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REMOTE SENSING OF SEA SURFACE SALINITY: A CASE STUDY IN THE BURDEKIN RIVER, NORTH-EASTERN AUSTRALIA

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ABSTRACT

The principles of remotely sensing sea surface salinity are briefly reviewed. The airborne instrument used for this study is a Scanning Low Frequency Microwave Radiometer (SLFMR). It has spatial resolution of typically 500m (depending on the altitude of the aircraft) and a salinity resolution of about 1 psu. This configuration is suitable for studying the dynamics of river plumes as they form on the continental shelf. The Burdekin River is one of Australia's major rivers with about 2.4% of the annual runoff from the continent. This river is in the dry tropics and has severe transient peaks which last for days to weeks during the summer monsoon season. The case study shows the river plume during growth and decay phases and is supported with *in situ* vertical profiles of water salinity and temperature. The river plume forms a classic low density layer at the surface, but its development and movement along the coast is a feature of the regional oceanography.

KEYWORDS: salinity; microwave radiometer; airborne; remote sensing; river plume; Burdekin River.

INTRODUCTION

The development of remote sensing of sea surface salinity is moving rapidly in the present decade. Problems of low signal-to-noise ratios have been overcome during recent years (Goodberlet et al., 1997). The family of instruments to which the SLFMR belongs originated with the multi-beam electronically scanned thinned array radiometer (ESTAR) developed in Massachusetts in the early 1990s (Le Vine et al., 1994), and used to map the Delaware coast using a NASA P-3 aircraft (Le Vine et al., 1998). ESTAR was developed primarily for soil moisture remote sensing and adapted for sea surface salinity. The SLFMR was optimised for sea surface salinity work and was flown on a DeHavilland Beaver aeroplane over some of the estuaries and coastal areas of the east coast of the US (Goodberlet et al., 1997). The SLFMR that we are using in Australia is similar to the original and also built by Quadrant Engineering (now ProSensing) in Massachusetts. The Australian SLFMR MkII has been evaluated and tested in the Herbert River estuary in North Queensland (Burrage et al., 2002; Burrage et al., 2003) to produce high quality maps of sea surface salinity in the river plume in the Great Barrier Reef waters.

The Great Barrier Reef World Heritage Area is one of the most pristine reef systems in the world, and there is a pressing need to understand the impacts of riverine runoff water. The catchments are generally of two types. The rivers in the wet tropics tend to be shorter and perennial with a modulation from summer to winter seasons. These rivers in the wet tropics are generally associated with rainforests in the upper catchment and sugar cane agriculture on the coastal plains. The rivers of the dry tropics are impulsive and transient, with high flood peaks following infrequent cyclonic events or periodic monsoon rain events lasting for several days. The rivers of the dry tropics generally have savannah grassland in the upper catchment with cattle and sheep grazing, and irrigated sugar cane farming in the river valleys interspersed with savannah grass and sparse eucalypt vegetation along the coast. Each of these river types has its characteristic runoff dynamics, and sediment and nutrient loads.

The Burdekin River is the biggest of the rivers which discharge into the Great Barrier Reef Lagoon. It is a river of the dry tropics with a large catchment in elevated grasslands, and a thriving irrigated sugar cane industry on the alluvial plains. The mean annual flow is $9.7 \times 10^9\ m^3$ (Wolanski, 1994) with discharge rates exceeding $10^4\ m^3s^{-1}$ for a flood peaks, (Wolanski and Van Senden, 1983).

Sediments from the Burdekin River provide significant input to the coastal zone, but are not observed to penetrate across the shelf to the sensitive main structure of coral reefs in the GBR. Belperio (1983) concluded that there is a prograding shoreline of about $2.5\ m\ yr^{-1}$ just north of the mouth of the Burdekin River, decreasing to $0.1\ m\ yr^{-1}$ in Halifax Bay, some 150 km to the north. Terrestrial sediments tend to be trapped into a coastal wedge, driven mainly by the prevailing southeasterly winds and the consequent northwards alongshore drift.

Terrestrial nutrients have the potential to be more significant to the well-being of the GBR because they are more mobile. We use salinity as a surrogate indicator for nutrients dissolved in the river runoff water. This does not address the deposition of nutrients into the sediment wedge, and possible re-entry into the water as the sediments are re-worked by wave-current processes on a seasonal time-scale. Wolanski and Van Senden carried out ship-borne observations of salinity along a series of zig-zag transects during flood periods in the wet season of January-February 1981. These were taken at weekly intervals following flood peaks and covered a large area extending about 300 km north from the river mouth. The present observations are on finer scales of time and space, and focus on the processes in the river plume at its source. A site map for the study area is shown in Fig. 1.

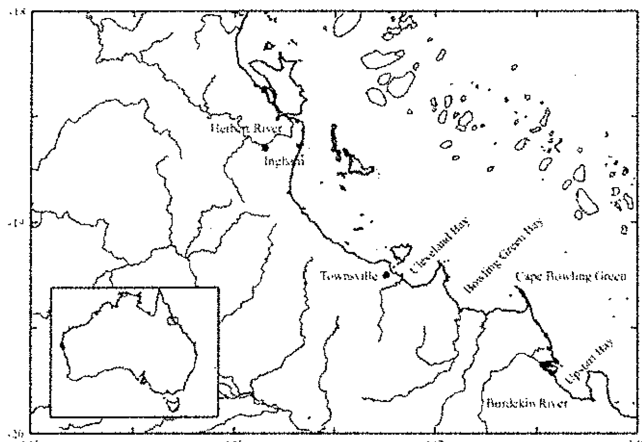

FIGURE 1: Site map for the study at the mouth of the Burdekin River in north-east Australia.

REMOTE SENSING OF SEA SURFACE SALINITY

The SLFMR is a passive microwave radiometer which measures the brightness temperature of the sea surface in a relatively narrow frequency band of 24 MHz at 1.413 GHz. The power in the frequency band B, emitted from a surface with emissivity e and temperature T K is

$$p = ekTB \tag{1}$$

(Klein and Swift, 1977) where k is Boltzmann's constant. The conventional Brightness Temperature (T_B) used in remote sensing is

$$T_B = eT. \tag{2}$$

The emissivity can be written in terms of reflectance, R, as

$$e = 1 - R \tag{3}$$

where the reflectance for a narrow band of frequencies can be written as

$$R = \left\{ \frac{|n-1|}{|n+1|} \right\}^2 \tag{4}$$

in terms of the refractive index, n. The physical basis of sea surface salinity observation by remote sensing lies with the fact that the refractive index, at microwave frequencies, is complex and depends on density as well as conductivity (and hence salinity). This is in contrast with the familiar technique of infrared remote sensing for sea surface temperature where the refractive index is independent of the conductivity of the water.

Klein and Swift, (1977) calculated the relationships between temperature, salinity and the measurable brightness temperature for passive radiation, and this is shown in Fig. 2. In tropical waters the algorithm for extracting sea surface salinity is well-conditioned because in the range 25-30° the brightness temperature is insensitive to the water temperature. The SLFMR receiver uses a null-feedback Dicke-switch technique described by Ulaby et al., (1981) and Skou, (1989). The receiver antenna consists of an 8 x 8 array of horizontal dipoles which are hard-wired to form a narrow beam in the along-track dimension, and by feeding through a Butler matrix (Skolnik, 1980) to form a set of six selectable narrow beams in the cross-track dimension.

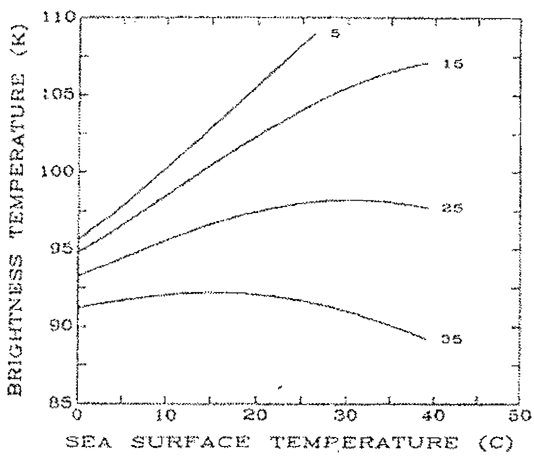

FIGURE 2: Theoretical brightness temperature for the 1.413 GHz miocrowave band as a function of sea surface temperature and sea surface salinity. (After Klein and Swift, 1977).

As the aeroplane flies along, the beam is switched to successive positions across the track, nominally at nadir angles ±8°, ±22° and ±37°. The dwell time on each beam position is typically 0.5 s and, with some time for computer house-keeping, the sweep across the swath is repeated about every 4 s. Each beam has an angular dimension of about 15° which corresponds to a pixel size of about 1 km on the sea surface when the aeroplane is flying at 3000 m altitude. The flight path is prepared before the flight and in Figure 3 we show the plan for the first flight on 18 February 2002. The flight crew consist of the pilot and co-pilot/navigator and the flight scientist. Operational rules are that the scientist can change the flight plan *en route*, with the pilot having ultimate discretion on the flight.

Probably the most important specification for the radiometer is the Noise Equivalent Delta Temperature (NEDT), because this determines the sensitivity of the instrument. The NEDT depends on the bandwidth, dwell time, the receiver noise temperature, and antenna losses, For our SLFMR the NEDT is estimated to be 0.5 K, and using Fig.2 we can convert this to about 1 psu for the resolution of sea surface salinity.

RESULTS

1. River Flow

The river flow data for February 2002 is shown in Fig. 4. This is a typical minor flood event for a transient river in the dry tropics. The onset is rapid, following a localised rain event in one arm of the catchment. The decay is the typical hydrological logarithmic shape, returning to the base flow after only a few days

We were already in the field in the Herbert River area some 200km to the north with the airborne SLFMR and CTD and nutrient sampling equipment when the rain event occurred. We diverted our resources to observe the growth and decay of the minor flood

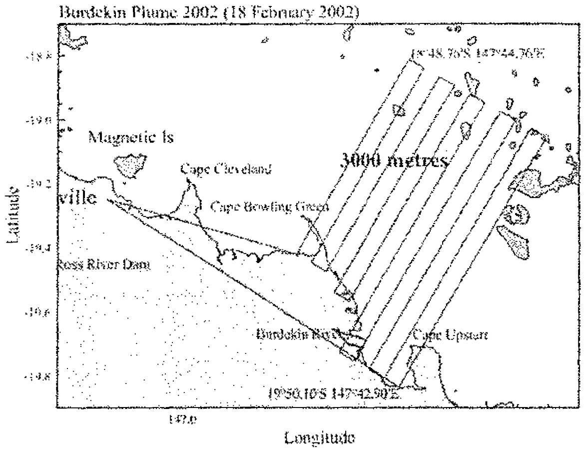

FIGURE 3: Fligth plan for the mission on 18 February 2002.

discharge into the Great Barrier Reef Lagoon.

2. SURFACE SALINITY *IN SITU*

We were able to take a transect of sea surface salinity measurements between 1300 - 1500h on 22 February 2002 to approximately coincide with the SLFMR flight that evening 1900- 2300h.

The transect in Fig. 5 shows a slight decrease in salinity in the first 2 km from the

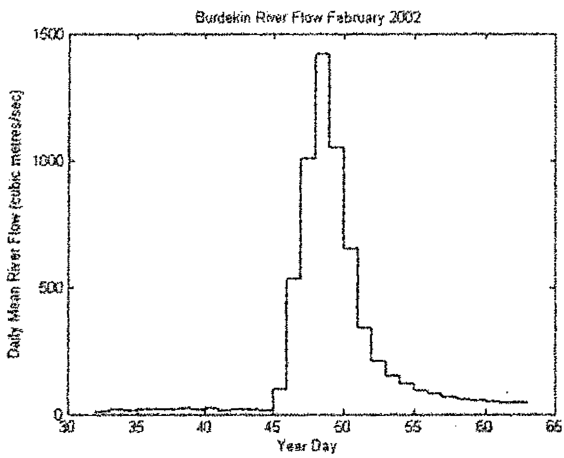

FIGURE 4: Burdekin River discharge for February 2002 showing the minor flood event peaking on 18 Feb 2002.

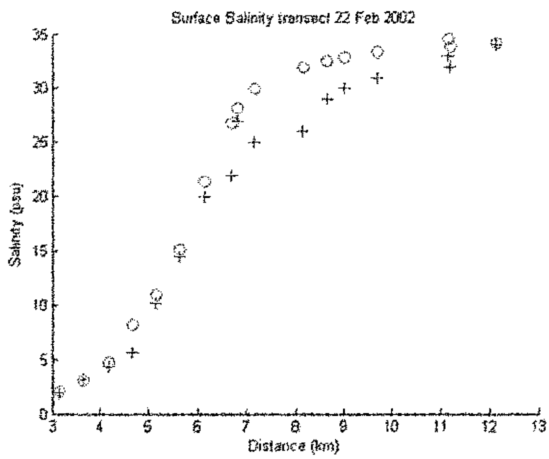

FIGURE 5: Surface salinity along a transect across the river plume. 22 Feb 2002. + refractometer; o SLFMR.

shore. Between 5 and 7km there is a steep gradient with the salinity changing from about 6 psu to about 25, followed by a steady increase towards 34 psu at the end of the transect. From the boat we observed a possible density front about 80m offshore where the salinity decreased slightly. At no other time did we observe a convergent front with the slick line we would normally expect with a gradient of 0.01 psu/m in the surface salinity. The conditions were a 5 knot wind from the south-east, waves less than half a metre and 10% cloud cover. The water appeared a uniform green colour. It appears that kinetic energy of the flow in the plume was dominating over the baroclinic effects at the edge of the plume. The surface salinities along this transect are compared with those measured by the SLFMR in Fig. 5.

3. Sea Surface Salinity from the SLFMR

The SLFMR was flown on three occasions during this event. The first map (Fig 6) was made on 18 February 2002 which was the day of maximum stream flow in the river.

The low salinity (<5psu) tongue of water extends all the way to Cape Bowling Green on the north side. This coast-hugging feature results from a combination of Coriolis effect which turns flow to the left in the southern hemisphere, and the prevailing south-easterly wind (Wolanski and Van Senden, 1983; Belperio, 1983). The river water also fills Upstart Bay on the south side. There is a clear patch of higher salinity

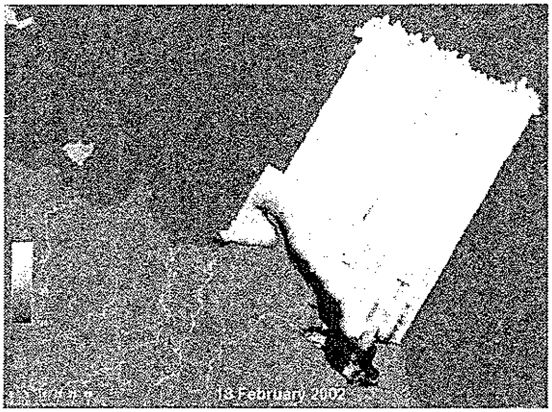

Figure 6: SLFMR map taken on 18 February 2002.

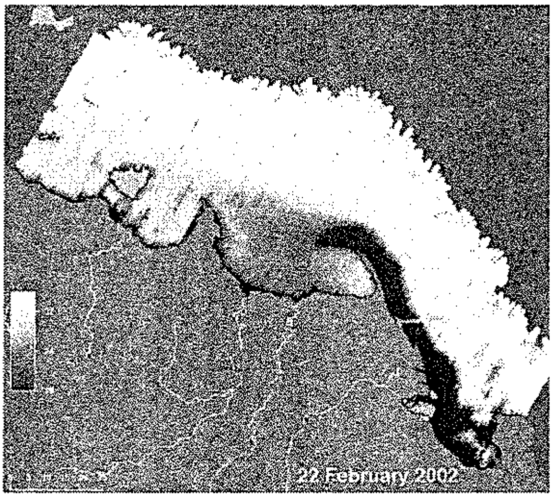

Figure 7: SLFMR map taken on 22 February 2002. The transect line for the near-simultaneous surface measurements is shown.

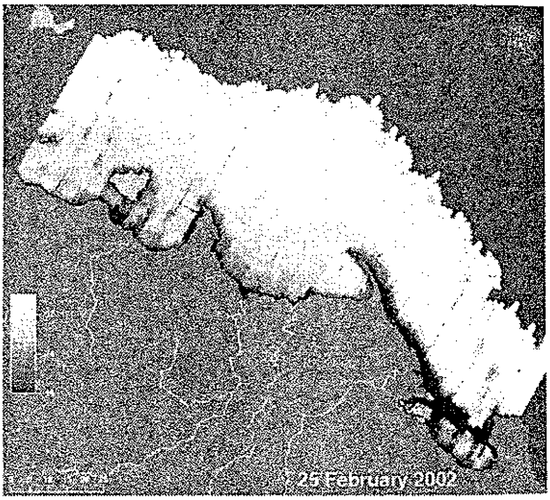

Figure 8. SLFMR map taken on 25 February, 2002

water isolated in Upstart Bay. This implies that there is a closed circulation in the Bay with upwelling at the centre delivering higher salinity water to the surface. To a lesser extent a similar entrapment of higher salinity water appears in the south end of Bowling Green Bay in Fig. 6..

It is interesting to watch how these features develop over the next few days. Fig. 7 was made on 22 February 2002. For this flight we altered the flight plan because we had learned that the river water was staying close to the coast and penetrating further northward which would take it off the original plan.

The tongue of low salinity water has broadened over the three day interval and the plume extends into Bowling Green Bay. There is very little mixing across the shelf. An anti-clockwise eddy in the south end of Bowling Green Bay is now quite clear from the distribution of the water at 16-18 psu. The presence of the 24-30 psu water in Bowling Green Bay supports the concept of an upwelling core. In Upstart Bay the core has increased salinity compared with the previous map, which indicates an upwelling core. There is a suggestion that the same dynamic process is beginning to happen in Cleveland Bay on Fig. 7.

The third sea surface salinity map (Fig. 8) was made on 25 February when the river discharge had returned almost to its base level (Fig. 3). The tongue of low salinity water is now retracting with a flattening of the off-shore gradient. The anti-clockwise eddies in Bowling Green and Cleveland Bays are still evident. The high salinity core in Upstart Bay has increased in area and moved closer to the coast. The direct connection of low salinity surface water from the river mouth around the north-east side of the eddy suggests that this is a clockwise eddy, in contrast to the circulation in the two bays on the north side of the river. There is very slow cross-shelf transport.

CONCLUSIONS

These results show the value of sea surface salinity maps in understanding coastal processes. Three SSS maps were made of a minor flood plume of the Burdekin River, and on one occasion we were able to make an *in situ* transect of surface salinity. The SSS maps confirm previous evidence that the flood plume stays close to the coast, driven by the Coriolis effect and by the prevailing south-easterly wind. Eddies formed from headland friction in the bays to the north, and in both cases there was evidence of an upwelling core. Upstart Bay to the south behaved differently. There was an eddy with a high salinity core of surface water surrounded by lower salinity water. By examining flow connections we conclude that this was a clockwise eddy with an upwelling core. It appears that the momentum of the river plume and its consequent tendency to form a clockwise eddy dominates over the synoptic scale forcing which occurs in the other bays.

This little case study has given a new insight into circulation in the three bays adjacent to the Burdekin River mouth. It illustrates the value and potential of this new remote sensing technology.

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