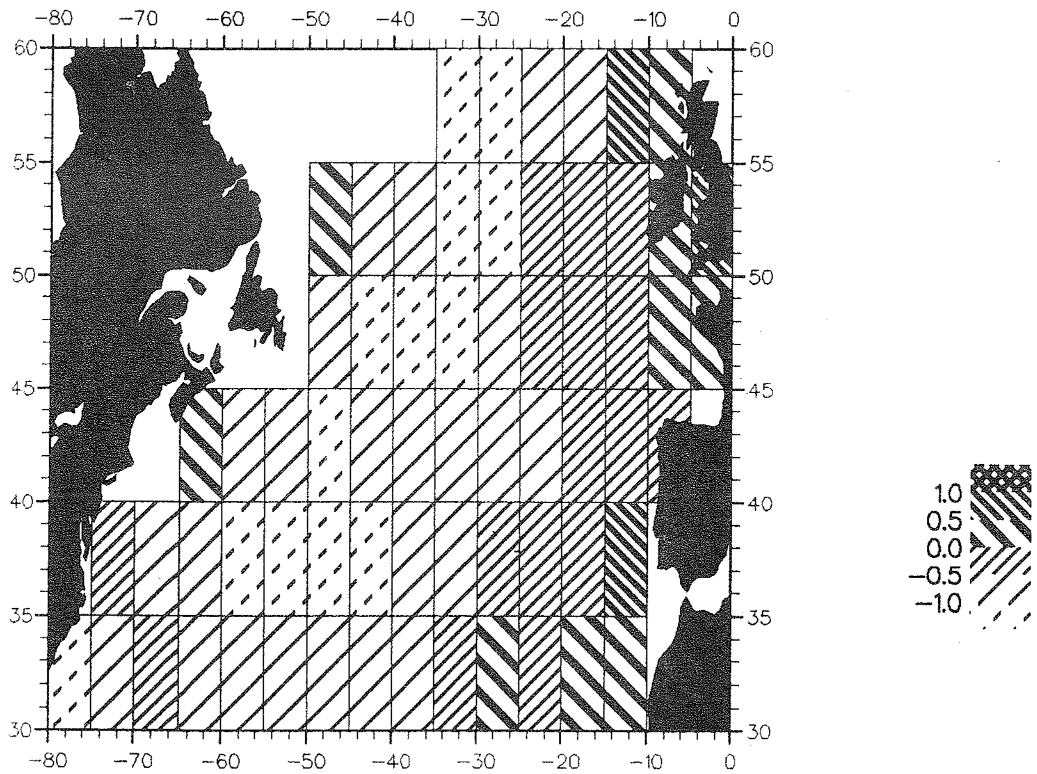
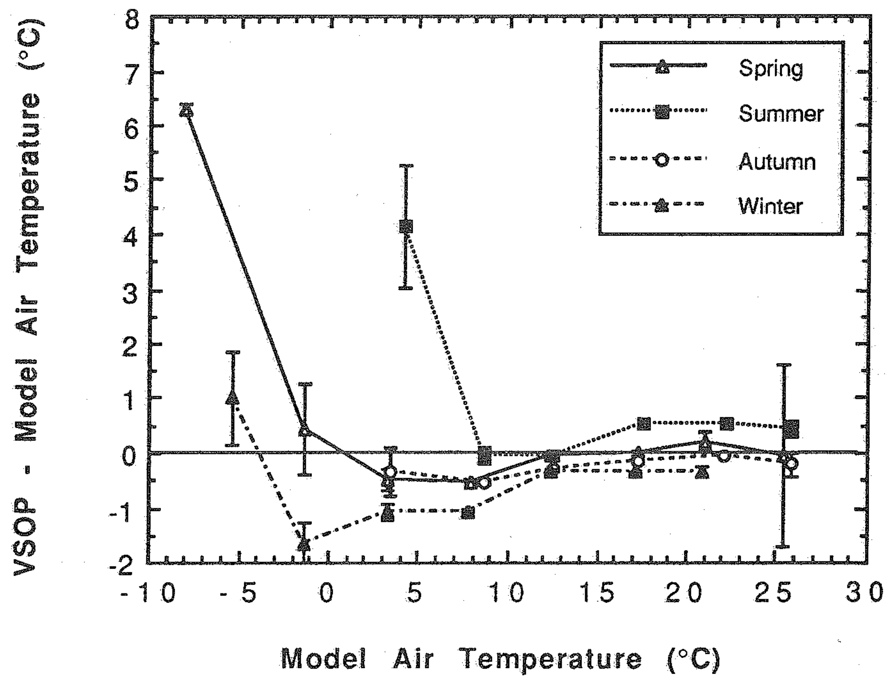


Figure 7.4c (top) - Nighttime Summer (May to September inclusive) air temperature difference from model (°C) averaged in 5° squares over the North Atlantic.

Figure 7.4d (bottom) - Nighttime Winter (November to March inclusive) air temperature difference as in 7.4c.



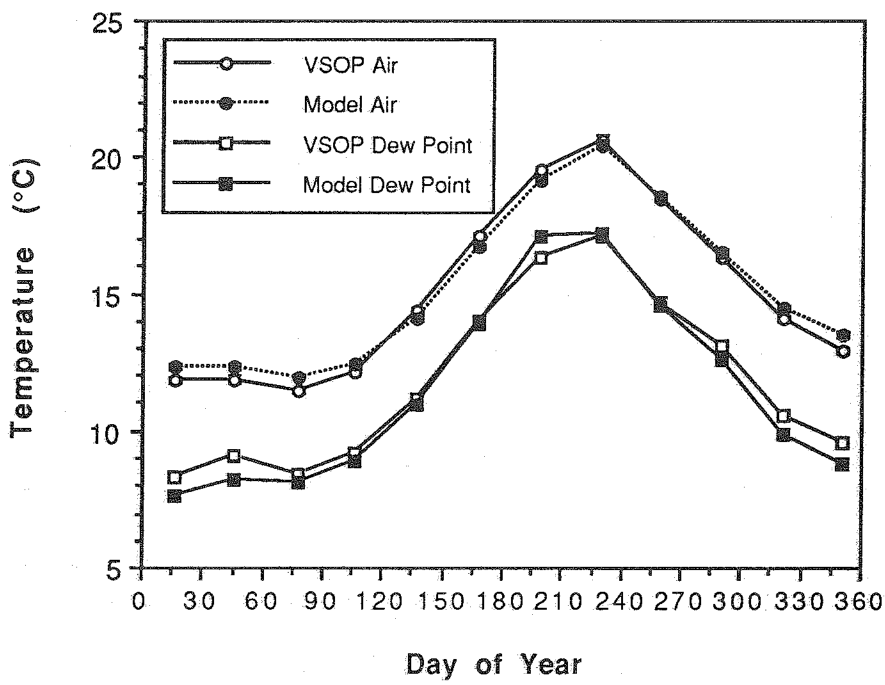


Figure 7.4e (top) - Difference between VSOP and model air temperatures by season (Spring, March to May; Summer, June to August; Autumn, September to November; and Winter, December to February).

Figure 7.4f (bottom) - VSOP and model air and dew point temperatures averaged in 30 day sections.

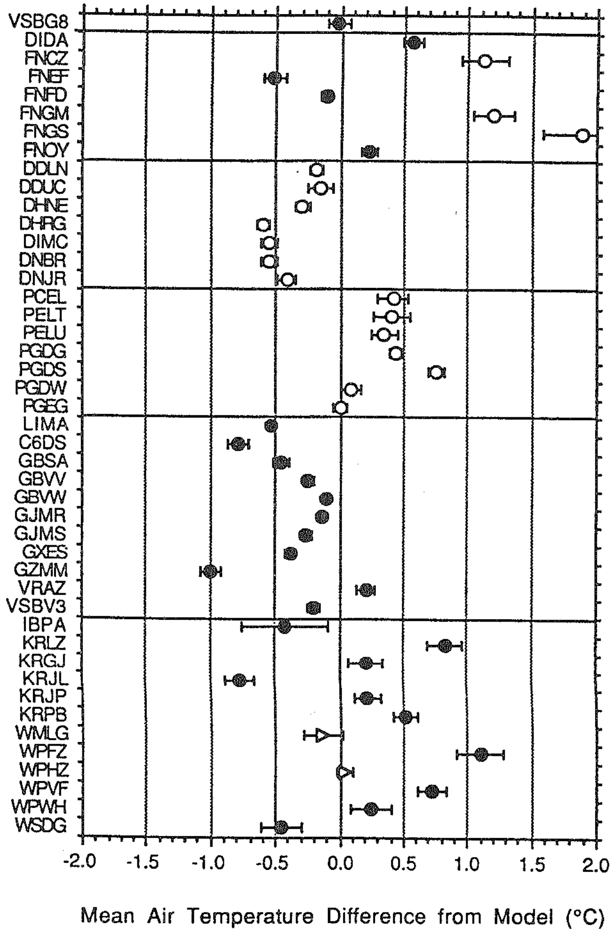
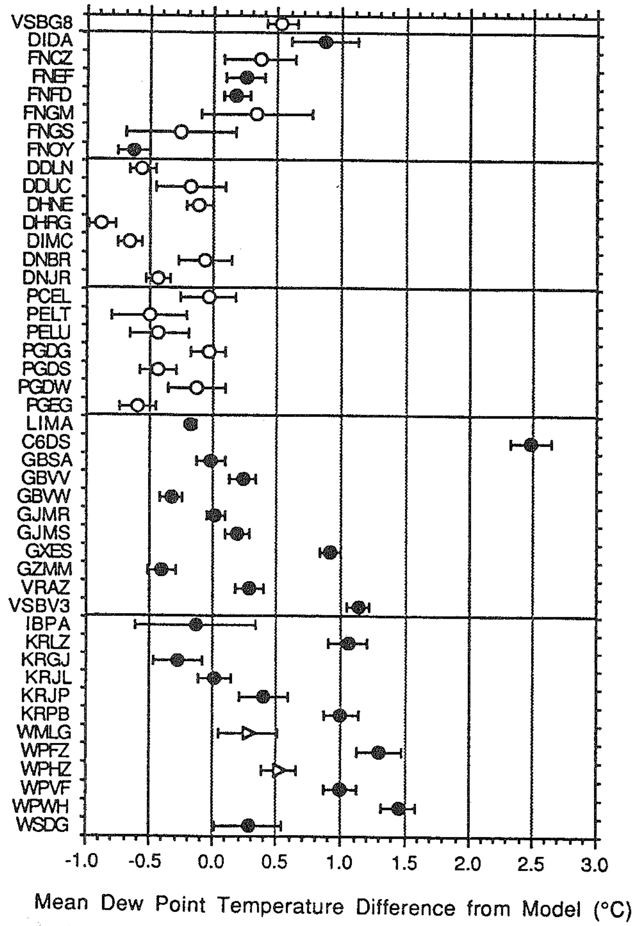


Figure 7.5a - Mean air temperature difference from model (°C) by method (screen, psychrometer or unreported) by ship callsign.



● Screen ○ Psychrometer Δ Unknown

Figure 7.5b - Mean dew point temperature difference from model (°C) by method (screen, psychrometer or unreported) by ship callsign.

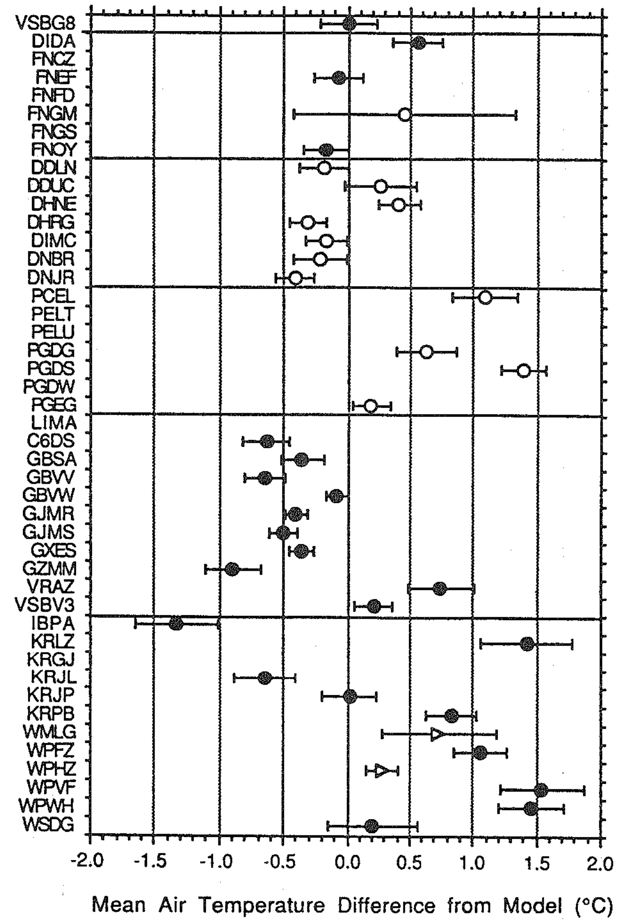
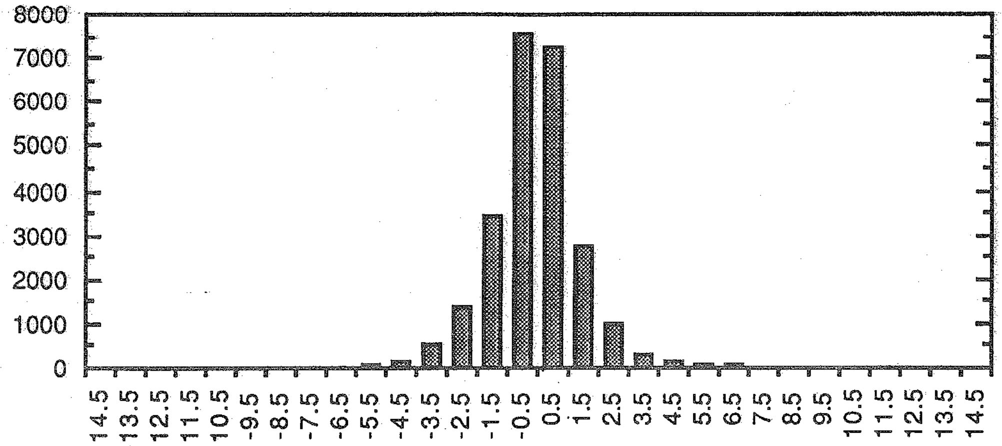


Figure 7.5c - Mean air temperature difference from model (°C) by method (screen, psychrometer or unreported) by ship callsign for region -20 to -10 °W by 45 to 50°N for the period February 1989 to February 1990



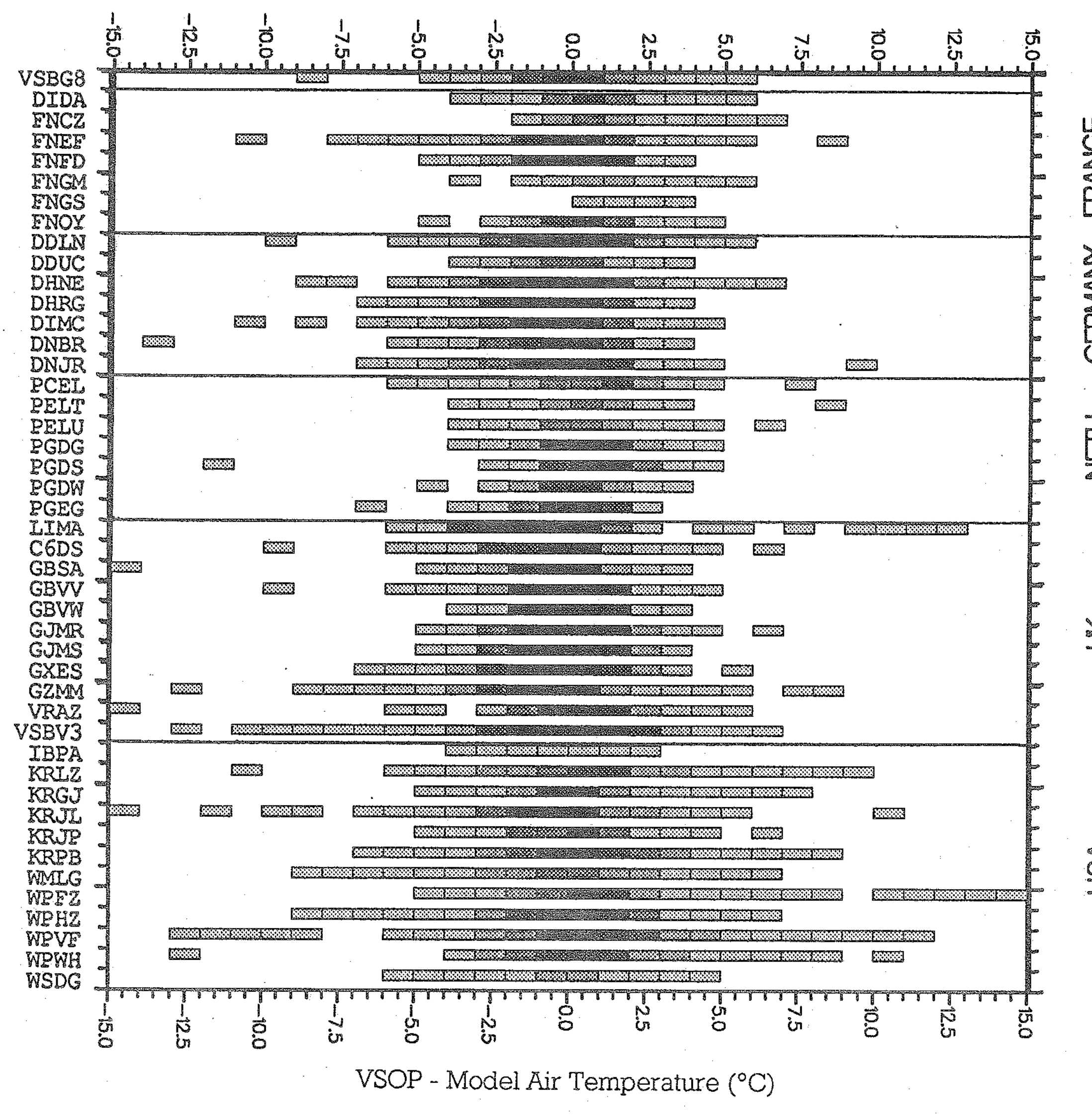
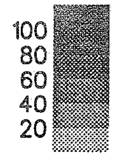


Figure 7.6a (top) - Histogram showing number of VSOP observations differing from model air temperatures ranging from -15 to 15 °C

Figure 7.6b (bottom) - Numbers of VSOP observations differing from model air temperatures by ship for temperature differences ranging from -15 to 15 °C. Shading indicates numbers of observations per 1°C range.



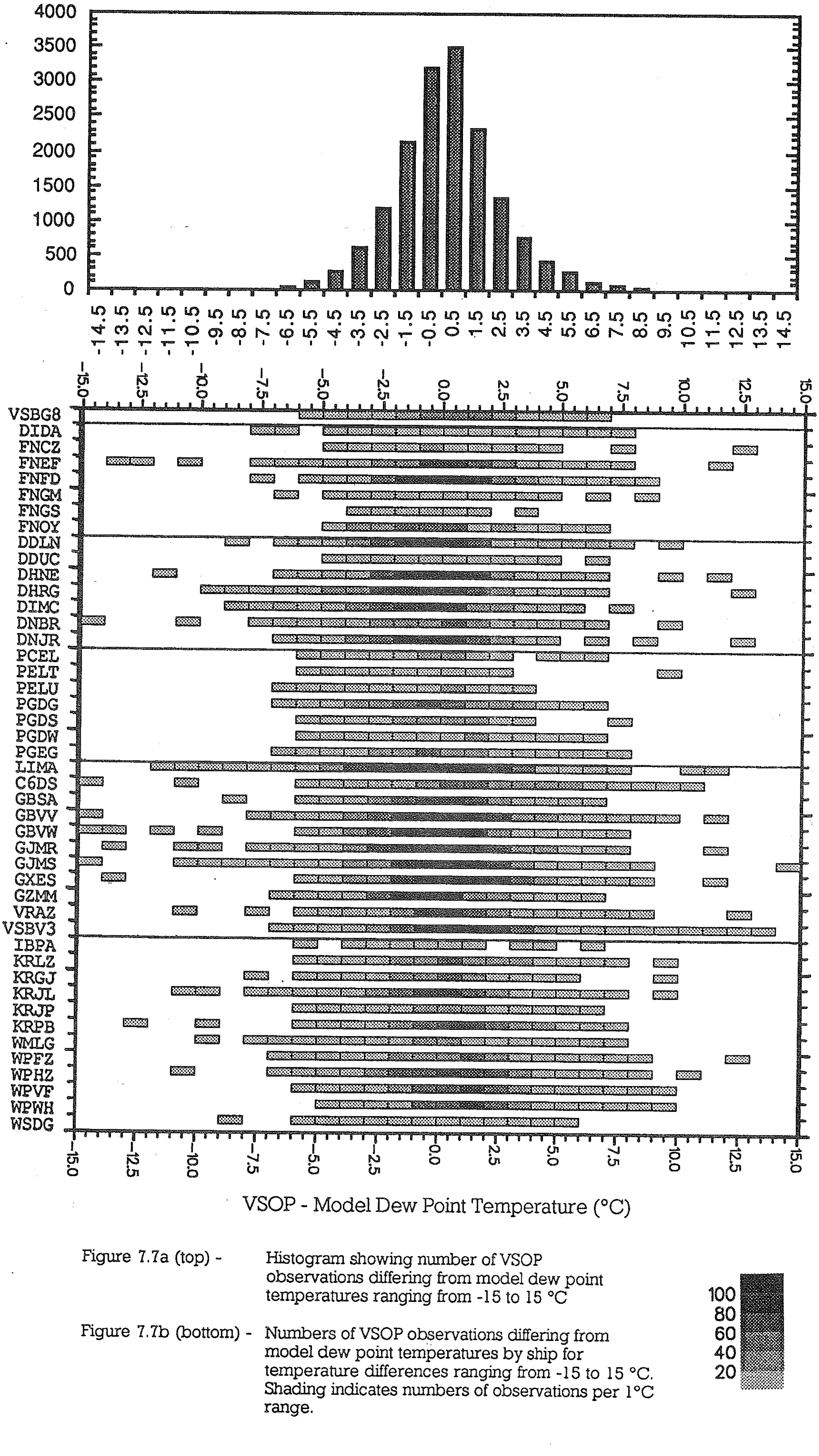
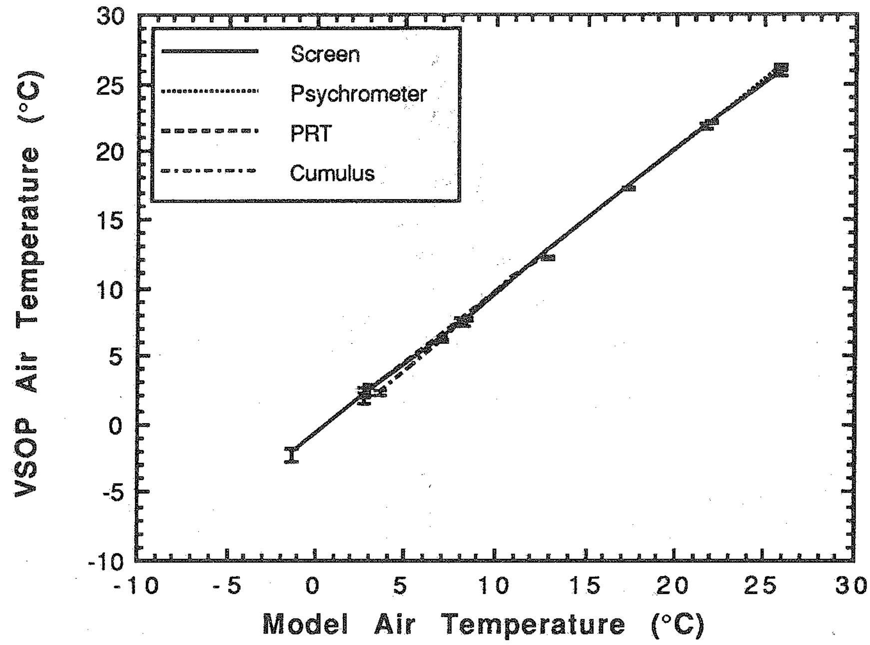


Figure 7.7a (top) - Histogram showing number of VSOP observations differing from model dew point temperatures ranging from -15 to 15 °C

Figure 7.7b (bottom) - Numbers of VSOP observations differing from model dew point temperatures by ship for temperature differences ranging from -15 to 15 °C. Shading indicates numbers of observations per 1°C range.



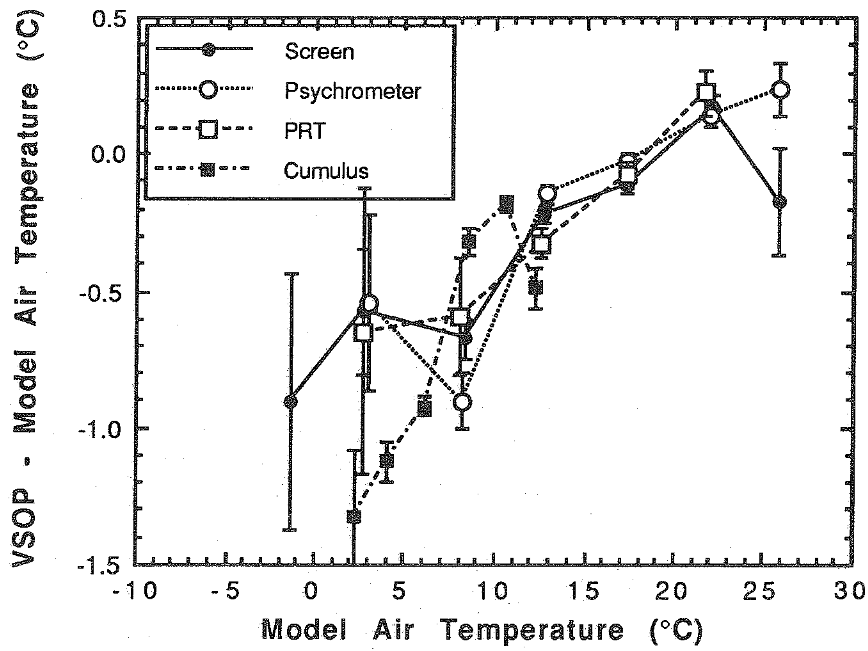
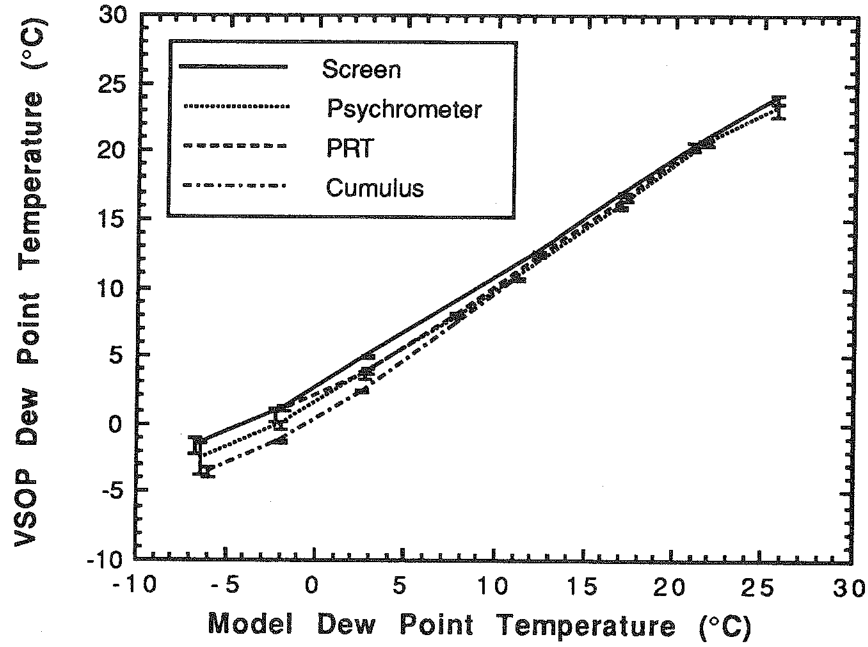


Figure 7.8 a (top) - VSOP measured air temperature binned on model air temperature separately for temperatures measured by screen, psychrometer, PRT and by the Ocean Weather Ship Cumulus.

Figure 7.8 b (bottom) - Differences in VSOP measured air temperature from model values binned on model air temperature separately for temperatures measured by screen, psychrometer, PRT and by the Ocean Weather Ship Cumulus.



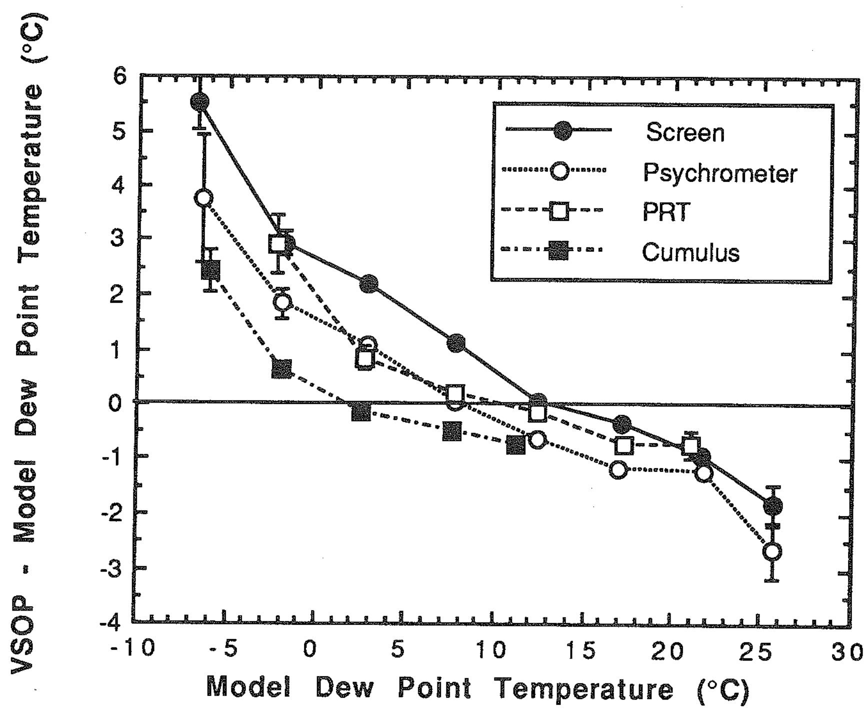
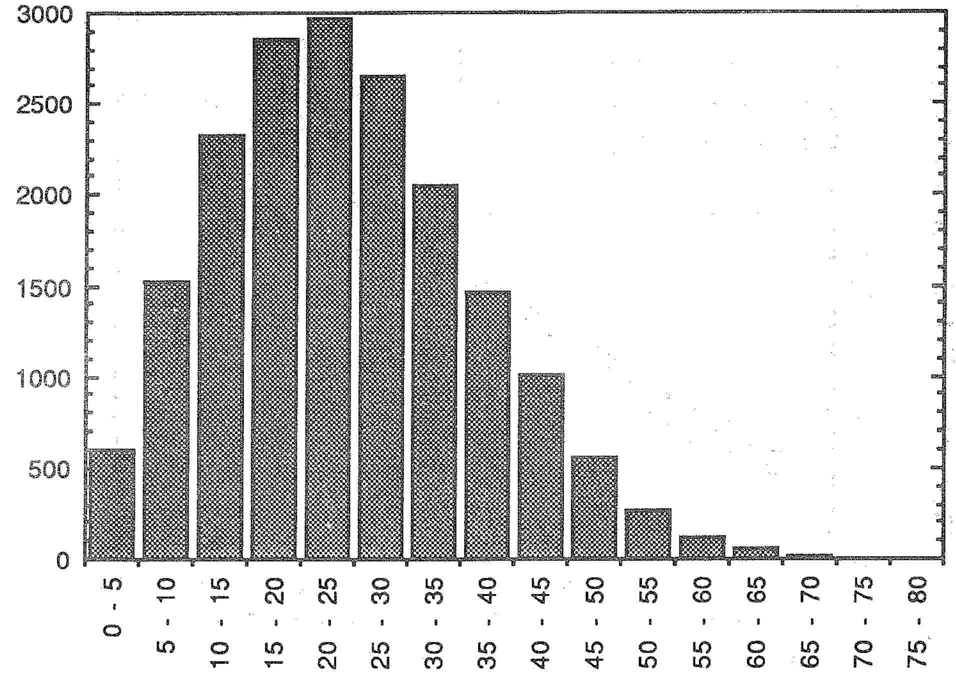


Figure 7.9 a (top) - VSOP measured dew point temperature binned on model dew point temperature separately for temperatures measured by screen, psychrometer, PRT and by the Ocean Weather Ship Cumulus.

Figure 7.9 b (bottom) - Differences in VSOP measured dew point temperature from model values binned on model dew point temperature separately for temperatures measured by screen, psychrometer, PRT and by the Ocean Weather Ship Cumulus.



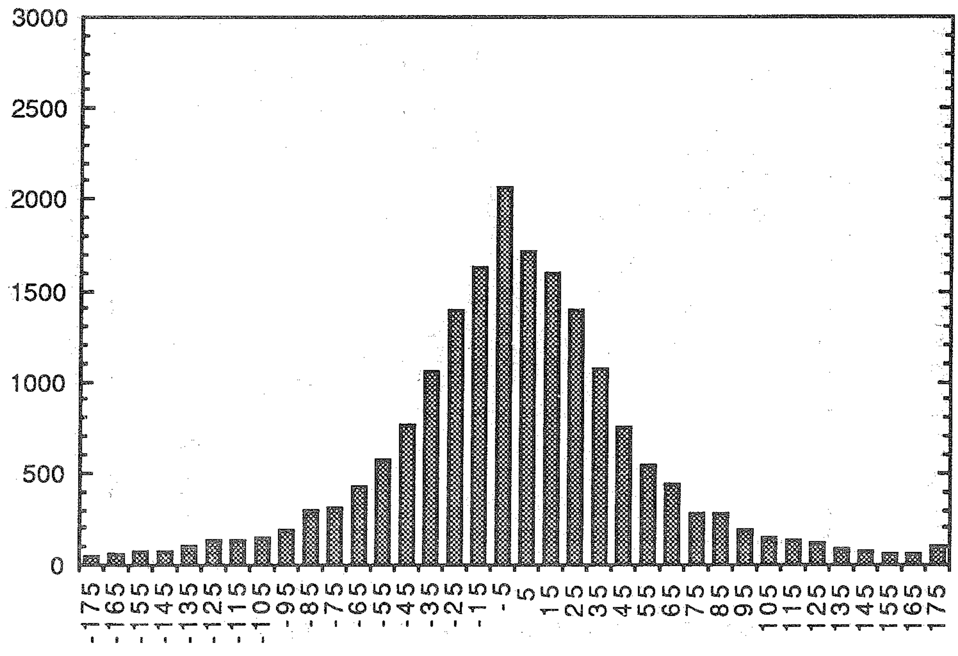
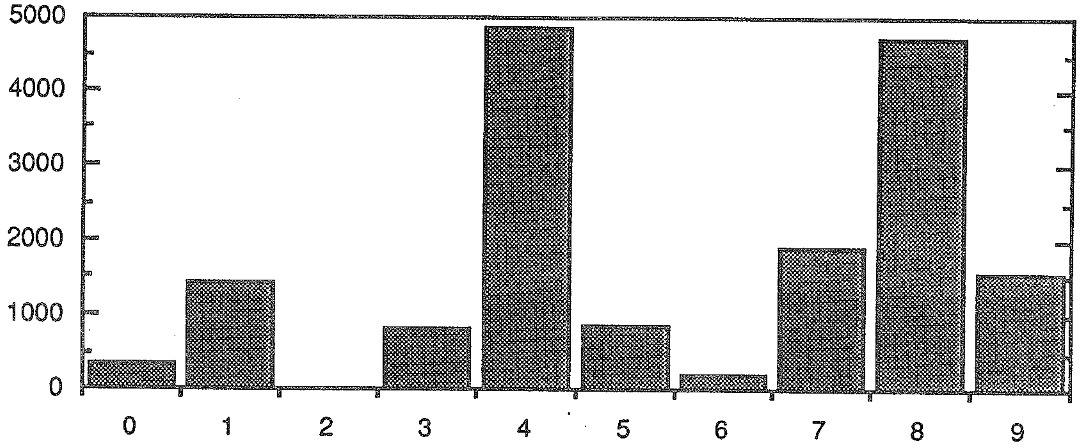


Figure 7.10 a (top) - Histogram showing number of VSOP observations made at relative wind speeds ranging from 0 to 80 knots in 5 knot intervals.

Figure 7.10 b (bottom) - Histogram showing number of VSOP observations made at relative wind directions ranging from -180 to 180° off bow in 10° intervals



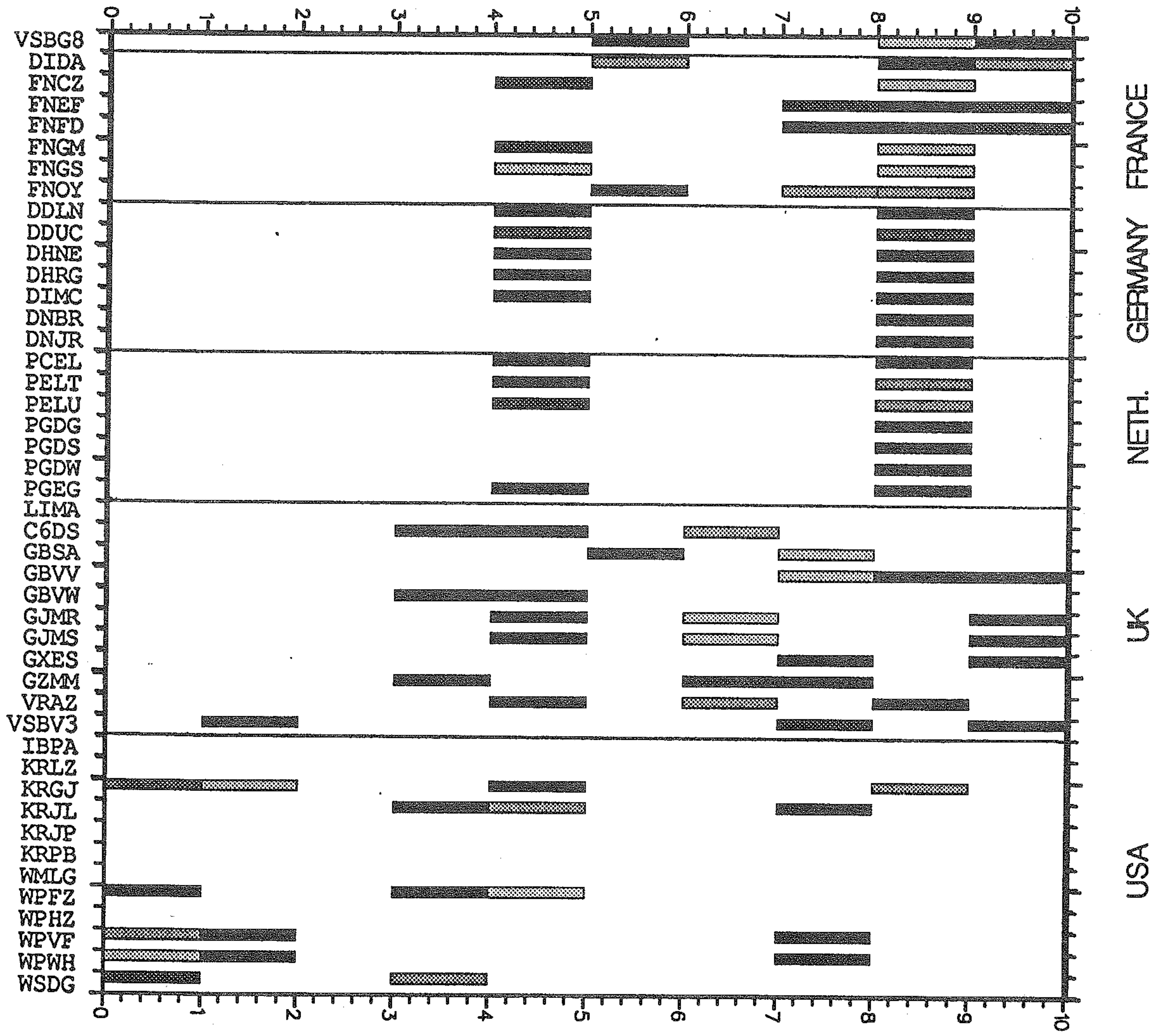
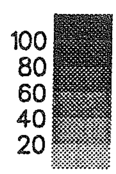


Figure 7.11a (top) - Histogram showing number of VSOP temperature observations rated at exposure indices from 0 (poorly exposed) to 9 (well exposed)

Figure 7.11b (bottom) - Numbers of VSOP observations by ship rated at exposure indices 0 to 9 as in 7.11a



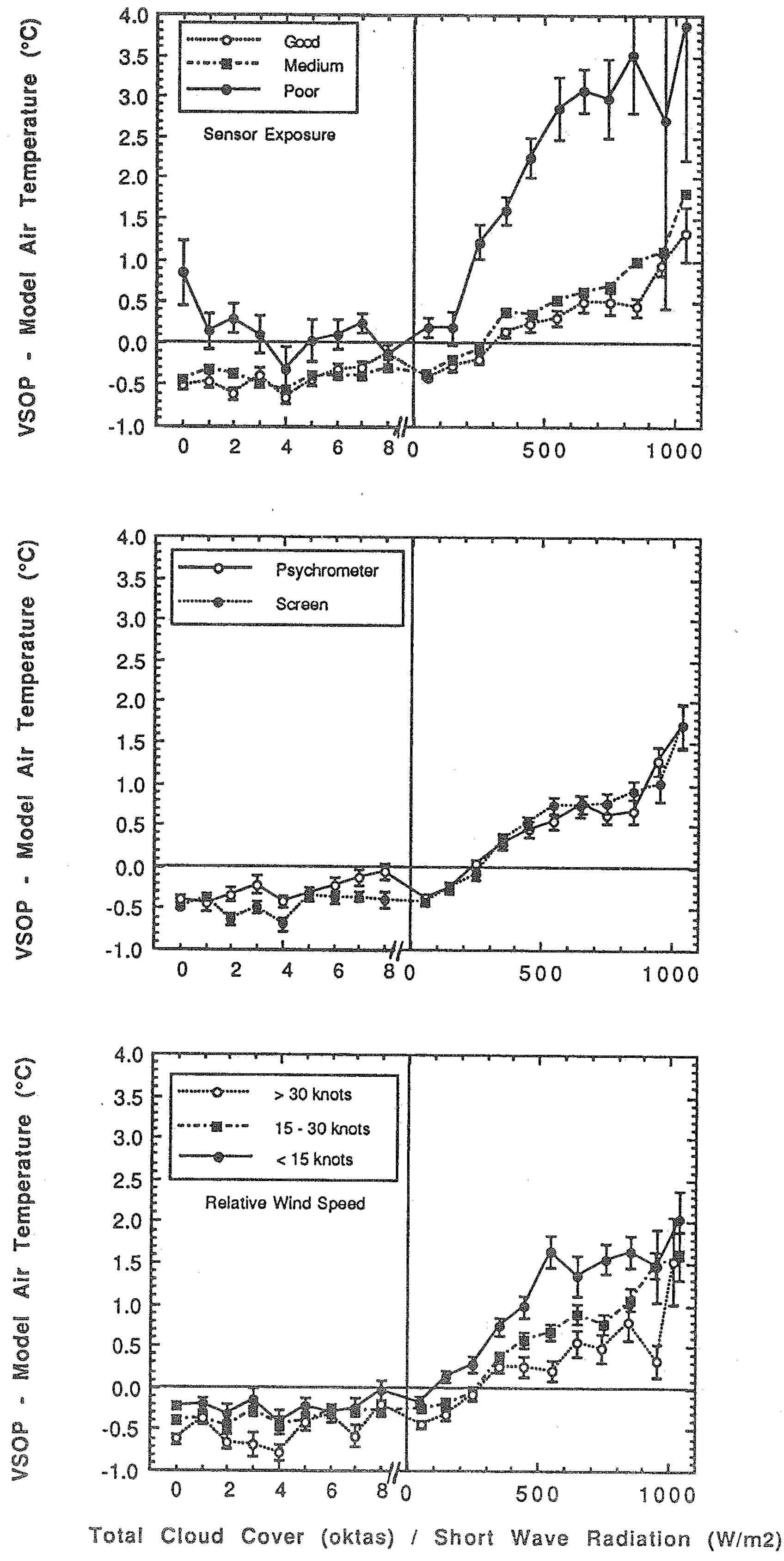
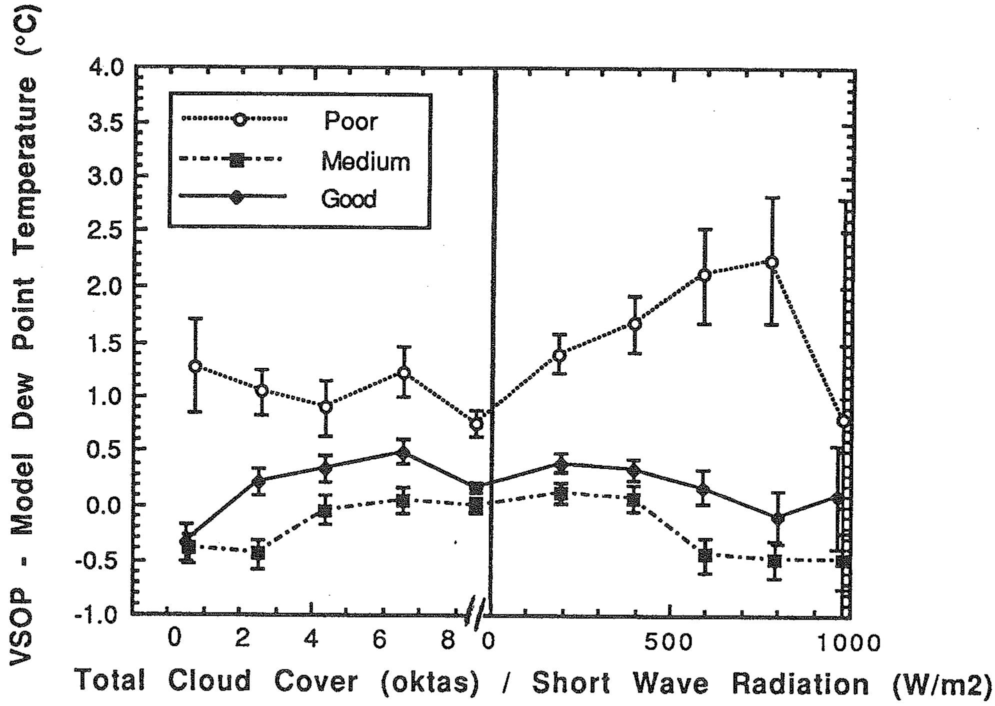


Figure 7.12a (top) -	VSOP measured air temperature differences from model binned on short wave radiation for daytime measurements and total cloud cover for nighttime measurements separately for sensors with good, medium and poor exposures
Figure 7.12b (centre) -	As 7.12a except data divided by measurement technique (screen or psychrometer)
Figure 7.12c (bottom) -	As 7.12a except data divided by relative wind speed at time of measurement



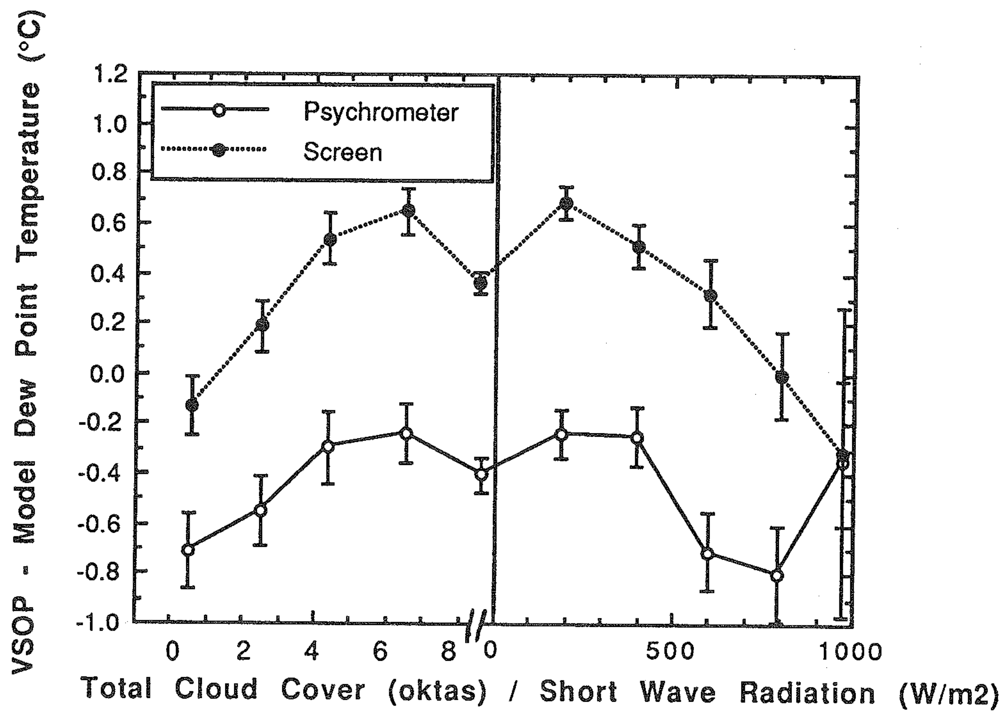
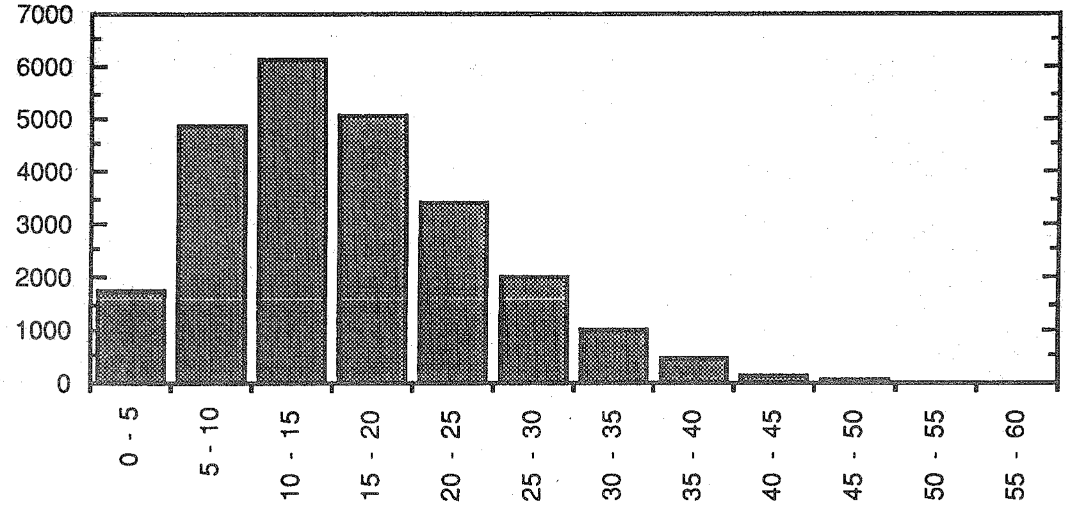


Figure 7.13a (top) - VSOP measured dew point temperature differences from model binned on short wave radiation for daytime measurements and total cloud cover for nighttime measurements separately for sensors with good, medium and poor exposures

Figure 7.13b (bottom) - As 7.13a except data divided by measurement technique (screen or psychrometer)



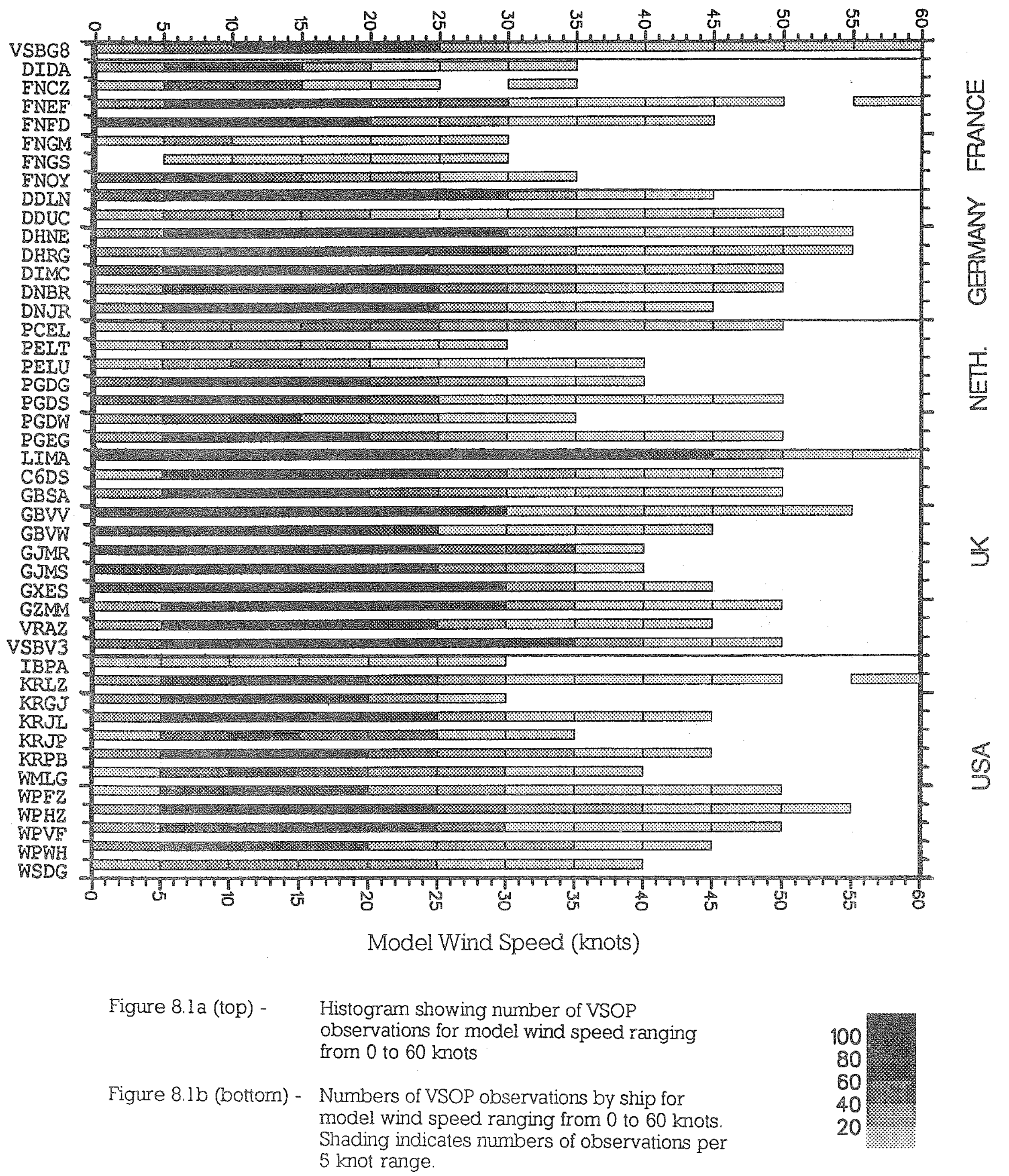


Figure 8.1a (top) - Histogram showing number of VSOP observations for model wind speed ranging from 0 to 60 knots

Figure 8.1b (bottom) - Numbers of VSOP observations by ship for model wind speed ranging from 0 to 60 knots. Shading indicates numbers of observations per 5 knot range.

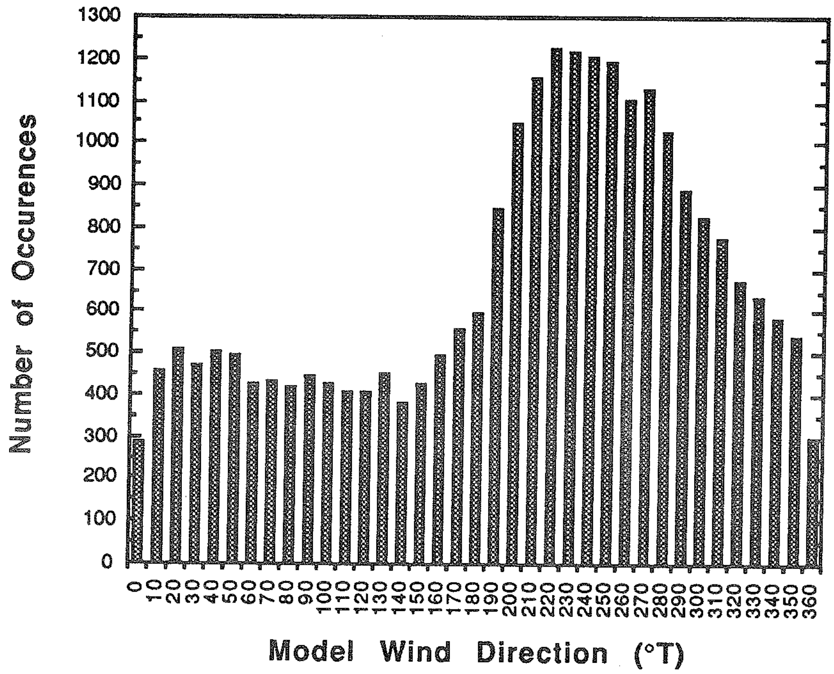
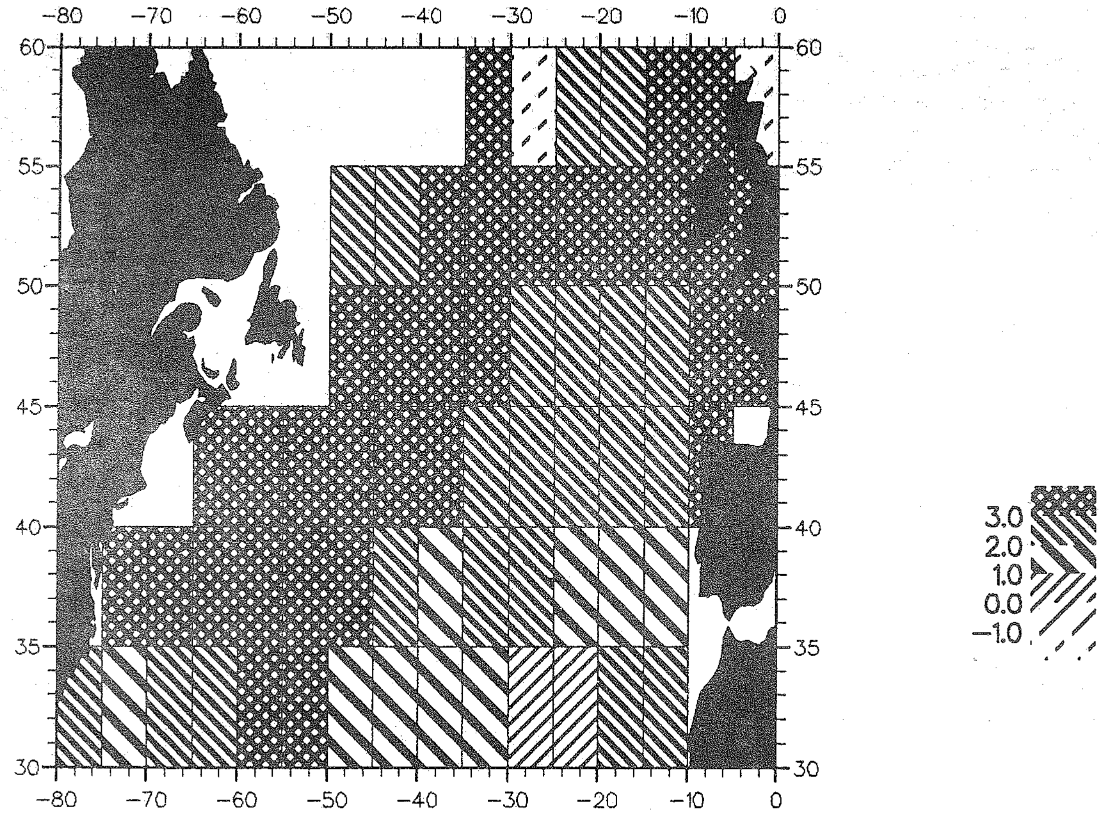


Figure 8.1c - Histogram showing number of VSOP observations made at model wind directions from 0 to 360 °T in 10° intervals.



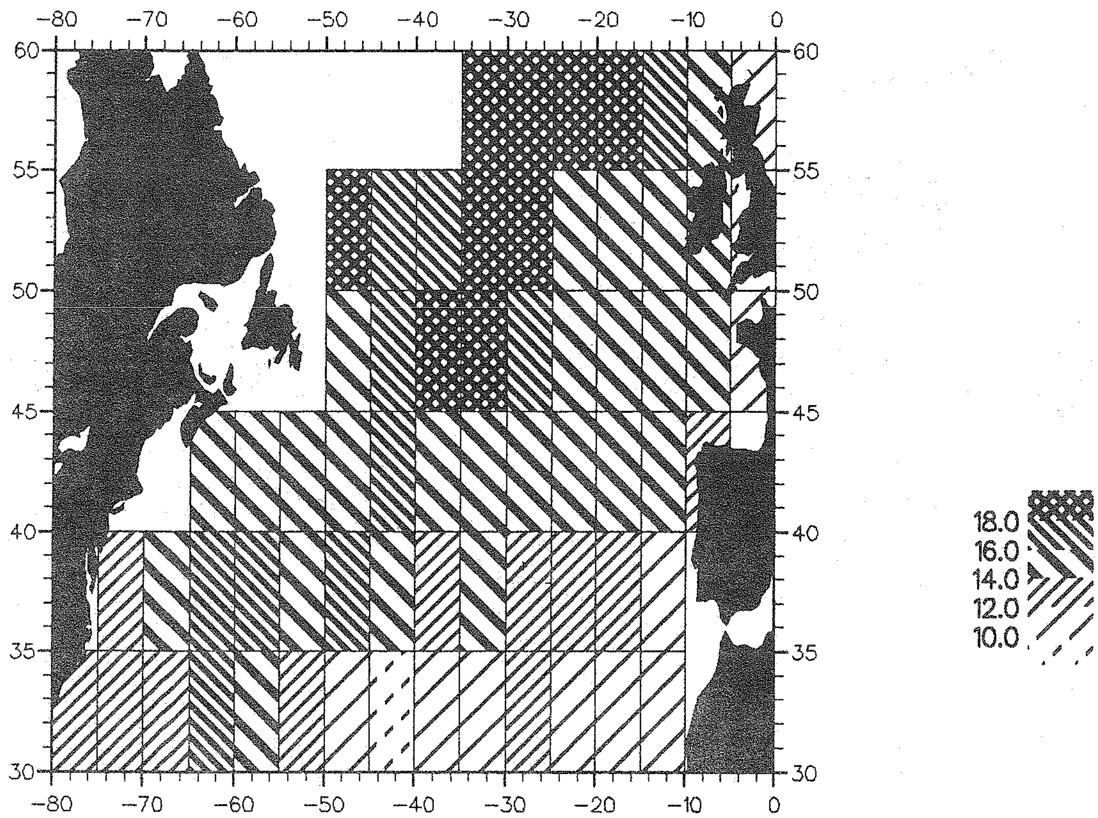
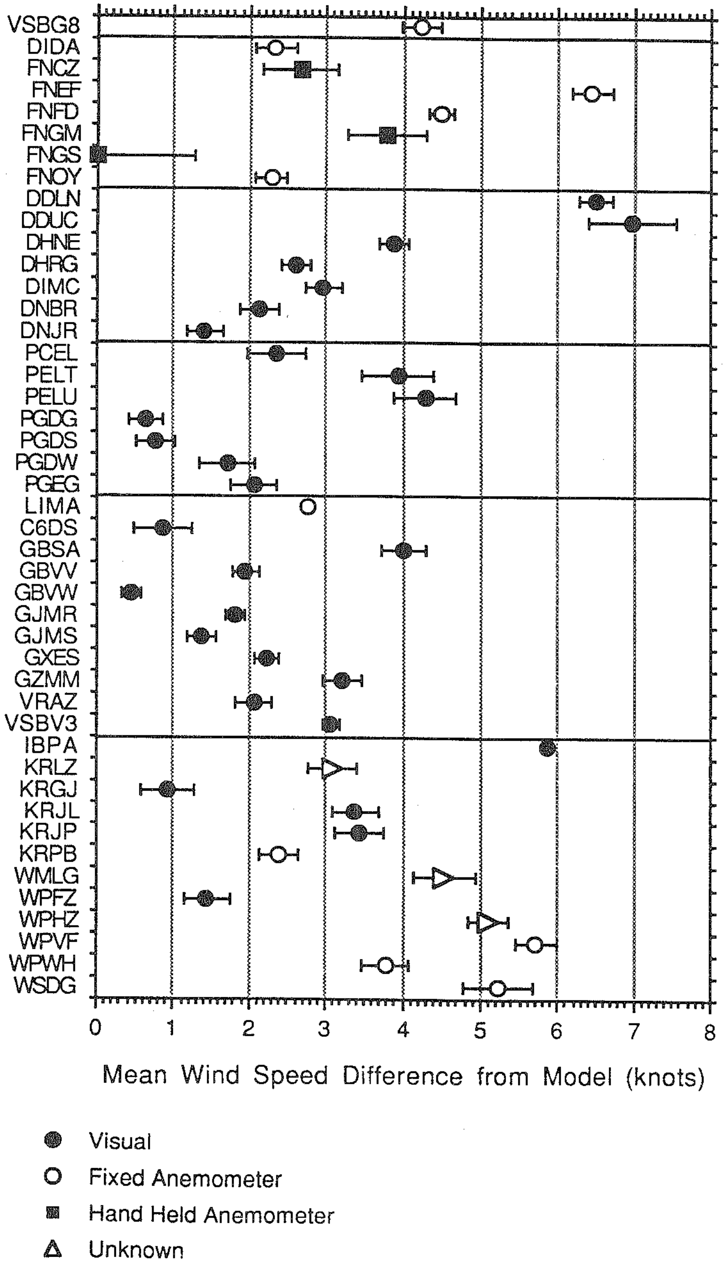


Figure 8.2 (top) - Wind speed difference from model (knots) averaged in 5° squares over the North Atlantic.

Figure 8.3 (bottom) - Model wind speed (knots) averaged in 5° squares over the North Atlantic.



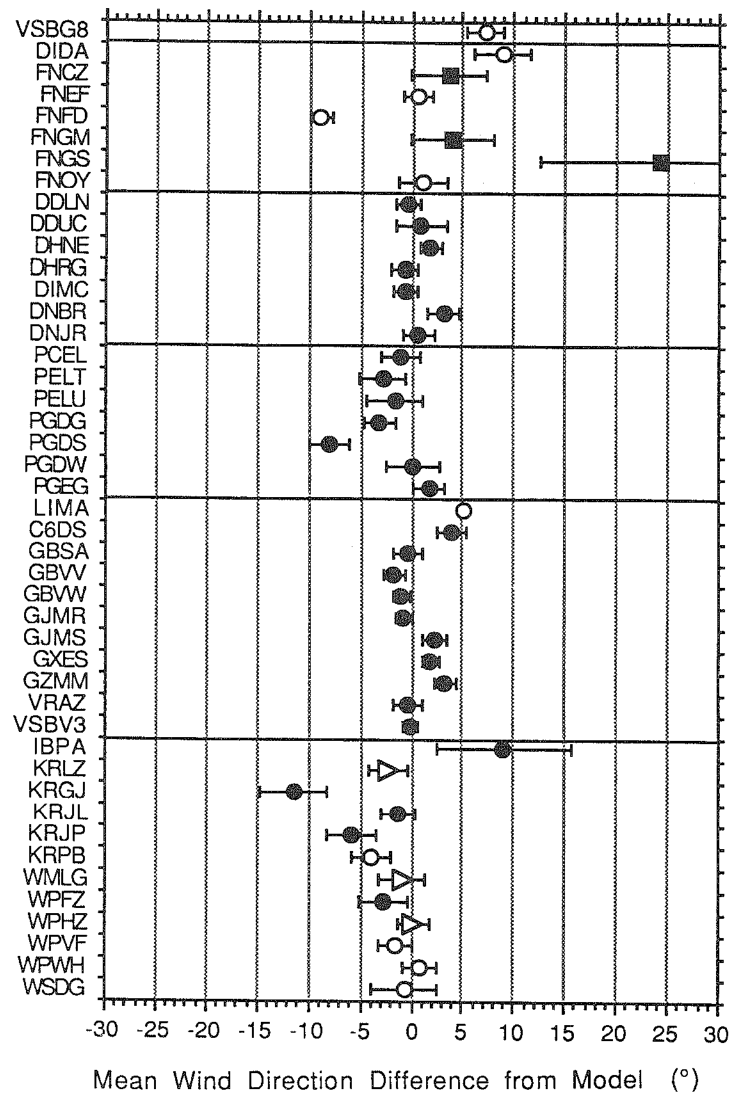
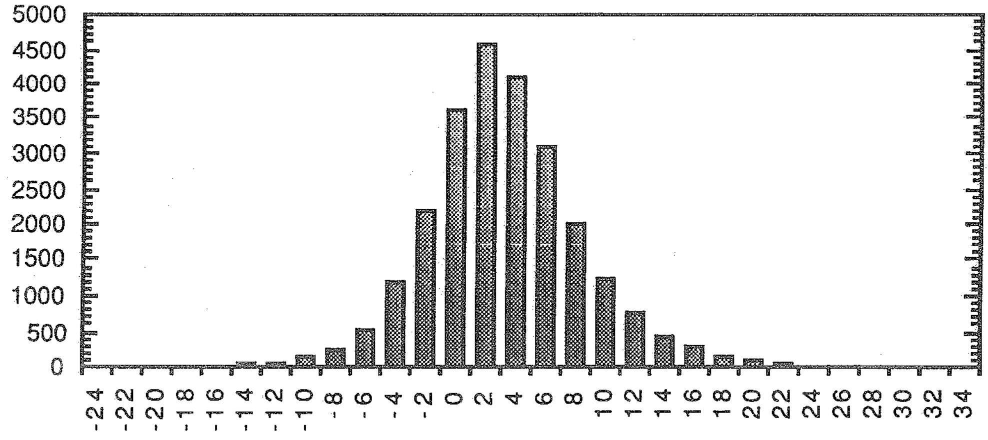


Figure 8.4a (left)- Mean wind speed difference from model (knots) by method (visually estimated, anemometer, hand held anemometer or unknown) by ship callsign.

Figure 8.4b (right) - Mean wind direction difference from model (degrees) by method (visually estimated, anemometer, hand held anemometer or unknown) by ship callsign.



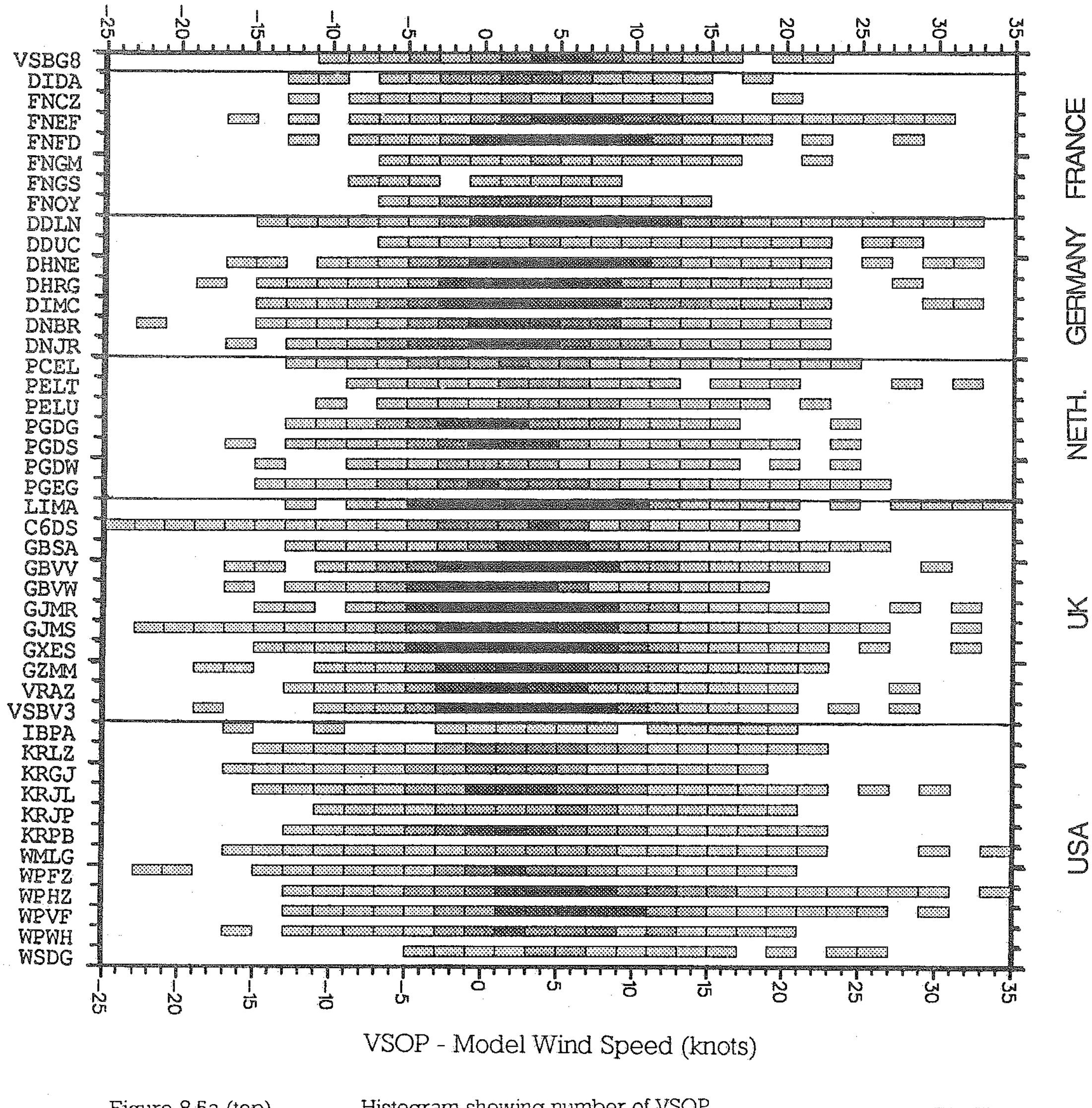
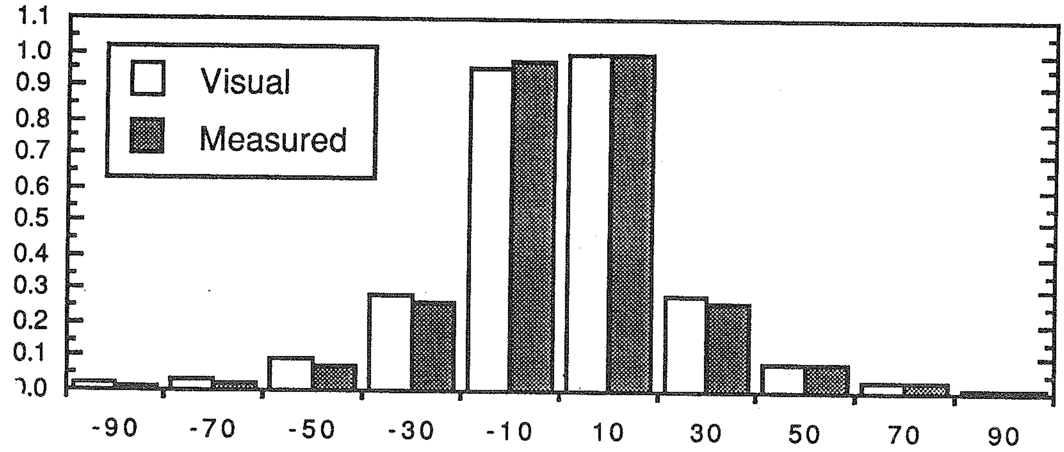


Figure 8.5a (top) - Histogram showing number of VSOP observations differing from model wind speeds ranging from -25 to 35 knots

Figure 8.5b (bottom) - Numbers of VSOP observations differing from model wind speeds by ship for wind speed differences ranging from -25 to 35 °C. Shading indicates numbers of observations per 2 knot range.



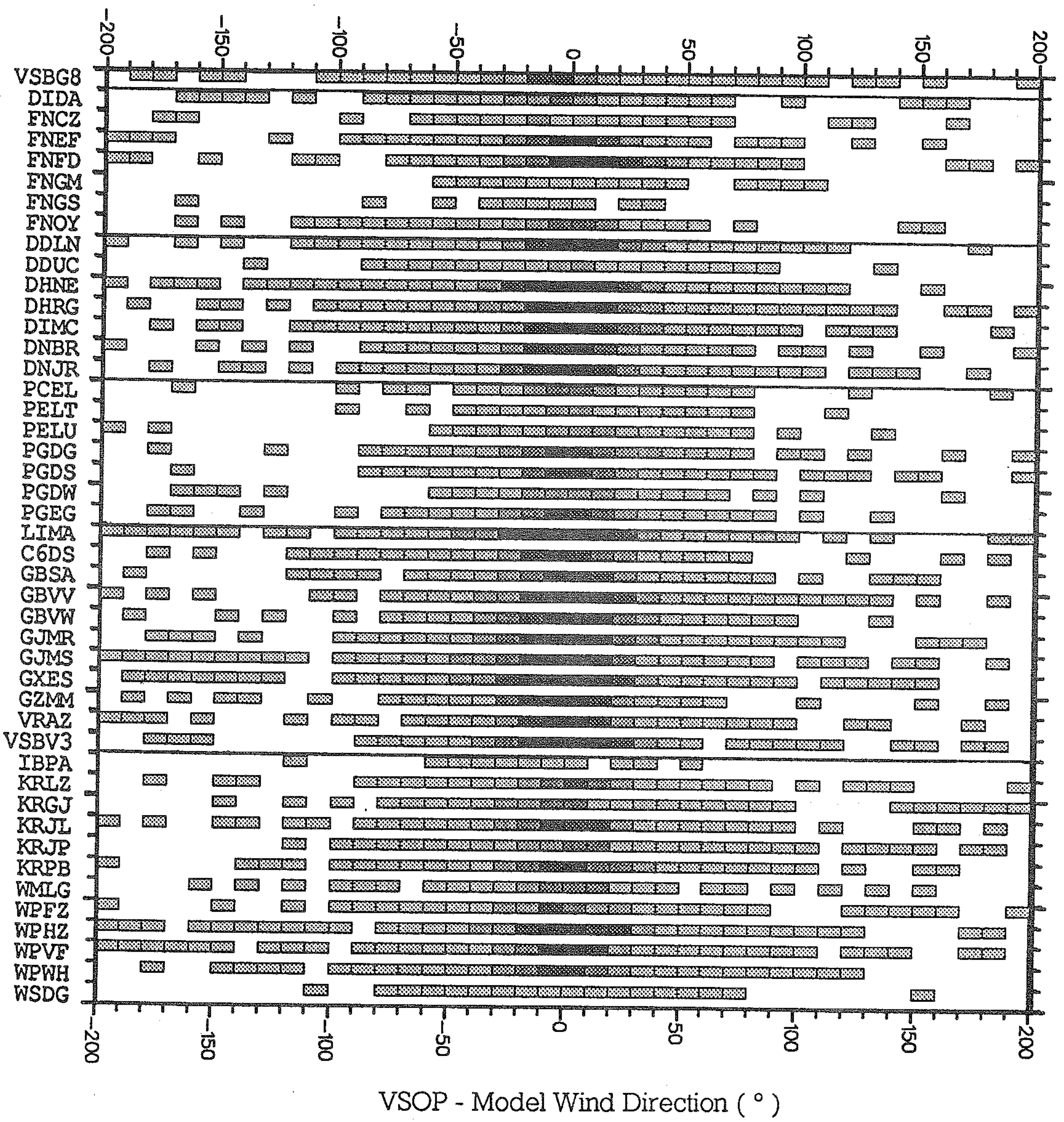
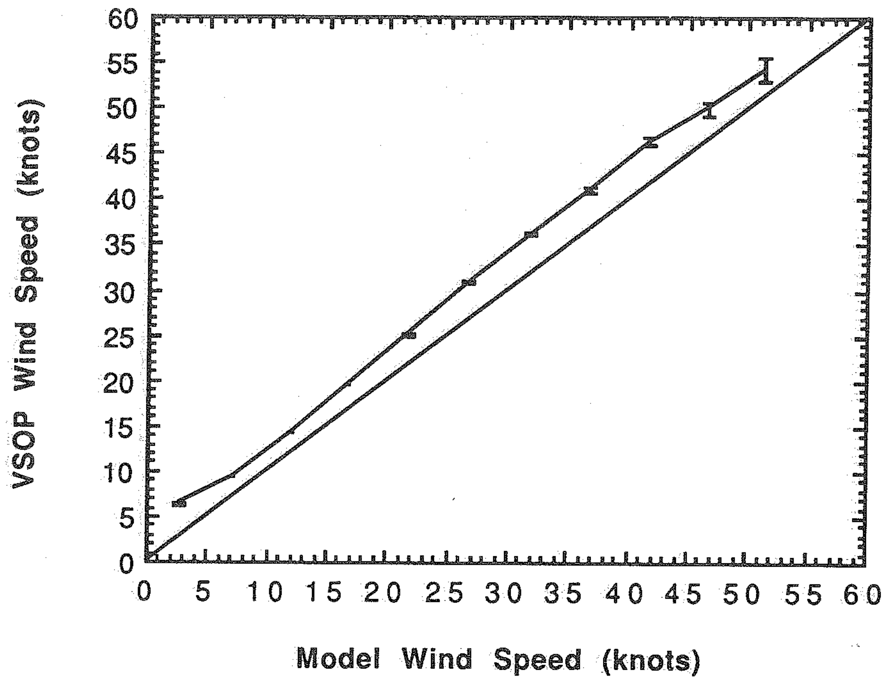


Figure 8.5c (top) - Histogram showing number of VSOP observations differing from model wind direction ranging from -90° to 90° for visually estimated and anemometer wind directions

Figure 8.5d (bottom) - Numbers of VSOP observations (all methods) differing from model wind direction by ship for wind direction differences ranging from -200° to 200°. Shading indicates numbers of observations per 10° range.



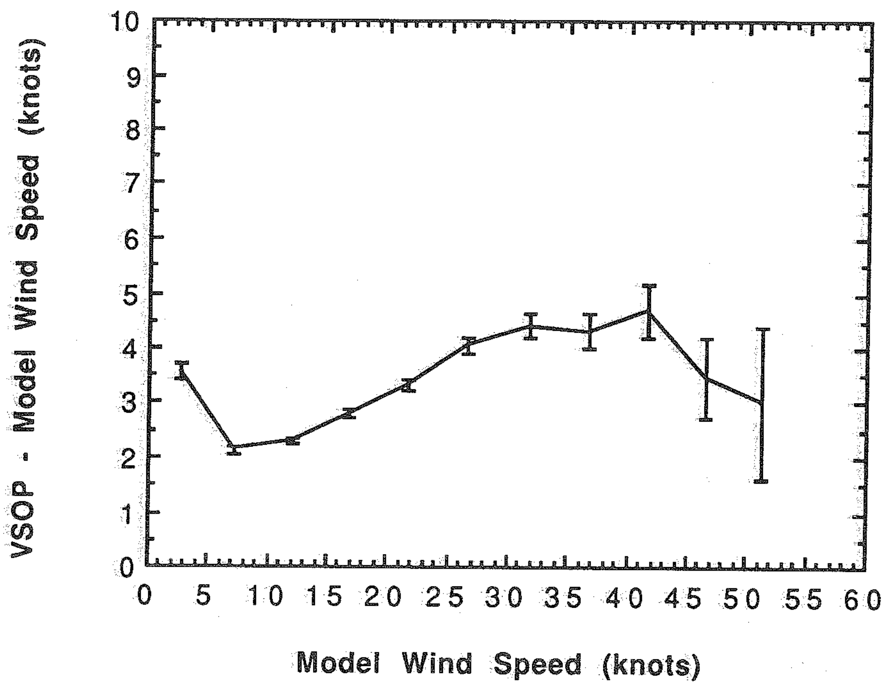
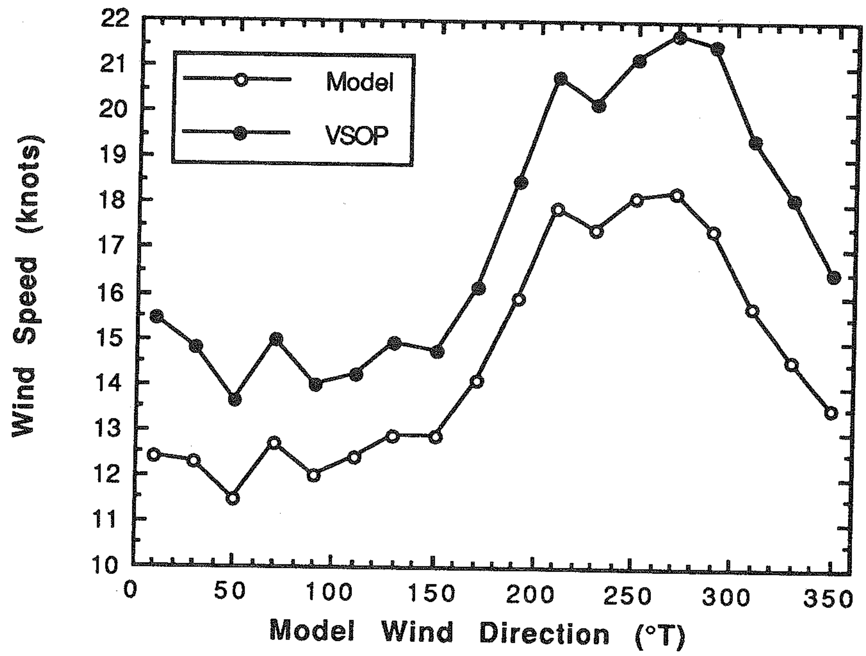


Figure 8.6 a (top) — VSOP measured wind speed (knots) binned on model wind speed (knots)

Figure 8.6 b (bottom) — Differences in VSOP measured wind speed from model values (knots) binned on model wind speed (knots)



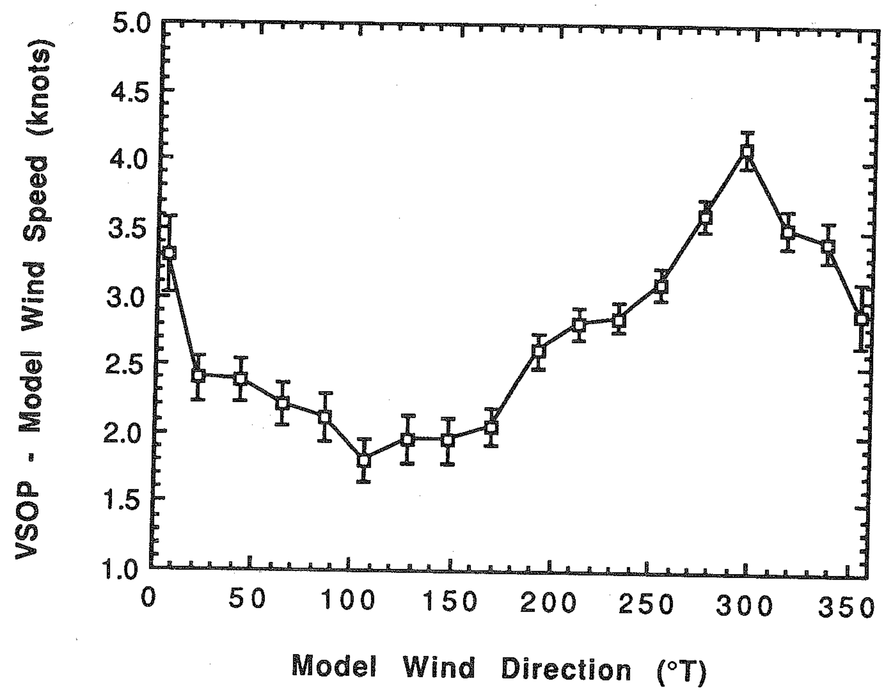


Figure 8.6 c (top) - VSOP and model wind speeds (knots) binned on model wind direction (°T)

Figure 8.6 d (bottom) - Differences in VSOP measured wind speeds from model values (knots) binned on model wind direction (°T)

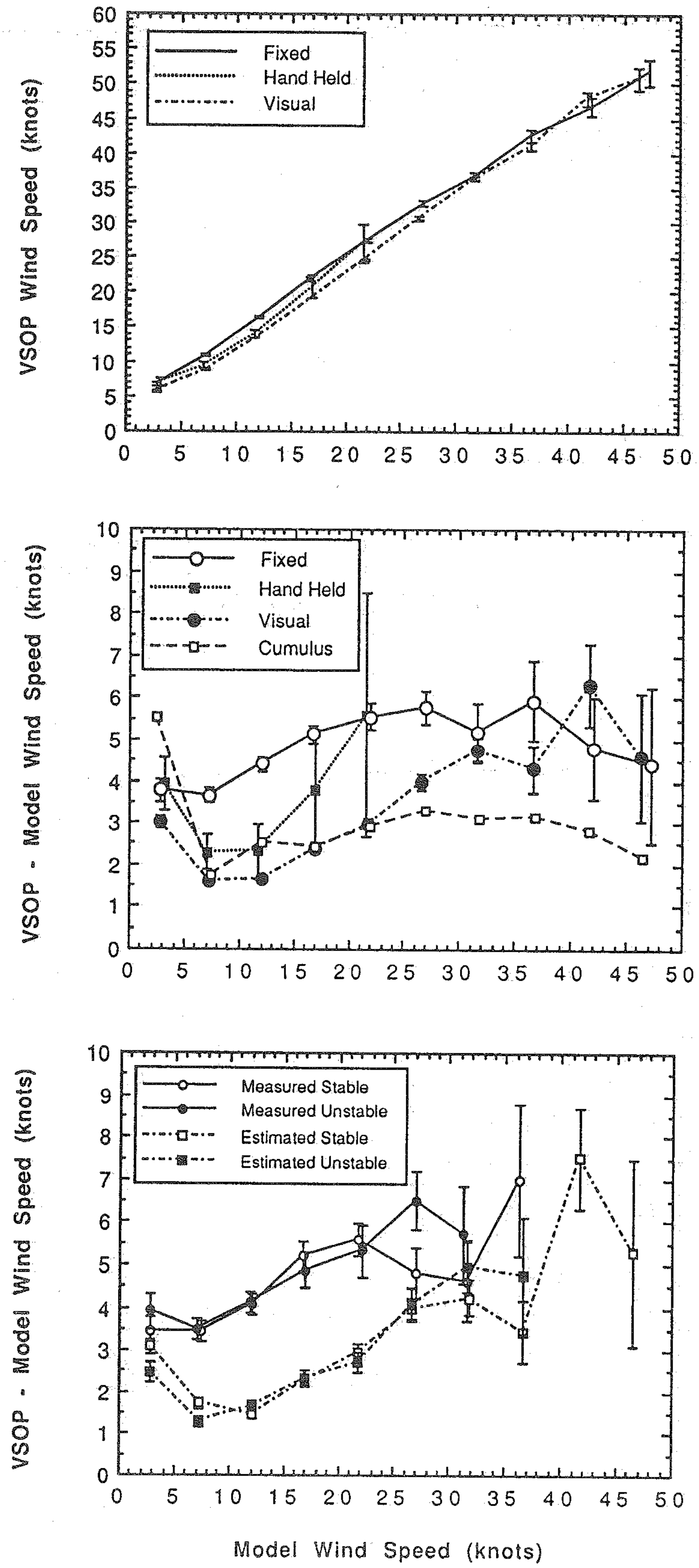
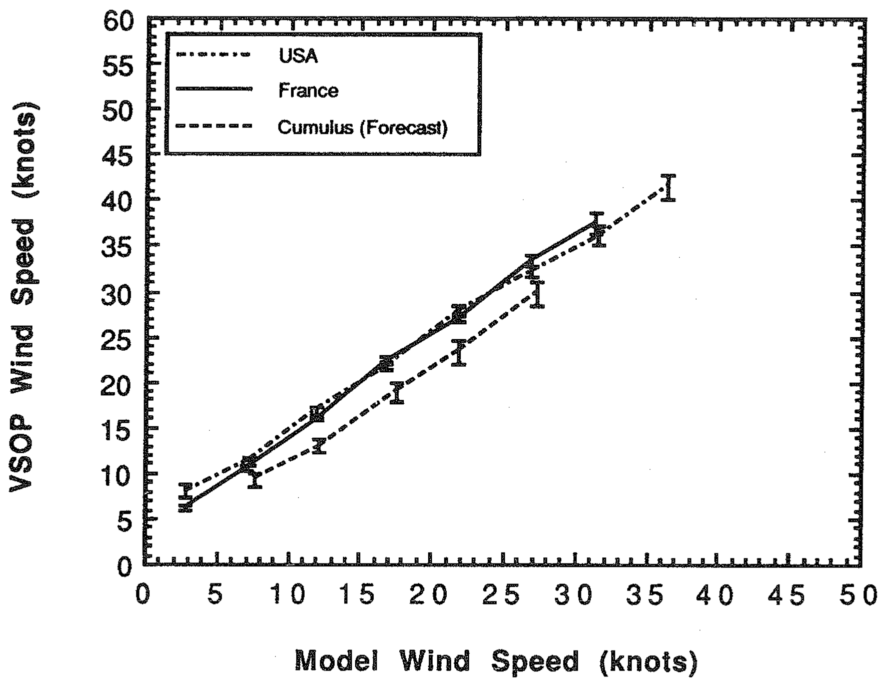


Figure 8.7a (top) - VSOP measured wind speeds (knots) binned on model wind speed (knots) separately for fixed anemometers, hand held anemometers and visually estimated winds.

Figure 8.7b (centre) - VSOP measured wind speed differences from model (knots) binned on model wind speed (knots) for sensors as in 8.7a

Figure 8.7c (bottom) - As 8.7b except data divided by visually estimated and measured wind speeds and also by stable (air temperature greater than sea temperature) and unstable conditions (air temperature less than sea temperature)



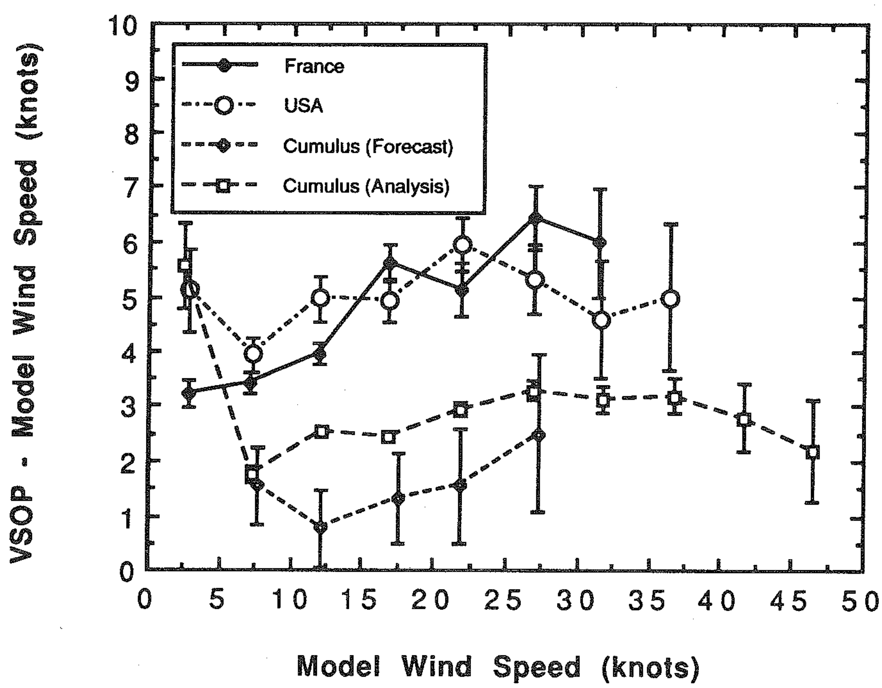


Figure 8.8 a (top) — VSOP measured wind speed (knots) binned on analysis model wind speed (knots) by country for anemometer measured data. Ocean Weather Ship Cumulus wind speed data are also plotted against forecast model wind speeds.

Figure 8.8 b (bottom) — Differences in VSOP and Ocean Weather Ship Cumulus measured wind speed (knots) from analysis model values binned on model wind speed (knots). Differences in Ocean Weather Ship Cumulus wind speeds from forecast model data are also plotted.

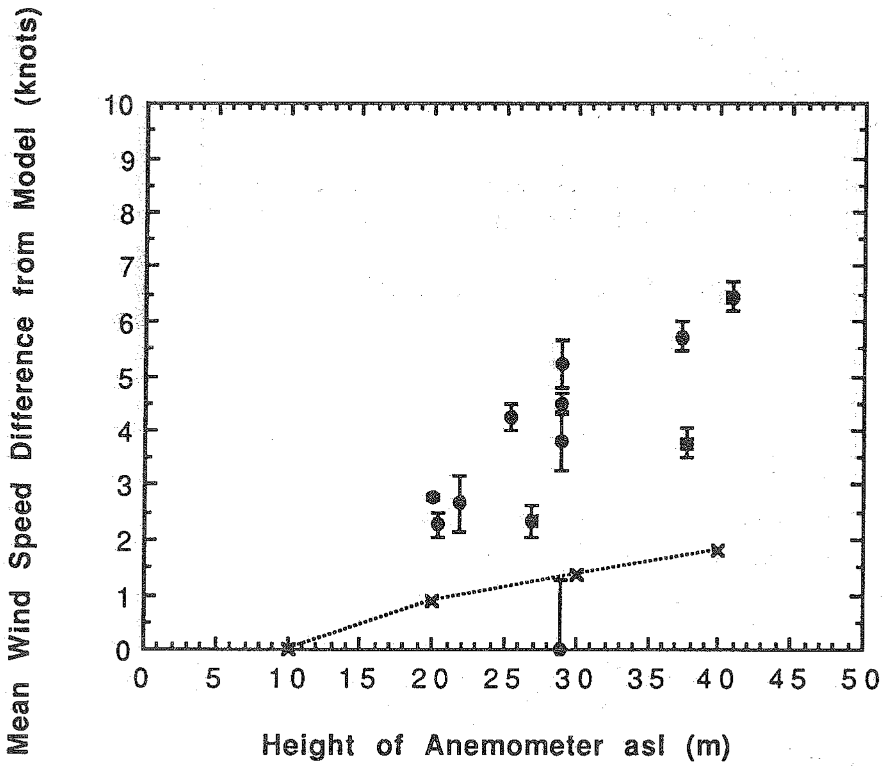
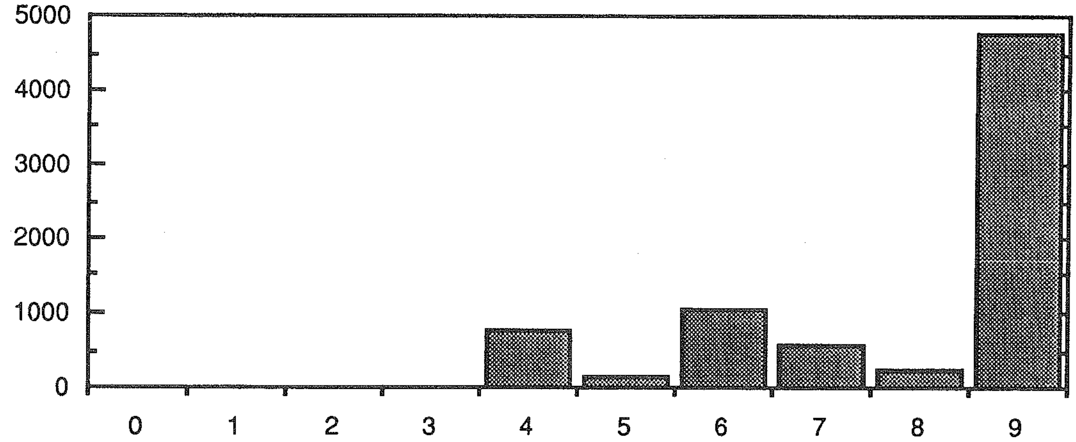


Figure 8.9 - Graph showing VSOP wind speed difference from model (knots) by ship (scatter points). Line indicates correction from anemometer height to 10 m above sea level.



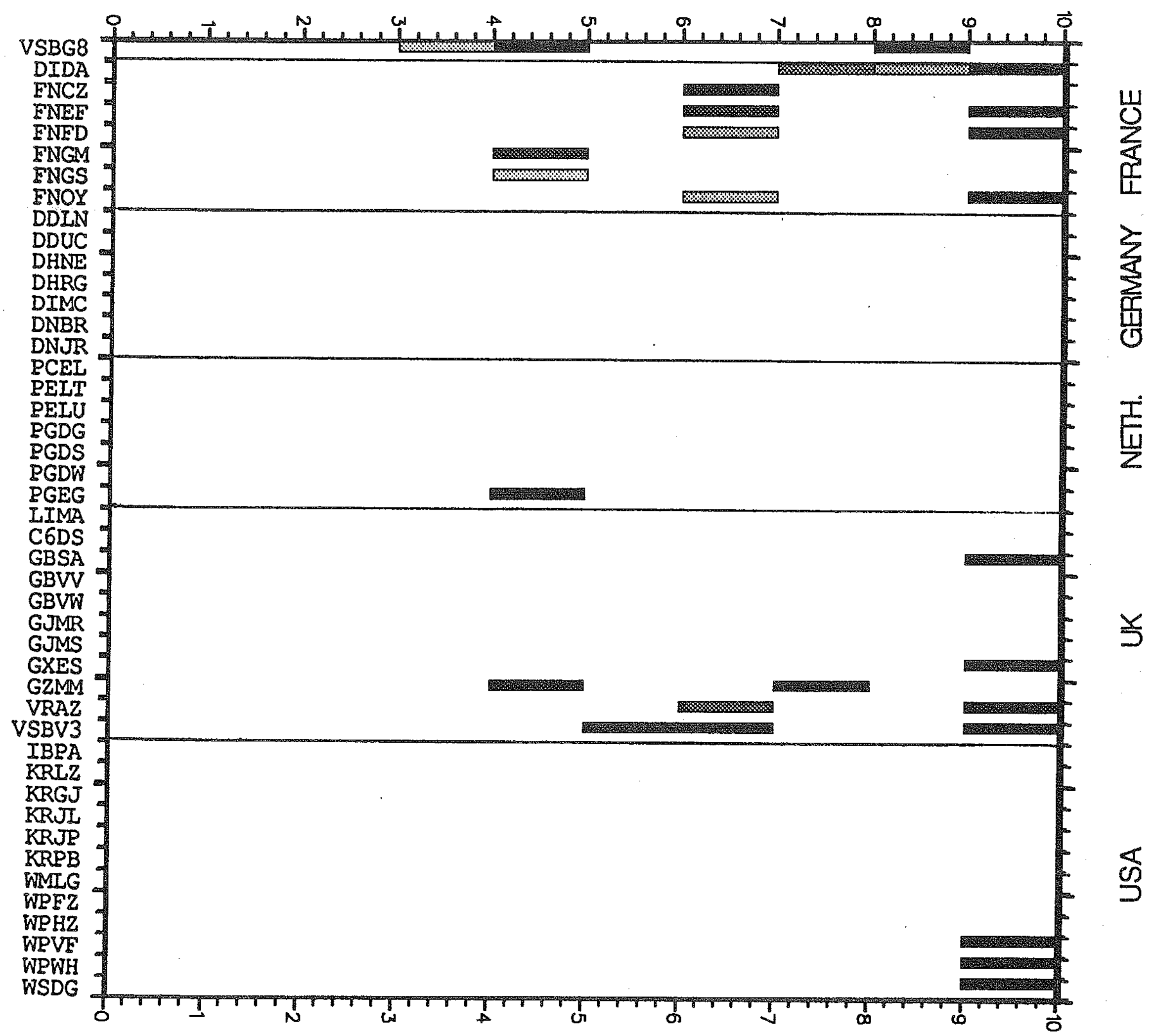
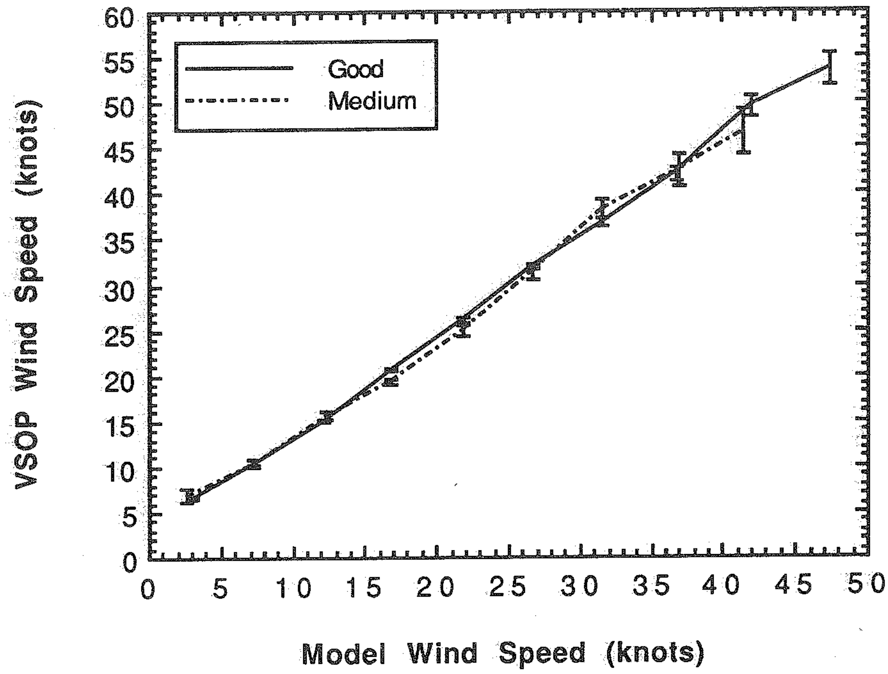


Figure 8.10a (top) - Histogram showing number of VSOP wind observations rated at exposure indices from 0 (poorly exposed) to 9 (well exposed)

Figure 8.10b (bottom) - Numbers of VSOP observations by ship rated at exposure indices 0 to 9 as in 8.10a



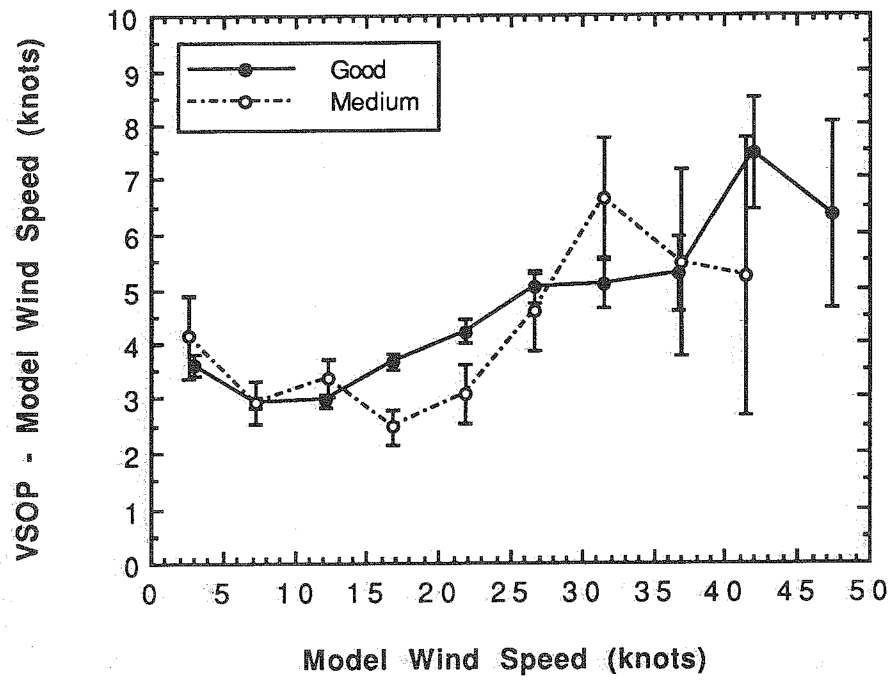
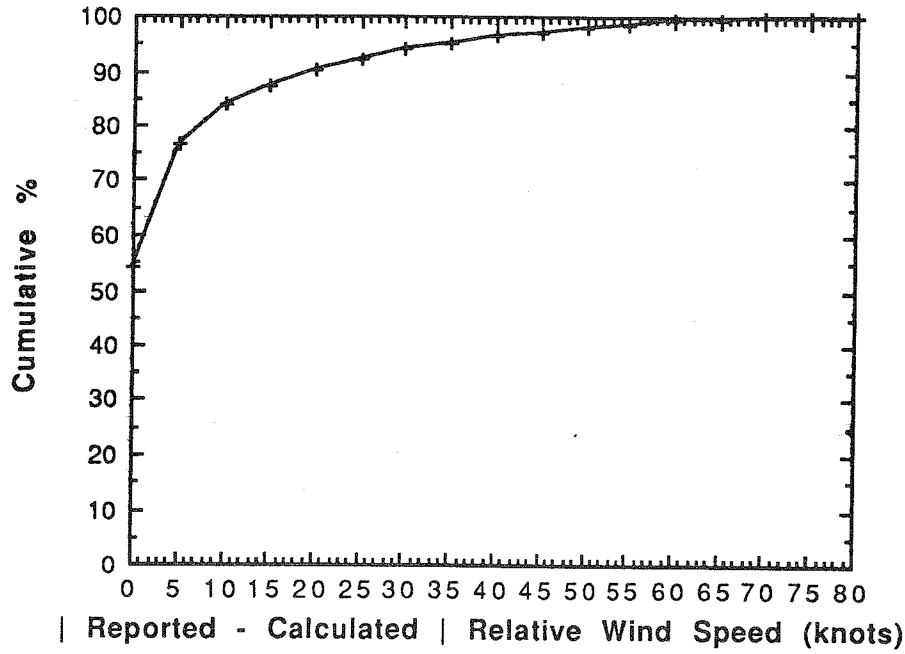


Figure 8.11 a (top) VSOP measured wind speed (knots) binned on model wind speed (knots) by anemometer exposure. Good represents anemometer exposure indices 6 to 9 and medium represents anemometer exposures 3 to 5.

Figure 8.11 b (bottom) Differences in VSOP measured wind speeds from model values (knots) binned on model wind speeds (knots) by anemometer exposure as in 8.11a.



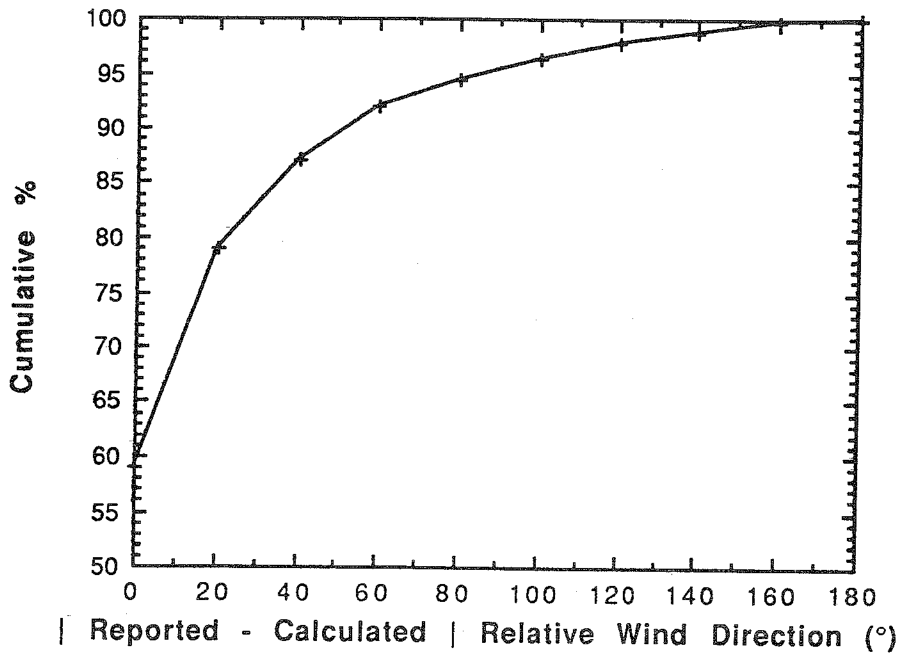
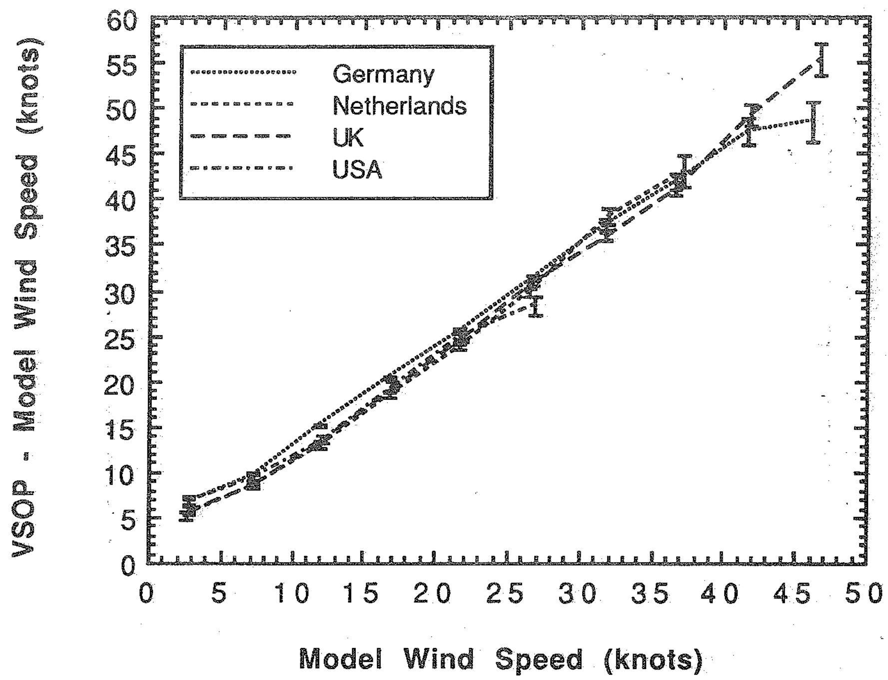


Figure 8.12a (top) - Cumulative percentage plot of difference in relative wind speed (knots) reported by VSOP and that calculated from reported true wind speed and direction and ships speed and heading.

Figure 8.12b (bottom) - Cumulative percentage plot of difference in relative wind direction (°) reported by VSOP and that calculated from reported true wind speed and direction and ships speed and heading.



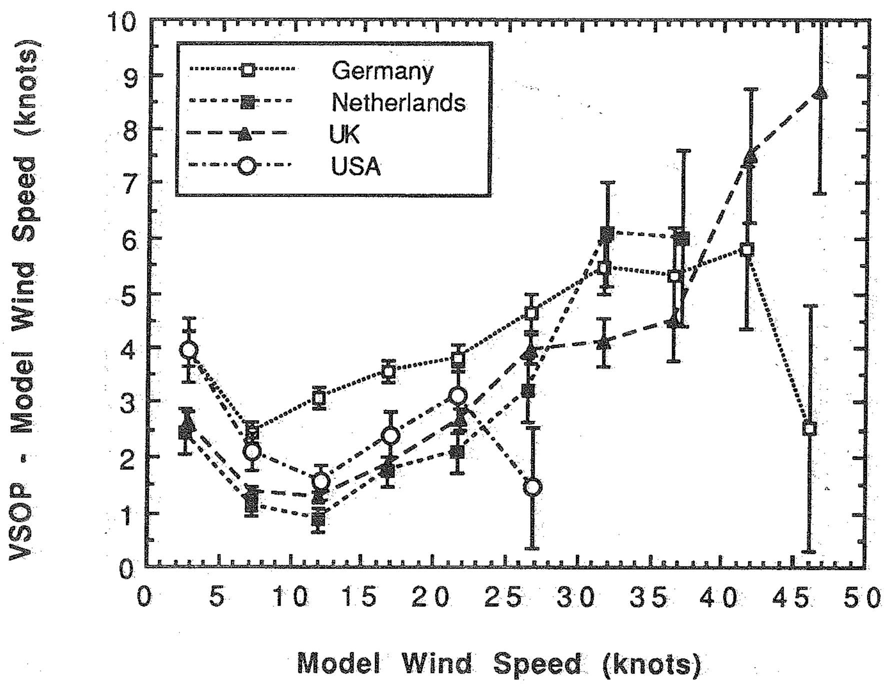
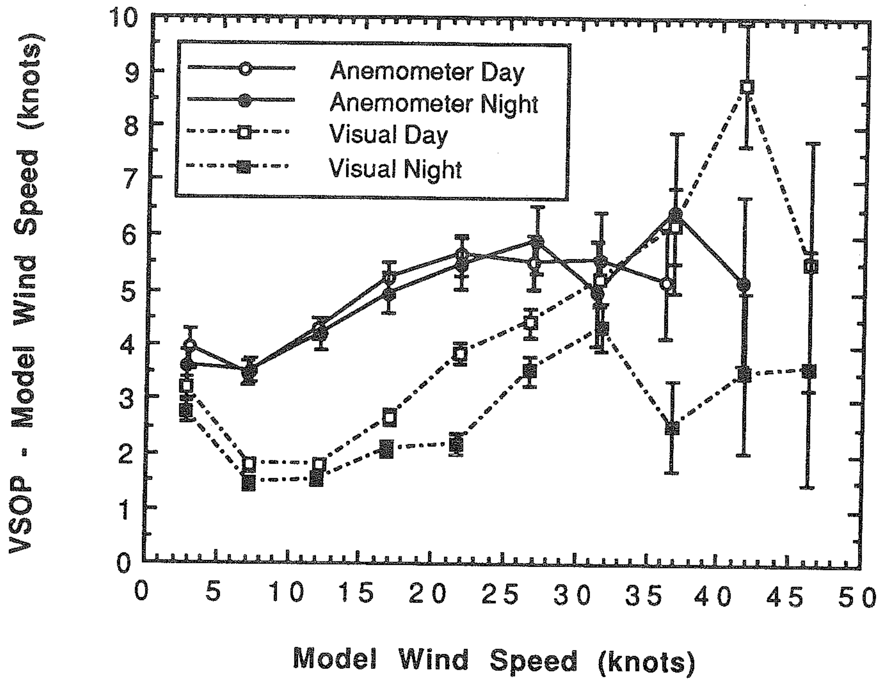


Figure 8.13a (top) - VSOP measured wind speed (knots) binned on model wind speed (knots) by country for visually estimated data.

Figure 8.13b (bottom) - Differences in VSOP measured wind speed (knots) from model values binned on model wind speed (knots).



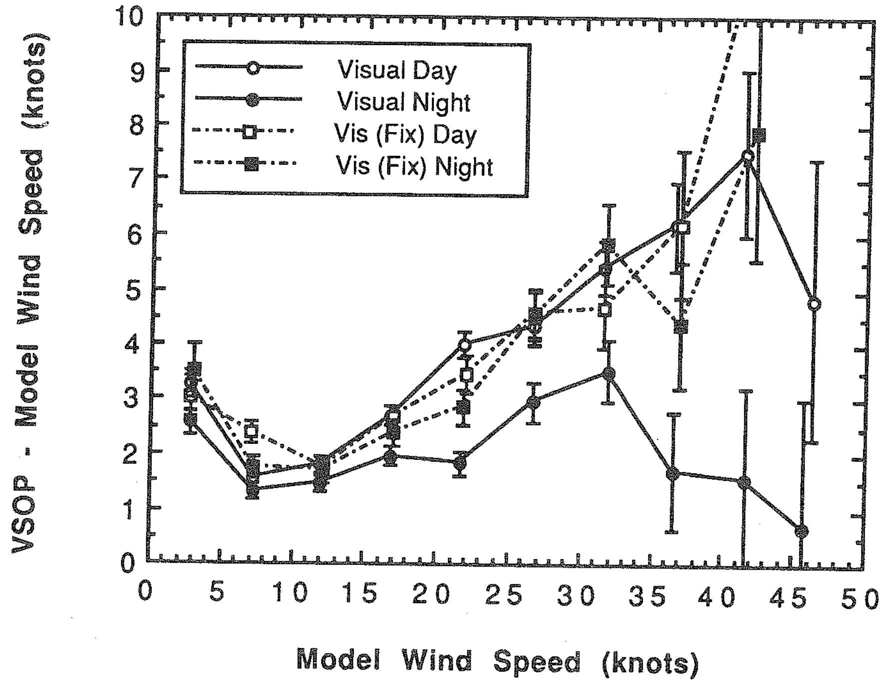
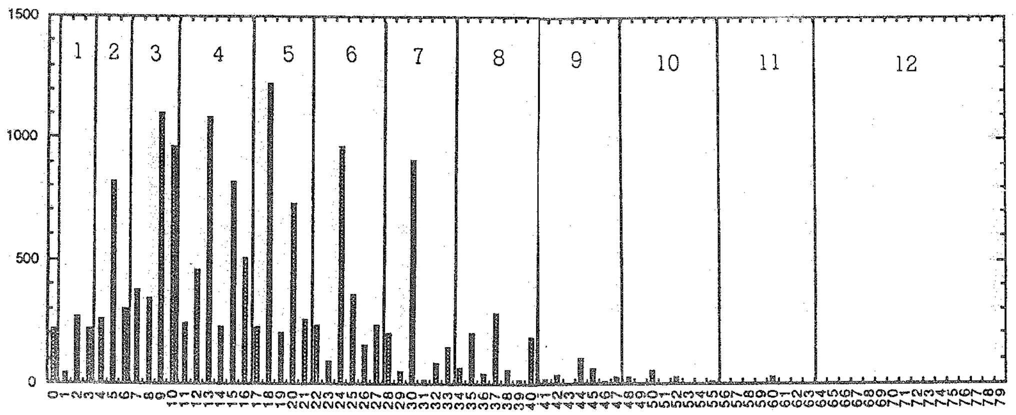


Figure 8.14a (top) - VSOP reported wind speed (knots) binned on model wind speed (knots) separately for anemometer and visual winds and for day and night observations.

Figure 8.14b (bottom) - VSOP measured wind speed (knots) binned on model wind speed (knots) separately for visual winds reported on ships with and without fixed anemometers and for day and night observations.



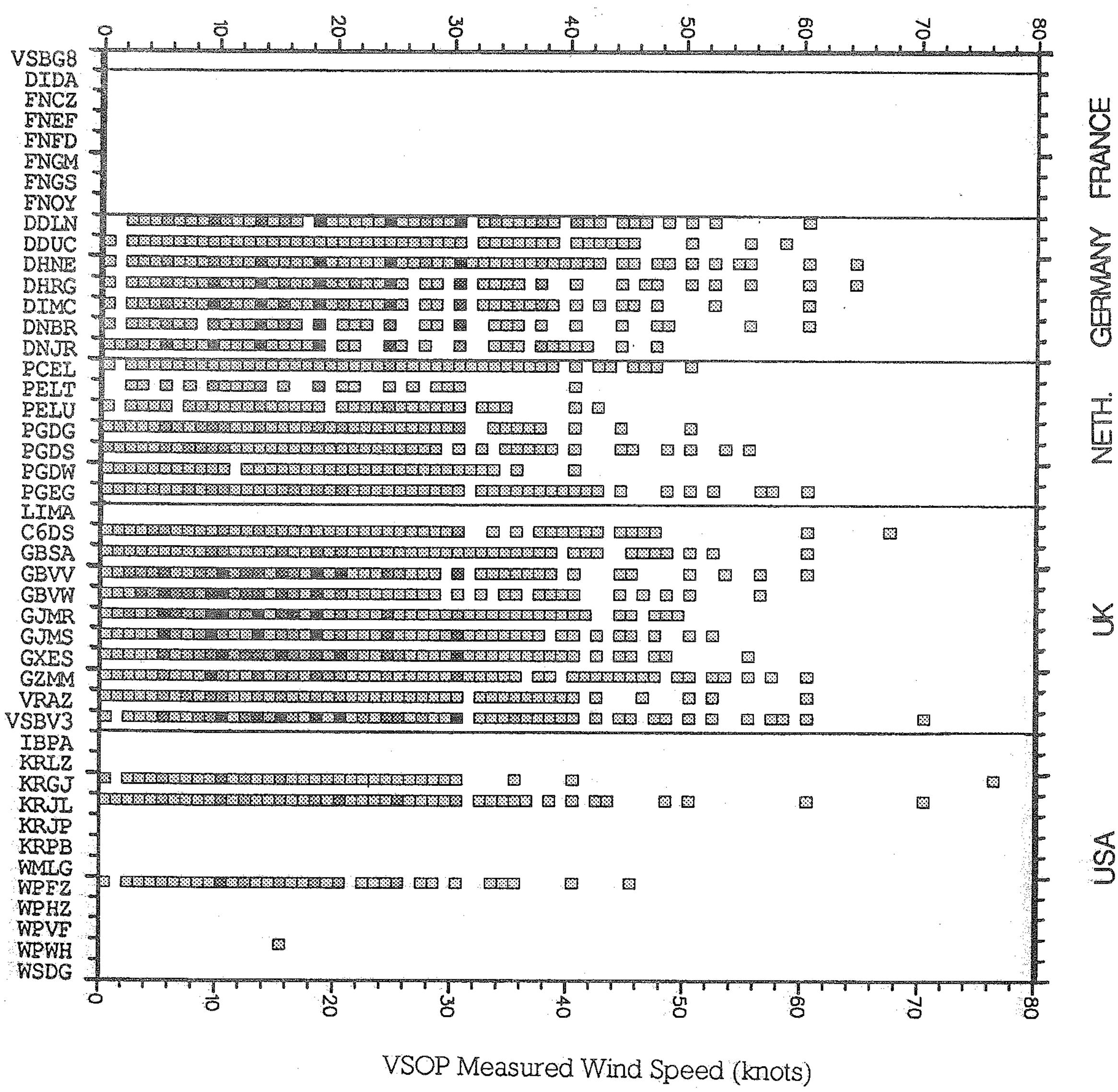
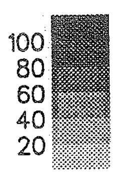
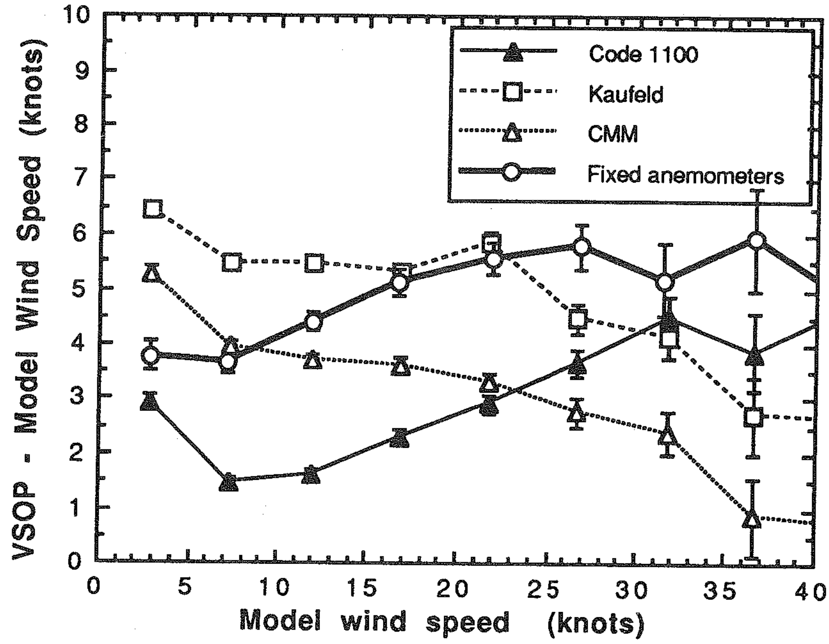


Figure 8.15a (top) - Histogram showing number of estimated VSOP wind speed observations for VSOP wind speed ranging from 0 80 knots. Numbers indicate Beaufort Scale Intervals.

Figure 8.15b (bottom) - Numbers of estimated VSOP wind speed observations by ship for VSOP wind speed ranging from 0 to 80 knots Shading indicates numbers of observations per 1 knot range.





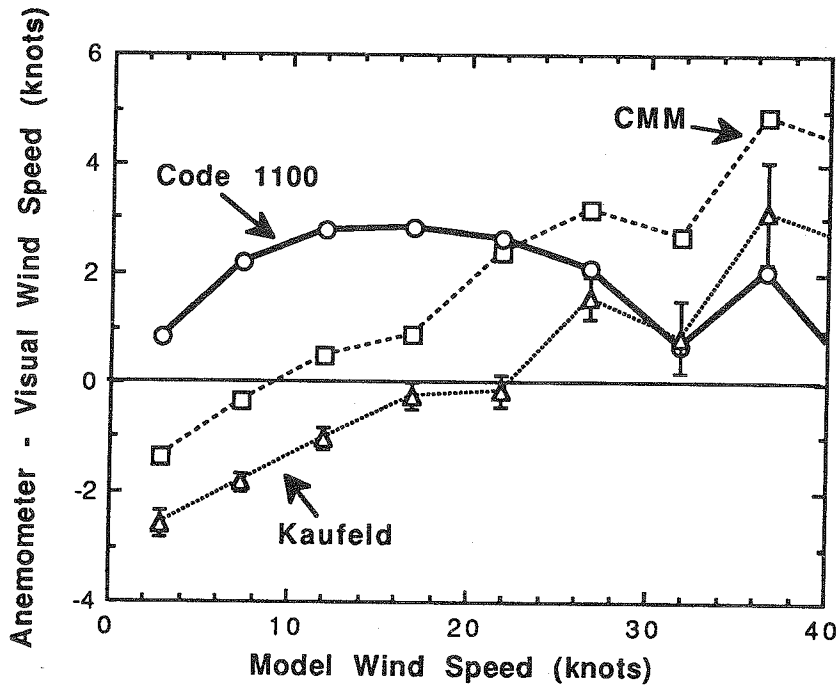
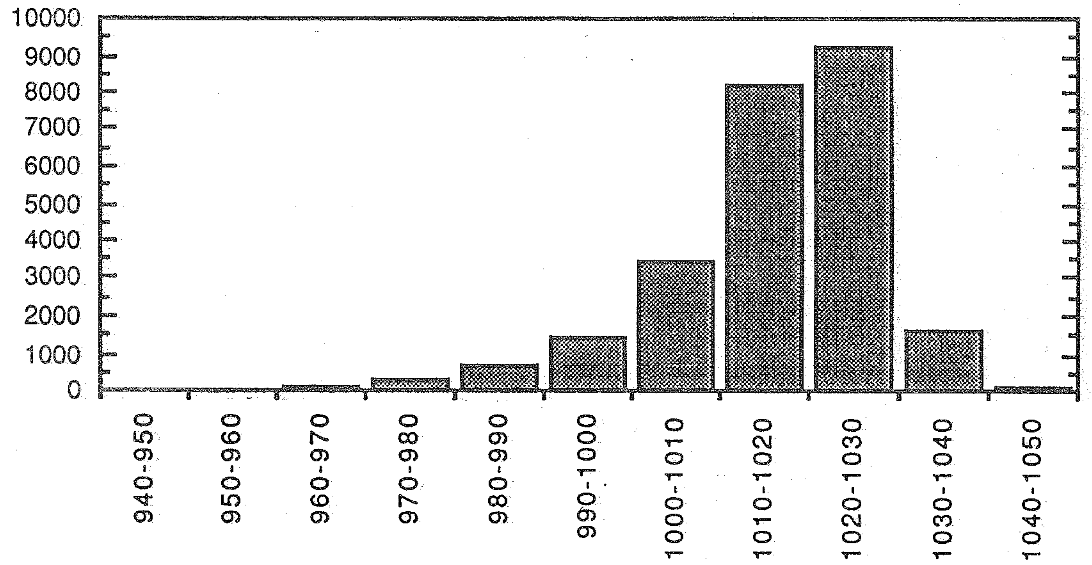


Figure 8.16a (top) - Differences in visually estimated VSOP and model wind speeds with different Beaufort Scale conversions (Code 1100, Kaufeld and CMM) and VSOP anemometer winds against model wind speed (knots).

Figure 8.16b (bottom) - Differences in VSOP anemometer and visually estimated winds against model wind speed (knots) for Beaufort Scale conversions as 8.16a.



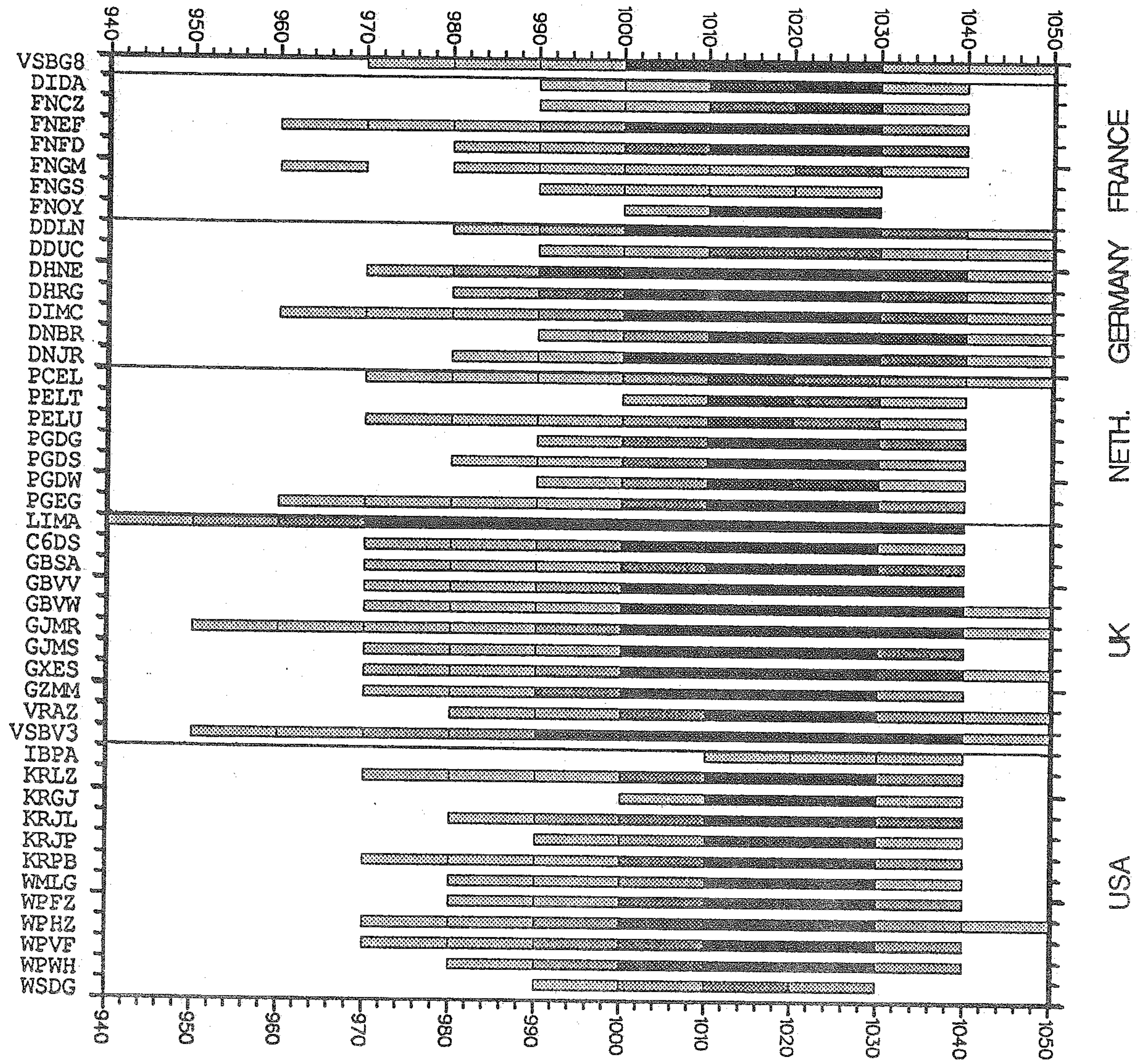
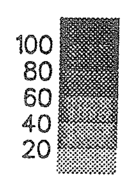


Figure 9.1a (top) - Histogram showing number of VSOP observations for model pressures ranging from 940 to 1050 mb

Figure 9.1b (bottom) - Numbers of VSOP observations by ship for model pressures ranging from 940 to 1050 mb. Shading indicates numbers of observations per 10 mb range.



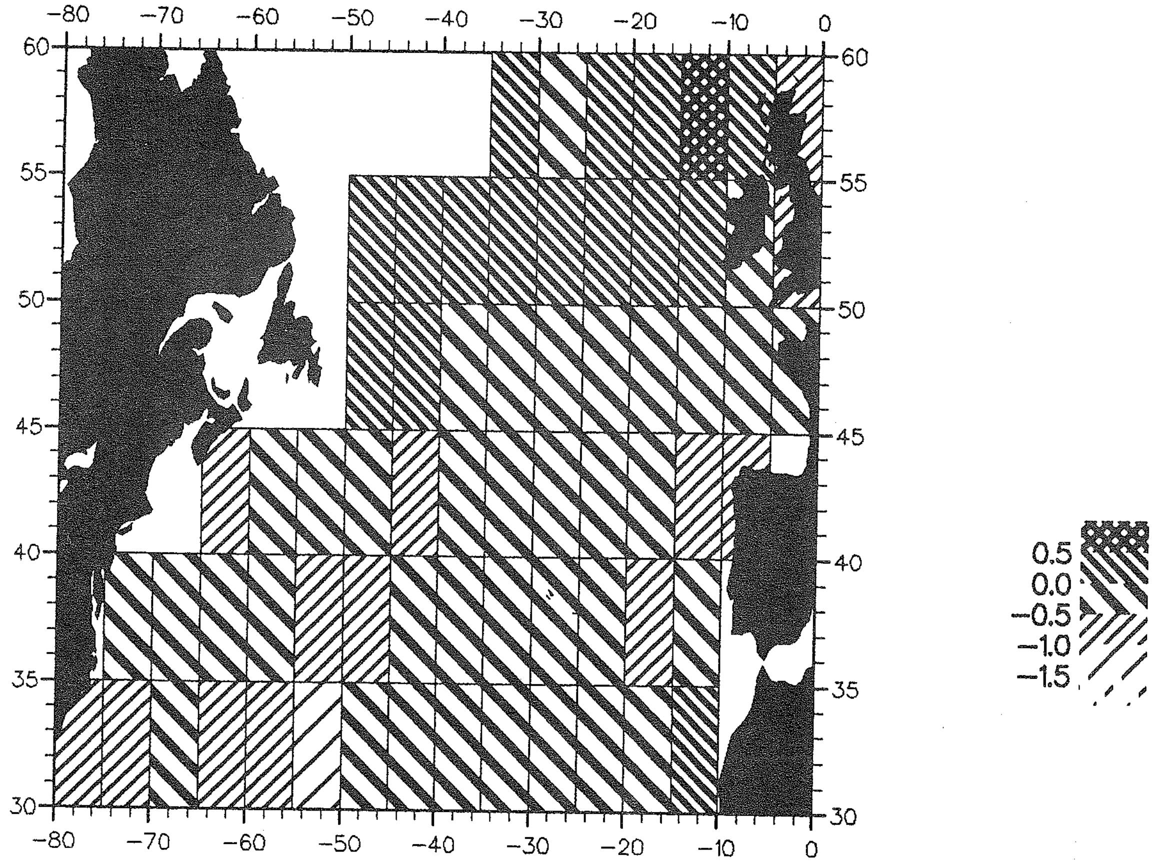


Figure 9.2 - Pressure difference from model (mb) averaged in 5° squares over the North Altantic.

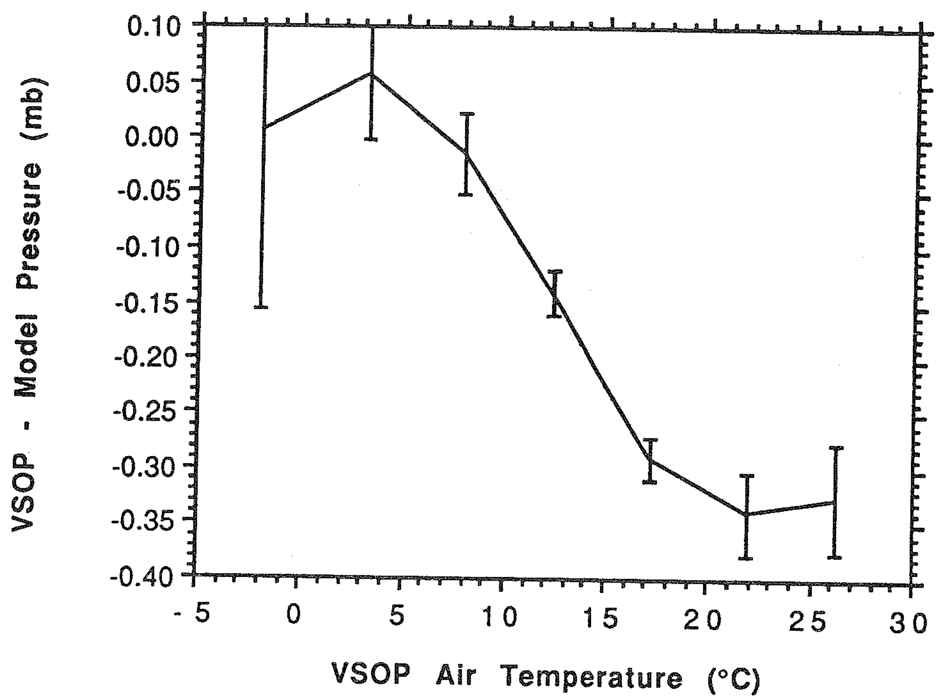


Figure 9.3 - Differences in VSOP measured pressures from model values (mb) binned on VSOP measured air temperature (°C)

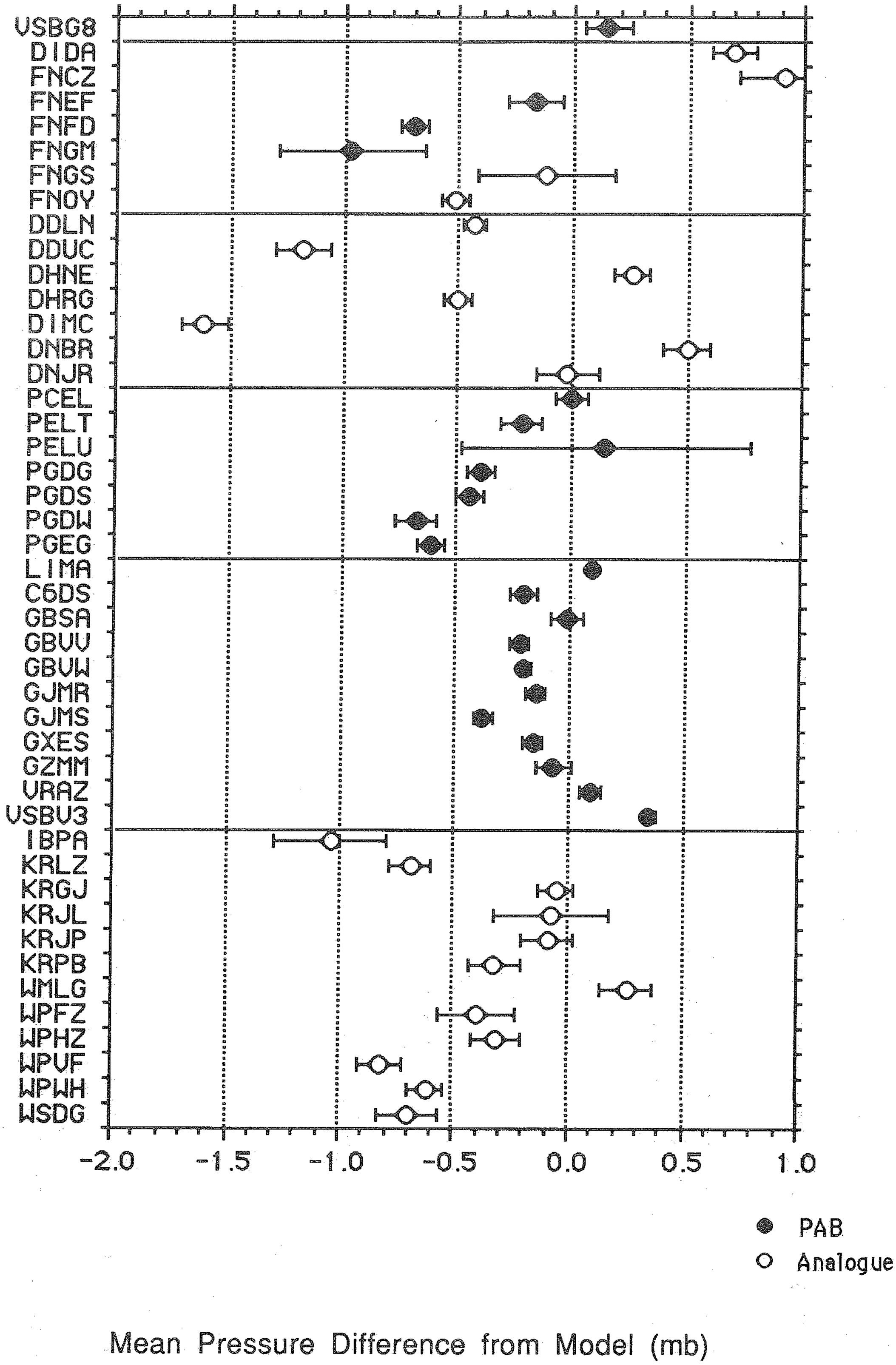
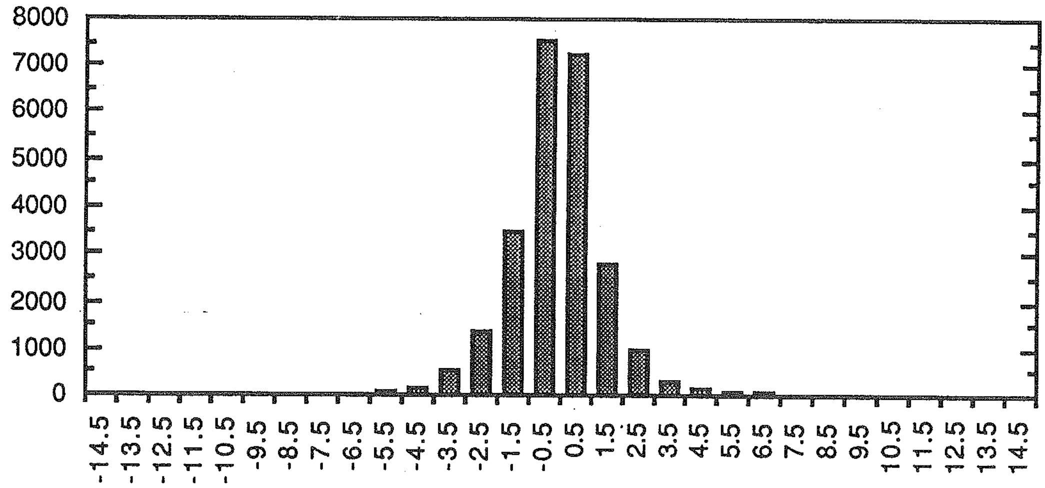


Figure 9.4 - Mean pressure difference from model (mb) by ship callsign.



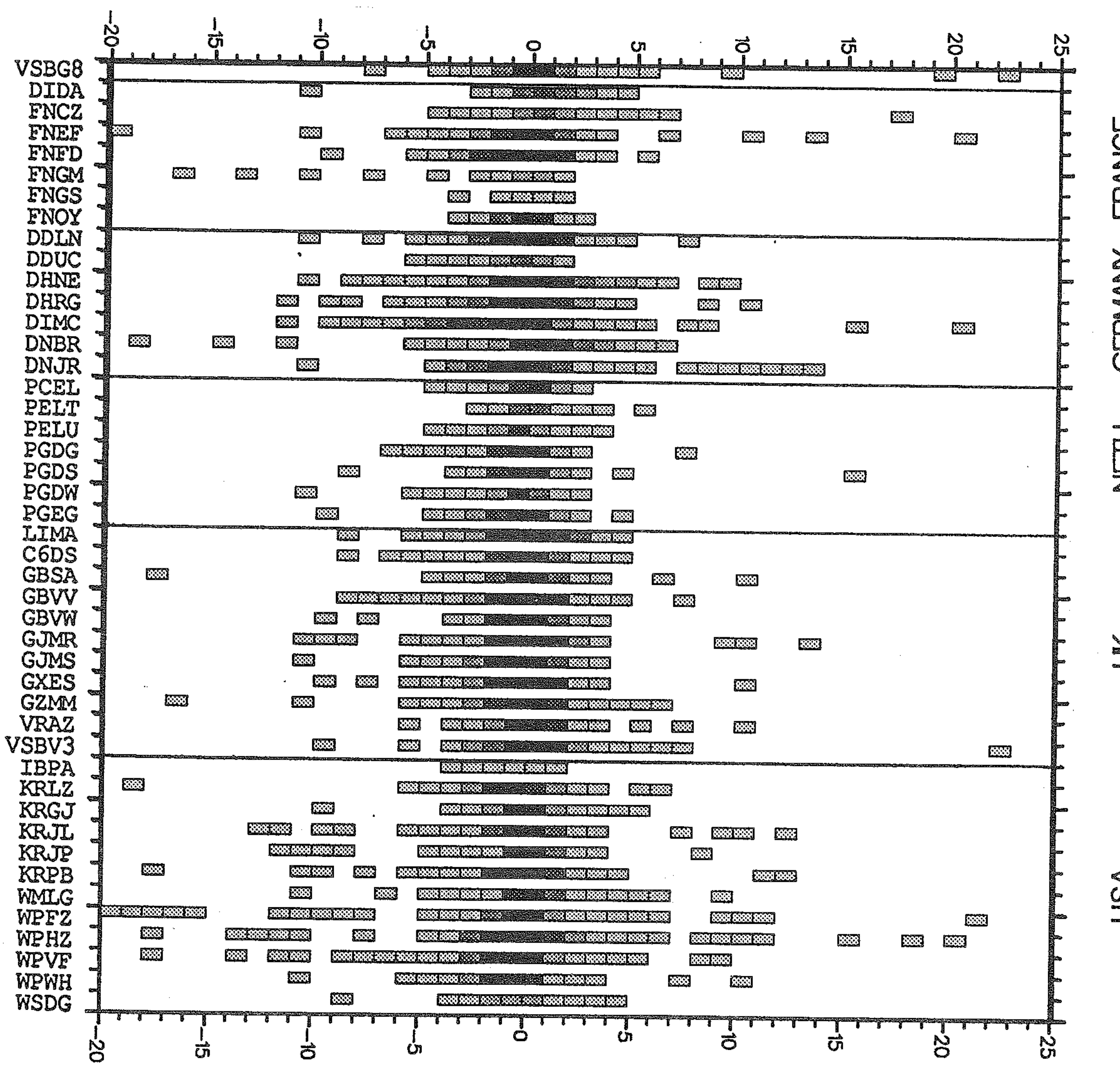
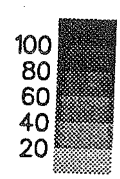
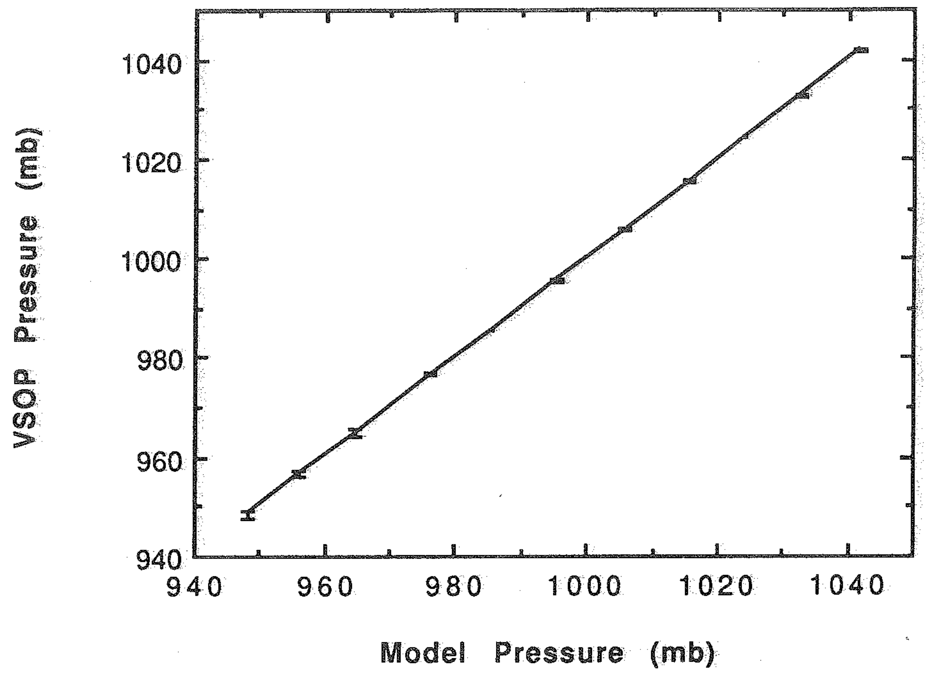


Figure 9.5a (top) - Histogram showing number of VSOP observations differing from model pressure ranging from -15 to 15 mb

Figure 9.5b (bottom) - Numbers of VSOP observations differing from model pressures by ship for pressure differences ranging from -20 to 25 °C. Shading indicates numbers of observations per 1mb range.





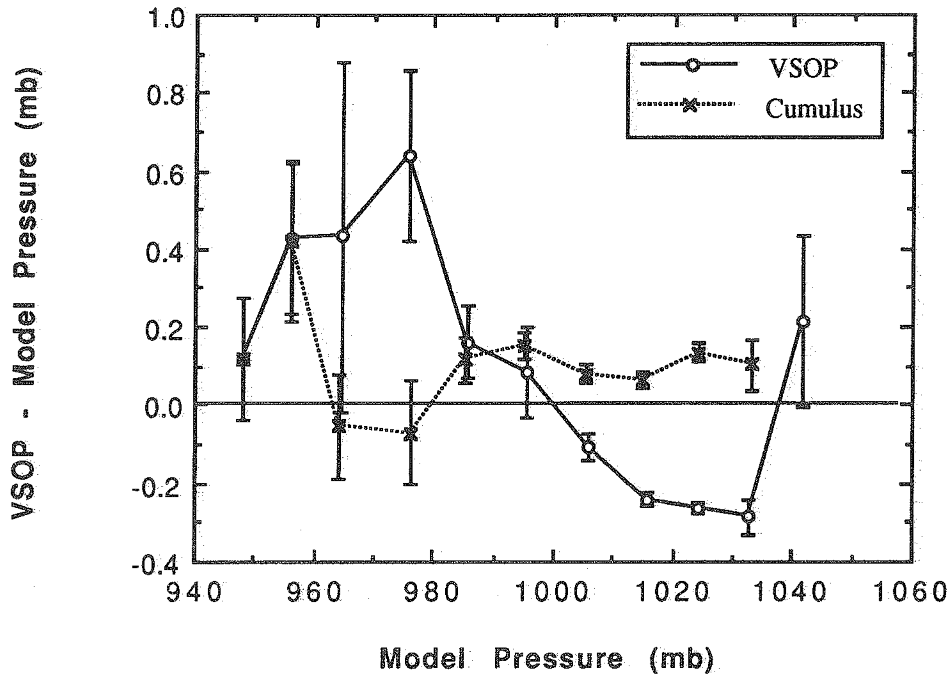
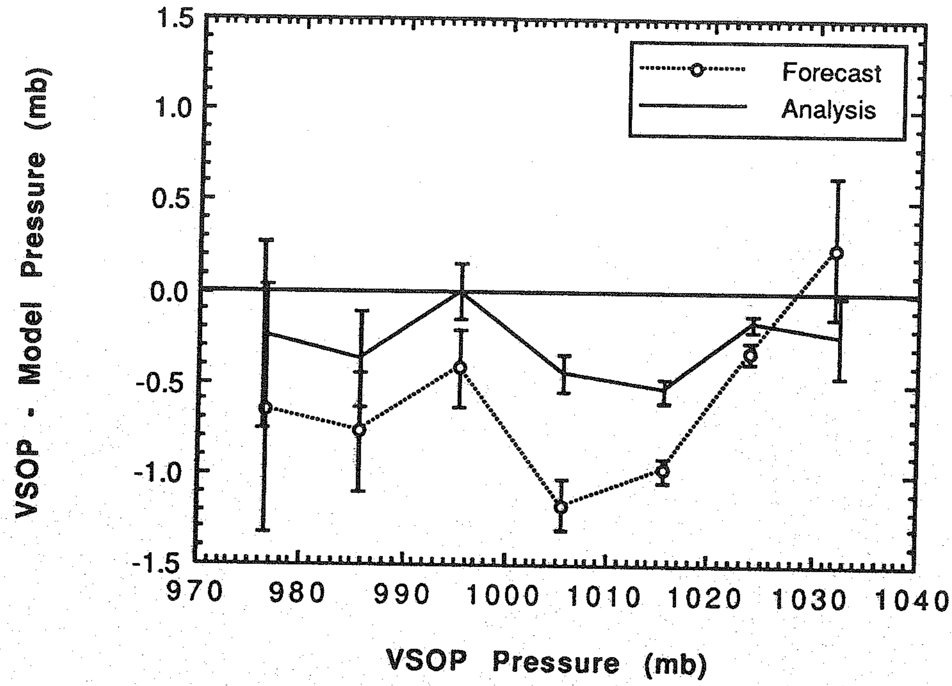


Figure 9.6 a (top) VSOP measured pressure binned on model pressure

Figure 9.6 b (bottom) Differences in VSOP and Ocean Weather Ship Cumulus measured pressures from model values binned on model pressure



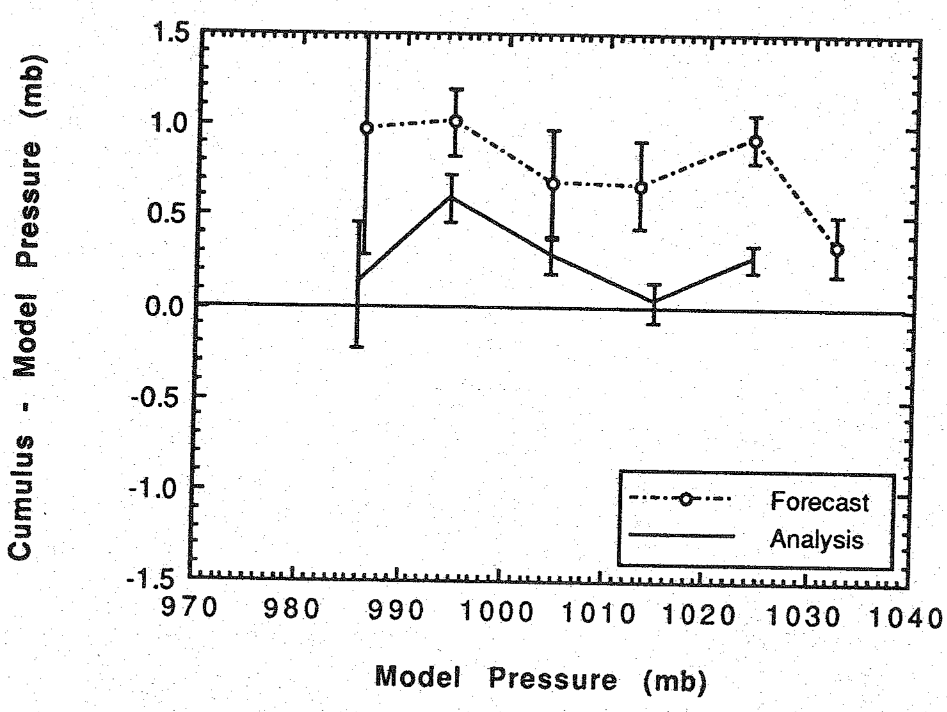


Figure 9.6 c (top)	Differences in VSOP measured pressures from analysis and forecast model values (mb) binned on VSOP pressure (mb).
Figure 9.6 d (bottom)	Differences in VSOP and Ocean Weather Ship Cumulus measured pressures (mb) from analysis and forecast model values binned on model pressure (mb).

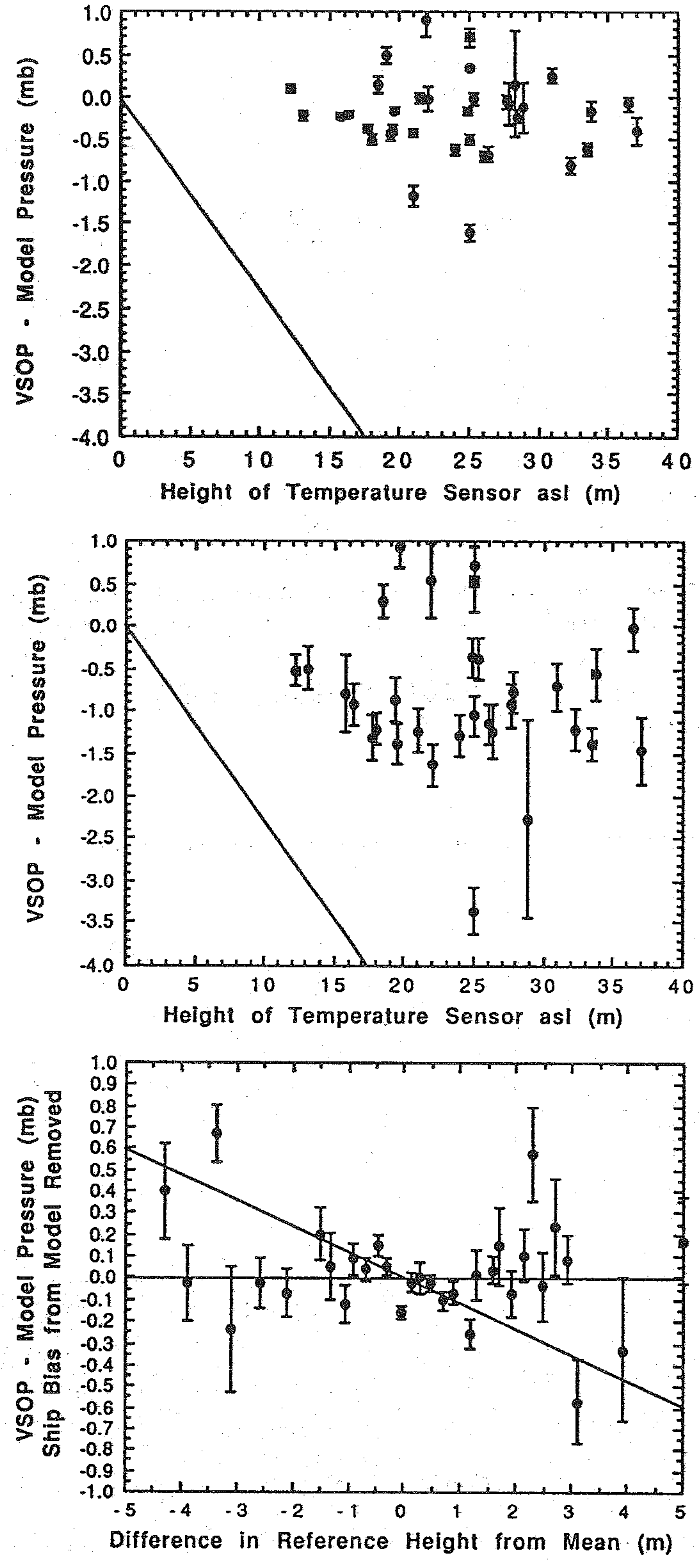


Figure 9.7 a (top) - VSOP pressure difference from model analysis data (mb) against height of temperature sensor (m) by ship. The line shows the expected relationship if no pressure correction was applied

Figure 9.7 b (centre) - VSOP pressure difference from model forecast data (mb) against height of temperature sensor (m) by ship. Line as 9.7a.

Figure 9.7 c (bottom) - VSOP pressure difference from model analysis data (mb) binned on difference in reference level from the ship's mean reference level (m). The line shows the expected relationship if no correction is made for variations in ship's draft