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The Seabreeze 2009 experiment: investigating the impact of ocean and atmospheric processes on radar performance in the Bay of Plenty, New Zealand

S.A. Garrett[1,*], D.E. Cook[1], R.E. Marshall[2]

[1] *Defence Technology Agency, New Zealand Defence Force, HMNZ Naval Base, Auckland 0744, New Zealand*
[2] *Naval Surface Warfare Center Dahlgren Division, Dahlgren Virginia, USA 22448*

Abstract

Researchers from New Zealand and the USA have successfully completed a two week field experiment, Seabreeze 2009, in the Bay of Plenty, New Zealand. The aim of this experiment was to observe radar performance during sea breeze/land breeze coastal mesoscale circulations. This experiment used a range of permanent, stationary observatories in the region to gather atmospheric observations. These data were supplemented by diurnal onshore and offshore soundings, a high-density of offshore vertical profiles from kite-mounted sondes, floating sea surface temperature (SST) sensors, weather buoys and an array of meteorological observations collected using the Defence Technology Agency's Unmanned Aerial Vehicle (UAV) system. A total of eight days of simultaneous measurements of one-way 9.4 GHz (X band) radar propagation and environmental parameters affecting refractive conditions were measured in a variety of synoptic conditions. Strong sea breeze signatures were observed on seven days during the measurement period. Seabreeze 2009 forms one of the most detailed investigations of radar performance during coastal mesoscale circulations ever undertaken, and is the only dataset of its kind from the Southern Hemisphere. This research has, therefore, expanded the geographical and temporal range of data currently available to researchers and modelers.

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* Corresponding Author email: s.garrett@dta.mil.nz (Sally Garrett)

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1 Introduction and aims

1.1 Radar and sea breeze circulations

Observations and numerical weather prediction modelling have demonstrated that electromagnetic (EM) waves may be significantly modified in the coastal atmospheric environment (Brooks et al., 1999; Atkinson and Zhu, 2006). In particular, the vertical profiles of moisture and, to a lesser extent, air temperature are mostly responsible for the way the EM energy will transmit in a given atmosphere. Strong changes in temperature and water vapour vertical gradients in the coastal atmospheric boundary layer may have significant impacts on the performance of marine surface sensor and communication systems. Further complexities in EM transmission occur in the coastal environment from the localised interaction of the atmosphere with coastal landforms, giving rise to topographic air flows and diurnally paced sea and land breezes (Meyer, 1971; Haack et al., 2010).

Sea breeze circulations are characterised by the onshore movement of maritime air, driven by the pressure gradient produced from thermal heating of the land (Simpson, 1994). The onshore movement of this maritime air over the coast is associated with a drop in temperature, an increase in humidity and changes in wind direction (Brown, 1960). Early experiments conducted by Atlas (1960) and Eastwood and Rider (1961) recorded variations in radar performance as a sea breeze front approached, and concluded that these were related to marked changes in the refractive index at the front (Eastwood, 1967).

National defence agencies employ high resolution numerical weather prediction (NWP) models coupled with sensor performance models to forecast the impact of weather on sensors. Sea breeze fronts are characterised by rapid and often spatially-complex shifts in atmospheric parameters, resulting in increased refractivity and marked changes in radar performance. As such, the onset of a sea breeze circulation provides researchers the opportunity to test the performance of coupled NWP and radar performance models, through a variety of conditions over a short time frame.

To date, there exists only a few detailed datasets of simultaneous measurements of radar propagation and atmospheric conditions affecting refractivity during land/sea breeze circulations (Silveira and Massambani, 1995; Burk and Thompson, 1997). The most complete set of data (approximately 65 hours in total) was collected at Wallops Island, USA in 2000 (Stapleton et al., 2001). These data have provided much needed insights into sea breeze driven radar propagation and have directly contributed to the development and validation of propagation models (Haack et al., 2010). However, no equivalent information currently exists for Southern Hemisphere coastal environments nor for locations away from a continental landmass.

1.2 Aims

In a first attempt to fill this lacuna in data, the Defence Technology Agency (DTA) of the New Zealand Defence Force, with their international defence partners, have successfully completed a two week field experiment, Seabreeze 2009, in the Bay of Plenty, New Zealand. The primary aim of this experiment was to gather contemporaneous paired measurements of radar propagation and the prevailing environmental conditions affecting EM propagation and refractivity in the coastal environment. In doing so, we aim to improve the scope and availability of datasets worldwide that are capable of validating coupled NWP and radar performance models.

2 Experimental design

2.1 Rationale

The Seabreeze 2009 experiment was designed to optimise the collection of data required to validate NWP and radar performance models. The validation process is comprised of four stages. First, the NWP model outputs will be compared with observations collected throughout the Bay of Plenty, to develop an understanding of the models ability to predict synoptic-scale events. To achieve this, synoptic radiosonde profiles and point measurements of atmospheric parameters were collected from 23 February to 6 March 2009.

The second stage of validation involves the comparison of modelled radar performance (seeded with observations of refractivity) with measured radar performance. The Seabreeze 2009 experiment centred on the measurement of one-way X band radar propagation between a shore based receiver and three commercial radars mounted on a ship transiting at distances of up to 60 km offshore. Refractivity along the transit during the propagation experiment was quantified using point and profile atmospheric measurements.

The third stage is to compare the measured refractivity environment discussed above with high resolution NWP outputs. The final stage of our validation process is to compare the modelled radar performance driven by NWP outputs with the measured radar performance. The full results of these validation studies will be presented in subsequent series of papers by the Authors. In this report, we detail the Seabreeze 2009 experiment in full and a description of the data captured.

2.2 Site description

The Seabreeze 2009 field experiment was conducted in the area surrounding Thornton Beach, in the eastern Bay of Plenty, New Zealand (Figure 1). The Thornton Beach area was selected to host the trial for several reasons. First, preliminary research by the authors showed that strong and consistent sea-breezes developed during the summer months in the region. This complements earlier studies of wind climates in the Bay of Plenty that produced some evidence of strong diurnal summer winds (Kingsland et al., 1998), suggesting these processes may be common features of the region’s summer climate. Secondly, the eastern Bay of Plenty is characterised by low relief coastal plains suitable for

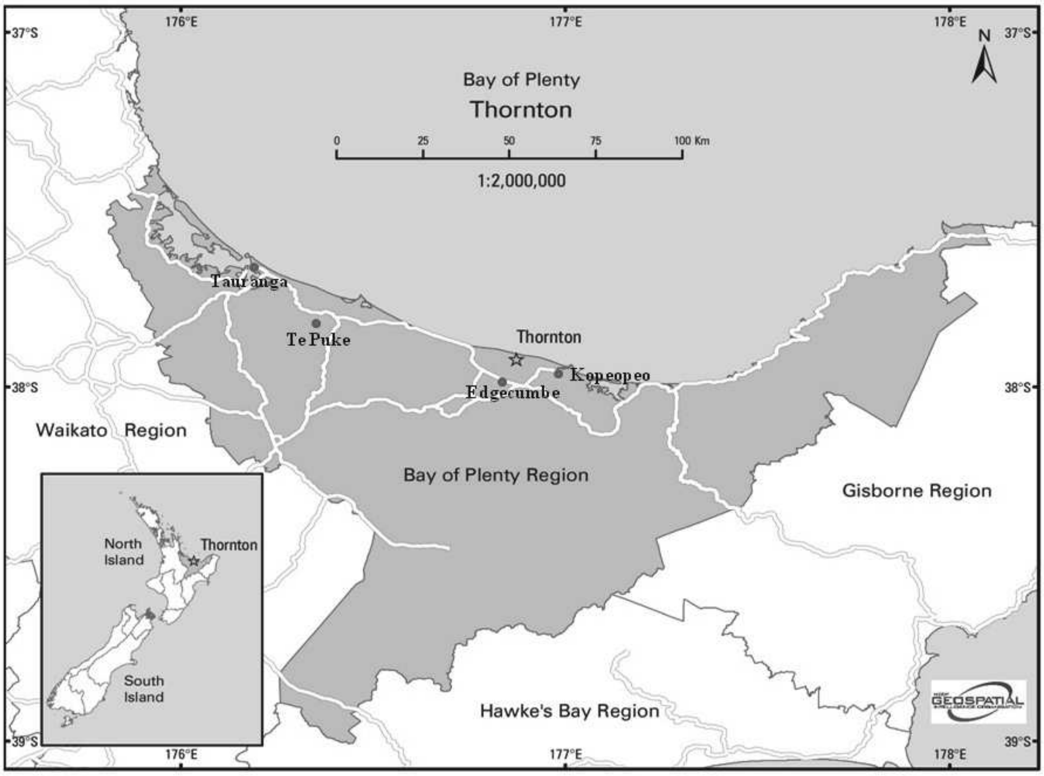

Figure 1. Location map of the Bay of Plenty region, North Island, New Zealand. The location of weather stations used in this study are marked by filled circles.

significant inshore penetration of sea breeze circulations (Figure 2); sites further west along the bay have the advantage of having the dominant sea breeze direction being perpendicular to shore, but have only narrow coastal plains. Thirdly, the area is sparsely populated and this segment of the coastline not intensively used, which made the logistics of conducting a large scale radar propagation experiment easier.

3 Methods

3.1 One-way radar propagation measurements

The signal sources for radar propagation measurements were provided by three commercial off-the-shelf X band (9.4 GHz) pulsed radars (Table 1) mounted on a ship (the RV Macy Grey) that transited along a bearing of 320º (True) between

0.5 and 65 km from the shore-based radar receivers. The radar units rotated at 24 or 27 rpm and transmitted horizontal polarised signals. Onshore at Thornton Breach (Figure 2), radar signals were received using a Teki X Band receiver developed by the New Zealand Defence Force that is available commercially from MarOps Ltd. The Teki radar receiver was mounted at a height of 15 m above mean sea level (AMSL) and operated at a frequency of 9400 ± 100 MHz, with horizontal polarization and a scan rate of 3° per second.

The Teki receiver measured the total power received in the X band. The power from each radar unit was then separated using the characteristics of each radar pulse. The Teki system is designed primarily to measure the characteristics of radars; as such, the system was not calibrated to provide information on the absolute power received onshore. However, the range-response of the Teki system is calibrated; thus the change in power received over distances recorded

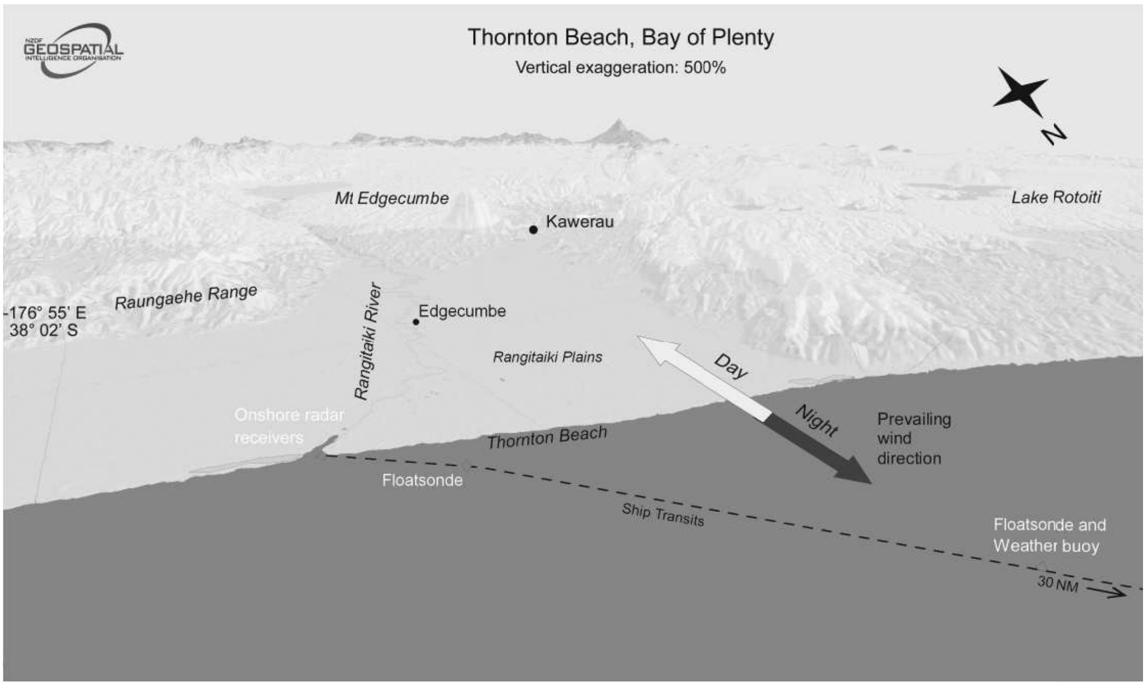

Figure 2. An oblique perspective of the central Bay of Plenty region, New Zealand, centred on the Thornton Beach area where the Seabreeze 2009 trial took place.

Table 1. The characteristics of the X-band pulsed radars operated at Seabreeze 2009. In addition to the three main modes of operation tabled here, the Northstar radar was on occasion operated in a fourth mode (1.0 µs ± 25%, 650Hz ± 5%).

Radar unit	Power (kW)	Height (m)	Frequency (MHz)	Horizontal beam width (°)	Vertical beam width (°)	Mode 1	Mode 2	Mode 3
Pathfinder SL70	2	8	9400 ± 30	5.2 ± 10%	25 ± 20%	0.28 µs ± 30% (666 Hz)	0.67 µs ± 30% (1333 Hz)	-
Navico AA010024	2	7.4	9445 ± 30	5.2 ± 10%	30 ± 20%	0.08 µs +50/-25% (2250 Hz)	0.3 µs +50/-30% (1200 Hz)	0.8 µs ± 25% (600 Hz)
NorthStar NS-RDR1042MD	4	6.8	9410 ± 30	4 ± 10%	30 ± 20%		0.2 5 µs ± 25%, 1700 Hz ± 5%	0.5 µs ± 25%, 1200 Hz ± 5%

by the Teki system may be directly compared with either modelled radar data or other radar systems. A series of quality assurance checks were completed in this experiment to ensure that the changes in relative power received each day were due solely to variations in the propagation environment between the transmitter and the receiver units, rather than artefacts of the hardware used.

3.2 Atmospheric measurements

3.2.1 Radiosondes

Synoptic soundings at 01:00 NZDT (12:00 UTC) were executed at sea-level, onshore at Thornton Beach using Vaisala RS92 sondes paired with a Marwin 12 receiver and GC25 ground check set. Weather balloons were partially under filled in order to slow their ascent to a minimum velocity of 2 m s^{-1} (after Bailey, 2000) thus ensuring that adequate ventilation of the sensors was achieved while enabling an increase in the vertical sampling resolution of the sounding. Additional daytime soundings were made offshore from aboard the RV Macy Grey, at locations along the transit path during propagation measurements. The timing and location of these sounding was guided by high resolution NWP forecasts. Synoptic soundings were collected at 13:00 NZDT (00:00 UTC) along the transit 11 km from the receivers and 7 km from the closest land. This position was selected to ensure NWP model outputs for this point would be located at sea.

3.2.2 Kite sondes

A conventional fishing kite was adapted so that it could transport a Vaisala RS92 sonde. The kite was connected to a motorised winch and flown off the aft deck of the same ship used to transmit the radar in this experiment. Vertical profiles of air temperature, relative humidity and barometric pressure were obtained by raising and lowering the kite (up to 400 m AMSL) while the boat transited away from shore. The Marwin 12 receiver was operated in 'Research Mode' which allowed continual sampling of the atmosphere regardless of whether the sonde was ascending or not.

3.2.3 Unmanned Aerial Vehicle (UAV) observations

The DTA's Kahu UAV system (Strong and Ashman, 2008) was fitted with a Vaisala HMP50 sensor to collect low-altitude relative humidity and temperature measurements (Table 2). The sensor was mounted underneath the wing of the UAV beyond the influence of jet wash from the propeller and to prevent direct exposure of the sensor to solar radiation. The UAV conducted a variety of missions over the eight day experiment that maximised both the UAV's performance and its meteorological sampling capabilities. Measurements of relative humidity and temperature were collected at eight Hz with these data transmitted instantaneously from the UAV to an onshore base station for storage and processing. Corresponding air pressure measurements were collected using the UAV's on-board sensor (Motorola MPXA4115A). UAV meteorological data were typically collected between 70 and 400 m altitude and at distances up to 14 km offshore (Figure 1). The timing and altitude of the flights was guided by high resolution NWP forecasts.

Table 2. Key characteristics of the DTA Kahu UAV system. After Strong and Ashman (2008)

Mean take-off weight	3 kg	Payload weight	1 kg
Cruising speed	30 knots	Maximum speed	45 knots
Endurance	Up to 2 hours		
Wingspan	2.2 m		
Range	c. 25 km (radio-link/mission limited)		
Motor	Electric direct-drive brushless motor		
Battery	16 Cell Lithium-Ion Polymer		
Launch	Hand-launched with manual or automatic landing		
Base station	Laptop Ground Station with mapping overlay and graphical control of aircraft		
Communications	Freewave radio 900MHz		
Communications range	Up to 14 nmi at 50 m AMSL		

3.2.4 Fixed weather stations

Meteorological observations were collected from four weather stations (either New Zealand Met Service or Environment Bay of Plenty sites) during the experiment (Table 3). Data from these stations were complemented by observations from a Weather Pro Plus automated weather station erected at the Thornton Beach site.

Table 3. Weather stations that contributed observations to the Seabreeze 2009 experiment.

Station Name	Latitude (º S)	Longitude (º E)	Height (m)	Temperature	Relative Humidity	Pressure	Wind
Edgecumbe	37.980	176.829	7.3				*
Kopeopeo	37.960	176.981	2	*	*	*	*
Tauranga	37.673	176.196	4	*	*	*	*
Te Puke	37.779	176.326	17	*	*	*	*

3.3 Oceanographic measurements

3.3.1 Floatsondes

Two floating pontoons were constructed from closed-cell foam and enclosed in a light-weight aluminium frame and attached by shock-cords to buoys moored at fixed distances offshore (Figure 2). The floatsondes were weighted in such a way that they maintained a near-constant depth in the water regardless of wave activity. Hobo U22 sensors were carefully positioned within the base of the floats so that measurements of sea skin temperature at 0.02 m depth were collected at either one second or one minute intervals. These data were stored internally and then downloaded several times a week.

3.3.3 DTA weather buoy

The DTA weather buoy is a 1.8 m diameter discus buoy with a mast of six metres length that features a range of meteorological sensors collecting observations at a frequency of 1 Hz (Figure 3, Table 4). These data were held in flash memory

Figure 3. The DTA weather buoy deployed during the Seabreeze 2009 experiment in the Bay of Plenty, New Zealand.

Table 4. Sensor specifications for the DTA weather buoy.

Observation	Sensor make/model	Resolution	Accuracy (± 2 σ)
Barometric Pressure	Vaisala PTB100A	0.1 hPa	0.3 hPa
Air/Sea Temperature	YSI 44032	0.1 ºC	0.2 ºC
Relative Humidity	Vaisala HMP45D	0.1 %	2% (0-90% RH), 3% (90-100% RH)
Wind Speed	R.M. Young Anemometer #05106	0.1 ms^{-1}	0.3 ms^{-1} or 2%
Wind Direction	R.M. Young Anemometer #05106	0.1º	3º

and the first two minutes of every 15 minute block of data were packaged and transmitted near-instantaneously ashore via Freewave radio. The buoy was deployed 11 km offshore from Thornton Beach for the duration of the trial (Figure 2). Measurements of surface wind speed and direction, air temperature and relative humidity were made at 2 m and 6 m above sea level at the buoy. Water temperature at 1 m depth was recorded via a thermistor located within the buoy.

4 Data description

4.1 Synoptic conditions during the Seabreeze 2009 experiment

Two low pressure systems passed over New Zealand during the period of the experiment. On 23 February 2009 a low pressure system moved away from New Zealand bringing a westerly gradient over the study area. A high in the Tasman Sea then intensified and moved south then crossed the South Island. On 26 February a tropical depression moved south into the Tasman Sea, bringing humid air to Thornton Beach from the north east. This system brought strong winds, and heavy rain preventing boat and UAV operations between 27 February and 1 March. This second low pressure system crossed the South Island and a high pressure developed to the North of the North Island.

4.2 Radar, atmospheric and oceanographic data capture

Eight days of concurrent one-way X band propagation and atmospheric measurements were collected (Table 5). Propagation data were collected during daylight hours from 23–27 February and 2–4 March 2009.

Table 5. Meteorological data capture during the Seabreeze 2009 experiment. Areas shaded in grey represent complete data days. The absence of ESM radar data mid-trial (shaded red) was due to adverse weather conditions in the Bay of Plenty. Times are expressed in UTC format.

Date	23 Feb	24 Feb	25 Feb	26 Feb	27 Feb	28 Feb	1 Mar	2 Mar	3 Mar	4 Mar
UAV data		1100 1400 1600	1100 10400 1600	0800 1300	-	-	-	1100 1600	1300 1500 1800	1500
Radar										
Kite-sondes	1650	1510	0930		1010 1420			1040 1950	1000 1200 1540 1355	
Weather buoy										
Floatsondes	-	-	-	-	-	-				
RS92 radio-sondes		1220	0100 1030 1300 1245	0100 0704 1020 1300 1242 1355 1447	0100 1300	0100 1300	0100 1300	0100 0954 1110 1300 1556 1951	0100 1055 1300 1332 1355 1450 1650	0100 1000 1300 1614

A total of 113 atmospheric profiles were measured; 30 radiosondes tethered to free-floating balloons and 83 kite-tethered profiles. The maximum height that kite profiles attained was 400 m. Atmospheric pressure, relatively humidity and temperature observations were collected during 14 UAV flights with a total flight time of over 12 hours (Figure 4). Three main flight patterns were employed. Upwards spiral flight paths were flown to capture vertical atmospheric profiles.

Horizontal profiles were recorded through the use of either reverse sawtooth shaped flight paths (typically within a vertical range of 500 m) or alternatively using long horizontal flights at specific altitudes. The use of the UAV to gather meteorological observations allowed insights into the horizontal structure of sea breeze circulations to be made; information that could not be obtained by the use of weather stations or radiosondes alone.

Figure 4. UAV flights paths (pink lines) flown during the Seabreeze 2009 experiment, Bay of Plenty, New Zealand.

Sea breeze circulations were recorded on seven days during the experiment. In each case the criteria for a sea breeze (Azorin-Molina and Martin-Vide, 2007) was met with a wind direction change of 120–180° and an increase in wind speed by 1.5 m s-1 between measurements collected at 08:00 NZDT (two hours after sunrise) and before 21:00 NZDT (two hours before sunset). These changes were not attributed to the synoptic conditions in the Bay of Plenty. On five days of the experiment the sea breeze penetrated up to 10 km inland, across the Rangitikei Plains to Edgecumbe (Figure 2).

The mean wind direction at the shore based radar receivers during sea breeze circulations was 320°T, with a mean wind speed of 7.9 m s^{-1}. The onset of the sea breeze before 12:30 NZDT resulted in a rapid change in wind direction and speed, but humidity remained constant and temperature continued to rise at the same rate as before the wind change due to solar heating. On days when the sea breeze developed after 12:30 NZDT, air temperatures decreased by 1°C and humidity increased by 0.5 g kg^{-1} within an hour of the onset. This change in specific humidity was less than 5% of the average value of 11.5 g kg^{-1} measured at the weather buoy for all days in the experiment.

To analyse the radar data collected at Seabreeze 2009, the Advanced Refractive Effects Prediction System (AREPS) (Patterson, 2007) was used to model the received power for the onshore receivers in a standard atmosphere. In AREPS, a standard atmosphere is based on the assumption of a linear decrease in temperature with height from the surface up to the tropopause. Modelled data from AREPS was thus compared to the measured data to identify if standard radar propagation had occurred during the experiment. Modelling of the radar performance offshore of Thornton Beach using AREPS (Figure 5) showed large variations in the predicted received energy within 10 km of the receiver, which are best explained by multipath effects (Skolnik, 2008). The receiver power then decreases at a rate of 1.8 dB km^{-1} at 10–45 km offshore. At ranges beyond 45 km, the modeled received power decreased by 0.7 dB km^{-1}.

At distances of less than 10 km from land, the measured relative received power was affected by multipath interference on all days of measurement. At ranges greater than 10 km, measurements of relative received power decreased with distance at rates less than those predicted by AREPS. This was the case for all days in our experiment with the exception of 24 February, when at distances of 39–65 km offshore an increase in received relative power was measured.

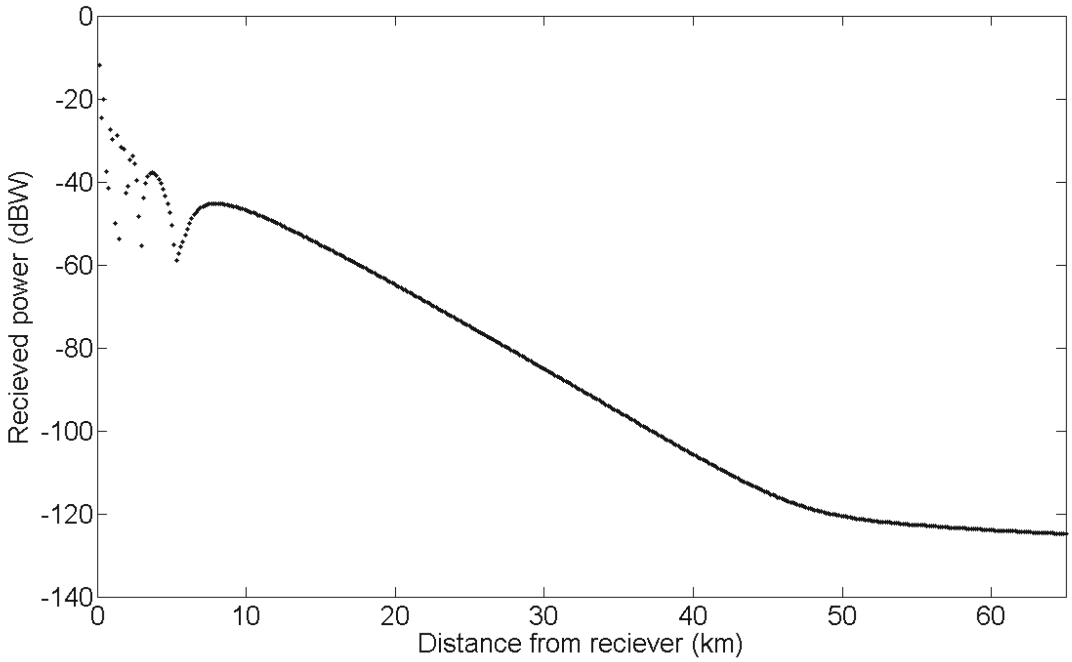

Figure 5. AREPS modelled received power with range offshore, Bay of Plenty, New Zealand. The AREPS model run was setup with the Teki receiver at 15 m AMSL and a 2 kW Navico radar at 7.4 m AMSL, mirroring the radar equipment setup in the experiment.

Transits completed before the onset of the sea breeze were characterised by decreases in relative received power of c. 1.2 dB km^{-1} when ≥10 km offshore. During onshore sea breeze winds, relative received power onshore had similar decreases when radars were operated 10–15 km offshore, followed by a smaller decrease of ≥0.1 dB km^{-1} when the radar transmitter was beyond 15 km offshore.

4.3 Propagation measurements during the onset of a sea breeze

On 24 February, a weak sea breeze developed while the RV Macy Grey was already 39 km offshore transmitting radar to shore. This allowed us the opportunity to directly monitor radar performance immediately prior, and during the development of a sea breeze. The 65 km transit began this day at a distance of 2 km from the receiver at 12:00 NZDT. Between 12:00 and 14:00 NZDT, the weather buoy recorded winds blowing from the west at an average speed of 3.7 m s^{-1} and with 9.6 g kg^{-1} specific humidity. The relative received power decreased at 1.7 dB km^{-1} as the ship transited from 10 to 38 km offshore.

At 14:30 NZDT (with the radar at 39 km offshore) wind speeds at the weather buoy decreased to 1.2 m s^{-1} and backed through the south to an easterly direction. The specific humidity increased during the change to 10.5 g kg^{-1}. At this time the measured relative received power rapidly decreased by 40 dB of relative received power. At 15:00 NZDT the wind built from the north with an average wind speed of 5.8 m s^{-1} and a specific humidity of 10.1 g kg^{-1}. The relative received power increased as range increased during this time at a rate of 1.8 dB km^{-1}. At 65 km in range the received power onshore was the same as at 20 km. The return ship transit began at 65 km from the receivers at 16:00 NZDT. At distances between 20 and 65 km offshore there was less than 0.1 dB km^{-1} decrease in relative received power suggesting that refractive conditions were trapping the radar energy close to the sea surface where both the receiver and transmitter were positioned. Closer to shore, at 10–20 km, the rate of decrease was the same as the previous transit (1.7 dB km^{-1}).

4.4 Summary and comparison with the Wallops 2000 dataset

In total, 47 hours of one-way radar propagation data were collected during the Seabreeze 2009 trial. Our new dataset includes detailed information on radar propagation and refractivity during a variety of synoptic conditions in at distances of up to 65 km offshore in the Bay of Plenty, New Zealand. The location of our experiment, in the temperate, maritime environment of the North Island of New Zealand, has ensured that this new dataset represents radar performance in an environment that is markedly different from the continentally influenced Wallops 2000 Microwave Propagation Measurement Experiment, held in Virginia USA.

In contrast to the Bay of Plenty environment, the Wallops 2000 experiment was located on the east coast of the USA, with a strong continental influence providing a major source of dry air immediately inland of the field experiment (Haack et al., 2010). The average atmospheric moisture at Wallops 2000 of 7.2 g kg^{-1} at their weather buoy location; in this study, the average was

11.5 g kg^{-1} at the weather buoy. Another significant difference in the two datasets is that during our experiment the variations between onshore and offshore flow were not associated with larger variations in moisture as was the case during the Wallops 2000 experiment.

A final difference between our experiment and that conducted at Wallops Island is how each experiment was designed. The height of the X band radar receiver at the Seabreeze 2009 experiment was 16 m lower than at Wallops Island, while the radar we used in the Bay of Plenty was a commercially available pulsed system rather than the continuous wave model used in the US experiment. The commercial pulsed radar was used for our experiment because and understanding of this type of radar is more applicable to the New Zealand Defence Force. The implications of these two different experimental designs, along with the environmental differences between the two studies, on the datasets will be explored in future research by the Authors.

5. Conclusions and future research

The purpose of our article has been to describe a large, multi-disciplinary field experiment that was undertaken in the coastal environment of the Bay of Plenty, New Zealand. Seabreeze 2009 is the first experiment of its kind to have taken place in the Southern Hemisphere, where measurements of one-way radar frequency performance have been paired with simultaneous measurements of atmospheric and ocean conditions. During the eight days of the experiment in February and March 2009, 47 hours of continuous one-way X band radar propagation data were collected during a variety of environmental conditions. Sea-breeze circulations were observed on seven of the eight days of the experiment, with the sea breeze penetrating up 10 km inland from the coast. On at least one day of the experiment, a sea breeze circulation began midway through a ship ranging at distance off shore, allowing us to record in detail one-way radar propagation immediately prior to, and during, the development of a sea breeze circulation. Preliminary results presented here suggests that the study greatly extends our collection of field observations of radar propagation during sea breeze conditions, which to date have only been collected from only a narrow range of environments worldwide.

The data set generated from the Seabreeze 2009 experiment is currently being analyzed by the same meteorologists and radar engineers that analyzed the Wallops 2000 dataset (Haack et al., 2010). The full results of this work, and a detailed comparison with the Wallops 2000 data set, will subsequently be presented in a series of papers by the Authors.

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