Observations of Sea-Surface Temperature for Climate Research [and Discussion]

J. E. Harries, D. T. Llewellyn-Jones, P. J. Minnett, R. W. Saunders, A. M. Zavody, P. Wadhams, P. K. Taylor and J. T. Houghton

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Observations of sea-surface temperature for climate research

By J. E. Harries, D. T. Llewellyn-Jones, P. J. Minnett,
R. W. Saunders† and A. M. Zavody
Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, U.K.

The measurement of global sea-surface temperature (s.s.t.) from space, with high absolute accuracy, is one of the important requirements of the World Climate Research Programme (W.C.R.P.). This paper considers the definition of measurement aims based on considerations of specific types of scientific problem, and gives as examples discussion of two particular problems, first the possible influence of Pacific s.s.t. on the lower stratosphere, and second the role of s.s.t. in the cloud–climate feedback process. Following this, a brief review is presented on current status in satellite measurements of s.s.t. with both infrared and microwave techniques, and the paper concludes with a description of a future s.s.t.-measuring instrument, the Along-Track Scanning Radiometer (ATSR).

1. Introduction

The oceans are a major store of heat in the Earth's climatic system, though the details of how this heat energy is transported around the globe are only beginning to be understood (Hastenrath 1982). In their effect upon the atmosphere, and therefore on the climate as it is sensed by man, the oceans act as a vast thermal reservoir and so our present insubstantial understanding of what processes govern the interactions of the oceans and the atmosphere represents a major gap in our ability to understand, and eventually to predict, the climate.

The influence of the oceans on the atmosphere is determined by a number of parameters, but two in particular – direct radiation and release of latent heat through evaporation – are directly related to the temperature of the sea surface, the layer of ocean directly in contact with the air. Thus, while remote sensing of sea-surface temperature (s.s.t.) from space can give us information only from the skin depth, which may be only a few micrometres (infrared) or few millimetres (microwave) deep, and which may be at a rather different temperature from the bulk of the surface water (Paulson & Simpson 1981), this information is of great value to climate research.

Thus satellite remote sensing of s.s.t. has a major role to play in climate research. The accuracy of the determination of s.s.t. must, however, be very high indeed. A target of ± 0.2 K absolute accuracy has been quoted by scientists involved in the planning of the World Climate Research Programme (World Climate Research Programme 1981). This measurement accuracy is needed on a global scale, and must be made in the presence of not only instrumental noise and systematic errors, but through the partially absorbing and emitting atmosphere which, even in the most transparent 'windows', can bias the observed temperature by between 1 and 20 K depending on atmospheric conditions. This is because the main absorber in the 10–12 μm atmospheric window, which is widely used for s.s.t. measurements, is water vapour, so that the atmospheric bias is particularly great in tropical regions (where most of the oceanic heat storage occurs), and is very variable around an orbit of the Earth. As a further indication of the importance of atmospheric effects, we should note in passing that the National Oceanic

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† Present address: E.S.O.C./M.D.M.D., Robert-Bosch-Strasse 5, 6100 Darmstadt, F.R.G.

and Atmospheric Administration has ceased issuing s.s.t. data from spaceborne sensors in tropical regions owing to the influence of aerosols in the stratosphere after the El Chichon volcanic eruption in March 1982. Despite these very serious difficulties in the science of measurements, the potential rewards to geophysics from having accurate s.s.t. measurements globally are so great that major efforts to overcome all problems are justified.

The paper will begin with a short discussion of the accuracy requirements for the measurements, on the basis of the type of scientific problems to be addressed. This will be followed by a discussion of two particular scientific problems that demand high-accuracy measurements of s.s.t. for their solution: the first concerns a possible 'tele-connection' between the Pacific Ocean surface temperature and the humidity of the stratosphere; the second concerns the role of s.s.t. in determining the sign and magnitude of cloud–climate feedback. Subsequently, a brief review of current status in measurements of s.s.t. from space, by both infrared and microwave passive remote sensing, will be given. The paper will conclude with a description of a future instrument, the Along-Track Scanning Radiometer, which will introduce new techniques with the aim of improving accuracies of s.s.t. measurements to a level where they will be of direct value to climate research.

2. Definition of required accuracies

To establish the specification of future measurement systems, the W.C.R.P. (World Climate Research Programme 1981) has considered a variety of types of geophysical problem in which s.s.t. might be an important factor, defined in terms of the temporal and spatial scales of the processes involved, and have suggested what measurement accuracies are required in each case. These definitions are given below.

(*a*) *Large-scale processes*

An example is inter-annual anomalies, scale 20° longitude by 10° latitude, lasting for several months. Such anomalies can probably cause changes in the atmospheric global circulation, or might be indicators of past atmospheric fluctuations. Typical peak amplitudes are *ca.* 2 K; an absolute accuracy of *ca.* 0.2 K is therefore required. S.s.ts can be averaged in time and space (e.g. for 30 days over 300 km), although smaller scales are important in terms of aliasing (e.g. eddies). Very important information about large-scale processes is obtained if measurement accuracy $\Delta T \leqslant 0.5$ K; much less information if $\Delta T \approx 1$ K; virtually no information if $\Delta T > 1$ K.

(*b*) *Mesoscale processes*

Examples are meanders of boundary currents, or eddy-shedding processes. Such mesoscale processes may be early indices of climatic change. S.s.t. is required in terms of a time series of patterns, which may be related to underlying dynamics. Data are required on scale of several kilometres and several days.

(*c*) *Small-scale processes*

Examples are oceanic and continental shelf fronts. Small-scale processes may be significant for climate modelling, and need to be parametrized. Small-scale processes are also important in the understanding of the sampling problem implicit in larger-scale measurement. A high spatial resolution (not more than 1 km) is required. S.s.t. data can be usefully combined with visible imagery radiation in such studies.

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With these various points in mind it is possible to define measurement specifications for the three classes of problem, and these are summarized in table 1.

Table 1. Accuracies of measurements of sea-surface temperature

	(*a*) *large-scale processes*
absolute temperature accuracy	± 0.2 K
spatial averaging interval	200–300 km
temporal averaging interval	20–40 days
type of data product	isotherm contours in map coordinates
	(*b*) *mesoscale processes*
absolute temperature accuracy	± 1.0 K
spatial averaging interval	5–10 km
temporal averaging interval	3.5 days
type of data product	isotherm contours in map coordinates
	(*c*) *small-scale processes*
absolute temperature accuracy	± 2.0 K
spatial averaging interval	1.0 km
temporal averaging interval	instantaneous
horizontal gradient accuracy	0.5 K/1.0 km
type of data product	gridded images located to ± 10 km

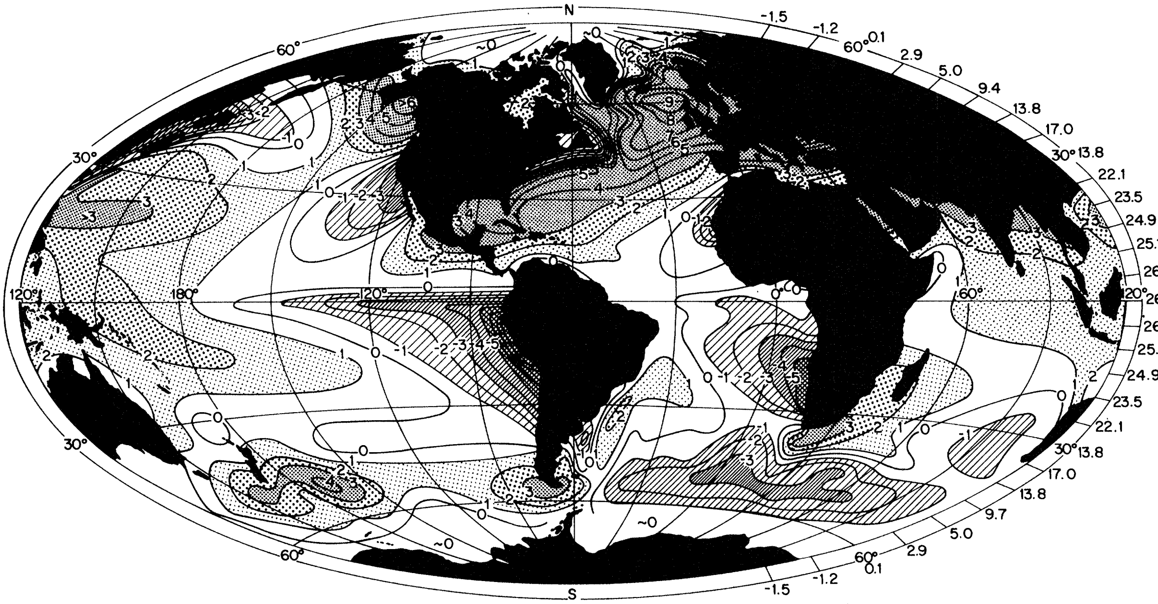

Figure 1. The deviations from zonal average sea-surface temperature (s.s.t.), adapted from Bjerknes (1969). Numbers at right are the zonal means, calculated excluding land surfaces. Contours are departures from zonal means, in kelvins; hatched areas are cold anomalies; stippled areas are hot anomalies.

3. Examples of research use of s.s.t. data

(*a*) *A possible tele-connection between the Pacific Ocean and the stratosphere*

Figure 1 (taken from Bjerknes (1969)) shows the deviation of s.s.t. from the long-term zonal average in a given latitude band (i.e. the zonal mean anomalies in s.s.t.) over ocean regions. This figure contains a number of details, but the point that we wish to stress here is that the Pacific Ocean exhibits a warm-to-cold gradient from west to east of about 7 K along the

Equator. This represents a vast thermal heat engine. As Bjerknes (1969) points out, this intense gradient of s.s.t. anomaly drives an equatorial surface easterly circulation. This circulation forms a closed cell – the Walker circulation – with a rising branch over the western Pacific and descending branch over the colder eastern waters.

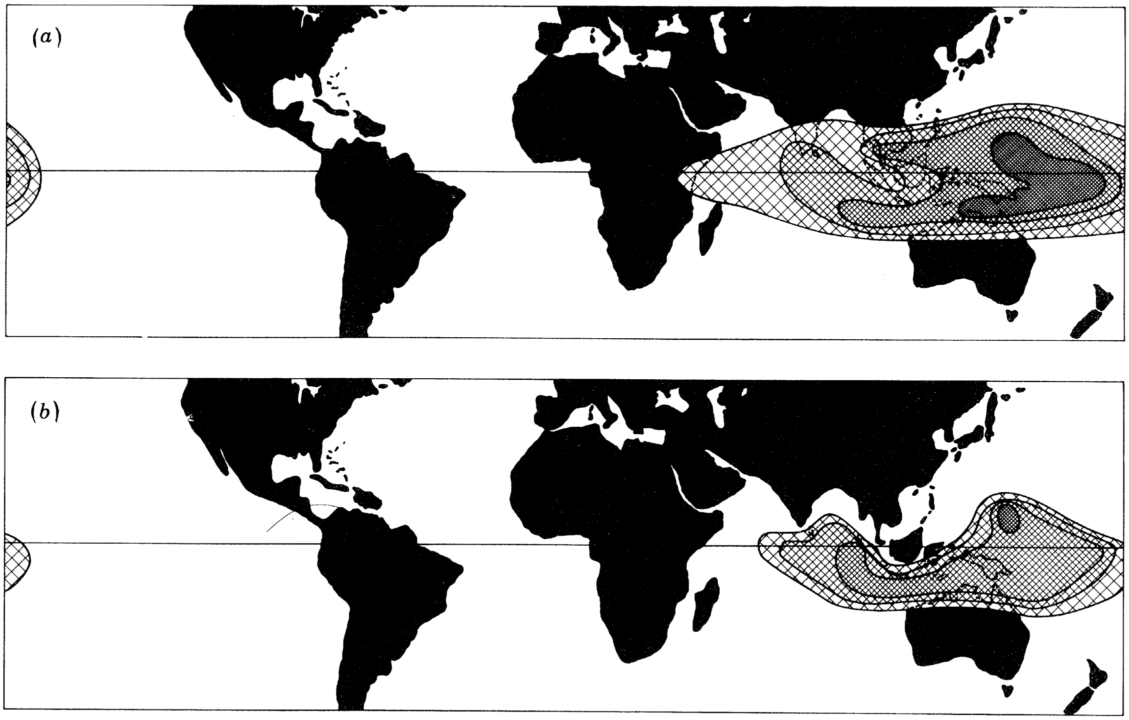

FIGURE 2. Contours of frequency of 100 mbar level temperature occurring below −82.4 °C. Data are averages for 1970–80, and monthly means for (*a*) January and (*b*) March are shown. Contours are for 10%, 30%, 50% and 90%, and are darker for higher percentages. (Taken from Newell & Gould-Stewart (1981).)

It is to be expected that the rising branch, and indeed the return flow (westerly at high levels), will not be confined to the upper troposphere, but will affect the tropopause region and the lower stratosphere. A recent study by Newell & Gould-Stewart (1981) has shown that the local tropopause temperatures (or, more precisely, the temperatures at the 100 mbar† level were actually considered) are colder in the western Pacific – southeast Asia sector of the equatorial zone than anythere else on Earth, at this pressure level. Their study considered the fraction of time for which the 100 mbar temperature was lower than −82.4 °C (which corresponds to the frost-point at 100 mbar for a volume mixing ratio of 3.5×10^{-6}, which is representative of mean observed water vapour mixing ratios in the lower stratosphere (see, for example, Harries 1976)). In other words, they studied those parts of the atmosphere that could physically be responsible for freeze-drying stratospheric air as suggested in the Brewer–Dobson theory (Brewer 1949). Newell & Gould-Stewart found that in data taken over the period 1970–80 there was a large area centred at about 160° W and on the Equator, where in January 90% of the 100 mbar temperatures were lower than −82.4 °C. This area shrank seasonally to a minimum in about July when in a restricted area over the Indian subcontinent and southeast

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† 1 mbar = 100 Pa.

Asia the frequency of temperatures this low was only 10 %, and zero everywhere else. Then the area and frequency increased again through the autumn, to a maximum in January. Figure 2 illustrates some of Newell & Gould-Stewart's results, for January and March.

In returning to the discussion of the Walker circulation it is therefore tempting to consider the physical connection that might exist between the Pacific Ocean 'heat engine' and the dryness of the lower stratosphere. The basic circulation system is shown in figure 3*a* (taken from Julian & Chervin (1978)), which depicts a schematic cross section across the equatorial Pacific with warm waters in the western ocean. The rising branch of the Walker circulation is particularly vigorous, partly because of the direct heating by the ocean but also because of the latent heat of evaporation due to the large amount of moisture picked up by the surface easterly part of the circulation. This powerful ascending motion leads to extreme cooling at tropopause levels, presumably once the air has been dried by precipitation and cloud formation during the ascent. Again, satellite cloud photographs quoted by Bjerknes (1969) seem to confirm this process.

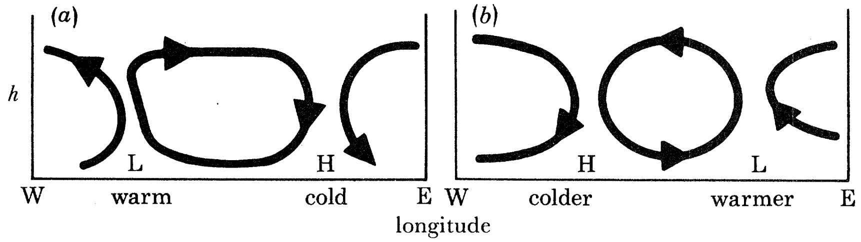

FIGURE 3. Schematic cross section, looking north, of the equatorial Pacific. Main features of atmospheric circulation are shown by arrows. (*a*) 'Normal' Walker circulation; (*b*) disturbed circulation during the 'El Niño' event.

Thus the suggestion of a 'tele-connection' between the Pacific and the stratosphere relies on the following series of qualitatively understood steps (a more quantitative assessment remains to be carried out):

(i) warm W Pacific, cold E Pacific, along the Equator;

(ii) direct Walker circulation (tropical easterlies at surface);

(iii) strong ascending branch in W Pacific (direct heating and moisture leading to wet adiabatic ascent);

(iv) very low tropopause temperatures;

(v) control of humidity of stratosphere by 'freeze-drying'.

If this conjecture is true, there are two very interesting corollaries: first, this region must be the entrance for most stratospheric air, because dryness seems to be a universal feature of the stratosphere, once well clear of local tropopause effects (Harries 1976); and second, we have seen a marked annual cycle in the 100 mbar tropopause temperatures as reported by Newell & Gould-Stewart, and it is of interest to further consider what connection this might have with the annual variability in stratospheric humidity observed in northern mid-latitudes by Mastenbrook (1980), Harries (1973) and others.

Before we leave this subject, it is interesting to consider the 'El Niño'. This is an oceanographic event that affects fishing off the western coast of South America, about which much has been written (for instance by Julian & Chervin (1978), Volkov (1981) and Weare (1982)). During El Niño the eastern tropical Pacific becomes much warmer than usual, and this disrupts fish feeding cycles. The phenomenon is associated with a number of other processes, but it is difficult to unravel which are precursors to others because of the obvious feedback nature of atmosphere–ocean interactions. However, El Niño is clearly of some potential relevance to the mechanism proposed above, and so we shall consider it briefly here.

The phenomenon (Weare 1982) is associated with a warming (*ca.* 3 K) in the eastern Pacific and a slight cooling (*ca.* 0.5 K) in the west. The surface easterlies reverse (see figure 3*b*), the 'head' of water that had been built up by the previous prevailing easterlies is released, and an equatorially trapped wave propagates eastwards across the equatorial ocean, with some reflexions and poleward propagation occurring as this wave intersects with the South American continent. It is believed that these events trigger the Southern Oscillation. The main question in the present discussion is, if course, the potential effect of the complex of phenomena known as El Niño on the stratospheric water vapour cycle, since the Walker circulation injection process described above is disturbed.

(*b*) *Cloud–climate feedback*

Schneider (1972) suggested the use of a parameter, δ, which would be a measure of the sensitivity of the net radiation balance of the Earth's climate to changes in the fraction of cloud cover, A_c.

$$\delta = \partial R_{\text{net}}/\partial A_c, \tag{1}$$

where

$$R_{\text{net}} = Q_0(1-\alpha_s)(1-A_c)+Q_0(1-\alpha_c)A_c-F. \tag{2}$$

In (2), Q_0 is solar flux, α_s is surface albedo, α_c is cloud albedo, and F is outgoing thermal flux. Combining (1) and (2) leads to

$$\delta = -Q_0(\alpha_c-\alpha_s)-\partial F/\partial A_c. \tag{3}$$

From a consideration of (1) and (2) we can see that if $\delta < 0$ the cloud albedo effect dominates, and if $\delta > 0$ the cloud greenhouse effect dominates.

We should also note that the outgoing flux, F, is a very strong function of, among other things, the s.s.t. Also, the cloud parameters A_c, α_c and T_c (cloud-top temperature) are important.

Theoretical estimates of δ (Hartmann & Short 1980) range from -35 to -100 W m^{-2}. When we remember that typical net fluxes of heat absorbed by the oceans are of the order of 50 W m^{-2}, we can see that the theory is not in a position to establish a satisfactory understanding of the significance of cloud–climate feedback, and that an accurate empirical determination based on direct measurements is very important indeed. To obtain useful accuracy G. Molnar (personal communication 1981) has shown that errors in measurements of s.s.t. and other parameters need to be reduced to the following levels:

$$\left.\begin{aligned}\Delta T_{\text{s.s.t.}} &\approx 0.2\ \text{K};\\ \Delta T_c &\approx 0.2\ \text{K};\\ \Delta A_c &\approx 0.03.\end{aligned}\right\} \tag{4}$$

Such measurement accuracies are very demanding indeed: however, the importance of accurate s.s.t., and other, data in achieving an understanding of this fascinating problem is clear.

4. RECENT SATELLITE MEASUREMENTS OF S.S.T.

Satellite measurements of s.s.t. are, of course, already available. For example, N.O.A.A. normally issues data derived from the Advanced Very-High-Resolution Radiometer (AVHRR) instrument on the Tiros/NOAA polar orbiting satellites (although this service has recently been interrupted in the zone 10°–40° N, by the effects of aerosols from the El Chichon volcanic eruption earlier in 1982). Also, the Jet Propulsion Laboratory (J.P.L.) has published a global map of s.s.t. for January 1979, based on data from the High-Resolution Infrared Sounder (HIRS/2) and Microwave Sounding Unit (MSU) instruments. However, the accuracies of such data do not yet meet the requirements laid out in § 2 above. In this section we consider current status in both infrared and microwave remote sensing of s.s.t.

(*a*) *Infrared results from the Advanced Very-High Resolution Radiometer Mk* 2

At the R.A.L., workers have been comparing s.s.t. data from the AVHRR/2 instrument on the NOAA 7 satellite with in-situ s.s.t. data provided by a number of collaborating institutions (see appendix 1): detailed results may be found in Saunders *et al.* (1983), but a brief summary will be given here.

The s.s.t. (T_s) is a complicated nonlinear function of the measured radiances; however, it is usually sufficient to use a linear approximation of the form

$$\text{(day)}\ T_s = C_0(\alpha)+C_1(\alpha)\,T_{11}+C_2(\alpha)\,T_{12}, \tag{5}$$

$$\text{(night)}\ T_s = C_0'(\alpha)+C_1'(\alpha)\,T_{11}+C_2'(\alpha)\,T_{11}+C_3'(\alpha)\,T_{3.7}, \tag{6}$$

where T_s is surface temperature, α is airmass and T_{11}, T_{12} and $T_{3.7}$ are apparent temperature measured in the 11, 12 and 3.7 μm channels. It is sometimes necessary, e.g. in the tropics, to introduce higher-order terms.

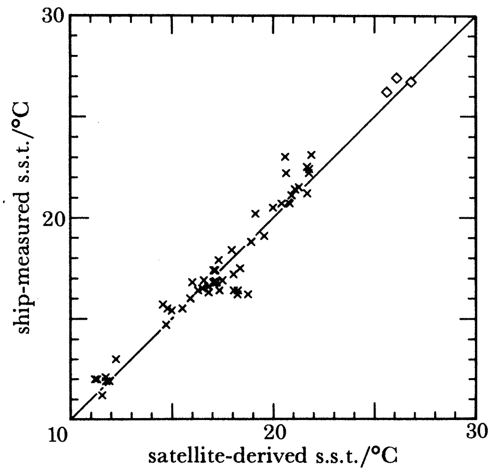

FIGURE 4. S.s.t. measurements from the NOAA 7 AVHRR/2 instrument, compared with ship and buoy data. Latitude range is 5° S to 65° N, and number of cases is 53. Standard deviation of the difference between AVHRR and ship is ± 0.88 K, with no significant systematic difference. ×, North Atlantic points; ◇, tropical points. (After Saunders *et al.* (1983).)

The coefficients C_n, C_n' have not been determined from empirical models of atmospheric transmission as has been the normal practice by previous workers, but have been derived directly from spectroscopic parameters. In this analysis the effects of clouds in the field of view have been eliminated by using a statistical histogram technique described by Harris *et al.* (1981). The comparisons with surface data have been made in the region 37° to 65° N, and some additional data in tropical regions.

The results obtained for a sample of 53 cases, between approx. 10 and 27 °C, are

$$\Delta T_{\text{r.m.s.}} = \pm 0.88\ \text{K}$$

and

$$\Delta T_{\text{systematic}} = -0.09\ \text{K}.$$

The results are shown in figure 4.

The fact that there is no large systematic bias in these results suggests that the modelling procedures used are basically correct. The r.m.s. scatter in the results requires further investigation, as the sampling techniques used for the ground observations obviously contribute to this figure.

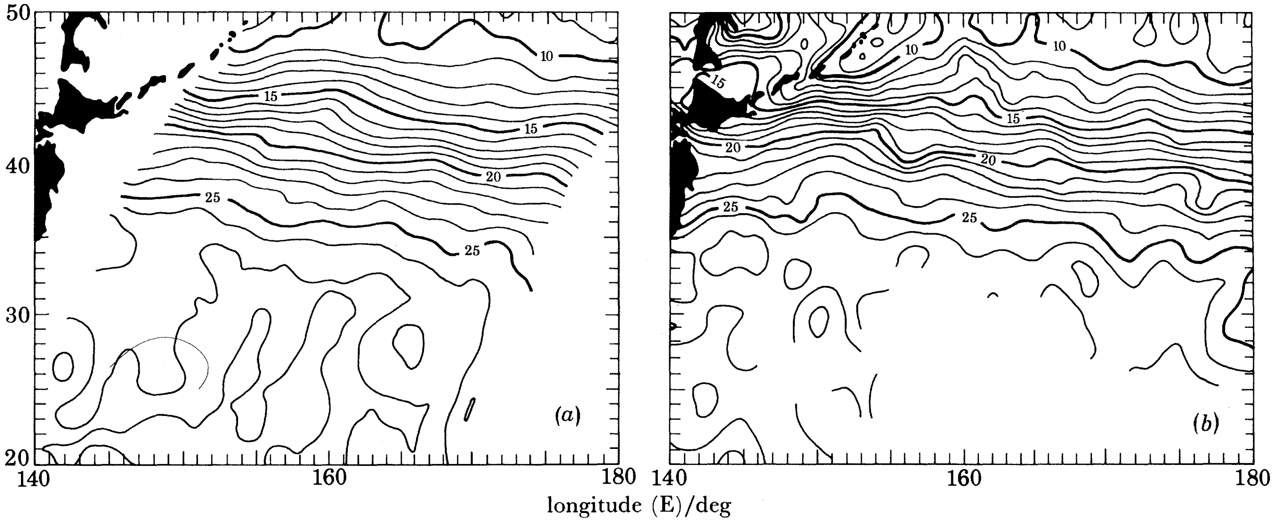

FIGURE 5. S.s.t. mapped data for period 7 July to 6 August 1978, for the northwestern Pacific area: (*a*) from the Seasat SMMR instrument, and (*b*) from ship data. Contours are in degrees Celsius. (From Bernstein (1982).)

(*b*) *Microwave* SMMR *results*

The Scanning Multichannel Microwave Radiometer (SMMR) was a passive radiometer instrument carried on both Seasat and Nimbus 7. Bernstein (1982) has reported a study of s.s.t. based on the Seasat data. Figure 5 shows a comparison of s.s.t. maps generated (*a*) from SMMR and (*b*) from ship data for the northwestern Pacific region, showing the generally good correlation between the two maps. The r.m.s. difference between these mapped data is ± 0.75 K, with a bias, or systematic error, of + 0.22 K (SMMR warmer). These data apply to the period 7 July to 6 August 1978, and several thousand individual measurements are included in both cases. The structure of the detail in the two results is somewhat different, however, with the

TABLE 2. NUMBERS OF DATA POINTS (N) AND THEIR STANDARD DEVIATIONS (σ) ABOUT THE MAPPED SURFACES OF FIGURE 5

	SMMR		ship	
dates	N	σ/K	N	σ/K
7–18 July 1978	1732	1.96	3573	2.39
19–27 July 1978	1032	1.05	2034	1.72
28 July to 6 Aug. 1978	1105	0.97	916	1.55
overall, 7 July to 6 Aug. 1978	3869	1.51	6523	2.10

Seasat data rather more featureless than the ship data. A more quantitative assessment has also been attempted by Bernstein (1982) and is reproduced in table 2.

The reason suggested by Bernstein for the rather greater error in the 7–18 July period (table 1) is due to the fact that more measurements close to land occurred, which were contaminated by the rather intense sidelobes of the microwave device's field of view. Overall the ship data show more scatter, which is perhaps not surprising because many different ships contributed to the average. The final feature to note from table 2 is that the standard deviation of the individual data from the SMMR, about the smoothed mapped data from the SMMR (see figure 5*a*), is ± 1.51 K, although substantial empirical corrections to the measured radiances based on post-launch validation experiments have been used.

(*c*) *Summary*

Table 3 summarizes these two cases. Since previous analyses by other workers have shown similar results (see, for example, McClain 1981), we may take these new results as fair indications of current status.

TABLE 3. SUMMARY OF S.S.T. MEASUREMENTS

parameter	infrared (Saunders *et al.* 1983)	microwave (Bernstein 1982)
$\Delta T_{\mathrm{r.m.s.}}/\mathrm{K}$	± 0.88	± 1.51 (± 0.75 mapped)
$\Delta T_{\mathrm{systematic}}/\mathrm{K}$	− 0.09 (AVHRR/2 colder)	+ 0.22 (SMMR warmer)
$\Delta x/\mathrm{km}$	50 × 50 (1 × 1 pixel)	150 × 150
N	53	3869
range of $T/°\mathrm{C}$	10–27	10–29

It should be added that microwave techniques have considerable potential owing to their capacity for penetrating clouds. However, the emission processes are more complex than in the infrared (depending critically upon sea-state for example) and much development is required in this area.

5. THE ALONG-TRACK SCANNING RADIOMETER

So far in this paper we have discussed some of the many exciting scientific questions in climate research that require accurate measurements of s.s.t. for their solution. Also, we have shown by the brief review in the previous section that present capabilities of measurement are not yet good enough to provide the accuracy of better than 0.5 K required to resolve many of these questions. In an attempt to improve this situation, a new instrument, the Along-Track Scanning Radiometer (ATSR), is being developed in the U.K. for flight on the first European Space Agency remote sensing satellite, ERS-1, in 1987.

The ATSR will for the first time enable us to view in quick succession the same patch of ocean surface at two different angles through the atmosphere with one instrument. This allows us to eliminate the variable part of the signal in the two measurements, to leave the constant term, which is of course the radiance corresponding to the s.s.t. In this way we avoid the need to rely entirely on multispectral corrections for the atmosphere, which is the technique adopted in present-day infrared sounders. This is particularly important in conditions of high atmospheric correction (e.g. in equatorial regions), and when layers of attenuating material that are optically 'grey' (i.e. spectrally featureless), such as thin cirrus, atmospheric aerosols and hazes, are in the field of view. (This would be of particular value when large amounts of volcanic aerosols are present.) The multispectral approach does, of course, have advantages, and because of this, ATSR will carry three co-registered channels at 3.9, 11 and 12 μm, each capable of two 'looks' at the same scene.

The instantaneous field of view is equivalent to a 1 km × 1 km pixel at the surface in the nadir direction, which is imaged onto the photoconductor detectors by an *f*/2.3 off-axis paraboloid mirror. The aperture is 10 cm, and the detectors are cooled to *ca.* 80 K by a closed-cycle Stirling refrigerator.

TABLE 4. PREDICTED ATSR PERFORMANCE (STANDARD DEVIATIONS IN KELVINS)

operational night and day mode (11 and 12 μm channels only)

radiometer bias	visibility	11 and 12 μm	11 μm	12 μm
none	clear	0.21	0.41	0.65
	mixed	0.36	0.51	0.78
1% change in emissivity of calibration black body between 11 and 12 μm	mixed	−2.2	0.7	—

clear-air night-only mode (3.7 μm channel available)

radiometer bias	visibility	3.7 μm	3.7 and 11 μm
none	clear	0.15	0.10
	mixed	1.8	0.75

The ATSR is being built by a consortium consisting of scientists from the Rutherford Appleton Laboratory, Mullard Space Science Laboratory of University College London, Oxford University, and the Meteorological Office. In addition, a small microwave radiometer is being added, to increase the accuracy of the atmospheric water vapour determination needed for the highest accuracy in s.s.t. measurements, by the French Centre de Recherches en Physique de l'Environment Terrestre et Planetaire. A number of other European laboratories are contributing to the ATSR programme in areas such as surface measurements and data investigations.

It is important to point out that the idea of using a two-look technique for measurements from space is not entirely novel. For example, Fleming (1980) discusses using a tomographic technique for increasing the vertical spatial resolution of atmospheric temperature soundings; Chedin *et al.* (1982) discuss the use of polar orbiter (Tiros) and geostationary satellite (Meteosat) data to determine s.s.t. to an accuracy of *ca.* 1 K; and Zandlo *et al.* (1982) report a similar study with the use of Tiros and GOES measurements.

The predicted performance of the ATSR has received considerable attention (Zavody 1981). Calculations have been carried out by using a sophisticated line-by-line computer model of the atmospheric spectrum, to simulate ATSR results. These calculations (see also Minnett *et al.* 1982) have considered a wide range of model atmospheres (polar to tropical), molecular absorption and re-emission, and aerosol scattering. A noise equivalent temperature of 0.5 K was assumed for the radiometer. A summary of the findings is given in table 4: the numbers quoted are standard deviations in kelvins, and the number of cases used (different atmospheres) was 59. The results demonstrate a number of points.

First, if the radiometer has zero bias (systematic error), standard deviations of ± 0.21 K in a clear atmosphere and ± 0.36 K in a mixed or partly cloudy (up to 90 % covered) scene are possible. If, however, a 1 % difference in emissivity of the calibration targets exists at 11 and 12 μm, table 4 shows that a multichannel approach leads to large errors (2.2 K) so that a conventional radiometer (e.g. AVHRR) would be useless, whereas once such an error is detected

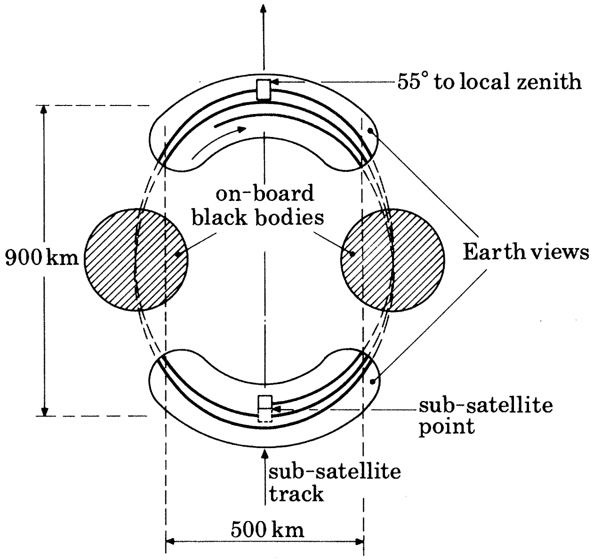

FIGURE 6. The field-of-view scan pattern for the ATSR. A conical scan directs the view in turn to the sub-satellite direction, calibration target 1, a forward direction (about 55° to local zenith) and calibration target 2.

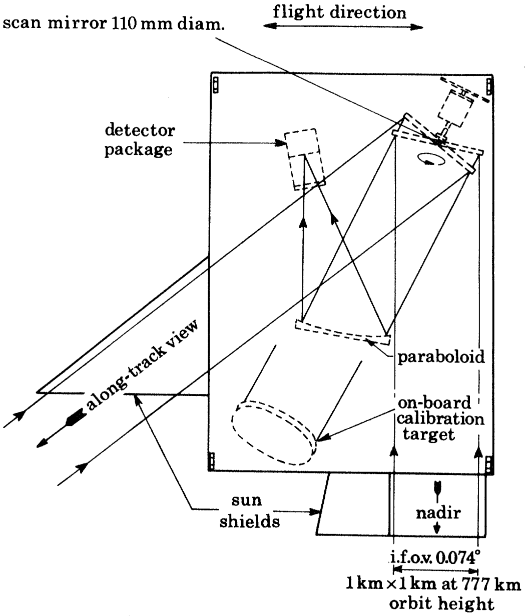

FIGURE 7. The internal optical scheme of the ATSR. Radiation is received by an asymmetrically mounted plane mirror, which performs a conical scan at *ca.* 6 Hz. An $f/2.3$ off-axis paraboloid collects radiation from the scanning mirror and directs it onto the cooled detector assembly. The positions of calibration targets and sunshields are indicated. I.f.o.v., instantaneous field of view.

(e.g. by ground truth comparisons) an ATSR type of device can constrain such errors to *ca.* ±0.7 K by use of only one channel and two looks. At night the absence of scattered solar radiation means that the 3.7 μm channel can be added, to yield clear-air s.s.t. measurement accuracies as low as ±0.10 K; however, as is shown by the mixed case, scattering by haze is dominant at these shorter wavelengths. Figure 6 illustrates the scan pattern of the ATSR, which illustrates how a conical scan pattern yields data at the sub-satellite point, at a forward angle of about 55°, and two calibration measurements in between. The scan pattern is synchronized with orbit height and velocity to ensure contiguity between scans. Figure 7 illustrates schematically the internal optical system. Scanning is carried out by an asymmetrically mounted rotating plane mirror. The accuracy and thermal stability of the black-body calibration targets is a crucial part of the ATSR design and is receiving particular attention at M.S.S.L. and the Meteorological Office. Finally, figure 8 shows an artist's cut-away view of the instrument. The curved nadir and forward apertures can be seen, as can the calibration targets. The Stirling-cycle coolers are a vital part of the design, though we shall not discuss them further here. The complete instrument measures 570 mm × 380 mm × 540 mm, weighs 45 kg and consumes a mean power of 50 W.

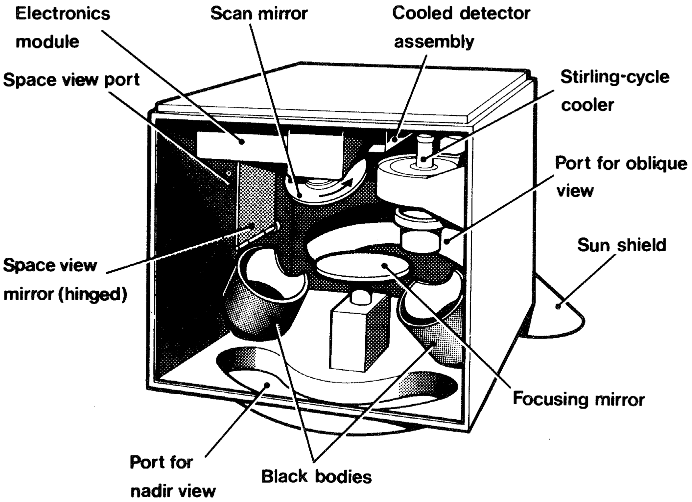

FIGURE 8. A schematic cut-away diagram of the ATSR. The curved apertures for the nadir and forward views are shown, as well as the scanning and the off-axis paraboloid mirrors. The layout of other units, such as the electronics, the calibration black bodies and the Stirling-cycle cooler are shown.

Much more detail than it is possible to give here is available from the ATSR project team at R.A.L. However, we should add that the ATSR experiment promises to provide measurements of s.s.t. and of cloud parameters (A_c, T_c) with absolute accuracies that perhaps for the first time will be consistent with the needs of climate researchers as quoted in § 2 of this paper. It is therefore a very exciting prospect, though somewhat daunting in view of the very high accuracies and levels of instrumental performance that are being sought.

6. CONCLUSION

Measurements of sea-surface temperature at high absolute accuracy are of great importance in climate research. Two examples of scientific problems requiring such data have been given in this paper, though a number of others could have been discussed. The first of these examples referred to the thermal driving of the tropical atmosphere by the Pacific Ocean, with possible implications for the humidity of the stratosphere: if the model proposed is verified, we might at last be approaching a satisfactory understanding of a long-standing problem, the water budget of the stratosphere. Our second example stressed the importance of accurate measurements of s.s.t. in empirically determining the magnitude (and sign) of cloud–radiation feedback processes.

These examples will, it is hoped, have served to stress the importance of accurate s.s.t. data. The remainder of the paper has considered the present and future status of global measurements of s.s.t. from satellites. In this context a number of further points need to be made. First, it is clear that while present instruments perform well, improvement of the order of threefold or fivefold in absolute accuracy are still required. Secondly, the problems in climate research for which we require measurements of s.s.t. need such data on a truly global basis, without gaps, and without problems of temporal or spatial aliasing: present satellite systems do not provide this comprehensive coverage. Thirdly, we must recognize that no one technique has all the answers, and without doubt we shall require – for s.s.t. measurements and probably all others too – a mix of techniques. Particularly, for s.s.t. measurements, scientists should strive to achieve a combination of improved infrared and microwave measuring systems in spacecraft. Finally, as an extension of the last point, we should not forget that surface measurements will always be an important component of any global measurement system, whether for calibration or to study detailed processes inaccessible to satellite remote-sensing systems: the accuracy and reliability of the surface measurements, too, require improvement, because these are often the standards against which we compare our more global data sets.

We gratefully acknowledge the valuable contributions and helpful discussions provided by a number of colleagues in a number of the areas discussed in this paper. In particular, mention should be made of E. J. Williamson, C. G. Rapley, I. Barton and G. Molnar.

Appendix 1. Collaborating groups supplying ship s.s.t. data

Nederlands Centrum voor Oceanografische Gegevens at K.N.M.I., de Bilt, the Netherlands; *Tydeman Cumulus* and *Noord Hinder*
Marine Information and Advisory Service, at I.O.S., Wormley, U.K.; *Discovery*
R. D. Pingree, Marine Biological Association, Plymouth, U.K.; *Frederick Russell*
J. Meincke, University of Kiel, F.R.G.; *Meteor*
U. Herrmannsen, University of Kiel, F.R.G.; *Poseidon*
H. M. van Aken, University of Utrecht, the Netherlands; *Tyro*

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Discussion

P. Wadhams (*Scott Polar Research Institute, University of Cambridge, U.K.*). The ATSR discussed by Dr Harries will have a footprint of 1 km² on the ocean surface. When an instrument of this kind passes over sea ice – as it will during the high polar orbit of ERS-1 – it sees a composite surface temperature. A polar icefield is composed mainly (95 % or more) of thick sea ice with a surface temperature close to that of the air, which may be –30 °C in winter. A small percentage of the surface, however, consists of open or recently refrozen leads with a surface temperature of –1.8 °C or somewhat less. The massive contrast between these two types of surface temperature allows the composite temperature sensed by the instrument to be a measure of the fraction of the icefield occupied by leads.

J. E. Harries. This is certainly true, though the interpretation of structure within the footprint, or instantaneous field of view, of a remote sensor has to be carried out with great care, taking into account such aspects as the field of view response function and the modulation transfer function of the optical and electronic system: for instance, the response to this structure will depend on its apparent frequency, measured at the instrument output.

P. K. Taylor (*Institute of Oceanographic Sciences, Wormley, U.K.*). The ATSR views a given area of ocean through two different atmospheric columns. Is it necessary to assume that each column has similar atmospheric structure and is cloud-free, and to what extent does the oblique viewing angle restrict the ability to detect sea-surface temperature in regions containing clouds?

J. E. Harries. It is necessary to assume that each column has similar atmospheric structure, although on the scales involved atmospheric inhomogeneities are likely to be quite small and their effects on the signals received at the satellite have been shown, in simulations, to be small. Concerning clouds, it is necessary only that the cloud cover within a 50 km × 50 km array of pixels is less than about 90 %; in such cases statistical methods can be used to derive clear-column surface temperature.

The obliqueness of the viewing angle does, for example, change the shadowing or masking effects of clouds, though geometrical corrections can, of course, be made. The most severe problem in this case arises with multiple-layer clouds. While our simulations so far indicate that these problems will not undermine the achievable accuracies with ATSR, they (the problems) are nevertheless important enough to warrant further study.

J. T. Houghton, F.R.S. (*Rutherford Appleton Laboratory, U.K.*). I should like to point out a potentially very important application of the accurate measurement of sea-surface temperature. The questions are often asked: How can climate change be measured? Are measurements available to show how climate changed over the last 100 years and can we observe changes in the future? Regarding temperature change, our current assessments are based on measurements at a few sites where careful records have been kept over a long period. Such sites are limited to a few countries at mid-latitudes in the Northern Hemisphere and therefore represent a very inadequate sample so far as the whole globe is concerned. Consistent measurements of the temperature of the sea surface from satellites would overcome the sampling problem very well and would be very suitable for looking at climatic trends provided that they could be made with sufficient accuracy. An accuracy of say better than 0.2 K would be required. The ATSR, if carefully built and calibrated, should approach this sort of accuracy.