Report of

GODAE High-Resolution SST Workshop

30 Oct - 1 Nov
Joint Research Centre, Ispra, Italy

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1 - Opening

Craig Donlon welcomed participants on behalf of the Joint Research Centre. He described their mission and the interests of JRC in marine science and sea surface temperature.

The Chair (N. Smith) introduced the agenda (Attachment I) and also added his welcome to the participants (the attendance list is at Attachment II). The meeting agreed to try and complete much of its work in plenary rather than break out into sub-groups (as suggested in the Agenda). Presentations by Harris, Ward, Quarterly, Barron, Evans, Mutlow and Ouberhuis were added to the agenda.

The Chair noted the considerable material provided as background for the meeting, much of which was compiled into the "Welcome Package" provided by Craig Donlon (this material is also at http://www.bom.gov.au/bmrc/mrlr/nrs/oopc/godae/HiResSST/). The abstracts from those presentations are at Attachment III. The Chair expressed his thanks to the many people that participated in discussions prior to the meeting, some of whom were unable to be at JRC.

The workshop was arranged around presentations from the participants on various aspects of developing a global high resolution SST data set, using Ian Robinson's background paper as a template. The Chair noted that the objective was to openly raise all of the issues (content, operations, feasibility, requirements, distribution, validation, etc.) associated with the development of a global high resolution SST data set.

2 - Overview and Requirements

Neville Smith presented the paper "Global Measurement of Sea Surface Temperature: Some new perspectives" by Ian Robinson and Craig Donlon (abstract in Attachment III). He noted that the paper represented a review of methods for observing and estimating SST and discussed the several issues that faced the present project. The paper outlined the opportunities for developing a new generation SST product, based on a more refined approach to the definition of SST and multiple in situ and satellite observation techniques. The paper also addressed several of key issues that needed to be addressed at this workshop that, in part, provided the basis for the Agenda.

The Workshop agreed that the paper provided an excellent background, developing the outline provided in the Prospectus and consolidating the discussion that took place at the fourth meeting of the International GODAE Steering Team (May 2000).

The Workshop also highlighted several issues that needed to be considered in developing the next phase of the project. These included

- Definition of SST (or proper description of the data related to SST)
- The distinction between products and SST data bases
- The need to consider confirmed new capabilities (e.g., the transition to NPOESS)
- The fact that the GOES will lose split window capability
- The need to provide an acceptable and scientifically robust link to climate products
- The perspective of models taking data forward / backward in the retrieval process and the role they might play in providing estimates of SST

The Chair then provided a brief overview of the Global Ocean Data Assimilation Experiment and SST (see Le Traon *et al.* in Attachment III). In particular he noted

- Blending and integration of different data types (assimilation) is a recurring theme through GODAE;
- GODAE has a fundamental dependence on SST data and products and is thus keen to provide a framework for developing an advanced system for SST;
- In particular, he noted that the global perspective of GODAE demanded attention to the many gaps in present products (often not quantified) and improved representation of observational errors in data products;
- The value-adding partner activities of GODAE (e.g., coastal forecasting also required improved products, particularly in terms of resolution; and
- Several associated activities (e.g., numerical weather prediction (NWP), research programs (CLIVAR, GEWEX) and climate monitoring) need a new generation of product.

The workshop noted that (ocean and atmosphere) systems are inevitably becoming more integrated and complex; retrievals and estimates for sea temperature require more and more information. Any advanced system for SST must take into account this increasing complexity and also the opportunities that it provides.

Jim Cummings then provided an overview of the operational SST and sea-ice analysis system at Fleet Numerical Meteorological and Oceanographic Centre (FNMOC; Attachment III). He noted that FNMOC represented the user side of a partnership with NAVO (the data providers; see later presentation by Doug May). He noted some of the difficulties associated with the present method for distributing relevant information for SST analyses included lack of necessary metadata on the GTS, variations among centers in reception of data, and lack of knowledge on the methods used for retrieving sea-ice information.

The diurnal cycle is not resolved by current Navy operational analyses but it is recognized as a requirement for weather prediction and ocean forecasts. Cummings noted that, on occasions, the lack of resolution for the diurnal cycle could cause problems (the first-guess is based on a linear regression from the last analysis). He described progress with the Coupled Ocean-Atmosphere Model Prediction Systems (COAMPS) and noted that the ocean component was yet to be fully implemented.

Aerosols are a major source of bias in the retrieval process from radiometer data. Cummings described the experimental aerosol analysis system being developed by the Navy (NAAPS) and indicated that it would provide useful information for retrieval and quality control. NAAPS doesn't yet do volcanoes; would like to detect it at the level of input data (irradiance) and do the corrections at that level rather than on broad scales like in Reynolds and BMRC system. He also mentioned the high-resolution wind product developed by Roger Daly (around 20 km) and noted its relevance to the SST problem.

The U.S. is hosting a GODAE data and product server at Monterey and is already providing navy data and products. Cummings noted that this server would be a powerful facility for any advanced SST data project. Database issues and the issue of reanalysis were raised in the general discussion. How do we develop robust and useful servers that serve the broad community, from those who place a high premium on immediacy and timeliness, to those who care most about quality and are willing to work off-line (e.g., climate assessment)?

3 - The Physical Character of SST

This discussion was led by Bill Emery (see Abstracts in Attachment III). He discussed the general issue of estimating Sea Surface Temperature from infrared satellites and in situ temperature data. He noted that SST and the sea temperatures immediately beneath the surface were subject to many physical processes at the air-sea interface, many of which involved complex non-linear interactions.

Emery noted that the skin - sub-skin temperature difference (hereafter referred to as ΔT_{SKIN}; see Figure 1) was a function of both surface wind speed and surface heat flux. In principle, given knowledge of the surface wind and ΔT_{SKIN} we could infer the surface heat flux. In an analysis of in situ radiometer measurements there appeared to be three regimes: free convection, low wind but significant heat flux; forced convection where the wind speed is large; and a case where breaking capillary waves were the dominant mechanism determining ΔT_{SKIN}.

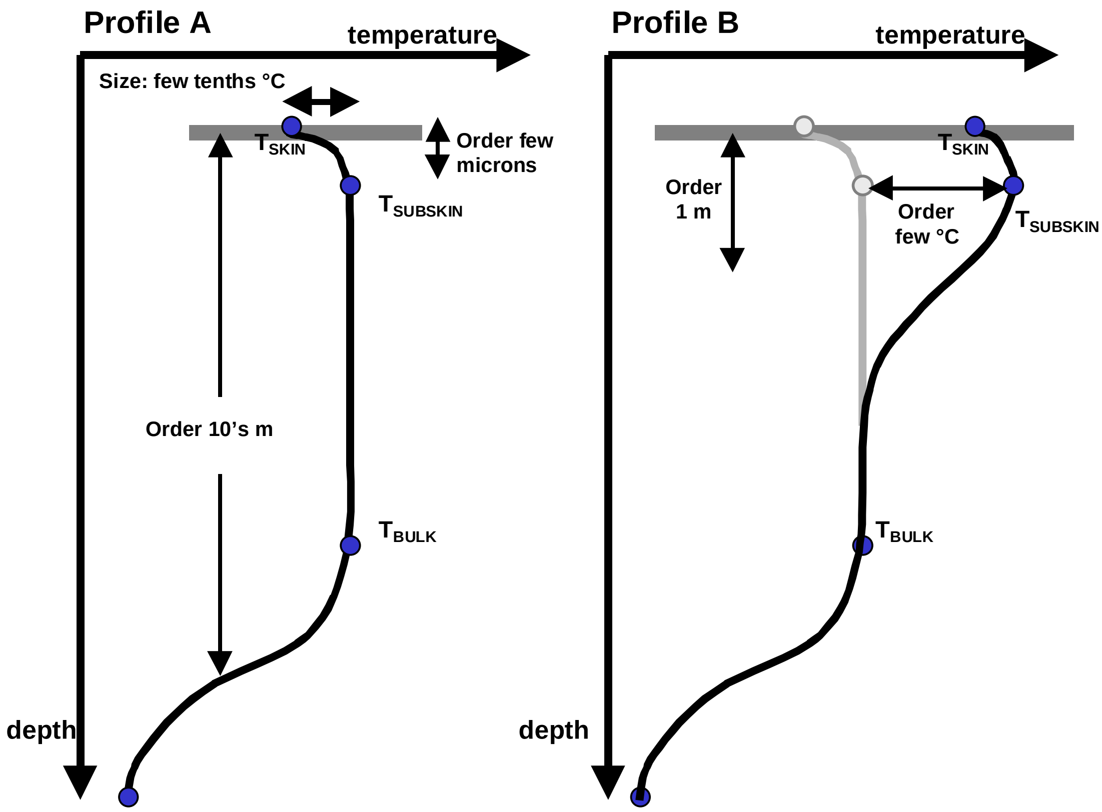

Figure 1. Schematic of sea temperature profiles near the surface (adapted from Peter Taylor). The profiles are for (A) nighttime and daytime moderate to strong winds and (B) daytime light wind conditions. See text for discussion.

There was an extended discussion on the separation (distinction) of these regimes and on the practical implications (an extensive discussion that related to this subject and instigated by Peter Taylor is included in Attachment III). For the first two cases the main debate focused around the demarcation point (suggestions from 3 m/s to 9 m/s). It was also pointed out that surface wind wave and swell effects might need to be included (the orbital motion of the waves also acts to reduce ΔT_{SKIN}).

Discussion

One thing that is agreed is that the term "sea surface temperature" as it has been used to date is a poorly defined term. It is clear there is not a single definition and that we need to include at least three parameters to provide a minimal description of the sea temperature near and at the surface: a skin temperature, a sub-skin temperature, and a bulk (mixed-layer) temperature.

4 - Measuring and estimating SST

Pierre le Borgne described the project involving SST in the Ocean and Sea-Ice group of the Satellite Applications Facility and the use of SST data in MERCATOR (see Attachment III). Le Borgne noted that they employ different algorithms for day- and night-time retrievals of GOES data (Non linear (by day) and triple window (by night) algorithms have been used for GOES-08 data). Figure 2 provides an example. The retrieved SSTs from GOES matched up to in situ measurements rather better than expected - both the bias and rms differences were not significantly different from those of the NOAA AVHRR.

This project opted to estimate what they termed the sub-skin temperature - the temperature immediately beneath the surface skin layer (see Figure 1). As discussed above, this temperature can be measured in situ using conventional platforms (buoys, moorings, ships) during the nighttime and during high wind conditions. They used the former data to calibrate their retrievals for SST. Le Borgne noted that the efficiency of cloud clearing was perhaps the single most important process in the analysis. Cloud masking is the biggest contributor to decreasing error. The project also provides estimates of solar irradiance. He also noted the "midnight sun" effect in GOES when the radiance properties of the instrument can introduce biases.

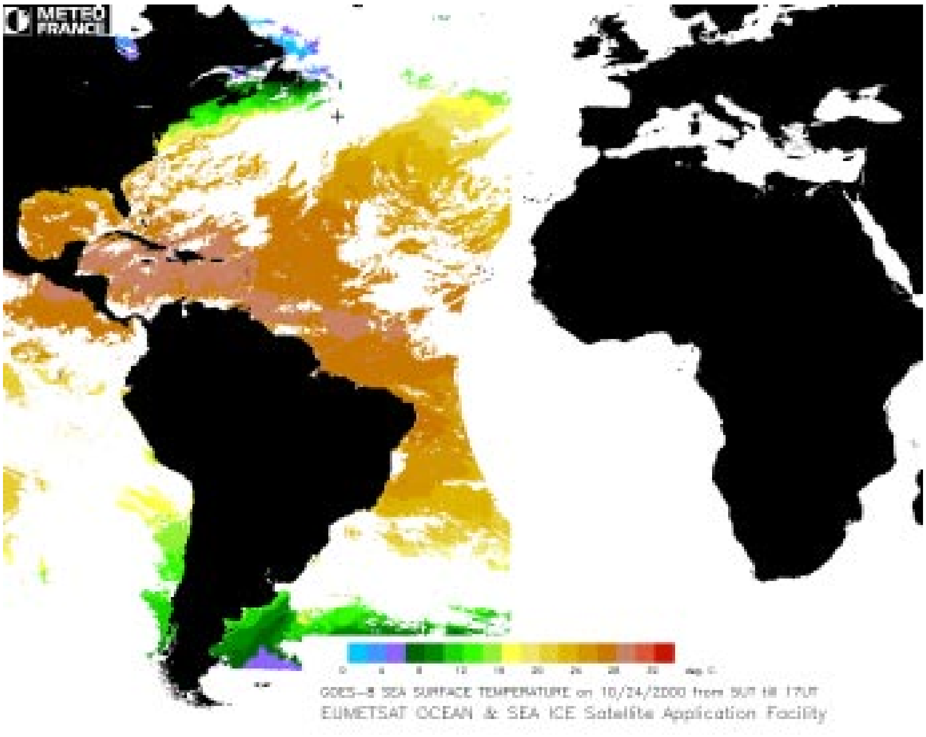

Figure 2. Sea surface temperature derived from GOES-8 data for the 12 hour period from 5UT on 24 October 2000 (provided by P. Le Borgne).

The products will be distributed from an open server at IFREMER. At the moment the supported formats include HDF, GRIB and pgm (see abstract from Richard Legeckis in attachment III). The MERCATOR project will use GOES-East and MSG derived SST on a 3 hourly basis with the sub-skin SST definition. The match-up data base contains data from drifting buoys (from the GTS); if the cloud coverage is > 60% no match up done.

Doug May described Navy MCSST processing at NAVOCEANO (see Attachment III). Satellite data provide the main source of information for SST estimates. Among the many uses for such products are ocean feature maps and 3D ocean assimilation (see later discussion by Barron). NAVO is responsible for the MCSST product (formerly done by NESDIS, and now using a non-linear algorithm; NLSST) and also produces altimeter products. The activity includes estimates for all water-covered regions of the ocean down to about ~ 7 km. The turn-around is about 3 hrs. The database is a revolving database with 8 days of the most recent data retained. They do the processing orbit-by-orbit, 14 orbits per day, on 4 km x 4 km resolution and produce data on an 8-km grid (all 4km have to be clear).

Buoys are matched with a 25 km x 4 hour window; they are not used to "correct" retrievals. There are around ~ 6000 night and 2800 day match-ups typically.

GOES west provides around 4M observations per day while there is around 1M from GOES-East. The present expectations are that GOES retrievals will be available operationally by Feb 2001. They can do T_{SKIN} by changing to a split-window algorithm (Peter Schluessel et al). This bias on a monthly basis is normally around 0.1C and doesn't drift beyond 0.2C for about 10 yr.

At present NAVO does not have responsibility for distribution of the data (this is done by NOAA/NESDIS) but there seemed no reason why the data could not be provided via the GODAE server. NESDIS takes a sub-sample of these data for the GTS.

Chelle Gentemann described methods for estimating SST from satellite microwave measurements (see Attachment III and the following presentation by Kawamura). The procedure relies on the multiple channels available on the TRMM satellite Microwave Imager (TMI) and uses the ~ 10 GHz channels to eliminate atmospheric effects. The retrievals are done using a 2-stage regression. Global (equatorial) coverage is achieved in 3 days, only missing data when it is raining. Microwaves penetrate the cloud layer with little attenuation, giving an uninterrupted view of the ocean surface. This is a distinct advantage over the more traditional infrared measurements of SST, which are obstructed by clouds. There is a bias when the wind is in same direction as the satellite view; they are presently use NCEP winds off-line to remove this bias.

The rms match-ups for single observations are 0.55C for TAO; 0.5C for PIRATA; and ~ 0.6 for NDBC surface buoys. The algorithm is effectively providing an estimate for the sub-skin temperature (the microwave sensor samples over a layer many times thicker than the few microns of the skin layer).

Gentemann also noted that there was a bias due to the antenna: the antennae is exposed to diurnal and seasonal variations of insolation so 97% is true signal, the other 3% from this effect.

Chelton and Gentemann have shown that the coverage in the tropical regions is excellent. Near the tropical instability (Legeckis) waves, the TMI data are able to provide resolution (in time and space) that is not possible with AVHRR data. Gentemann also showed data from Hurricane Danielle where the conventional analyses (e.g., NCEP) put the SST too warm (because AVHRR is limited by clouds) whereas TMI showed a cool patch (Figure 3). It is argued that these temperature changes were critical for the evolution of the cyclone.

Chris Mutlow noted that some care has to be taken with MI and IR intercomparisons since the space-time sampling is quite different - IR samples better at some times of day when there is less cloud. Jorge Vazquez suggested it would be useful to compare TMI SST and Pathfinder products.

They are planning to set up comparisons with future mission (e.g., AMSR on ADEOS II. See the Kawamura presentation).

The data are available on the web site [http://www.remss.com/] (3-hour delay).

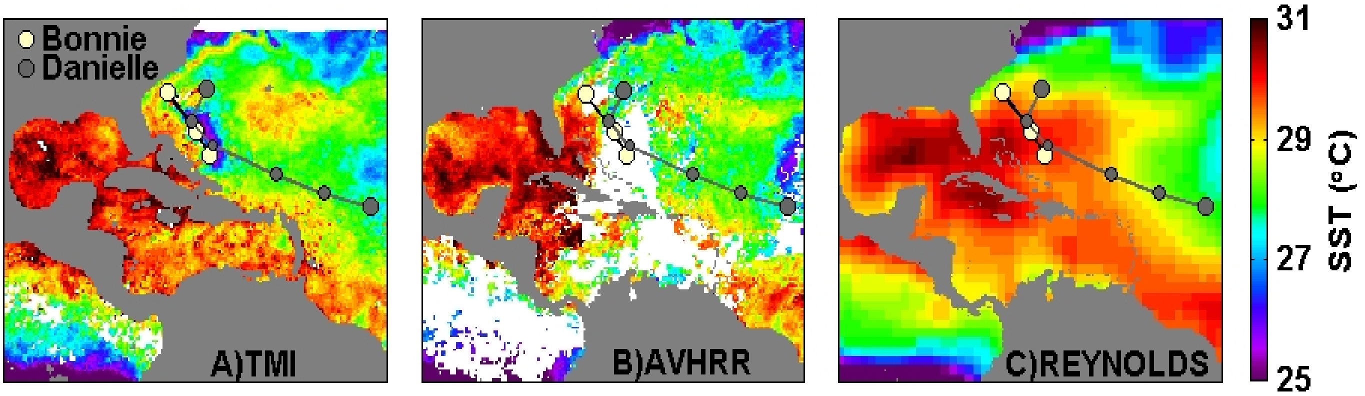

Figure 3. SST during Hurricane Danielle. TMI (left panel) views the cold wake from the preceding Hurricane Bonnie but AVHRR (middle panel) misses it due to cloud cover. The operational NCEP analysis (right) lacks both the data and temporal/spatial resolution.

Hiroshi Kawamura introduced activities of Japan and, in particular, discussed SST retrievals from TRMM and plans for using ADEOS III data (Attachment III). From their work the TRMM/TSI rms match-ups were around 0.7C, noting the broader sampling. Such accuracy is more than useful for many applications. The satellite provides good coverage in severe cloud cases, though there is some coastal inference. The main message is passive microwave measurements greatly enhance coverage. For example, during February 2000, the coverage from AVHRR, GMS/VISSR and TMI was, respectively, 29%, 38% and 76%. Figure 4 shows data from January 1999.

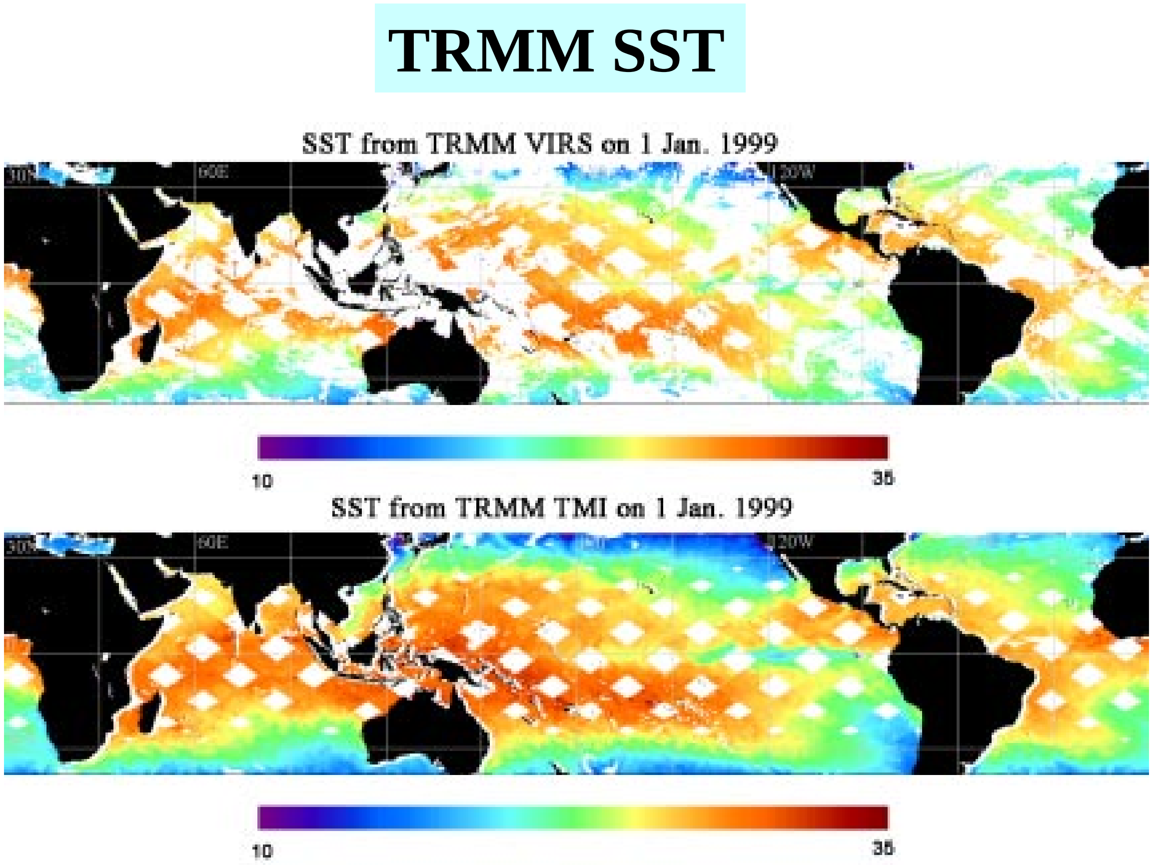

Figure 4. SST analyses derived from the TRMM radiometer (top) and microwave (bottom) instruments. Note the enhanced coverage in the tropical regions.

The GLI and AMSR instruments on ADEOS II promise greatly enhanced capability. Collaborations with Ian Barton, Frank Wentz, and others have been established in order to develop skin, bulk, and microwave (sub-skin) estimates of SST. The proposal is to combine GLI data (order 1 km resolution, 0.1 accuracy) with AMSR microwave data (order 50 km, 0.5C accuracy) for blended products. They will be closely examining diurnal issues.

At present, the VISSR is being used to construct estimates of solar radiation and to drive a model to get diurnal variation. The method was trialled through the NSCAT period using the PWP model. The conclusion is that if you have solar radiation and wind, and skin SST, you can calculate T_{bulk} with some fidelity.

Kawamura then described some initial plans to produce blended products using ADEOS II data, consistent with the initial objective of the high-resolution SST project. They would produce two data sets. The NW Pacific component would focus on a 1 km gridded product; daily max and min Ts; daily bulk estimates at 1, 10 and 50 m. The data would be derived from ADEOS II SST (GLI and AMSR) + AVHRR + GMS + sat winds, insolation + in situ OI combined. The global product would have less detail and might not be produced in real-time.

They have conducted a survey of user requirements (see accompanying Box). One interesting conclusion was that there was no user requirement for diurnal products (only delayed demand by science). Of course, to deliver the accuracy you need for other applications one needs to consider aliasing by the diurnal cycle. Bob Evans noted (in relation to the modeling) that it was not just a

User Requirements for New Generation SSTs

Meteorological Agency, Fishery Agency
Maritime Safety Agency (Coast Guard), JAMSTEC

- Daily One-degree Gridded Global SSTs for Weather Prediction (Real Time)
- Future Sea-Surface Boundary Layers Model for SST and Ice Predictions and Mixed-Layer analyses
- 10km Global SSTs for Fishery Use (Real Time)
- Daily Regional 1km SST for World Oceans (On-Demand but Real-time)
- Detection of all SST Fronts associated with significant oceanic currents (Real Time)
- 0.5K Accuracy and Continuous Supply

No User Needs for Diurnal SST Information!!

(Information supplied by H. Kawamura)

case of taking data into models: we need to be able to bring the strengths of models back to data sets. It is only through this process that we can ultimately achieve the aims of this project.

Bob Evans described some recent results from MODIS. He noted that use of MODIS data is "not without its challenges". Evans described several of the issues including the fact that the 12-bit information has been effectively reduced to 10. The instrument gives thermal images similar to AVHRR (1 km) but also has a mid-wave algorithm to give detail not possible with AVHRR.

Evans looked at some of the results from the Mediterranean in more detail. He showed MODIS was able to reveal very detail on eddy-like structures and revealed very interesting fine structure at the pixel level (Donlon noted such features were also seen in ATSR). He noted the dual application of IR and ocean color could be very effective. He noted the extra power of bringing knowledge of the environment to the process of retrieving physical variables: a stratified environment.

Evans noted that errors are distributed / attributed to many different sources and we are challenged to actually get the right data to test this. Direct radiation measurements were one option.

The workshop made the general comment that validating very fine structures was extremely difficult. Indeed, the detail available from instruments like MODIS, and from the next generation instruments like GLI, ATSRR-II and NPOESS, were beyond the direct approach: they simply could not get near the synoptic spatial resolution. Intercomparisons of global products, and with information derived from other sensors (e.g., altimetry and ocean color) provided perhaps the only viable option.

Chris Mutlow briefly described the ATSR data (see the Robinson and Donlon paper for detail). He noted that ATSR retrievals are completely independent of buoys (the algorithms are direct); they use radiosondes in the algorithms and exploit the dual look capability of ATSR to improve quality. It theory, such radiometer estimates are probably the next "baseline" behind direct radiometer measurements at sea. Processing is with about 3 hours delay (10 orbits on-line and three are missing).

5 - Processes affecting SST estimates

Ian Barton discussed issues related to the diurnal cycle (see Attachment III). He noted that the "old SST philosophy" aimed for an accuracy of around 0.5 - 1.0C. There are now demands for climate accuracy exceeding 0.25C and for more reliable cloud clearing procedures. The dual-look ATSR approach with 12-bit digitization, the low noise detectors to be available on NPPOESS, and the use of two black body references, will enable a much better SST product. The issue of diurnal variations and possible aliasing of this effect will then become a major issue.

Barton supported the definitions for SST discussed above, in particular the use of the term sub-skin for sea temperature just beneath the skin layer (see Figure 1). He presented data from several Franklin cruises that made direct radiometer measurements. The nighttime ΔT_{SKIN} differences were around 0.16C (skin cooler than sub-skin). In the daytime the spread was wider and the mean difference closer to zero (the warm and cool skin cases tend to cancel). Barton emphasized that you need both SST and wind measurements.

There was some discussion on how useful microwave - IR differences might be, but it is complicated.

Barton's presentation emphasized yet again the importance of distinguishing day and night time temperature measurements. In effect, any climate product that is unable to make such a distinction is likely to have diurnal effects aliased into the product.

Gary Wick discussed GOES SST measurements and diurnal issues. He has calculated the hourly variation of total matches and finds a diurnal bias due to the "midnight effect" (apparently due to the direct irradiance of the instrument which affects the calibration).

In order to predict ΔT_{SKIN} Wick couples a simple mixed layer parameterization (Fairall's warm layer model) with the Price-Weller-Pinkel (PWP) mixed-layer model (this model is somewhat limited because of the a priori assumption of a well-mixed layer). He also used the Kantha and Clayson model (a Mellor-Yamada 2.5 level type model). The models are very dependent on input information, particularly insolation. Doing the inverse calculation (inferring bulk from skin) is much more difficult (in effect there are many solutions that might be consistent). His calculations highlighted the difficulties of assuming the mixed-layer is in fact well mixed with respect to temperature: the joint effect of T and S can be important.

Brian Ward described results from an Argo-like profiler that sampled just the near surface waters but could cycle through several times while collecting T on vertical scales of order 2 cm (see Attachment III). The instrument cycles through about 10 m ascending steadily over around 20 s. The trials were accompanied by direct radiometer measurement (M-AERI). The results showed a mostly a cool skin - driven by surface heat fluxes (mainly radiation) - but very large gradients over 6 m: sometimes more than 4C. These results suggest that getting a bulk SST may be rather more problematical that hitherto realized. Figure 5 provides an example of the data.

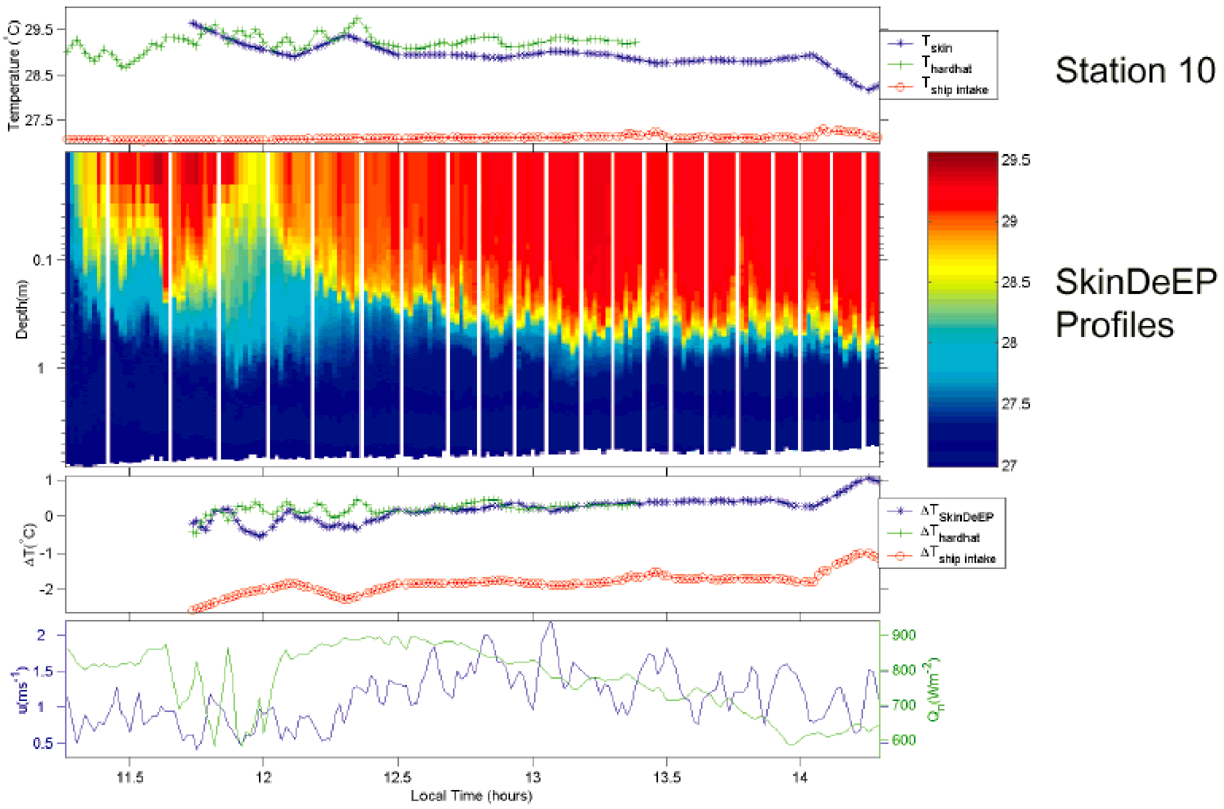

Figure 5. (Provided by B. Ward) Time-series of temperature data from M-AERI (T_{skin}), HardHat, and ship intake (top curves); from the SkinDeEP profiles (middle); and derived ΔT values and wind speed and net heat flux (bottom).

One of the limitations of the results was the lack of information on horizontal variability and salinity. It was not clear whether there may have been compensating salinity gradients (and hence still well mixed) or whether the waters were indeed highly stratified (the time series and fine structure suggested the latter).

The workshop participants agreed that these results were very exciting and that further research should be encouraged.

Graeme Quarterly briefly described some intercomparisons of SST products from ATRS and TMI (see Attachment III). He focussed initially on the Agulhas retroflection region and compared monthly products from TMI and ATSR. There were significant differences, probably due in part to sampling differences (Gentemann noted that the EORC TMI data still contain the antenna bias (version 6 will remove this bias). One of the conclusions from this presentation was that comparisons and blending of the Level 3 product are difficult; you should do it at the data level (Level 2).

Brenda Topliss provided a perspective from the high latitude (NH) cooler regions (see Attachment III). Ice and clouds are clearly a major issue in these regions and effective spatial coverage in the Labrador Sea is poor. The study concluded the NOAA algorithms were effective for polar seas - there was no need for a different regional algorithm.

The comparison of MCSST and Pathfinder products revealed considerable scatter. The high-latitude problem is very tough. They are providing the data to the environmental community (MCSST) through the National Data Holding. Out of three potential products for the region, about ½ are successes! AMSR is potentially available for the future.

Discussion Points

- Core message about the power of developing regional data bases in such a way that the global community can work from them;
- Theme of coincident wind and SST data (and solar);
- The testing (Cal/Val) of these advanced remote systems is a major challenge;
- For climatologies (time means) does it make sense to chase fine scales in, say, a monthly climatology (issues of balancing spatial and temporal scales and understanding predictability); and
- Is it time to start focusing on the inter-calibration of different sensors - this might bring more power?

6 - Operational implementation: toward a consensus

In this session, the workshop began considering consensus on actions and plans required for the future. The Robinson and Donlon paper provided the following breakout of the issues:

6.1 - Sampling, validation and intercomparisons

Space-time sampling issues
- *Polar orbiting infra-red sensors to provide the baseline*
- *Alternative observations must be found for cloudy regions*
- *Gap-filling as last resort*

Issues of accuracy and calibration
- *Infra-red baseline measurements*
- *Establish BOTH $T_{SKIN}/T_{SUBSKIN}$ and T_{bulk} data products*

Craig Donlon led off the discussion with a view on the path toward a global in situ validation plan (Attachment III). He noted the considerable detail and very fine resolution now available from SST-related products. It is apparent that we cannot simply rely on "scoring" of products: we must develop a method for determining the quality of the inputs as well as the quality of the outputs (products). Such validation of the data streams is a way of proving their value.

The methodology will be different from, say, top-of-the-atmosphere estimates of incoming radiation where the target field comes directly from the measurement. In the case of SST, we must take account of merging of geophysical parameters and the information that is required to make that merging most effective.

Donlon proposed the development of 2 x 2º Diagnostic Data Sets (DDSs) that would which bring together Level 1 and Level 2 satellite and in situ data. He emphasized that the 2 x 2º suggestion should not be regarded as strict and that the DDSs should not necessarily be fixed (in location) or permanent. The DDSs would archive all the over-passes for a specific site - the 2 x 2º dimension would keep the data flow to a manageable amount and prevent the maintenance of the sites getting out of hand.

The workshop agreed that such a concept was needed (see following section).

Donlon then considered the issue of validation of satellite measurements. He noted the importance of wind (see previous discussion and Taylor *et al.* in Attachment III). He further noted that, in relation to the establishment of in situ radiometer measurements, sea state is clearly a factor. Donlon concluded that below 6 m it is mandatory to have in situ radiometers; above 6 m, it is useful. Using some guidelines originally developed by Peter Minnet, he suggested around 15 radiometers per climatic region and, assuming we can divide the globe into around 3 climatic regions, about 45 in all.)

Donlon also raised the issue of inter-comparison of in situ radiometers (Ian Barton later briefly described plans for such a workshop: A 2nd International Workshop on Intercalibration of Radiometers, proposed for March 2001, Miami) and the issue of better organized in situ buoy calibration.

This presentation generated considerable discussion. The testing and proving of SST information needs to be seen in a more general framework with intercalibration / intercomparison of different satellite data (AVHRR, ATSR, GOES, …), fixed-point testing (DDS, moorings), spatial patterns (e.g., from VOS, RVs), broad-scale testing (drifting buoys), etc. This view was later developed into a broader framework (Section 7).

The very obvious point of validating very rich data sets from satellites with "independent", but very limited, in situ data was also raised.

The workshop also noted the importance of validation by the user community: testing by looking at the happiness of various user groups.

Bill Emery briefly discussed the accuracy of in situ sea surface temperatures used to calibrate infrared satellite measurements. He discussed the utility of buoys for validation and noted that in general buoys are not calibrated before deployment. Emery spoke in favor of a radiometer validation program from SOOP; the cost may be around $25K per ship. Participants recognized that some remain unconvinced of the need for radiometer validation: there are already very sophisticated radiometers in space gathering many, many such observations. However, the Workshop agreed with the reasoning put forward by Donlon and Emery and suggested a limited program, at least as part of a Pilot Project, was very well justified.

Gary Wick provided a brief description of work by Andy Jessup on a new radiometer. This work is funded as part of the MODIS validation program. Jessup is designing an autonomous radiometer package, potentially for use on RVs and VOS. The biggest concern was with the external black body whether it is without error (transparent window problems, etc.). The instrument has been tested on the TAO array and is being tested on the Polar Star and Polar Sea. Jessup is interested in a 3rd package being deployed on VOS.

Jorge Vazquez then described research comparing Pathfinder SSTs with MCSST and ATSR products (Attachment III). Vazquez noted that the loss of the 3.7-micron channel on board the ATSR-1 instrument appeared to have a larger effect on the nighttime differences. The application of a cloud removal model to the ASST data led to a mean difference of 1.40°C, with MPFSST warmer than ASST and a standard deviation of 0.57 were calculated. A significant drop from 36%

to 14% in the percent variance explained by the first mode indicates that applying the cloud removal algorithm has removed a significant signal from the difference maps.

A comparison of ATSR2 data for the period 1997-2000 yielded a bias and rms difference of 0.69 and 0.43, respectively. For nighttime data they were 0.87 and 0.37. For 1999, alone the results were 0.31 and 0.43 (day) and 0.49 and 0.39 (night) suggesting the algorithm is now working considerably better.

6.2 - Assimilation and estimation: deriving useful products

The Robinson and Donlon paper noted several practical problems that must be addressed.

- In situ validation - adequate sampling
- SST recovery from microwave radiometry.
- SST from geostationary platforms
- Establish effective data merging for all inputs
- Establish a sound cloud-gap-filling strategy

There were also several allied issues:

- Harmonize SST products for operational and climate applications
- Is it necessary to specify a particular SST product?
- The adoption of new SST definitions by models

To some extent, many of these issues have already been addressed above. However, we are still missing the "application" perspective.

Mohammed Ouberhuis described some of the assimilation work being carried out at JRC. They are using a PE model (Ispra-mix) with the Kantha and Large mixing model, with a near-interface transport parameterization (skin layer). The adjoint of the Ispramix model is being used with a cost function geared for estimation of mixed layer parameters. Ouberhuis showed several results for large-scale fields. One important point was the need to have error bars attached to data sets, particularly SST.

Charlie Barron discussed the Navy ocean modeling and data assimilation systems. The inputs include daily analyses of surface elevation (SSH from TP and ERS) and SST (based on MCSST; 20 km x 6 days; takes about 50 min on 14 CPU Origin; about 14 Mb storage). They combine alimeter and SST plus historical data to produce synthetic T(z) and S(z). Very high resolution SST does appear to have a significant impact.

Barron then described the present operational 1/16º NLOM (layer) model and noted that this would shortly be supported by a 1/4→1/8º NCOM (PE) model. Results with a 1/32º NLOM showed very realistic patterns. Experiments with a relocatable POM with tides seemed to give improvements.

Andy Harris discussed some considerations for assimilation of satellite data into a SST analyses. He noted the need to have global confidence in retrievals. This could be done with in situ based algorithms (i.e., tie the retrievals to observed in situ SST) or by using radiative-model based retrievals. The method needs a common reference, say 1 m temperature, and observational error covariances. Harris discussed a methodology whereby AVHRR and GOES data were regressed against ATSR and TMI data in order to validate cloud detection (to get error covariances).

Harris emphasized that we should approach the data in a consistent way; we should promote a framework that is theoretically sound and extendable (robust to developments). Quality control and cloud clearing were identified as the important issues. Confidence limits should be provided from the cloud clearing procedures.

The issue of "climate quality" was also discussed - 0.1ºC accuracy is usually quoted. There does seem to be a paradox. Climatologists confidently mix data from many ships and buoys together, many with uncertain calibration and unquantified errors, but assumed to be estimating some "bulk SST". Monthly and annual compositing is assumed to improve the accuracy. It is acknowledged the records have inadequate spatial sampling and coverage. Satellites do have rigorous on-board calibration and, by comparison, sample both space and time very well, yet few, if any, climatologists regard satellite-based SST as reliable.

7 - Development of Plan

The participants agreed to develop a Pilot Project within the framework of GODAE. Four tasks were agreed:

(1) Develop a working (strategic) plan
- Prospectus and workshop papers provide basis (IR, CD)
- Develop 4 themes

(2) Form a project Science Team for oversight of the Project
- Find Chair
- Order 8-10 members

(3) Have plan reviewed by advocates and non-advocates
- Outline by 1st quarter 2001; draft finalized by mid 2001

(4) Conduct Pilot project according to plan and schedule

7.1 - Development of 4 themes

The participants agreed to develop the outline according to four themes (7.1.1 - 7.1.4). In the following, the initials against themes and areas denote individuals who are expected to play a role (**BOLD** is used to denote expected leaders).

- Testing, proving and refining the data sources [**CD**, IR, WE, RE, IB, PM, PKT]
- Integration and assimilation: the data providers (basis: proposal of HK; project of O&SI SAF; NAVO; … [**PLeB**, DM, HK, CG, CM]
- Users and application: the data users [GODAE; NWP (global and regional), climate monitoring, coastal/regional/local, science and technology; AH, **JC**/CB, HR, JV, HK, BT, N Rayner, JThiebaux/RR]
- Research and Development [**GW**, BW, Bob E, GQ, GdeL]

Consistent with the previous discussion on the characterization of near-surface/surface temperature, the workshop suggested three distinct, but connected aspects related to the characterization of sea (near-) surface temperature that need to be considered (this break-out is relevant to all 4 themes).

(i) Skin T: Radiative transfer models
- radiance data from space (AVHRR, ATSR, GOES, …)
- the radiative transfer models / algorithms
- independent ground testing: VOS, reference sites

(ii) Sub-skin T: Microwave estimates; some subset of the *in situ* data set
- TMI, AMSR and the associated algorithms/models

- Nighttime and high-wind buoy, mooring and ship hull measurements

(iii) Bulk temperature data

- All buoys, moorings, ships, T(z)

7.1.1 - Testing, proving and refining the data sources

This theme is focussed on the data sources and the methods used to take raw data (Level 1) to a physical variable (a sea surface temperature), Level 2. The workshop identified three types of activity:

(a) Diagnostic Data Sets (DDSs)

Following the paper of Donlon the workshop agreed that an important activity must be the analysis and diagnosis of the Level 1 data stream. It would mainly involve aspects (i) and (ii) above. The suggestion was to consider data in boxes of around 200-km dimension though it was emphasized that this should not be consider a tight constraint. The activity would consider data at the individual pixel scale (full temporal and spatial resolution). In general, the baseline data would be considered in the following order:

(1) Direct radiometer measurements
(2) ATSR-type remote radiometer measurements
(3) General remote radiance measurements

Intercomparisons, analyses, and diagnoses would be conducted using satellite-to-satellite and satellite-to-in situ direct matches. We would expect indices to be developed for the main platforms indicating how data sources compared with each other.

The discussion on skin and sub-skin temperatures and the dependence on wind speed and heat flux emphasized the importance of maintaining a line of ancillary data in the DDSs. In order of importance, these include wind, solar S/W, surface heat flux, NWP fields, and atmospheric profiles.

The workshop noted that there were many related activities underway. Bob Evans described the data base at Miami and the fact that elemental data were maintained and diagnostics generated for certain regions. ***Craig Donlon agreed to act as a focal point for collecting information on such activities.***

The workshop also agreed that a prioritized list needs to be developed of those elements that should be included in a typical DDS. It was emphasized that not all DDS sites would be comprehensive and that, in some cases, there may be no in situ data source. The Chair noted that a set of fixed-point and "line mode" reference sites were being developed for the ocean climate observing system. The VOS-Clim project aims to develop a set of high quality VOS lines through an enhanced metadata system and is likely to maintain a comprehensive data base related to these ships. Fixed-point sites (e.g., WHOI surface flux buoys, TAO and PIRATA) were also being developed in conjunction with the NWP community (the SURFA project). The workshop agreed that this offered some opportunity for collaboration. Bill Emery agreed to attend the SURFA Workshop (December 2000, San Francisco) to provide liaison between this project and the climate activities.

The DDSs would need to be flexible according to the capacity and resources available. In some cases they may be maintained real-time and in other cases delayed mode. In many cases, we might expect comprehensive satellite and in situ data. While the general aim is for a sustained network, it might also be expected that some sites would be "dynamic", even mobile (though this could have some problems). The expectation was for order 50-100 sites. With such a number, the data flow should not be an issue and resources would be manageable. It was recognized that, in order for the sites to be sustained, the project would have to find agencies with a long-term vested interest in maintaining such facilities. At the moment there did not seem to be a compelling reason for have the DDS's centralized.

Finally, it was noted that one of the main functions of the DDS would be to assess the sufficiency of information available for Level 1 to Level 2 processing. If it is deemed inadequate and inappropriate, the DDS provides a mechanism to entrain Level 0 and/or additional data.

Four outcomes were identified:

- Real-time and delayed mode statistics on matches between satellite data streams and satellites and in situ data;
- Improvements in algorithms for retrieval of SST estimates (either skin or sub-skin);
- Improved validation / calibration of the remote sensing data stream; and
- An enhanced reference / base for detailed data relevant to scientific and technical development.

(b) Regional data gathering and assembly

The next stage up from the DDS concept will be mainly carried out during regionally based data gathering and assembly, such as discussed in the NAVO (Doug May), Kawamura and Le Borgne presentations (the second Theme; see below). The focus will be on Level 2 data and will involve evaluation and intercomparison of data from various sources including skin temperature estimates from radiometers, sub-skin estimates from microwave instruments and from night-time and/or high wind speed in situ measurements; and (c) other in situ measurements.

The move from highly detailed sites (the DDS concept) to regions precludes routine intercomparison and evaluation at the level of pixels, mainly because of the cost and volume of data. However testing and proving of data streams on the scale of regions provides a very robust measure of the effectiveness of various approaches and provides a system that is more directly relevant to those providing resources. It also has the advantage of keying in on regional interests and expertise and thus enhancing the value and quality of data streams.

Intercomparisons and monitoring of data streams within the region will be the main activity. However region-to-region intercomparisons (at the overlaps) will provide an important means for calibrating and standardizing the methods being used.

(c) Global intercomparisons

This is the next step up from the regionally based activity and involves evaluation and testing of global data streams and data sets. The move from regions to global scales will limit the level of detail but we expect much of the activity to be focussed around coarse Level 2 data and Level 3 data. The intercomparisons will be similar to (b) but there will be an increased focus on the climate qualities of the data and thus on the in situ bulk temperature measurements. One might also anticipate that information fed back from users (e.g., SST analyses assimilated into GODAE models) will assume a higher profile here (the feedback from users to this Theme will be critical for all activities).

For this stream in particular, issues of data delivery and timeliness will be important, as they will certainly affect the level of refinement that will be possible. One might also expect that pathfinder-like activities would be an important element. At this level, it will also be possible to intercompare SST products with other GOOS data and products (e.g., from *Argo* or altimetry).

The Workshop noted that there will be a strong dependence of (c) on (b), and that in turn both will rely on the DDS type activity for information on the detail.

7.1.2 - Integration and assimilation: the data providers

This theme is focussed on the development and coordination of initiatives and activities involved with the development of SST data streams and databases (real-time and delayed mode). The Workshop had seen several presentations and comments on such activity:

- The ocean and sea-ice satellite application facility described by Pierre Le Borgne;
- The ideas presented by Hiroshi Kawamura for a NW Pacific region activity;
- The activities at the NAVOCEANO (Doug May) and associated activities at NOAA/NESDIS;

It was noted that similar activities were also underway at several operational agencies (e.g., The Met. Office, the Bureau of Meteorology) and that we might anticipate regional interest in Northern Hemisphere polar waters (as described by Brenda Topliss).

The theme is based around integration and merging of Level 2 data and the development of databases for a variety of users (Theme 3 below). The Workshop recognized that the most effective path for this Theme would involve building on and working with the several activities that are already underway. These activities in effect provide the starting point for Theme 2 in the Pilot Project.

The discussion on the physical character of SST led by Bill Emery emphasized the need for ancillary data if the various samples of sea temperature are to be interpreted correctly. Such knowledge is mandatory if different data types are to be integrated into a single database in such a way that preserves the true value of the observation.

Cloud clearing for space-based radiometer measurements was identified as perhaps the most critical of all the steps in the development of SST data sets. It is clear there have been considerable advances in recent years to the point where greater confidence can now be attached to retrieved data. However, diagnostics from this process are not always retained and have only rarely been exchanged among centers. The Workshop concluded that such intercomparisons should be encouraged and that confidence limits should be routinely attached to all SST data sets.

It is the Theme that will be most involved in dialogues concerning requirements and the availability of data, particularly remotely sensed data. It was noted that through GOOS/GODAE and the Rolling Review process developed by CBS of WMO, a set of requirements had been established for SST data taking into account all of the users mentioned under Theme 3. This process sought to match the availability of data, from both existing and future missions, with the documented utility. Where requirements were more than availability the space agencies undertook to consider remedies, taking into account the likely value of projected applications. The data and statistics gathered under Theme 2 will be the most reliable guide to the actual data flow (c.f. the theoretical projections). It was also noted that the Ocean Theme under the Integrated Global Observing Strategy had been involved in analyzing requirements.

There was considerable discussion of databases. It was noted that several groups already have advanced systems in place and that, in general, there was consistency between their approaches. It was also noted that there was general enthusiasm for improving the coordination between these activities. The databases will not be uniform in terms of content or detail. Some centers will specialize in a subset of the data types, but perhaps at higher levels of detail, while others will be aiming for more comprehensive data holdings but perhaps not at the level of detail of the specialized centers. Many of the centers will be involved with real-time databases (e.g., the GODAE server at Monterey) but others will be involved with both and/or specialize in re-processing and refinement of data (e.g., the Pathfinder project). The Workshop agreed that both real-time and off-line aspects were important.

Access and distribution were important points in the discussion. With the emphasis on GODAE as the main user (see Theme 3), this provided a better guide to the typical access and distribution requirements, as well as the typical resolution. GODAE users will be both real-time (e.g., as described by Jim Cummings presentation) and off-line (e.g., climate data assimilation), but with greatest emphasis on the former. SST data will thus need to be available around 3-6 hours after measurement with appropriate time and location information as well information on its type (skin, sub-skin or bulk) and estimated observational error (the latter will be a function both of measurement and retrieval method and of the compositing (space and time averaging) performed in producing the datum.

Access and distribution will be greatly aided by providing the data in forms that are readily recognized (HDF and NetCDF, or 8-bit binned) and on servers with a capacity to handle large volumes of data. The servers at Monterey (the US GODAE Server) and at IFREMER are typical of what will be required. However it was also pointed out that the framework for the databases should be extendable - for example, we may anticipate demand for resolutions as fine as 1 km in the near future.

It was also noted that there is great value in having the SST data streams and databases integrated with other related data. Surface wind speed data is critical for ocean applications. However, consistency and integration also greatly aids assimilation in atmospheric, oceanic and coupled models. We do not expect the user base to be narrow. Several participants pointed out how data are often exercised in unexpected ways, often by people outside the scientific community, and that the Pilot Project should thus be prepared to allow wide and open access.

Finally, it was noted that the Pilot Project plan should develop guidelines and priorities for the databases. For example, what fields should be considered mandatory and what level of metadata should be supported? A guide to the protocols and standards should also be developed, perhaps with a set of principles to guide participants. The population of the databases would largely be determined by the individual centers, though the above mentioned will provide guidelines. All participants agreed that an open policy was desirable. It might also be anticipated that the content and operation of regional and global centers might differ (see, e.g., the presentation of Kawamura).

Standards for data compression will be adopted. At this stage, no compelling case could be found for providing mirror sites. In most cases, centers will be running at near full capacity and there will be little room to admit data sets that simply replicate those held elsewhere. Moreover, the synchronization of such data sets would pose significant difficulties.

7.1.3 - The Product Line and Users

This theme focuses on the data users and the development of Level 3 products and beyond. The presentations of Cummings, Barron, Topliss, Harris, Kawamura, and le Borgne provided many examples of the likely diverse use of SST data.

The Workshop felt the Pilot Project would be more easily developed if GODAE was seen as the primary driver and that the Project was integrated within the activities of GODAE. This enabled an immediate characterization of the data requirement and for the method of use (assimilation). Time and space scales are clearly an input characteristic - as a guide, GODAE will likely need SST data on 10-50 km space scales and time scales of order a day (these requirements were supplied to the requirements data base of WMO). The Workshop participants also noted the need for vision - the utilization of data (the requirements) are closely linked to current availability and experience but future systems will provide new opportunities and, almost inevitably, heightened requirements. This Theme must also embrace the opportunistic and unexpected users. The Workshop heard of many positive experiences of unexpected utilization (e.g., in the Pathfinder project) and that often such users were very sophisticated and well informed.

The Workshop also discussed the importance of the methodologies being used to assimilate SST data. Andy Harris noted the importance of a common framework, that was extendable and that was consistent with modern approaches to assimilation (e.g., variational, adjoint, Kalman filters). In some cases, the ingested information would be Level 3 data while in other cases users would prefer access to Level 2 data. We might also anticipate some demand for Level 1 data. It was also noted that models of many varieties were becoming an increasingly integral part of the Level 2 to Level 3 production line. Knowledge gained from research activities (Theme 4) was essential for the activities under Theme 3.

The Workshop provided the following list of users and brief characterization of their main needs (e.g., space-time scales, domain and windows, timeliness, quality, and coherent products).

- Weather prediction
  - Demands range from global ~ 100 km to regional ~10km; daily (no smoothing?)
  - skin/subskin differentiation not important (now)

- Ocean applications (GODAE stream)
  - BCs for ocean prediction, S-I prediction, ocean climate estimates
  - ~ 20-50 km, daily;
  - skin/subskin – bulk temperature differentiation of some importance on climate scales
  - Must have attached error estimates

- Climate / long-term monitoring
  - High quality (skin/bulk differences matter)
  - Consistency with existing products a major issue
  - Scales of several hundred km and monthly

- Science and technology
  - Skin temperature issues matter
  - Integrated and coherent data sets
  - Metadata critical
  - Typically at the demanding end of spatial and temporal resolution (over-sampling of phenomena)

- Coastal / local / regional
  - sub-sampling for targeted users
  - regional sub-sampling, e.g. fisheries, coastal measurement
  - 10 km and finer; at least daily
  - quality requirements less stringent

The inputs to this Theme are generally at Level 2 with the outputs at Level 3. Note however that some user groups will want Level 2 data directly. Consistency, integrity, and contiguity of products is important.

A process for feeding user responses back to the data providers (Theme 1) and data assemblers (Theme 2) will be extremely important. In many cases, activities under this theme will be co-located with those under Theme 2, perhaps also Theme 1.

The Workshop also highlighted the need for a systems approach and the fact that the Pilot project was looking at a new generation of data systems and products. It was also emphasized that the same product will often be used by a variety of users and that this multiple use provides added strength and efficiency to the activity. The broad audience also provides a wide advocacy for the SST products and greater access to resources, though this broad use should not come at the expense of a well-focussed Pilot Project. Both political and societal advocacy is needed if the requisite resources for the Project are to be found; the GODAE Pilot Project concept provides an efficient and effective mode for taking advantage of such investment.

7.1.4 - Research and Development

This theme was added because the Workshop recognized that there were certain activities that, while seen as essential, did not easily fall within the continuing and sustained activities of Themes 1 through 3. The research described by Brian Ward (shallow profilers) and Gary Wick (measurements of the skin-bulk temperature difference) provide two such examples. Several participants emphasized the importance of such work along the line of the activities of the DDS and other activities under the other Themes. As noted above, such R&D is critical to effective application of the state estimation (assimilation) approach. The activities include both scientific and technical issues.

Participants were asked to provide examples of needed R&D and to develop within the Project plan a prioritized list of such activities.

7.2 - Schedule for the project

The Workshop agreed that the momentum of the discussions must be maintained and that the fifth meeting of the GODAE Steering Team might be an appropriate target for the first draft of the Project Plan (tentatively entitled "The Initial Plan for a GODAE Advanced SST Data and Product System"). Further, the participants agreed to aim for completion of the Initial Plan by around June, in time for the first formal meeting of the Joint Technical Commission for Oceanography and Marine Meteorology (the intergovernmental guardians of such activities).

A Science Team for the Project will be formed. Dr Craig Donlon as agreed to act as the provisional Chair. Terms of Reference for the Team will be developed as soon as possible. It is expected it will comprise order 8-10 members representative of the above Themes.

7.3 - Resource issues

The Workshop discussed opportunities for support of the Pilot Project. It was noted that the range and depth of existing activities provided an excellent basis for further development.

Within Europe, the European Union Framework 5 provided some opportunities though competition was very strong. The SAF project presently enjoyed such support with Meteo France providing matching resources. Many operational agencies in Europe already devoted considerable resources to SST data gathering and SST products.

The EU "Concerted Action"/Thematic Network (shared action) area also provided some opportunities. There was considerable interest in data (satellite, in situ) fusion. It was noted that METOP had shared data exchange but no shared application activities; the project can perhaps motivate this.

The Initial Plan will need to be careful articulating the benefits and outcomes from the project and make the case that such a project is in the (collective) interests of the agencies.

Several participants noted that there has been some difficulties in the US proposing such work. There were opportunities emerging associated with NPOESS. The strong support for the GODAE server provided a springboard for additional activities.

In general, the Workshop participants were confident that the existing high level of importance attached to SST data and products could be exploited in support of the Project. The Project objectives would need to be focussed and appropriate to the perceived needs.

8 - Summary and Close

The Chair summarized agreed actions.

(A1) Meeting report (NS)
(A2) Place presentations on web (NS)
(A3) Develop a working (strategic) plan (CD, IR, NS)
(A4) Gather information on existing DDS-like activities (CD)
(A5) Form a project Science Team for oversight of the Project (NS)
Developing Themes:
(A6) Testing, proving and refining the data sources [**CD**, IR, WE, RE, IB, PM, PKT]
(A7) Integration and assimilation: the data providers [**PLeB**, DM, HK, CG, CM]
(A8) Users and application: the data users; [AH, **JC**/CB, HR, JV, HK, BT, N Rayner, JThiebaux/RR]
(A9) Research and Development [**GW**, BW, Bob E, GQ, GdeL]

The Workshop was drawn to a close at 1600 Wednesday 1 November. The Workshop participants thanked JRC as local hosts for the hospitality and, in particular, Craig Donlon and colleagues for their work in preparing for the Workshop. The Chair noted the many constructive discussions before and during the Workshop and was confident the outcome would be an extremely interesting Project.

Attachment I: Agenda

OCTOBER 30th

08:30 Transport from Hotel to JRC
09:00 Registration
09:30 Opening

The workshop will then hear presentations from the participants on various aspects of developing a global high resolution SST dataset. These will be grouped around the various scientific and technical issues that were identified in the Prospectus and in the ensuing discussion. The object is to openly raise all of the issues (content, operations, feasibility, requirements, distribution, validation, etc.) associated with the development of a global high resolution SST dataset.

09:45
Overview and requirements

- Global Measurement of Sea Surface Temperature: Some new perspectives (Ian Robinson and Craig Donlon)
- The Global Ocean Data Assimilation Experiment and SST (Neville Smith, Pierre-Yves Le Traon)

10:45 Coffee break
11:00 Presentations (Cont.)

- Operational SST and sea ice analysis system at FNMOC (Jim Cummings)
- Discussion

The Physical Character of SST

- Estimating Sea Surface Temperature From Infrared Satellite and In Situ Temperature Data (Bill Emery)
- Characteristics of SST variability
- Discussion

12:30 Lunch

14:00
Measuring and analyzing SST

- Platforms for measuring SST
  GOES SST issues (Legeckis, not attending)
- Sampling issues
- Processes affecting SST estimates
  The issue of the diurnal cycle - Ian Barton
- Approaches to SST recovery from space
- Analyses and products
  Navy MCSST processing at NAVOCEANO (Doug May)

16:00 Coffee break
16:20 Presentations (Cont.)
Estimating SST when we cannot "see" it

- Satellite Microwave Measurements of Sea-Surface Temperature (Gentemann et al)
- Estimates from TRMM, etc (Kawamura, Wick, ...)
- Discussion

17:30 Transport from JRC to the Hotel

OCTOBER 31st

08:30 Transport from Hotel to JRC
09:00
Operational implementation: toward a consensus

At this point we wish to start working toward a consensus on actions and plans required for the future. There will be several presentations to lead the discussions off before breaking into discussion groups.

Space-time sampling issues

Polar orbiting infra-red sensors to provide the baseline
Alternative observations must be found for cloudy regions
Gap-filling as last resort

Issues of accuracy and calibration

Infra-red baseline measurements
Establish BOTH TS and Tbulk data products

- Toward a global in situ validation plan (Craig Donlon)
- Accuracy of In Situ Sea Surface Temperatures Used to Calibrate Infrared Satellite Measurements - Emery et al

10:45 Coffee break
11:00 Presentations (Cont.)

Practical problems to be solved

In situ validation - adequate sampling
SST recovery from microwave radiometry.
SST from geostationary platforms
Establish effective data merging for all inputs
Establish a sound cloud-gap-filling strategy

Allied issues

Harmonise SST products for operational and climate applications
Is it necessary to specify a particular SST product?
The adoption of new SST definitions by models

12:30 Lunch

14:00 Identification of working groups

Working group discussions: Development of a more detailed scientific and technical strategy (writing) for developing a high resolution SST dataset. (According to the above breakdown?)

16:00 Coffee
16:20 Working group discussions (Cont.)

17:00
Plenary Discussion of initial thoughts

17:30 Transport from JRC to Hotel.

NOVEMBER 1st

09:00 Working groups and writing

10:15 Coffeee break

10:45 Presentation of working group conclusions and reccommendations.
11:45 Development of an Outline plan and schedule for the project.

12:30 Lunch

14:00 Development of a plan and schedule for the GODAE-SST project.

16:20 Summary of workshop, action plan and timetable.

17:30 Close of Workshop Transport to airport/hotel/station etc.

Attachment II: Participants

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Attachment III: Abstracts

INTERPRETATION OF SATELLITE-DERIVED SEA SURFACE TEMPERATURES

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(Submitted to Advances in Space Research
Please do not copy or cite without the permission of the author)

ABSTRACT
Over the last twenty-five years sea surface temperatures have been available from satellite observations through the application of simple algorithms applied to infrared observations. Algorithm coefficients have been derived from simple regression analyses between surface and space-based observations. Accuracies in the order of 0.6 K have been obtained. However we are now receiving data with improved precision and thus increased care must be exercised in the derivation of algorithm coefficients and the interpretation of the derived temperatures. The most important ancillary data required are estimates of the surface wind speed and future satellites should include such capability if accurate estimates of the mixed layer sea surface temperature are to be obtained. Ship measurements showing the effect of surface wind speed on the vertical structure of near-surface water temperature are presented.

OCEAN AND SEA ICE SAF SST FOR GODAE/MERCATOR.

P. Le Borgne* H.Roquet*, P.Y. Le Traon**
Meteo-France/Lannion **CLS/Toulouse

The SST assimilation in MERCATOR will be prepared in the framework of the MERCATOR/ PAM (Prototype Atlantique Mediterranée). From the launch of MSG onwards a SST data set will be build in real time with the following characteristics:

Content: SST (definition: T(2)) + quality indexes
Coverage: Atlantic + Mediterranean Sea (100W-45E, 60S-60N)
Origin: GOES-East + MSG
Time sampling: three hourly
Resolution: 0.1 degree
Validation information: Match up data base built on a routine basis
Auxiliary data:
Three-hourly radiative fluxes (O&SI SAF)
Wind stress (Ifremer)
Turbulent heat fluxes (Ifremer)
Needed complementary information: polar orbiter fine scale SST over the same area for intercomparison.

SST IN THE FRAMEWORK OF THE OCEAN AND SEA ICE SAF

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Abstract:
The characteristics of the SST fields produced in the Ocean and Sea Ice Satellite Application Facility (O&SI SAF) are the following: European seas: origin: AVHRR; resolution: 2 km; time sampling: 4 times a day (reduced to 2 times a day after the failure of NOAA-15). Atlantic: origin: AVHRR + GOES-East + MSG, resolution: 0.10 degree; time sampling: hourly data delivered through 3-hourly and 12-hourly means. The production of the SST fields has started in October 1999 with NOAA-14-15 and GOES-8.
Definition: bulk SSTs are produced at present, but discussions are ongoing on this subject and the definition may change.
The algorithms used have been derived from simulations made with Modtran applied on Radio sounding profiles. Non linear split window algorithms have been applied on the AVHRR data (mid and high latitudes). Non linear (by day) and triple window (by night) algorithms have been used for GOES-08 data.
Validations have been made on a routine basis for one year (Nov.1999 Oct. 2000) by comparisons with buoy measurements. The main results for cloud free validation boxes are given here below:

	Nb of cases	bias (C)	standard deviation (C)
NOAA-14 day	797	-0.13	0.47
NOAA-14 night	442	-0.02	0.53
GOES-08 day	8437	0.04	0.58
GOES-08 night	4490	0.16	0.44

Real time examples can be seen at http://www.meteorologie.eu.org/safo

AN OPERATIONAL SYSTEM

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The presentation will be a description of the operational SST and sea ice analysis system at FNMOC (Fleet Numerical Meteorology Oceanography Center, Monterey, CA, USA). The operational SST and sea ice analyses are performed in real-time at FNMOC and are of moderate-to-high resolution (83 km global with several nested regional grids of 27 to 9 km). What we're doing operationally at FNMOC is very much like the strategy outlined in the prospectus so I think a description of the current "state-of-the-art" is appropriate. In addition to a description of the system, my talk would include a description of the QC procedures, examples of validation/verification, product use and our moderate to long-term plans for system improvement. I'll forward my registration form when my travel plans become final.

GLOBAL *IN SITU* VALIDATION

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This is a short discussion for a global in situ validation plan using in situ observations. In particular, this would be an opportunity to present recent European developments for operational ship of opportunity in situ (radiometer) validation systems. Pre-operational pilot systems will be making thir debut deployments in early 2001 under the ESA ERS-ATSR, ENVISAT-AATSR and the EUMETSAT MSG/SEVIRI AO validation plans. In situ observations play such a crucial role for us because they provide our baseline credibility. We are proposing to do things that have been resisted for nearly 20 years (wrongly in my opinion). We need to be ready with solid evidence that we have provideda new SST product family that:
(a) is of a sufficient standard to be used confidently for data assimilation into ocean/a tmosphere models
(b) capitalises on the strengths of specific satellite instruments (e.g. thre accurate calibration of the ATSR, the excellent spatio-temporal coverage of the AVHRR and the diurnal signal of the geostationay instruments, use of Microwave imagers) while minimising the induced "niose" of their shortfalls.
(c) is derived using "sensible" (i.e., useful in an operational context) and validated data fusion/merging methodology and algorithms.

In each case it is clear that independent in situ validation data have a pivotal role. Additionally (although perhaps not immediately obvious as a part of the GODAE workshop) we may add :
(d) reliably and sensibly continues the option to use traditional use of bulk SST as a variable while at the same time promote the adoption of skin SST as the more physically meaningful quantity with respect to satellite IR observations.
to the list of topics requiring in situ validation data. This is more of an educational exercise. During the many discussions I have had focussed on satellite SST, its when the in situ data show up that the debate gets interesting and people are prepared to listen. As I mentioned in a previous message, while we should not dwell on the validation issue too much, a short sharp discussion is required to insure that we can allay our critics and to prepare ourselves for the tasks at hand: it feels better to have some evidence that our data fusion/merging schemes are working correctly rather than an intuitive guess. We can then honestly look our users squarely in the eyes and say "These are your confidence limits" go forth and assimilate !

TOWARD AN VALIDATION PLAN FOR THE GODAE HR-SST DATA PRODUCTS

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Validation of satellite observations to the highest possible standard is a critical component of any project proposing to provide a new class of data product. A poor sea surface skin temperature (SSST) validation strategy may compromise the quality of the GODAE High Resolution project because of an inability to quantify appropriate SSST product confidence limits. This presentation reviews some of the options that are available for the on-going global validation of satellite SST measurements. Particular emphasis is placed on the use of new autonomous ship of opportunity radiometer systems together with ship and well calibrated buoy and ship subsurface "bulk" sea surface temperature (BSST) observations. BSST data can only be used to validate skin temperature data sets at wind speeds > 6 ms-1 after adjustment for a cool skin temperature bias. The need for a co-ordinated, cost effective strategy implemented through the generation of a framework that will develop a diagnostic data set (DDS) is discussed. The DDS will comprise of in situ and satellite data collected at globally distributed instrumented sites that characterise the range of global ocean and atmospheric conditions. At each site, any satellite data considered appropriate to the project effort (IR, MW, VIS, Active MW) should be automatically archived, preferably at source, for a small (2deg x 2deg area). Together with in situ observations collected at each DDS site, the DDS will provide a data set suitable for (a) the validation and inter comparison of satellite data and (b) a data set to test and validate data fusion/merging strategies. It is foreseen that the DDS is an “open” system based on distributed archives.

ESTIMATING SEA SURFACE TEMPERATURE FROM INFRARED SATELLITE AND IN SITU TEMPERATURE DATA

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(Paper accepted for BAMS)

Abstract

Sea surface temperature (SST) is a critical quantity in the study of both the ocean and the atmosphere as it is directly related to and often dictates the exchanges of heat, momentum and gases between the ocean and the atmosphere. As the most widely observed variable in oceanography, SST is used in many different studies of the ocean and its coupling with the atmosphere. We examine the history of this measurement and how this history led to today's practice of computing SST by regressing satellite infrared measurements against in situ SST observations made by drifting/moored buoys and ships. The fundamental differences between satellite and in situ SST are discussed and recommendations are made for how both data streams should be handled. A comprehensive in situ validation/calibration plan is proposed for the satellite SSTs and consequences of the suggested measurements are discussed with respect to the role of SST as an integral part of the fluxes between the ocean and the atmosphere.

ACCURACY OF IN SITU SEA SURFACE TEMPERATURES USED TO CALIBRATE INFRARED SATELLITE MEASUREMENTS

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(submitted to J. Geophys. Res.)

Abstract

The present computation of sea surface temperature (SST) from infrared satellite measurements requires the availability of a sample of in situ (drifting buoy and/or ship) SST measurements, to compute by regression the algorithmic coefficients for the infrared data. Ignoring the fundamental difference between satellite measured "skin SST" and buoy/ship measured "bulk SST" we analyze past buoy, and ship SST data to better evaluate the errors involved in the routine computation of SST from operational satellite data. We use buoy and ship SST data for two years (1990 and 1996) from the Comprehensive Ocean-Atmosphere Data Set (COADS) as well as two years of previously cloud cleared satellite radiances with matching drifting/moored buoy SST data from the NASA Pathfinder SST data set. We examine the in situ SST data for geographic distribution, accuracy, and self consistency. We find that there are large geographic regions that are not sampled by the present drifting buoy network, a natural consequence of the fact that most buoys are not deployed to measure in situ SST for satellite infrared SST calibration. There are marked interannual differences in the buoy coverage with 1990's buoy SSTs restricted to the tropical Pacific and the high-latitude North Atlantic. Variability in comparisons between buoy SSTs suggest that these measurements have a basic error of about 0.4 °C. Comparing moored with drifting SSTs we find that for the equatorial Pacific they are basically the same with a moored-drifter SST mean difference of 0.046 °C and an RMS difference of 0.1 °C. Using all of the moored versus drifter comparisons out of the equatorial Pacific we had a mean difference of -0.1 °C and an RMS temperature difference of 0.6 °C. Ship SSTs are noisier and have a significant warm bias relative to drifting buoy SSTs. We explore the SST accuracy changes that occur with variations in sampling coverage used for the SST algorithm regression computation. We vary both the total amount of points and we also restrict the regression data to regional sampling biases. Surprisingly the total number of calibration SST values can be quite small if they cover all latitudes. In fact data restricted to 30°N to 30°S performed just as well as a slightly larger data set that covered all latitudes. Regression data sets confined to the tropics (10°S< lat<10°N) or the polar (>50°) regions result in SSTs that exhibit large errors. We conclude that buoy SSTs can have residual bias errors of about 0.15 °C with RMS errors closer to 0.5 °C. Ship SST bias and RMS errors are significantly larger which is unfortunate in light of the excellent geographic coverage. Geographic data distributions are important with the primary requirement being a global coverage even with a smaller number of points. Any restriction of the regression buoy SST data to high or low latitudes leads to significant errors in the resulting SST algorithms.

SATELLITE MICROWAVE MEASUREMENTS OF SEA-SURFACE TEMPERATURE

Chelle Gentemann, Frank Wentz, and Deborah Smith

A new satellite microwave radiometer is providing global measurements of the surface temperature of the world's oceans in all weather conditions except rain. Microwaves penetrate the cloud layer with little attenuation, giving an uninterrupted view of the ocean surface. This is a distinct advantage over the more traditional infrared measurements of SST, which are obstructed by clouds. Considering that clouds cover roughly half the Earth, the microwave measurements are giving a more complete picture of the global temperature field. Comparisons with ocean buoys show a rms difference of about 0.6°C, which is partly due to the satellite-buoy spatial-temporal sampling mismatch and the bulk versus skin temperature difference. The microwave sea-surface temperature (SST) retrievals are yielding new insights in a number of areas, including tropical instability waves, marine boundary layer dynamics, and hurricane intensity prediction.

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ADEOS-II SEA SURFACE TEMPERATURE

Hiroshi Kawamura
Tohoku University/NASDA EORC

ADEOS-II planned to be launched in November 2001 has two SST sensors, i.e., Global Imager and Advanced Microwave Scanning Radiometer. These two sensors have wide swaths to cover global oceans and conduct simultaneous measurements. Combination of cloud-free microwave measurement by AMSR and high-spatial resolution IR measurement by GLI can contribute to new global SSTs retrieval. Surface winds derived from the ADEOS-II SeaWinds are valuable to investigate ADEOS-II SST characteristics since it is derived independently from AMSR. In the presentation, potential of the ADEOS-II SST sensors will be discussed in relation to the GODAE requirement.

Needs of Japanese oceanographic community for new SSTs were discussed in the new-satellite SST committee in these several months. The operational and scientific needs for the new generation SSTs (ADEOS-II SSTs and GODAE-SST) will be also presented.

GOES SST

Richard Legeckis (not attending)

Subject: GODAE SST meeting
Date: Tue, 28 Aug 1956 00:16:33 +0000
From: Richard <rlegeckis@nesdis.noaa.gov>
To: N.Smith@bom.gov.au, craig.donlon@jrc.it, Ian.Barton@marine.csiro.au,William.Emery@colorado.edu, rlegeckis@nesdis.noaa.gov,revans@rsmas.miami.edu, MayD@navo.navy.mil,Pierre.Leborgne@meteo.fr

Due to travel conflicts, I will not attend the Ispra meeting but hope each of you at least enjoy a toast of red wine in my memory as you debate the issues of SST. Except Emery will enjoy some milk. I am very sad in not being able to participate and enjoy "solo mio".

Since the Neville's idea is to produce a pratical SST product, I hope you can consider the GOES-8 and -10 SST. One important practical aspect of merging different SST data sets is to have the SST values in a "binned" lat/long array as a 8-bit image (0-255) which can be easily displayed on 8-bit graphics monitor. Here are some reasons:

Pierre Leborgne will be at the meeting and can show their GOES-8 Atlantic SST in 0.1 deg bins at hourly time step and SST (C) = - 3 + 0.15 x where x = 0 to 255 100W- 45E, +/- 60 lat
NESDIS is also producing a comparable G-8 and G-10 GOES SST product in bins at 20 sample/deg with SST(C) = - 3.15 + 0.15 x x = 0 to 255 and displayed at hourly intervals from 180W - 30 W and 60N - 45S. The 8-bit array size is 3000 x 2100 (6 MB / hour)

Doug May can fill you in on the Navy's approach for the GOES SST product since I am not familiar with his output format yet.

Bob Evans recently provided be with some AVHRR GAC SST data off Baja California which is also binned with SST = - 3 + 0.15 x and x = 0 - 255 at about 8 km/ sample at 12 hour intervals.
You may now wonder why I am obsessing about and repeating the 8-bit 0 - 255 intervals. The answer is that the volume of GOES hourly data and AVHRR, MODIS, TRMM data etc can quickly saturate ones ability to assimilate, validate, and evaluate the data.
The solution is to produce global binned data sets in the 8-bit format which can then be merged and evaluated to produce a practical SST product. The results (8-bit images) can then be viewed in animation to give you an nearly instant view of your efforts.
In a nutshell, to make a better, multi-satellite SST product you will have to design it so that contributions from a variety of satellites and in-situ sources can me merged together with repeated iterations. The 8-bit BINNED format (equal lat/lon bins) is ideal for this purpose.
Match-up statistics are used to determine the quality of the SST but the images provide an overall view of what, where, and when the SST data are actually being produced. Gaps due to clouds, missing data, or other factors are also clearly evident.

My proposal is that the 8-bit image (2-D array) is the optimum approach for the end product. It does not preclude the preparation of the data by individuals in a preferred manner as long as at least one end product, from each satellite, is prepared and distributed in the 8-bit format.
Hourly data can be merged at 6 - hour intervals and four images per day (365 x4) produce 1460 images / year. Using animation at 10 frames /sec the annual data set can be viewed in just 2.5

minutes. We now have about 2 years of the GOES experimental SST data and the view of the oceans is spectacular (if not always accurate due to development changes, noise, navigation etc.) So much for the 8-bit SST files. The other related issue is that we need comparable global images (also 8-bit) of cloud cover to show the distribution in time and space of persistently cloudy areas to show where SST is not available. Here, animation again will play a key role. In other words, lets keep all those cloudy areas that are thrown away during SST cloud tests. A big challenge for the meteorologists.
NCEP (Jonh Janowiak) is presently saving global GOES files of channel 4 (11 micron) at full 4 km resolution every 30 minutes in a binned format for rain estimation. Each 30 min. file is a monster (60 MB) since it spans the globe but at least someone is thinking of the global view. For global GOES SST we still await future improvements such as MSG in 2002 ??? and other efforts ???.

OPERATIONAL OCEANOGRAPHY AND PREDICTION – A GODAE PERSPECTIVE

P.Y. Le Traon[1], M. Rienecker[2], N. Smith[3], P. Bahurel[4], M. Bell[5], H. Hurlburt[6], P. Dandin[7]
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(Abstract from Paper submitted to Ocean Observations for the 21st Century)

Abstract
This paper gives an overview of the Global Ocean Data Assimilation Experiment (GODAE) focusing on aspects relevant to the development of a global ocean observing system and to the demonstration of its scientific and practical societal benefits. The main operational applications which are expected to benefit from the global and integrated approach of GODAE are presented : climate and seasonal forecasting, strategic and tactical applications, marine safety and marine meteorology, fisheries, offshore industry and shelf and coastal applications. User requirements are identified and the benefits of the integrated and global GODAE approach for meeting these requirements are emphasized. We then proceed to the relationship between GODAE and the design/development of an ocean observing system. The observing system being contemplated now (and at this Conference) appears to meet the main GODAE requirements. As GODAE evolves, a better analysis of data utility and data needs will be possible and more specific requirements will be made. Through the development of applications and users, GODAE will become a powerful means for defining and promoting the scalability, the maintainability and sustainability of the observing system.

NAVY MCSST PROCESSING AT NAVOCEANO

Doug May

Abstract: NAVOCEANO is the National Core Processing Center for the production of global real-time Multi-Channel Sea Surface Temperature (MCSST) data from digital satellite data. The MCSST data is utilized operationally within thermal analyses and circulation models at NAVOCEANO as well as at other oceanographic and weather centers in the United States. NAVOCEANO recently rewrote the existing MCSST processing software to increase data quantity and improve structural design, functional performance, data quality monitoring and process monitoring. A new initiative at NAVOCEANO is also underway to produce MCSSTs from geostationary GOES satellite data every hour. Examples of MCSST data coverage and utilization will be presented. These additions enhance the MCSST data available to Navy oceanographic and atmospheric models/analyses and sustain NAVOCEANO's SST processing responsibilities to internal and external customers.

COMMENTS ON THE REQUIREMENTS FOR SHIP-BORNE RADIOMETERS FOR VALIDATION OF SATELLITE-DERIVED SEA-SURFACE TEMPERATURES.

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The purpose of comparing surface radiometric measurements with satellite-derived skin SSTs is a validation of the atmospheric correction. Thus the requirements on the number and quality of the comparisons are determined by the properties and the effects of the atmosphere, have assumed to be clear of clouds.

The accuracy requirement can be set at 0.1K or better, given that the size of the temperature deficit in the radiometer channels used for SST measurements is ~1 to ~8K.

The required numbers are harder to establish, but one approach is to consider the variance in brightness temperatures within a given "climate region" in a given time interval.

This was done some time ago (Minnett, 1986) where I looked at the numbers of randomly selected atmospheric profiles (radiosondes) that were needed to produce a stable estimate of rms retrieval error of an AVHRR-type SST algorithm. This was found to be ~100 profiles in a month for the North Atlantic area. A significantly smaller number would not sample the full range of atmospheric variability.

Given 60 possible overpasses of a satellite sensor in a month (assuming no swath overlap, as occurs at high latitudes, and assuming there is no need to treat day and night passes independently), this requires ~1.5 radiometers in the field.

Given that only ~10% of all possible overpasses are likely to pass stringent cloud screening, this number should be increased to 15.

Assuming three or four distinct climate regimes (e.g., high, mid and low latitude zones), this number becomes ~45, with some reduction at high latitudes for the possibility of swath overlap.

Given that seasonal, rather than monthly, comparisons can be made, reduces the number back to ~15.

If validation of narrow swath instruments, such as AATSR on ENVISAT, is to be contemplated, this number must be increased by factor of 4 or 5. However, by compositing data from the same season from successive years, the number can be reduced at the cost of reliable temporal information over the lifetime of the satellite sensors.

Reference: Minnett, P.J., 1986. A numerical study of the effects of anomalous North Atlantic atmospheric conditions on the infrared measurement of sea-surface temperature from space. J. Geophys. Res., 91, 8509-8521

COMPARISON OF MONTHLY CLIMATOLOGIES (ATSR VS. TMI)

Graham Quartly
Southampton Oceanography Centre

To meld data from different sensors, it is important to understand the error characteristics of each so that the various datasets can be harmonised. As an example I look at the differences in the monthly climatologies obtained from ATSR-2 (a quality infra-red sensor) and TMI (a passive microwave instrument). By considering monthly maps from each source I am not looking at individual point matchups, but the errors in retrieving a representative time-average for a location. Although apparently more relevant to climate science than near real-time applications, the discovery of significant regional biases between the two fields gives some idea of the difficulty of merging data from two very different sources. Given that the spatial pattern of the mismatch of the two datasets does not appear constant, one cannot simply apply a regional offset to bring the two consistently into alignment. The spatial structure of the mismatch tends to contain zonal features, especially in the equatorial and northern Pacific. Information on the spatial correlation of these errors can aid in the near real-time combining of daily data from such diverse instruments.

GLOBAL MEASUREMENT OF SEA SURFACE TEMPERATURE: SOME NEW PERSPECTIVES

Ian S. Robinson and Craig J. Donlon

Abstract:
The measurement of global sea surface temperature (SST) from space is well established with 20 years of useful data already acquired. Yet the more stringent sampling requirements and the higher degree of accuracy now demanded for applications in both climate monitoring and operational oceanography are increasingly difficult to meet with the standard meteorological polar orbiting sensors that have been the basic sensors used for global SST mapping. The established methods and sensors for measuring SST, both in situ and in space, are reviewed, compared, and their major limitations are identified. Mention is made of phenomena which complicate an apparently simple measurement, such as the presence of clouds and the contamination of the stratosphere by volcanic aerosols. New approaches for remotely sensing SST are mentioned, including the along track scanning radiometer, noting the improved infrared sensors now planned for geostationary platforms and weighing the benefits of merging data from microwave radiometers. The conventional buoy-calibration of SST measurements from space is complicated by the variable thermal structure of the upper few metres of the ocean. The recent improvement of radiometers for ship deployment has led to better understanding of the thermal skin of the ocean which suggests a new approach for the validation of SST algorithms based on radiation transfer models. Finally, a future strategy for combining measurements from many types of sensor in order to achieve the required accuracy and sampling rate of SST data products, and to identify some of the remaining scientific challenges in this field is outlined.

COMMENTS ON *IN SITU* DATA

Peter Taylor, SOC

Gentlemen,
Here are a few thoughts mainly triggered by Bill Emery et al.'s papers. Hopefully they will be of some small use, I'd be interested in Bill's comments wih regard to whether I've misinterpreted his comparison data! I avoided sending them to the whole mailing address list but perhaps one of you might raise them if appropriate!
I'm sorry I can't make the meeting but will instead be attending the VOS-Clim planning meeting. I suspect that some of the conclusions from the Godae meeting may be of relevance to VOS-Clim and perhaps vice versa, so we will need to keep coordinated.
Cheers, Peter K. T.
****

Brief Notes on Emery et al. (2000): "Accuracy of in situ SST used to calibrate IR satellite measurements" and one or two other comments!

Peter K. Taylor, Southampton Oceanography Centre, October 2000.

Abstract

The RMS errors for drifting buoy and ship SST data are derived from the RMS differences quoted by Emery et al. (2000a). Although the derived RMS ship error (about 0.8C) is roughly half than that quoted by Kent et al. (1999) it is still about 4 times worse than that for the drifting buoy data. However the quality of the ship data set used was probably dominated by having about 2/3 of the reports derived from Engine Room Intake readings. The quality of reports from ships equipped with hull contact sensors is expected to be similar to the quality of the drifting buoy data. The number of ships so equipped is increasing and it would be unfortunate if this potential source of high quality data were ignored. Recent advances in through-hull acoustic data transmission suggest that significantly more ships will be fitted with hull contact sensors in future.

For wind speeds above a few m/s the temperature measured by hull contact sensors corresponds to both the bulk and mixed layer temperatures (within about 0.1C). The mixed layer temperature is required for studies of longer time-scale processes. For purposes such as satellite validation, the bulk temperature may be adjusted to give an approximate skin temperature by correcting for the skin temperature deviation (about 0.15C, Donlon et al. 1999). It is only for low wind speed conditions, < 5 m/s (although my guess is that this is a rather high threshold), that the skin effect becomes significantly variable. At these low winds other processes may also have an effect (such as diurnal thermoclines and freshwater lenses). It has been suggested that chosen ships should be fitted with radiometers to investigate these effects. It would be best if any such action be coordinated with the proposed JCOMM ship-board observations group.

1. Error estimates

Emery et al. (2000a) quote RMS differences for comparisons of drifting buoy and ship observations of SST which can be used to determine the random error for the different observations. Since the RMS difference has contributions from the errors in each of the observations, for comparisons between similar data sources the error variance will be half the mean square difference and the RMS error the square root of the error variance. Having thus independently calculated the error variance for both ships and buoys, further estimates can be obtained from the ship v buoy comparisons. Thus an estimate of the error variance for ship observations is the difference between the mean square ship-buoy difference minus the error variance for buoys. Emery et al. (2000a) state that the seasonal differences were not significant. Thus, using the figures in their tables and taking mean square values for the four months which they show (weighted by the proportions of data in each month) the following table of mean RMS errors can be calculated:

Table 1. Mean RMS errors (C) for a SST determination based on Emery et al. (2000a).

method	up to 110 km	50 km	5 km	0 km
drifter v drifter	0.65	0.41	0.19	0.15
drifter (v ship)	0.89	0.83	0.45	0.38
ship (v ship)	0.96	1.15	0.79	0.74
ship (v drifter)	0.94	1.29	0.87	0.81

Here the "0 km" value has been obtained by the somewhat dubious method of extrapolating from the 50 km and 5 km values. However it is not significantly different from the 5 km value.

Both methods of estimating the RMS error for the ship data give similar results indicating a typical value of about 0.8°C. This appears to be significantly less than the mean value of 1.5 ± 0.1C suggested by Kent et al.(1999) who calculated differences using data separations of up to 300 km. It also is on the low side of their histogram of values for 30°x30° latitude x longitude regions (Figure 1). Unless I have misinterpreted the Emery et al. (2000a) data, this suggests that Kent et al. (1999) did not fully remove spatially variability from their error estimates.

The errors in the drifter data are larger when calculated from the comparisons with the ships compared to the drifter v drifter comparisons. However since the ship data is significantly worse than the drifter data one might expect the drifter v drifter comparisons to be more reliable. This suggests RMS error values of about 0.2C for the drifters, slightly better than the 0.3C to 0.4C suggested by Emery et al. (2000a) but similar to the value quoted from Swenson (0.15C). Note that Gilhousen (1987) estimated a random error of 0.2C or moored buoy data and that Emery et al. (2000a) find similar statistics for moored and drifting buoys.

The conclusion is that the ship data is significantly worse than the buoy data which is considered "unfortunate in the light of the excellent geographical coverage". However I will suggest in the next section that the ship statistics are degraded by values from Engine Room Intake (ERI) thermometers and that bucket or hull mounted sensors provide better data.

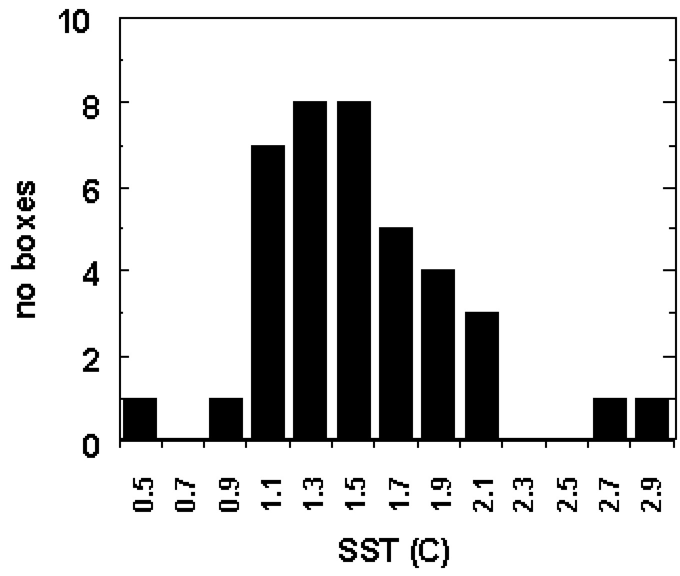

Figure 1. Histogram of SST errors for ship data estimated by Kent et al. (1999).

2. Dependence of errors on method

Firstly note that the impression given by Emery et al. (2000b) that it is only some research ships that report bucket temperature is not correct. Until recently around one third of all VOS SST reports were bucket measurements. This proportion is decreasing as Meteorological Agencies which preferred the bucket method have installed more hull contact sensors, a particular example is the Deutscher Wetterdienst. However that also implies that the number of hull contact derived SST data is now not negligible. These different methods have very different characteristics. Elizabeth Kent at SOC is presently conducting a thorough comparison of the quality of different types of SST data. However for the moment we must still rely on the results from the VSOP-NA experiment (Kent et al. 1991, 1993). These are summarised in Table 2. The method adopted for the VSOP-NA project was to use a background field as a means of comparing one type of measurement with an other. For SST the background field was derived from a combination of climatology, persistence, and seven types of observations including ships, drifting buoys, and satellite data. All types of ship data were given the same weighting. Thus while the magnitude of the values shown in Table 2 reflects to some extent the characteristics of the background field, the magnitude of the relative differences due to different observation methods should be correct.

Table 2. Summary of results from the VSOP-NA experiment (Kent et al. 1991, 1993). The number of ships using each method is followed by the overall mean difference between the reports and the comparison SST analysis field with the standard error for this mean. Then taking the mean difference for individual ships, the columns show the maximum and minimum bias and the scatter of the bias values. Finally, as an indication of the random errors, the mean standard deviation of the differences for individual reports from each ship and the scatter in this value is shown.

method	no of ships	overall mean difference (C)	Statistics between individual ships:				
			max mean diff.	min mean diff.	s.d. of mean diffs	mean s.d. of reports	s.d. of means
ERI	27	0.45 ± 0.15	2.32	-2.83	1.05	2.21	1.79
bucket	21	-0.01 ± 0.09	0.63	-0.67	0.32	1.16	0.6
hull	6	-0.02 ± 0.04	0.35	-0.37	0.23	0.97	0.46

First consider the mean bias. Clearly the ERI values are warm compared to the bucket and hull values . Our assumption is that it is the ERI values which are too warm - by 0.45C in the mean although Taylor et al. (1999) suggested 0.35C to be more typical. The bucket and hull methods show negligible bias compared to the background field (which was probably dominated by satellite and to a lesser extent drifting buoy data). This interpretation is in accord with the Emery et al. (2000a) comparisons, which show that a mix of all ship SST methods resulted in a warm bias of 0.28° (equivalent to an ERI bias of about 0.4° if 2/3 of the reports were from ERI). However note that the scatter of the mean bias values for individual VSOP-NA ships was large, about 1°C and the largest mean bias observed was an ERI thermometer reading **cold** by nearly 3°C (this fell off the graph in the original VSOP-NA analyses!). There was also much scatter in the individual reports with a mean value of over 2 degrees and a scatter about that of 2 degrees. Some ships which used the ERI method were quite good whereas other ships really were very bad! Thus the mean ERI bias was not well defined by the VSOP-NA sub-set of ships.

In marked contrast to the ERI data all the statistics for the bucket and hull contact methods are very much better. For the ships using hull contact sensors (admitted only 6) all the mean biases were within ±0.4C and the scatter of these biases was about 0.2C. The mean standard deviation of the differences for individual reports was about 1 ± 0.5 C. This consistency from ship to ship suggests that much of the latter value was caused by factors such as small scale variability and the characteristics of the background field rather than errors in the reported SST data.

3. Discussion

While Emery et al. (2000a) have shown that the quality of SST values from VOS is poor, their conclusions are based on a data set which probably contained about 2/3 reports from ERI thermometers. Had the comparisons been limited to ships using bucket or hull contact sensors the quality of the ship data would have been found to be much better. For many years the research ship Discovery has been fitted with a UK Meteorological Office type hull contact sensor. Our experience is that this sensor tracks the inlet temperature readings from a thermosalinograph to better than 0.1C. However the sensor does exhibit a slow calibration drift, recalibration at least once per year is desirable. Very similar results were obtained by Emery et al. (1997) who suggested an accuracy for hull contact sensors on merchant ships of about 0.1C provided the sensors were first individually calibrated.

The number of hull contact sensors in use on merchant ships has increased significantly in recent years and is likely to increase rapidly in future. One problem with regard to their installation has previously been the cost of running cable through and between interior water-tight compartments of the ships. However Woods Hole Oceanographic Institution (WHOI) have now developed a system which uses acoustic transmission of data through the ship's hull. We have just tested a WHOI system on the Antarctic research/supply ship RRS James Clark Ross. A hull contact sensor was installed and SST values were successfully transmitted acoustically at ten minute intervals to the data logging system. Hourly values of meteorological and navigation data were automatically transmitted back to land using the "Orbcomm" satellite system. The data were received at SOC as email messages with typical delays of a few hours (the "non-urgent" priority class was used).

The conclusion is that the increasing number of VOS equipped with hull contact sensors provide a potentially important source of subsurface SST data that is in additional to the data from drifting buoys. Under most conditions these ships define the mixed layer temperature which is required for longer time scale studies. For wind speeds above about 5 m/s, the skin SST value may be obtained from these subsurface data by adjusting the subsurface SST value by about -0.15C (Donlon et al., 1999). At lower wind speeds, the effects of a diurnal thermocline or freshwater lens (e.g. Barton, 2000) could be measured using a trailing thermistor. However this is probably not practicable for use from VOS and there is also evidence (e.g. Barton, 2000, Donlon et al. 1999) that the skin temperature deficit may be significantly larger compared to higher wind speeds. It is these cases which require the use of an IR SST determination.

It is expected that the subset of VOS for climate (a JCOMM sponsored project provisionally entitled VOS-Clim) will have hull contact sensors. These ships may or may not be suitable choices for the installation of IR radiometers (as suggested by Emery et al. 2000b). However it is also perhaps worth noting that there is an increasing number of different observing systems which are based on the use of VOS and a growing concern that the cooperation of the shipping industry may begin to be strained. For that reason, the JCOMM sub-group for the VOS have suggested combining the existing VOS (meteorological), ASAP (radiosonde), and SOOP (mainly XBT) panels into a single ship-board observations group. Any operational project to place IR sensors on VOS and to improve the meteorological data (Emery et al. 2000b) should be coordinated either with these individual panels or, eventually, the single ship-board observations group.

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Subject: Re: SST workshop
Date: Mon, 23 Oct 2000 11:51:50 -0600
From: Bill Emery <William.Emery@colorado.edu>
To: "Peter.K.Taylor@soc.soton.ac.uk" <Peter.K.Taylor@soc.soton.ac.uk>
CC: craig.donlon@jrc.it, Dick Reynolds <Richard.W.Reynolds@noaa.gov>,Ian Robinson <Ian.S.Robinson@soc.soton.ac.uk>,Neville Smith <N.Smith@bom.gov.au>,Ian Barton <Ian.Barton@marine.csiro.au>,Trevor Guymer <thg@soc.soton.ac.uk>, sandrac@frodo.colorado.edu,Gary Wick Gary.A.Wick@noaa.gov

Peter,
I have now read through your write-up find as usual that we agree on most things. Your main point is that our comparison of ship SSTs was biased by the use of injection temps (your ERI for eng room injection). That is completely true and I have no arguments about that.

I am glad that you have looked at our 97 paper based on some hull contact work that we did (following the example in Kent et al). We had excellent results as long as we had regular calibration which you agree with. We had one issue with this hull project that I don't know how you, the JCOMM, et al handle and that is the change in water line with the varying load of the ship. We wanted to have our sensor as close to the waterline as possible which meant that when the ship was loaded it was too deep and when empty it was above the waterline no longer measuring SST. As we discussed in the paper we found that if we put 3 sensors in a vertical line we could always be sure to have one sensor below but still very close to the water line. How does the JCOMM installation handle this problem? We also had serious insulation problems to protect our sensors from the heat in the nearby engine room. I assume the JCOMM installation is similarly protected? We did have a problem stringing wires so the WHOI acoustic trick sounds great to me.

I don't know anything about JCOMM and wonder if there might be some way to participate with them. You suggest that these JCOMM ships might carry the skin SST radiometers which I think is ideal. I was going to push for a skin sst radiometer along with an array of hull contact sensors to do the skin and bulk temperatures. We are still a long way off from understanding the skin-bulk SST relationship and more data would be extremely valuable. Can you put me in touch with these folks so that I can figure out how to work with them on the future SST validation systems? (Again sorry you won't be at the meeting). What is the JCOMM VOS subgroup? I would like to talk with them. We have learned a couple of new things that you might appreciate.

I have copied your comments to Sandra Castro and Gary Wick. Most of these new ideas come from Sandra's (phd) analysis of our various sets of skin - bulk SST measurements. Using this temperature difference from a wide range of geographic and seaonal measurements she has found that she can separate the measurements into at least 3 regimes. The first is the "free convection" case which is the low wind condition where air-sea heat flux controls the bulk-skin temperature difference. Even you agree that under these conditions we must have a radiometric measurement of skin SST. The next regime is the "turbulent shear" regime where wind stress now dominates the bulk-skin relationship. This is the domain where you suggest that things will be mixed up enough that we could use the bulk (ship or buoy) SST to compare with the IR satellite SST. Unfortunately it is not that simple. Even though this is the domain where we have the greatest number of observations the mean bulk-skin SST difference is not always zero. Certainly there are a large number of times when the bulk-skin SST difference is exactly zero but there are a considerable number of other times when this difference is as large as +1,+2 C or between -1 and -2 C. Thus, we need to have radiometric skin SST measurements even in this shear domain if we want to get it to be precise. Of course we still need the bulk SST measurements which we think the hull SST is the best way to go.

Sandra has also discovered a regime she calls "microscale breaking" where the turbulence is not a direct consequence of the wind stress but rather is generated but the breaking down of capilliary waves (and other waves that Soloviev calls "rollers"). In this domain the bulk-skin difference is not a function of wind stress or heat flux but rather is controlled by the breakdown of these waves. The waves of course are generated by the wind and this condition only exists at higher wind speeds. In reality the free convection is present at all wind speeds depending only upon the time of day and cloud cover. In the intermediate "shear" regime the wind mixed turbulence dominates over the heat flux exchange and there is a dependence of the bulk-skin SST difference on the wind speed. In the "microscale breaking" category the SST difference no longer depends directly on wind speed or heat flux and instead is a function of the convective time scale. The bulk-skin differences in this regime range from 0 to about 3 C. Sandra is improving this classification by dividing the wave breaking regime into capilliary waves and "rollers." This complexity just indicates the variable nature of the bulk-skin SST difference which makes it impossible to suggest a simple dependence on wind speed to erase the SST difference. It is strong support for the use of VOS mounted radiometers to measure the skin SST directly. Again it is assumed that we will have hull contact sensors to give us the bulk SST. Only with this type of an installation will we be able to properly calibrate present and future satellite IR instruments while perfecting our understanding of this important SST difference. I believe that it is this bulk-skin difference that has a lot to do with the air-sea heat flux and is one of many important keys to resolving the global heat exchange issue.

best regards, Bill
ps About your "trailing thermistor" I think it is a very important measurement but think it is practically impossible on a VOS. The beauty of the hull sensors with the radiometers is that in principle the system will work without any operator intervention. Clearly for the first while we will want one of the ship's officiers to look after the radiometer to make sure it does not get contaminated with salt spray, etc. These are the critical limitations for a completely automated system. Once we can handle those then we can put radiometers on open ocean moored buoys to compliment our VOS ships measurements.

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 12:25:37 +1000
From: Neville Smith
To: Bill Emery
Bill, Peter
Thanks for copying that discussion. We do have to be very careful that the various SST projects do not trip over each other in an effort to do good. I will bring along one or two OHs describing JCOMM, including the role of VOS-Clim and the likely merger of the ASAP/SOOP/VOS implementation groups. I am also aware of another WS to be held next year that Chris Folland is involved with, mainly focussed on historical SST data sets, but also very interested in the interpretation of mixed layer, bulk and skin SST.

No matter how the discussions go I think we do have to consider development of forward and backward models for subsurface SST <-> skin SST. It seems we do have enough knowledge to do this now. Agreement on such models will be critical for maintaining confidence of the climate community who have built their knowledge on subsurface SST, and emerging communities who do seem to care about diurnal cycles and skin SST, principally within GEWEX. Any suggestions for calibration and in situ data will need to balance continuity issues as well as new needs emerging from this refined treatment of SST (e.g., radiometers on VOS). As Peter notes, we do have a good strucuture in JCOMM for considering such issues.

I have placed Peter's comments and the discussion on the web as I think it clarifies several aspects of our discussion.
Thanks agin to both of you for spending some time thinking about these issues.
Neville

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 10:20:23 +0100
From: "Peter.K.Taylor@soc.soton.ac.uk"
Hi Bill,
Thanks for your comments.
Re.
> We had one issue with this hull project ...that is the change in
>water line with the varying load of the ship.
...on the VOS the present practise is to only use one sensor so it must be mounted deep enough to be always under water. In the VSOP-NA project the sensor depths ranged between 1m (more generally 4m) to 8m - similar to the ERI depths. The lack of bias between the results from the bucket and hull sensors suggests that this depth was not a problem on average. But we do have to accept that these sensors will not detect a diurnal thermocline. And yes, they are insulated from the ship's heat. By all accounts (a pub conversation with Margaret Yelland) the WHOI acoustic system worked like magic - plug it in, switch it on, and it was working!
Re.
>What is the JCOMM VOS subgroup? ..Neville can explain all! Re. your comments on the skin bulk differences.
... I was just relying on the Donlon et al. (1999) conclusion that above 6m/s wind speed the skin is 0.14C (plus or minus 0.1) colder than the bulk - I certainly didn't say it was zero. If Sandra Castro's work shows that much greater differences are common at higher wind speeds then we need to know about them - but until convinced otherwise, from my limited observational experience I would agree with Donlon et al. At low wind speeds (<6m/s) the skin-bulk difference is much more varied and at very low wind speed (<3 m/s) we add the problem of diurnal thermoclines. Below 5 m/s (say) we also have problems with our flux parametrisations. Not only is there the problem of handling the approach to the (atmospheric) free convection limit but also there is increasing evidence that (even in the 2 m/s to 5 m/s range) the effects of swell can make the roughness length (and hence all the transfer coefficients) variable and even MO theory may break down! ...What are the typical wind speed limits of Sandra's regimes?
Cheers, Peter

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 13:40:28 +0200
Sender: c_donlon@jrc.it
Hello:

I wanted to comment on the last set of mail discussing the relationship between wind speed and SSST-BSST difference. The Donlon et al (1999) results are supported by independent observations from both Peter Minnett using the M-AERI and from Ian Barton (see his paper on the GODAE High res. SST web site) and also using ATSR and TAO data (See Murray et al, 2000 GRL). These independent analyses, in different Oceans and different seasons all agree exceptionally well. The mean skin temperature "bias" (it's not actually a bias but a small gradient that agrees well with the dT model of Soloviev and Schluessel) is ~0.15K +/-0.7. A paper is now in progress that collectively presents these data with an important application of the result: to validate and perhaps more importantly, compare, complementary IR satellite SST data using high quality buoy and ship BSST obs. in wind speed regimes > 5m/s.

I'm confused about the high dT values mentioned (> 1K at wind speeds > 5m/s) data which I do not have an obvious answer for: it will be interesting to discuss this further next week. However, I have found that considerable quality checks are required to be sure of a trouble free in situ data set. In our data, there are a small number of anomalies which I suspect are related to data quality: periods of ship operations, instrument maintenance etc. For example, once when I was servicing the installation on the fore-mast of the JCR, I noticed the ships cook taking his mid-morning cigarette break. He would make his way to the bow of the ship, coffee in hand, and peer over the bow. We had a very tight tolerance on the location of the radiometer beam clearing the guard-rail and his presence could be seen as a warm skin event in our data !! While this is almost certainly not the reson for the high dT values discussed before, it serves as an example.

Finally, fhile in situ radiometers should be considered as the only viable data set for validation of satellite SST data in low wind speed conditions, there are considerable problems of deployment and a degradation of data quality when operated in heavy seas and strong winds. I'm actively working to deploy autonomous radiometers on VOS style ships through the Anglo-US ISAR collaboration but my feeling is that these instruments should be seen in a more holistic view. There is no substitute for the "High Quality" BSST measurements provided by the buoys and ships. Radiometers should be seen as complementary to this exceptionally widespread (both in time and space) data for considering the low wind speed regime (which is characteristic of significant ocean areas and seasons), development of transfer equations for moving between BSST and SSST and, a deeper understanding of the physics at the interface along the same lines as Bill Emery discussed previously. I believe that we simply cannot continue to rely on in situ radiometer systems to provide the operational on-going validation of satellite SST data because we may never obtain the necessary coverage. However, without widespread in situ radiometery, we may never unravel the intracacies and subtleties of the air-sea interface and the information content of satellelite data. Looking forward to the meeting next week and its a shame Peter Taylor cannot be with us.

Best regards,
Craig

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 08:35:44 -0600
From: Bill Emery

Neville,
I am not sure that we are really ready to directly model the bulk - skin relationship. Gary Wick will, I am sure, speak to this as well as to other issues related to the validation. Did I remember to copy you on my response to Peter T? In reality we agree on the use of hull sensors on ships as the best (probably even better than buoys) way to get bulk SST. There is no way to escape the need for measuring skin SST for satellite IR validation and that will hopefully be abundantly evident next week. We are making progress in understanding the bulk - skin SST relationship but it is sufficiently complex that at present there is no way to circumvent this need for in situ skin SST measurements. I would like to work with the JCOMM group to bring this to pass. Dick Reynolds says he can put me in touch with the US part of this activity. Perhaps you and Peter could assist in getting those of us interested in putting radiometers on VOS ships in touch and working with these JCOMM folks. We did have a NOAA sponsored hull sensor project that went very well and convinced me of the value of this technology. There is a ship loading issue that I need to resolve with Peter but I certainly always considered the hull sensor as part of any installation on a validation ship.
cheers, Bill

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 08:56:22 -0600
From: Bill Emery

Peter,
I somehow failed to explain Sandra's analysis to you correctly. She has analyzed all of the data sets that we have on bulk, skin SST data. She has the data from Schluessel in 84 all the way up to the present (Wick, Schluessel, Jessup, Donlon, Minnett, etc). In fact sheis putting these all on a CD rom for those intereseted in these problems. As a consequence her wind speeds cover the entire range. In Craig's analysis he saw a case where the higher wind corresponded to a near zero difference between skin and bulk SST. In the large collection of data that Sandra is analyzing she sees such cases but also sees a lot of cases where that is not the case and bulk - skin SST differences are quite large. She also finds this regime where the bulk - skin SST difference does not depend on either wind speed or heat flux as the turbuloence is created by the "breaking" of capilliarywaves and the vorticity of the local surface gravity wave field.

All of our models up to now have not included the effects of waves and swell. Gary Wick talked many times about it but never got anything specific going. It is something that Sandra is going to have to think about in moving her analyses into the model domain. There is still a lot to do to figure all this out. One thing is clear, however, we need to make in situ skin SST measurements on a continuing basis to cal/val IR satellite SST estimates.
cheers, Bill

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 09:42:12 -0600
From: "Gary A Wick"
Hi Everyone,

I feel I should also make a brief comment on the discussion of the cool skin at high wind speeds. I think it is very important to remember that speaking of a mean cool skin of ~0.15 +/- 0.07 above some threshold windspeed is a statistical result derived from looking at a large number of measurements. I agree that this result may be useful in the validation of satellite SST and I think that is the primary focus here. Where I believe we must be careful, however, is in using this to draw strong conclusions about the physics of the skin layer.

I believe (Craig, correct me if I am wrong) that the +/- 0.7 error bars are statistical in nature - such as +/- one standard deviation. There are going to be those exceptional conditions where the differences fall outside this range due to additional dependencies on other parameters. I just took part in an experiment with Andy Jessup where he was carefully studying the sea surface with an infrared imager. Under stable conditions with very small or negligible heat flux there appeared to clearly be times when there is no skin layer or the skin is less than 0.08 K cooler than the bulk water. Additionally, over the small areas considered, the magnitude could change fairly rapidly as conditions evolved.

There is still a need for a more complete understanding of the exact physical behavior of the skin layer. As long as we realize that there may be those exceptions and understand the possible uncertainties then we can consider speaking of generalities based on knowledge of the wind speed alone.
Best regards,
Gary
****
Gary A. Wick phone: (303) 497-6322
NOAA/ETL fax: (303) 497-3794
Mail Code: R/ET1A
325 Broadway e-mail: gary.a.wick@noaa.gov
Boulder, CO 80305
****

Subject: Re: SST workshop
Date: Tue, 24 Oct 2000 14:56:39 -0600
From: Bill Emery
Craig,

It has taken a bit of time to respond to this email. Here is what I have found out thanks to Sandra and Gary. First I read Sandra's plots wrong. What I thought was delt was really renewal time. She has some very nice plots that show the observed delt as functions of wind stress and heat flux. I will bring these along. These do indeed suggest at the highest wind speed the delt is converging to a constant somewhere around your 0.15 C. The scatter is still a bit larger than 0.07 C. This convergence does not really emerge until about 10 m/s below which the mean delt is certainly higher than 0.15 C with a much bigger scatter. This diagram includes your two cruises which by themselves show a smaller scatter.

Gary argues strongly for an "intermediate" approach where we don't have enough ship based radiometers to do the skin SST validation and suggests that maybe for these higher wind conditions we can use a constant as you suggest. From this combination of data sets it is clear that this can only be for winds above 10 m/s. This also gives us the difficult problem of measuring the wind near the drifting buoys. We will have to use either model analyses or something like SSM/I both of which have very poor spatial resolutions which may produce a wind not really related to the buoy bulk SST. As I said I will bring these plots along and we can talk about them.

Sandra has done an excellent job of filtering out questionable data so I think it is not likely to be attributed to that. Certainly for my past comments the problem was my incorrect reading of her scales. I will write some labels on them to make that clear.
I really disagree with you on the in situ radiometer program. I am fairly certain that in the future we will have enough ships instrumented to make the routine cal/val of satellite IR data. Here in the US we have an ideal opportunity with the NPOESS system which has specified that all SSTs be skin SSTs and NPOESS will have a very substantial validation program. If we can get some going now we will be in very good shape when NPOESS comes along at the end of the decade. I strongly agree with Peter Taylor that the correct bulk SST measurement is a hull contact sensor on a VOS ship. At least we will have a pretty good idea of where in the water column that measurement is made. The buoys move up and down in the wavefield and so it is difficult to know where they are measuring. Also there are different buoys, using different thermistors all of which are not calibrated once they are in the buoy. I would really like to see a drifting buoy project that was set up specifically for SST validation. We would certainly put them in different places to provide info that is not routinely available. One point of the Emery et al 2k paper is that using other folks buoys which are deployed for regional current studies gives us a non-ideal distribution of data points which can really skew the SST regression values.

I am glad to hear that you are working on VOS radiometers as I see this as the only solution. In our paper for BAMS I make that point very strongly and offer a candidate set of ship routes that would give us global coverage in most places once a month. In the southern ocean trips are only in the austral summer so we won't have winter coverage. I will talk a bit about this as well.

Finally in wrapping up my earlier statement I don't think the radiometer is needed only for the low wind speed conditions. It may not be needed for the very high (> 10 m/s) wind speed conditions but it is certainly the only way to overcome the general change in delt with wind speed and the relatively high scatter for delts with wind between 5 and 10 m/s. I think it is easiest to just plainly say that we need the radiometric skin SST along with the hull sensor BSST to first validate the satellite IR data and second learn more about the bulk - skin (delt) temperature difference.

cheers, Bill

Subject: Re: SST workshop
Date: Wed, 25 Oct 2000 10:40:26 +0200
Sender: c_donlon@jrc.it
Hello:

Thanks for the comments from both Gary and Bill on my earlier mail. I'm glad that Bill was able to clear up the larger dT values at higher wind speeds as I was worried about that ! Firstly, in response to Gary on the question of error bars on the dT data. You are quite right in that these are statistically derived from my data alone and provide a simple, basic assessment of the variability of dT. However, in the face of this, I should like to point out that there are some fundamental difficulties in making precise in situ SSST measurements from a ship at this level of accuracy (~0.05 K). In a recent paper, (Donlon and Nightingale,The Effect of Atmospheric Radiance Errors in Radiometric Sea Surface Skin Temperature measurements", Applied Optics, 39, 2397-2392,2000) we show that the limit of accuracy is not the radiometer but the correction for down-welling radiance reflected at the sea surface into the radiometer. Using both observations and monte-carlo style model simulations, we show that errors >> 0.1 K are easily possible (and are perhaps always present in all data) if an inappropriate sky temperature correction is made (due to changing cloudiness, ship movements etc.). Further complications arise be cause of large and small scale surface roughness spreading the reflected lobes- especially for clear sky conditions which is exactly when we need the data for satellite validation. I speculate that this is probably the geophysical limit to the accuracy of in situ radiometer measurements.

In other words, it's actually suprising that the scatter we see in these data is so small and a credit to the engineering teams that have developed the state of the are in situ instrumentation (M-AERI and SISTeR radiometers in this case) ! I have copied the paper as an attachment for those who are interested.

On the question of radiometers providing adequate data for satellite validation, a recent paper by Kearns et al. (BAMS, 81, July 2000), from 6 lardge research cruises conducted over a 3 yr period, they have only 219 match ups with AVHRR satellite data and ship obs. For myself, we are even worse off when using the ATSR sensor (narrow swath and poor repeat orbit pattern) and from 5 cruises over a 4 yr period we have less than 50 match ups ! (Thats nearly a year of my life at sea !) As you all know, each cruise is a considerable effort at an even more considerable cost. These factors are the driving fores that prompted me to design and build the autonomous ISAR radiometer. While I agree that further fundamental research is required to understand the intracacies of the skin-bulk difference - which can only be done using in situ radiometers, I'm not so sure that in situ radiometers alone can provide the necessary data to provide on-going satelitte SST validation- even with 20 or 40 autonomous ISAR radiometers for which I have worked so hard on during the past 3 years. Even with these, it will be a massive effort to maintain their calibration and functionality in an operational sense.

I think that the critical questions relate more to the space-time averaging of both satellite and in situ data: we are always dealing with a mean quantity here. The satellite provides a spatial mean in ~90usecs whereas in situ data (from a ship) provide a spatio-temporal mean along a ship track in the order of 10's of minutes (Aircraft provide a better approach but have other problems relating to atmospheric correction and radiometer response times). What I am advocating is that we can use the huge quantities of in situ BSST to provide a psuedo-skin measurement for a specific wind speed regime to an accuracy of 0.1 +/-0.1 K. Considering the results of Donlon and Nightingale (2000), we don't do much better with in situ radiometers even if in the lab we can calibrate them to an accuracy of 10^-2 !!! (Actually, this is a dissapointing result for me if the truth be known !!)

In conclusion, I agree with Bill and Gary: we should _always_ advocate the use of in situ radiometers to validate satellite SST data (especially at this time when we need futher funding to support a VOS style autonomous in situ system). In addition, there is a need to continue to research the subtleties of the SSST-BSST relationship for air sea gas and heat exchange, which again, is only possible with quality in situ radiometers. We also need to refine the measurement technique itself. Nevertheless, there is a need to suppliment this "Class 1" type validation effort with a "Class 2" effort consisting of autonomous in situ radiometers and quality (and the emphasis here is on quality) drifters, moorings and ship temperatures to provide a pragmatic solution to the long-term validation of satellite SST measurements.

Take care and see you all next week,
Best regards,
Craig

Subject: Re: SST workshop
Date: Wed, 25 Oct 2000 15:27:11 +0100
From: "Peter.K.Taylor@soc.soton.ac.uk"

I'm happy to agree with Craigs last messages (I can't believe we seem to be converging on some sort of consensus!). Have a good workshop, Peter K.T.

Subject: Re: SST workshop
Date: Wed, 25 Oct 2000 21:44:23 -0600
From: Bill Emery
Dear Peter,

Yes to bring this exchange to a close I too have to agree with Craig's last statement:
"In conclusion, I agree with Bill and Gary: we should _always_ advocate the use of in situ radiometers to validate satellite SST data (especially at this time when we need futher funding to support a VOS style autonomous in situ system). In addition, there is a need to continue to research the subtleties of the SSST-BSST relationship for air sea gas and heat exchange, which again, is only possible with quality in situ radiometers. We also need to refine the measurement technique itself. Nevertheless, there is a need to suppliment this "Class 1" type validation effort with a "Class 2" effort consisting of autonomous in situ radiometers and quality (and the emphasis here is on quality) drifters, moorings and ship temperatures to provide a pragmatic solution to the long-term validation of satellite SST measurements."

I recognize his concern for the overall accuracy of the ship based skin radiometer measurements but I think that is something we have to tackle once we have such measurements. The problem I have now is that any suggestion that we can use a constant correction to the bulk SST is grasped by so many as the answer and it really is not. It is gratifying that all of the many measurements that Sandra has looked at show a relative "convergence" to a delta-T value (a bit more like 0.2 C than 0.15 when we add the MAERI measurements to the ROSSA data). There is still considerable scatter at these points but the scatter is certainly lower when compared to the lower wind speeds. Also this phenomenon starts to occur after 10 m/s. This scatter leaves us with the persistent need to measure the skin SST and be glad that we have folks like Craig worried about doing it correctly. This is going to be a real learning process but we won't get NAVO and FNMOC to change to skin SST until we can provide them with the in situ skin measurements to take care of the cal/val concerns. The good thing is that we have ISAR, Andy Jessup's radiometer package and our (as yet un-named) radiometer that we can employ for these ship radiometer measurements. We are in a much better position to advocate and carry out this type of a measurement program than we were 3-4 years ago.

It should be a great meeting and we should have a lot of fun talking about these subjects.l
cheers, Bill

A "COLD" PERSPECTIVE

B.J. Topliss,
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This perspective is based on a variety of issues likely to be involved in producing any high-resolution, full coverage product suitable for the Canadian Atlantic region. Prior BIO cal/val studies for AVHRR and MCSST product validations have highlighted several topics all inter-linked with the issues of coverage and seasonality.

At high latitudes in-situ coverage is usually poor. This makes a satellite product valuable but limited with regard to validation. The Atlantic Canada region covers a sea surface temperature range from freezing to the high twenties. The atmospheric properties can range from ultra-clear with exceptionally low attenuation coefficients in arctic regions to high humidity in the southern ocean regions and high aerosol content in the southern coastal regions. These same geographical variations also appear as seasonal variations. At present both our cal/val and product validation studies have qualitatively used skin effects, wind, solar heating and atmospheric properties as the rationale for poor matches.

Regional validation of the MCSST product gave consistent comparisons with in-situ data but often appeared unrealistically limited in its coverage in colder regions. The data were considered reliable enough to be made available in discrete form to supplement regional data holdings, and in map form to investigate patterns of SST-anomalies for fisheries studies.

The Pathfinder product was initially very encouraging, it appeared to offer much better data coverage and good resolution but when regionally validated it gave consistently poorer in-situ comparisons. It was noticeably poorer at low temperatures. These underlying product-problems again translated to both seasonal and geographical issues which severally affect Canadian regions. Hence it was not possible either to use the 2 products in a cross-validation mode in northern waters or to merge the 2 data sets.

A published ATRS study simply deemed the North-West region of the Atlantic Ocean to have yielded anomalous [ATSR] data. Will ATSR-2 do the same? So our question for this workshop is, "If we do take care of the skin effects, diurnal heating, and aerosols to what extent can we still expect residual seasonal biases and how will we determine these"? All these issues impact a cold region of the ocean which plays a key role in the ocean-atmosphere climate system, so accurate monitoring is crucial.

There appears to be a strong need for a rigorous validation process for any product. Most clients/users are not confident enough with a satellite-SST product to accept a switch to a skin-temperature product. There appears to be a strong need for a dual product, providing bulk-SST for environmental users and skin-SST for the specialists.

A COMPARISON BETWEEN SEA SURFACE TEMPERATURES AS DERIVED FROM THE EUROPEAN REMOTE SENSING ALONG-TRACK SCANNING RADIOMETER AND THE NOAA/NASA AVHRR OCEANS PATHFINDER DATA SET

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ABSTRACT

The paper focuses on the comparison between the NOAA/NASA AVHRR Oceans Pathfinder sea surface temperature (SST) data set and SST as derived from the Along-Track Scanning Radiometer (ATSR) on board the European Remote Sensing Satellite (ERS1) (ASST). These two data sets provide an unique opportunity for comparing, on global scales, two independent satellite derived SST retrievals. The comparison was done for data between 1992 and June of 1996. In a preliminary step, mean values and standard deviations of the residuals as defined by the differences between the (Modified Pathfinder SST algorithm) MPFSST and the co-located in-situ Pathfinder matchup database were calculated. Globally, as defined by the mean difference, the MPFSST was colder than the in-situ data by -0.01ºC with a standard deviation of 0.54ºC. However these results were found to vary between ocean basins. The Caribbean showed the largest difference with a warm mean difference of 0.24ºC and a standard deviation of 0.56ºC.

Mean differences and standard deviations of the residuals as defined by MPFSST - ASST were calculated. The loss of the 3.7 micron channel on board the ATSR-1 instrument appeared to have a larger effect on the nighttime differences and thus application of the model to remove residual cloud cover only had a significant impact on the nighttime statistics. A mean difference of 1.40ºC, with MPFSST warmer than ASST, and a standard deviation of 0.57 were calculated after the application of the cloud removal model to the ASST. To confirm that part of the differences between the MPFSST and the ASST was due to residual cloud cover, a set of EOFs were extracted from the MPFSST-ASST difference maps, before and after applying the cloud removal model to the ASST. A significant drop from 36% to 14% in the percent variance explained by the first mode indicates that applying the cloud removal algorithm has removed a significant signal from the difference maps. The mean bias for the summation of the first two EOFs is reduced from 0.59ºC to 0.34ºC and the standard deviation from 0.19ºC to 0.16ºC. Thus, a minimum 0.25ºC of the signal in the difference maps is due to residual cloud cover in the ASST data. It is concluded that with improved cloud detection and atmospheric corrections being applied to the ASST, along with improvements to the MPFSST, achieving a 0ºC mean difference and a standard deviation of < 0.3ºC for global climate studies is possible.

AN AUTONOMOUS PROFILER FOR NEAR SURFACE TEMPERATURE MEASUREMENTS

B. Ward[1] and P.J. Minnett [2]
[1] Geophysical Institute, University of Bergen, All´egaten 70, N5007 Bergen, Norway.
[2] Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, Miami, Florida 33149-1098, USA.
(Accepted for the Proceedings Gas Transfer at Water Surfaces 4th Interna-tional Symposium, Miami Beach, Florida USA. June 5-8, 2000.)

Abstract This paper describes the profiling instrument SkinDeEP (Skin Depth Experimental Profiler), which measures the temperature of the water column from a depth of about 6 metres to the surface with high res-olution thermometers. The instrument operates in an autonomous mode as it has the capability to change buoyancy by in ating a neoprene blad-der attached to the body of the profiler. Measurements are recorded only during the ascending phase of the profile so as to minimise disturbances at the surface. Results from deployment of the profiler show strong tempera-ture gradients within the bulk waters under conditions of high insolation. These data were compared to the skin temperatures as measured by the M-AERI (Marine-Atmosphere Emitted Radiance Interferometer), a high accuracy infrared spectroradiometer. The corresponding bulk - skin tem-perature differences (_T) were shown to have strong dependence on the depth of the bulk measurement during the daytime with low wind speeds, but at higher wind speeds, the depth dependence vanishes. One set of pro-files under nighttime conditions is also presented, showing the presence of overturning and thus a heterogeneous temperature structure within the bulk.

SOME ISSUES FOR THE GODAE SST WORKSHOP

Gary Wick
NOAA/ETL
Mail Code: R/ET1A
325 Broadway
Boulder, CO 80305
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Subject: Re: GODAE meeting
Date: Thu, 19 Oct 2000 15:55:00 -0600
From: "Gary A Wick" <Gary.A.Wick@noaa.gov>
To: craig.donlon@jrc.it, N.Smith@bom.gov.au
Hi Craig,
....
I took a quick glance at the preliminary agenda and feel that the workshop should be very interesting. You asked previously about a couple sentences on what I might talk about at the workshop. From the agenda I see two primary areas where I feel I might have most input. The first is on the GOES SST measurements and diurnal issues. I have some results that highlight the difficulty in obtaining accurate measurements of the diurnal cycle from the direct GOES measurements. The second area is on potential integration of infrared and microwave products. This work is just getting going so I am only beginning to explore the degree of complexity that will be required in the blending process. The main results I have looked at so far are initial comparisons between some of the ir and microwave products to understand their differences. I should note that I do not have my own microwave SST product at this point but am only exploring combination of existing products.

I don't need to make "formal" presentations in these areas - I think the discussion is the more relevant goal. Perhaps the nature of what I would say can be based on what we need to push the discussions in the proper directions. Depending on your and Neville's feelings, I could put together something of an extended abstract on one of the areas as Neville suggested.

Under the framework of the validation plan, I could also provide a short description of Andy's progress with his radiometer for him

You asked about involvment in the blending work - I think there are some excellent opportunities for us to work together on this and get some good results. We should talk more about an approach together if we can around the workshop. I plan to explore more elaborate merging techniques but want to first see just how much work is justified based on the accuracy and differences of the products.

Cheers,

Gary