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Part 1 - *In situ* sensors

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Weather

September 2002 Vol. 57 No. 9 pp. ii & 315-320

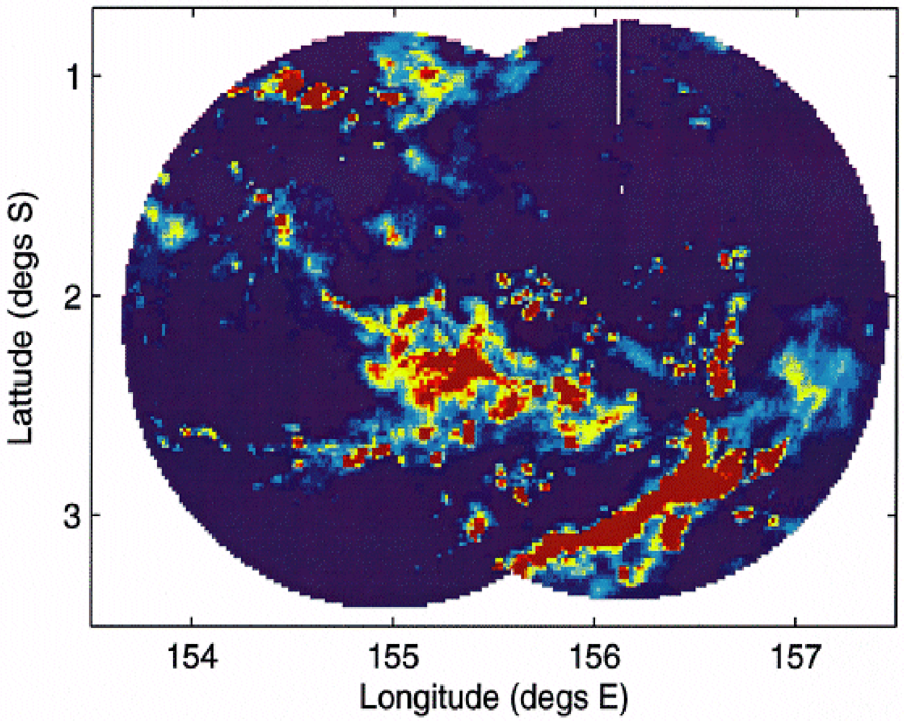

Fig. 2 Example of ship-borne radar data from the Tropical Ocean Global Atmosphere Combined Ocean Atmosphere Response Experiment. There were two ships, with each radar covering a disc of radius 120 km. The heavier rain rates are in red. (See article on p.315.)

Nacreous cloud

CT © Mike Cinderey

Nacreous cloud south-south-west of Easton, Middlesbrough, 1515 GMT on 16 February 1996

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Printed by PAGE BROS, NORWICH for the Publishers, the
ROYAL METEOROLOGICAL SOCIETY, 104 Oxford Road, Reading, Berks, RG1 7LL

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Measuring rainfall at sea: Part 1 – *In situ* sensors

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Rainfall is an important climatic variable. Extremes in rainfall accumulations over land – either floods or droughts – have major societal implications and are obvious. At sea, the effects on human activity are less evident, apart from the inconvenience to deck passengers on cruise liners! However, improved knowledge of the rainfall associated with weather systems approaching the UK from the Atlantic would be beneficial to weather forecasting, especially if assimilated into atmospheric models. There is an additional, more subtle, effect involving the ocean itself. At sea, the balance between precipitation and evaporation provides a critical feedback in climate change. The present ocean circulation involves both surface and deep currents (see Fig. 1), with the passage of water from the former to the latter occurring in the Labrador and Greenland Seas where intense cooling by the winds makes the surface waters dense enough to sink to the ocean bottom – a process known as 'deep convection'. However, where precipitation exceeds evaporation the surface waters become fresher, and thus less dense, making them less susceptible to deep convection.

Long-term changes in the freshwater balance (evaporation minus precipitation and ice melt) can thus potentially change the location and extent of such deep mixing, and ultimately disturb the 'conveyor belt' illustrated in Fig. 1. Some modelling studies suggest that a change in the freshwater flux could trigger 'abrupt climate change', leading to a marked reduction in UK temperatures over a decade, as the country loses the benefit of weather systems heated by their passage over warm Atlantic waters (Ellett 1993).

However, before we panic about long-term changes in rainfall and impending climatic catastrophe, we need to know how much rain falls at sea, and what is the natural variability on seasonal and interannual time-scales. This is not so simple a measurement task as it is on land, where there exist a large number of raingauges, and the whole of the British Isles and neighbouring waters are covered by a rainfall radar network. In this article we look at the various *in situ* technologies for recording rain rates at sea; a succeeding article will cover techniques using satellite data.

Ship-borne observations

Clearly, it would be a great waste of resources to deploy ships solely to give point observations of rainfall; however, much has been achieved simply by using the 'present weather' reports returned by various ships at the synoptic hours. Such observations are subjective, and do not correspond directly to actual rain rates. However, Tucker (1961) did develop a realistic-looking climatology of the North Atlantic through ascribing specific rain rate values to the various classes of 'present weather' reported by the ten weather ships stationed there during the late 1950s. Petty (1995) extended the climatology by using the reports from voluntary observing ships on a global basis. The accuracy of individual rain observations is probably no better than a factor of two and, whilst those regions along the principal shipping lanes are fairly well sampled, there are large expanses of the ocean for which no observations are reported for months at a time.

For many meteorological parameters, datasets can be extended greatly by the instrumentation of voluntary observing ships. Although this has been done for rain, the individual measurements have large biases that vary from ship to ship and direction of travel relative to the wind. This is because the ship's superstructure

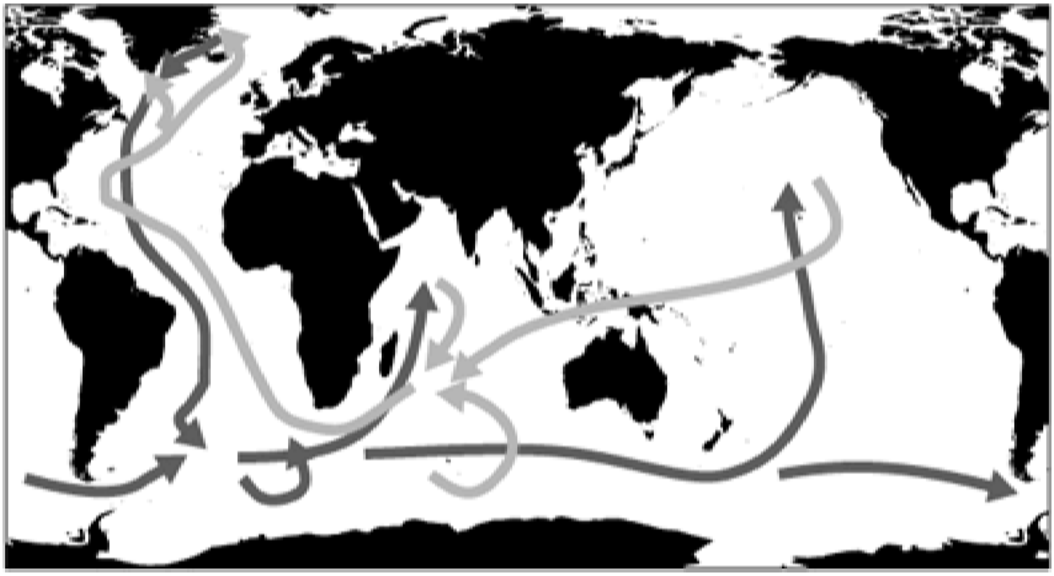

Fig. 1 Thermohaline 'conveyor belt' (after Broecker 1991, modified D. Webb, personal communication). Surface currents are marked in light grey, with sinking of surface waters occurring in the Labrador and Greenland Seas, followed by the deep circulation indicated by the dark arrows, with a gradual rise to the surface around Antarctica and throughout the Indian and Pacific Oceans.

greatly affects the local airflow, leading to a change in the wind speed of ±30% and, more importantly, preventing many of the smaller raindrops from entering any collection flask.

Rather than contend with using small collecting vessels and attempting to correct for the distortion of the airflow, we may use the ship as a platform for a meteorological radar station. This can allow frequent measurements and areal coverage rather than providing solely point measurements. Such systems were deployed in intensive field campaigns such as the GARP Atlantic Tropical Experiment and the Tropical Ocean Global Atmosphere Combined Ocean Atmosphere Response Experiment (TOGA COARE) (see Fig. 2, inside front cover). As this requires dedicated research ships, these instruments are available only for local experiments or validation of satellite algorithms.

Of course, all large vessels already have radar systems on them for navigation purposes. Recently, Lebedev and Tomczak (1999) looked at the possibility of calibrating them to yield rainfall rates. One of the problems is that ship radars may be susceptible to instrument drift. This is true even for land-based systems, which have to be regularly recalibrated with respect to raingauges. Even assuming that calibration of the ship radars is perfect, there are still large errors in the retrieval of rain rate. This is because the rain rate and radar reflectivity (the parameter measured) are related to the drop size distribution (DSD) through different expressions (Spilhaus 1948). Thus whilst, in general, heavier rain rates have a greater reflectivity, a few large drops at the beginning of a downpour may have the same reflectivity as a large number of small drops near the end of a storm, but the latter will have a much greater rain rate. For instance, in TOGA COARE the rain rate inferred assuming the system to be convective was only half that calculated if the system was deemed to be stratiform. Doviak (1983) details some of the other errors in using a single reflectivity measure to infer rain rate, and discusses the options of using dual-frequency or dual-polarisation systems.

There is a final factor that affects the representativeness of all rain estimates from ships, and that is the 'fair weather bias', *i.e.* the tendency of ships' captains to select the quickest or most expeditious route, avoiding most predicted storms. This bias is a key motivator for the use of buoy-mounted systems, where a carefully planned network of observation sites can be established.

Buoy-mounted sensors

The potential advantages of developing buoy-mounted systems are that they will sample all conditions in their region evenly, that they do not affect the rain's descent through distortion of the airflow, and that they should be relatively cheap to maintain in the large areas of ocean poorly sampled by ship traffic. Of course, it is important that the sensor package has a low power requirement and is robust enough to withstand the rigours of long-term deployment at sea, given the scarcity of shipping for deployment and maintenance. Here we examine a number of candidate technologies.

Many land-based stations use tipping-bucket gauges for recording rainfall. These are of little use in a rough marine environment, where the rocking of the instrument will give false readings of rain; however, new technologies are emerging that could prove to do a better job in a wide variety of conditions.

The first of these is an adaptation of the simpler technology of the collection flask (see Fig. 3(a)). This instrument records rain accumulation rather than rain rate, but the latter can be found by differencing the time record. The height of the water column is determined through changes in the capacitance across an insulator, with the device being set to empty automatically whenever it fills up. Such instruments have been successfully deployed for a year at a time on the TOGA–TAO (Tropical Atmosphere Ocean) moorings in the equatorial Pacific (Nystuen and McPhaden 2001); there the main problem was modern-day pirates stealing the equipment from the buoys!

An alternative application of recording electrical capacitance is the inclined capacitance plate, which has interwoven electrical contacts (Fig. 3(b)) and is used to provide instantaneous rainfall rates. Raindrops on the plate affect the capacitance between the two terminals; gravity and/or a heating circuit remove the drops from the plate. The problems are that the plate needs to be directed into the wind, and that sea spray can lead to a coating of salt on the surface. In our trial with a rudimentary system, we found it unreliable in the high humidity conditions found at sea.

Another approach is to use a pressure-sensitive diaphragm to record the momentum of each impacting raindrop. The earliest designs used a flat horizontal membrane (*e.g.* Joss and Waldvogel 1967); more recently, investigators have proposed using a microphone with a spherical surface (Förster 1994) that can thus detect raindrops equally well from all directions (Fig. 3(c)). The terminal velocity of raindrops increases with size and wind speed; thus some calibration is required to infer mass of drop from the impulse it generates. A typical size for such a sensor is ~5 cm across, which gives a reasonable sensitivity in light to heavy rain. Because of the small surface area it is not reliable at very low rain rates, and there are significant errors in very heavy rains where the sensor cannot distinguish the impacts of individual drops.

A different idea is to count the raindrops through their effect on a light beam (Wang *et al.* 1978). Raindrops falling between the light source and the receiver will diminish the signal for a tiny fraction of a second (Fig. 3(d)). Larger drops will have a greater effect, and thus there is scope to both count and size the drops. In practice, a filter is designed to pick out the variability on a certain time-scale, corresponding to the flight time of a raindrop in the beam. Typically, there is some electrical noise in the source and receiver circuits, giving a little variability in perfectly dry conditions. To make a clearly detectable change Nystuen *et al.* (1996) found the rain rate had to exceed $0.4\,\mathrm{mm\,h^{-1}}$ (a light drizzle). The lenses have to be heated or else condensation on them can lead to spurious detections of rain. Although the sensor must be mounted well above the surface of the sea, occasional spray will lead to the deposition of salt crystals on the lenses thus affecting performance.

A very different approach is to use a hydrophone (an underwater microphone) to detect the sound generated by rain. This is not placed near to the surface to detect individual raindrops, but 10 m or more down, so that it is responding to the average rainfall over a large catchment area (Fig. 3(e)). This large area being monitored gives the system a good sensitivity to light rain; the problems are in distinguishing the sound of rain from other sources, and in yielding quantitative estimates of the

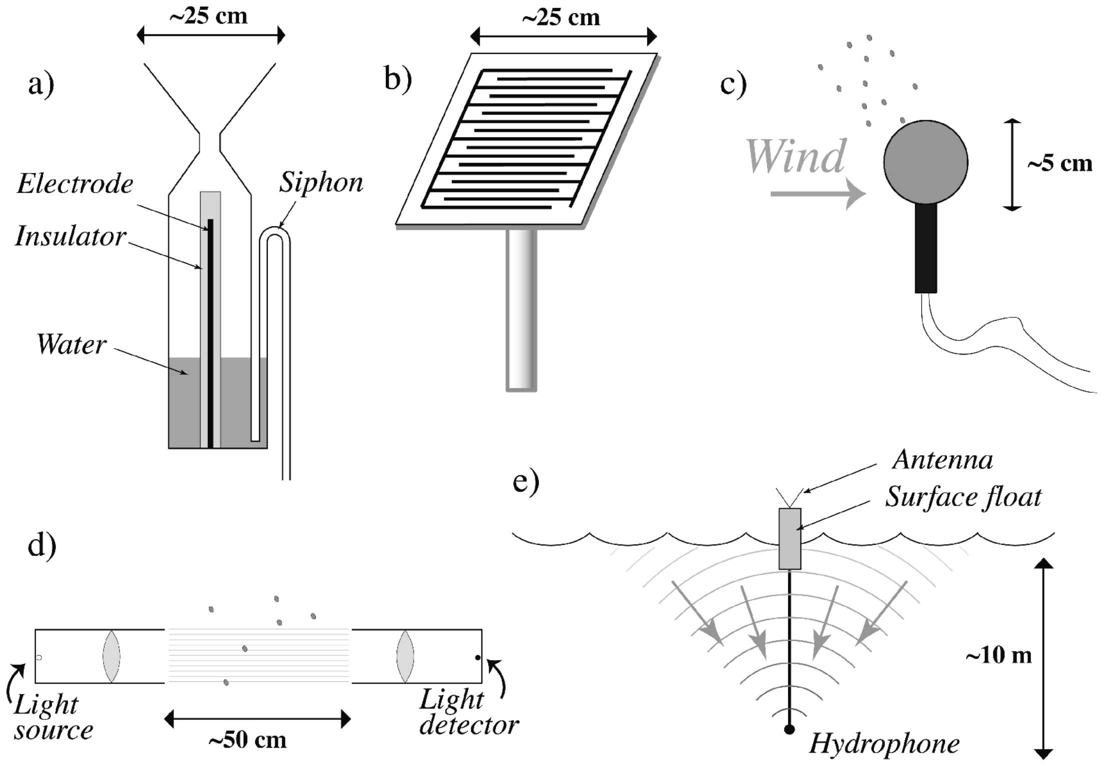

Fig. 3 Schematic of various technologies suitable for deployments on buoys: (a) collection flask recording capacitance across insulator between the electrode and the water column; the siphon empties the flask once it has filled; (b) inclined plate, such that trickling rain reduces the capacitance between the two terminals; (c) spherical pressure sensor, provides an omni-directional response; (d) light transmissometer, detecting fluctuations in light intensity due to intervening raindrops; and (e) acoustic raingauge, which senses rain over a large area of the water surface

rain rate. Rain generates sound through a variety of mechanisms – the initial drop impact, ringing of generated air bubbles, and (for the larger drops) through various splash products. It is usually possible to discern the distinctive spectra of rain in the presence of both wind and wave activity. Nystuen and Selsor (1997) have used such sensors on expendable drifters; if an underwater acoustic sensor is to be deployed on a moored buoy, the mooring line must not generate noise itself and must be arranged so that the hydrophone's umbilical cable does not get wrapped around it.

Various of these technologies have already progressed from testing in the controlled conditions of the laboratory to evaluation in the real world. The important differences are the effects of wind and waves. Above-surface systems need to be mounted high enough not to confuse spray from breaking waves with rainfall. This in turn requires large buoys, so as to provide stable platforms that will not rock in the slightest wind. All the buoy systems discussed have relatively low power requirements (to enable long deployments), and contain no moving parts (which could wear out through use, or be caused to seize up by encrusted salt grains).

In a monitoring exercise near Miami, where the average duration of rain from a passing storm is ~26 minutes, Nystuen (1998) deduced that an adequate monthly climatology could be recorded by an instrument only operating for one minute in every ten, with a consequent saving in power consumption and data transmission. For weather-forecasting applications, better temporal sampling would be required of individual storms. At Southampton Oceanography Centre we have been evaluating the reliability and accuracy of the acoustic

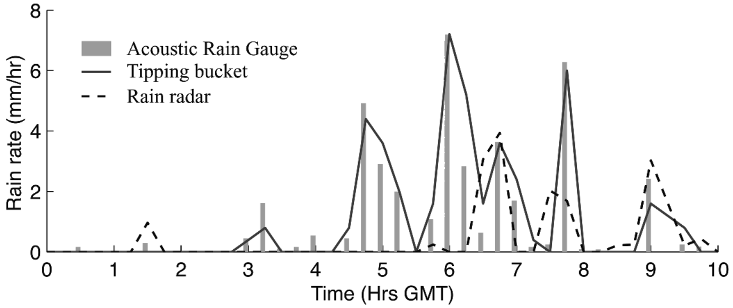

Fig. 4 Comparison of 15-minute average rain rates from acoustic system with conventional tipping-bucket gauge and meteorological radar. (Note the radar values are instantaneous observations every 15 minutes for a 5 km × 5 km cell.) Data are from Loch Etive (Argyllshire) on 24 May 2000.

system in collaboration with the Met Office. In tests in a sheltered loch (Quartly *et al.* 2001), the acoustic system gave closer agreement with a nearby tipping-bucket gauge than did the meteorological radar coverage (Fig. 4); we have yet to try it in more exposed conditions.

Summary

The task of providing reliable *in situ* measurements of rainfall is both important and challenging. Such a task is not readily done on ships, as they avoid the worst weather and the ship's superstructure affects local measurements. A number of *in situ* technologies have been described that are suitable for deployment on buoys, and which have low power requirements and no moving parts that could seize up. Of these, the systems using the capacitance flask, light beam and hydrophone appear the most promising.

Nystuen and McPhaden (2001) and Nystuen *et al* (1996) have tested all three in tropical locations. The optical system suffers from a drift in calibration, as the lenses become progressively caked with salt crystals. The collection flask does not provide instantaneous measurements such as peak rain rate, but rather an integral quantity – the total accumulation of rain. It is believed to be accurate, but suffers from a little data loss during the siphoning operation. The acoustic system provides an estimate over a much larger area than the others (see Fig. 3(e)), which is a bonus as a large areal average is preferable to a point measurement, both for satellite validation and local studies of freshwater input. However, at present, more work is required to minimise the effect of extraneous sounds (whether from the mooring line, distant shipping or marine life).

The development of systems to work in all waters is far from trivial. The higher-latitude oceans provide a rougher environment, possibly countenancing against those that involve above-surface instrumentation. Also, in the colder climes an increased proportion of the precipitation falls as hail or snow, which affects the performance of all three devices: the different particle size and velocity of snow will cause a marked change in the occultation time of the light beam; snow impacts on the water surface generate a very different acoustic spectrum to rain; and the collection flask will require a heater, so that the capacitance measured is of a *water* column and so that siphoning will operate. None of these technologies have yet been thoroughly tested in all climatic regimes.

In our next article we look at the various space-borne technologies. Although these give a better global coverage, *in situ* measurements will remain important both for validation and for providing frequent temporal sampling. The development of reliable low-cost systems will greatly aid in the understanding of rain systems originating over the Atlantic, thus contributing to our ability to predict rainfall.

Acknowledgements

We are grateful to Paul Kucera for provision of the TOGA COARE data, and to Jeff Nystuen and Peter Taylor for comments and advice.

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