G
C
O
S

GLOBAL
CLIMATE
OBSERVING
SYSTEM

WMO **UNESCO** **UNEP** **ICSU**

WORLD METEOROLOGICAL
ORGANIZATION

INTERGOVERNMENTAL
OCEANOGRAPHIC COMMISSION

REPORT OF THE OOPC/AOPC WORKSHOP

ON GLOBAL SEA SURFACE TEMPERATURE DATA SETS

(Palisades, N.Y., USA, 2-4 November 1998)

November 1999

GCOS - 57
GOOS - 79
(WMO/TD No. 978)

UNITED NATIONS
ENVIRONMENT PROGRAMME

INTERNATIONAL COUNCIL FOR
SCIENCE

TABLE OF CONTENTS

ANNEXES

- An Operational Near-Real-Time Global Temperature Index (R. Quayle *et al.*)
- SST Anomalies and Climate Requirements (D. Harrison)
- Techniques Used in the Construction of GISST (N. Rayner *et al.*)
- Operational SST Analysis in the Japan Meteorological Agency, and Historical Japanese Marine Meteorological Data, the Kobe Collection (T. Manabe *et al.*)
- The Bureau of Meteorology SST Analysis System (N. Smith *et al.*)
- Real-Time Ocean Data Assimilation at the U.S. Navy Fleet Numerical Meteorology and Oceanography Center (J. Cummings)
- Differences in Sea Surface Temperature Analyses (R. Reynolds)
- Reduced Space Approach to the Optimal Analysis of Historical SST: Accomplishments, Difficulties, and Prospects (A. Kaplan)
- The Accuracy of Sea Surface Temperature Data from Voluntary Observing Ships (P. Taylor *et al.*)
- Strategy for Creating Homogeneous Sea-Ice Concentration Data Sets (D. Parker *et al.*)
- The SAF on Ocean and Sea Ice: Objectives and Development Plan (L.-A. Breivik *et al.*)
- The Role of Skin Sea Surface Temperature (SST) in the Development of SST Products (B. Emery *et al.*)
- Requirements for GCOS Sea Surface Temperature and Sea-Ice Data Sets (D. Parker)

REPORT OF THE OOPC/AOPC WORKSHOP
ON GLOBAL SEA SURFACE TEMPERATURE DATA SETS

I.   Introduction

At the fourth meeting of the Atmospheric Observation Panel for Climate (AOPC) of the Global Climate Observing System (GCOS) in Honolulu during April 1998, the Panel recommended that a workshop on global sea surface temperature (SST) data sets be held. The goals of the workshop would be to assess global SST data sets, and to recommend to the AOPC and its companion Ocean Observations Panel for Climate (OOPC) criteria to be satisfied by GCOS SST analyses.

The workshop was asked to accomplish several actions, and to produce a report with recommendations to its sponsors. In this report, we summarize the characteristics of the observations used to produce analyses (gridded fields) of SST, and assess the differences among various sea-ice analyses and recommend methods for using them to produce high-latitude SST fields. The report further assesses differences among, and strengths and weaknesses of, the various SST analysis products available, including both historical time series and current near-real-time analyses. Finally, the group considered whether it could establish specific criteria to be satisfied by SST analyses that can be certified as adequate for GCOS.

II.   Meeting Summary

The meeting was hosted by the International Research Institute (IRI) for Climate Prediction, and was held at the campus of the Lamont-Doherty Earth Observatory of Columbia University from 2-4 November 1998. Twenty-two scientists from 6 countries attended, and many useful and productive discussions, both within the meeting and outside, resulted. A List of Participants and the Provisional Agenda are attached to this report. All the members of the Organizing Committee felt that the Workshop was extremely useful, and one of our strongest recommendations is that the working level discussions that were initiated and facilitated by this meeting should be encouraged to continue.

Topics addressed by the Workshop included applications, analyses and observations. The meeting began with relevant presentations, continued with working sessions during which substance for this report began to be developed, and concluded with a plenary where draft reports were presented. Three Working Groups were defined: Observations, chaired by P. Taylor, Analyses, led by R. Reynolds, and Sea Ice, led by N. Rayner.

E. Harrison and D. Parker discussed the requirements that led AOPC and OOPC to organize the Workshop, as well as aspects of the state of SST analysis and observation in general. J. Hansen described the needs of global circulation models for SST analyses, and presented the results of some experiments that illustrated the sensitivity of models to differences in SST analyses. M. Crowe described efforts to

produce global surface temperature time series for the investigation of global change, and the dependence of those efforts on SST analyses.

This opening was followed by a sequence of reports on the status and practice of SST analysis at various centers. T. Manabe, E. Ebert, R. Reynolds and J. Cummings presented the operational SST analyses at the Japan Meteorological Agency, the Australian Bureau of Meteorology, the U.S. National Centers for Environmental Prediction (NCEP), and the U.S. Navy Fleet Numerical Meteorology and Oceanography Center, respectively. R. Reynolds also compared results from 6 different SST analyses. N. Rayner and A. Kaplan then described efforts at the U. K. Meteorological Office (UKMO) and the Lamont-Doherty Earth Observatory to develop and implement methods to extend SST analyses throughout the past century, an effort vital to the diagnosis of long-time-scale climate variability.

The Workshop then received a set of presentations on various aspects of the global observing system that is used for SST, including *in situ* (ship and buoy), and satellite observations. P. Taylor discussed errors in, and possible corrections for, SST observations from ships. D. Parker described the experience of the UKMO in correcting errors in, and using, ship observations. R. Evans presented results of highly-accurate radiometric experimental observations of SST. H. Roquet described the planned operational system being developed for SST and other oceanic parameters derived from the Meteosat Second Generation (MSG) geostationary satellites and the Meteosat Operational Program (MOP) polar-orbiting system. W. Emery discussed the problems involved in using radiometric observations of SST from satellites, which reflect the extreme upper surface, or skin, with *in situ* measurements from ships and buoys, which are more representative of the temperature at depths of 1 to several metres.

Since the distribution and density of ice cover has strong implications for the analysis of SST in high latitudes, the Workshop was fortunate to hear several presentations on methods for deriving such information. R. Grumbine described the operational system for deriving sea-ice data for use at NCEP. J. Maslanik followed with a presentation that summarized the various sources of historical and current information on the extent and density of sea ice. D. Parker discussed how sea-ice information from these sources might be made more homogeneous.

III.   Recommendations

A number of important recommendations were put forward by the Working Groups (WGs). They are described in detail in the Working Group reports, and are summarized here. Of these recommendations, an implicit one stands out as particularly relevant to the future of the Global Climate Observing System.

In order to ensure the availability of sea surface temperature and sea-ice analyses that are suitable for the goals of the Global Climate Observing System, a Sea Surface Temperature (SST)/Sea Ice (SI) Project should be initiated. The primary objective of this project will be to ensure that continuing

effective communication among the scientists and institutions working on SST and SI analyses leads to GCOS-quality SST and SI products.

A summary of the other recommendations follows:

Historic data sets

- Recognizing that the identification and digitization of historical SST data sets has the potential to add significantly to the SST database and therefore is crucial for climate research, the WG recommends that the present activities (for example digitization of the Kobe collection) be continued.

- However, the WG noted that it is important that a quality assessment of newly-digitized data sets be made and that the errors be characterized before such data sets are inserted into the SST database.

- As far as is possible, historical data sets must be accompanied by meta-data detailing the methods of observation, instrumentation, etc.

Characteristics of SST measurements

- Given that we do not have a globally robust formula for the surface skin effect and that such a formula is required for compatibility between satellite and *in situ* temperature measurements, the WG recommends the deployment of a limited number (about 20) of ship-borne instruments capable of skin temperature measurement together with near surface (trailed thermistor) and hull-contact SST sensors and good mean meteorological measurements to allow estimation of the surface heat fluxes and wind stress.

- The WG noted that there is a need to better determine the error characteristics of the different methods of *in situ* SST measurements - bucket, Engine Room Intake (ERI), hull-contact sensor, etc., and in particular different types of drifting buoy - as has presently been done for the ship-borne sensors as a class.

Satellite SST data

- The WG noted that the new multi-channel satellite sensors (for example the SEVIRI on MSG, and the VIIRS on NPOESS) offer future potential for improved SST determination; however these changes in observing technique and the continuing problems besetting SST retrieval (for example, due to clouds, aerosol etc.) imply that there will be a continuing need for *in situ* data for calibration adjustment for the foreseeable future. The WG recommended that such need would be met by maintaining an array of surface drifting buoys (but not by profiling floats of the type envisaged, for example, for the ARGO project). Further, the WG recommended that these drifting buoys report on a frequent basis; 8 times daily is desirable to resolve the diurnal cycle.

- Noting that, for example, exploitation of the ATSR sensor had been limited due to the lack of an accessible real-time product, the WG urged that future satellite products be made readily available to all potential users.

In situ SST data

- The WG considered that there is an urgent need for meta-data with regard to the characteristics and calibration details of the many types of drifting buoys. While the WG understood, and welcomed, that a WMO-47 type publication was to be made available for drifting buoys in the near future, the WG recommended that information on the buoy type should be transmitted in the data message along with the buoy identification number.

- The WG urged that the calibration procedures for drifting buoys be adequately documented and archived through WMO; furthermore that an open ocean comparison of the characteristics of the different drifting buoy designs should be performed.

- The WG recommended that potential users be made aware that, while XBTs (expendable bathythermographs) may be used to obtain the sea temperature at a few metres depth in a similar manner to Engine Room Intake SST data, they do not provide a well-calibrated surface SST value.

- The WG recommended that the accuracy of SST data from Voluntary Observing Ships (VOS) be improved by provision of more complete and accurate meta-data for the individual ships. Noting further that the use of acoustic through-hull data transmission offered the potential for low cost installation of single or multiple hull-contact sensors on VOS, the WG recommended the installation and maintenance of well-calibrated hull-contact sensors on VOS as the preferred method of SST measurement.

Availability of Meta-data

- The WG noted that all data from all sensor types were likely to be biased to a varying extent and that this bias should be removed before use in an SST analysis; however this requires that the relevant meta-data be available in real time at the analysis centres and the WG recommended the more general use of the electronic version of the List of Selected Ships.

SST Analysis Comparisons

- Careful examination of the method of converting from ice to SST is needed. A combination of the NCEP and UKMO methods could give better results than either alone.

- SST intercomparisons (1982-present) should be extended into earlier years.

- Further SST analysis comparison criteria such as the location and spatial extent of the 18°C water and the equatorial warm pool were also needed.

- SST analysis error estimates should be computed along with the means.

- There should be an archive of the SST analyses so that users interested in special applications, e.g. fisheries, could have access to the products.

- It is important that this SST analysis intercomparison continue so that differences can be better quantified and methods can be developed to minimize these differences. Furthermore, analyses continue to change, which requires a continued re-evaluation of the differences. Thus, **an international group should be established as part of the AOPC or OOPC to continue the SST intercomparisons and to develop better standards for these comparisons**[1].

Ice-zone Buoys

- For measuring the SST near sea ice the WG suggested consideration, by those more expert in making observations in sea-ice areas, of the deployment from aircraft of low cost disposable SST buoys which exploit the recent development of relatively cheap GPS and satellite communications systems.

Sea-ice Data

- **Hemispheric scale** comparisons between sea-ice data sets utilizing different microwave algorithms and between these data and aircraft or *in situ* observations are needed. These will inform users what they are gaining or losing by using one algorithm rather than another.

- Processing differences between sea-ice microwave products are non-negligible, but their importance on climatic space and time scales needs to be assessed.

- A complete, self-consistent reanalysis of the whole microwave sea-ice period needs to be done and brought up to date.

- As SST data sets are generally created on latitude/longitude grids, sea-ice products should also be provided on regular grids (as well as polar-stereographic), so customers do not introduce errors during re-gridding.

- Detailed research into the differences between sea-ice data from different sources is needed.

- Hemispheric-scale observations of actual melt-pond areas are required, so that the effect of these on microwave-derived sea-ice data can be better understood.

- Historical information on Antarctic sea-ice variability pre-1973 must be identified and processed into a useful form. Current reconstruction techniques may provide a more useful assessment of the position of the ice edge than contemporary hand-drawn climatologies, which may be too poorly understood to use.

---

[1] A Working Group on Sea Surface Temperature was subsequently established (June, 1998) under the chairmanship of R. Reynolds.

IV. Reports of the Working Groups

IV.A   Working Group 1: Observations – Chair: P. Taylor

IV.A.1   Introduction

With regard to the Terms of Reference (ToR) for the meeting, two were considered relevant for discussion in the Observations WG:

ToR 1: Summarize the characteristics of the observations used to produce analyses (gridded fields) of SST.

ToR 5: Establish specific criteria to be satisfied by SST analyses that can be certified as adequate for GCOS.

Since it was assumed that ToR 5 would also be addressed by WG 2, most of the WG 1 discussions focussed on ToR 1. However, some discussion of the required accuracy took place during the meeting.

IV.A.1.1   *Accuracy requirements*

Specifications for the accuracy of the SST were presented during the meeting. Harrison (1998) reviewed the variability of SST and the magnitude of typical anomalies. Having removed the month-to-month seasonal variation of SST, the residual variability of monthly-averaged SST is typically small. The larger variabilities that occur in the North Pacific, El Niño, and Gulf Stream regions, are typically about 0.5 to 0.75°C. The standard deviation of the SST anomaly is rarely greater than 0.75°C, at maximum 1.25°C. The size of significant regional SST anomalies is at maximum 2°C from the average; being occasionally more only due to El Niño. Parker (1998) noted that the global average SST change during the last hundred years or so is about 0.5°C.

Further considerations with regard to SST accuracy are that climate models and coupled air-sea models are very sensitive to the SST which needs to be very accurate (order ±0.1°C) to properly represent the interaction at the sea surface. For example, for air-sea flux calculation, SST accuracy of 0.2 or 0.3°C is needed in tropical regions with somewhat less stringent requirements (~0.7°C) at higher latitudes (Taylor, 1984).

The implication is that the desirable maximum bias, accuracy and precision for SST data is of order 0.1°C. Since 0.1°C is rarely achieved for individual SST observations (see below), observations may need to be suitably averaged to achieve the required accuracy and a policy of over-sampling is desirable. Thus, a tentative criterion for SST analyses to be certified as adequate for GCOS would be that any biases should have been corrected and the data averaged to an extent that an accuracy of 0.1°C is achieved. However, this may not be possible until better understanding of the surface skin effect (see below) is achieved. There is also the important proviso that the time and space resolution of the product must be adequate for the purpose for which it is required!

IV.A.1.2   Definition of Sea Surface Temperature

Accuracy to the order of 0.1°C requires a precise definition of what is meant by the term SST, since different measurement techniques return temperature values having different characteristics.   For example, Figure IV.A.1 shows two idealized sea temperature profiles.   Profile A is typical for nighttime conditions and also for daytime when the wind speed is greater than, say, 5 m/s and surface cooling is taking place.   There is a relatively cool surface skin, with a thickness measured in microns, overlying an isothermal layer which is well mixed over a depth of the order of tens of metres or more.   Note here our definition of surface cooling; it is that the heat transferred from the ocean to atmosphere by the sensible, latent and net longwave fluxes is greater than the small fraction of the short-wave heating which is absorbed in the ocean surface skin.   Profile B is typical of daytime profiles for winds less than, say, 3 m/s and conditions of surface cooling but net ocean heating.   A diurnal warm layer has formed below the surface skin. The extent to which this warm layer is vertically mixed, and the threshold wind speed for transition between profiles A and B, depends on the balance between the wind mixing and the net heating. Detecting the occurrence of profile B is most important in the tropics where the high SST values can lead to significant turbulent fluxes even under light wind conditions. However, profile B can occur in all ocean regions given the right conditions.

Using Figure IV.A.1, we shall define the following temperatures:

T(1) is the surface skin temperature.   This is the temperature that physically controls the surface fluxes. It may be measured radiometrically from ships and other *in situ* platforms, and by satellite-borne radiometers provided the atmospheric effects are properly corrected.   Normally, the surface skin is colder than the water just beneath the skin, however occasions exist (for example with advection of warm, moist air over a colder sea producing low cloud or fog) when the skin may be warmer.

T(2) is the bulk temperature just below the skin. For profile A, T(2) is well defined and is measured by SST buckets and drifting buoys. For profile B, vertical gradients in the near-surface layer may prevent accurate measurement of T(2).

T(3) is the bulk mixed layer temperature. Typically, this would be the temperature measured by VOS using either ERI temperatures or hull-contact sensors.   Depending on buoy design, it may also be that measured by some drifting buoy sensors.
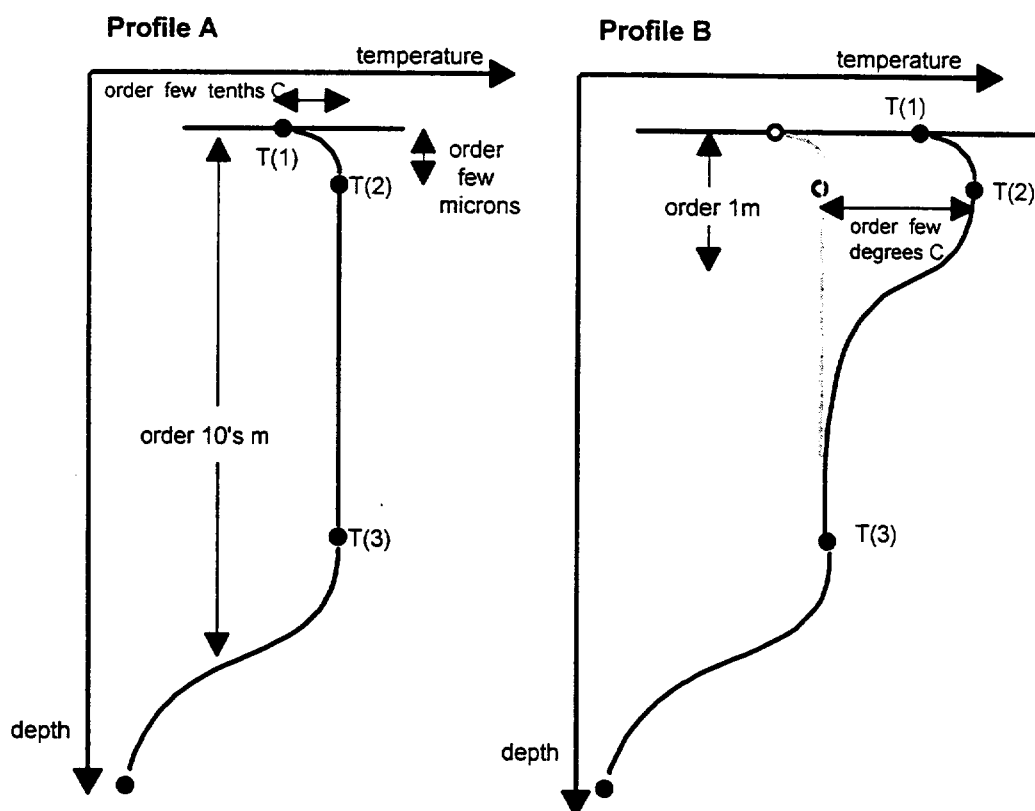
Figure IV.A.1. Schematic profiles for (A) nighttime and daytime moderate to strong winds and (B) daytime light wind conditions. See text for discussion.

The different temperatures are associated with different volumes of water and therefore vary on different typical time scales (Table IV.A.1). We emphasize that T(1), as may be estimated from radiometric data, is the physically correct SST for flux estimation. However, T(1) is associated with the thin ocean surface skin and thus varies on the rapid time and space scales associated with variations in the wind stress and the heat fluxes. Thus, even if all atmospheric effects were removed, different satellite passes over a given area may be expected to give T(1) values which vary by a few tenths C, apparently introducing noise into the data set. Noting that T(2) varies on longer time scales, an alternative approach might be to parameterize the difference (T(2)-T(1)) as part of the bulk flux estimation. This is possible, in theory at least, because the difference depends on the instantaneous flux values at the time of the observation. The TOGA COARE algorithms (Fairall *et al.* (1996), and Liu *et al.* (1979)) are examples of bulk formulations which include a skin effect parameterization. Problems with this approach are that we do not have a globally robust model for the skin effect, that the needed variables for flux estimation are not necessarily measured at the same time as the SST, and also that (in the case of profile B) significant variations in T(2) take place over periods of hours. Note also that if T(2) is used for flux calculations, there are certain (rare) conditions where the transfer coefficients for sensible and latent heat assume negative values.

Quantity	Layer thickness	Time variation
T(3)	Order 10's m	Days
T(2)	0 to a few m	Hours
T(1)	Microns	Minutes

Quantity	Value	
	Profile A	Profile B
T(2)-T(3)	≈ 0	up to a few °C
T(2) - T(1)	0.3° ± 0.2°C	0.3° ± 0.2°C

Table IV.A.1. Typical values, associated layer thickness, and time variation scales for the different SST values defined in Figure IV.A.1: (upper) layer values; (lower) temperature differences. Note that significant departures may occur away from these "typical" values. For example, values for T(2) - T(1) of 1°C to-0.5°C have been reported.

Because the bulk temperature (T(3)) varies relatively slowly, estimates of T(3) may be composited over several days. Most traditional SST products are, in effect, fields of T(3) estimates. In some cases this is explicit, for example if only nighttime SST data are used. Much of the time T(2) ≈ T(3) and all bulk SST estimates give the same temperature. However, where profile B exists, use of T(3) to define the SST can lead to errors of a few degrees C. Also, in this case, there are practical difficulties in obtaining an accurate measurement of T(2). It is desirable to relate T(2) to T(3), but this depends on the integrated fluxes over a time period of several hours prior to the observation and an ocean mixed-layer model must be used. The TOGA COARE algorithm (Fairall *et al.*, 1996) is an example of a flux algorithm which includes a simple mixed-layer model.

IV.A.2   Characteristics of different methods of SST estimation

IV.A.2.1   *Satellite data*

Advantages: Infrared radiometers carried by satellites provide the potential for SST measurement over the global ocean on a regular repeat basis.

They provide estimates of the skin temperature (T(1) in Figure IV.A.1) which is the quantity on which the surface fluxes depend.

Disadvantages: In many applications the bulk temperature (T(3)) is traditionally used rather than the skin temperature. At any time, significant areas of the ocean are cloud covered and data from different over-passes must be composited. Atmospheric water vapour, aerosols, and clouds have all the potential to significantly bias the data. Reliable cloud clearance remains a problem, as does the effect of sub-pixel cloudiness. The measurements rely upon a small number of sensors with the possibility of changes in sensor characteristics between satellites.

The standard operational instruments since 1978 have been different variants of the AVHRR carried on the NOAA series of polar-orbiting satellites. The onboard calibration of the AVHRR and correction for atmospheric transmission effects does not reliably produce the required SST accuracy. Thus, calibration adjustments and data verification require comparisons between the AVHRR data and *in situ* data; SST data from drifting buoys are used for this. The result is that, in the absence of errors due to atmospheric transmission effects, the AVHRR would measure a skin temperature offset by the mean observed skin temperature averaged over the buoy data set used to adjust the calibration. Since this buoy data set may be formed from a varying mix of buoy types (e.g. glass spheres, or PVC spar buoys), the actual depth represented in the buoy data is not clear. However, the temperature is likely to be nearer to T(3) than T(2) in Figure IV.A.1.

The ATSR instrument, flown on the ERS satellites, was designed to view each ocean cell through two different atmospheric paths to allow explicit correction of the transmission effects. This is potentially a major advance. However, the meeting considered that the ATSR had not yet fully fulfilled its promise due to the failure of one channel on the ERS-1 instrument and problems with the cloud clearance algorithm. Because the ATSR was not part of the core payload for the satellites, the data were not widely available in operational mode and this had limited their exploitation. The AATSR to be flown on ENVISAT is part of the operational suite, so the data access problem should be resolved.

The GOES 8, 9 and 10 satellites all have split window channels similar to the AVHRR. They have only a 4-km spatial resolution and the adopted sampling scheme produces full disk images only every 3 hours. There are some problems with the calibration systems on board and the calibrations are believed to have sometimes changed between scan lines. In the next generation of GOES satellites they plan to drop the split window and only have an 11-micron channel for SST. The idea is that other channels on GOES can be used for the atmospheric corrections. However, there is concern that this will significantly degrade the SST retrievals.

The Meteosat Second Generation satellite (launch late 2000) will carry a SEVIRI sensor (Roquet, 1998). This has 12 channels at Visible, IR and Water Vapour wavelengths. It will provide 3km resolution at nadir with a 1km high-

resolution visible channel. The great advantage of this instrument is that, being mounted on a geostationary satellite, it will provide data at 15-minute intervals allowing much more effective compositing of cloud-cleared data.

IV.A.2.2 Ship data

Ship SST data are obtained mostly from Engine Room Intake (ERI) thermometers or (perhaps 1/3 of the modern data) from SST buckets. A small but increasing number of ships use hull-contact sensors which, if carefully calibrated, appear to give the most consistent SST data (Kent et al., 1993; Emery et al., 1997). Although the VOS are asked to report temperatures in tenths °C, many reports are given to half or whole degrees. This may reflect the confidence the ship's officers have in the accuracy of the reading, particularly for ERI data. Taylor (1998) presented results that suggested that, compared to hull-contact sensors, ERI SST data were warmer under most conditions, on average by 0.35C although there was significant scatter about this typical value. Individual ships using ERI readings had mean biases between -0.5°C (too cold) and +2.3°C (too warm). Bucket measurements were found to be biased compared to hull values only during sunny daytime conditions when they gave on average SST values about 0.3C warmer. Although this might have been due to near-surface ocean heating, Taylor suggested that it was more likely due to the buckets heating on deck. However, Taylor demonstrated that there were possible inconsistencies between the comparisons for different ship data, and ship data and buoys. Furthermore, Parker (1998) presented data that showed different characteristic biases between the observing methods. A plot of the zonal averages of "bucket" minus "non-bucket" SST values for the period 1975 to 1981 indicated the non-bucket values to be 0.1 to 0.2C warmer except in the high latitude northern hemisphere (Folland et al., 1993). More detailed study of the regional comparisons on which the zonal averages were based suggested that the buckets were biased cold in some high ocean to atmosphere heat flux areas.

A historic reconstruction of the global SST time series (Parker, 1998; Folland and Parker, 1995) assumes that SST data were, on average, biased cold in 1860 by about 0.1C with this bias increasing to 0.4C in 1940 due to the increased use of canvas buckets. It was then assumed that wartime conditions resulted in a wholesale switch to ERI SST data; those buckets used after that time were assumed to be of insulated construction. Thus, no correction is applied for the period 1942 to the present. Comparisons of the trend in the corrected SST with nighttime marine air temperatures and temperatures over land suggest that these adjustments were successful. However, the evidence presented at the meeting indicates that residual biases exist between different present-day methods of SST measurement. Since, in future, the mix of measurement methods will change (for example with increased use of hull-contact sensors), it is urgent that these residual SST biases be better quantified so that future climate trends can be accurately detected.

IV.A.2.3   *Buoy data*

Drifting buoys are important for providing data away from shipping lanes and also for providing the data used for satellite calibration adjustment. However, concern was expressed at the meeting that we do not have sufficient knowledge of the characteristics of the various different types of drifting buoys with respect to SST measurement. The type of each drifting buoy must be known and the calibration details fully documented. Ideally, the buoy type should be included in the data message along with the identification number.

The most useful moored buoys are those in the open ocean, such as JMA buoys and the TAO array. For example, the sensors of JMA buoys (for example at 38°N/134.5°E, 29N°/135°E, 28°N/126°E) are well calibrated and monitored, and the observations from the fixed positions are operationally distributed 8 times per day. Unfortunately, many moored buoys are deployed near coasts where high SST gradients are likely. They are of limited value for satellite data verification and are not routinely used for satellite calibration adjustments. Research buoys designed to allow flux determination are important for verification of SST analyses and climatological SST data sets (Taylor, 1998). Carefully-calibrated sensors may be deployed at various depths in radiation shields (e.g. Weller *et al.*, 1998). Since these buoys are limited in number and deployment duration. their great value is as a "withheld" data source which has not been used in, or had a significant impact on, the various SST analyses.

IV.A.2.4   *Combining satellite and in situ data*

Ideally the data would be corrected for the surface skin effect before these comparisons. However, for this, and in general for combining satellite and *in situ* SST data, a more precise formula for the relationship between the skin and bulk SST is required. Because the noise in the atmospheric transmission corrections for satellite SST data is greater than the skin-bulk difference, developing such a formula will require a large database of *in situ* data. *In situ* measurement of the skin temperature, $T(1)$, is not trivial. It can be done accurately (to 0.01C) by instruments such as the MAERI (Evans, personal communication, 1998) which are complex and expensive (a few $100K). With care, it can be done to better than 0.1C by instruments costing around $15K (Emery, 1998). Further comparison of these instruments is desirable. It is suggested that the simpler instrument could be deployed on, say, 20 ships together with near-surface ($T(2)$ at around 2 to 3 cm) SST data from trailing thermistors and bulk temperatures, $T(3)$, from hull-contact sensors. Good mean meteorological data for determining the turbulent and radiative heat fluxes and the wind stress would also be required.

IV.A.2.5　Summary of data characteristics

Table IV.A.2 summarizes the characteristics of different SST data sources to the extent that the WG participants knew them.

Method	Depth range m	Precision K (1)	Est. RMS Accuracy K (1)	Bias Extremes K (1)	Sampling characteristics (1)	Period available	Refs/ Notes
AVHRR	~ 10^{-6}	0.1	±0.5 to 1.0	-2 to -3	~<50% global daily	1979 on	(2)
ATSR	~ 10^{-6}	0.05	±0.25	-3 to +0.3	<< AVHRR	1996 on	(2)(3)
SEVIRI	~ 10^{-6}	0.25	±0.5	-2	Cloud-free areas global every 15 minutes	2000 on	
VIIRS	~ 10^{-6}	0.05	0.1		Same as AVHRR		
ERI	3 to >20	≥ 0.2	±1.5	-0.5 to +3.0	Ship routes	Mainly 1940 on	(4)(5)
Bucket	0 to 1	≥ 0.1	±1.0	-0.2 to +1.0	Ship routes (especially N. Atlantic)	1860 on	(4)(5) (6)
Hull contact	3 to >10	≥ 0.1	±0.2	< ±0.5	Limited no. ship routes	?1970 on	(4)
Trailed thermistor	0.01 to 0.1	0.1	±0.1	< ±0.5	Some research ships	Sporadic	
Thermosalinograph	3 to 10	0.001	±0.01	<< ±0.1	Research ships	Sporadic	
XBT	3 to 10	0.1	±0.2	0.2 to few C	Chosen ship routes + navy		(5)
In situ radiometer	1 micron	0.1 or better	Depends on calibration		Research vessels only at present: future merchant ships		
Drifting buoy	1-3m	?	?	?			
Moored buoy	Various	Depends on buoy			Specific buoy arrays, mainly coastal or tropical		
Flux buoy	< 1	0.001	±0.005	<< ±0.1	Deployed in research programmes	Sporadic	(7)

Notes:

(1) Estimated typical values for present-day data
(2) Barton (1995)
(3) Harris *et al.* (1995)
(4) Kent *et al.* (1993)
(5) Folland *et al.* (1993)
(6) Folland & Parker (1995)
(7) Hosom *et al.* (1995)

IV.A.3.　Recommendations of the Observations Working Group

Note: These recommendations are presented in the order in which they were discussed; they are not in any order of priority. The recommendations are addressed to the AOPC and OOPC for consideration and implementation.

IV.A.3.1　Historic data sets

The WG understood that the issue of historic data sets was discussed in more detail at the International Workshop on Digitization and Preparation of Historical Surface Marine Data and Meta Data, 15 - 17 September, 1997, Toledo, Spain; however, the report of that Workshop was not available to the WG. Accordingly the following resolutions were adopted:

- Recognizing that the identification and digitization of historical SST data sets has the potential to add significantly to the SST database and therefore is crucial for climate research, the WG recommends that the present activities (for example digitization of the Kobe collection (Manabe, 1998)) be continued.

- However, the WG noted that it is important that a quality assessment of newly-digitized data sets be made and that the errors be characterized before such data sets are inserted into the SST database.

- As far as is possible, historical data sets must be accompanied by meta-data detailing the methods of observation, instrumentation, etc.

IV.A.3.2   Characteristics of SST measurements

Noting the different characteristics of different methods of SST observation (section IV.A.2.1 to IV.A.2.3 above), the WG made the following recommendations:

- Given that we do not have a globally robust formula for the surface skin effect and that such a formula is required for compatibility between satellite and in situ temperature measurements, the WG recommends the deployment of a limited number (about 20) of ship-borne instruments capable of skin temperature measurement together with near-surface (trailed thermistor) and hull-contact SST sensors and good mean meteorological measurements to allow estimation of the surface heat fluxes and wind stress.

- The WG noted that there is a need to better determine the error characteristics of the different methods of in situ SST measurements - bucket, ERI, hull-contact sensor, etc., and in particular different types of drifting buoy - as has presently been done for the ship-borne sensors as a class (e.g. Kent et al., 1998 - see Taylor, 1998).

IV.A.3.3   Satellite SST data

- The WG noted that the new multi-channel satellite sensors (for example the SEVIRI on MSG, and the VIIRS on NPOESS) offer future potential for improved SST determination; however, these changes in observing technique and the continuing problems besetting SST retrieval (for example, due to clouds, aerosol etc.) imply that there will be a continuing need for in situ data for calibration adjustment for the foreseeable future. The WG recommended that such need would be met by maintaining an array of surface drifting buoys (but not by profiling floats of the type envisaged, for example, for the ARGO project). Further, the WG recommended that these drifting buoys report on a frequent basis; 8 times daily is desirable to resolve the diurnal cycle.

- Noting that, for example, exploitation of the ATSR sensor had been limited due to the lack of an accessible real time product, the WG urged that future satellite products be made readily available to all potential users.

IV.A.3.4   *In situ SST data*

- The WG considered that there is an urgent need for meta-data with regard to the characteristics and calibration details of the many types of drifting buoys. While the WG understood, and welcomed, that a WMO-47 type publication[2] was to be made available for drifting buoys in the near future, the WG recommended that information on the buoy type should be transmitted in the data message along with the buoy identification number.

- The WG urged that the calibration procedures for drifting buoys be adequately documented and archived through WMO; furthermore that an open ocean comparison of the characteristics of the different drifting buoy designs should be performed.

- The WG recommended that potential users be made aware that, while XBTs (expendable bathythermographs) may be used to obtain the sea temperature at a few metres depth in a similar manner to ERI SST data, they do not provide a well-calibrated surface SST value.

- The WG recommended that the accuracy of SST data from VOS be improved by provision of more complete and accurate meta-data for the individual ships. Noting further that the use of acoustic through-hull data transmission offered the potential for low cost installation of single or multiple hull-contact sensors on VOS, the WG recommended the installation and maintenance of well-calibrated hull-contact sensors on VOS as the preferred method of SST measurement.

IV.A.3.5   *Other recommendations*

- The WG noted that all data from all sensor types were likely to be biased to a varying extent and that this bias should be removed before use in an SST analysis; however, this requires that the relevant meta-data be available in real time at the analysis centres and the WG recommended the more general use of the electronic version of the List of Selected Ships (WMO Report No. 47).

---

[2] WMO Report No. 47 is the List of Selected Ships, which is updated on a regular basis. Following the Workshop, Peter Dexter (World Weather Watch, WMO) confirmed that a proposal was agreed at the last CMM session (Havana, March 1997) for the Marine Climatology sub-group to develop a meta-data catalogue for all types of Ocean Data Acquisition Systems (ODAS), both drifting and non-drifting (see paragraph 7.3.9 of the final report of CMM-XII). The person in charge of the project is Joe Elms of NCDC/NOAA who hopes to present a proposed format to the next Sub-group on Marine Climatology meeting.

- For measuring the SST near sea ice, the WG suggested consideration, by those more expert in making observations in sea-ice areas, of the deployment from aircraft of low cost disposable SST buoys which exploit the recent development of relatively cheap GPS and satellite communications systems.

IV.B   Working Group 2: SST Analyses – Chair: R. Reynolds

IV.B.1   Findings

An initial comparison of six SST analyses was summarized by Reynolds (1998). These analyses either used *in situ* data alone or used both *in situ* and satellite data. The results showed that satellite data improved coverage over *in situ* data alone but needed to be used with a real-time bias correction. The results also suggested that although real-time bias corrections were successful, a small persistent negative residual satellite bias of approximately 0.1°C often remained. However, there were also large-scale differences among the *in situ* analyses of this magnitude that could persist for several months. Because the *in situ* database is similar and shared, the differences are most likely due to data processing methods. Monthly RMS differences among analyses were in the range 0.2°C to 0.5°C between roughly 40°S and 60°N except in coastal areas. They were larger outside this latitude belt. In particular, *in-situ*-only analyses had differences greater than 1°C south of 40°S.

The Working Group felt that this study was a good initial step. However, they felt that additional work was needed to clarify and extend the results. The most important effort was to find the best method of using sea-ice information to determine SSTs in and near the marginal ice zone.

There are several different methods of using sea ice to specify SSTs. In the NCEP analysis (Reynolds and Smith, 1994), an SST value of -1.8°C is added at locations where the sea-ice concentration is equal to or above 0.5. Here, sea-ice concentrations are defined as the area covered by ice with values that range from 0 to 1 where 1 is completely ice covered and 0 is ice free. The Naval Research Laboratory (NRL, J. Cummings, personal communication) and the Australian Bureau of Meteorology Research Centre (BMRC, N. Smith, personal communication) methods are similar to the NCEP method. The U.K. Meteorological Office (UKMO) method described in Rayner *et al.* (1996) is more complicated and perhaps the most realistic. In this method, a relation between SST and sea-ice concentration, I, is defined by

$$SST = a\,I^2 + b\,I + c \quad (1)$$

In (1) a, b, and c are constants determined by climatological collocated match-ups between SST and I with the constraint that SST = -1.8°C or 0°C when I = 1 over the ocean or fresh water lakes, respectively.

One of the most important problems with these methods is the uncertainty of the sea-ice concentrations. To illustrate this, climatological sea-ice concentrations are shown for July in Figure IV.B.1 for two analyses. The first, combined from Nomura (1995) and Grumbine (1996), the Nomura/Grumbine analysis, is an objective analysis of microwave satellite observations (SMMR and SSM/I); the second, the National Ice Center analysis (Knight, 1984), is a subjective analysis of *in situ* and satellite microwave and infrared observations (see also Rayner, 1999). The concentrations of the Nomura/Grumbine analysis are much lower than the National Ice Center analysis. This typically occurs during summer when melt water is present at the surface of the sea ice. In this case, the microwave satellite algorithms produce a negatively-biased sea-ice concentration.

To compare the SST inferred from the ice, the coefficients a, b, and c, were computed using monthly Northern Hemisphere collocated *in situ* SST data and Nomura/Grumbine sea-ice concentrations on a one-degree grid from 1982-1997 where a, b and c vary by calendar month. The SSTs were then computed from (1) for both climatological ice concentrations shown in Figure IV.B.1 and then compared with the SSTs obtained from a climatological analysis of profiles of temperature vs. depth produced by the U.S. Navy (Teague, 1990). The differences (see Figure IV.B.2) show that the SSTs generated from both sea-ice climatologies (especially the Nomura/Grumbine) are too warm. If the comparison is repeated, using the simpler NCEP method where SSTs of $-1.8°C$ are generated for values of I greater than or equal to 0.5, the differences are much smaller (see Figure IV.B.3). In general, the SST differences are smaller in winter months. However, the NCEP method gives a better fit to the Navy SST climatology.

IV.B.2   Recommendations

- Careful examination of the method of converting from ice to SST is needed. In the fit using the UKMO method, most of the collocated SST and ice observations occur at low ice concentrations (I<0.5), which are located near the outer edge of ice. Comparison of Figures IV.B.2 and IV.B.3 suggests that this method may not be applicable to the interior of the high-latitude Arctic. The results also suggest that a combination of the NCEP and UKMO methods could give better results than either alone.

- The period of the intercomparisons (1982-present) should be extended into earlier years.

- Further comparison criteria such as the location and spatial extent of the $18°C$ water and the equatorial warm pool were also needed.

- Error estimates should be computed along with the means.

- There should be an archive of the analyses so that users interested in special applications, e.g. fisheries, could have access to the products.

- It is important that this intercomparison continue so that differences can be better quantified and methods can be developed to minimize these differences. Furthermore, analyses continue to change, which require a continued re-evaluation of the differences. Thus, an international group should be established as part of the AOPC or OOPC to continue the SST intercomparisons and to develop better standards for these comparisons.

# July Ice (1979–92)

Nomura/Grumbine
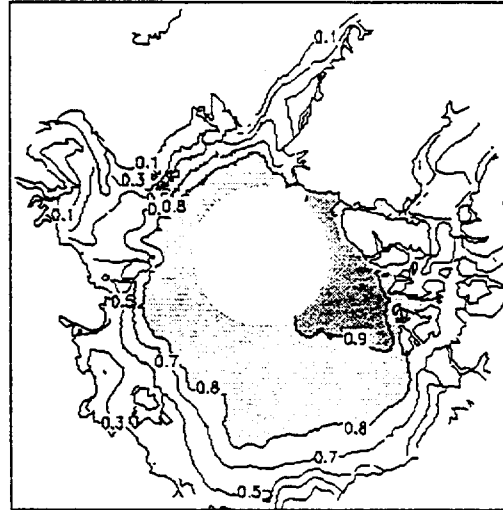
National Ice Center

Figure IV.B.1. Sea-ice concentrations, for the Arctic for July for the period 1979 to 1992. The upper panel shows the analysis from Nomura and Grumbine; the missing data near the pole occurs because of lack of satellite observations. The lower panel shows the analysis from the National Ice Center. The range is 0 (0%) to 1 (100%). The contour intervals are 0.1, 0.3, 0.5, 0.7, 0.8 and 0.9 with heavy contours above 0.7 and shading above 0.8.

July SST Diff. (UKMO fit)
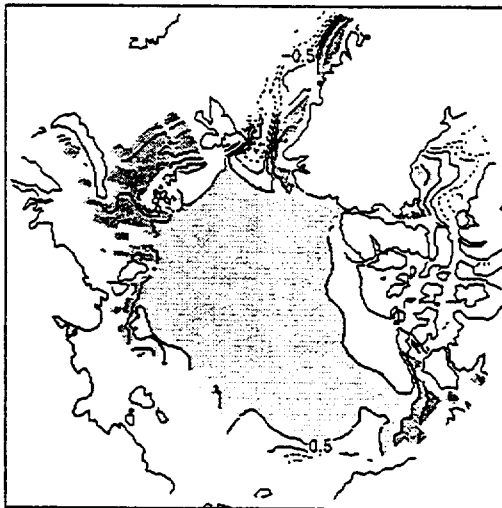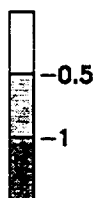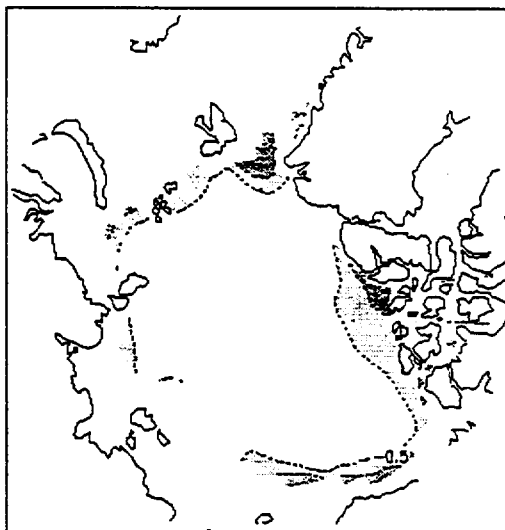
Nomura/Grumbine — Navy
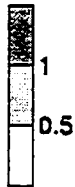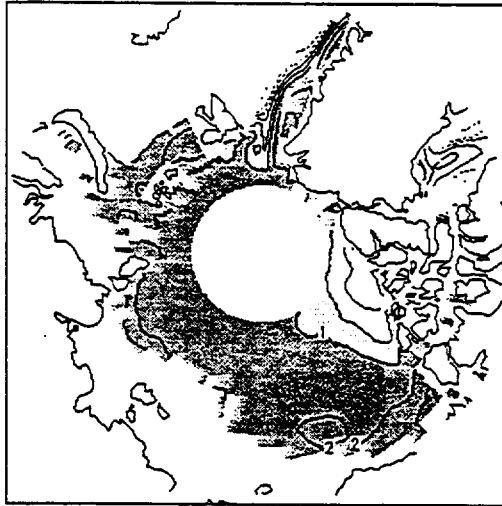
National Ice Center — Navy

Figure IV.B.2. SSTs (°C) computed from sea-ice concentration climatologies (from Figure IV.B.1) using the UKMO fit (see text) minus the US Navy's Arctic SST climatology. The upper panel SSTs are derived from Nomura and Grumbine, the lower panel from the National Ice Center. The contour interval with heavy lines is 1°C; extra contours with light lines are at –0.5°C and 0.5°C. Differences **above** 0.5°C are shaded.

July SST Diff. (NCEP 0.5)
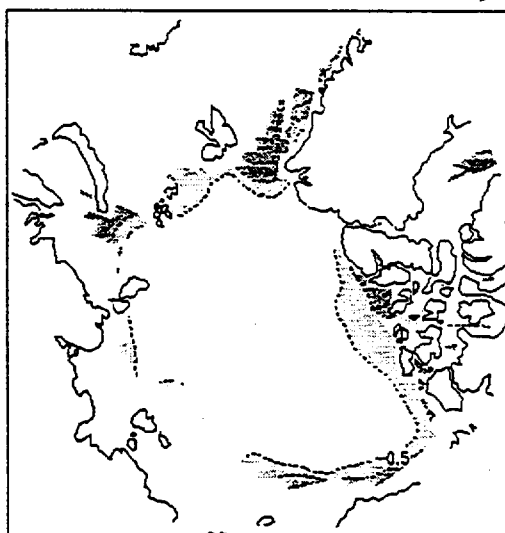
Nomura/Grumbine — Navy

−0.5

−1

National Ice Center — Navy

Figure IV.B.3. SSTs (°C) computed from sea-ice concentration climatologies (from Figure 1) using the NCEP method (see text) minus the US Navy's Arctic SST climatology. The upper panel SSTs are derived from Nomura and Grumbine, the lower panel from the National Ice Center. The contour interval with heavy lines is 1°C; extra contours with light lines are at − 0.5°C and 0.5°C. Differences **below** 0.5°C are shaded.

IV.C   Working Group 3: Sea Ice – Chair: N. Rayner

IV.C.1   Introduction

          One of the Terms of Reference (ToR) for the meeting was discussed by
the sea-ice Working Group (WG):

          ToR 2: Assess the differences among various sea-ice analyses and recommend
          methods for using them to produce high-latitude SST fields.

          The first part of this formed the bulk of the discussions of the WG: the latter part
is also addressed partly by WG 2.

          Sea-ice information is an important part of any globally complete SST data set,
whether it be operational daily fields or historical monthly fields for the past 130 years.
Gridded sea-ice concentration information can be used to help define the variations of
temperature of areas of open water near and within the margins of the ice edge. We focus
in this report on the use of sea-ice information in the context of SST analyses and mainly on
considerations for long historical SST data sets, such as Global sea-Ice and Sea Surface
Temperature (GISST) (see Rayner and Parker (1998)).

          Sea ice has historically been observed using a variety of methods and in
different levels of detail. When a long continuous record of sea-ice concentration is
required, data have to be obtained from a variety of sources. It is important then that these
constituent data have consistent representations of observed sea-ice concentration if
unrealistic trends and discontinuities are to be avoided in the longer record. All data sets
are likely to contain reasonably consistent representations of sea-ice extent (i.e. the total
size of the region covered by sea ice). However, the important parameter from the
perspective of high-latitude SST variability is the variation in sea-ice concentration in each
grid box and hence total sea-ice area (defined here to be concentration multiplied by the
area of the grid box).

          The different historical observed sea-ice data sets currently available have been
developed to serve various objectives. These different objectives have led to those data
sets being quite heterogeneous in character. In addition, data sets comprising digitized
chart information differ substantially from those based on satellite "observations". If they are
combined to create an historical record of sea-ice area change without complete
understanding of those differences, unrealistic trends and discontinuities in sea-ice area will
result.

          Section IV.C.2 outlines the main differences seen by the WG between existing
large-scale sea-ice data sets, and the problems that these heterogeneities can cause when
using them to create a long record of high-latitude SST. Section IV.C.3 proposes work that
the WG believes will help to reconcile these differences.

IV.C.2   Findings

IV.C.2.1   *Characteristics of currently available sea-ice data sets*

Several hemispheric or global scale sea-ice data sets are available which could be used (and have been used) to produce high-latitude SST fields. Other data are available which indicate the extent of sea ice at certain locations or in relatively small regions, but here we concentrate on the large-scale records known to the members of the WG. The characteristics, period and original purposes of the data are summarized in the following sub-sections (see also Maslanik (1998)).

IV.C.2.1.1   *Walsh Arctic data set*

This is a set of end-of-month sea-ice concentration fields for the Northern Hemisphere for 1901-1995, covering the Arctic Ocean and peripheral seas. It has itself been assembled from a variety of regional and hemispheric sources (Walsh (1978). The data are available from the National Snow and Ice Data Center (NSIDC) http://www-nsidc.colorado.edu). These data were collated to provide a relatively uniform set of sea-ice extent for all longitudes as a basis for hemispheric-scale studies of observed sea-ice fluctuations (Walsh (1978)).

Prior to the availability of satellite-retrieved concentrations (in particular microwave observations from Scanning Multi-frequency Microwave Radiometer (SMMR) and Special Sensor Microwave/Imager (SSM/I) instruments flown on Nimbus 7 and DMSP satellites), information was obtained from hand-drawn charts. Ice concentration is gridded in tenths (i.e. 10/10 is complete ice cover). Original data sources were: Danish Meteorological Institute; Japan Meteorological Agency; U.S. Naval Oceanographic Office; Kelly (1979) ice extent grids; Walsh and Johnson (1978) / U.S. Navy/NOAA National Ice Center (NIC); NIC Climatology; temporal extension of Kelly (1979) grids and NASA-derived ice concentrations from SMMR and SSM/I. In the period when directly-observed sea-ice concentrations were not available, a marginal sea-ice zone (i.e. an area of partial sea-ice cover near the ice edge) was added to the fields. Seasonally-averaged ice concentration drop-off rates were calculated from satellite observations and applied to the ice edge. As there were no data at all for September-March 1901-1956, fields were created by extending information for April-August forward and backward in time using known autocorrelations. This blend of data sets has the advantage of data for all years since 1901; other data sets are incorporated when appropriate. However, the fields contain little information within the ice pack prior to the inclusion of satellite retrievals; it is set to complete cover. The data are not entirely hemispheric: the Great Lakes and the Caspian Sea are not included prior to the microwave retrievals. Indeed, as this is an amalgamation of heterogeneous data types (see Section IV.C.2.2), there is a discontinuity in the total sea-ice area in the Walsh data set when the microwave data begin (J.E. Walsh, pers. comm., see documentation at http://www-nsidc.colorado.edu).

IV.C.2.1.2 *NIC and AARI digitized charts*

This is a set of quasi-weekly sea-ice concentration and extent for both the Northern (90-45N) and Southern (90-50S) Hemispheres for 1973-1994, digitized by the National Climatic Data Center (NCDC) from NIC charts (Knight (1984), available from http://www-nsidc.colorado.edu). The hand-drawn charts were based upon U.S. Navy, Canadian and Danish aerial reconnaissance and from retrievals from Advanced Very High Resolution Radiometer (AVHRR), SSM/I and other satellite instruments, and were built up over a period of days.

A digital version of the Russian Arctic and Antarctic Research Institute's (AARI) detailed sea-ice charts for 1953-1990 for much of the Northern Hemisphere, developed from aircraft and satellite observations is also available (data available from http://www-nsidc.colorado.edu). Like the NIC data, these charts were developed mainly for shipping purposes. They are being blended with those of the NIC as part of the Joint U.S./Russian Environmental Working Group (EWG) project (M. Serreze, pers. comm.). Detailed information is available from the NIC data for the marginal ice zone (MIZ) in areas of NIC operational interest. The data do not suffer from problems due to summer melt conditions (see discussion of microwave data below). However, the areas given best attention are selective and any differences in analysis arising from, for example, a change of analyst are non-reproducible (Maslanik (1998)). Information for operationally-irrelevant regions is of low resolution and different quality. The Northern Hemisphere data are not truly hemispheric: inland seas are not included.

IV.C.2.1.3 *Satellite-based microwave data*

Sea-ice "observations" made by microwave instruments carried on satellites have been available for every other day from the SMMR and daily from the SMM/I. Several data sets are available, based on different algorithms to interpret microwave-derived brightness temperatures. Each algorithm (e.g. NASA Team, Bootstrap) produces a data set with slightly different characteristics. Comparisons of different algorithms is beyond the scope of this report, but the availability of a number of such data sets raises an important question (see Section IV.C.3).

Examples of a couple of data sets derived using the NASA Team algorithm are:

1. The NASA Goddard Space Flight Center (GSFC) sea-ice concentration data set (Cavalieri *et al.* (1997), available from http://www-nsidc.colorado.edu) is derived from both SMMR and SSM/I retrievals. It is a homogenized record of sea-ice concentration spanning two instruments and several platforms for October 1978-December 1996.

2. The NOAA operational sea-ice data set (Grumbine (1996) and Grumbine (1998)), available from http://polar.wwb.noaa.gov).

These data are capable of being truly global and contain information on inland lakes and seas. They provide details of real sea-ice concentration variation within the ice pack. Data are affected by weather, but this can be filtered out. Land contamination can lead to spurious sea-ice appearing around the coasts, but careful use of land/sea masks helps to remove this. However, thin ice is not identified as such by the SMM/I: instead it is returned as a mixture of thick ice and open water. Ponds resulting from summer melting on top of the ice cause the microwave instrument to return a 10-30% lower than actual concentration of sea ice.

IV.C.2.1.4 Antarctic climatologies

Two complete southern hemispheric pre-1973 climatologies are known to the members of the WG, both obtained from atlases. A German climatology for 1929-1939 can be found in Deutsches Hydrographisches Institut (1950). Tolstikov (1966) depicts the ice edge seen during Russian expeditions between 1947 and 1962.

Ice edge positions shown in these atlases are derived from a number of visits over a period of years. There is little indication in the maps of concentration variations, so these must be reconstructed before the data can be used to create SST fields (an initial attempt has been made in the construction of the GISST data set (Rayner et al. (1996)). These climatologies, being based on observations taken on board ship, also do not show any summer melting from the coast outwards.

IV.C.2.2 Difficulties encountered when using sea-ice concentration to specify SST

It is clear that sea-ice data gathered from a variety of sources have different characteristics. Even concentration data for the same month, but from different sources can give very different pictures of the variation within the pack. The histograms in Figure IV.C.1 illustrate this. Here, the chart derived NIC data set (Knight (1984)) and the satellite-derived GSFC data set (Cavalieri et al. (1997), data provided by NSIDC, University of Colorado, Boulder, CO.) are compared. A period of overlap is considered: 1979-1994. Histograms of concentration in classes of tenths have been made for each data set in the Northern and Southern Hemispheres in January and July.

Northern Hemisphere winter distributions appear to be consistently represented in both data sets (see (a) and (b)), but it is clear that a very different picture of the Northern Hemisphere summer ice pack results. The increase in concentrations below 0.9 and resultant decrease of those above 0.9 in (c) and (d) is in part a result of the influences on the microwave instrument of melt ponds and flooding and slush at the snow/ice interface (J. Maslanik, pers. comm.).

The Southern Hemisphere summer (see (e) and (f)) does not suffer the same problem: a consistent pattern of concentration variation emerges from both data sets. However, a similar-looking discrepancy does occur in the winter (see (g) and (h)). This is likely to be partly a result of lack of detail in the NIC charts, as there can be less interest in sea-ice variations around Antarctica in the winter. It could also be partly underestimation in the GSFC data in areas of thin ice or in the MIZ (R. Massom, pers. comm.).

The conflicting information that we see in these data sets can present us with difficulties when trying to use the sea-ice data to specify high-latitude SST. If we use data which are under-representing the amount of sea ice present, the resultant SST is likely to be too warm, and if we use overestimates of ice concentration it is likely to be too cold. Moreover, if we assemble a long data set from several of these different data types, we are likely to introduce spurious variation into the sea-ice record and thus into the SST. So, some adjustment of these data sets is necessary first to create a more homogeneous sea-ice record.

Which data should be adjusted and by how much is not always obvious. As we have seen by looking at just two such data sets, they may each have particular times of the year for which they could be considered reliable and some times for which they might be less so. When we are faced with the prospect of having to make such adjustments to data for which there is no alternative information source, the task is even more difficult.

Indeed, if the data set is to be used to force a GCM, these decisions could be model dependent: how the model treats sea ice might influence how it should be specified.

IV.C.3   Recommendations

As has already been discussed, sea-ice observations from different sources have very different characteristics. In this section, we describe how data sets might be homogenized in order to derive self-consistent high-latitude SST fields and recommend to the AOPC/OOPC work which would aid the important process of piecing together long-term variations from different and sometimes sparse data sources.

IV.C.3.1   *Homogenization of data sets*

Parker (1998) describes the basic structure of the strategy adopted to create a sea-ice data set for use in the ECMWF 40-year Reanalysis project (ERA40) and in the next version of the GISST data set. The main obstacles to such an exercise are: lack of information on ice pack variability in pre-satellite data; effects on microwave-retrieved satellite data of summer melt conditions in the Arctic, and the lack of hemispheric-scale data in the Southern Hemisphere pre-1970s. A quick fix for the first two of these problems was attempted in the ERA40 data set. In summary, fields for 1957 onwards were collected from some of the sources described in Section IV.C.2. Structure was added within the ice pack to fields based on hand-drawn chart information using a microwave-derived climatology. Fields from SMMR and SSM/I data were used for recent years, but contemporaneous chart data enabled calculation of corrections for the bias in these data in summer due to surface melting.

This procedure was adopted owing to time constraints; a more complete homogenization would take longer than the few months that were available and would require some of the investigations proposed in the following section.

IV.C.3.2   *Future work*

The primary goal for these proposals is to create a homogenized sea-ice concentration record that can be used in climate change studies, in particular in historical SST data sets. Therefore, we have proposed projects that will enable us to better understand the differences between available data sets, which is necessary before we can adequately combine them.

Some of these proposals are simply to remove obstacles to understanding arising from processing of the data, leaving only those due to actual data characteristics to be solved.

* **Hemispheric scale** comparisons between data sets utilizing different microwave algorithms and between these data and aircraft or observations are needed. These will inform users what they are gaining or losing by using one algorithm rather than another.

* Processing differences between microwave products are non-negligible, but are they important on the time and space scales that we are interested in here? This needs to be assessed.

* A complete, self-consistent reanalysis of the whole microwave period needs to be done and brought up to date.

* As SST data sets are generally created on latitude/longitude grids, sea-ice products should also be provided on regular grids (as well as polar-stereographic), so customers do not introduce errors during re-gridding.

* Detailed research into the differences between data from different sources is needed.

* Hemispheric-scale observations of actual melt-pond areas are required, so that the effect of these on microwave-derived data can be better understood.

* Historical information on Antarctic sea-ice variability pre-1973 must be identified and processed into a useful form. Current reconstruction techniques may provide a more useful assessment of the position of the ice edge than contemporary hand-drawn climatologies, which may be too poorly understood to use.
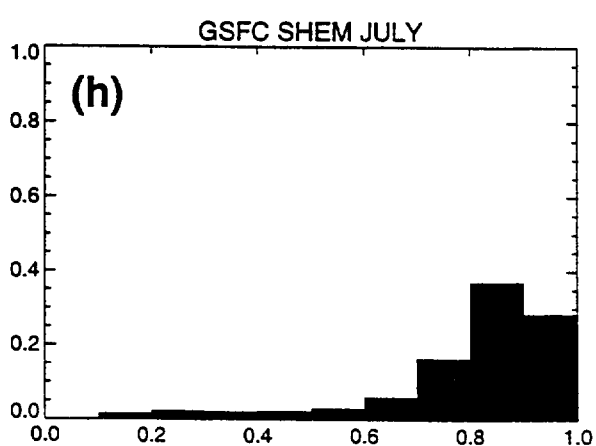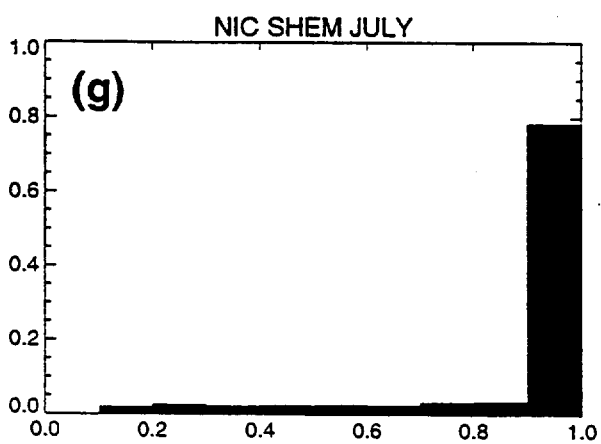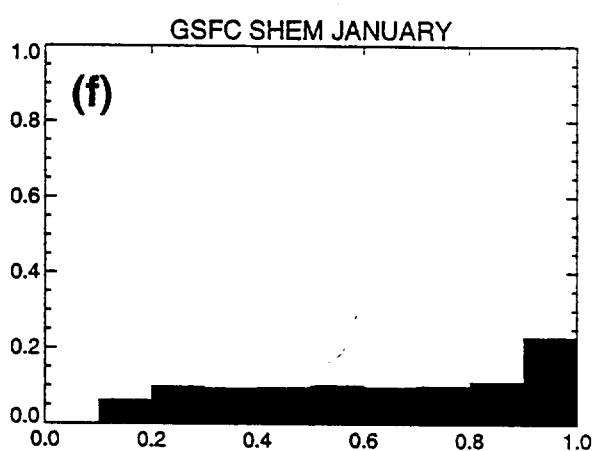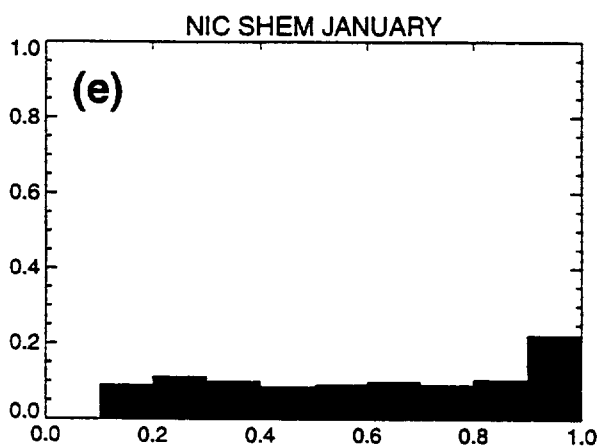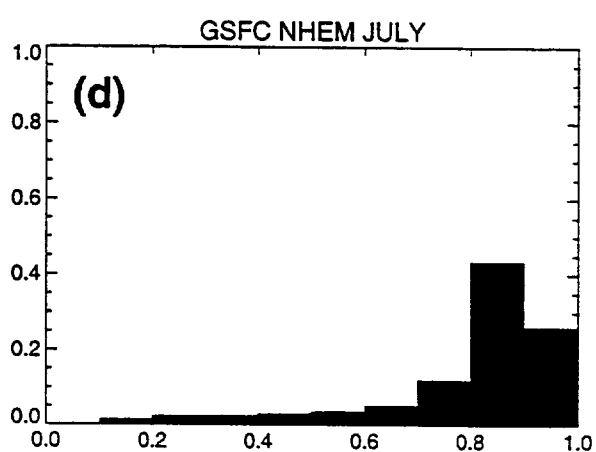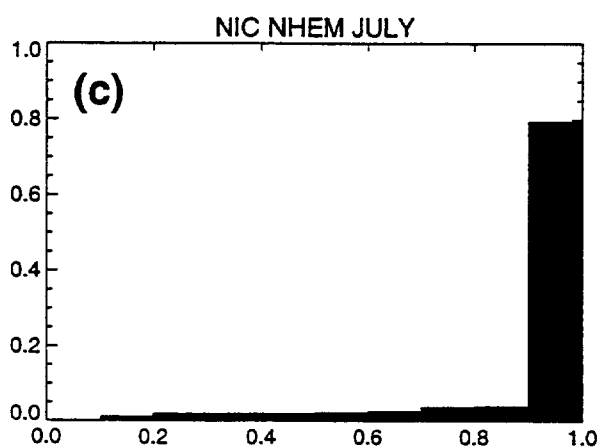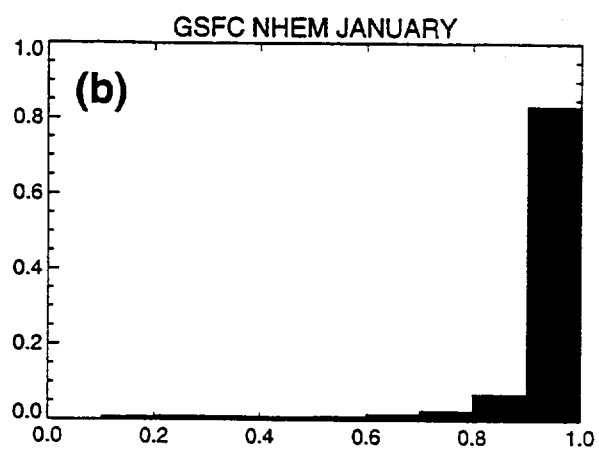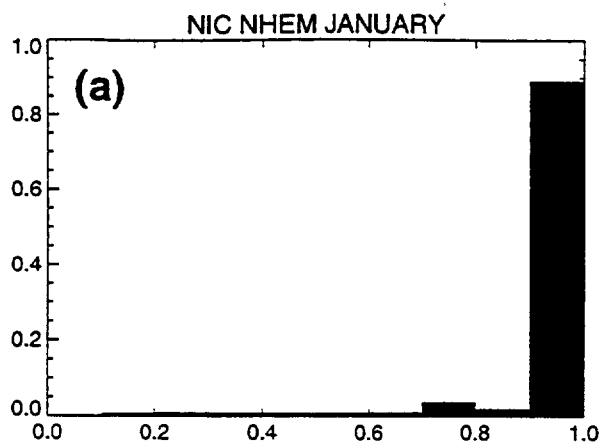
Figure IV.C.1. Histograms of sea-ice concentration in two data sets for 1979-94: NIC digitized charts and GSFC SMMR/SSM/I blend.

28

IV.C.4   Abbreviations and Acronyms

AARI   Arctic and Antarctic Research Institute
AATSR   Advanced Along Track Scanning Radiometer
AOPC   Atmospheric Observation Panel for Climate
ARGO   A proposal for a drifting buoy array (not an acronym)
ATSR   Along-Track Scanning Radiometer
AVHRR   Advanced Very High Resolution Radiometer
BMRC   Australian Bureau of Meteorology Research Centre
CMM   Commission for Marine Meteorology (of WMO)
COARE   Coupled Ocean-Atmosphere Response Experiment
DMSP   Defense Meteorological Satellite Program
ECMWF   European Centre for Medium-Range Weather Forecasts
ENVISAT   ESA Environmental Satellite
ERA40   ECMWF 40-year Reanalysis Project
ERI   Engine Room Intake
ERS   European Remote Sensing satellite
EWG   Environmental Working Group
GCM   General Circulation Model
GCOS   Global Climate Observing System
GISST   Global sea-Ice and Sea Surface Temperature
GOES   Geostationary Operational Environmental Satellite
GPS   Global Positioning System
GSFC   Goddard Space Flight Center
IR   Infra-Red
IRI   International Research Institute (IRI) for Climate Prediction
JMA   Japan Meteorological Agency
MIZ   Marginal Ice Zone
MOP   Meteosat Operational Program
MSG   Meteosat Second Generation
NASA   National Aeronautics and Space Administration
NCDC(US)   National Climatic Data Centre
NCEP   U.S. National Centers for Environmental Prediction
NIC   Navy/NOAA National Ice Center
NOAA(US)   National Oceanic and Atmospheric Administration
NPOESS   (US) National Polar-orbiting Operational Environmental Satellite System
NRL   Naval Research Laboratory
NSIDC   National Snow and Ice Data Center
OOPC   Ocean Observations Panel for Climate
RMS   Root Mean Square
SEVIRI   Spinning Enhanced Visible & InfraRed Imager
SI   Sea Ice
SMMR   Scanning Multi-frequency Microwave Radiometer
SSM/I   Special Sensor Microwave/Imager
SST   Sea Surface Temperature
TAO   Tropical Atmosphere Ocean (buoy array)
TOGA   Tropical Ocean Global Atmosphere programme

ToR	Terms of Reference
UKMO	U. K. Meteorological Office
VIIRS	Visible/Infrared Imager/Radiometer Suite
VOS	Voluntary Observing Ships
WG	Working Group
WMO	World Meteorological Organization
XBT	Expendable BathyThermograph

IV.C.5   References

Barton, I. J., 1995: Satellite-derived sea surface temperatures: current status. *J. Geophys. Res.*, **100**(C5), 8777 - 8790.

Cavalieri, D.J., C.L. Parkinson, P. Gloerson, and H.J. Zwally, 1997: Arctic and Antarctic sea-ice concentrations from multichannel passive-microwave satellite data sets: October 1978 to September 1995, User's Guide. NASA Technical Memorandum 104627.

Deutsches Hydrographisches Institut, 1950: Atlas of ice conditions in the North Atlantic Ocean and general charts of the ice conditions of the North and South Polar regions. Deut. Hydro. Inst. Pub. No. 2335, Hamburg.

Emery, W.J., 1998: Paper presented during the meeting, see Annex III.

Emery, W.J., K. Cherkauer, B. Shannon and R. W. Reynolds, 1997: Hull-mounted sea surface temperatures from ships of opportunity. *J. Atmos. & Oceanic Tech.*, **14**(5), 1237-1251.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson and G. S. Young, 1996: Bulk parameterisation of air-sea fluxes for TOGA COARE. *J. Geophys. Res.*, **101**, 1295 - 1308.

Folland, C. K. and D. E. Parker, 1995: Correction of instrumental biases in historical sea-surface temperature data. *Q. J. Roy. Met. Soc.*, **121**(522), 319 - 367.

Folland, C. K., R. W. Reynolds, M. Gordon and D. E. Parker, 1993: A study of six operational sea surface temperature analyses. *J. Climate.*, **6**(1), 96 - 113.

Grumbine, R.W., 1996: Automated Passive Microwave Sea-ice Concentration Analysis at NCEP. U.S. Department of Commerce, NOAA, NWS, NCEP Technical Note.

Grumbine, R.W., 1998: NCEP operational sea-ice data sets. Paper presented during the meeting, see Annex III.

Harris, A. R., M. A. Saunders, J. S. Foot, K. F. Smith and C. T. Mutlow, 1995: Improved sea surface temperature measurements from space. *Geophys. Res. Letters*, **22**(16), 2159-2162.

Harrison, E., 1998: Paper presented during the meeting, see Annex III.

Hosom, D. S., R. A. Weller, R. E. Payne and K. E. Prada, 1995: The IMET (Improved Meteorology) ship and buoy systems. *J. Atmos. & Oceanic Tech.*, **12**(3), 527 - 540.

Kelly, P.M., 1979: An arctic sea-ice data set, 1901-1956. Glaciological Data, Report GD-5: Workshop on Snow Cover and Sea-Ice Data, pp101-106. World Data Center-A for Glaciology (Snow and Ice).

Kent, E. C., P. K. Taylor, B. S. Truscott and J. A. Hopkins, 1993: The accuracy of Voluntary Observing Ship's meteorological observations. *J. Atmos. & Oceanic Tech.*, **10**(4), 591 - 608.

Kent, E. C., P. Challenor and P. Taylor, 1998: A Statistical Determination of the random errors present in VOS Meteorological reports. *Journal of Atmospheric and Oceanic Technology (submitted)*.

Knight, R.W., 1984: Introduction to a new sea-ice database. *Annals of Glaciology*, **5**, pp81-84.

Liu, W. T., K. B. Katsaros and J. A. Businger, 1979: Bulk parameterisation of air-sea exchanges of heat and water vapour including the molecular constraints at the interface. *Journal of the Atmospheric Sciences*, **36**, 1722-1735.

Manabe, T., 1998: Paper presented during the meeting, see Annex III.

Maslanik, J., 1998: Characteristics of sea-ice data sets. Paper presented during the meeting, see Annex III.

Nomura, A. 1995: Global sea-ice concentration data set for use with the ECMWF re-analysis system. ECMWF Re-Analysis Project, Report Number 2, (ECMWF, Reading, Berkshire, UK).

Parker, D.E., 1998: Strategy for creating homogeneous sea-ice concentration data sets. Paper presented during the meeting, see Annex III.

Rayner, N.A., E.B. Horton, D.E. Parker, C.K. Folland and R.B. Hackett, 1996: Version 2.2 of the Global sea-Ice and Sea Surface Temperature Data Set, 1903-1994. Climate Research Technical Note No. 74, unpublished document available from the Meteorological Office, London Road, Bracknell, U.K.

Rayner, N. A., 1998: Report of working group 3: Sea ice, see Annex III.

Rayner, N.A. and D.E. Parker, 1998: Techniques used in the construction of GISST. Paper presented during the meeting, see Annex III.

Reynolds, R. W., 1998: Differences in Sea Surface Temperature Analyses. Paper presented during the meeting, see Annex III.

Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J. Climate*, **7**, 929-948.

Roquet, H., 1998: Paper presented during the meeting, see Annex III.

Taylor, P. K., 1984: The determination of surface fluxes of heat and water by satellite microwave radiometry and *in situ* measurements. *NATO ASI, Series C: Mathematical and Physical Sciences: Large-scale oceanographic experiments and satellites*, C. Gautier and M. Fieux, Ed., *Vol.128*, D.Reidel, 223 - 246.

Taylor, P.K., 1998: Paper presented during the meeting, see Annex III.

Teague, W. J., M. J. Carron and P. J. Hogan, 1990: A comparison between the Generalized Digital Environmental Model and Levitus climatologies. *J. Geophys. Res.*, **95**, 7167-7184.

Tolstikov, E.I. (Ed.), 1966: Atlas of the Antarctic, vol. 1., 126. Glav. Uprav. Geod. Kart. MGSSSR, Moscow.

Walsh, J.E., 1978: Data set on Northern Hemisphere sea-ice extent. Glaciological Data, Report GD-2, part 1, 49-51. World Data Center-A for Glaciology (Snow and Ice).

Walsh, J.E. and C.M. Johnson, 1978: Analysis of Arctic sea-ice fluctuations 1953-1977. *Journal of Physical Oceanography*, **9**, 580-591.

Weller, R. A., M. F. Baumgartner, S. A. Josey, A. S. Fischer and J. Kindle, 1998: A one-year record of atmospheric forcing from the Arabian Sea. *Deep Sea Research, (submitted)*.

ANNEX I

PROVISIONAL AGENDA, WORKSHOP GOALS AND TERMS OF REFERENCE

Provisional Agenda

The Workshop will have approximately 17 presentations, falling roughly into the following areas: Observations (*In situ*, Satellite and Ice), Analyses (Operational and Extended) Applications, and Requirements. We propose the following order of presentation:

Monday, November 2, 1998

9:00 -10:30	Welcome, logistics, Workshop goals, and requirements (Moura/Arkin, Harrison, Parker)
11:00 -12:00	Applications (Hansen - modelling, Crowe - global temperatures)
12:00 -5:30	SST analyses (Manabe, Ebert, Reynolds, Cummings, Parker, Rayner, Kaplan)

Tuesday, November 3, 1998

9:00 -12:30   Observations:
In situ (Taylor, Parker)
Satellite (Emery, Evans, Roquet)
Sea Ice (Parker/Rayner, Maslanik, Grumbine)

Each presentation will be 20 minutes, with significant discussion time for each segment. While it may seem odd to hear about the observations after the applications and analyses, we thought that this order would help to provide the context for the observations. We would like to encourage all the participants to keep the Workshop goals and terms of reference in mind when preparing their presentations.

After lunch on Tuesday, we will break into working groups, each of which would work up a topic for discussion. We tentatively plan on three groups with focal topics of sea ice, SST analyses, and observations. Each group will describe its findings (facts upon which they agree) and make recommendations that speak to the Workshop goals. The most recent statement of the Workshop Goals and Terms of Reference are attached.

We will reconvene Wednesday morning for interim reports, with a closing plenary after lunch (or before, if everyone works quickly). Participants are invited to provide extended abstracts (up to 4 pages including figures) for the report.

Workshop Goals

To assess global sea surface temperature (SST) data sets and to recommend to the Oceanic and Atmospheric Observation Panels for Climate criteria to be satisfied by Global Climate Observing System (GCOS) SST analyses.

Terms of Reference

1.   Summarize the characteristics of the observations used to produce analyses (gridded fields) of SST.

2.   Assess the differences among various sea-ice analyses and recommend methods for using them to produce high-latitude SST fields.

3.   Assess differences among, and strengths and weaknesses of, the various SST analysis products extant.

4.   Include both historical time series and current near-real-time analyses.

5.   Establish specific criteria to be satisfied by SST analyses that can be certified as adequate for GCOS.

ANNEX II

LIST OF PARTICIPANTS

Name	Affiliation	Country
Organizing Committee		
Phillip Arkin	IRI	USA
Ed Harrison	NOAA/PMEL	USA
David Parker	UK Met.Office	UK
Richard Reynolds	NOAA/NCEP	USA
Attendees		
Teruko Manabe	JMA	Japan
Herve Roquet	Meteo France	France
Peter Taylor	IOS	UK
Beth Ebert	BMRC	Australia
Jim Cummings	FNOC	USA
Bob Evans	RSMAS	USA
Nick Rayner	UK Met.Office	UK
Alexey Kaplan	LDEO	USA
Bill Emery	U. Colorado	USA
Jim Maslanik	U. Colorado	USA
Bob Grumbine	NOAA/NCEP	USA
Mike Crowe	NOAA/NCDC	USA
Jim Hansen	NASA/GISS	USA
Nick Tausnev	NASA/GISS	USA
Larissa Lazarenko	NASA/GISS	USA
Dave Adamec	NASA/GSFC	USA
Max Suarez	NASA/GSFC	USA
Michele Rienecker	NASA/GSFC	USA

ANNEX III

EXTENDED ABSTRACTS

An operational near-real-time global temperature index

Robert G. Quayle, Thomas C. Peterson, Alan N. Basist, and Catherine S. Godfrey

National Climatic Data Center (NCDC) NOAA/NESDIS, Asheville N.C.

Abstract. To capture the global land surface temperature signal in a timely way, a blend of traditional long-term in situ climatic data sets, combined with real time Global Telecommunications System monthly CLIMAT summaries is employed. For the global sea surface, long-term ship data climatologies are combined with a blend of ship, buoy, and satellite data to provide the greatest possible coverage over the oceans. The result is a global century-scale surface temperature index that closely parallels other widely published global surface temperature measurements and can be updated monthly a week or two after the end of a month.

Introduction

It seems paradoxical that we need near-real-time data for a system that responds as slowly as climate, but recent paleoclimatic evidence and the recent warmth of the globe suggest that this paradigm is not always justified. Moreover, as nations struggle to develop effective environmental policies, the observed data become a critical part of these ongoing discussions and the meteorological infrastructure of the globe is also geared to real-time operation. Therefore, both the need for, and the capability for, delivering near-real-time climatic analyses are quite real. In fact, timely climatic information (provided when there is a maximum of interest) may be the best way to provide reliable information to the greatest number of people.

Surface Land Temperatures

Surface land air temperature (LAT) climatology (at instrument shelter height) is derived from the Global Historical Climatology Network version 2 data set (GHCN, Peterson and Vose 1997). GHCN v.2 includes previously unavailable Colonial Era data that fill in data sparse times and places (Peterson and Griffiths 1997). All data are processed via the Climate Analysis System developed at NCDC. The update system subjects the most recent data to a rigorous quality control (Peterson et al. 1998a). Its unique duplicate preservation scheme preserves the integrity of the input data streams (Peterson and Vose 1997). The First-Difference area averaging technique thrives on these duplicates and maximizes the global data available for analysis (Peterson et al. 1998b). Homogeneity adjustment procedures developed over several years assures objective, reproducibly homogeneous time series (Peterson and Easterling 1994, Easterling and Peterson 1995, Peterson et al. 1998c). Data volume varies from several hundred stations per year to several thousand (Peterson and Vose, 1997). For 1997, over 14,000 individual station monthly records are used in the analysis to produce 5x5 degree grid box data that are summarized into hemispheric and global averages.

Sea Surface Temperatures

The Global Ocean Surface Temperature Atlas (GOSTA, Bottomley et al. 1990), provides over a century of global-scale 5x5 degree grid box in situ Sea Surface Temperature (SST) means by year through 1996. This application uses the U. K. Meteorological Office SST version called UKMO HSST, in the form of anomalies with respect to a 1961-90 averaging period (Folland et al. 1993). For near-real-time updates, the most timely and geographically complete data available are the National Centers for Environmental

Prediction - Optimum Interpolation (NCEP OI) blended satellite, ship, and buoy SST data set (Reynolds and Smith 1994), also in monthly 5x5 degree grid box format, available for all years since 1982. NCDC produces global averages and the accompanying anomaly series from both data sets. To produce a long time series (beginning in 1880) with maximum contemporary coverage, these two SST data sets are combined. To fuse the two time series, a simple linear regression is performed for global monthly (and annual) mean anomalies for the years 1982-1997, using NCEP OI SST with respect to 1982-1997 as the dependent variable and UKMO HSST with respect to 1961-90 as the independent variable. A plot of the annual means is shown in Figure 1.

Global Annual Mean Sea Surface Anomalies (C), 1982-1997
x= UKMO HSST with respect to the 1961-90 mean
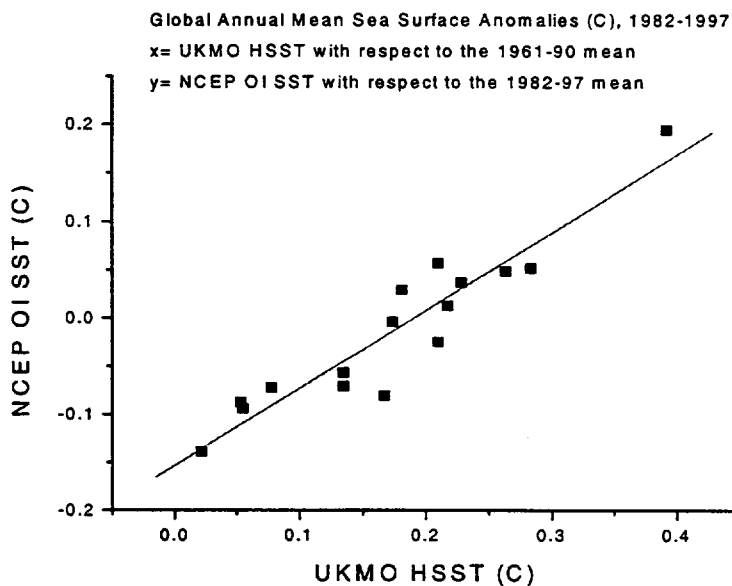y= NCEP OI SST with respect to the 1982-97 mean

Fig. 1. A simple least-squares linear regression of global mean annual SST anomalies, 1982-1997: x = UKMO HSST wrt 1961-90 and y = NCEP OI SST wrt 1982-97. The correlation coefficient is 0.93.

The fit is very good, with r = 0.93, considering the areas covered are somewhat different, with ship data available primarily along shipping lanes, and blended NCEP OI data being virtually global because of the satellite data. The relationship between global mean annual modeled NCEP OI SST anomalies (SST_{OI}) and UKMO HSST anomalies (SST_{UK}) is described via the regression equation:

(1) $SST_{OI} = 0.80 \ SST_{UK} - 0.15$, where anomalies are in deg. C.

The offset, -.15, adjusts the averaging period for the modeled NCEP OI SST anomaly to 1961-90, while the .8 factor reflects the reduced trend of NCEP OI SST compared to the UKMO data. A similar relationship exists for each month. Using the monthly equations, UKMO HSST data are converted to modeled NCEP OI SST anomalies (from 1961-90 means) for each month from 1880 thru 1981. The NCEP OI SST data are appended to this record, and are updated shortly after the end of each data month. For plotting purposes, the data are then adjusted to anomalies from a 1880-1997 averaging period. Figure 2 is a plot of these data from 1950 to 1997 (upper) and 1880 to 1997 (lower). On a globally averaged basis, the NCEP OI data are somewhat cooler than the UKMO HSST data because of differences between the NCEP and UKMO sea ice - SST conversions, and under-correction of satellite SST in areas of sparse ship and buoy data, primarily the southern hemisphere mid-latitudes. The former problem is being

addressed by international standardization, while NCEP is researching ways to correct the latter (Reynolds, personal communication, 1998). The results of these studies will be used to guide possible future enhancements to this index.
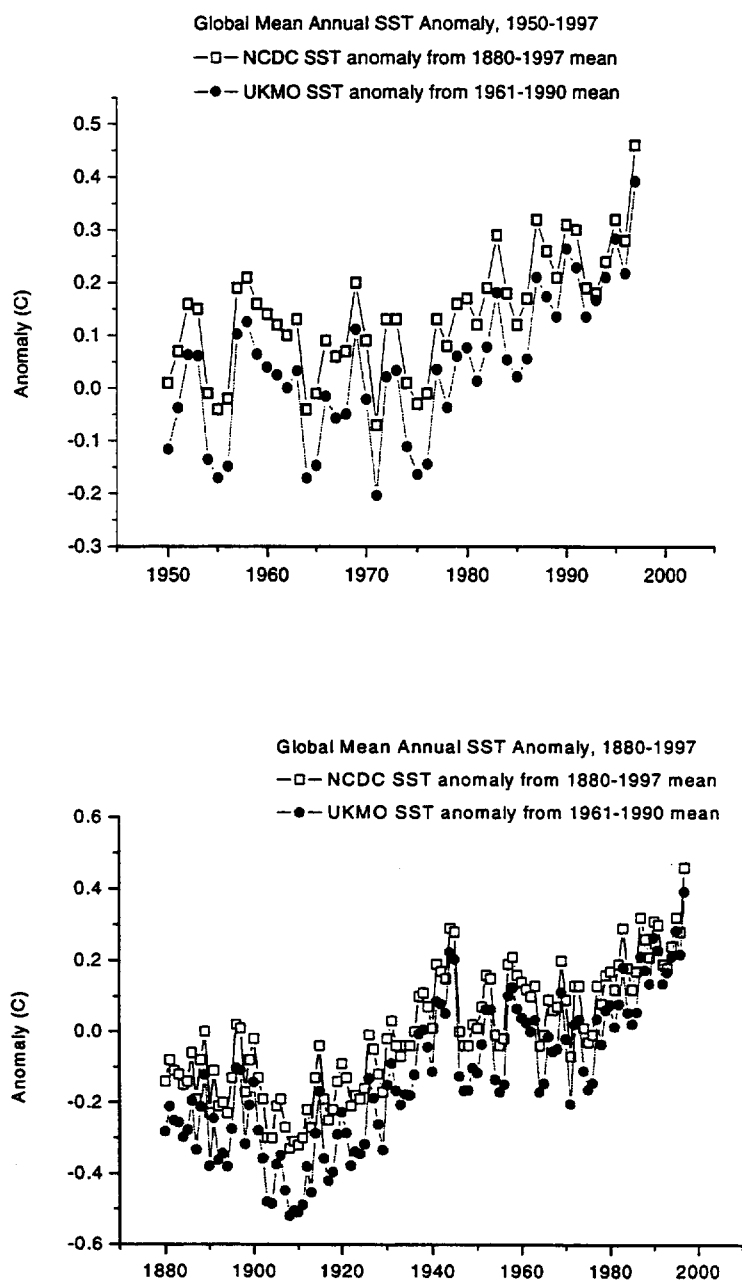
Fig 2. The NCDC (Modeled NCEP OI, wrt 1880-1997) and UKMO (wrt 1961-90) global sea surface temperature anomaly series, 1950-1997 (upper, for detail), and 1880-1997 (lower, for long term perspective).

The Global Index

NCDC now has readily updatable global Surface Land Air Temperature (LAT) and global SST anomalies through the latest month of complete SST and CLIMAT data (World Meteorological Organization encoded data transmitted over the Global Telecommunications System, 2 to 10 days after the end of a data month). Note that the LAT data set is essentially independent from the SSTs, and LATs are summarized independently from SSTs. To combine these data into a simple index, the LAT is weighted with a coefficient of 0.3 (since about 30% of the surface of the Earth is land) and the SST with 0.7 (as the globe is about 70% ocean). The result is shown in Figure 3.

Combined Surface Land and Sea Temperature Index

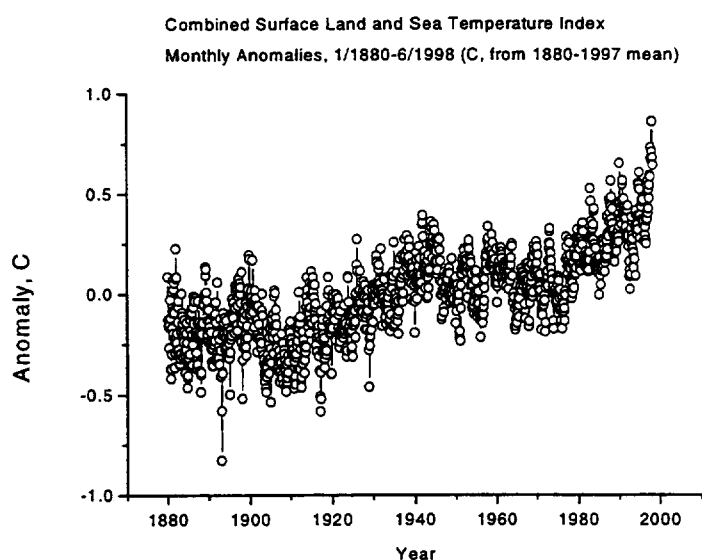Monthly Anomalies, 1/1880-6/1998 (C, from 1880-1997 mean)

Fig. 3. The January 1880 to June 1997 NCDC combined land plus ocean surface monthly temperature anomaly index series wrt 1880-1997.

It is called an index (as it is a combination of air and sea temperatures, and ignores ice-covered sea). When the new index is compared to similar data developed at the NASA Goddard Institute for Space Studies (www.giss.nasa.gov, documented in Hansen and Lebedeff 1987; Reynolds and Smith 1994; Smith et al. 1996), the match is very good (r=0.95) for the period for which Hansen has a land-ocean product (1950 to the present, also using NCEP OI SST). The match (r= 0.87) with the current global benchmark surface data set (Jones 1994 with updates, Figure 4) for the period 1880-1996 is also relatively good, particularly for a near-real time index.

Global Temperature Estimates

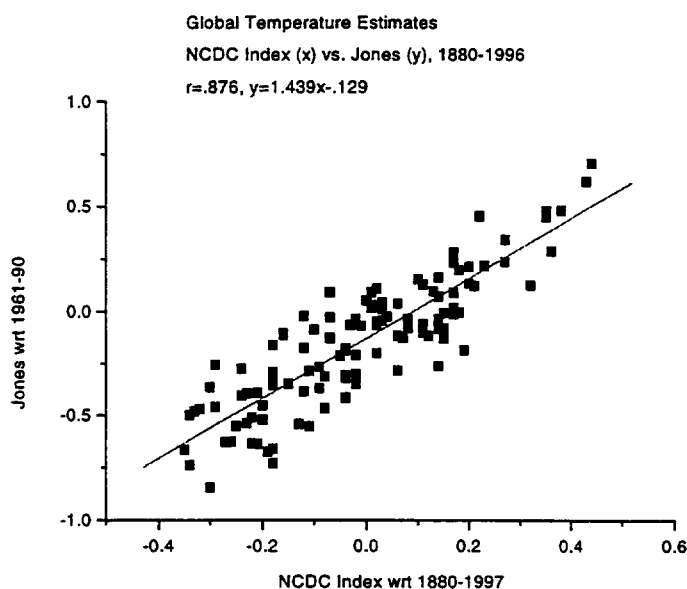NCDC Index (x) vs. Jones (y), 1880-1996

r=.876, y=1.439x-.129

Fig. 4. A simple least-squares linear regression of global mean annual surface temperature anomalies (deg. C), 1880 to 1996: x = NCDC index wrt 1880-1997; y = Jones wrt 1961-90. The correlation coefficient is 0.87.

In summary, we believe we have combined the three best data sets in the world for their respective specialties: UKMO HSST for long-term SST; NCEP OI SST for recent decades; and the GHCN for global land surface temperatures. While not sophisticated, the technique is robust and the results, predictably, compare favorably with other widely used analyses.

References

Bottomley, M., C. K. Folland, J. Hsiung, R. E. Newell, D. E. Parker, *Global Ocean Surface Temperature Atlas "GOSTA"*, Bracknell [England] U.K.: Meteorological Office; [Cambridge]: Massachusetts Institute of Technology, 1990. (337pp) Also see:
http://www.meto.govt.uk/sec5/CR_div/climate_index/hadley_mohsst.html

Easterling, D. R. and T. C. Peterson, A new method for detecting and adjusting for undocumented discontinuities in climatological time series. *Int. J. Climatol. 15* (4), 369-377, 1995.

Folland, C. K., R. W. Reynolds, M. Gordon, and D. E. Parker, A study of six operational sea surface temperature analyses. *J. Climate 6* (1), 96-113, 1993.

Hansen, J., and S. Lebedeff, Global trends of measured surface air temperature. *J. Geophys. Res. 92* (D11), 13,345-13,372, 1987. Updated at ww.giss.nasa.gov.

Hansen, J., R. Ruedy, M. Sato, and R. Reynolds, Global surface air temperature in 1995: Return to pre-Pinatubo level. *Geophys. Res. Lett 23* (13), 1665-1668, 1996.

Jones, P. D., Hemispheric surface air temperature variations: A reanalysis and update to 1993. *J. Climate 7* (11), 1794-1802, 1994.

Peterson, T. C. and D. R. Easterling, Creation of homogeneous composite climatological reference series. *Int. J. Climatol. 14* (6), 671-679, 1994.

Peterson, T. C. and R. S. Vose, An overview of the Global Historical Climatology Network temperature data base. *Bull. Amer. Meteor. Soc. 78* (12), 2837-2849, 1997.

Peterson, T. C. and J. F. Griffiths, Historical African data. *Bull. Amer. Meteor. Soc. 78* (12), 2869-2871, 1997.

Peterson, T. C., R. S. Vose, R. Schmoyer, and V. Razuva.v, Quality control of monthly temperature data: The GHCN experience. *Int. J. Climatol.*, (in press), 1998a.

Peterson, T. C., T. R. Karl, P. F. Jamason, R. Knight, and D. R. Easterling, The First Difference Method: Maximizing Station Density for the Calculation of Long-term Global Temperature Change. *J. Geophys. Res. (Atm.)*, (in press), 1998b.

Peterson, T. C., D. R. Easterling, T. R. Karl, P. Ya. Groisman, N. Nicholls, N. Plummer, S. Torok, I. Auer, R. Boehm, D. Gullett, L. Vincent, R. Heino, H. Tuomenvirta, O. Mestre, T. Szentimre, J. Salinger, E. Fprland, I. Hanssen-Bauer, H. Alexandersson, P. Jones, D. Parker, Homogeneity adjustments of in situ atmospheric climate data: A review. *Int. J. Climatol.*, (in press), 1998c.

Reynolds, R. W. and T. M. Smith, Improved global sea surface temperature analyses using optimum interpolation. *J. Climate 7* (6), 929-948, 1994.

Smith, T. M., R. W. Reynolds, R .E. Livezey, and D. C. Stokes, Reconstruction of historical sea surface temperature using empirical orthogonal functions. *J. Climate 9* (6), 1403-1420, 1996.

SST Anomalies and Climate Requirements

D.E.Harrison, PMEL/Hayes Center, NOAA/Univ of Washington, Seattle, WA

deh@atmos.washington.edu

We have come to appreciate that SST anomaly patterns exist on many space and time scales. Many of the patterns that are persistent over a season or longer have been described or revisited over the past decade. These include seasonal anomalies like the Pacific-North American pattern (e.g., Renwick and Wallace, 1996) and Pacific-South American patterns (Garreaud and Battisti, 1999); the seasonal/interannual El Nino-Southern Oscillation phenomenon (e.g., Harrison and Larkin, 1998); the decadal changes of the Pacific Decadal Oscillation (Mantua et al, 1997), North Atlantic Oscillation and the Arctic Oscillation (e.g., Thompson and Wallace, 1998); and longer term features (e.g., Zhang et al, 1997, IPCC,1990). Over most of the globe the SST changes associated with seasonal and longer time scale climate phenomena are smaller than the changes that occur in the normal seasonal march (see figure 1 discussion, below). Yet the weather impacts on mankind associated with these modest but persistent temperature anomaly patterns can be important. GOOS and GCOS seek to implement an integrated observing and analysis system adequate to provide the SST analyses needed to determine the important patterns of climate anomalies. This brief note will describe the amplitude, space and time scales of some of the known SST climate anomalies and thereby provide a framework for setting the accuracy seek in our SST analyses.

First, it is important to put the climate anomalies in perspective; the standard deviations of SST provide a useful framework (Figure 1). Figure 1a shows the standard deviation of monthly mean SST values from the COADS data set over the period 1946-1993. Figure 1b shows the standard deviation of the climatological seasonal march; it is clear that the climatology accounts for the major part of the signal over most of the globe. Figure 1c shows the standard deviation of the `climate' SST anomaly data (the anomaly data have been smoothed with a 3-month running average and a moderate space filter). As mentioned above, the climate anomaly standard deviation is greater than the seasonal march standard deviation primarily in the central equatorial Pacific ocean. There are interesting large scale patterns of the climate anomaly standard deviation. The largest amplitude pattern is the familiar `cold tongue/South American coast' pattern associated with ENSO (e.g., Harrison and Larkin, 1998), but there is a second large scale pattern in the North Pacific, with an east-west axis roughly along 40 N and a sector of the NW North Atlantic also has varibility that stands out from the background. The North Pacific SSTA variability is clearly associated with ENSO and the PDO, as well as with the Arctic Oscillation. (Unfortunately, the COADS data distribution does not permit useful examination of the signals over much of the southern hemisphere, particularly south of 30S, Garreaud and Battisti obtained their results from the NCEP/NCAR reanalysis, which used a combination of in situ and satellite and ice data).

As noted previously, the amplitude of these climate anomaly standard deviations is quite small: 1.0C or less in the Pacific Cold Tongue and in the heart of the North Pacific maximum and 0.75C or less in the NW North Atlantic maximum. Over most of the globe there is less than 0.5C in the climate SST standard deviation. Typical maximum climate SST amplitudes will be less than 3 standard deviations, and most of the time will be within two standard deviations. The total climate signal - all of the phenomena listed in the introductory paragraph - is encompassed within these values. Figure 2 and Figure 3 provide sample time series of SSTA from places in the Pacific and Atlantic that have good data and clear climate signals. Figure 2a is for the central equatorial Pacific and shows the dominance of interannual variability in this region; there is also some decadal modulation, but there is little trend over this 50 year period. Figure 2b is for the central North Pacific and shows that the signal is split fairly evenly between seasonal-to-interannual and longer time scales; there is substantial trend, but this cannot be separated meaningfully from the decadal signal with only a 50 year record. Figure 3a is for a region of the northwest North Atlantic where the decadal and longer time scale signal is clear, although there are also some interannual time scale features. Figure 3b is for the equatorial Atlantic, for contrast; there is little SSTA variability here. No four time series can illustrate the full range of SSTA behavior found around the globe, but these illustrate the types of behavior that we seek to monitor, understand and forecast.

The behavior of SSTA at any particular point likely is of little climatic impact. It is when large scale patterns of SSTA form or decay that climatic significance is possible. The papers referred to above provide our best present knowledge of the SSTA patterns associated with the seasonal , interannual and decadal phenomena that have known climatic impact. Unfortunately we have little enough in situ data over large parts of the southern hemisphere and at high latitudes in the Northern Hemisphere that our knowledge of the climatically important patterns may be significantly imperfect in these regions. Garreaud and Battisti (1998) extended the COADS-based analysis of Zhang et al (1997) to include the southern hemisphere, and find substantial high-latitude anomaly correlations with indices of ENSO and decadal variability that have unexpectedly small meridional and zonal scales in the regions where our knowledge of SST is particularly limited. It remains to be determined if these aspects are artifacts of the way SST information was inserted in these areas in the Reanalysis, or are real features of the climate system. It is important to find out which.

Given that the accuracy of the many traditional SST observations is 0.5C or worse, it is clear that both bias and sampling errors must be limited as much as possible if we are to be able to study the climate SST variability with confidence. The error sources, total error estimates of our historical and present-day SST information, and adjustments that are being made to our historical archives to try to compensate for changing observational techniques, will be discussed by others in this workshop. Sampling error will be touched on in this workshop, but is not simple to quantify. There are many different regimes of SST variability in the world ocean and different sampling issues are associated with different observing techniques; confident sampling error estimates can only be made in the few special places where high quality, high time resolution time series have been made. Further, satellites observe the ocean skin temperature, which can be substantially different from the bulk mixed layer temperature that is traditionally measured in situ, as will be discussed elsewhere. Unfortunately, many of the error sources are unlikely to produce random errors.

To describe the state of monthly SSTA over the globe for climate purposes is technically within our grasp, but will require dedicated and on-going efforts to collect in situ data in undersampled regions, as well as improved bias correction proceedures for satellite SST. To understand the time rate of change of climate SST anomalies on seasonal to interannual time scales will require knowing monthly SSTA at the level of about 0.2C even in the Pacific equatorial wave guide. Regional century long trend knowledge needs area average anomaly values to an even more exacting standard. Meeting these latter standards poses substantial challenges to the existing system and to straightforward extensions of it.

REFERENCES:

Garreaud, R.D. and D.S. Battisti (1999). Interannual ENSO and interdecadal ENSO-like variability of the tropospheric circulation in the southern hemisphere. J. Climate (in press).

Harrison, D.E. and N.K. Larkin (1998): El Nino surface temperature and wind anomalies, 1946-1993. Rev. Geophysics, 36,353-399.

Intergovernmental panel on climate change. (1990) Climate change: The IPCC Scientific Assessment. Eds. Houghton, Jenkins and Ephraums. Cambridge University Press, Cambridge, UK

Mantua, N.J., S. Hare, Y. Zhang, J. Wallace and R. Francis. (1997). A Pacific Interdecadal Climate Oscillation with impacts on salmon production. Bull. Am. Met. Soc., 78, 1069-1079.

Renwick, J. and M.J. Wallace (1996). Relationships between North Pacific wintertime blocking , El Nino, and the PNA Pattern. Mon. Wea. Rev., 124, 2071-2076.

Thompson, D.W.J. and M.J. Wallace (1998). The Arctic Oscillation signature in the Wintertime geopotential height and temperature fields. Geophys Research Lett., 25, 1297-1300.

FIGURE CAPTIONS:

Figure 1. The standard deviations of COADS SST, 1946-1993 (adapted from Harrison and Larkin, 1998). a) The total standard deviation of monthly mean SST, in degrees Celsius. b) The standard deviation of the monthly mean climatology, a measure of the amplitude of the normal seasonal march. c) The standard deviation of the Climate SST signal, computed from the monthly mean anomaly values after smoothing with a three month running average and a moderate spatial filter.

Figure 2. Example time series of seasonally smoothed SSTA (degrees C) in the Pacific. a) The central equatorial Pacific, with strong interannual (ENSO) variability and little trend. b) The central middle-latitude North Pacific, with variability on each of the climate time scales discussed above.

Figure 3. Example time series of seasonally smoothed SSTA (degrees C) in the Atlantic. a) The tropical Atlantic, with its characteristically small variability. b) The NW North Atlantic, with smaller variability than in the North Pacific and with a very different distribution of variability with time.
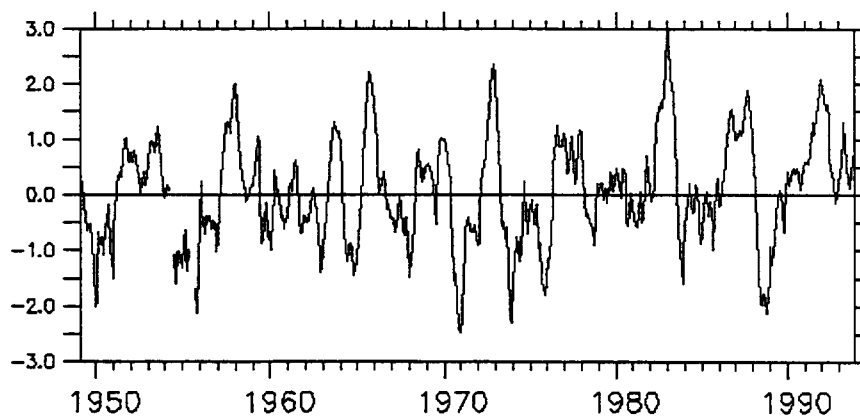
FERRET (GUI) Ver. 4.91
NOAA/PMEL TMAP
Nov 29 1996 16.35:30
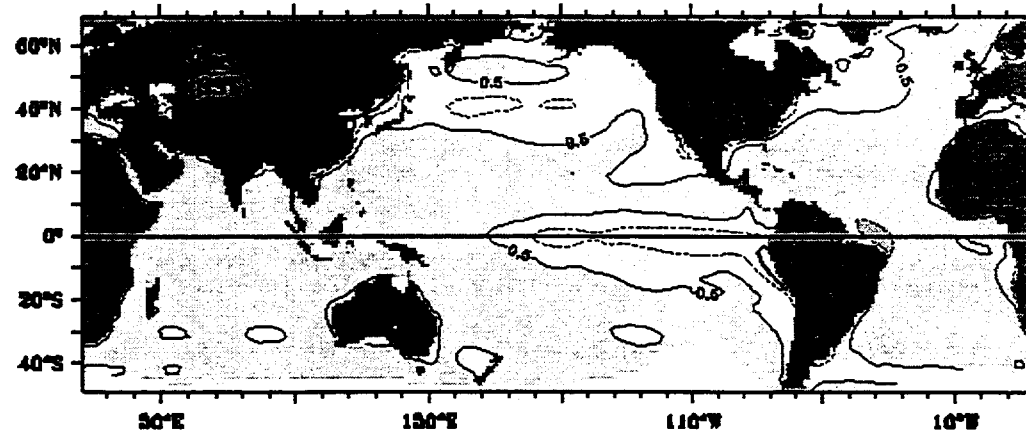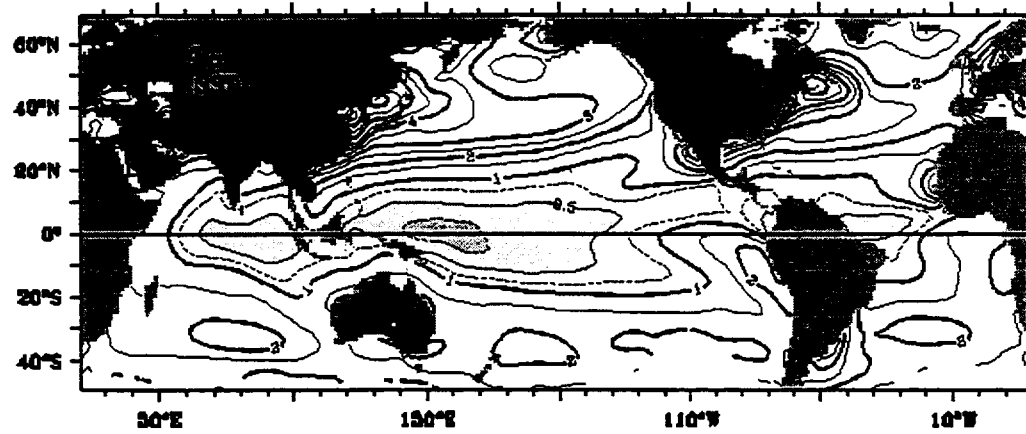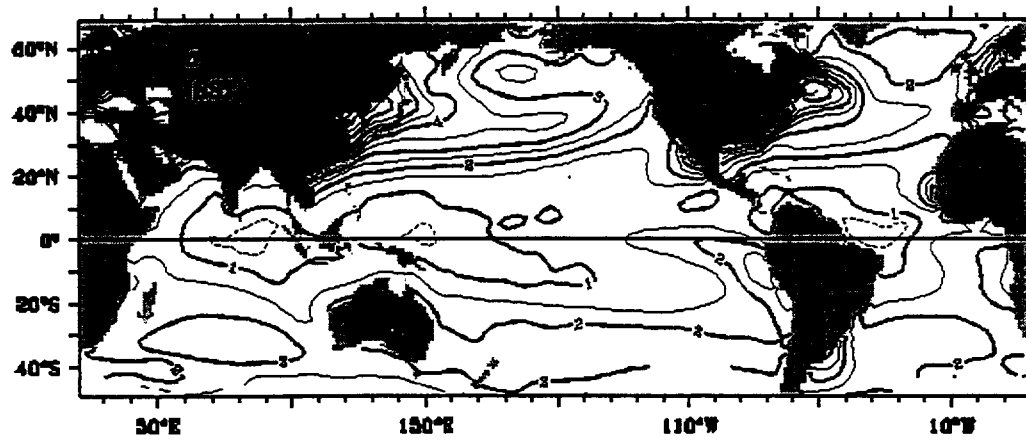
LONGITUDE : 179E
LATITUDE : 41N
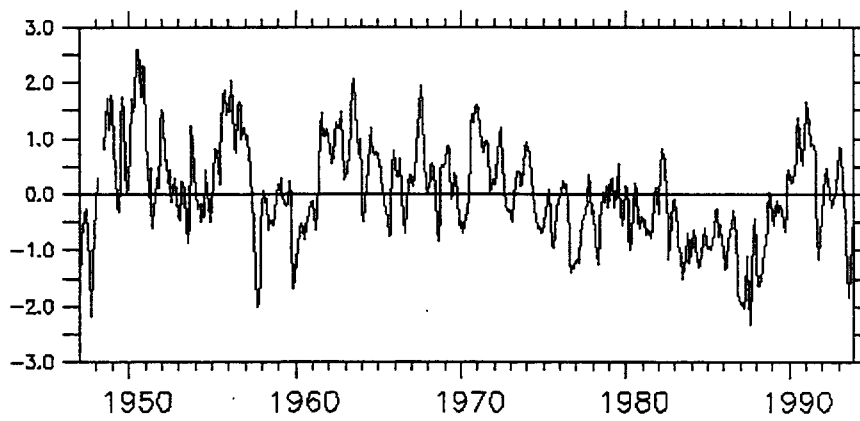
Seasonal SSTA, North Pacific

FERRET (GUI) Ver. 4.91
NOAA/PMEL TMAP
Nov 29 1996 16.36:03

LONGITUDE : 141W
LATITUDE : 1S

Seasonal SSTA, Equatorial Pacific

LONGITUDE : 41W
LATITUDE : 49N

FERRET (GUI) Ver. 4.91
NOAA/PMEL TMAP
Nov 29 1995 16.37:33
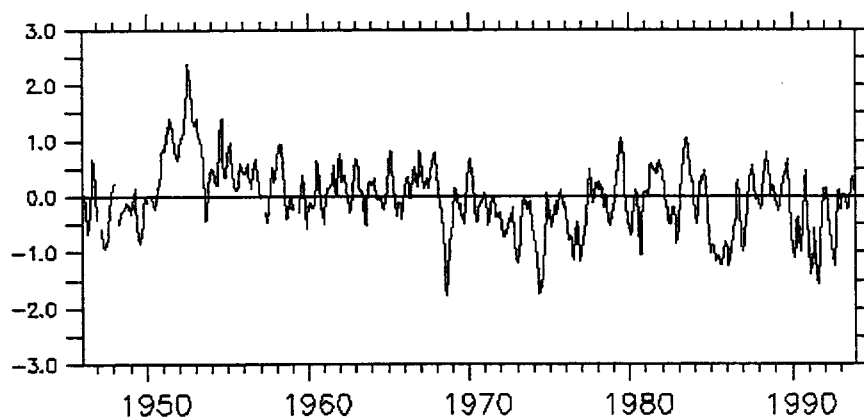
Seasonal SSTA, NW North Atlantic

FERRET (GUI) Ver. 4.91
NOAA/PMEL TMAP
Nov 29 1995 16.40:35

LONGITUDE : 39W
LATITUDE : 7N
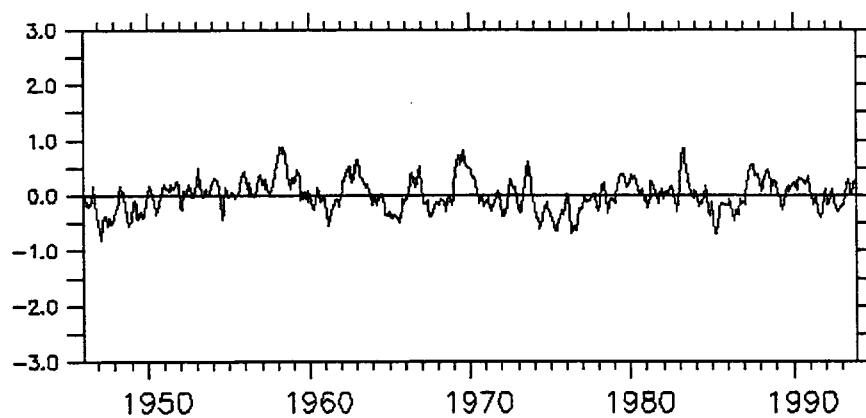
SSTA, Equatorial Atlantic

Techniques Used in the Construction of GISST.

N.A. Rayner and D.E. Parker

Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, Berkshire, RG12 2SY, U.K.

1. Introduction.

Global sea-Ice and Sea Surface Temperature (GISST, Parker et al (1995b), Rayner et al (1996)) is a monthly, globally complete historical sea-ice and SST data set for 1871-present. The SSTs in GISST are mainly based on a monthly 1° latitude by 1° longitude (hereafter 1° area) resolution SST and sea-ice climatology for 1961-90 and the Meteorological Office Historical SST (MOHSST, Parker et al (1995a)) observed *in situ* SST data set, expressed as anomalies from the same climatology. As the spatial availability of observed SST data varies with time, the resolution on which the anomalies are analysed also varies and is coarser than 1°. However, owing to the 1° area climatology, GISST is defined on 1° area resolution throughout the period. GISST is used by many groups for coupled and ocean model validation, atmospheric model forcing and Reanalyses and climate variability studies.

The Folland and Parker (1995) "bucket corrections" have been applied to the gridded *in situ* SST data up to 1941 to remove heterogeneities in the data which result from changing measurement practices. These corrections aim to make the early data comparable to those obtained using a modern mix of sampling methods (engine intakes, insulated buckets, buoys, etc.).

Bias-corrected AVHRR SST data are used to augment the *in situ* data from 1982 onwards.

Sea-ice data have been obtained from a number of sources (Rayner et al (1996)). Sea-ice concentration within each 1° area grid box is used to specify SST in areas with coincident sea-ice and open water in the marginal ice zone (MIZ) by means of regression relations.

In order to make the data set globally complete, particularly prior to the availability of satellite data, several methods were used to complete and smooth the open-ocean SST fields:

- EOF reconstruction: used successfully to reconstruct variability back to 1871 in GISST2.3b and 3.0;
- Data-adaptive smoothing between reconstructed and observed SST: values are smoothed if the difference between the data within any grid box and the average of its neighbouring boxes is greater than a predetermined threshold. The smoothing is weighted by the number of observations contributing to each grid box;
- Poisson blending: used both to bias-correct AVHRR SST and to fill any remaining data-voids between the open-ocean reconstruction and MIZ SST;
- Reduced Space Optimum Interpolation (RSOI, Kaplan et al (1997)): used in the development of GISST4.

GISST has strengths and weaknesses, like any analysis of historical data. Here we will outline the techniques listed above, discuss the strengths and weaknesses of GISST and present the improvements being made to the data set.

2. Marginal Ice Zone SST Specification.

Availability of sea-ice concentration data enables specification of SST within the MIZ using regression relationships derived from SST observed in these regions. Full details of the regression technique can be found in Rayner et al (1996), but we present a summary here for completeness.

In situ observed SST for 1961-90 have been used in the Northern Hemisphere and AVHRR SST for 1982-94 have been used around Antarctica. Coincident SST/sea-ice data pairs were binned into 360 overlapping 31° longitude bands for the Arctic, separately for each season. Pairs for all longitudes together were used in the Antarctic. The fresh water Great Lakes were treated separately.

For each 1° area SST value, the average sea-ice concentration in a surrounding 5° area grid box was used. These pairs were averaged for classes of sea-ice concentration in tenths, for concentrations

greater than 0 and less than 10 tenths. Quadratic relationships were fitted such that at complete sea-ice cover (i.e. 10 tenths) SST was fixed equal to -1.8°C (0°C in the Great Lakes).

1° grid boxes containing sea-ice concentration greater than 0 and less than 10 were assigned an SST value using these relationships. In the Arctic, the relationship for the 31° band centred on the target box in the appropriate season was used along with the sea-ice concentration in that 1° box. In the Antarctic, the pan-longitude relationship for the appropriate season was used.

3. Open Ocean SST Analysis.

In recent versions of GISST, an EOF-based technique has been used to reconstruct SST anomaly fields. A more rigorous but related procedure, Reduced Space Optimum Interpolation (RSOI, Kaplan et al (1997)), will be used in the next version, GISST4.

In both methods, a set of EOFs, E, of SST anomaly variability calculated using data from a recent well-observed period are used to reconstruct past fields. It is thus assumed that patterns of variability contained within these modes are valid for earlier periods. A truncated set of EOFs is projected onto the data available for each historical month, T_o (the subscript o on E in the equations denotes that we are using only those elements of E which coincide with data values). The reconstruction is fitted to the observations in a least-squares sense, which results in a set of time coefficients, a, for all EOFs used.

The difference between these two methods can be summarised by the following two matrix equations:

$$a = (E_o{}^T E_o)^{-1} E_o{}^T T_o \quad (1)$$

$$a = (E_o{}^T R^{-1} E_o + \Lambda^{-1})^{-1} E_o{}^T R^{-1} T_o \quad (2)$$

The simple method, described by (1), gives good results when data are reasonably well spread spatially and made up of a good number of observations. However, in extremely data-sparse times (e.g. during World Wars), unless kept in check by using fewer EOFs, spurious large anomalies can be produced.

Optimum Interpolation using EOFs, or RSOI, described by (2), has two checks built in to prevent this. The method performs a weighted least squares fit of the reconstruction to the observations in EOF space. In this case, the weights, R^{-1}, are the inverse of a combination of data error and truncation error estimates.

The forms of the two equations are very similar, except for the inclusion of the weights and an extra term, Λ^{-1}, in (2). The extra term is a diagonal matrix of eigenvalues. This acts to suppress the contribution to the reconstruction from lower eigenvalue (and hence less important) EOFs. This term allows the use of the whole truncated of the set of EOFs, no matter how sparse the data, removing much of the awkwardness of the simple reconstruction method.

It was found to be necessary to separate the reconstruction of the secular trend from that of the shorter-term variability. The first EOF of a low-pass filtered set of GISST1 SST anomalies for 1901-1990s (variability greater than eight years retained) is used to subtract the spatially varying "trend" reconstruction from the observed data. The time series of this EOF correlates extremely well with the global average SST anomaly filtered in the same way. The spatial pattern is mostly positive but with negative weights to the southeast of Greenland. Once the data have been detrended, short period regional and local variability is reconstructed using EOFs of recent detrended data. The two sets of reconstructions are then added together to give the completed anomaly fields.

4. Data-adaptive Smoothing between Reconstructed and Observed SST.

In some versions of GISST, the reconstructed SSTs are used to fill gaps between the available observed data. There are two reasons why it might be preferable not to use the reconstructed values only:

1. If we used only the reconstruction, the analysis would be adequate only where there were sufficient data to define EOFs. If the reconstruction is used to fill gaps between the observed data, all available data can be exploited.

2. Reconstructed fields do not always capture the full strength of well-observed unusual, yet perfectly valid, anomalies.

Hence, the incomplete fields of observed data are "filled" with the reconstructed SST and the resultant fields selectively smoothed. Smoothing is performed if the value within a grid box differs significantly from the average of those in its neighbours. Weighted averages of all these data are calculated and the target box replaced. Weights are defined by the constituent number of observations in each box and so the smoothing is data-adaptive.

5. Poisson Blending.

Poisson blending (see Reynolds (1988)) is used both to interpolate the areas which remain unfilled after EOF-based reconstruction and MIZ SST interpolation, and to bias-correct AVHRR SST data.

EOFs are defined only in those grid boxes where data are available for at least 50% of the seasons of the period of data used to calculate the EOFs (1950s-90s). This often leaves the Southern Ocean and part of the southeast Pacific Ocean unfilled. Here the field is completed by first adding the reconstructed anomaly fields back to the 1961-90 climatology, attaching the MIZ SST data and bridging the gap using the Laplacian of the 1961-90 climatology.

In past versions of GISST, completed fields of AVHRR SST have been used in a similar way to fill gaps between *in situ* data from 1982 onwards. In this case, it was the Laplacian of the monthly fields of AVHRR SST which was used.

6. Strengths and Weaknesses.

So what are the strengths and weaknesses of the GISST analyses?

GISST

- Is globally complete by virtue of the inclusion of sea-ice information and the use of the various interpolation methods described above.
- Includes the Folland and Parker (1995) instrumental corrections.
- Contains consistent variation of SST with sea-ice concentration.
- Has been found to contain a good reconstruction of ENSO variability back to the late nineteenth century (see for example Kestin et al (1998)).
- Contains a separate spatially varying "trend" reconstruction.

However, some earlier versions of GISST also

- Suffer from reduced temporal coherence of fields where Poisson blending has been used to merge AVHRR SST and *in situ* data.
- Contain sea-ice data from different sources which have inhomogeneous characteristics. This has led to a spurious apparent large decrease of sea-ice area, particularly in the Southern Hemisphere in GISST2.3b and 3.0.

As in all reconstructed data sets based on observed data of variable quality, poor data coverage can lead to some uncertainty in the reconstructions, which should be used with great care.

7. Improvements.

Several improvements are being made to GISST now, or will be very soon.

- GISST4 will utilise an anomaly analysis on a 2° cross-equatorial grid. This should help to better resolve the equatorial cold tongue.
- An improved method to correct biases in AVHRR SST will be used in GISST4, involving RSOI analysis of the satellite period.
- An homogenised sea-ice data set is being developed and will be included in GISST4.

• Fields for 1960-95 in GISST4 will be based on a combination of Met. Office marine data and COADS on 1 degree resolution. This will enable better quality control than previously, which is important for EOF reconstruction techniques.

• Once the observation by observation blend of the Met. Office marine data, COADS and recently digitised data has been completed, a new GISST will be created.

8. Summary.

GISST is a globally-complete monthly sea-ice and SST data set for 1871-present. It is made globally complete by a combination of MIZ SST regression, EOF-based interpolations of open-ocean SST; separate trend reconstruction; Poisson blending between data-rich regions and MIZ; data-adaptive smoothing between reconstructed and observed data and augmentation of the *in situ* analysis by AVHRR SST when available.

GISST has been shown to contain a good reconstruction of ENSO variability and is constantly developing.

References.

Folland, C.K. and Parker, D.E. (1995) "Correction of instrumental biases in historical sea surface temperature data" Quarterly Journal of the Royal Met. Soc., v121, pp319-367.

Kaplan, A., Kushnir, Y., Cane, M.A., and Blumenthal, M.B. (1997) "Reduced Space Optimal Analysis for Historical Data Sets: 136 years of Atlantic Sea Surface Temperatures" Journal of Geophysical Research, v102, nC13, pp27835-27860.

Kestin, T.S., Karoly, D.J., Yano, J-I, and Rayner, N.A. (1998) "Time-Frequency Variability of ENSO and Stochastic Simulations" Journal of Climate, v11, pp2258-2272.

Parker, D.E., Folland, C.K., and Jackson, M. (1995a) "Marine Surface Temperature: Observed Variations and Data Requirements" Climatic Change, v31, pp559-600.

Parker, D.E., Folland, C.K., Bevan, A., Ward, M.N., Jackson, M., and Maskell, K. (1995b) "Marine Surface Data for Analysis of Climatic Fluctuations on Interannual to Century Timescales" *in Natural Climate Variability on Decade-to-Century Time Scales*, ed. D.G. Martinson, K. Bryan, M. Ghil, M.M. Hall, T.R. Karl, E.S. Sarachik, S. Sorooshian and L.D. Talley. National Academy Press, Washington, D.C..

Rayner, N.A., Horton, E.B., Parker, D.E., Folland, C.K., and Hackett, R.B. (1996) "Version 2.2 of the Global sea-Ice and Sea Surface Temperature Data Set, 1903-1994" Climate Research Technical Note No.74, unpublished document available from the Hadley Centre, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SY, UK.

Reynolds, R.W. (1988) "A Real-Time Global Sea Surface Temperature Analysis" Journal of Climate, v1, pp 75-86.

Operational SST Analysis in the Japan Meteorological Agency,
and historical Japanese marine meteorological data, the Kobe Collection

Teruko Manabe and Tadashi Ando
Climate and Marine Department, Japan Meteorological Agency

1. Introduction
The Oceanographical Division (OD) in the Japan Meteorological Agency (JMA) makes a variety of oceanographic products including SST analyses. JMA started to make operational SST analyses in 1947 and since then the analysis area, methods and products have changed a number of times. At present, monthly SST analysis (grid resolution 2°) for the global ocean, 10-day (1°) for the western North Pacific and daily (0.25°) for the seas around Japan are operationally produced.

In this report, we first introduce the operational monthly and 10-day SST analyses initiated in 1991 using *in situ* observation. Secondly, the daily SST analysis using both satellite and *in situ* data is described. Finally, digitization of the historical marine logbooks called the "Kobe Collection" is introduced.

2. Monthly and 10-day analyses using *in situ* data
The data sources of the analyses are the *in situ* observations obtained through the GTS in the forms of WMO messages, namely SHIP, BUOY, BATHY, TESAC and TRACKOB, and those observed by Japanese domestic organizations, such as the Maritime Safety Agency, Fisheries Agency, etc. The analysis method is a kind of objective analysis, called the "correction method". The method involves averaging together data within a specified spatial-time region to grid the data, and then adjusting the gridded values through a series of averages using smaller and smaller averaging areas (Cressman, 1959)

The monthly and 10-day (1 to 10, 11 to 20 and 21 to the last day of the month) analyses are made as follows. The analysis is operationally performed every 10 days to determine 1-degree square grid point values (GPVs) for the global ocean. For the global analysis, 2-degree square monthly GPVs are determined by arithmetically averaging the three 10-day analyses in the calendar month, that is a total of twelve 1-degree square GPVs are averaged for the monthly 2-degree square GPVs. Since January 1998, the arithmetic average of daily SST analysis in the seas adjacent to Japan (see section2) is applied into the relevant area in 10 day and monthly analyses. As operational JMA products, the 10-day analysis in the western North Pacific (equator-60°N, 100°E-180°E) and the monthly analysis in the global ocean (80°S-80°N) are operationally disseminated to domestic/international users through the radio facsimile and/or in a publication "Monthly Ocean Report". In the Monthly Ocean Report, other products based on the analyses, such as long time series of SST anomalies in selected areas are also shown.

In 1991, when the OD started the above operational analyses, the Division performed SST reanalysis by the same method dating back to 1946 (Marine Department ,1991). Figure 1 is the 30 year mean monthly SST and its standard deviation for November based on the reanalysis. The data used in the reanalysis were COADS (data period: 1946 -1986) and observations collected via GTS and from domestic organizations and stored in the JMA archival (data period: 1967 - 1991). The historical global SST GPVs since 1946 are available through the WMO Distributed Data Base (http://ddb.kishou.go.jp). The file in the Data Base is operationally updated every month.

The problems of the analysis that we recognize are, (1) there are areas of no GPVs available where *in situ* observations are sparse, (2) as the correction method does not depend on the statistics of the SST observations and time/space correlation field, the interpolation is not an optimum one and it is difficult to estimate errors of the analysis, and (3) as the grid is not assigned to the equator, it is not appropriate to monitor some phenomena such as the equatorial up-welling.

3. Daily SST analysis using NOAA/AVHRR and *in situ* observations in seas around Japan
The OD has recently developed a new analysis using both satellite and *in situ* data by optimal interpolation (OI) for daily SST analysis with spatial resolution of 0.25-degree square grids in the region between 20°N and 50°N from 120°E to 180°E. The main purposed of the new analysis is for monitoring the phenomena of small time/space scales in seas around Japan, such as the meander of Kuroshio and the intrusion of the Oyashio cold water.

The satellite data used for the analysis are SST GPVs at 0.25 by 0.25-degree produced by the Meteorological Satellite Center (MSC) of the JMA from the NOAA/AVHRR data received at the center using the Multi-Channel SST (MCSST) retrieval algorithm developed by NOAA/NESDIS.

Parameters to be used for OI were determined by using satellite SST GPVs for the period from October 1993 to May 1996. The e-folding spatial correlation scale is between 87km and 809km (average 448km) and e-folding time scale is 23 days. Ratio of variances of the first guess error to observational error ($\bullet = \bullet_c / \bullet_{obs}$) is 0.754 for the

satellite data. The ratio for in situ data was estimated to be 0.656, which is 87% of that for satellite, considering the ratio of variance of the *in situ* observation (1.37) to that of satellite observation (1.58).

Although SSTs derived from the MCSST retrieval algorithm are already tuned to the *in situ* SST observations by surface drifting buoys, many authors have pointed out that there continue to exist some biases between the satellite-derived SST and *in situ* SST depending on the values of SST. MSC (1997) reported that the bias is as large as 0.9°C in comparison between the 0.25-degree square GPVs and observations by moored and drifting buoys.

The OD reexamined the bias of the 0.25-degree square GPVs using highly reliable SST observations by research vessels and JMA's moored buoys. A total of 4080 matchups are obtained from March 1996 through December 1997. The coefficients used in the MCSST algorithm are unchanged during the period. Table 1 shows the bias and RMS difference between the NOAA-12/AVHRR SSTs and *in situ* SSTs for every 5-degree band of SST values. The bias reaches -1.06°C for SSTs warmer than 25°C, which is almost the same as the RMS difference. In our operational analysis, temperature depending bias is determined linearly interpolating the bias determined in every 5 degree. At present, we are using NOAA-14/AVHRR SSTs. The biases for NOAA-14/AVHRR SST are not so large and lie between -0.4°C and +0.3°C.

The daily SST analysis is available on the NEAR-GOOS Real Time Data Base operated by JMA (http://goos.kishou.go.jp).

TEMPERATURE (°C•	0-5	5-10	10-15	15-20	20-25	25-30
Bias (°C)	-0.24	-0.20	-0.33	-0.41	-0.22	-1.06
RMS difference (°C)	2.00	1.50	1.14	1.32	1.27	1.11
Number of match-ups	30	138	526	818	1469	1099

Table 1. Bias and RMS difference between NOAA-12/AVHRR SSTs and in situ SSTs during the period from March 1996 through December 1997.

4. Kobe Collection - newly digitized historical marine meteorological data relevant to climate issues-

The Kobe Marine Observatory, which is a field office of the JMA, collected and stored surface marine meteorological data (SST, air temperature, air pressure, wind, etc) obtained by ships over the period from 1890 to 1960: the Kobe Collection (Komura and Uwai, 1992). In all, the data obtained by merchant ships, fishing boats and research vessels number about 6.8 million. Among them, all the data after 1933 (about 2.7 million) were digitized under a joint project of JMA and NOAA in 1961 and the digitized data have already been included in the COADS Release 1.

Historical marine meteorological observations such as the Kobe Collection are essential to the assessment of natural and anthropogenic climate change on decadal to century time scales. Because there is great interest in the earlier observations, JMA started to construct a digital data base of the pre-1933 merchant ships data in the Kobe Collection, under projects subsidized by the Nippon Foundation with the cooperation of the Japan Weather Association (JWA) in 1995. Under the projects, about 1.3 million reports have been digitized and 0.25million more reports will have been digitized by the end of FY 1998, i.e. March 1999. Among them, a total of 1,045,862 reports were quality checked and will soon be available on CD-ROM to the public. Of the digitized and quality checked reports, 82.8%, 11.5% and 5.7% were in the Pacific, Indian and Atlantic Oceans, respectively. Figure 2 shows the yearly distribution of the reports of the Kobe Collection and the Comprehensive Ocean-Atmosphere Data Set(COADS) (Slutz, et. al ,1985) in the Pacific Ocean. Because JMA put priority on digitizing reports in period when the community had data shortages, the number of data during W.W.I. will increase greatly by the addition of the newly digitized Kobe Collection data to COADS. JMA will continue to make efforts to digitize as many reports as possible. JMA believes that the newly digitized reports will significantly contribute to improvement of historical time series.

JMA is planning to make a reanalysis GPV of marine meteorological elements, including SST, since the beginning of this century. The newly digitized Kobe Collection, as well as previously available data, will be included in the GPVs. In the reanalysis, efforts will be made to address the anticipated biases of the old data, and we shall introduce a new analysis method

Reference

Cressman, G. P., 1959: An operational objective analysis system. *Monthly Weather Review*, 87, 10, 367-374.

Komura, K. and T. Uwai, 1992: The collection of historical ships data in Kobe Marine Observatory. *Bull. Kobe Marine Observatory*, 211, 19-29

Manabe, T, 1998: Digitization of the Kobe Collection. *Proceedings of International Workshop on Digitization*

and Preparation of Historical Surface Marine Data and Metedata, World Meteorological Organization, in press.

Marine Department, 1991:*Climatic Charts of Sea Surface Temperatures of the western North Pacific and the Global Ocean*. March 1991, Japan Meteorological Agency, 51pp

Meteorological Satellite Center, 1997: *Meteorological Satellite Center Product Monitoring Report.*, September 1997. 9pp.

Slutz, R.J., S.J. Lubker, J.D.Hiscox, S.D.Woodruff, R.L.Jenne, D.H.Joseph, P.M.Steurer and J.D.Elms, 1985: *Comprehensive Ocean-Atmosphere Data Set, Release1*. NOAA Environmental Research Laboratories, Boulder, Colorado, 268pp, (NTIS PB86-105723)

NORMAL of SEA SURFACE TEMPERATURE
(1961-1990)   NOVEMBER
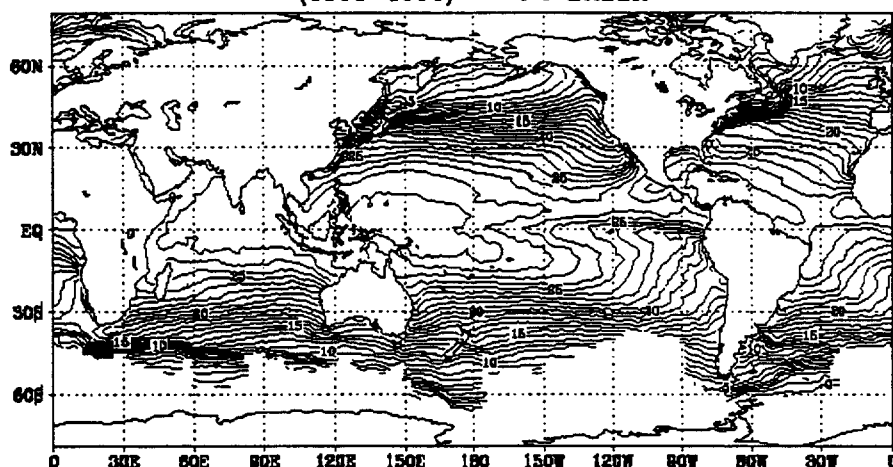
STANDARD DEVIATION of SEA SURFACE TEMPERATURE
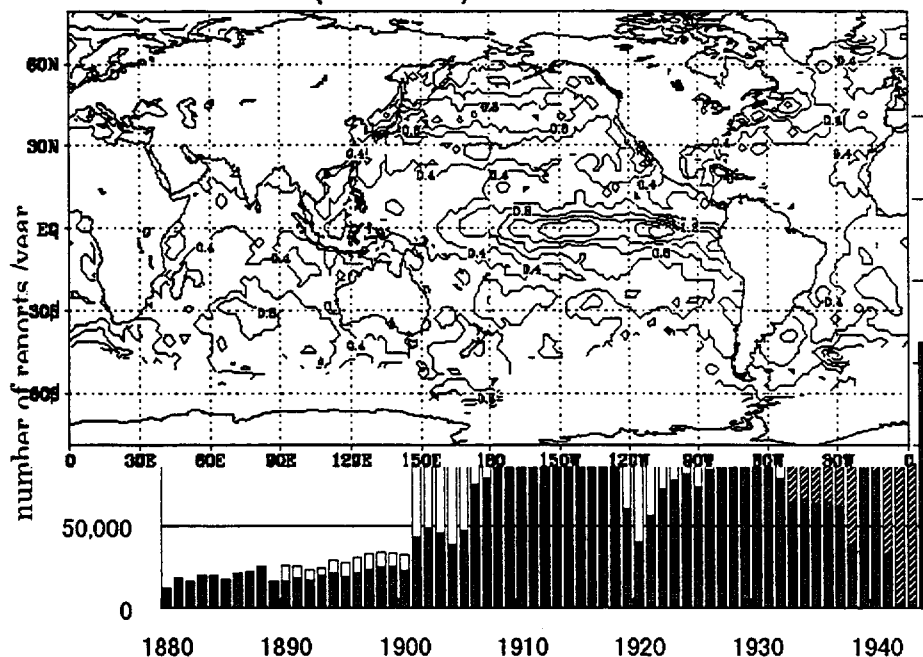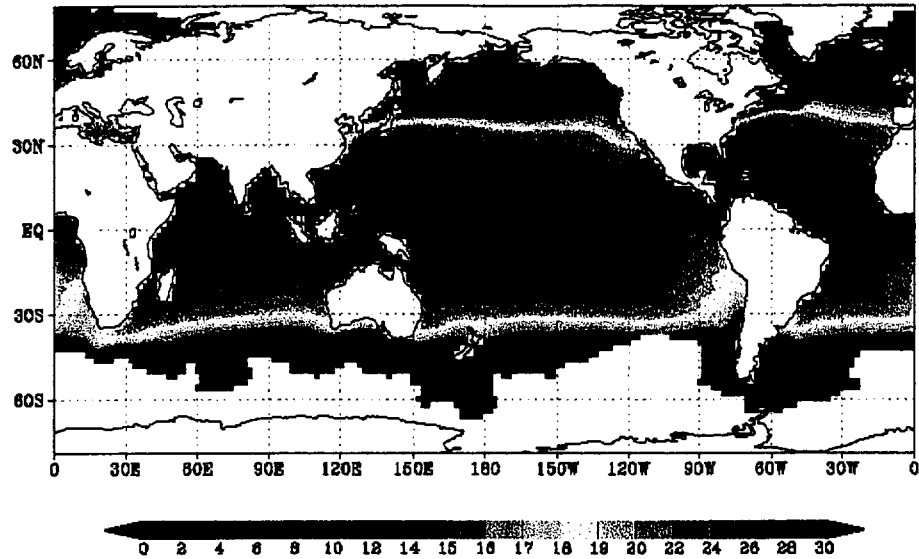(1961-1990)   NOVEMBER

Figure 1.   Normal (top) and standard deviation (bottom) of the monthly global SST field for November.   The averaged period is from 1961 to 1990.

Figure 2   Yearly distribution of the reports of the Kobe Collection and the Comprehensive Ocean-Atmosphere Data Set (COADS) in the Pacific Ocean.

NORMAL of SEA SURFACE TEMPERATURE
(1961–1990)   NOVEMBER

STANDARD DEVIATION of SEA SURFACE TEMPERATURE
(1961–1990)   NOVEMBER
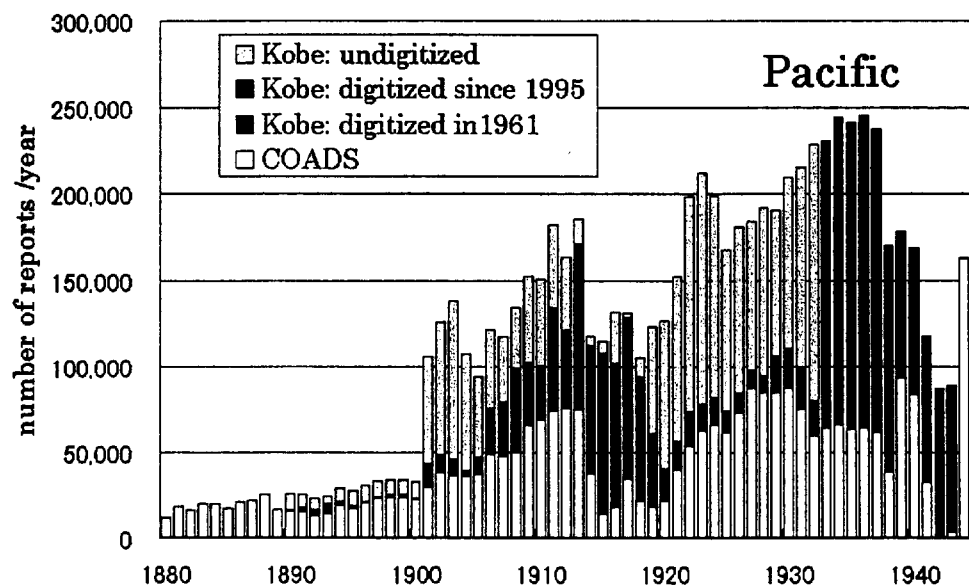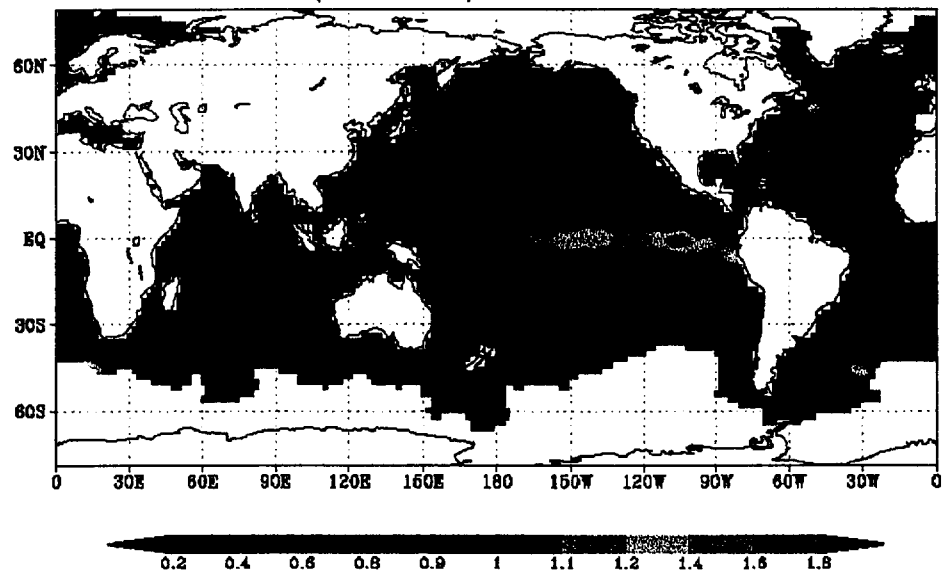
The Bureau of Meteorology SST analysis system

Neville Smith, Beth Ebert and Graham Warren
Bureau of Meteorology, Melbourne

[An informal paper produced as background for the OOPC/AOPC Workshop on SST Analyses for Climate, International Research Institute, LDEO, Palisades NY USA, Nov 10-12 1998.]

1. Introduction

The following is a brief account of the methods used in the Bureau of Meteorology operational sea surface temperature (SST) analysis system. The system was established to provide routine products for numerical weather prediction models (global and regional) and for seasonal climate monitoring and prediction.

The system was developed using a strategy similar to that adopted for subsurface ocean analyses (Smith 1995), and using expertise developed in the Bureau National Meteorological Centre for real time data handling and analysis. The Bureau had for many years relied on climatology to constrain forecast models. As the models developed, the errors introduced by this assumption became more significant, particularly for regional applications. In the late 1980's, the operational systems began using analyses provided by the US National (now) Centres for Environmental Prediction (Reynolds 1988) but difficulties with communications and the need to have greater reliability motivated actions to develop a local product.

At around the same time, BoM climate monitoring services were beginning to make more use of ocean data, both surface and subsurface, and while timeliness was certainly not as great an issue, there was a clear feeling that the Bureau should progress toward its own analysis system for SST.

The products described herein are mostly accessable via
http://www.bom.gov.au/bmrc/mrlr/nrs/climocan.htm.

2. The Method

The analysis method is discussed in Smith (1995) and references therein. In brief, it is a univariate statistical interpolation system. The elements are:

(a) *Inputs*
  - Direct observations via SHIP (volunteer merchant vessel fleet), BUOY (surface drifters and moored surface buoys such as the Tropical Atmosphere-Ocean array) and BATHY (from expendable bathythermographs taken by the volunteer merchant fleet).
  - Remote samples, principally from the AVHRR instrument on the NOAA polar orbiters, processed by Navy/NESDIS and provided via the GTS at around 200 km global resolution.
  - Sea-ice edge data from NOAA/NCEP.
  - For the regional (daily) analysis, data are derived from the local AVHRR retrievals.
  - Climatology, from Reynolds and Smith (1994).

- Statistical parameterisations for the forecast/first-guess error variances and covariances, and for observational (sampling) errors.
- Statistical forecasts based on a combination of climatology (low weight) and the previous analysis, with the estimated error of the previous analysis being used to fix the forecast error (weight) and the current analysis.

(b)   *Processing*

- Analyses are done once per week using data from 0Z on the Monday through to 24Z on the following Sunday, on a 1 degree grid (25 km for the finescale regional analysis).
- Objective quality control (checks against the forecast and cross-validated against surrounding data), with a black-list maintained for suspect data sources.
- Statistical (optimal) interpolation. The first phase involves a large-scale analysis of the direct (assumed unbiased) and remote (possibly biased) data, with the assumption that any errors introduced into the satellite data via atmospheric interference (see Reynolds, 1988) manifest with large spatial scales. The buoy data are assumed more accurate than VOS data (a relative weight of around 2:1). The difference between these two analyses is assumed to be an estimate of the bias in the remote data, accurate to around 0.2-0.3C on monthly time scales and the 750 km spatial scales of the coarse analysis. The second phase uses all data, but with the calculated bias subtracted from the satellite data, and finer spatial scales (100-200 km).
- For the regional analysis, the scales are 30-50 km and the 1 degree analysis is used to correct possible bias in the local retrievals.

(c)   *Outputs*

- Gridded SST analyses, once per week for the global analyses on a 1° grid, and daily for the regional analyses on a 0.25° grid.
- Estimates of the analysis error for the analysis, typically 0.2-0.3C, but with regional variations.
- Statistics against individual platforms and some measures of performance.
- Quality control statistics.

At high latitudes, measurements of the ice extent are used to set the "SST" (through pseudo-obs) to freezing at all points poleward of the edge. The usual covariance scales are then used to merge this information with data equatorward of the edge. The sea-ice "observations" are given small observational error variances to ensure the analysis is tightly constrained in the vicinity of the analysed edge. In the absence of any other observations, the implied anomalies (away from the Reynolds climatology) would decay equatorward on around a 150 km scale.

The method was first implemented in 1993 but during 1994 and 1995 several changes occurred, including amendments to the blending technique, introduction of the black-list for bad buoys (and VOS), and introduction of the ice-edge scheme (prior to that we in fact used the NCEP analyses).

It should be noted that the present system was devoted NWP and seasonal climate applications and little attention has been paid to the scheme's qualities for climate change diagnoses. Many of the assumptions, it must be admitted, are *ad hoc*, and do not have sound foundations in the literature. These include the assignment of error variances and covariance parameterisations.

3. Products

Included here are several of the products that are used routinely for atmospheric model forecasts. Figure 1 shows the global SST anomaly for a recent week. For the purposes of monitoring seasonal to interannual

variability the analysis system has proved more than satisfactory. Having the system on site allows rapid investigation of possible problems or of unusual patterns, some of which may be due to bad data. Figure 2 shows an analysis for the regional system that uses local retrievals. Figure 3 shows a Hovmoller diagram of SST variations in the vicinity of the equator for the period in which the SST analysis system has been operating. Again, it is clear that the scheme is able to capture the large interannual variations around Australia. Some of the features that appear at high latitudes have caused concern, both because of issues with the satellite data in the vicinity of cloud and because of the lack of suitable in situ data. Isolated buoys are difficult to quality control because of the paucity of independent information and failure to capture a poor sample can have serious ramifications for the climate signals.

Figure 4 shows an empirical-based seasonal rainfall forecast based on the patterns of global SST variation. The Climate Analysis Centre of the Bureau is moving away from schemes based solely on the SOI and toward schemes that draw on the global SST analyses. Figure 5 shows the evolution of the "popular" El Nino indices, plus the Indian Ocean index, a measure of the Indian Ocean dipole strength.

4. Sensitivity Studies

Both NCEP and BMRC assume drifter data are more useful (accurate) than ship data (for BMRC, the relative impact is around 1.7:1; for NCEP it is somewhat higher). Research on the North Atlantic VOS system suggested hull-contact sensors could greatly reduce the errors associated with ship data. These facts suggest that the sampling strategy could be approached in (at least) two ways. For areas where the analysis error is not adequate, implementation of hull-contact sensors on ships might be sufficient to reduce the analysis error to the required standard. Improved VOS could be traded off against drifter deployments. Alternatively, if an existing drifter program was already achieving the required standard, then the case for adding hull-contact sensors to VOS is much reduced. For completely data void regions there are at present no alternatives to drifters.

Some preliminary observing system sensitivity experiments were done with the BoM SST analysis system. The idea was to test the impact of "improved" ships through examination of the expected error (or as shown here, by looking at the information value of the network). Figure 6 shows estimates of the in situ "information density" for (a) all in situ data, (b) just ships, and (c) just buoys. There are some problems with the way these experiments were set up but they do not affect the main message. That is, in some regions (e.g., the N. Atlantic) there is clearly redundancy (the VOS could do it all). In other regions, like the Indian Ocean, a high-quality VOS plus drifters is likely best. In other regions, such as the Southern Ocean, greater drifter density is required.

5. Conclusions

The BoM SST analysis system has served its main purpose well over its short life time. The bias correction technique is somewhat different from elsewhere (e.g., Reynolds and Smith) but it is not clear it has any distinct advantages. There is almost no scrutiny of the data stream (the exception being Australian-sourced data) so great reliance is placed on the automated quality control procedures. They can be incestuous, with bad data protecting bad data, and errors propagating in time due to the statistical forecast technique. Very little work has gone into analysing the long-term climate signal (resources are not available to conduct a re-analysis such has been done elsewhere).

The pressure from NWP is for even finer resolution, particularly in time. This may not be possible with the present global data set. This then raises a question of maintaining consistency. Can, say, a daily global product, with fine spatial resolution be used for both climate and short-range applications. At what point

will we be able to exploit dynamical and physical models for the SST forecast? Particular care will be needed in these cases to protect long-term signals.

In some regions, with care and attention paid to the in situ network, we could operate more efficient observing systems. We should also be exploiting more satellite data.

References

Drowsdowsky, W and L. Chambers 1998. Near-global SST anomalies as predictors of Australian seasonal rainfall. BMRC Research report.

Reynolds, R.W. 1988. A real-time global sea surface temperature analysis. *J. Climate, 1,* 75-86.

Reynolds, R.W. and Smith, T.M. 1994. Improved global sea surface temperature analyses using optimum interpolation. *J. Climate, 7,* 929-948.

Smith, N.R., The BMRC ocean thermal analysis system, Aust. Met. Mag., 44, 93-110, 1995b.

Figures

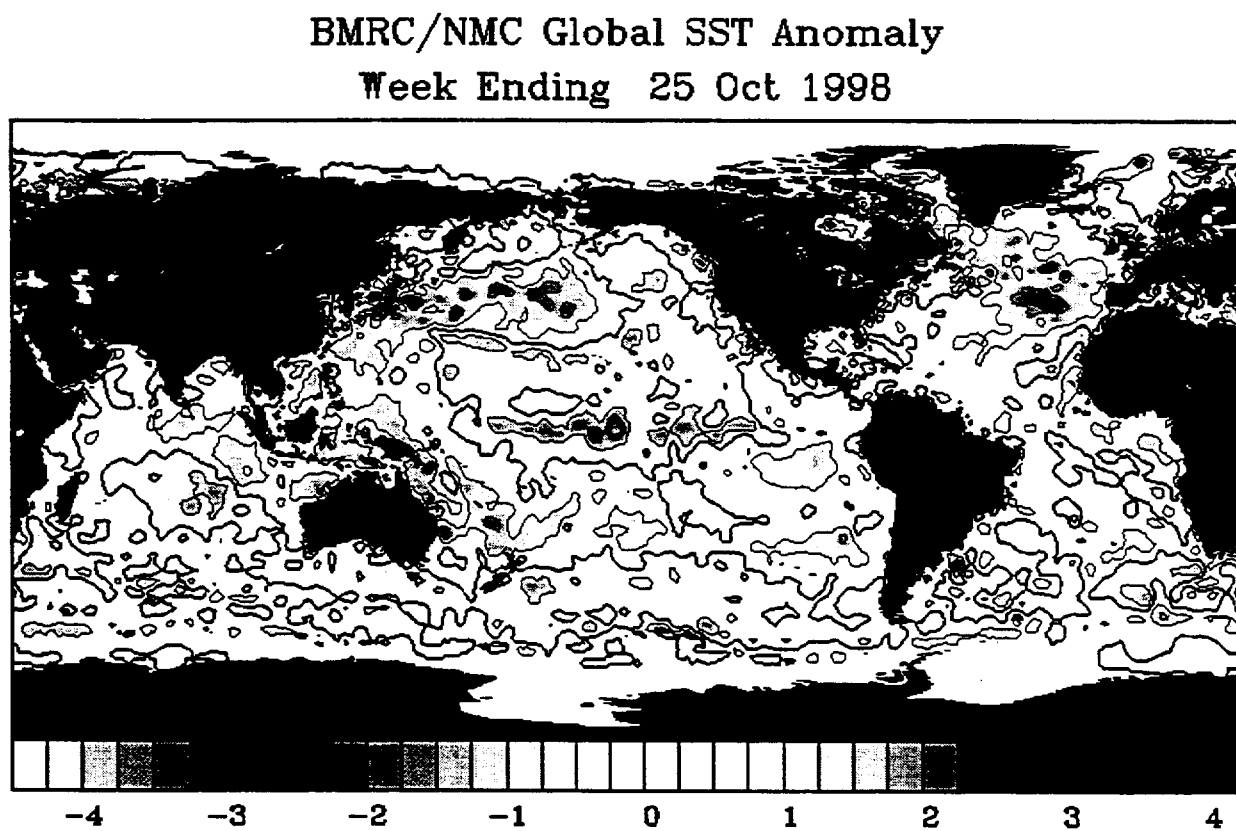## BMRC/NMC Global SST Anomaly
Week Ending 25 Oct 1998

Figure 1. SST anomaly from the BoM operational analysis for the week ending 25 October 1998 (see URL http://www.bom.gov.au/bmrc/mrlr/SST_anals/SSTA_NOW.gif).
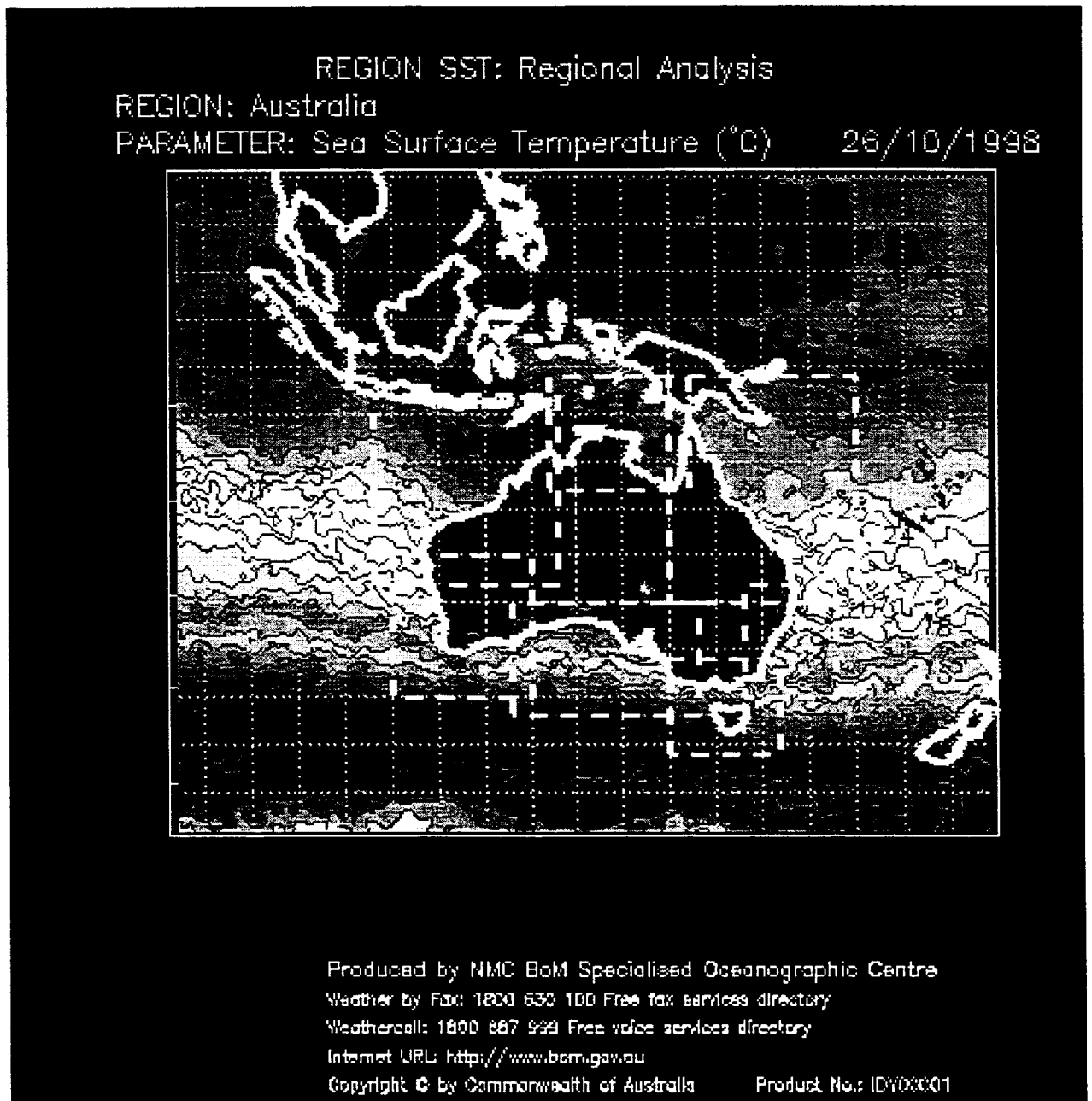
Figure 2. An example of the Bureau of Meteorology regional SST analyses for the 26 October 1998.
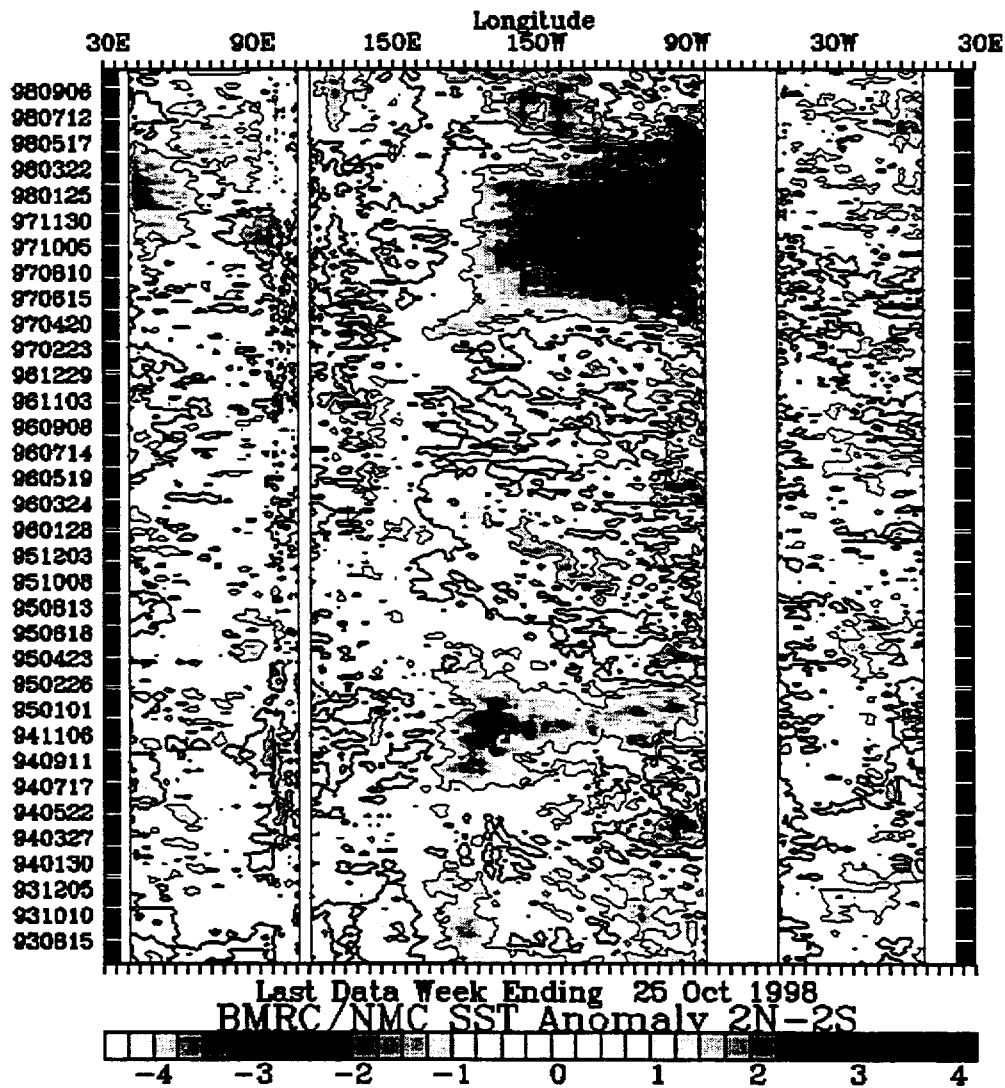
Figure 3. Hovmoller diagram of SST variations in the vicinity of the equator since the inception of the SST analysis system. Clearly the scheme is more than able to capture variability from intraseasonal scales out to the interannual (see http://www.bom.gov.au/bmrc/mrlr/SST_anals/SSTAHM.gif).
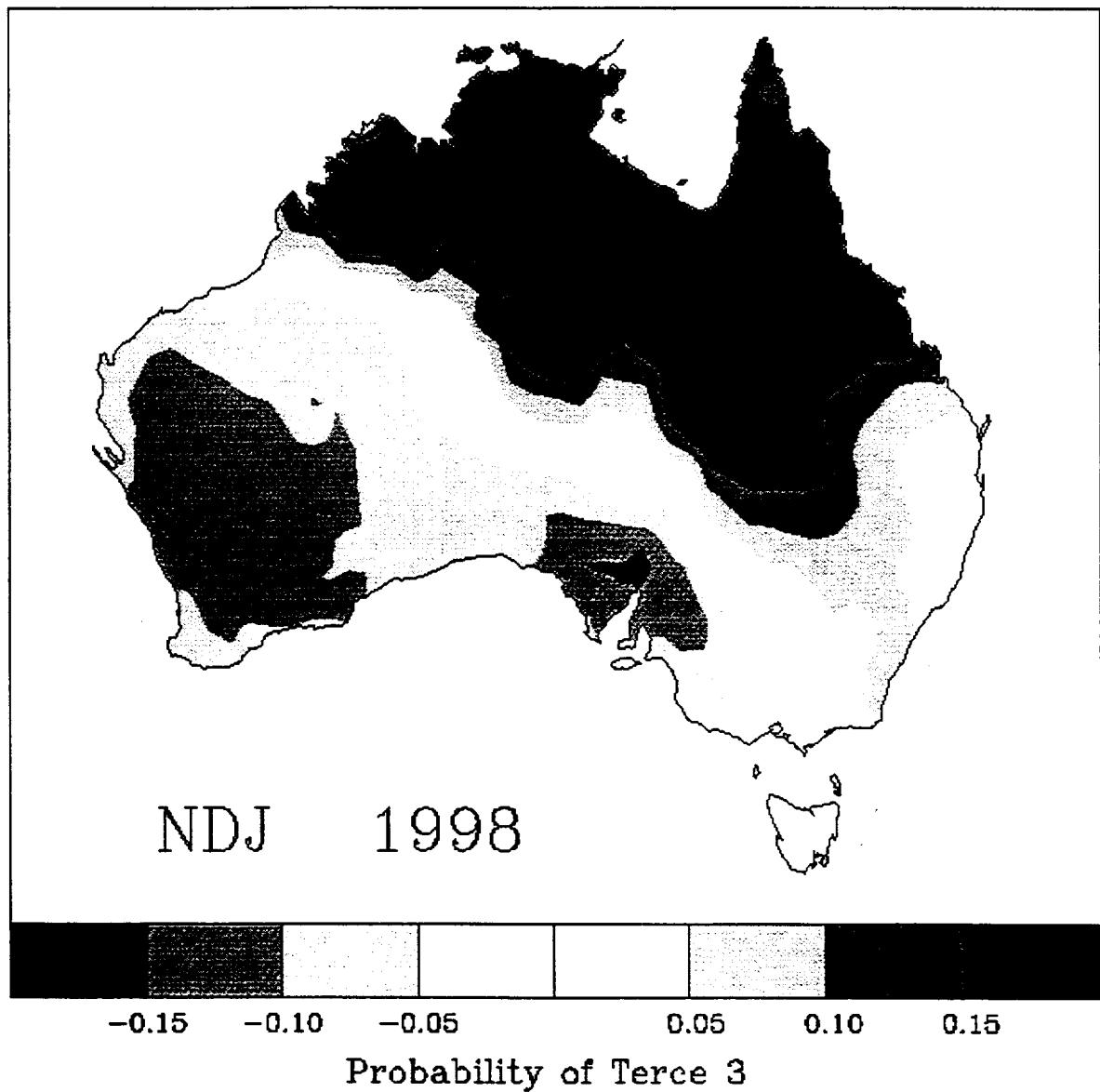
Figure 4. A probability forecast for seasonal rainfall based on EOFs of SST variability and the BoM SST analysis. The red areas show regions of increased probability of rainfall deficiencies (Drosdowsky and Chambers 1998).
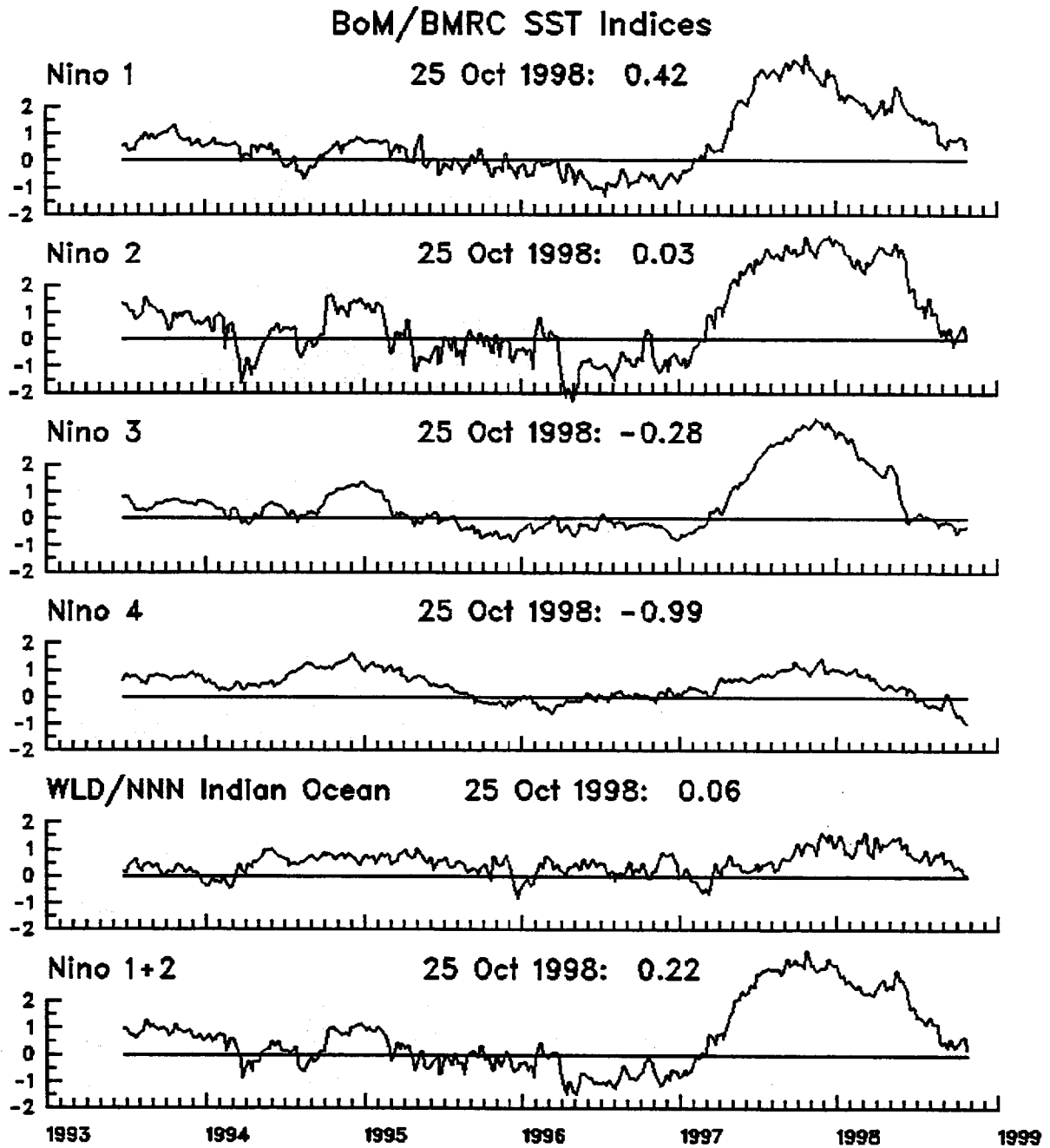
Figure 5. Some climate indices derived from the BoM SST analysis system. The Indian Ocean index is routinely compared with an equivalent index derived from NCEP's analysis and the differences are generally 0.1°C or less.
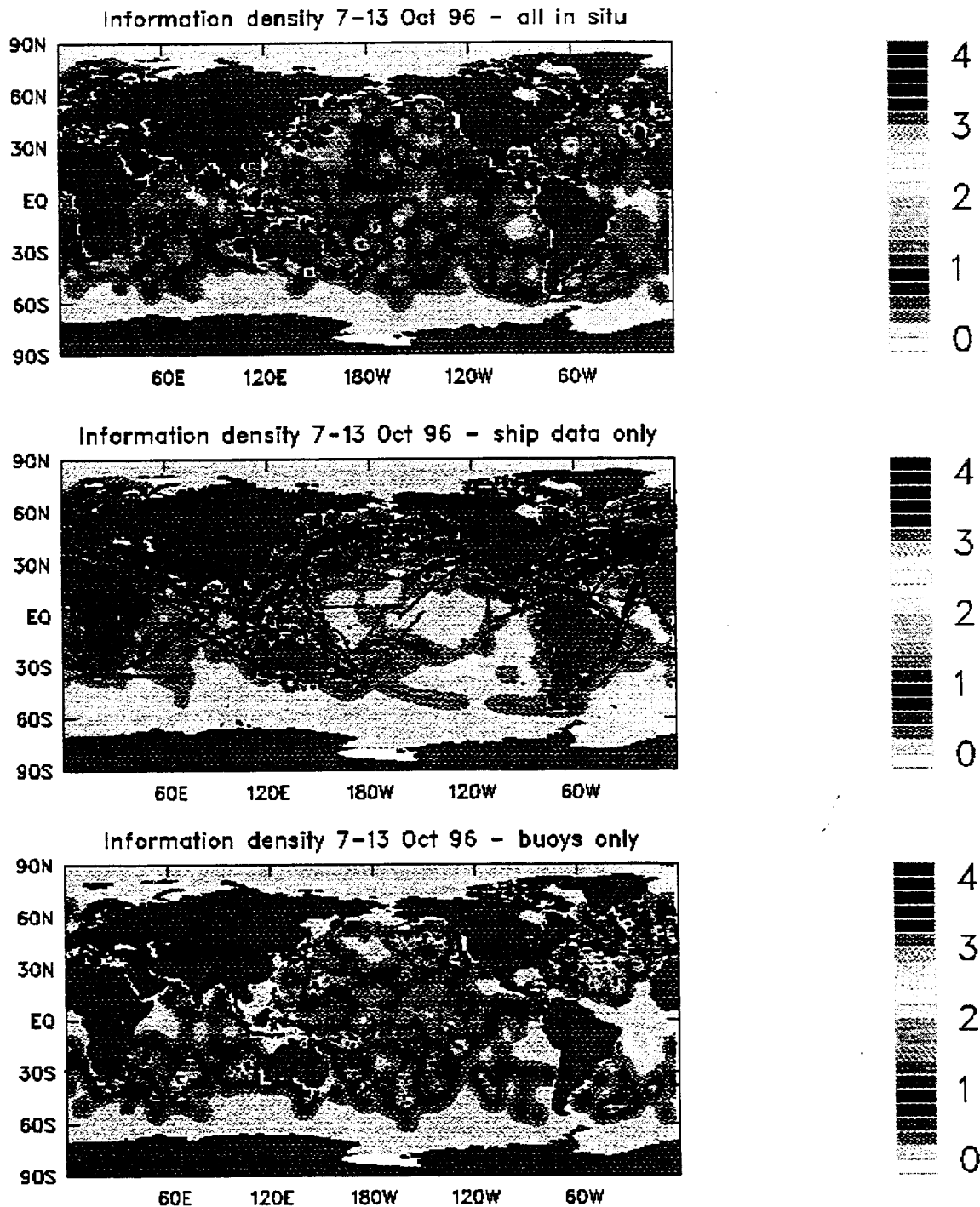
Information density 7-13 Oct 96 - all in situ

Information density 7-13 Oct 96 - ship data only

Information density 7-13 Oct 96 - buoys only

Figure 6. Some results from an observing system sensitivity experiment with the BoM SST analysis system. (a) Pattern of information density when all data are include (dark means more information). (b) For VOS only. (c) For data buoys alone. The units are (approximately) the number of samples per decorrelation ellipse.

Real-Time Ocean Data Assimilation at the U.S. Navy Fleet Numerical Meteorology and Oceanography Center

James A. Cummings
Marine Meteorology Division
Naval Research Laboratory
Monterey, California, USA 93943

U.S. Navy ocean data assimilation systems are designed to produce eddy resolving nowcasts of ocean mass structure and velocity in real-time. The objective analysis method currently under development at the Naval Research Laboratory, Monterey is a fully three-dimensional oceanographic multivariate optimum interpolation algorithm (MVOI), similar to the analysis systems in use by the major operational atmospheric forecasting centers. The correlated multivariate analysis variables are geopotential and the u-v velocity components. Temperature and salinity observations are used to compute geopotential and in mid-to-high latitudes a geostrophic assumption is used to derive expressions for the geopotential/velocity background error covariance. In this way adjustments to the ocean's mass field are correlated with adjustments to the ocean's flow field, and a short-term model forecast (or previous analysis) provides the analysis background field. Temperature and salinity observations are analyzed simultaneously with geopotential and velocity as uncorrelated scalar variables, much as moisture is analyzed in an atmospheric analysis system. The vertical covariance function in the ocean MVOI is non-homogeneous with depth, thereby allowing for shorter vertical scales in the mixed layer and thermocline, and longer vertical scales at greater depths. The first application of the new ocean MVOI analysis system will be the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) in operational use at the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey.

The greatest difficulty of any ocean data assimilation is the lack of synoptic real-time data at depth. On a global basis the daily accumulation of expendable bathythermograph (XBT) data routinely available to an ocean MVOI analysis is approximately 250 reports. Virtually no salinity observations are available in real-time. This is clearly not enough information for an eddy resolving analysis. Synoptic temperature data are routinely available at the surface in the form of satellite derived sea surface temperature (SST) retrievals (MCSSTs), but this presents the further difficulty of effectively coupling the abundant surface and sparse subsurface data in the analysis. Several studies have shown that sea surface height (SSH) observations from satellite altimeters can be used to infer subsurface temperature and salinity structure. These relationships have been incorporated into a synthetic profile algorithm developed by the Naval Research Laboratory, Stennis Space Center, that uses real-time estimates of SST and SSH as predictor variables in climatological based regression models. The synthetic temperature and salinity profiles are generated at an adequate sampling density to allow the ocean MVOI analysis to resolve mesoscale ocean structures and gradients, even in

data sparse areas. The synthetic profiles are appended to the real-time observations and assimilated in the same way as any other observation, but with unique error characteristics specified. The accuracy of the synthetic profiles are dependent primarily on the accuracy of the SST and SSH measurements used in the estimation of the predictor fields.

The ocean MVOI analysis system is executed on both global and regional, limited-area, geographic domains at FNMOC. The analysis system supports a variety of map projections (Mercator, Lambert Conformal, Polar Stereographic, Spherical) and can be run on a nested grid structure at various grid resolutions producing multi-scale analyses. The update cycle of the ocean MVOI is independent of the atmospheric analysis update cycle, and post-time analyses can be run to process delayed-mode observations. Timely receipt of ocean observations is an important issue for a real-time system, and particularly so when the system is run in a coupled mode with the atmospheric forecast model. The system must be able to handle the inevitable delays in the receiving and processing of observations at the production center.

SST and sea ice are analyzed simultaneously in the ocean MVOI analysis and are used as the lower boundary conditions of the atmospheric model. The sea ice and SST analyses are cross validated by (1) setting positive sea ice concentration retrievals to 0% ice when SST exceeds $1^{\circ}C$; and (2) inserting supplemental SST observations at the freezing point of sea water into the analysis when the sea ice concentration exceeds 55%. The freezing point depression of seawater is computed using model forecast or synthetic profile derived salinity values. The SST and sea ice analyses are slowly restored to the NCEP SST and ECMWF ice climatologies, respectively, in the long-term absence of observations. This is accomplished by inserting into the analysis supplemental observations generated from the climatologies at geographic locations where SST has not been observed for 20 days and sea ice has not been observed for 10 days.

Observation quality control is an important aspect of the ocean MVOI analysis system. The need for quality control (QC) is fundamental; erroneous data can cause an incorrect analysis, rejecting extreme data can miss important events. The decisions made at the quality control step are likely to affect the success or failure of the entire analysis/forecast system. In the ocean MVOI, results from a series of QC data checks are combined in a decision making algorithm to determine overall quality of the observations. No decision is made on the fate of the observation in the analysis (accept, reject, correct) until all of the QC methods have been applied. The primary purpose of the QC system is to identify observations that are obviously in error, as well as the more difficult process of identifying measurements that fall within valid and reasonable ranges, but are erroneous. A secondary purpose is to determine sources of error (sensor drift, bias, calibration) and propose a series of corrections (manual or automatic). An ancillary use of the QC system is the creation and maintenance of an analysis-forecast increment database for use in the *a posteriori* computation of observation/forecast errors and MVOI covariance models. QC procedures common to all data types include land/sea boundary checks and background field checks (previous analysis, forecast, 30-day means, climatology). Prediction errors for the different background fields are computed from

bin-averaged estimates of a 30-day sliding window of field increments containing only observations that have previously passed the QC and will be used in the subsequent analysis. QC procedures unique to different data types include; location (speed) test for drifting buoy and surface ship observations; instrumentation error checks for XBTs; sensor drift for fixed and drifting buoys; and large-scale bias detection for satellite retrievals of SST.

Improvements in the ocean MVOI analysis system are dependent upon increasing the real-time data coverage of *in situ* and remotely sensed data as well as improvements in the quality control of these data. In particular, the detection and correction of large scale biases in remotely sensed SST is an important issue for a coupled system. For example, to help in the detection of MCSSTs contaminated by atmospheric dust, NRL is developing an aerosol analysis/prediction system that will provide estimates of aerosol optical depth contemporaneous with the satellite SST retrieval. New sources of SST from GOES satellites and low-resolution microwave instruments also need to be investigated.

Differences in Sea Surface Temperature Analyses

Richard W. Reynolds
National Centers for Environmental Predictions
NWS/NOAA, Room 807
5200 Auth Road
Camp Springs, MD 20746 USA

Sea surface temperature (SST) analyses are used for climate modeling and diagnostics as well as boundary conditions for atmospheric models. The purpose of this note is to compare the accuracy of different SST products. The comparison starts in 1982 because that is the first complete year in which SST retrievals were available from the Advanced Very High Resolution Radiometer (AVHRR) instrument.

For this study six different SST analyses are used. The analyses are from the UK Meteorological Office (UKMO, Parker, et al., 1994 and Parker, et al., 1995), the Japan Meteorological Agency (JMA, T. Manabe, personal communication), the Lamont-Doherty Earth Observatory (LDEO, Kaplan, et al., 1996), the Naval Research Laboratory (NRL, J. Cummings, personal communication), the Australian Bureau of Meteorology Research Centre (BMRC, N. Smith, personal communication) and the National Centers for Environmental Predication (NCEP, Reynolds and Smith, 1994). All data sets were available for the entire period except the LDEO (January 1982 to December 1991), the BMRC (July 1993 to December 1997), and the NRL (January 1995 to December 1997). The JMA and LDO analyses and this version of the UKMO analysis used only in situ data; the other three used satellite and in situ data. Of the three analyses which used satellite data, only the NRL analysis did not use a real-time correction of the satellite data. All analyses are converted to lowest common resolution, monthly on a five-degree grid.

To contrast analyses with and without satellite data, the monthly SSTs for the NCEP and UKMO analyses are shown for December 1997 in figure 1. The respective anomalies, partially resulting from the strong El Niño, are generally quite similar with the exception that the satellite data gives the NCEP better coverage. Differences between the two analyses tend to be largest near the limits of the in situ SST data. The results show that analyses without satellite data cannot fully cover the global oceans because of the limited coverage of in situ data.

To illustrate these differences over time, the time series for the monthly global average, computed from 60°S to 60°N for the period 1982-1997, is shown in figure 2. Because the global coverage of the UKMO analysis is not complete, the analyses were computed only over regions where both analyses were defined. The result shows that the UKMO tends to be slightly more positive, roughly 0.1°C, than the NCEP analysis from 1990 onwards. To determine if the differences were due to incompletely corrected satellite bias, a special version of the NCEP analysis was computed without the real-time bias correction of the satellite and also shown in the figure, labeled NCEP (NO). The differences between the two NCEP versions are much larger than the differences between the UKMO and bias corrected NCEP version. In particular, the

impact of the large negative satellite biases from the volcanic aerosols from El Chichón (1982-83) and Mount Pinatubo (1991-92) are clearly evident (e.g., see Reynolds, 1993). These results indicate the importance of the real-time satellite bias correction.

Although the differences between the UKMO and the bias corrected NCEP analysis are less than 0.1°C, they are important because they persist over most of the 1990s. To examine the latitude dependence of these differences, zonal differences are shown for the NCEP, BMRC, UKMO and JMA analyses in figure 3 for the period July 1993 to December 1997. This period was selected so that two independent analyses were available using in situ and bias corrected satellite data. The results show that all analyses are within 0.1°C of each other between roughly 20°S and 50°N. However, over this same latitude range, the agreement between the two in situ only analyses and between the two in situ and bias corrected satellite analyses is better than 0.05°C. South of 20°S the close agreement between the two in situ analyses begins to break down due to a scarcity in the number of in situ observations.

The monthly RMS differences for the NRL, BMRC, UKMO and JMA analyses are computed relative to the NCEP analysis for January 1995 to December 1997 and shown in Figure 4. The figure shows that monthly RMS differences on a 5° grid are less than 0.5°C between roughly 40°S and 60°N except in coastal areas (especially western boundaries) and that south of 40°S in situ only analyses show differences greater than 1°C. The NRL RMS differences tend to be larger than the BMRC differences in the eastern tropical Atlantic between the equator and 20°N. The NRL analysis does not have a real-time satellite bias correction, and this region has persistent satellite biases due to the presence of Sahara tropospheric dust. The UKMO in situ only analysis shows higher RMS differences than the JMA in situ only analysis. This is due to the fact that the UKMO product is an intermediate product which is later finalized by the addition of satellite data (Rayner et al., 1996). The LDEO analysis, not shown, is an analysis of the UKMO data and has RMS differences very similar to those shown by the JMA analysis.

These results show that there can be very large differences when uncorrected satellite retrievals are used. Thus, analyses using satellite retrievals without careful bias correction should not be used for climate studies. The results also demonstrate the advantage of using corrected satellite retrievals in analyses can improve the coverage. However, the results also suggest that it is difficult to remove all satellite biases and that some residual remains. This is illustrated in the tendency of SST analyses using the same data sources to be similar as shown in figures 3 and 4. Unfortunately, the figures also show that reliance on in situ data alone does not eliminate differences among the analyses.

Intercomparison of different SST analysis is important to indicate overall accuracies. However, further work is needed using the input data to better quantify the differences shown here. In addition, the use of sea ice to augment the SST data has not been discussed. There are large high latitude differences among analyses which use sea-ice data due to different ice products as well as different algorithms of converting ice concentration to SSTs. The ice and derived SSTs are based on assumptions which need to be verified with independent data.

References

Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan, 1998: Analyses of global sea surface temperature 1856-1991. *J. Geophys. Res.*, **103**, 18567-18589.

Parker, D. E.,P. D. Jones, C. K. Folland and A. Bevan,1994: Interdecadal changes of surface temperature since the late 19th century. *J. Geophys..Res.*, **99**, 14377-14399.

D. E. Parker, C. K. Folland, and M. Jackson, 1995: Marine surface temperature: observed variations and data requirements. *Climatic Change*, **31**:559-600.

Rayner, N. A., E. B. Horton, D. E. Parker, C. K. Folland and R. B. Hackett, 1996: Version 2.2 of the global sea-ice and sea surface temperature data set, 1903-1994, Climate Research Technical Note CRTN 74, 43pp. {Available from, the Meteorological Office, London Road, Bracknell, U. K.]

Reynolds, R.W., 1993: Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures. *J. Climate*, **6**, 768-774.

Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analyses. *J. Climate*, **7**, 929-948.

Figure Captions

Figure 1.   SST anomalies from the UKMO and NCEP analyses for December 1997. The NCEP analysis uses in situ and biased corrected satellite data; the UKMO analysis uses in situ data only. The contour interval is 1°C. Positive contours are solid lines; negative contours are dashed. Light shading indicates where there are adequate SST data.

Figure 2.   Averaged (60°S to 60°N) SST anomalies from the UKMO and NCEP analyses. The times series labeled "**NCEP (NO)**" is from a special version of the NCEP analysis without the real-time bias correction of the satellite data (see text). The averages are computed over common areas where all analyses are defined.

Figure 3.   Zonally averaged mean SST anomalies for the period, July 1993 to December 1997. The NCEP and BMRC analyses use in situ and biased corrected satellite data; the UKMO and JMA analyses use in situ data only. The averages are computed over common areas where all analyses are defined.

Figure 4.   Monthly RMS differences of the NRL, BMRC, UKMO, and JMA analyses relative to the NCEP analysis for January 1995 to December 1997. The contour interval is 0.5°C with shading above 0.5°C. There is an additional light contour line at 0.2°C and a heavy contour line at 0.3°C. The NRL analysis uses in situ and uncorrected satellite data. The NCEP and BMRC analyses use in situ and biased corrected satellite data; the UKMO and JMA analyses use in situ data only.
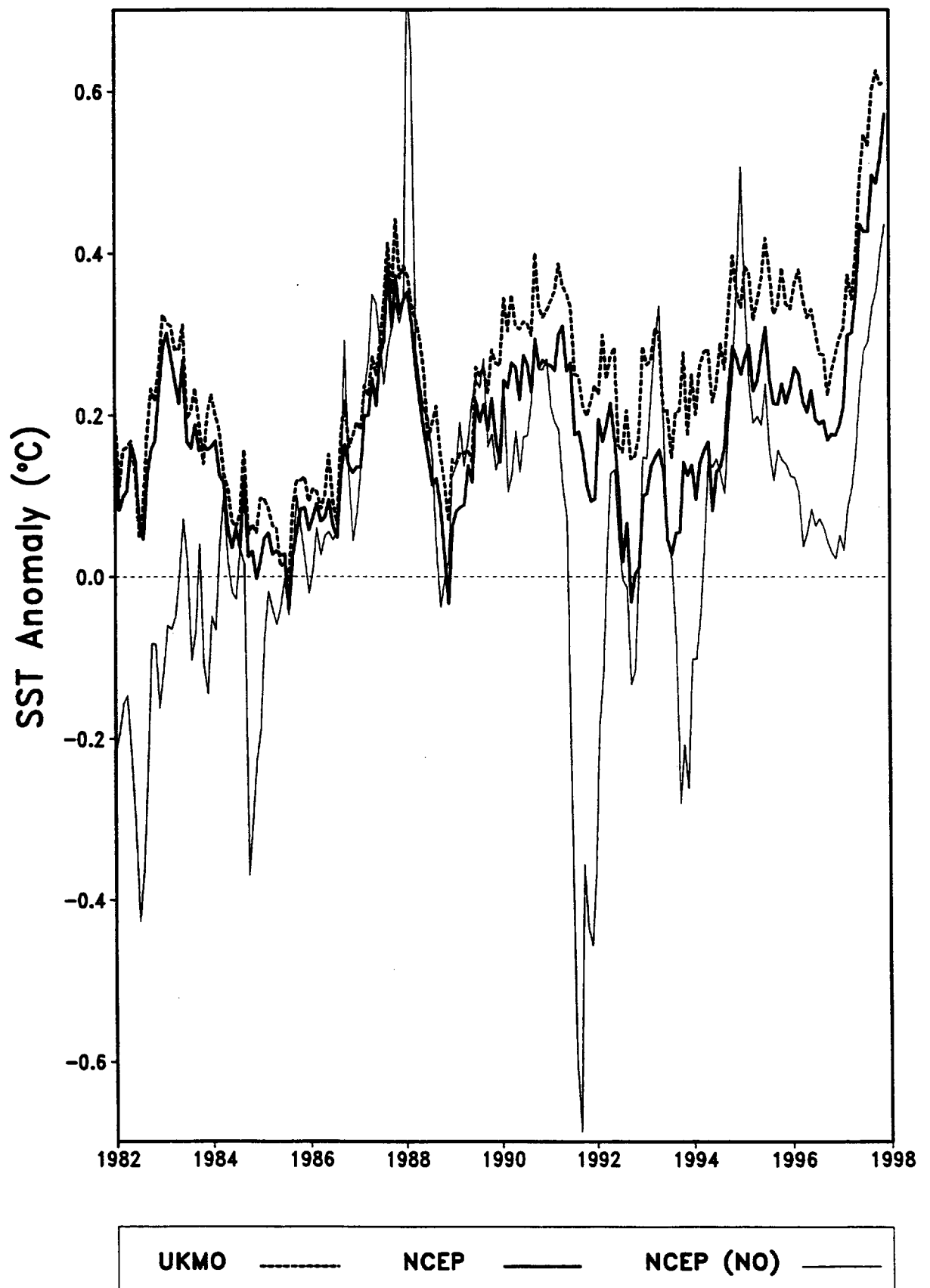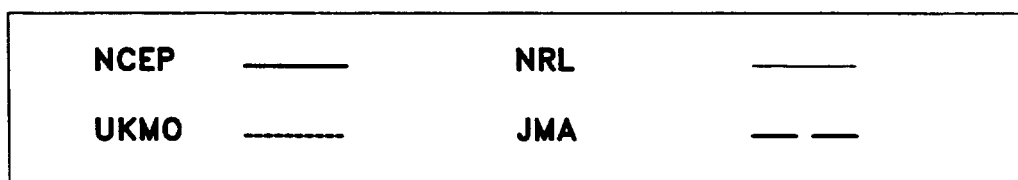
December 1997

UKMO SST Anomaly (°C)
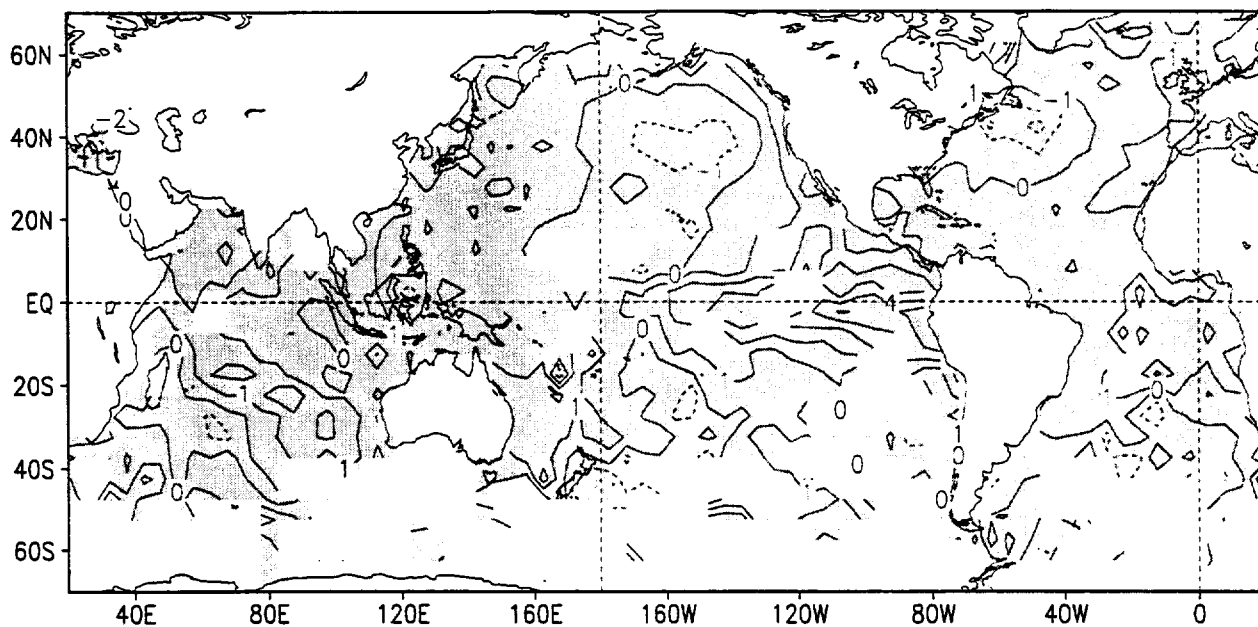
NCEP SST Anomaly (°C)
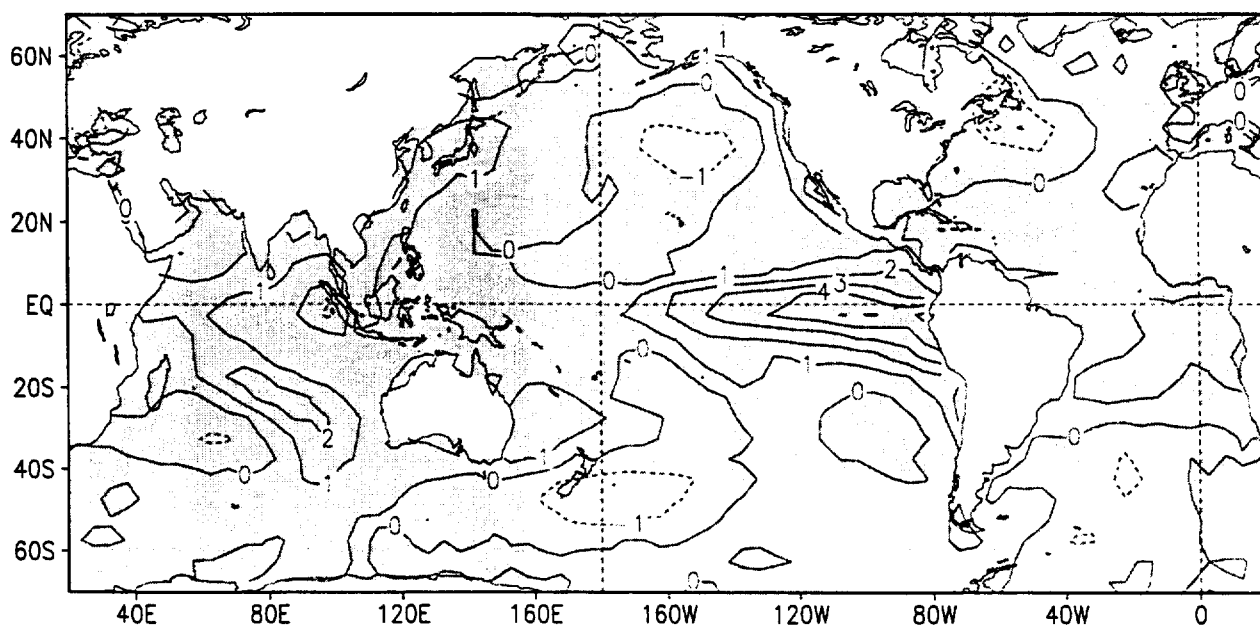
SST Anomaly: 60°S-60°N

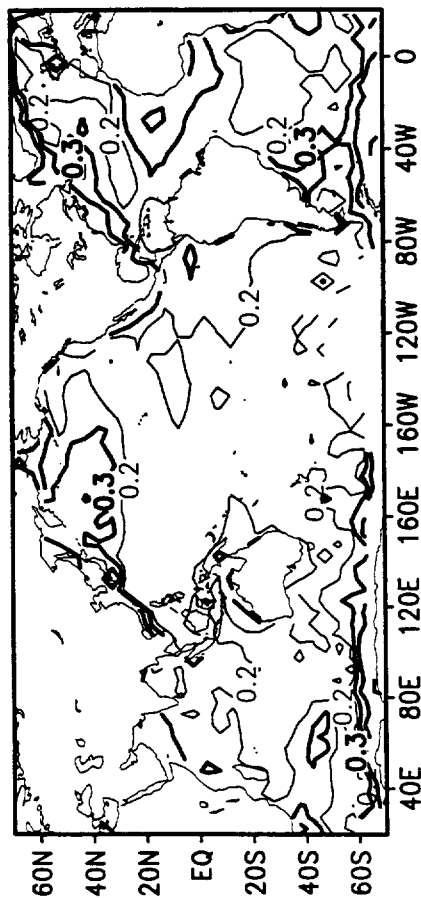| UKMO | .... | NCEP | ———— | NCEP (NO) | ——— |

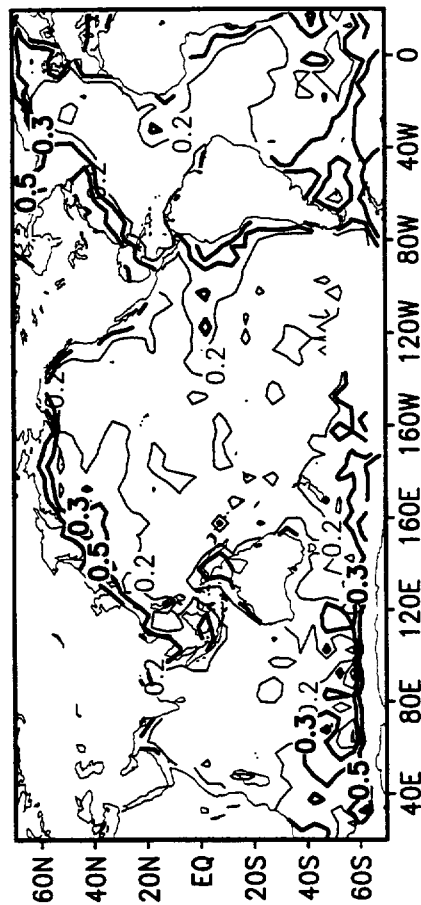July 1993 – December 1997
Mean Zonal SST Anomaly
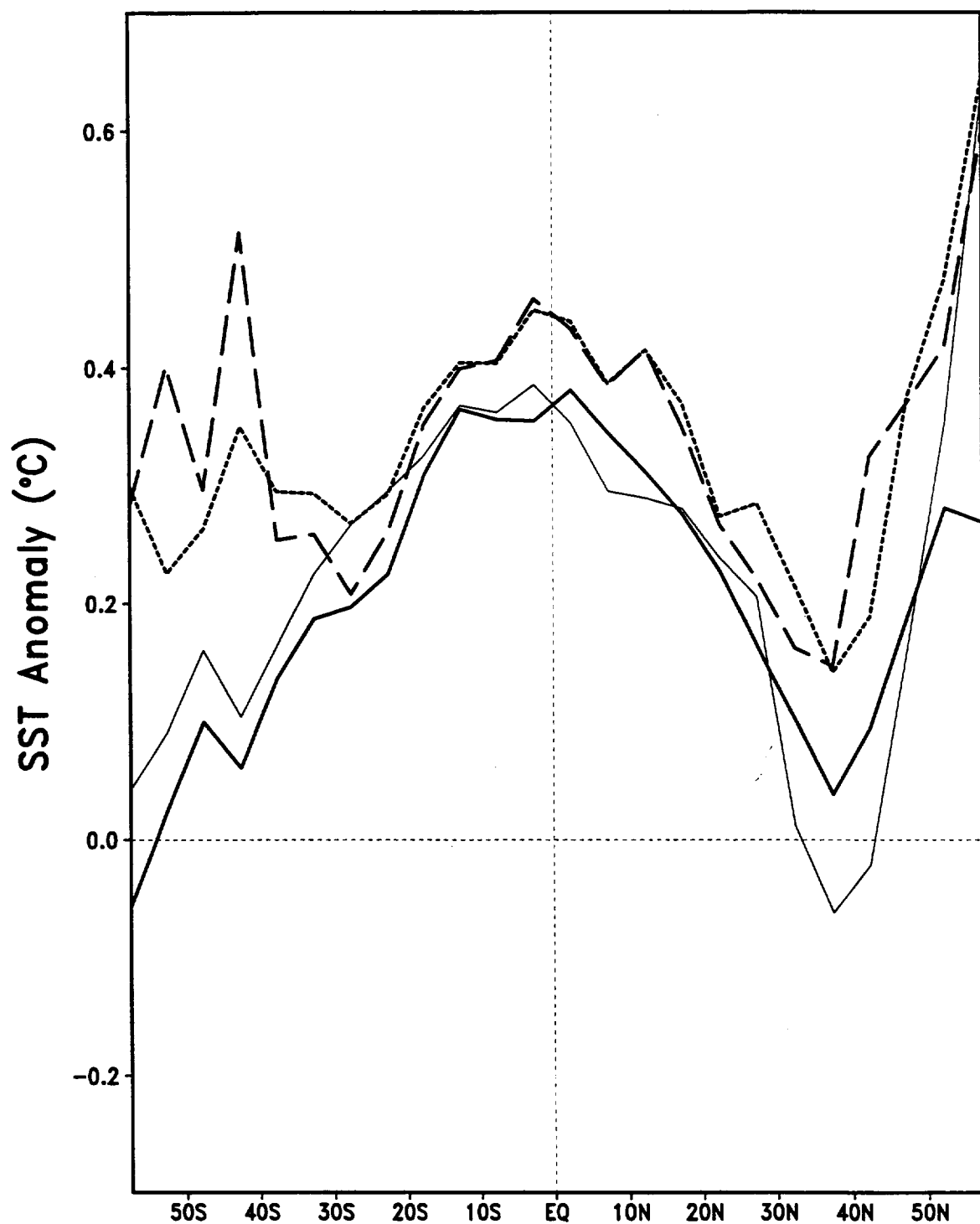
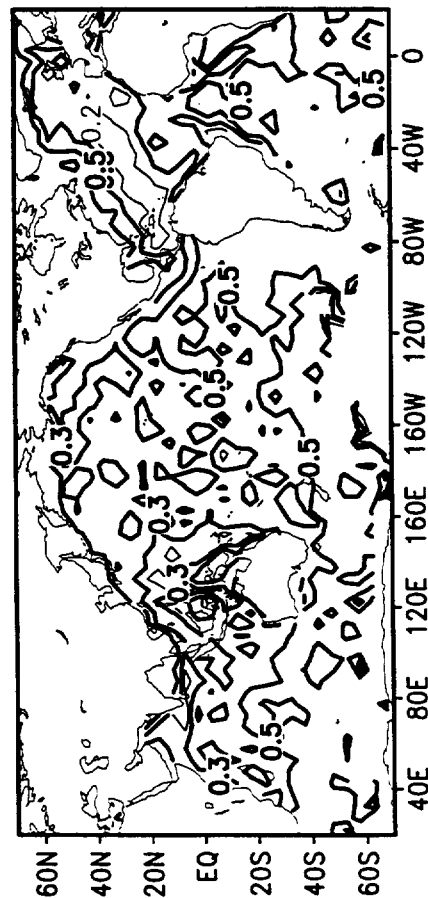RMS Relative to NCEP: January 1995 – December 1997
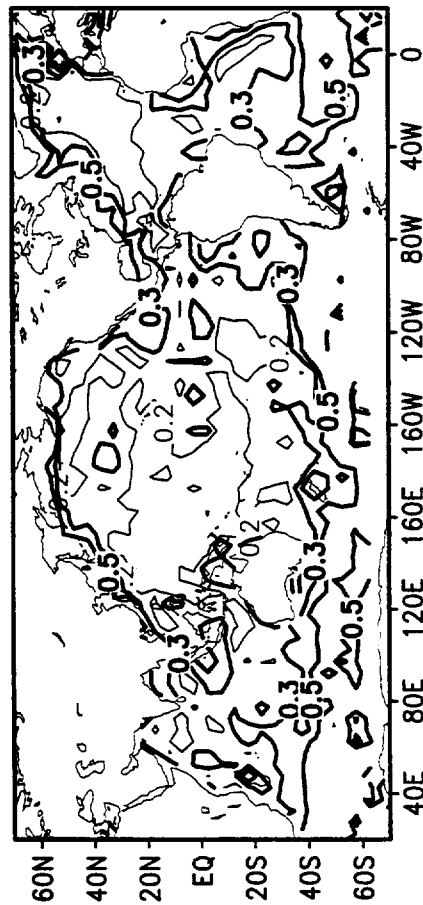
NRL SST Anomaly (°C)

BMRC SST Anomaly (°C)

UKMO SST Anomaly (°C)

JMA SST Anomaly (°C)

REDUCED SPACE APPROACH TO THE OPTIMAL ANALYSIS OF HISTORICAL SST: ACCOMPLISHMENTS, DIFFICULTIES, AND PROSPECTS[1]

Alexey Kaplan

Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10964

1 Introduction

Use of leading empirical orthogonal functions (EOFs) for reconstructing historical data sets and sea surface temperature (SST) in particular has become quite popular in recent years [Shriver and O'Brien, 1995; Smith et al., 1996; Rayner et al., 1996]. Kaplan et al. [1997] combined this approach with the least squares based optimal estimation to formulate reduced space analogues of the traditional technique of optimal analysis (optimal interpolation (OI), Kalman filter (KF), optimal smoother (OS)). Application of the reduced space optimal smoother to the historical SST observations resulted in a near-global $5° \times 5°$ resolution analysis of SST for 1856-1991 [Kaplan et al., 1998a] publicly available at

http://ingrid.ldgo.columbia.edu/SOURCES/.KAPLAN/.RSA_MOHSST5.cuf/.dataset_documentation.html

Section 2 summarizes the advantages of the reduced space optimal estimation and puts it into the context of more traditional objective data analyses. Section 3 describes the difficulties currently experiencing by the method applications, and section 4 suggests the ways of resolving the difficulties and directions for the further work.

2 Accomplishments

Least-squares-based popular methods of data analysis, such as optimal interpolation (OI), Kalman filter (KF), or optimal smoother (OS), are supposed to give optimal solutions if certain requirements are satisfied, among which is that covariance matrices of all errors involved are known. However, in actual applications to the problems of climate research the realistic dimensions of data are often large enough to warrant two outcomes:

1. error covariance matrices are not known in all their details since there are not enough data to resolve them completely, so some crude parameterizations are used instead,

2. if no simplifications are done, optimal data analysis procedures are very expensive (OI), extremely expensive (KF), or prohibitively expensive (fixed-interval OS).

Both these difficulties, however, can be dealt with at once if certain features of optimal solutions of realistic climate fields are taken into account.

Consider as an example a standard OI problem whose solution is a minimizer T of the cost function

$$\mathbf{S}[T] = (HT - T^o)^T R^{-1}(HT - T^o) + (T - T^b)^T C^{-1}(T - T^b). \qquad (1)$$

Here T^o is a vector of observations, T^b is a first guess (background) solution, H is a transfer matrix from a complete field to the set of observed points, R and C are covariances of observational and first guess errors respectively. Solution to this problem is

$$T = P\left(H^T R^{-1} T^o + C^{-1} T^b\right),$$

where

$$P = \left(H^T R^{-1} H + C^{-1}\right)^{-1}$$

---

is estimated covariance of its error.

Let us subtract the first guess solution from the estimated field, so that the new $\mathcal{T}$ is $\mathcal{T} - \mathcal{T}^b$ and new $\mathcal{T}^o$ is $\mathcal{T}^o - H\mathcal{T}^b$ (if the first guess solution is a climatological field, then we redefined the signal to be a field of anomalies). After such change in definitions the matrix C becomes the covariance of the signal $\langle \mathcal{T}\mathcal{T}^T \rangle$. It can be expanded into its canonical representation

$$C = E\Lambda E^T, \tag{2}$$

E being a matrix of eigenvectors (EOFs if C is effectively a sample covariance estimate), and Λ is a diagonal matrix of eigenvalues. We can use eigenvector patterns to rotate an estimated field

$$\mathcal{T} = E\alpha \tag{3}$$

so that $\alpha = E^T\mathcal{T}$ becomes a new unknown: a vector of projections of a target field on eigenvectors.

For simplicity let us consider the case of a completely observed system ($H = I$) with white uniform error ($R = rI$). OI solution for such a system has a closed form for each component of α:

$$\alpha_i = \frac{\lambda_i}{\lambda_i + r}\alpha_i^o$$

($i = 1 \cdots N$ is an index of components, eigenvalues and eigenvectors, $\alpha^o = E^T\mathcal{T}^o$ is a vector of projections of the observed field $\mathcal{T}^o$ on eigenvectors). As usual we assume that eigenvalues are arranged in a descending order. The often case then is that $\lambda_N \ll r \ll \lambda_1$. This means that $\alpha_1 \approx \alpha_1^o$, and $\alpha_N \approx 0$. In other words, the standard least squares procedure of OI in its search for the optimal solution will dampen the observed values of all eigenvector amplitudes whose energy in the signal does not dominate over the observational error. To those eigenvector modes which suppose to have energy much below the level of observational error, no energy will be allowed in the OI solution. This means that the classical OI procedure effectively discards from the solution all modes with eigenvalues much smaller than the observational error.

Consequently, computing the OI solution in all its details (projection to all EOFs) is superfluous: results as good can be achieved by computing only projections on some set of leading eigenvectors. Moreover, details of the solution on small scales (projection to high number eigenvectors) is controlled by the fine details of the covariance matrix C which usually cannot be reliably estimated from the data. Large scale patterns of C (leading eigenvectors), however, can be estimated in a more reliable way. Approximation of C in (2) by only a few leading terms (truncation) results in infinite coefficients in the second term of the cost function (1) which totally disallow projection of the solution on truncated modes. The same result, of course, can be achieved by truncating the eigenvector representation of the solution (3) to begin with. We call such a truncation a reduced space representation of the solution; inserting the truncated form of (3) into cost functions followed by their minimization with regards to the low-dimensional vector α allowed to develop the reduced space analogues of the OI, KF, and OS algorithms [Cane et al. 1996; Kaplan et al. 1997].

While these solutions are formally suboptimal among full grid solutions, they are optimal among all reduced space solutions, being also far cheaper and much easier to feed by a priori error covariance information. For the settings which allow direct comparison, the solutions in the reduced space prove to be not inferior to the actually existing full grid solutions [Cane et al. 1996]. The reason for that is the poor representation of small scales in full grid error covariance estimates. As a result, full grid data assimilation on small scales does more harm than good. Moreover, the assimilation for those scales represents the major computational expense of the entire procedure. Hence the savings of reduced space analysis occur at the scales which are not really constrained by the data. Estimation on such scales is meaningless, but the traditional schemes cannot selectively cut off computation there. The tunable nature of the dimension of a reduced space allows to put

into the solution all scales down to the smallest resolved by available data, and the choice of leading EOFs for a basis guarantees to some extent the minimal dimension of the analysis space.

We applied the reduced space OS to produce the near-global analysis of $5° \times 5°$ SST anomaly grids for the period 1856–1991 [Kaplan et al. 1998a]. Observational data used in this work is known as MOHSST5 compilation of ship observations produced by the U.K. Meteorological Office [Bottomley et al. 1990; Parker et al. 1994]. Top panels of Figure 1 demonstrate potential of the reduced space optimal estimation: out of sparse observations available for December 1877 (which is known to be a year of the tremendously warm El Niño – southern oscillation (ENSO) event) the analysis produces quite believable structure of a very strong El Niño. In order to verify the credibility of such reconstructions, we took the data for December 1986, a recent well observed El Niño episode (Figure 1, middle panels), and corrupted them in simulation of 1877 sampling: the 1986 data were dropped out from all space points where they were not available for 1877, and those left were perturbed by noise reciprocating improvements in the quality of observations over almost a century. For these severely deranged data (Figure 1, bottom panels), the OS analysis produced the 1986 El Niño pattern only slightly weaker than that obtained for the full data. Figure 2 shows the monthly values of the analyzed NINO3 (mean SST for the easter n equatorial Pacific $5°S-5°N$, $150°-90°W$), a familiar ENSO index, with 3σ error bars supplied by the analysis. Obviously, the analysis eliminates a great deal of noise present in direct NINO3 estimates from the observed data, and agrees well with land-based empirical ratings of El Niño events. Note that the reduced space optimal analysis produces theoretical estimates of solution error which were thoroughly verified in this application.

Further applications of the same methodology at this time include $5° \times 5°$ resolution analysis of historical marine sea level pressure [Kaplan et al. 1998c] and first steps on the way of SST reconstruction from paleo proxies (coral $\delta^{18}O$ and tree ring width chronologies) [Evans et al., 1998ab, Kaplan et al. 1998b].

3 Difficulties

Advantages of the reduced space optimal analysis do not come for free: they are based on our knowledge of a priori error estimates, namely covariances of observational error R and of the solution C. Both this covariances can be computed only approximately from the observations.

In computing R (which allows the algorithm distinguish between poor and high quality super-observations) we use intrabox variability and number of observations for the superobservational bins. Unfortunately, we had to use estimates from the COADS dataset [Woodruff et al. 1987] for that as the U.K. Met Office does not maintain any intrabox statistics but winsorized means in its official data format. Our estimates of observational error are far from being perfect: Figure 3 shows the map of our estimates of the error which a single ship observation makes compared to $5° \times 5°$ superobservations (these values were used in the analysis of Kaplan et al. [1998a]). Comparison of this map with the map of random error estimates by Kent et al. [1998] brings mixed conclusions. Granted the latter map does not include any kind of sample error, that explains much larger values on the Figure 3 in the regions of Gulf Stream and Kuroshio. However, outside of these areas the map of Figure 3 should still be giving larger values everywhere. This does not seem to be the case, but the rough correspondence between the map values is still encouraging. Clearly a lot more work should be done in this direction till really reliable observational error estimates will enter SST gridded analyses. Important step on this way would be to bring to the attention of all data centers the necessity to include the statistics of intrabox distributions into their standard data formats, rather than just provide box mean values. This seems to be particularly crucial on the rise of large blending project of COADS and UKMO data banks.

The problems with the reliable estimate of C are even more fundamental: the present applications

of the reduced space optimal analysis all have coarse resolution and are globally incomplete: there are not enough observations to estimate long term (at least a few decades long) covariance of SST even with the resolution $2° \times 2°$ for the entire world ocean. This severely limits the usage of such analyses for AGCM studies. While one solution would be to use shorter periods for the covariance estimation [e.g. Smith et al. 1996] (which potentially makes it less suitable for reproduction long term SST variability), another way to approach the problem is sketched in the next section.

4 Prospects

Multivariate approach can empower the reduced space reconstruction technique. Principal modification of the reduced space optimal analysis that can produce high-resolution globally complete fields is to separate an estimated field into a few pieces which correspond to different scales of resolution (and thus variability). Different pieces are observed through different sources (e.g. the most of the ocean $5° \times 5°$ resolution piece is well observed by ships during last 50 years, and $1° \times 1°$ variability within $5° \times 5°$ boxes plus all variability in the Southern ocean can be estimated from NCEP OI [Reynolds and Smith 1994] for the last 15 years, etc) and can be subjected to multivariate EOF analysis, each piece being a separate variable in this analysis. These multivariate EOFs then used for the reconstruction of all pieces together, and thus for the entire high-resolution globally-complete field. This approach has certain "modular" nature because of which it allows to push further in both directions: very large scale variability can be estimated for very long periods from the paleodata, extending the analysis to very long periods, and certain areas of high gradients and/or good observational networks can be "refined" by adding special high resolution "patches."

Multivariate approach can produce truly global surface temperature fields: SST on the ocean, air temperature on the land – each part will benefit from the covariances with the other. And finally we will have error bars on the rising global mean timeseries – IPCC might get interested in such a project.

Reduced space optimal analysis approach can possibly be useful even for NCEP OI bias correction procedure.

We believe that the technique of reduced space optimal estimation should be used more systematically in application to all climate variables for which historical (COADS) data sets are available, e.g. meridional and zonal winds, marine air temperature, humidity, or (non-COADS) precipitation, possibly sea surface height.

References

Bottomley, M., C.K. Folland, J. Hsiung, R.E. Newell, D.E. Parker, 1990: *Global Ocean Surface Temperature Atlas*. HMSO, London

Cane, M.A., A. Kaplan, R.N. Miller, B. Tang, E.C. Hackert, and A.J. Busalacchi (1996). Mapping tropical Pacific sea level: data assimilation via a reduced state space Kalman filter. *J. Geophys. Res.*, **101**, 22599–22617.

Evans, M., A. Kaplan, and M. Cane, Optimal sites for coral-based reconstruction of sea surface temperature, *Paleoceanography*, **13**, 502-516, 1998a.

Evans, M., A. Kaplan, and M. Cane, Cross-validation of a sparse network of coral data and sea surface temperatures: Potential for coral-based SST field reconstructions, *Paleoceanography*, submitted, 1998b.

Kaplan, A., Y. Kushnir, M.A. Cane, and M.B. Blumenthal, 1997: Reduced Space Optimal Analysis for Historical Datasets: 136 years of Atlantic Sea Surface Temperatures. *J. Geoph. Res.*, **102**, 27,835–27,860.

Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856-1991, *J. Geoph. Res.*, **103**, 18,567-18,589, 1998a

Kaplan, A., M. Evans, M. Cane, and R. Villalba, Globality and optimality in SST field reconstructions from tree rings: ENSO and more, *Pole–Equator–Pole Paleoclimate of Americas (PEP1) Conference,*

Merida, Venezuela, March 16-20, 1998b.

Kaplan, A., M. Cane, Y. Kushnir, Reduced Space Optimal Interpolation of Historical Marine Sea Level Pressure: 1854–1992, *in prep.*, 1998c.

Kent, E.C., P. Challenor, and P. Taylor, A statistical determination of the random errors present in VOS meteorological reports. *Journal of Atmospheric and Oceanic Technology*, submitted, 1998.

Parker, D.E., P.D. Jones, C.K. Folland, and A. Bevan (1994). Interdecadal changes of surface temperature since the late nineteenth century. *J. Geophys. Res.*, **99**, 14,373–14,399.

Reynolds, R.W., and T.M. Smith, 1994: Improved global sea surface temperature analysis using optimum interpolation. *J. Climate*, **7**, 929-948.

Shriver, J.F., and J.J. O'Brien, 1995: Low-frequency variability of the equatorial Pacific ocean using a new pseudostress dataset: 1930-1989. *J. Climate*, **8**, 2762-2786.

Smith, T. M., R. W. Reynolds, R. E. Livezey, and D.C. Stokes, 1996: Reconstruction of historical sea surface temperatures using empirical orthogonal functions. *J. Climate*, **9**, 1403-1420.

Woodruff, S.D., R.J. Slutz, R.L. Jenne, and P.M. Steurer, 1987: A comprehensive ocean–atmosphere data set. *Bull. Amer. Meteor. Soc.*, **68**, 521-527.
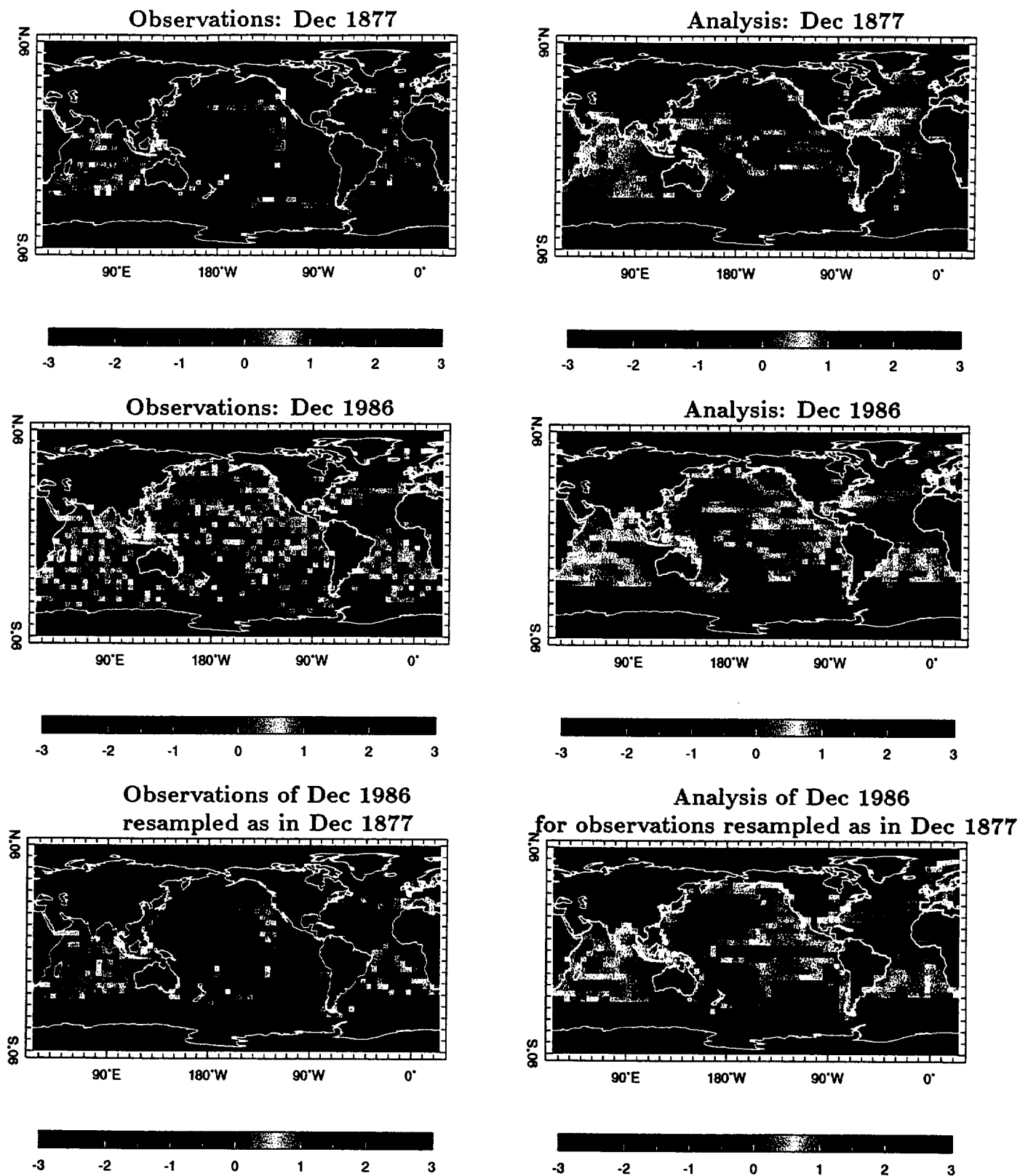
Figure 1: Available SST observations and their reduced space OS analysis for December 1877 (top panels) with verification through the experiment with 1986 data: simulated OS analysis for December 1986 using the data distribution of 1877 (bottom panels) versus the standard OS analysis for December 1986 with all available data (middle panels). Units are $^{\circ}C$.
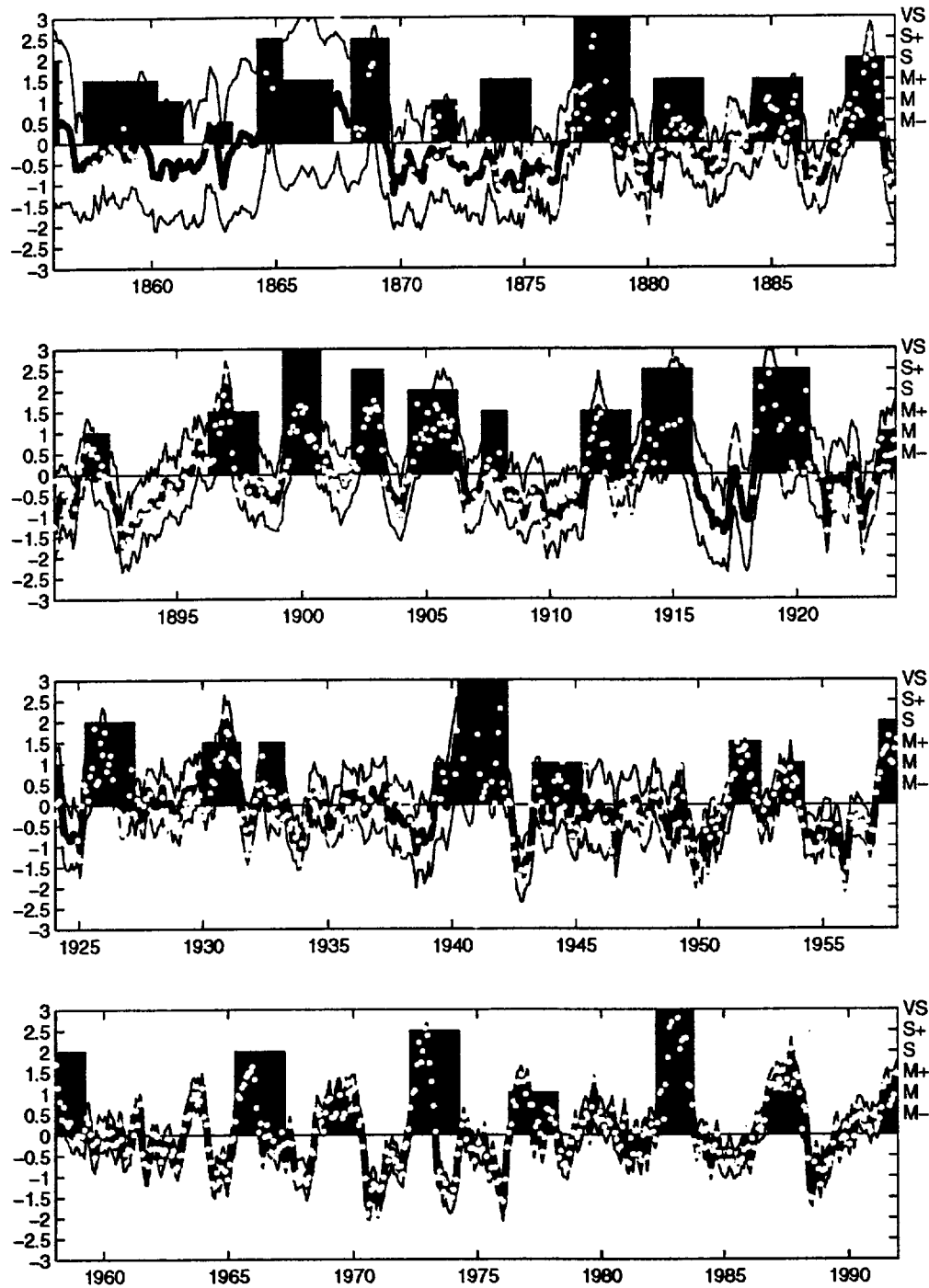
Figure 2: The reduced space optimal smoother reconstruction of the NINO3 index based on ship observations of SST (thick solid line). Also shown are 3σ error bars on the analysis values (thin lines), the straight estimates of NINO3 from raw data (dots), and the ENSO event ratings of *Quinn et al.* [1987] (histogram bars). Histogram bars are scaled to the *Quinn et al.* [1987] ratings: M-, M (moderate), M+, strong (S), S+, and very strong (VS). The reconstructed NINO3 identifies 28 of 37 events listed by *Quinn et al.* [1987], and the magnitude of events are in good agreement.

Figure 3: Intrabox (5°×5°) standard deviation estimates for monthly SST anomalies, °C, as used in the historical SST analysis of Kaplan et al. [1998]

THE ACCURACY OF SEA SURFACE TEMPERATURE DATA FROM VOLUNTARY OBSERVING SHIPS.[1]
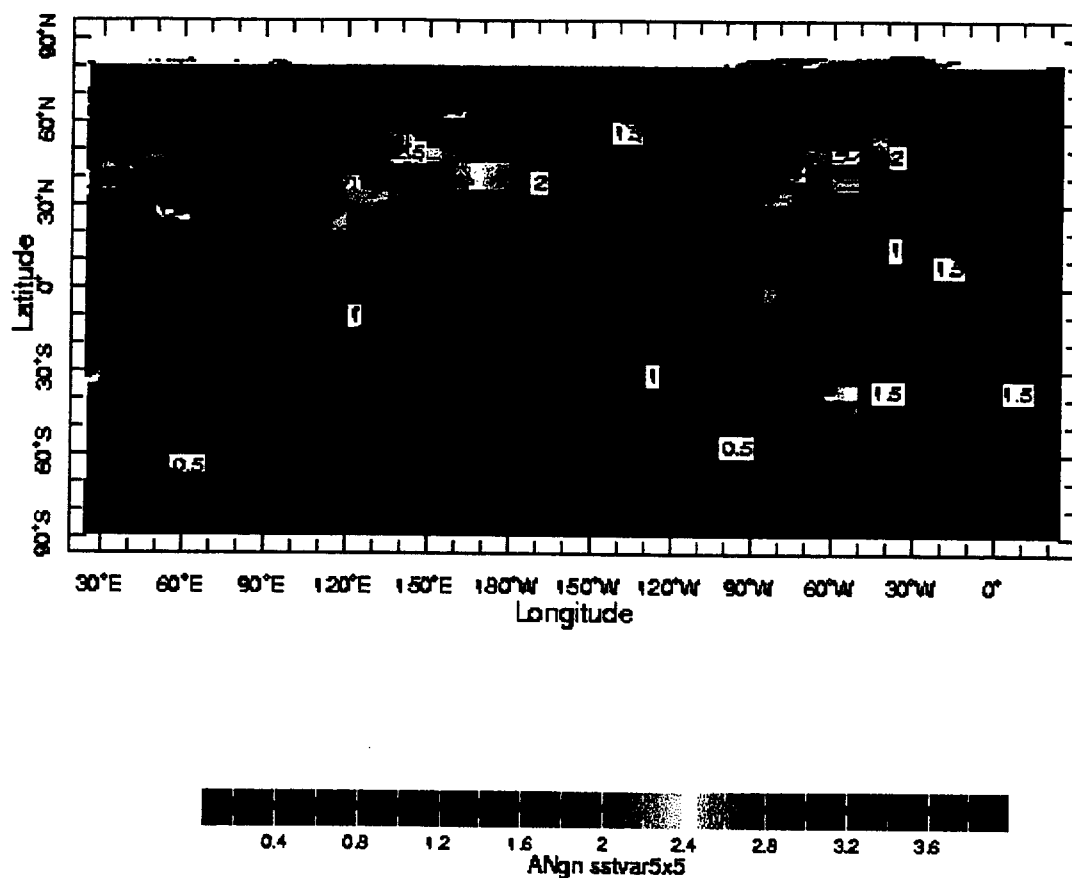
Peter K. Taylor, Elizabeth Kent, and Simon Josey

James Rennell Division, Southampton Oceanography Centre,

Southampton, SO14 3ZH, UK

1. Introduction

This talk will review the results for sea surface temperature (SST) from the Voluntary observing ship Special Observation Program - North Atlantic (VSOP-NA) project. Guided by those results the SST values used in the new SOC air-sea flux climatology were corrected: engine room intake (ERI) SST data were reduced by 0.35°C . It will be shown that the resulting SOC climatology SST fields are about 0.2°C cold compared to the NMC SST fields and also against the WHOI IMET buoy deployments. However this apparent agreement between the NMC fields and the buoy data may well be fortuitous. The question is just how accurately can we define the absolute value for SST?

2. Systematic errors in ship data.... the VSOP-NA project

The VSOP-NA project (Kent et al. 1991, 1993a) involved 46 Voluntary Observing Ships (VOS) operating on North Atlantic routes. The instrumentation and observing methods used on the ships were carefully documented (Kent and Taylor, 1991) and an atmospheric forecast model was used as a means of comparing one set of ships with another. The VSOP-NA results quantified systematic biases in most of the observed variables - SST, air temperature, winds, dew point, etc. but biases in the resulting heat flux estimates tended partially to cancel (Kent and Taylor, 1995; Josey et al. 1998). An example of the VSOP-NA results for SST is shown in Figure 1. Using the model as a comparison standard (Figure 1a) the bucket and hull sensor data were in reasonable agreement at night, while the ERI data was comparatively warm. The hull contact data were less scattered than those from other methods. Using the hull contact data as a reference (Figure 1b) showed that the ERI data were on average biased high by between 0.2 and 0.4°C, a typical mean value was 0.35°C but individual ships had mean biases between - 0.5°C (too cold) and +2.3°C (too warm). Figure 1b also indicates that the bucket values were possibly about 0.1°C cold at night but became biased warm by up to 0.4°C with increasing solar radiation. Incidentally, increasing sunshine had a much greater effect on the air temperature measurements with biases of a few degrees (Kent et al., 1993b) although the humidity measurements were not affected (Kent and Taylor, 1996).

3. Random errors.... the semi-variogram technique

Whereas the VSOP-NA experiment attempted to quantify the systematic errors in the ship data, Kent et al. (1998) have recently used the semi-variogram technique to quantify the random errors. In this method, the mean squared difference between pairs of SST data from
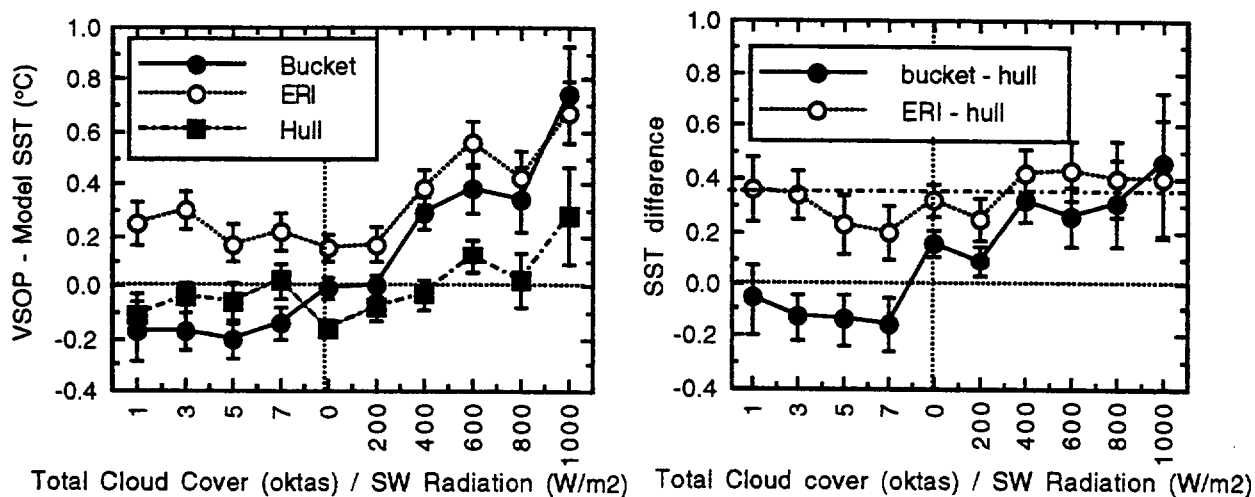

Figure 1. Comparisons of SST data obtained from the VSOP-NA ships using SST buckets, engine room intake thermometers, and hull contact sensors. Night time data is plotted against total cloud amount and day time data against the estimated solar (short wave) radiation.
a. (left) mean difference (ship data - model value)
b. (right) mean difference using the hull contact sensor data as a reference.
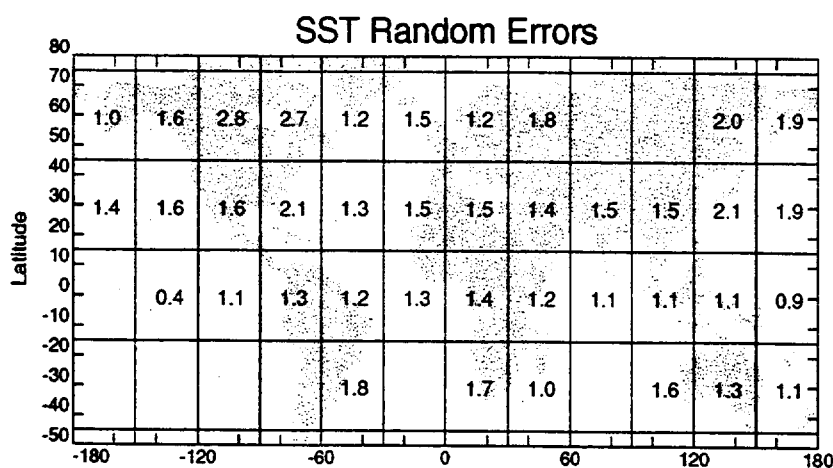
Figure 2. Estimate of the rms error for individual ship observations of SST calculated for the ocean areas shown. In blank regions there were too few ship reports to make a reliable estimate (Kent et al. 1998).

different ships is calculated for different ranges of ship separation. The intercept (obtained by extrapolation to zero separation) represents twice the rms error squared. Depending on ocean area the rms errors for individual SST observations typically ranged between 1 and 2°C with a tendency for larger errors to be in coastal regions at mid- and high latitudes and smaller values to occur in the equatorial seas (Figure 2). Kent et al. (1998) also evaluated the effect of the VSOP- NA corrections. Whereas height correcting the anemometer winds and using the Lindau (1995) scale for visual winds reduced the random error for wind observations by 10 to 15%, correcting the SST data had negligible effect on the calculated rms error.

4. The SOC Surface Flux Climatology

The new SOC Surface Flux Climatology (Josey et al. 1996: 1998) was produced under contract to the Hadley Centre, UK Meteorological Office. The present version uses the VOS

data in the COADS release 1a (Woodruff et al., 1993) with bias corrections based on the VSOP-NA results applied using meta-data from the annual List of Selected Ships ("WMO - 47", e.g. WMO, 1990). Thus engine room intake SST values were reduced by 0.35°C and data for which the observation method was unknown were reduced by 0.2°C (to reflect the proportion of ERI data from the fleet as a whole). This SST correction decreased the ocean cooling through the turbulent heat fluxes. The largest changes were -5 W/m² in the sensible heat flux (N. Pacific in January) and, for the latent heat flux, -10 W/m² in the Kuroshio region in January and also over much of the tropical Pacific in July.

5. Comparison with NMC SST analyses

The SOC climatology has been compared with the output from an Atmospheric Model Intercomparison Project (AMIP) run of the Hadley Centre HADAM3 atmospheric model. The SST specified for AMIP was based on National Meteorological Centre (NMC) analyses for 1979 to 1988. These rely on ship observations so a bias of about 0.2°C might be expected (given the mix of ERI and other measurements). Comparison for different ocean regions shows an average bias of that amount (Table 1.).

Table 1. Mean difference between SOC and NMC SST values for selected ocean regions.

Area	SOC - NMC (°C)
East sub-tropical Pacific	-0.14 ±0.02
West sub-tropical Pacific	-0.25 ±0.02
Kuroshio region	-0.16 ±0.03
TOGA COARE	-0.30 ±0.02
Atlantic (Subduction expt.)	-0.22 ±0.05
Arabian Sea	-0.18 ±0.03
All	-0.21 ±0.01

6. Comparison with IMET buoy deployments

Compared to the high quality SST measurements from the IMET buoy deployments (Weller and Anderson, 1996; Weller et al., 1997; Weller et al., 1990) SOC values show a mean offset, being colder by about 0.3°C. At a given site, this offset tends to be greater when the SST is greater (Figure 3). This suggests that, since the IMET buoy sensors were at between 0.5 to 1m in depth (substantially shallower than most VOS observations), near surface SST gradients may have caused this difference.

Table 2 Comparison of SOC SST and NMC SST analyses with IMET buoy deployments.

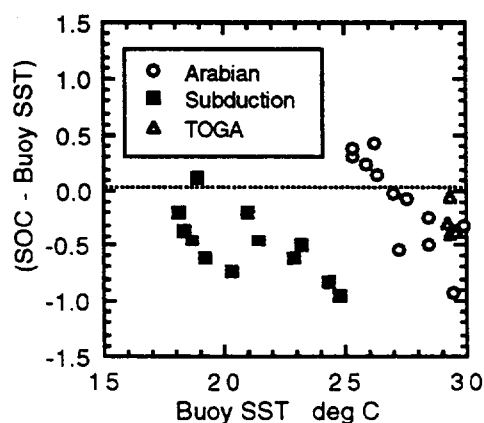| IMET deployment	SOC SST		NMC SST	
	mean	s.e.	mean	s.e.
Subduction	-0.5	±0.1	-0.3	±0.1
Arabian Sea	-0.1	±0.1	0.1	±0.1
TOGA	-0.3	±0.1	0.1	±0.1
All	-0.29	±0.07	-0.06	±0.08

Figure 3. Comparison of SOC SST values with IMET buoy deployments.

7. Summary and Conclusions

The ERI SST measurements during the VSOP-NA project were biased warm, on average by between 0.25 and 0.45°C. For that reason, ERI SST data in the SOC climatology were reduced by 0.35°C (unknown method data were reduced by 0.2°C). However unlike the other VSOP-NA based corrections, the rms errors in the VOS SST data were not reduced. The SST field in the SOC climatology is cold compared to the NMC SST fields used in AMIP by about 0.2°C. But this is expected given the proportion of ERI observations in the data set. However the SOC SST field is also about 0.3°C cold compared to the IMET buoys: although the SOC turbulent flux values were generally in good agreement with the buoys. This may be due to near surface sea temperature gradients at the buoy sites, although the magnitude of the effect seems rather large. Thus, while the apparent agreement between NMC analyses and the buoy SST's may be fortuitous, further work is desirable to confirm the VSOP-NA results for ERI measurements. Above all, the study has confirmed that obtaining an accurate calibration of SST data to the desired 0.1°C is not an easy undertaking!

8. References

Josey, S. A., E. C. Kent, D. Oakley and P. K. Taylor, 1996: A New Global Air-Sea Heat and Momentum Flux Climatology. International WOCE Newsletter, 24, 3 - 5 + figs.

Josey, S. A., E. C. Kent and P. K. Taylor, 1998: New Insights into the Ocean Heat Budget Closure Problem from Analysis of the SOC Air-Sea Flux Climatology. Journal of Climate (submitted).

Kent, E. C., P. Challenor and P. Taylor, 1998: A Statistical Determination of the Random Errors Present in VOS Meteorological Reports. Journal of Atmospheric and Oceanic Technology (submitted).

Kent, E. C. and P. K. Taylor, 1991: Ships observing marine climate: a catalogue of the Voluntary Observing Ships Participating in the VSOP-NA. Marine Meteorology and Related Oceanographic Activities 25, World Meteorological Organisation, Geneva, 123 pp.

Kent, E. C. and P. K. Taylor, 1995: A comparison of sensible and latent heat flux estimates for the North Atlantic ocean. Journal of Physical Oceanography, 25(6), 1530 - 1549.

Kent, E. C. and P. K. Taylor, 1996: Accuracy of humidity measurements on ships: consideration of solar radiation effects. Journal of Atmospheric and Oceanic Technology, 13(6), 1317 - 1321.

Kent, E. C., P. K. Taylor, B. S. Truscott and J. A. Hopkins, 1993a: The accuracy of Voluntary Observing Ship's Meteorological Observations. Journal of Atmospheric and Oceanic Technology, 10(4), 591 - 608.

Kent, E. C., R. J. Tiddy and P. K. Taylor, 1993b: Correction of marine daytime air temperature observations for radiation effects. Journal of Atmospheric and Oceanic Technology, 10(6), 900 - 906.

Kent, E. C., B. S. Truscott, J. S. Hopkins and P. K. Taylor, 1991: The accuracy of ship's meteorological observation - results of the VSOP-NA. Marine Meteorology and Related Oceanographic Activities 26, World Meteorological Organisation, Geneva, 86 pp.

Lindau, R., 1995: A new Beaufort equivalent scale. Internat. COADS Winds Workshop, Kiel, Germany, 31 May - 2 June 1994, Institut fur Meereskunde, 232 - 252.

Weller, R. A. and S. P. Anderson, 1996: Surface Meteorology and air-sea fluxes in the western equatorial Pacific warm pool during the TOGA Coupled Ocean-Atmosphere Experiment. Journal of Climate, 9, 1959 - 1990.

Weller, R. A., M. F. Baumgartner, S. A. Josey, A. S. Fischer and J. Kindle, 1997: A one-year record of atmospheric forcing from the Arabian Sea. Deep Sea Research, (submitted).

Weller, R. A., D. L. Rudnick, R. E. Payne, J. P. Dean, N. J. Pennington and R. P. Task, 1990: Measuring near surface meteorology over the ocean from an array of oceanographic moorings in the sub-tropical convergence zone. Journal of Atmospheric and Oceanic Technology, 7, 85 - 103.

WMO, 1990: International list of selected, supplementary and auxiliary ships. , World Meteorological Organisation, Geneva, (annual publication).

Woodruff, S. D., S. J. Lubker, K. Wolter, S. J. Worley and J. D. Elms, 1993: Comprehensive Ocean-Atmosphere Data Set (COADS) release 1a: 1980-92. Earth System Monitor, 4(1), 4 - 8.

STRATEGY FOR CREATING HOMOGENEOUS SEA-ICE CONCENTRATION DATA SETS.

David E Parker
Hadley Centre, Meteorological Office Bracknell, United Kingdom

with inputs from Nick Rayner (Hadley Centre),
Bob Grumbine (NOAA)
and Jim Maslanik (Univ. Colorado)

26 October 1998

1. Characteristics of existing satellite-based datasets
      1.1. Walsh
      1.2. National Ice Center (NIC)
      1.3. Nomura-Grumbine (NG)
      1.4. Goddard Space Flight Center (GSFC)
2. What is required of a blend?
3. Blending techniques.
4. Proposed procedure.
Appendix: Acronyms.

1. CHARACTERISTICS OF EXISTING SATELLITE-BASED DATASETS.

1.1. Walsh

a. Period covered: 1901 to 1990, monthly.

b. Arctic only.

c. Based mainly on in situ (ship) data before 1973, then uses NIC? So information is more detailed in the marginal ice zone, and scanty within the ice pack.

1.2. National Ice Center (NIC)

a. Period covered: 1973-1994, weekly

b. Uses a time-varying mix of sources including in situ (ship) data, aircraft transects, radar, and AVHRR. The highest resolution data source available is used, largely to the exclusion of others. Did not use SSMI (or SMMR) before Nov 1994. SSMI is the data set of last resort.

c. Excludes Great Lakes.

d. Analysis is subjective. It concentrates on areas of operational interest: other areas are skated over and may change little with time. The high Arctic in winter is analyzed as 9-10 tenths: this is probably an overestimate. Regional accuracy will vary depending on data sources available and perceived importance of particular regions. Detail has increased recently in e.g. East Greenland current. The inhomogeneities in the NIC analysis are irreproducible.

e. Jan 1985 has unusually little ice in Laptev and East Siberian seas.

f. May be biased by some operational concerns, such as not wanting to indicate ice-free when ice may be present (Jim Maslanik's speculation).

g. Best for actual ice extent

h. Best for summer melt conditions

i. Lends itself to fairly straightforward merging with AARI charts, which will be quite accurate for eastern Arctic.

1.3. Nomura-Grumbine (NG)

a. Period covered: 1979-1998, once per 2 days to 1987 then daily. Available in near real time.

b. Based on SMMR to 1987 then SSMI.

c. SMMR/SSMI omit polar cap north of 87.5N owing to satellite orbit configurations. Nomura ascribed 100% coverage to this gap. Grumbine filled his fields north of 87.5N using Laplace's equation with the boundaries at 87.5N fixed by the ice analysis.

d. Up to Nov. 1991: created by Nomura from the NSIDC ice concentration grids. Bob Grumbine cannot reproduce Nomura's results with Nomura's program.

e. Dec 1991- sometime in 1994-5: created by Bob Grumbine from the NSIDC gridded TEMPERATURES using the Team algorithm as provided by Don Cavalieri. Small biases found (1% about 1/2 the time).

f. Sometime in 1994-5, the SSMI data set shifted from being the NSIDC CD-ROMs to the NWS operational data feed of SSMI. Concurrent with this, the base grid domain went from the NASA grid to being a more extensive (though still polar stereographic) grid which covered all the potentially ice-covered waters of the Northern Hemisphere.

g. Starting 31 October 1995: changed from a 1° grid to a 0.5° grid. This, and/or a concurrent change in the transfer method, had a non-negligible effect on the climate properties of the derived grids (Mike Fiorino detected this in preparing for AMIP II).

h. Oct-Mar 1995-6 requires reprocessing. Sept 1995 also suspect.

i. December 1987 is unreliable owing to temporary outage of SSMI.

j. Microwave sensing (SMMR, SSMI) underestimates ice fraction in summer owing to the presence of melt ponds and/or slush on ice surface (these appear more or less as "open water" to the algorithm).

k. SMMR, SSMI provide more spatial detail than NIC of conditions within the pack.

l. SMMR, SSMI have errors over open ocean and along coasts due to algorithm and data characteristics. These errors have not been removed from NG.

m. Algorithms, and assessments, have been designed primarily for hemispheric and global applications, such that they may be overall reasonably good, but with less accuracy than ice charts for specific locations such as regional MIZ conditions.

1.4. Goddard Space Flight Center (GSFC): Cavalieri et al. (1997).

a. Period covered: Oct 1978-1996, once per 2 days to 1987 then daily.

b. Based on SMMR to 1987 then SSMI.

c. Processed by Don Cavalieri et al. (SCIENCE, 278, 1104-1106, 7 Nov. 1997) so as to be homogeneous between SMMR and SSMI and between the SSMIs on successive satellites.

d. SMMR/SSMI omit polar cap north of 87.5N owing to satellite orbit configurations: Cavalieri et al. (1997) have not filled this gap.

e. December 1987 is missing owing to temporary outage of SSMI.

f. Microwave sensing (SMMR, SSMI) underestimates ice fraction in summer owing to the presence of melt ponds and/or slush on ice surface (these appear more or less as "open water" to the algorithm). (as comment j) of NG)

g. SMMR, SSMI provide more spatial detail than NIC of conditions within the pack. (as comment k) of NG)

h. SMMR, SSMI have errors over open ocean and along coasts due to algorithm and data characteristics. These errors have been removed from GSFC (they have not been removed from NG: see comment l) of NG)

i. Algorithms, and assessments, have been designed primarily for hemispheric and global applications, such that they may be overall reasonably good, but with less accuracy than ice charts for specific locations such as regional MIZ conditions (as comment m) of NG).

2. WHAT IS REQUIRED OF A BLEND.

2.1 Transfer to a common grid. In this process, it is desirable to:
  i) Preserve ice area
 ii) Preserve ice extent
iii) Preserve ice concentration temporal variability
 iv) Preserve ice concentration spatial variability
The Land Mask for both native and derived (latitude-longitude) grid should be consistent with these conservation principles. Beam Periphery land contamination effects should not be allowed to cause a bias. [Bob Grumbine produced a 10^6 km^2 change in ice area by going between two different, but reasonable, land masks].

2.2 The microwave data should be corrected for sensor drifts, and consistent processing methods should be used in implementing algorithms.

2.3 An algorithm correction may be applied for summer melt bias (IF it is thought that an atmosphere model should regard ponds as not open ocean).

2.4 The output time series should be homogeneous, i.e. trends and variations should reflect real changes in sea-ice concentration, not instrumental changes or processing changes such as change from end-of month to all-month data.

2.5. Because the series are expected to be updated using microwave data, then it is better to make the historical data consistent with these, rather than the reverse.

3. BLENDING TECHNIQUES.

3.1. Regressions, not necessarily linear, varying with season and location. A problem is that there may not be one-to-one correspondence, e.g. NIC could give 95% concentration where SSMI ranges from, say, 70% to 98%.

3.2. "Decision tree". This would be based on stating that one data set is likely to be better than another under a specific set of conditions. For example, one could make a list of assumptions such as (1) the SSMI data may be more accurate for ice fraction in the interior pack during cold months (except in the Antarctic, where the algorithm appears to underestimate ice fraction all the time); (2) the NIC ice charts are more accurate for marginal ice zones; and (3) the NIC ice charts are more accurate during peak melting conditions. Given these criteria, one would need to set up an "if/then" sequence of statements based on checks such as location, time of year, ice fraction, etc.

3.3. Cressman interpolation.

3.4. Optimum interpolation. Bob Grumbine supports this and has started to look at the relevant statistics for the sea ice. The ice has extreme spatial and temporal coherence. So he expect proper application of this statistical method will resolve most of the problems. The point generalizes to producing blends of multiple data sets.

3.5. Reduced-space optimum smoothing (A. Kaplan et al., JGR, 103, 18567-18589 (1998)). This might not give stable results for early years if there are very few input data. Extensive development and testing would be required.

4. PROPOSED PROCEDURE.

A two-stream process is recommended.

4.1 Rapid creation of acceptably homogeneous sea-ice concentration data sets.

4.1.1. Data for the UK Met. Office's GISST4 dataset, needed by the end of 1998 for the ECMWF 40-year (1958->) Reanalysis.

A modified "Decision tree" approach is proposed, according to which data set is deemed best in the particular circumstance. The blended data will be homogeneous with SSMI, to allow ready operational extension into the future, and to provide the ECMWF model atmosphere with a water surface where there are melt ponds.

First adjust each dataset to represent mid-month.

Next use GSFC to create an ice concentration climatology CC(LAT, LONG, MONTH) from GSFC(LAT, LONG, MONTH), remembering to fill the north polar cap by Laplacian (equivalent to bilinear in this case) interpolation north of 87 N.

Then create a blended dataset ICE(LAT, LONG, MONTH) as follows:

i) ARCTIC

Up to October 1978 AND December 1987:

If (WALSH(LAT, LONG, YEAR, MONTH) GE 0.9) THEN
            ICE(LAT, LONG, YEAR, MONTH) = CC(LAT, LONG, MONTH)

```
        ELSE
                ICE(LAT, LONG, YEAR, MONTH) = WALSH(LAT, LONG, YEAR, MONTH)

        ENDIF
```

November 1978 to November 1987 AND 1988 to 1994:

Comment: Avoid NG because of its heterogeneities and mysteries.

```
If (GSFC (LAT, LONG, YEAR, MONTH) GE 0.25) THEN
                ICE (LAT, LONG, YEAR, MONTH) = GSFC (LAT, LONG, YEAR, MONTH)
        ELSE
                ICE (LAT, LONG, YEAR, MONTH) = NIC (LAT, LONG, YEAR, MONTH)
        ENDIF
```
If (LAT GE 87N) FILL USING LAPLACE'S EQUATION WITH THE BOUNDARIES AT 87.5N
FIXED BY THE GSFC ANALYSIS.

1995 to 1996:

Comment: Avoid NG because of its heterogeneities and mysteries.
         There are no NIC data after 1994.

```
                ICE (LAT, LONG, YEAR, MONTH) = GSFC (LAT, LONG, YEAR, MONTH)
```
If (LAT GE 87N) FILL USING LAPLACE'S EQUATION WITH THE BOUNDARIES AT 87.5N
FIXED BY THE GSFC ANALYSIS.

1997 onwards:

Comment: NG is the only dataset available for this period. If its use causes
heterogeneity, it will be necessary to replace it by an updated GSFC when
available.

```
                ICE (LAT, LONG, YEAR, MONTH) = NG (LAT, LONG, YEAR, MONTH)
```

If (LAT GE 87N) FILL USING LAPLACE'S EQUATION WITH THE BOUNDARIES AT 87.5N
FIXED BY THE GSFC ANALYSIS.

ii) ANTARCTIC

Up to 1972:

Comment: Preserve GISST2 ice extents (which are based on climatologies) but make
the concentrations within the ice pack consistent with SSMI climatology.

```
If (GISST2ICE (LAT, LONG, YEAR, MONTH) GE 0.9) THEN
                ICE (LAT, LONG, YEAR, MONTH) = CC(LAT, LONG, MONTH)
        ELSE
                ICE (LAT, LONG, YEAR, MONTH) = GISST2ICE (LAT, LONG, YEAR,
MONTH)
        ENDIF
```

January 1973 to October 1978 AND December 1987:

```
If (NIC (LAT, LONG, YEAR, MONTH) GE 0.9) THEN
                ICE (LAT, LONG, YEAR, MONTH) = CC (LAT, LONG, MONTH)
        ELSE
                ICE (LAT, LONG, YEAR, MONTH) = NIC (LAT, LONG, YEAR, MONTH)
```

```
            ENDIF
```

November 1978 to November 1987 AND 1988 to 1994:

Comment: Avoid NG because of its heterogeneities and mysteries.

```
If (GSFC (LAT, LONG, YEAR, MONTH) GE 0.25) THEN
                ICE (LAT, LONG, YEAR, MONTH) = GSFC (LAT, LONG, YEAR, MONTH)
        ELSE
                ICE (LAT, LONG, YEAR, MONTH) = NIC (LAT, LONG, YEAR, MONTH)
        ENDIF
```

1995 to 1996:

Comment: Avoid NG because of its heterogeneities and mysteries.
        There are no NIC data after 1994.

```
                ICE (LAT, LONG, YEAR, MONTH) = GSFC (LAT, LONG, YEAR, MONTH)
```

1997 onwards:

Comment: NG is the only dataset available for this period. If its use causes
heterogeneity, it will be necessary to replace it by an updated GSFC when
available.

```
                ICE (LAT, LONG, YEAR, MONTH) = NG (LAT, LONG, YEAR, MONTH)
```

When done, plot time series of ice area for the regions used for the
diagnostics, including the Great Lakes, and examine subjectively for
homogeneity. I think this procedure has avoided problems in Jan 1985 (NIC), Dec
1987 (SSMI), Sept 1995-Oct 1996 (NG).

***
Note from Jim Maslanik: One option is: - for Southern Ocean, if Bootstrap ice
concentration is higher than GSFC ice concentration then use Bootstrap. This
would reduce the bias towards low concentration. However, it would introduce
heterogeneity as Bootstrap has only been applied to SSMI: we would need to
adjust the other data accordingly.
***

4.1.2. Data for ongoing climate simulations in the Hadley Centre.

These simulations have already begun using existing historical sea-ice.
Therefore, a version of the sea-ice data set is needed, which is homogeneous
with the historical data. Data sets will be selected as in 4.1.1, but the
historical ice concentrations will not be adjusted, whereas the microwave ice
concentrations will be adjusted to be equal to a historical concentration
climatology within the ice pack.

4.2 Reanalysis of the entire sea-ice database (Walsh, NIC/AARI blend,
ESMR/SMMR/SSMI) using optimum interpolation or reduced-space optimum smoothing.

This would replace the provisional data set created in 4.1.....in about two
years' time depending on research progress.

APPENDIX 1   ACRONYMS

AARI   Arctic - Antarctic Research Institute (St. Petersburg)

AVHRR   Advanced Very High Resolution Radiometer

ECMWF   European Centre for Medium-range Weather Forecasts

EOF   Empirical Orthogonal Function

ESMR   Electrically Scanning Microwave Radiometer

GISST   Global sea-Ice and Sea Surface Temperature (data set)

GSFC   Goddard Space Flight Center

JIC   Joint Ice Center [Suitland, MD, USA, now NIC]

MIZ   Marginal Ice Zone

NG   Nomura-Grumbine (sea ice data set)

NIC   National Ice Center (NIC) [Suitland, MD, USA, formally JIC]

NSIDC   National Snow and Ice Data Center [Boulder, CO, USA]

SMMR   Scanning Multichannel Microwave Radiometer

SSMI   Special Sensor Microwave Imager

THE SAF ON OCEAN AND SEA ICE : Objectives and Development Plan

L.-A. Breivik[1], A. Stoffelen[2], P. Le Borgne[3], H. Roquet[3]

1) Det Norske Meteorologiske Institutt (DNMI), Oslo, Norway
2) Koninklijk Nederlands Meteorologisch Instituut (KNMI), De Bilt, The Netherlands
3) Météo-France, Lannion, France

ABSTRACT

The development of the SAF on Ocean and Sea Ice started in 1997, in co-operation between Eumetsat, the National Meteorological Services of France, Denmark, the Netherlands, Norway and Sweden, and Ifremer. For the five year period 1997-2002, the objectives are :
- to define the algorithms for the retrieval of sea surface parameters from MSG and METOP instruments,
- to develop the software required to elaborate in near real-time the corresponding products from level 1.5/1B data,
- to implement and test this software in pre-operational processing chains, using data from existing satellites carrying similar instruments (GOES-8, NOAA/AVHRR, ERS2/AMI) and from MSG/SEVIRI during its commissioning phase,
- to disseminate and evaluate products on a pre-operational basis.

The corresponding products will cover the whole Atlantic Ocean and the European seas, through the combination of MSG, GOES-East and NOAA/METOP data. The key points concerning the choice of algorithms, the development and the validation plans are presented.

1. INTRODUCTION

The development of a Satellite Application Facility (SAF) on Ocean and Sea Ice is a co-operation between Eumetsat and Institutes from its Member States, and is an answer to the common requirements for the continuous acquisition of oceanic and sea ice data at the ocean/atmosphere interface, for the use by meteorologists, oceanographers, climate researchers and providers of ocean products.

This paper presents shortly the objectives of the project in terms of products, and gives an outline of its development plan and of the scientific approach which will be followed.

2. OBJECTIVES OF THE PROJECT

The objectives of the SAF development phase (1997-2002) are :
- to develop algorithms and software for the retrieval of sea surface parameters, in priority from future Eumetsat satellites (MSG and METOP),

- to perform at the end of the development period a pre-operational demonstration including near real-time products dissemination, using the data from precursor instruments flying on board existing satellites, and from MSG satellite during its commissioning phase (2001).

During this pre-operational demonstration phase, the products will be processed and delivered routinely to the users on a best effort basis. A proposal for the following operational phase of the Ocean & Sea Ice SAF should be provided to Eumetsat by the SAF Consortium at the end of the year 1999.

The list and characteristics of the products, approved by Eumetsat, are given in the following table:

PRODUCT	COVERAGE	HOR. RESOLUTION	TIME FREQUENCY	INSTRUMENT
SURFACE WIND VECTOR	Regional and Global	50 km (possibly 25 km)		AMI then ASCAT
ATLANTIC SST	100 W - 45 E	10 km	every 3 and 12 hour	GOES-E Imager, MSG SEVIRI and AVHRR
ATLANTIC RADIA-TIVE FLUXES	100 W - 45 E	10 km	every 3 and 12 hour	GOES-E Imager, MSG SEVIRI and AVHRR
SST AND STRUCTURES	Regional	2 km	every 6 hour	AVHRR
SEA ICE EDGE, COVER AND TYPE	Atlantic polar regions	10 km	daily (possibly every 12 hour)	AVHRR, SSM/I, AMI then ASCAT, ATOVS

In this table, regional products cover the European seas, including the NE Atlantic Ocean and the Mediterranean Sea. For Atlantic products, the coverage from 100 W to 45 E will be obtained through the combination of data from geostationary satellites (GOES-E, MSG) at low and mid latitudes and polar orbiting satellites (NOAA, METOP) at high latitudes.

All the products will be disseminated in near real-time (less than 2 hours after the acquisition of the last satellite data used) to the National Meteorological Services, through ground based communication lines including GTS. Some of them are also candidates for dissemination through the MSG data dissemination system. The following Primary Users of the SAF products have been identified : Numerical Weather Prediction centres, Marine meteorological centres, Ocean modelling centres, Polar research centres and Climate diagnostic centres. End users in the field of oceanic activities will access the product through their respective National Meteorological Services.

3. DEVELOPMENT PLAN AND SCHEDULE

The project is a co-operation between Eumetsat and the following Institutes from the Eumetsat Member States : Danish Meteorological Institute (DMI), Det Norske Meteorologiske Institutt (DNMI), Institut Français de Recherche pour l'Exploitation de la MER (IFREMER), Koninklijk Nederlands Meteorologisch Instituut (KNMI), Météo-France

and the Swedish Meteorological and Hydrological Institute (SMHI). Météo-France has been designated by Eumetsat as Host Institute for the Ocean & Sea Ice SAF, and is responsible for the overall development of the project, as well as for the development of the products derived from geostationary satellites.

The kick-off meeting of the project was held on 15-16 April 1997. The main milestones are the following : Requirements and Architectural Design Review (RADR) in April 1998, Mid-Term Review (MTR) in 1999, InTegration readiness Review (ITR1) in 2000, Integration and Test Review (ITR2) in 2001 and OPerations readiness Review (OPR) in 2002.

The first year of the project was mainly devoted to the complete review of the scientific problems involved and to the definition of the candidate algorithms and validation strategy. These points were addressed in the Science Plan, which was examined at the first review (RADR) in April 1998, as well as other documents (Project Plan, Software Requirements and Architectural Design documents). This first review was successful, and the project is now in its development phase.

The organisation and sharing of development tasks inside the SAF Consortium is the following :

■ Météo-France, Centre de Météorologie Spatiale (CMS) : overall project management, developments of SST and Radiative Fluxes products at low and mid latitudes from GOES-E and MSG Imagers, merging of the low and mid latitudes, and of the high latitudes parts of the Atlantic products
■ DNMI, DMI, SMHI : development of SST and Radiative Fluxes products at high latitudes from AVHRR, development of the Sea Ice products
■ KNMI, IFREMER : development of scatterometer wind product

During the pre-operational production and distribution phase, it is planned to have an acquisition and processing centre at CMS for the SST and Radiative Fluxes products at low and mid latitudes, and the integration of the final Atlantic products. Another acquisition and processing centre will be located in the Scandinavian countries for the high latitude products, and the last one at KNMI for the production of scatterometer winds.

4. SCIENTIFIC APPROACH

The general strategy for the development the products is the following :

■ to make maximal use of the existing expertise inside and outside the SAF Consortium, which has been developed from precursor instruments flying on board current satellites (GOES, NOAA, ERS, Meteosat)
■ to use these precursor instruments to start early in the project prototyping and validation activities, which should allow to be ready for processing data from the future Eumetsat satellites early after launch
■ to interact closely with the other ongoing developments at Eumetsat (other SAFs, MPEF), in particular with the SAF on Support to Nowcasting and Synoptic Meteorology for the cloud products (cloud detection and classification) needed to retrieve sea surface parameters from visible and infrared sensors.

4.1. Developments on SST algorithms

Concerning SST, a first set of operational algorithms for retrieving SST from NOAA-14, NOAA-15 AVHRR and from GOES-8 Imager data at low and mid latitudes have been defined and tested. The SST algorithms (non-linear, quadratic or water vapour dependent) were first defined on a data base of radiances simulated from radiosounding profiles using a radiative transfer model. The final tuning and comparison of the algorithms was performed using match-up data bases including collocated in-situ SSTs and satellite measured radiances. This two-step procedure allows to take explicitly into account problems like skin-to-bulk differences, and will allow to prepare SST algorithms for MSG Imager as soon as its filter functions are known.

4.2. Developments on Sea Ice algorithms

Concerning Sea Ice products, the proposed horizontal resolution and time frequency require a multi-sensor and multi-temporal approach, because of the specific cloud and illumination conditions in polar regions. The current task is to define and validate the best operational algorithm for each product (Sea Ice edge, concentration and type) and for each instrument (AVHRR, SSM/I, ATOVS, AMI/ASCAT). Afterwards, the chosen strategy is to use a Bayesian probabilistic approach to combine the information from all different sensors into a final merged product.

4.3. Developments on Scatterometer winds

Considering the state of the art for C-Band scatterometer wind processing (PRESCAT software), the main development efforts are devoted to the ambiguity removal problem, and to the characterisation of sea state effects in the geophysical transfer function. In relation with the development of the Sea Ice products, a real-time Sea Ice discrimination scheme is under development and will be implemented.

5. CONCLUSION AND PERSPECTIVES

The development of the SAF on Ocean and Sea Ice started in April 1997. The goal is to set up, at the end of the 5 year development period, an operational real-time system to produce and deliver oceanic surface products retrieved from Eumetsat satellite data. The SAF on Ocean and Sea Ice will represent a significant contribution from the European operational meteorological satellites to the observation and monitoring of the oceans after the year 2000.

The Role of Skin Sea Surface Temperature (SST)
in the Development of SST Products

Bill Emery, CCAR Box 431, Univ. Of Colorado, Boulder, Co., 80309
(with input from Gary Wick, NOAA and Craig Donlon, JRC)

Introduction

It is well known that due to its very high emissivity that water emits surface radiation only from a very shallow "skin" layer only a millimeter deep. Thus, an radiometer onboard a satellite can only "see" this skin SST. Due to the facts that satellite radiometers drift and that we do not have in situ measurements of skin SST we have traditionally computed an SST that mixes the skin SST from the satellite with a "bulk" SST measured by ships and now drifting/moored buoys. As a result the widely used SST analyses carry both bias (~ 0.3 K) and RMS errors (~ 1.0 K) in SST due to the neglect of the bulk-skin effect (Schlüssel et al., 1987; Schlüssel et al., 1990; Wick et al.,1992; Wick et al., 1997). The only near future solution to this situation is the creation and deployment of a number of shipborne skin SST radiometers that will collect the same type of radiative SST seen by the satellites but without the intervening atmosphere. These "in situ" skin SSTs can then be used to calibrate and validate the satellite radiometer SST values.

It is important to recognize that most present day ocean and coupled climate models do not resolve the skin effect explicitly. As a consequence it is not likely that these models can take best advantage of a shift to computing skin SSTs from the satellite data. Still it is important to improve our accuracy of the SST products and the incorporation of the skin effect is one thing that can be done to improve our SST accuracy. In addition it is the difference between the skin and the bulk SSTs (•T) that is closely coupled to the heat flux between the ocean and the atmosphere. This air-sea heat exchange is a critical component of the global climate system that must be properly understood to improve our modelling and prediction of climate change. A problem we still have at present is that without the in situ skin SST measurements we are forced to compute our skin SST algorithms using atmospheric simulations which can also be full of errors. Comparing some skin SST algorithms with the standard SST product has demonstrated that the skin SST are much too warm which is a problem particularly at night when the skin should be cool. This is likely due to an inappropriate treatment of the water vapor continuum in the atmosphere.

In this extended abstract we will briefly review some of the basic physics of the bulk-skin problem and explore how these factors influence our computation and analysis of SST. We will also examine some of these relationships to see how the bulk-skin temperature difference is related to the widely accepted forcing functions of wind and air-sea heat flux. Finally we will mention some of the activities going on to resolve this need for in situ skin SST measurements.

Dependence of •T on wind and heat flux

Many model and empirical studies (Brusaert, 1975a,b; Kantha and Clayson, 1994; Katsaros, 1977, Liu et al., 1979; Wick et al., 1997; Wick, 1997) have discussed the dependency of •T on the wind and air-sea heat flux. Earlier studies all studied the role of wind stress alone arguing that strong winds would eliminate the skin layer and let the satellite "see" the bulk temperature below. Later in his analysis of direct measurements of the skin and bulk SSTs Wick (1997) discussed the fact that the •T depended simultaneously on changes in both wind speed and the net air sea heat flux. The two plots in Fig. 1 summarize his conclusions showing that under

low net air-sea heat flux conditions •T was seen to decrease as expected with increasing wind speed. When the heat-flux was much larger it was possible to have •T actually increase as the
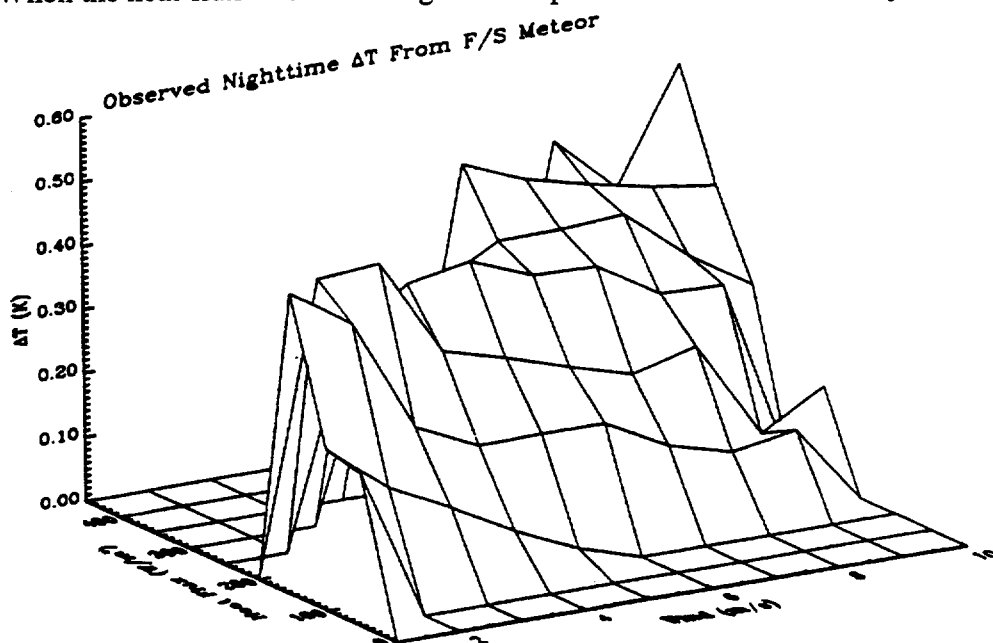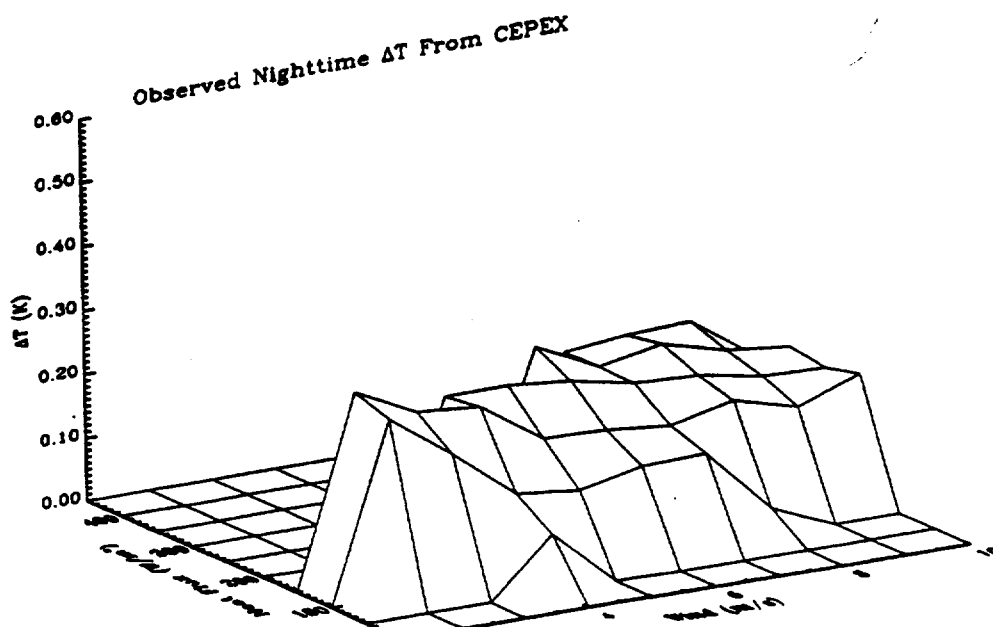

Figure 1 Nighttime ΔT measurements as functions of net heat flux and wind spee(

wind speed went up. This observation contradicts a later result by Donlon and Robinson (1997) where they conclude that for wind speeds above 10 m/s that •T essentially goes to zero. To test

this idea we looked at moored deep ocean buoys which recorded both wind speed and bulk SST. Using coincident weather satellite infrared radiometer data we computed the skin SST and computed •T by combining both kinds of SST. An example is shown here in Fig. 2 which clearly demonstrates that there is no dependence of •T on the wind speed. We tried a number of other SST algorithms
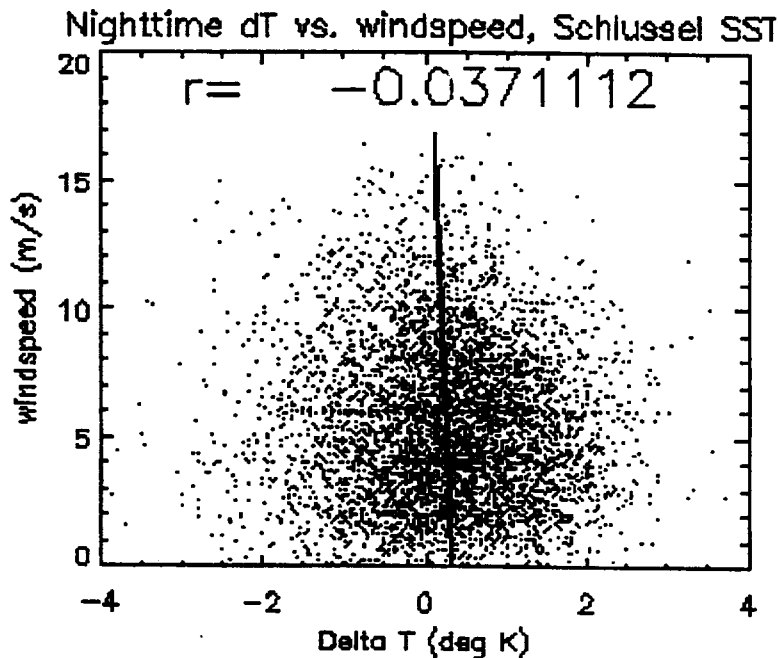

Fig. 2 T_{bulk} - T_{skin} as a function of wind speed using the Schluessel skin SST algorithm.

including the operational SST algorithms which mix satellite skin SST with bulk SST. The results were always the same. We believe that an improved approach will be to look for the unique cases that occur with low wind speeds during the daytime when a diurnal thermocline is formed beneath a warm near-surface diurnal layer. It is clear that there is no wind speed above which the skin layer is erased and T_{bulk} = T_{skin} regardless of the type of SST algorithm that is used.

For many years oceanographers have ignored the diurnal changes of SST primarily motivated by the fact that we have not had measurements that would resolve the space/time variations that might be associated with diurnal changes of SST. Single time series have been generated at moored buoys or coastal stations but then there are questions of how representative are these point measurements or what is the effect of horizontal advection. Until recently we have not had a capability to sample the infrared SST at intervals any shorter than a day. With the polar-orbiting satellites SST images are separated by 4 to 6 hours unable to resolve any diurnal change in SST. Lately the improvements with the newer GOES satellites have made it possible to examine the diurnal SST variations. Again recognizing that the infrared channels on GOES 8,9 satellites are only able to sense the skin SST we would like to know the amplitude of the diurnal variations in skin SST. In Fig. 3 we plot the diurnal variations of the measured •T bias and the •T computed using a skin layer parameterization model (Wick, 1997) driven by NCEP wind and heat fluxes.
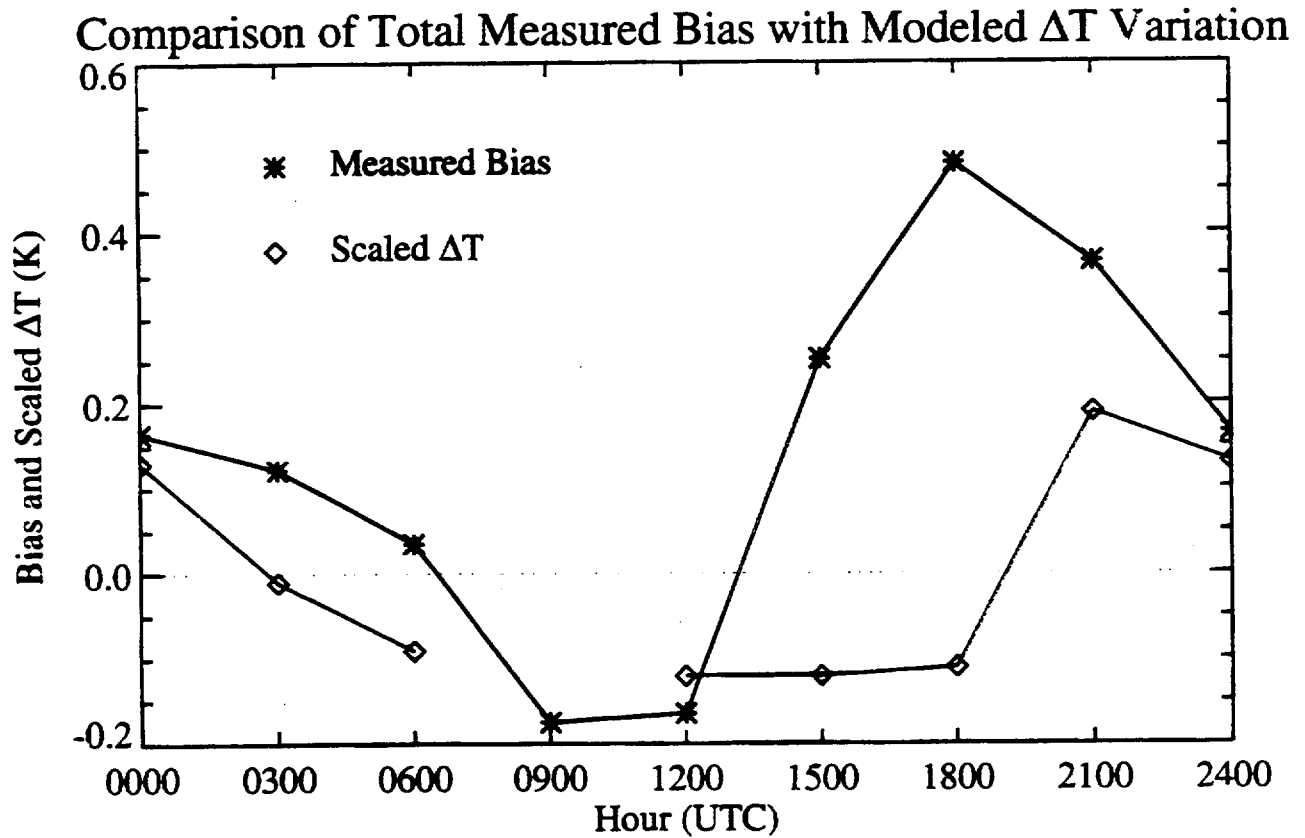
Comparison of Total Measured Bias with Modeled ΔT Variation

Fig. 3 Measured and simulated diurnal •T variations.

There is a marked diurnal cycle of the measured •T bias which passes through 0.0 in the early dawn hours and starts up again at noon. The maximum positive difference $(T_{bulk} > T_{skin})$ is at 18:00 hours suggesting very strong outgoing heat flux in the afternoon. The overall range of about 0.8 K is large enough to contribute a substantial error if the diurnal cycle is neglected. Negative values occur at midday when the diurnal layer warms significantly forming a warm near-surface layer which even with a superposed "cool" skin results in a skin temperature that is greater than the bulk temperature measured at 1 m or deeper. Clearly our present •T model is not yet accurate enough to replicate the measured diurnal variation in •T.

Global comparisons

For the present we are forced to use in situ SST measurements made by drifting buoys to "calibrate" the infrared sensors on environmental satellites. While this mixes satellite skin SSTs with buoy bulk SSTs we don't presently have any alternative to the drifting buoy measurements. In addition to the assumption that $T_{bulk} = T_{skin}$ this practice also takes the position that buoy SSTs are perfect which we are sure is not the case. Still relative to the calibrations that are needed for the infrared sensors the errors in the buoy SSTs seem quite small. Of greater concern are the errors in the present skin SST algorithms that appear when they are compared with the operational satellite SST products (Fig. 4). Using moored buoy data from the tropical Atlantic for the standard SST
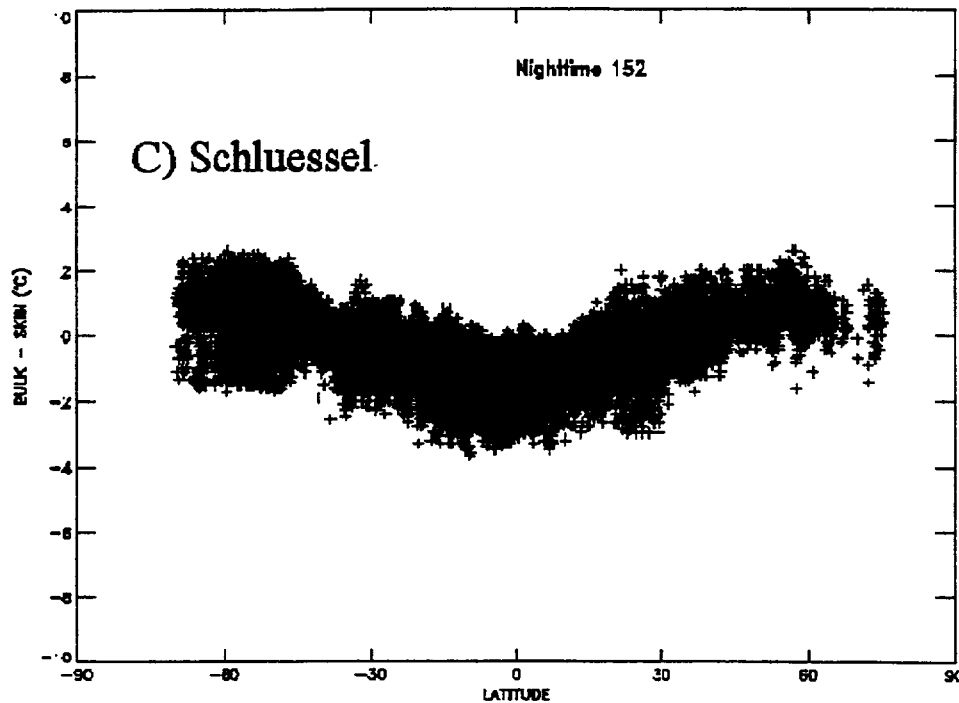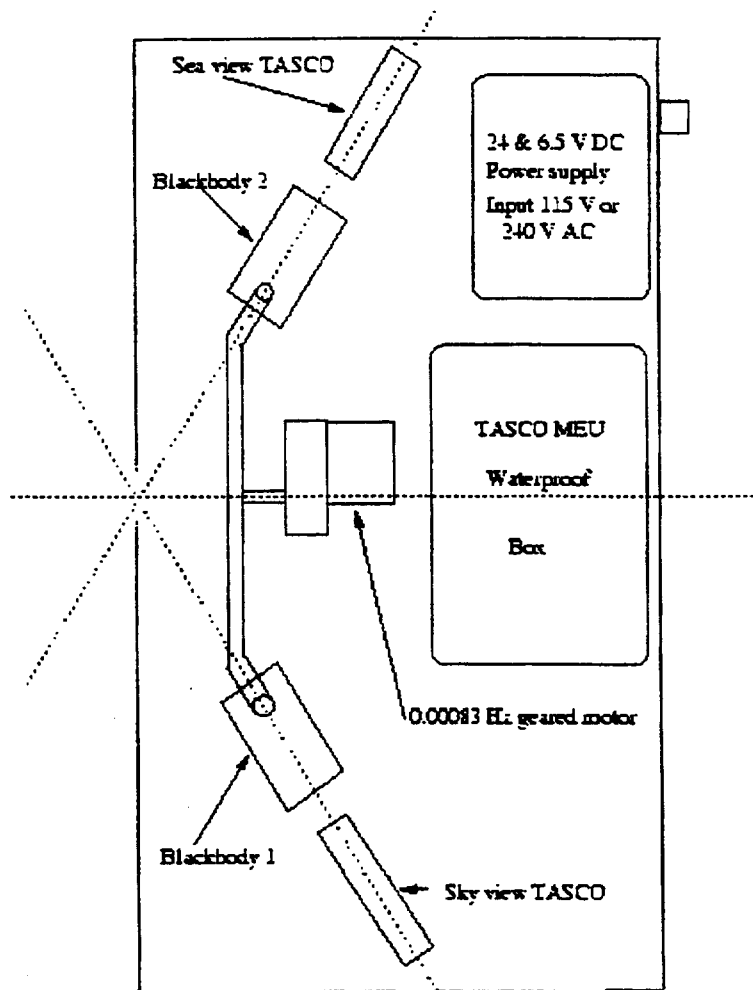
Fig. 4 Differences between the Schluessel skin SST and the SST computed by the U.S. Navoceano using buoy regressed coefficients.

algorithm the data from the entire Atlantic are used for the SST comparisons. Two different skin SST algorithms are tested: the first from Schlüssel et al. (1990) and the second are coefficients that Ian Barton (personal communication) computed using the radiative transfer code from Albin Zavody). Both the Schlüssel and Barton SSTs are generally "warmer" (negative differences) than the reference SST except at the higher latitudes. The likely explanation for these apparent biases is the treatment of the water vapor continuum in the radiative transfer codes.

The need for ground truth measurements

All of the skin SST algorithms are derived using "atmospheric simulations" where a suite of historical radiosonde profiles is used to represent global atmospheric conditions. The skin SST is considered to be the lowest level in the atmospheric simulation. In none of these cases are there in situ skin SST measurements to test against. What is really needed are skin SST measurements that can be used to replace the drifting buoy SSTs that are presently used for calibration. There are only two types of platforms that can provide this measurement base. The first are merchant ships of opportunity and the second are moored buoys. It is very difficult to build a skin SST radiometer that can operate relatively autonomously from a merchant ship. It is much more difficult to create a system that can operate autonomously from a moored buoy. For now we propose to instrument a series of merchant ships with low-cost skin SST radiometers (Fig. 5) that can collect

Sea view TASCO

Blackbody 2

24 & 6.5 V DC
Power supply
Input 115 V or
240 V AC

TASCO MEU

Waterproof

Box

0.00013 Hz geared motor

Blackbody 1

Sky view TASCO

Ship of oppotunity sea surface temperature radiometer
C. J. Donlon March 1997

Fig. 5 Skin SST radiometer system designed for a ship of opportunity deployment.

autonomously the skin SST data needed for satellite calibration. We will also take advantage of satellite systems for the realtime relay of data from these ships and eventually buoys. Once available this collection of skin SST radiometers will make it possible to formulate a skin SST based only on in situ measurements and not on atmospheric simulations.

References

Brutsaert, W., A theory for local evaporation (or heat transfer) from rough and smooth surfaces at ground level, Water Resources. Res., 11, 543-550, 1975a.

Brutsaert, W., The roughness length for water vapor, sensible heat, and other scalars, J. Atmos. Sci., 32, 2028-2031, 1975b.

Donlon, C.J. and I. Robinson, 1997: Observations of the oceanic thermal skin in the Atlantic Ocean. J. Geophys. Res., 102, 18,585- 18,606.

Kantha, L.H., and C. A. Clayson, An improved mixed layer model for geophysical applications, J. Geophys. Res., 99, 25,235-25266, 1994.

Katsaros, K. B., The sea surface temperature deviation at very low wind speeds; Is there a limit?, Tellus, 29, 229-239, 1977.

Liu, W. T., K. B. Katsaros, and J. A. Businger, Bulk parameterization of air-sea exchanges of heat and water vapor including the molecular constraints at the interface, J. Atmos. Sci., 36, 1722-1735, 1979.

Schluessel, P., H.Y. Shin, W.J. Emery and H. Grassl, 1987: Comparison of satellite derived sea surface temperatures with in situ skin measurements. J. Geophys. Res., 92, 2859-2874.

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

Wick, G. A., W. J. Emery, and P. Schluessel, A comprehensive comparison between satellite-measured skin and multichannel sea surface temperature, J. Geophys. Res., 97, 5569-5595, 1992.

Wick, G. A., Evaluation of the variability and predictability of the bulk-skin sea surface temperature difference with application to satellite-measure sea surface temperature, PhD dissertation, University of Colorado, 1995.

Wick, G.A., W.J. Emery , L.H. Kantha and P. Schluessel, 1996: The behavior of the bulk-skin temperature difference at varying wind speeds. J. Phys. Oceanogr., 26, 1,969 - 1,988.

REQUIREMENTS FOR GCOS SEA SURFACE TEMPERATURE AND SEA-ICE DATA SETS.

David E Parker

Hadley Centre, Meteorological Office, Bracknell, United Kingdom

ABSTRACT

Requirements depend on applications, namely:
        Climate change detection
        Simulation of climatic variations and changes
        Studies of multidecadal variability
        Calibration and validation of remote sensors
        Studies of the El Nino - Southern Oscillation
        Near-real-time climate monitoring
        Interannual climate prediction

These applications determine the requirements for homogeneity, precision, spatial and temporal resolution, coverage and length of sea surface temperature and sea-ice data sets.

HOMOGENEITY

The target sea surface temperature homogeneity is 0.1° C or less for climate change detection. To achieve this, it is necessary to take account of relative biases in sea surface temperature between measurements made from ships using uninsulated buckets, insulated buckets, engine inlet thermometers, and hull sensors. It is also necessary to allow for differences between ships, buoys and expendable bathythermographs (XBTs), and between in situ and satellite estimates. For sea-ice concentration, differences between in situ data, and satellite visual, infrared and microwave data must be accounted for. Biases of even a few percent will wreck many climate change detection studies, simulations of climatic variations and changes, and studies of multidecadal variability.

Adjustments to historical sea surface temperatures to compensate for the use of uninsulated buckets are discussed and presented in detail by Folland and Parker (1995). The homogeneity of more recent data is assessed by Folland et al. (1993) and by Kent et al. (1993). The implications of biases in sea-ice concentration for modeling studies have been known at least since the study of Simmonds and Budd (1991).

In many research studies, space-time patterns of climate variability on a range of time-scales are analyzed. To optimize such results, sea surface temperature and sea-ice data sets need to be homoscedastic, i.e. self-consistent in variance, in space and time. Figure 1a shows that this is the case in the midlatitude North Atlantic for the Global sea-Ice and Sea Surface Temperature GISST3.0 data set, but Figure 1b shows that in the same data set there has been an increase in the spatial variance of sea surface temperature anomalies in the tropical South Pacific where the analysis depends more on eigenvector-based interpolation than on local data in the early parts of the record.

PRECISION

The target sea surface temperature precision is 0.2° C at the specified time and space scales for most studies. Sea-ice concentration needs to be specified to the nearest 10%, but see above regarding biases.

SPATIAL RESOLUTION

A spatial resolution of 1° latitude x 1° longitude is needed for studies of the El Niño - Southern Oscillation and for calibration and validation of remote sensors.

TEMPORAL RESOLUTION

Monthly anomalies, in conjunction with a daily climatology, are needed for forcing model simulations of recent climate. But anomalies on time-scales of 5 days or less are required for some climate monitoring and prediction studies and for calibration and validation of remote sensors.

COVERAGE

Climate simulations and initialization of predictions require globally complete data. Studies of multidecadal variability and of the El Niño - Southern Oscillation require, in general, almost globally complete data.

Until the development of the GISST data sets (see e.g. Rayner et al., 1996), sea surface temperature data sets were incomplete, as documented by Parker et al. (1995) for the Met. Office Historical Sea Surface Temperature MOHSST6 data set. However, as Parker et al. (1995) also showed, there was potential for a substantial increase in coverage through blending of the U.K. Met. Office Marine Data Bank with the USA's Comprehensive Ocean-Atmosphere Data Set (COADS) and with hitherto undigitized marine data. The reliability of the interpolation in data sets such as GISST will improve if the basic observational data resource is enhanced.

LENGTH

Ideally, climate change detection should be supported by data records much more than a century in length. Studies of multidecadal variability need over a century of data, whereas studies of the El Niño - Southern Oscillation require several decades of data. Near-real-time climate monitoring and interannual climate prediction, along with calibration and validation of remote sensors, need up-to-date data.

REFERENCES

Folland, C.K. and Parker, D.E., 1995: Correction of instrumental biases in historical sea surface temperature data. *Quart. J. Roy. Meteorol. Soc.*, **121**, 319-367.

Folland, C.K., Reynolds, R.W., Gordon, M. and Parker, D.E., 1993: A study of six operational sea surface temperature analyses. *J. Climate*, **6**, 96-113.

Kent, E.C., Taylor, P.K., Truscott, B.S., and Hopkins, J.S., 1993: The accuracy of Voluntary Observing Ships' Meteorological Observations - Results of the VSOP-NA. *J. Atmospheric and Oceanic Technology*, **10**, 591-608.

Parker, D.E., Folland, C.K. and Jackson, M., 1995: Marine surface temperature: observed variations and data requirements. *Climatic Change*, **31**, 559-600.

Rayner, N.A., Horton, E.B., Parker, D.E., Folland, C.K. and Hackett, R.B., 1996:

Version 2.2 of the Global Sea-Ice and Sea Surface Temperature data set, 1903-1994. Climate Research Technical Note CRTN 74, Hadley Centre, Met. Office, Bracknell, U.K.

Simmonds, I. and Budd, W.F., 1991: Sensitivity of the Southern Hemisphere circulation to leads in the Antarctic pack ice. *Quart. J. Roy. Meteorol. Soc.*, **117**, 1003-1024.