

SPECIFIC CONTRIBUTIONS TO THE OBSERVING SYSTEM: SEA SURFACE TEMPERATURES

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ABSTRACT - Sea surface temperature (SST) observations have been made from in situ (ship and buoy) and satellites. SST analyses used for climate purposes must be constant in time and not influenced by the changes that have occurred in the type and number of SST observations. In particular, biases due to in situ instrument changes and satellite aerosol and cloud contamination must be corrected. The largest uncertainties in global analyses occur near the sea-ice margins where SST observations are sparse and where the accuracy of the analyzed ice concentration is not well known. High resolution SST analyses require the use of satellite as well as in situ SST data. For the high resolution analyses, the development of accurate algorithms to convert between skin SSTs measured by satellite and bulk SSTs measured by ships and buoys is critical. To improve these analyses additional satellite data are needed including microwave satellite data which are unaffected by clouds and geostationary satellite data which can resolve the diurnal cycle.

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 modeling. 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% 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, corrections for which are discussed by Folland and Parker (1995) and incorporated into UK Meteorological 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 thermistor or hull contact sensor and usually relayed in real-time by satellites. Biases in the SSTs from buoys can occur in some designs, e.g., 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 Fig. 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 due to in situ observations alone. The satellite retrievals allowed better resolution of small-scale features such as Gulf Stream eddies. In addition, 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 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 the 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 vapor. 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 0.5m). The tuning is done 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 the 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, the retrievals have a negative bias. Negative biases can also be caused by aerosols, especially stratospheric aerosols from large volcanic eruptions (e.g., see Reynolds, 1993). The ratio of the number of daytime to nighttime satellite retrievals is now roughly one to one. However, the ratio was roughly five to one prior to 1988. From 1989 to present the nighttime satellite algorithm was gradually modified to increase the number of nighttime 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 during 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 do high resolution SST analyses as discussed later.

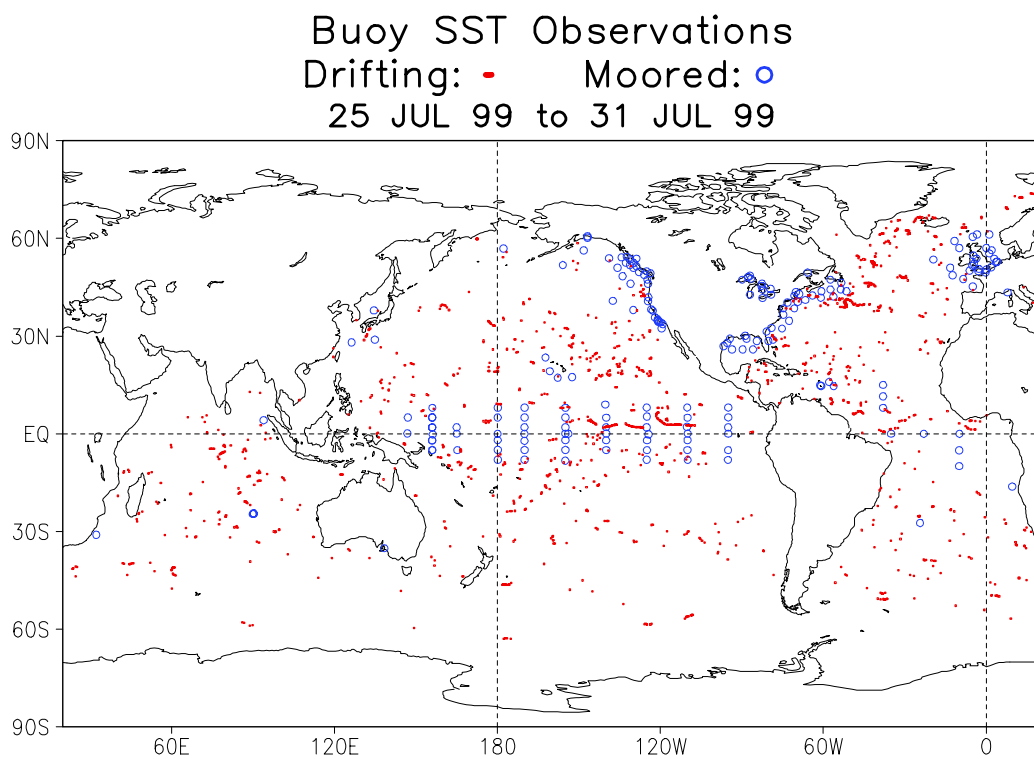
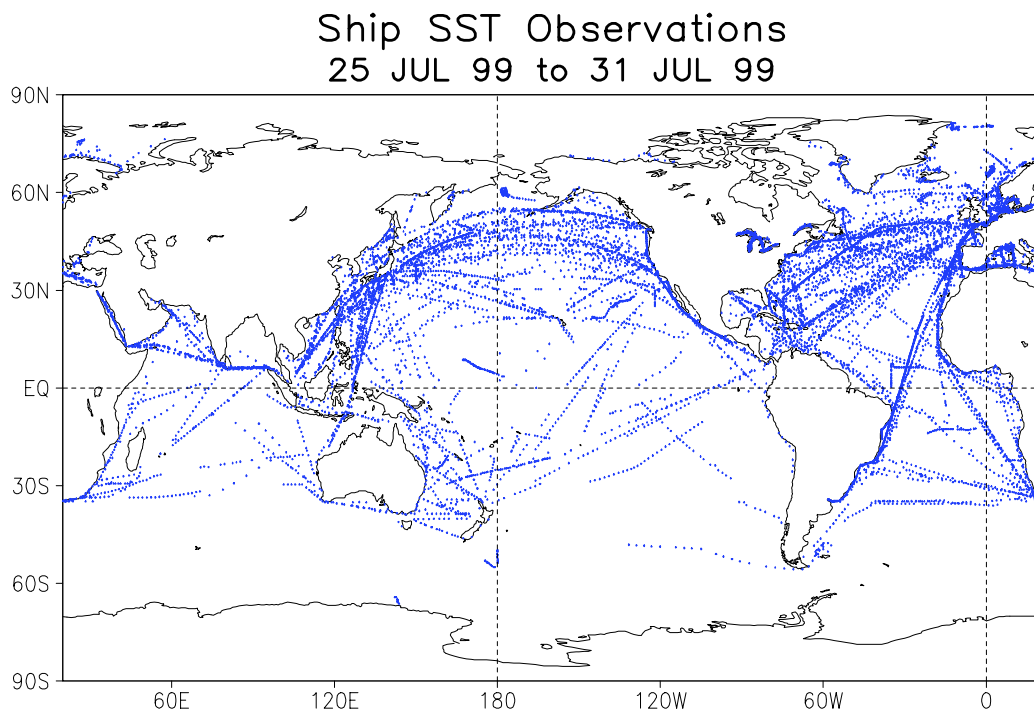


Fig. 1: Distribution of SST in situ observations from ships (top panel) and buoys (lower panel) for the week of 25-31 July 1999.

3 - CLIMATE SCALE SST ANALYSES

For 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 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 Centers 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 of Kaplan et al. (1998) henceforth LDEO. 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 which was held at the Lamont-Doherty Earth Observatory, 2-4 November 1998 and is updated here. This workshop study focused on the period 1982 to 1997 and added four additional analyses, the UK Meteorological Office Historical SST analysis, version 6, of Parker et al. (1994), henceforth MOHSST; 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	1979 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 $SST = -1.8^\circ\text{C}$ or 0°C when $I = 1$ over the ocean or fresh water lakes, respectively. In addition to uncertainties in these methods, the analyzed 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 Fig. 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.

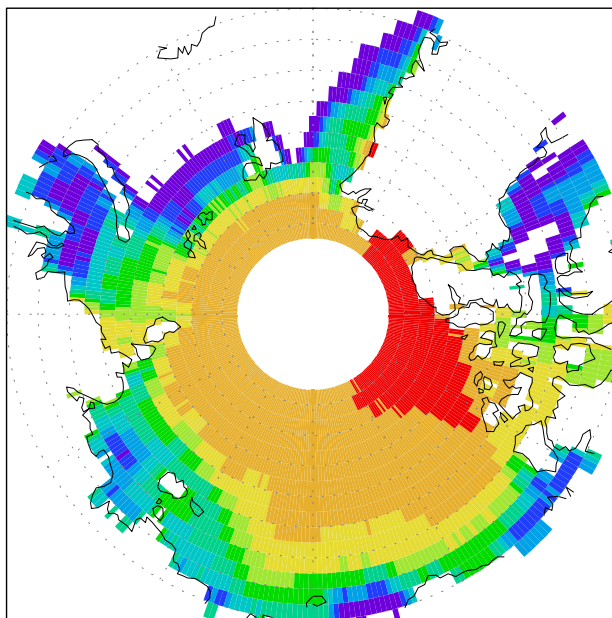
Both Hurrell and Trenberth (1999) and the workshop comparisons showed that differences among analyses were smaller within the tropics than the extratropics. This can be seen in the zonal averages shown for the four analyses with ice information in Fig. 3. The figure shows that Northern Hemisphere middle 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 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 . 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.

To illustrate the problems of a real-time satellite bias correction, the anomaly time series for the monthly OI and MOHSST SST anomalies, computed from 60°S to 60°N for the period 1982-1997, are shown in Fig. 4. This region was selected to minimize the impact of sea ice. Because the global coverage of the in situ data is not defined everywhere, the analyses were computed only over regions where MOHSST had values. The result shows that the MOHSST tends to be slightly more positive, roughly 0.1°C , than the OI analysis from 1990 onwards. The OI analysis has a real-time bias correction of the satellite data. To show the importance of this correction, a special version of the OI analysis was computed without the real-time bias correction of the satellite and also shown in the figure, labeled OI_NO. The differences between the two OI versions are much larger than the differences between the MOHSST and bias corrected OI analysis. In particular, impacts 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). Further study has shown that the average difference between the OI and MOHSST analyses during the 1990s is due to two effects: a residual under correction of the satellite biases in the OI and differences in the nonlinear in situ data screening procedures used in the OI and MOHSST.

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 Hemisphere where in situ observations were sparse. However, there were

July Ice (1979–92)

Nomura/Grumbine



National Ice Center

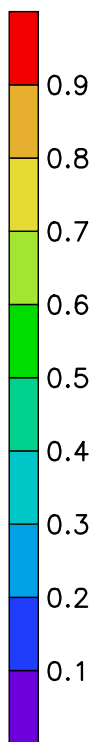
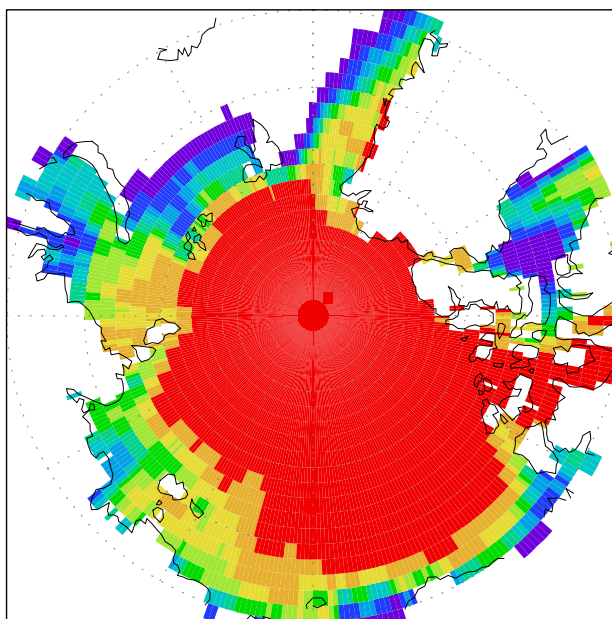


Fig. 2: Climatological sea ice concentrations for the Arctic for July for the period 1979 to 1992. The upper panel shows the analysis from Nomura and Grumbine; the missing data near the pole occurs because of lack of satellite observations. The lower panel shows the analysis from the National Ice Center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

January 1995 – December 1997
Mean Zonal SST Anomaly (°C)

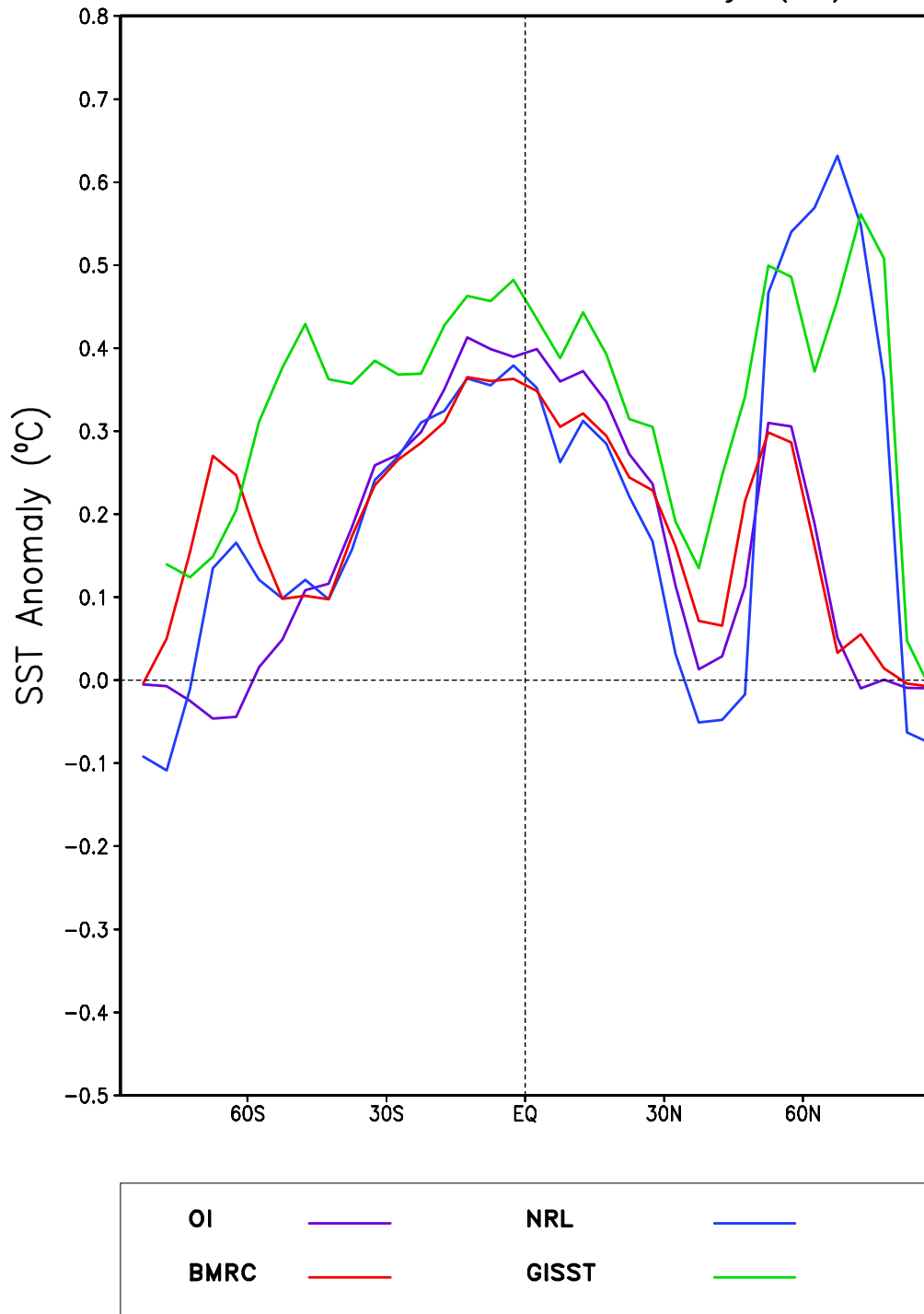


Fig. 3: Mean zonally averaged SST anomalies from four analyses for the period January 1995 to December 1997. All analyses used in situ and satellite SST plus SSTs generated from sea ice concentrations.

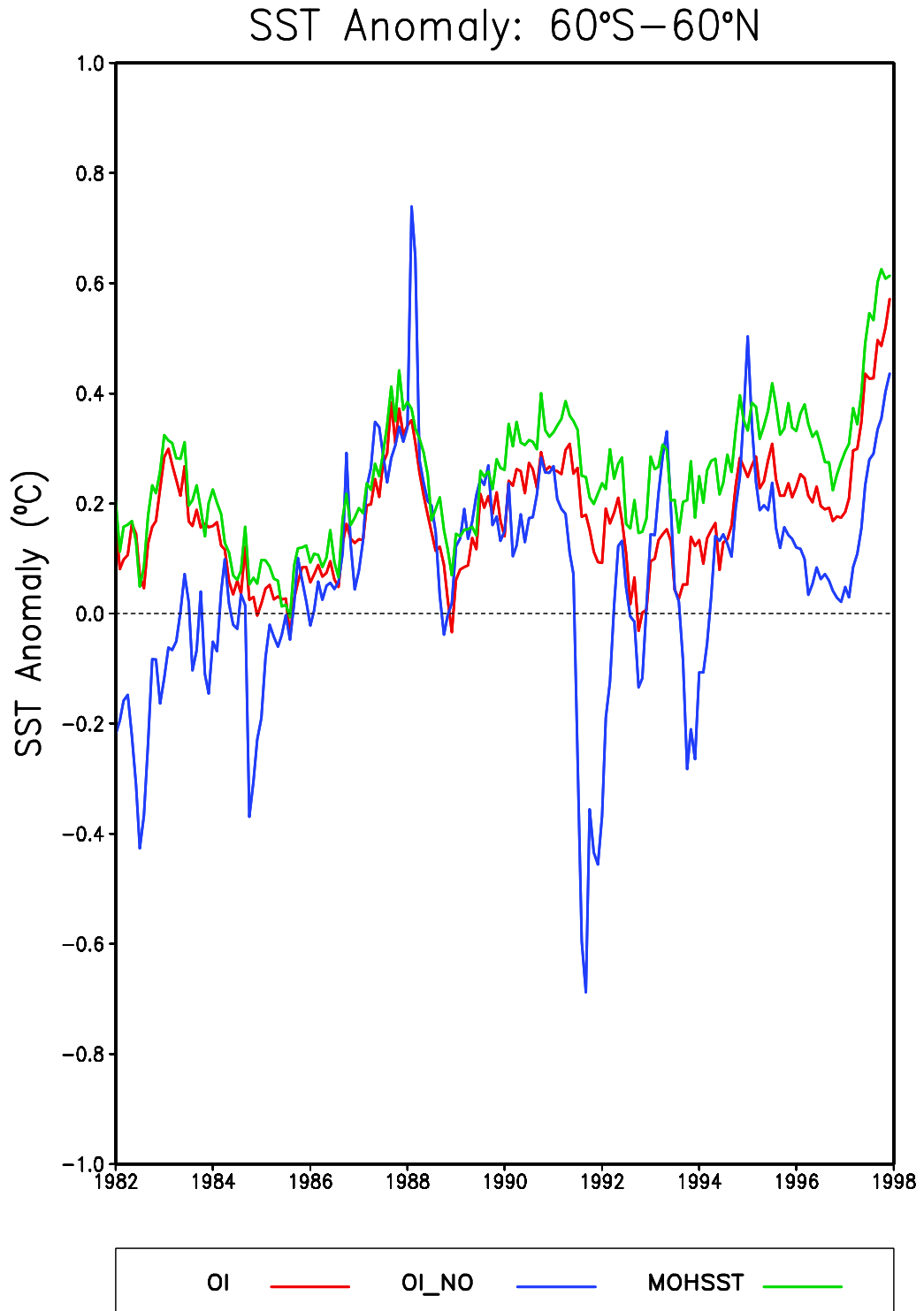


Fig. 4: Averaged (60°S to 60°N) SST anomalies from the OI and MOHSST analyses. The times series labeled "OI_NO" is from a special version of the OI analysis without the real-time bias correction of the satellite data (see text). The averages are computed over common areas where the MOHSST analysis is defined.

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 that were 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. For these analyses satellite data is essential.

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 Fig. 5 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 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 was 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 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, e.g., Tropical Rainfall Measuring Mission (TRMM), would produce SSTs which are unaffected by cloud cover. In addition, SSTs from US Geosynchronous Operational Environmental Satellites (GOES) satellites 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 vapor 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 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 are 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.

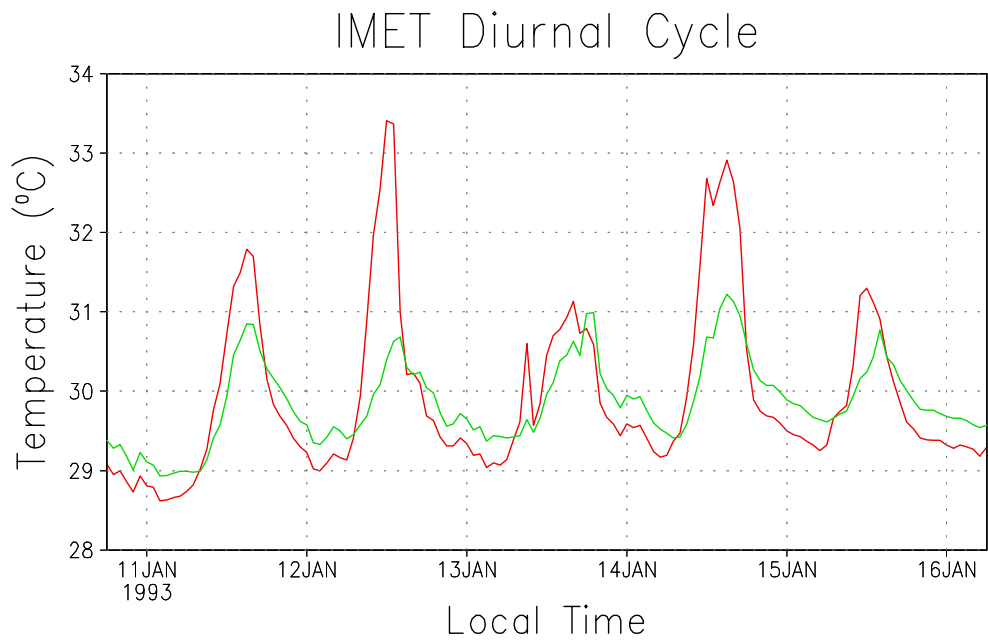
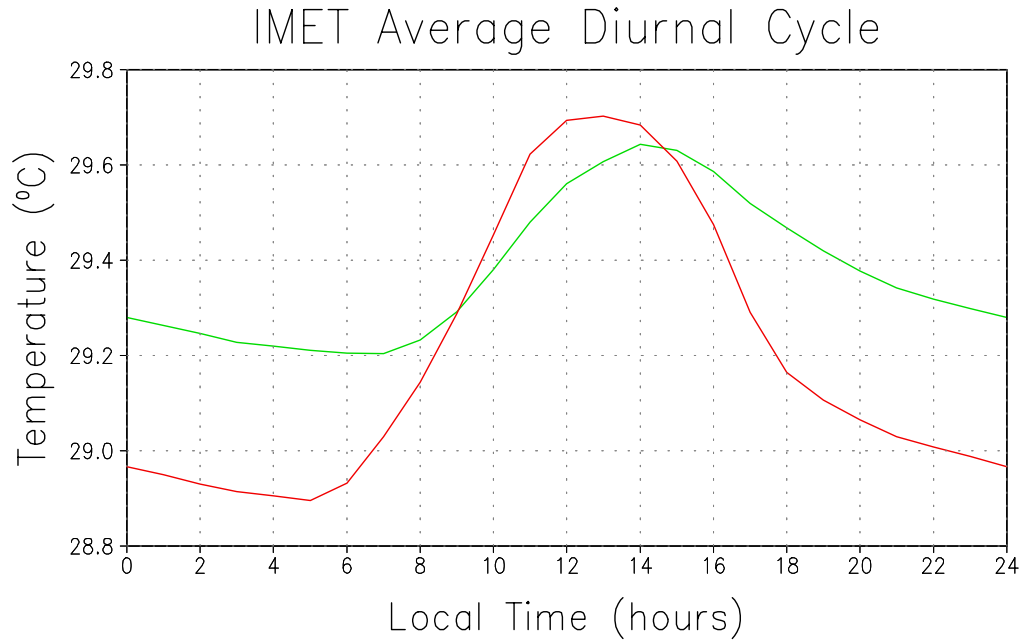


Fig. 5: Skin and Bulk SSTs (see text) from a buoy at 1.8°S and 156°E. The top panel shows the average diurnal cycle for the period October 22, 1992 to March 3, 1993. The bottom panel shows the variability in the diurnal cycle. In the bottom panel the labels on the x-axis are centered on local midnight.

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, use of accurate satellite data from multiple sensors including microwave and geostationary instruments are 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 resolution of vertical scales so that the differences in the 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. A parallel effort may be needed to include comparisons of high resolution SSTs analyses.

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