SPECIFIC CONTRIBUTIONS TO THE OBSERVING SYSTEM: SEA SURFACE TEMPERATURES

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1. INTRODUCTION

Sea surface temperature (SST) analyses are an important indicator of the coupling between the atmosphere and the ocean and may be the most important field for climate modelling. They are used for climate monitoring, prediction and research, as well as specifying the surface boundary condition for numerical weather prediction, and for other atmospheric simulations using atmospheric general circulation models. The purpose of this paper is to present the current and future status of SST data and SST analyses.

2. SST DATA

The longest data set of SST observations is based on observations made from ships. These observations include measurements of SST alone as well as temperature profiles with depth. However, the observations of SST alone dominate the data sets and account for more than 90 per cent of the observations. Although the earliest observations were taken in the first half of the 19th century, sufficient observations to produce a global SST analysis were not available until about 1870. From 1870 to present, the number of observations generally increased except for noticeable dips during the First and Second World Wars. In addition to the changes in the number of observations, the method of measuring surface marine observations changed over the period from temperatures measured from uninsulated buckets to temperatures measured from insulated buckets and engine intakes. These instrument changes resulted in biases in the data set, the corrections for which are discussed by Folland and Parker (1995) and incorporated into UK Met Office SST analyses. Although, as discussed in Kent *et al.* (1993), selected SST observations can be very accurate, typical RMS errors from ships are larger than 1°C and may have daytime biases of a few tenths of a degree C (Kent *et al.*, 1999).

SST observations from drifting and moored buoys began to be plentiful in the late 1970s. These observations are typically made by a thermistor or hull contact sensor and are usually relayed in real time by satellites. Biases in the SSTs from buoys can occur in some designs; for example, significant diurnal heating of the hull may occur under low wind conditions with some hull configurations. Although the accuracy of the buoy SST observations varies, the accuracies are usually better than 0.5°C, which is better than ships. In addition, typical depths of the observations are roughly 0.5 m rather than the 1 m and deeper depths from ships. The distribution of ship and buoy in situ SST observations (see Figure 1) shows that the deployment of the buoys has partially been designed to fill in some areas with few ship observations. This process has been most successful in the tropical Pacific and southern hemisphere.

In late 1981, accurate SST retrievals became available from the Advanced Very High Resolution Radiometer (AVHRR) instrument which has been carried on many NOAA polar-orbiting satellites. These retrievals improved the data coverage over that from in situ observations alone. The satellite retrievals allowed better resolution of small-scale features such as Gulf Stream eddies. In addition,

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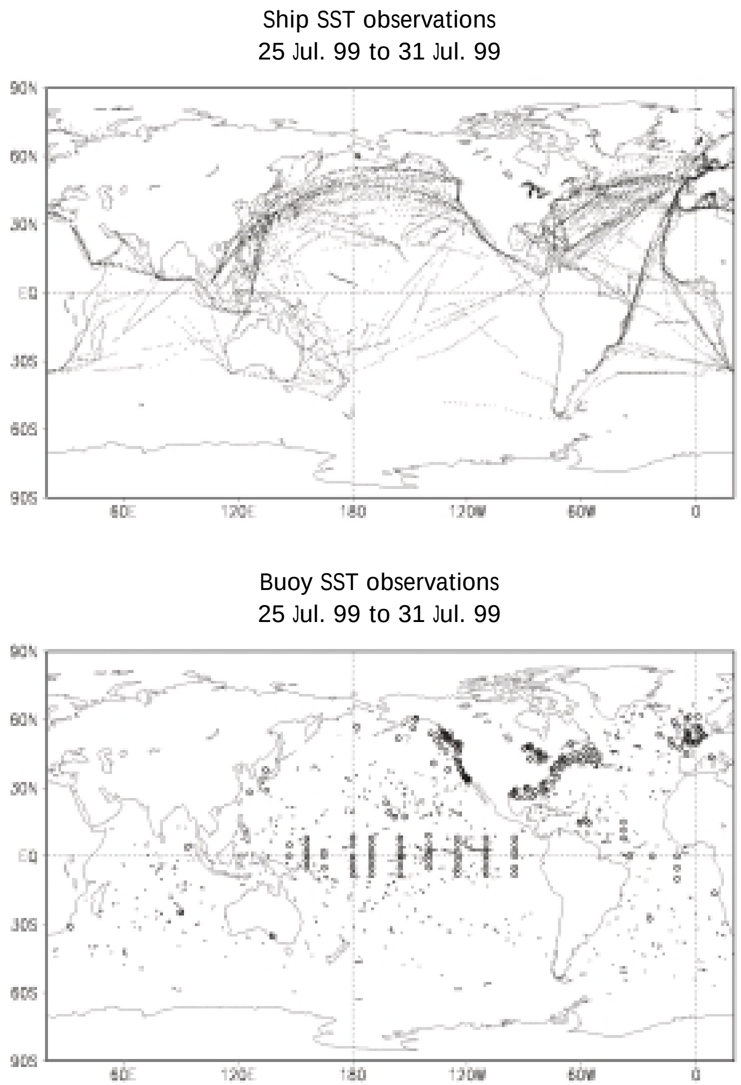

Figure 1 — Distribution of SST in situ observations from ships (top panel) and buoys (lower panel) for the week of 25–31 July 1999.

especially in the southern hemisphere, SSTs could now be observed on a regular basis in many locations. These data are produced operationally by NOAA's National Environmental Satellite, Data and Information Service (NESDIS) and also, during the last few years, by the US Navy.

Because the AVHRR cannot retrieve SSTs in cloud-covered regions, the most important problem in retrieving SST is to eliminate clouds. The cloud clearing algorithms are different during the day and at night because the AVHRR visible channels can only be used during the day. After clouds have been eliminated, the SST algorithm is derived to minimize the effects of atmospheric water vapour. The satellite SST retrieval algorithms are ‘tuned’ by regression against quality-controlled drifting buoy data using the multichannel SST technique of McClain *et al.* (1985). This procedure converts the satellite measurement of the ‘skin’ SST (roughly a micron in depth) to a buoy ‘bulk’ SST (roughly 0.5 m). The tuning is carried out when a new satellite becomes operational or when verification with the buoy data shows increasing errors. The AVHRR instrument has three infrared (IR) channels. However, because of noise from sun glint, only two channels can be used during the day. Thus, the algorithm is usually tuned separately during the day and at night and typically uses three channels at night and two during the day (Walton *et al.*, 1998). The algorithms are computed globally and are not a function of position or time.

If the retrievals are partially contaminated by clouds, they have a negative bias. Negative biases can also be caused by aerosols, especially stratospheric aerosols from large volcanic eruptions (for example, see Reynolds, 1993). The ratio of the number of daytime to night-time satellite retrievals is now roughly one to one. However, the ratio was roughly five to one prior to 1988. From 1989 to present, the night-time satellite algorithm was gradually modified to increase the number of night-time observations, while the daytime observations remained roughly constant. A reanalysis of the satellite data (now being completed by the Pathfinder project) would correct these differences and should be a better product for climate.

Future improvements in the SST observing system will primarily be due to new satellite data. A significant change occurred in 1999 when SSTs from a second polar-orbiting NOAA satellite were operationally processed for the first time. In addition, data from other satellites, including microwave satellites, which can see through clouds, and geostationary satellites, which can resolve the diurnal cycle, are now becoming available. This will make it easier to carry out high resolution SST analyses, as discussed later.

3. CLIMATE SCALE SST ANALYSES

For the purpose of this discussion, SST analyses have been divided into two groups: climate and high resolution. The climate scale analysis typically has temporal resolutions from weekly to monthly and spatial resolutions from 1° to 5°. These analyses use in situ SST data and may, or may not, use satellite SST data when available. As mentioned below, sea-ice concentrations may also be used to augment the SST data at high latitudes. These analyses are often used on seasonal and interannual scales for the monitoring and prediction of El Niño events, and on decadal and centennial scales for climate trend detection. In addition, the SSTs are used as the ocean boundary condition for atmospheric general circulation models. For these purposes, it is important that analysis methods be constant with time and not influenced by temporal changes in SST data. The latter is particularly difficult because not only did the number of in situ data generally increase with time, but additional data sources were added when observations from buoys, and of course satellites, became available.

To better understand the problems of climate scale SSTs, different SST analyses have been compared. Two studies will be discussed here. Hurrell and Trenberth (1999) compared four analyses: the National Center for Environmental Prediction (NCEP) optimum interpolation analysis, henceforth OI, of Reynolds and Smith (1994); the NCEP empirical orthogonal functions analysis, henceforth EOF, of Smith *et al.* (1996); the UK Meteorological Global Sea-ice SST analysis, version 2.3b, henceforth (GISST), of Rayner *et al.* (1996); and the Lamont-Doherty Earth Observatory analyses, henceforth LDEO, of Kaplan *et al.* (1998). A description of the data and analysis methods can be found in Hurrell and Trenberth (1999). The second study was presented at a Global Climate Observing System (GCOS) Workshop on Global Sea Surface Temperature Data Sets, held at the Lamont-Doherty Earth Observatory on 2-4 November 1998, and is updated here. This workshop study focused on the 1982-1997 period and added four additional analyses: the UK Met Office Historical SST analysis, version 6, henceforth MOHSST, of Parker *et al.* (1994); the Japan Meteorological Agency (T. Manabe, 1999, personal communication), henceforth JMA; the Naval Research Laboratory (J. Cummings, 1999, personal communication), henceforth NRL; and the Australian Bureau of Meteorology Research Centre (N. Smith, 1999, personal communication), henceforth BMRC. The resolution, period, and type of SST data used for each analysis are summarized in Table 1.

Table 1—SST analyses with analysis periods and resolution. All analyses used in situ (ship and buoy) data. Analyses using sea-ice data converted to SSTs are indicated by "yes" in the ice column. Analyses using satellite data are indicated by "yes" if used, or "corrected" if used with additional bias corrections. Months are noted under the "period" column if the analysis did not start in January.

Acronym	*Period*	*Resolution*	*Satellite data*	*Ice data*
BMRC	Jul.-93 to present	1°	Corrected	Yes
GISST	1871 to present	1°	Corrected	Yes
JMA	1982 to present	2°	No	No
LDEO	1856 to present	5°	No	No
MOHSST	1856 to present	5°	No	No
EOF	1950 to 1998	2°	No	No
OI	Nov.-81 to present	1°	Corrected	Yes
NRL	1995 to present	1/4°	Yes	Yes

Sea-ice information is used to generate additional SST data to augment other SST data in four of the analyses. The generation methods vary along with the accuracy of the sea-ice information. In the OI, BMRC and NRL analyses, an SST value representing the freezing point is added at locations where a specified sea-ice concentration is exceeded. The GISST method of generating SST from the sea-ice concentration, I, is more complicated and probably more realistic. In this method, a relation between SST and I is defined by a quadratic equation: $SST = a I^2 + b I + c$, where a, b and c are constants determined by climatological collocated match-ups between SST and sea-ice concentration, with the constraint that SST = -1.8°C or 0°C when I = 1 over the ocean or fresh water lakes, respectively. In addition to uncertainties in these methods, the analysed value of ice concentration as defined in different analyses is not accurately known, especially in summer. The climatological sea-ice concentrations are shown for July in Figure 2 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. The concentrations of the Nomura/Grumbine analysis are much lower because the microwave satellite instrument interprets melt water on top of the sea ice as open water.

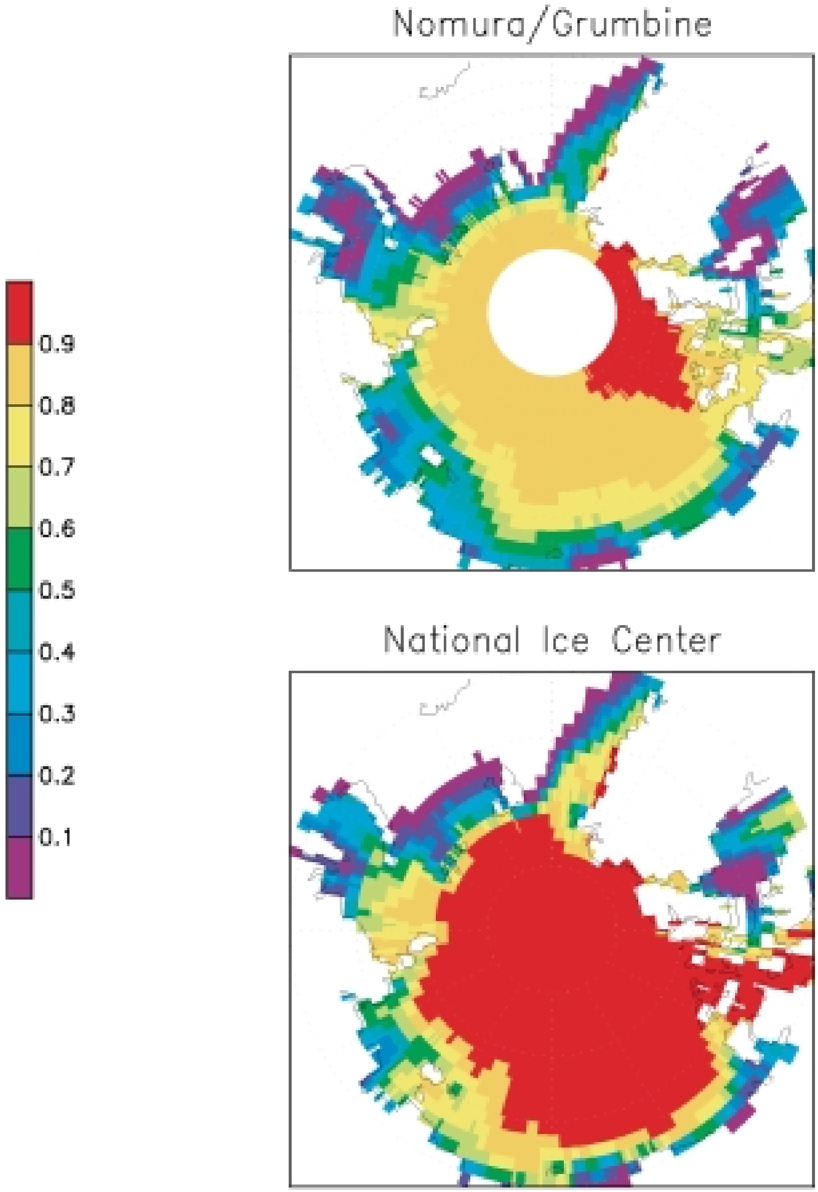

Figure 2— Climatological sea-ice concentrations for the Arctic for July for the 1979-1992 period. The upper panel shows the analysis from Nomura and Grumbine; the missing data near the pole occurs because of a lack of satellite observations. The lower panel shows the analysis from the National Ice Center (see text). The range of ice concentration is 0 (0%) to 1 (100%).

Both Hurrell and Trenberth (1999) and the workshop comparisons showed that differences among analyses were smaller within the tropics than the extratropics. This can be seen in the zonal averages shown for the four analyses with ice information in Figure 3. The figure shows that northern hemisphere middle latitude differences are smaller than middle and high latitudes differences in the southern hemisphere. However, the differences above 60°N are the largest due to uncertainties near, and within, the Arctic sea ice. The workshop comparisons found that the monthly RMS differences among analyses were whithin 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. Hurrell and Trenberth (1999) showed that monthly lag one autocorrelations appeared to be depressed in the GISST analysis during 1982-1997 compared to the other analyses. In addition, they found differences in the regional trends between the GISST and LDEO. LDEO used MOHSST, version 5, and GISST used MOHSST, version 6, as in situ input data. Thus, the differences may be due to changes in MOHSST or differences in the analysis methods.

The comparisons have shown that analyses using satellite data without careful bias correction should not be used for climate studies because of large potential biases in satellite retrievals. Satellite data can improve the coverage and spatial resolution of SST analyses and should be used with bias corrections. 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. These biases occurred primarily in the mid-latitude southern

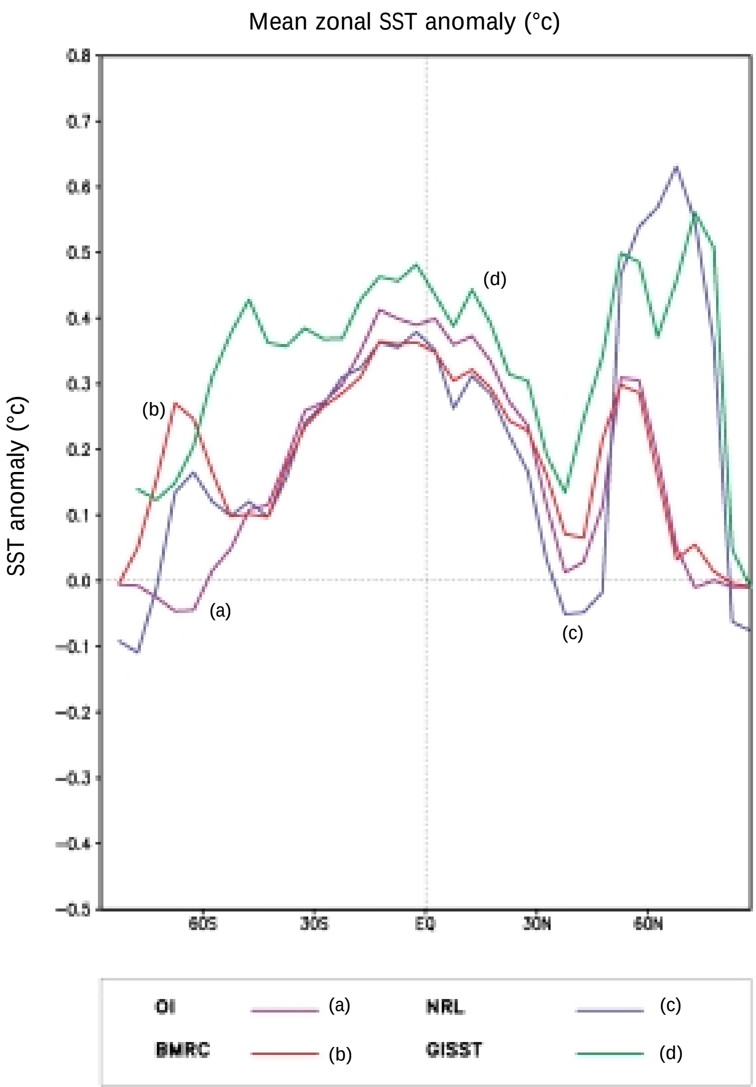

Figure 3— Mean zonally averaged SST anomalies from four analyses for the period January 1995 to December 1997. All analyses used in situ and satellite SST plus SSTs generated from sea-ice concentrations.

hemisphere where in situ observations were sparse. However, there were also large-scale differences among the in situ analyses of this magnitude which could persist for several months. These differences are most likely due to the nonlinear data procedures used to eliminate bad data rather than differences in the in situ data sets themselves. The largest differences among analyses with sea-ice data occurred near the sea-ice margins. The differences were due both to uncertainties in the ice analyses, as well as uncertainties in the method of converting from ice to SST.

4. HIGH RESOLUTION SST ANALYSES

High resolution SST analyses have spatial scales of 1° or higher and temporal scales of 24 hours or less. They have the same potential problems as those discussed for the climate SST analyses. However, the high resolution analyses have additional problems because the data are now relatively sparser, primarily because of shorter analysis periods. Satellite data are essential for these analyses.

In regions with light winds and strong net heat fluxes into the ocean, diurnal SST signals of several degrees C can occur. This signal may be very close to the surface and may not reach typical in situ observation depths. This problem is further complicated by satellite SSTs which measure a skin temperature which is typically 0.3°C colder than the layer immediately below the skin (see Webster *et al.*, 1996 for details). The tuning of the MCSST algorithm is based on assumed correlations of the skin and the bulk SST. This assumption begins to break down during the daytime when a diurnal signal is present in the SSTs. This problem is illustrated in Figure 4, which shows skin and bulk SSTs at a buoy deployed in light winds of the western tropical Pacific (Weller and Anderson, 1996). The upper panel shows the diurnal average; the lower panel shows a sample of the day-to-day variability. The differences caused by the potential decoupling of skin and

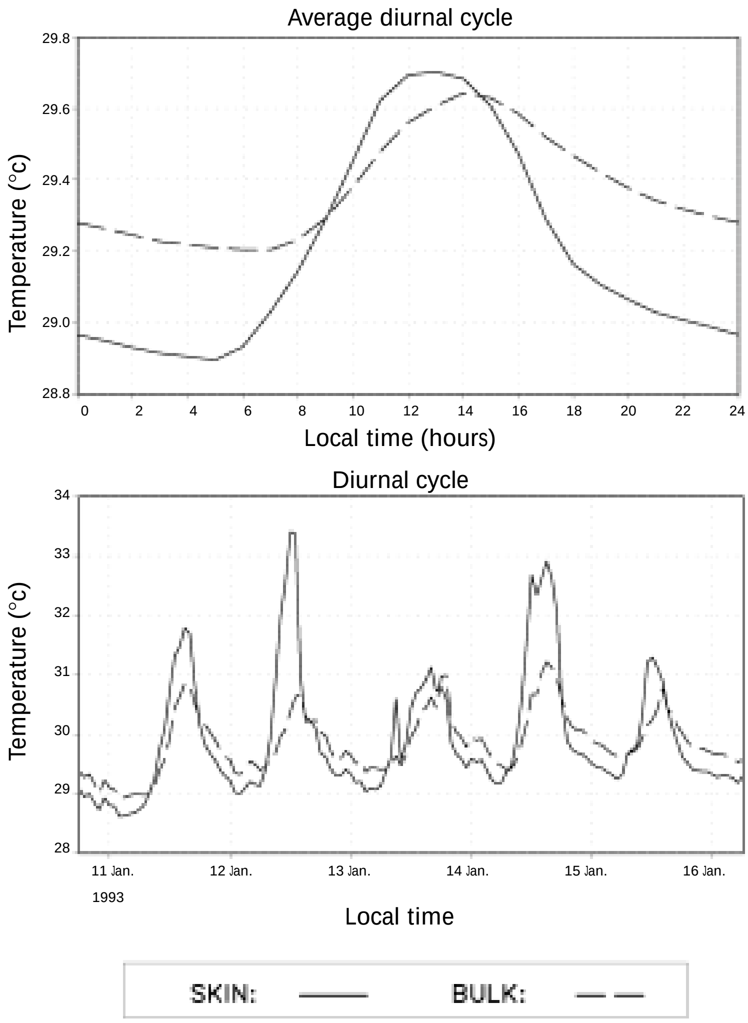

Figure 4— Skin and bulk SSTs (see text) from a buoy at 1.8°S and 156°E. The top panel shows the average diurnal cycle for the period 22 October 1992 to 3 March 1993. The bottom panel shows the variability in the diurnal cycle. In the bottom panel, the data labels indicate local midnight.

bulk SSTs are minimized by smoothing and by increasing the error statistics of day satellite SSTs relative to night. However, for high resolution SSTs, the vertical structure of the depth of the different observations must be properly resolved.

The satellite data used in the SST analyses listed in Table 1 are derived from the AVHRR instrument. Although there were two polar-orbiting satellites for most of the 1982-99 period, data were operationally processed from only one satellite until late spring 1999. Because of swath width limits, one satellite cannot see the entire globe twice a day. This problem is made worse by cloud cover, which further degrades the coverage. Thus, only analyses with a dynamical component may be able to properly interpolate the analysis in space and time.

This data coverage problem will become less critical when more satellite data become available. Accurate SSTs from a microwave instrument, for example, Tropical Rainfall Measuring Mission (TRMM), would produce SSTs which are unaffected by cloud cover. In addition, SSTs from US Geosynchronous Operational Environmental Satellites (GOES) are now available (Wu, 1999). The GOES instrument is similar to the AVHRR and can resolve the diurnal cycle in cloud-free areas. However, further research is needed to improve the retrievals, as discussed by Wick (1999). In addition, future GOES SST retrievals will be degraded because of instrument changes which make the correction for atmospheric water vapour more difficult.

Some improvements in the in situ data must also be made. Many of the open ocean buoys do not report SSTs at six-hour intervals so as to save on satellite transmission costs. For example, the TAO network of moored buoys in the tropical Pacific (McPhaden, 1995) would be ideal for determining the diurnal cycle if all the data collected by the buoys were available in real time. Metadata information on the characteristics of both ship and buoy SSTs is also needed to better define error characteristics so that better use can be made of the in situ data. In addition, more ship and buoy data are required south of 45°S where there are currently insufficient in situ data to completely correct any satellite biases.

5. CONCLUSIONS

For both climate and high resolution SST analyses, satellite data should be used with care. These data can greatly improve the coverage and spatial resolution of SST analyses. However, because of large potential biases in satellite retrievals, accurate bias corrections are needed, particularly for climate studies. For climate purposes, reliance on in situ data alone does not eliminate SST analysis differences. A careful intercomparison of the in situ data processing methods is needed to develop more uniform procedures. Because of large uncertainties in present ice analyses and the methods of converting from ice to SST, in situ observations of both SSTs and sea-ice concentrations are urgently needed near the ice.

For high resolution SST analyses, the use of accurate satellite data from multiple sensors, including microwave and geostationary instruments, is critical. In addition, dynamic models are needed to interpolate in both space and time in regions where SST data are missing. These models must include the resolution of vertical scales so that the differences in SST measurements from ships, buoys and satellites can be assimilated at the depths where the observations are made.

Intercomparisons of different SST products have shown important differences. It is important that SST intercomparisons continue so that analysis and data differences can be better quantified and methods can be developed to minimize these differences. Because analyses continue to change, a continued reevaluation of the differences is required. An international GCOS working group has been established by the Atmospheric Observation Panel for Climate (AOPC) and the Ocean Observations Panel for Climate (OOPC) to evaluate climate SST products. This effort should be extended to include high resolution SSTs analyses. A parallel effort may be needed to include comparisons of high resolution SSTs analyses.

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