# WAKASA BAY

## An AMSR Precipitation Validation Campaign

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A microwave radiometer experiment at Wakasa Bay—combined with concurrent convective systems observations over the Sea of Japan—collected a wealth of now publicly available in situ and remotely sensed data of midlatitude winter clouds and precipitation.

**GENERAL OBJECTIVE OF THE EXPERIMENT.** The Advanced Microwave Scanning Radiometer (AMSR) and AMSR for the Earth Observing System (AMSR-E) were built in Japan, with the AMSR-E being provided by the Japan Aerospace Exploration Agency (JAXA) to the National Aeronautics and Space Administration (NASA) for the *Aqua* satellite, launched in May 2002. The Wakasa Bay campaign, another cooperative effort between the United States and Japan, was a major component of the AMSR precipitation validation program, and its objective was to validate the AMSR precipitation algorithm, especially at high latitudes.

This campaign focused on the physical validation of precipitation retrievals. For satellite validation campaigns this generally means collecting "ground truth" data. When suitable ground data are not available, as is typical over the ocean, the alternative is to model the errors. The observations collected during this experiment, which are available to the broad community, include ground and airborne radars, radiometers, and in situ data intended to extend our estimates of the magnitudes of the error sources to midlatitude winter conditions. Most of the data obtained during this campaign were for precipitation over the ocean; validation data for precipitation over land were obtained mostly from ground radars, rain gauges, and in situ measurements of snow depth.

In planning this campaign we considered length scales of precipitation [beam filling (BF)], freezing-level retrieval (FL), radiative transfer in the bright band (BB), snow measurement over ocean (SO), forward modeling (FM), rain/snowfall over land (RSL), cloud water (CLW) retrieval, surface emissivity/backscatter (SFC), drop size distribution (DSD), and case studies/time evolution (CS) (see the sidebar for an explanation of some of these terms). The synop-

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tic understanding of the different storms sampled became a very important by-product, and an interesting component of the Wakasa Bay campaign.


**Fig. 1. Wakasa Bay campaign geography.**

**THE EXPERIMENT SET UP.** Wakasa Bay, in the Sea of Japan, was chosen as the site for this campaign because of the diversity of its midlatitude winter precipitation (including extratropical lows, an upper-level low, and a winter monsoon), coupled with the existence of a ground Doppler radar on the coast, at Mikuni, as well as in situ observations (including snow and rainfall) available from Fukui Airport nearby (see Fig. 1). The NASA P-3 research aircraft was housed at Yokota Air Base (AB), outside Tokyo. Based at Nagoya Airport was the cloud physics–instrumented

**Table 1. Instruments, aircraft platforms, and base of operations during the Wakasa Bay campaign.**

| Location | Component | Instruments | Frequencies | Comments |
|---|---|---|---|---|
| Yokota Air Base | NASA P-3 | Airborne Multi-channel Microwave Radiometer (AMMR) | 21 and 37 GHz | Valid data at low altitudes, ascent, descent |
| | | Millimeter-wave Imaging Radiometer (MIR) | 89, 150, 183±1, 3, 7, 220, and 340 GHz | Swath: ±50° off nadir, external calibration |
| | | APR2 | 13.4 and 35.6 GHz | HH and HV polarization, 60-m vertical resolution, 10-km swath |
| | | PSR-CX | 10.7, 18.7, 21.5, 37, and 89 GHz, 9.6–11.5 $\mu$ | Conical scanner, V and H polarization |
| | | ACR | 94 GHz | HH and HV polarization, 120-m vertical resolution, below off 2.6 km MSL |
| Mikuni and Unami | Doppler radar | Radar | C band | Dual polarization, Doppler, 1° beamwidth, 2-$\mu$s pulse; 3D (CAPPI) and 2D RHI data |
| Fukui Airport | Ground-based data | Three ground microwave radiometers | 23.8 and 31.4 GHz, 23.8 and 36.5 GHz, nine channels: 50.8–58 and 90 GHz | 55° zenith angle |
| | | Microrain radar | 24 GHz | FM-CW radar, vertical and profile velocity |
| | | Precipitation gauges | Every minute | Electric balance |
| | | Optical sensors | | Concentration, drop size distribution, and vertical velocity of snowflakes |
| | | Automated weather station | Every 10 min | Air temperature, wind speed, RH, precipitation gauge |
| | | Radiosondes | 4 times daily | Also at Akita, Wajima, and Yonago stations and on three research vessels in the Sea of Japan |

Gulfstream II plane, deployed for the "Winter Mesoscale Convective Systems Observations over the Sea of Japan in 2003" ("WMO-03") campaign of Core Research for Environmental Science and Technology (CREST). The planes flew over both the Sea of Japan and in the West Pacific region, just east of Japan. A ground crew collected snow and rainfall data at Fukui Airport, near the Mikuni radar site.

*Instrumentation.* The campaign's instruments are shown in Table 1. A number of these were aboard the NASA P-3. The Airborne Multi-channel Microwave Radiometer (AMMR; Table 2a), a fixed-beam Dicke radiometer, yielded valid measurements when the aircraft was flying low or spiraling up or down. The total power, cross-track-scanning Millimeter-Wave Imaging Radiometer (MIR; Table 2a) measures radiation at seven frequencies. Scientists can infer brightness temperatures, water vapor profiles, and cloud information from the data gathered by these frequencies. The Airborne Precipitation

**Table 1. Continued.**

| Location | Component | Instruments | Frequencies | Comments |
|---|---|---|---|---|
| Nagoya Airport | Gulfstream II | Forward scattering spectrometer probe (FSSP), two-dimensional cloud optical array probe (OAP-2DC), two-dimensional precipitation optical array probe (OAP-2DP), Commonwealth Scientific and Research Organization (CSIRO) King liquid water probe (KLWC-5) | | Made by Particle Measuring Systems (PMS) |
| | | Cloud aerosol precipitation spectrometer (CAPS) | | Made by Droplet Measurement Technologies, Inc. (DMT) |
| | | Particulate volume monitor (PVM-100A) | Liquid water content, particle surface area effective droplet radius | Gerber Scientific, Inc. |
| | | Nevzorov total water content/liquid water content (TWC/LWC) probe | | Skytech Research, Inc. |
| | | Total air temperature (TAT) sensor | | Rosemount |
| | | Dewpoint hygrometer (Model-137) | | Edgetech |
| | | Lyman-alpha hygrometer (AIR-LA-1) | | Atmospheric Instrumentation Research, Inc. |
| | | Gust probe | Five-hole radome and pressure transducer | |
| | | Global positioning system (GPS) receiver | | Trimble (TNL 2100T) |
| | | Inertial Reference System (IRS) | | Honeywell (HG1050AD09) |
| | | Cloud radar (SPIDER*) | 95.04-GHz reflectivity, Doppler velocity, Linear Depolarization Ratio (LDR) | National Institute of Information and Communication Technology (NIICT) airborne cloud profiling radar, nadir-, or side-looking mode |
| | | Microwave radiometer (WVR-1100) | 23.8 and 31.4 GHz | Radiometrics Corporation |
| | | GPS dropsonde (RD93) | | Vaisala |
| | | Video cameras (forward and downward) | | Hi8 |

*SPIDER is not an acronym. In Japanese, both cloud and spider are pronounced "kumo," so NIICT (CRL) nicknamed their cloud radar "SPIDER."

**Table 2a. Key parameters of AMMR and MIR**

| | AMMR | MIR |
|---|---|---|
| Channel center frequency (GHz) | 21, 37 | 89, 150, 183.3±1, 183.3±3, 183.3±7, 220, 340 |
| Beamwidth (°) | 6 | 3.5 |
| Sensitivity (K) | 0.5 | 0.5 |
| Accuracy (K) | ±4 | ±2 |
| Viewing angle (° from zenith) | ~15 | |
| Temporal resolution | 1 s | 3 s |
| Calibration with internal loads | Once per min | Once per 3 s |
| Angular swath (° from nadir) | | ±50 |
| Angular spatial resolution (°) | | 1.57 |

**Table 2b. APR2 key parameters**

| | | |
|---|---|---|
| Frequency (GHz) | 13.405 | 35.605 |
| Polarization | HH, HV | HH, HV |
| Antenna effective diameter (m) | 0.4 | 0.14 |
| Antenna gain (dBi) | 34 | 33 |
| Antenna sidelobe (dB) | –32 | –37 |
| Antenna beamwidth (°) | 3.8 | 4.8 |
| Peak power (W) | 200 | 100 |
| Bandwidth (MHz) | 4 | 4 |
| Pulsewidth (μs) | 10–40 | 10–40 |
| PRF (kHz) | 5 | 5 |
| Vertical resolution (6 dB, m) | 60 | 60 |
| Horizontal resolution (6 dB, m) | 730 | 920 |
| Ground swath width (km) | 10 | 10 |
| Ze minimum @ 10 km, 10 μs (dBZ) | 13 | 10 |
| Doppler precision (m s$^{-1}$) | 0.4 | 1.0 |

**Table 2c. PSR-CX key parameters**

| Channel frequency range (GHz) | Polarization | Beamwidth (°) | Spatial resolution from 6.7-km altitude (km) |
|---|---|---|---|
| 10.6–10.8 | V, H | 8 | 2.2 |
| 18.6–18.8 | V, H | 8 | 2.2 |
| 21.4–21.7 | V, H | 8 | 2.2 |
| 36.0–38.0 | V, H | 2.3 | 0.6 |
| 86.0–92.0 | V, H | 2.3 | 0.6 |
| 9.6–11.5 μm | V, H | 7 | 1.9 |

Radar 2 (APR2) is a prototype that, in addition to the real-time pulse compression and compact Local Oscillator/Intermediate frequency (LO/IF) module, also has copolarized [horizontal–horizontal (HH)] and cross-polarized [horizontal–vertical (HV)] reflectivity and Doppler velocity at two frequencies (see Table 2b). The Polarimetric Scanning Radiometer CX (PSR-CX) provides vertically and horizontally polarized measurements with C- and X-band radiometers. The PSR consists of a set of five polarimetric radiometers housed within a scan-head drum that rotates. Thus, the radiometers can view any angle with 70° elevation of nadir at any azimuthal angle (a total of 1.32 sr solid angle), as well as external hot and ambient calibration targets. In this campaign the PSR-CX was used in its conical scan mode. The key parameters of the PSR-CX are listed in Table 2c. The Radio Frequency/Intermediate Frequency (RF/IF) subsystem of the Airborne Cloud Radar (ACR; Table 2d) uses a combination of frequency mixing and multiplication to generate the transmitted signal at one of four frequencies in a 50-MHz band centered at 94.92 GHz

The Gulfstream II, provided by CREST, had all of the cloud physics instruments. The Japan Meteorological Agency (JMA) provided weather forecasting, ground observations, and ships at sea, and the JAXA AMSR science team provided radar, ground observations, and radiosondes.

*Flight lines.* Table 3 lists the flight lines during this campaign by the NASA P-3, and Gulfstream II (marked by an asterisk). A short description of the sampled systems follows, with a quick look at the data acquired. Table 4 presents a preliminary assessment of the campaign objectives and the corresponding flight days.

14 January 2003. The weather forecast was for snow showers along the northwestern coast of Honshu. Once on station, the P-3 flew a line north-northwest at 6.7 km, descended to 152 m, and returned to the initial position at the low level. At this position, the plane spiraled

back up to 6.7 km. This circuit was flown a total of 3 times. The first high-level portion of this circuit coincided with an *Aqua* overpass.

Liquid mixed with solid precipitation (snow) was observed at the initial position; this is consistent with a brightband observation. Only snow was observed during all of the low-level flights. This day's data were a good example of snow over an oceanic background. The system seems to have evolved during the 4 h of observations.

| Table 2d. ACR key parameters | |
|---|---|
| Channel frequencies (GHz) | 94.905, 94.915, 94.215, 94.935 |
| Peak transmit power (KW) | 1.4 |
| Maximum average transmit power (W) | 15 |
| Pulse widths (ns) | 250, 500, 1000 |
| Receiver noise figure (includes front-end loss) (dB) | 8.0 |
| Antenna aperture (m) | 0.3 |
| 3-dB beamwidth | 0.8 |

**15 January 2003.** The weather forecast was for snow showers over most of the mountains of Honshu north of Tokyo and along the Sea of Japan coast, as far south as Wakasa Bay. These flight lines were mostly over land, with some near coastal waters. The entire flight was 6.7-km altitude.

Numerous snow showers were observed all along the flight path by both radar systems. On the coastal water portion (near Fukui), the PSR-CX reported small liquid precipitation cells. These data provide a good dataset of snow over land.

**19 January 2003.** The weather forecast was for low pressure with rain south of Honshu, which was moving eastward and was expected to turn northeastward and intensify east of Honshu. The lines flown were in the northeast direction, at 6.1 and 6.4 km, with a low-level line at 152 MSL. At one point a spiral

**Table 3. Details of the NASA P-3 flights.**

| Date | Region observed | Flight altitude (km MSL) | Instrument status problems | Comments |
|---|---|---|---|---|
| 14 Jan 2003 | Northwest coast of Honshu | 7, 0.15 (three circuits*) | No PSR-CX data for the entire flight | Rain, then snow over ocean; BB visible |
| 15 Jan 2003 | Honshu | 7 | PSR-CX/89-GHz channel not operational | Snow showers over land |
| 19 Jan 2003 | Western Pacific | 6.3, 0.15 | All instruments operating well | Rain cells over ocean, snow, freezing level at 1.7 km |
| 21 Jan 2003 | Western Pacific | 7, 3 (two circuits) | All instruments operating well | Significant rainfall over ocean, freezing level at 1.6 km |
| 23 Jan 2003 | Western Pacific | 7, 3 (two circuits) | No MIR data | Rain over ocean; BB near 2.5 km |
| 26 Jan 2003 | Honshu | 7 | No MIR and PR2 data | Baseline around Fukui |
| 27 Jan 2003* | Sea of Japan | 7 (four lines**) | PR2/Ka-band portion had occasional interruptions | Stratiform rain over land; BB near 1.8 km |
| 28 Jan 2003* | Sea of Japan | 7 (four lines) | No AMMR data | Snow showers over land and water |
| 29 Jan 2003* | Sea of Japan | 7 (six lines) | No AMMR data | Widespread snow |
| 30 Jan 2003* | Sea of Japan | 7 (four lines) | No AMMR data | Light snow showers |
| 1 Feb 2003 | Honshu | 7 | No ACR data at the beginning of the flight | No precipitation, snow on the ground |
| 3 Feb 2003 | Western Pacific | 7, 0.15 (one circuit) | No APR data for the first 2 h of flight | Rainfall over ocean; spiral up through rain |

*A circuit is a flight that can be considered a vertical rectangle with the long sides at 7- and 0.15-km altitude and the short sides being the descent and ascent between the two levels.

**A line is a flight between two points at the same altitude. More than one line means that the lines were flown at the same altitude and shifted horizontally from one another.

**Table 4. Wakasa Bay campaign objectives with a preliminary assessment of corresponding flight days**

| Objective | Flight dates |
|---|---|
| Length scale of precipitation (beam filling), | 19, 21, 23, 28, 29 January, and 3 February |
| cloud water retrieval, | |
| drop size distribution | |
| Freezing level retrieval | 14, 19, 21, 23, 27 January, and 3 February |
| Radiative transfer in bright band, | 14, 19, 21, 27 January, and 3 February |
| forward modeling, | |
| surface emissivity/backscatter | |
| Snow measurement over ocean | 14, 21, 28, 29, 30 January |
| Rain/snowfall over land | 15, 27, 28 January, and 1 February |
| Case studies/time evolution | All except 26 January and 1 February |

up through a rain cell was performed. A wide variety of rain cell sizes were observed on all the legs. The flight line crossed a front evidenced by turbulence, rain, and a change in the wind. The front progressed eastward during the flight. The freezing level was very low [compared to the Kwajalein Experiment (KWAJEX) or the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Research Experiment (TOGA COARE)]: about 1.7 km. These are good data of a profile through the rain.

**21 January 2003.** A low formed over the Kanto Plain during the night, with rain and snow reported in the local area. The low moved rapidly into the Pacific Ocean, generating abundant rain. The lines flown were at 6.1 km in a northwest direction through the rain. One rain cell was sampled by spiraling up through it from 305-m altitude.

On the first line significant rainfall was observed: APR2 noted bright bands at altitudes ranging from 1 to 1.6 km. The spiral to altitude through the rain cell provided good rain profile data. The freezing level in this rain cell was at 1.5 km. A good set of oceanic rain observations with freezing levels ranging from 1 to 1.7 km were obtained.

**23 January 2003.** A low had passed out of the Yellow Sea, along the southern edge of Honshu. At the planned flight time the low was located near the southeast corner of Honshu and there was heavy, wet snow at Yokota Air Base. The weather at Yokota AB delayed takeoff for about 4 h. At the actual time of takeoff it was raining. The low was expected to track to the northeast and deepen. The flight line chosen was directly east, and it was flown only at a high altitude (6.4 km). The delay in the takeoff caused the *Aqua* satellite overpass (0343 UTC) to be missed, however, the lines flown were under three Tropical Rainfall Measuring Mission (TRMM) overpasses (at 0741, 0914, and 1046 UTC).

The flight lines were mostly in cloud at 6.4 km. Bright bands were observed near 2.5 km. By the time of the last flight line, the cold front had moved into the study area. Data from this flight complement the data from the two previous oceanic precipitation flights (19 and 21 January) by having more widely spread precipitation and the squall line.

**26 January 2003.** There were clear skies, with few clouds, over most of Honshu. A storm was approaching from the west, causing rain near the western tip of Honshu. The entire flight was at a high altitude (6.4–6.7 km). There was an *Aqua* overpass at 0412 UTC. This flight was a nonprecipitating baseline for the observations around the Fukui ground truth site. Clouds varied from scattered to broken, with a continual thin cirrus haze.

**27 January 2003.** A 999-hPa low in the central Sea of Japan was causing warm advection over central and northern Honshu with widespread, generally light rain over most of Honshu, but heavier rain near Nagoya. The light rain extended into the Sea of Japan with snow only at high elevations and extreme northern Honshu.

A joint mission between the Japanese Gulfstream II and NASA P-3 was flown. The two aircraft flew the same lines, but at different altitudes. The two lines were flown parallel to each other in a northeast direction. The P-3 altitude was at 6.4 km, and the Gulfstream II flew from 116 m to 1.5 km. The data lines were within the coverage of the two radars at Unami and Mikuni. There were no useful satellite overpasses.

Over the test area unusually uniform stratiform rain on most of the legs was observed. Bright bands were observed near 1.8 km. Cloud tops varied from near the freezing level up to the aircraft level.

This was the first attempt at coordinating the two aircraft, and it was quite successful. By getting some rain-over-land data on this day, all of the mission objectives were addressed.

**28 January 2003.** A 978-hPa low was located just west of Hokkaido. There was a strong onshore flow with scattered snow showers all along the central Sea of Japan coast of Honshu. This was coordinated flight between the NASA P-3 and the Japanese Gulfstream II. The flight lines were in the northeast direction, at 6.7-km altitude, over the Sea of Japan. The lines were flown twice with a PSR-CX, and an ACR calibration was done at the end points.

The return to Yokota Air Base was over the Fukui radar. The *Aqua* overpass was at 0359 UTC (during the first flight line). There was a TRMM overpass at 0615 UTC (during the last flight line). The Gulfstream-II flew the same lines, at altitudes from 4.7 km down to 305 m MSL.

There were scattered snow showers with a wide range of intensities over land, on the western slopes of the mountains of Honshu, and all through the over-water flight lines. Unfortunately, the Fukui ground site overflight happened during the turning points between flight lines, so there might not be any valid aircraft data available. There was a wide variety of small snow showers in the study area.

**29 January 2003.** The low that had been just west of Hokkaido had moved northward to the middle of Sakhalin Island and deepened to 979 hPa. There was a strong northwesterly flow over all of the Sea of Japan, and extensive areas of snow formed off the coast of Honshu and on the western side of the Japanese Alps.

The P-3 flew a northerly line over the Sea of Japan, at 6.7-km altitude. This line was repeated two more times with a PSR-CX calibration at one of the end points. The Gulfstream-II flew the same lines at altitudes varying between 4.7 km and 460 m MSL. There were two overflights over the Fukui ground station. There was no *Aqua* overpass during the flight. A TRMM overpass occurred at the time the flight ended at Yokota AB.

Widespread snow was observed on the western slopes of the Japanese Alps and into the Sea of Japan. This case with widespread snow coverage complements the previous day's scattered snow showers.

**30 January 2003.** A 978-hPa low was causing cold northwesterly flow across Sea of Japan and Honshu. Snow was predicted along the central Sea of Japan coast of Honshu.

The P-3 performed four northeast lines at a high altitude, starting at Fukui. The Gulfstream II flew underneath the P-3 over the same area at altitudes between 4.7 and 457 m MSL. There was an *Aqua* overpass at 0346 UTC and a TRMM overpass at 0559 UTC; both overpasses covered the area flown by the aircraft. Most of the observation area had light, isolated snow showers. These data were taken in very good coordination between the two aircraft.

**1 February 2003.** Moderate (10–15 kt) northwest winds and no precipitation for all of Honshu occurred on this day. The flight lines for this day were similar to the 26 January flight lines. There was an *Aqua* overpass at 0333 UTC and a TRMM overpass at 0411 UTC. There was no falling precipitation; this day's observations are of the snow on the ground near Fukui.

**3 February 2003.** There was a developing low with associated rain in the Pacific, southeast of the Kanto area. Lines were flown in the precipitating area, with a spiral down to 152 m MSL. through the rain. There was an *Aqua* overpass at 0320 UTC and two TRMM overpasses at 0223 and 0528 UTC. There was rain observed at different areas of the flight lines. There are good observations of rain profiles during the spiral up through the rain.

Two examples of the data acquired by the P-3 instruments are illustrated in Figs. 2a and 2b. The top two panels are data from the ACR, followed by the third panel, which is APR2 data. The bottom two panels are graphs of brightness temperatures retrieved by the MIR and PSR-CX. Note the bright band in the ACR and APR2 data from the 27 January flight.

**DATA AVAILABILITY.** Data taken during this campaign can be obtained from the National Snow and Ice Data Center (http://nsidc.org/data/amsr_validation/index.html) and JAXA/Earth Observation Research Center (http://sharaku.eorc.jaxa.jp/AMSR/data_val/index.html).

**SUMMARY.** The Wakasa Bay campaign, a joint experiment between Japan and the United States, was designed to answer specific questions regarding the need for the physical validation of rainfall retrievals from AMSR and AMSR-E microwave radiometers as well as more general questions about the remote sensing of rainfall and the evolution of midlatitude systems. These objectives are listed in Table 4. The aircraft payloads and surface facilities were selected to meet these objectives, with the NASA P-3 focusing on a remote sensing payload and the CREST Gulfstream II having in situ measurement capabilities. The good fortune of having appropriate meteorological events and designing flight lines to exploit them allowed us to meet the over-ocean subset of the objectives quite well. However, limited data were obtained for over-land raining conditions. These data may well prove useful

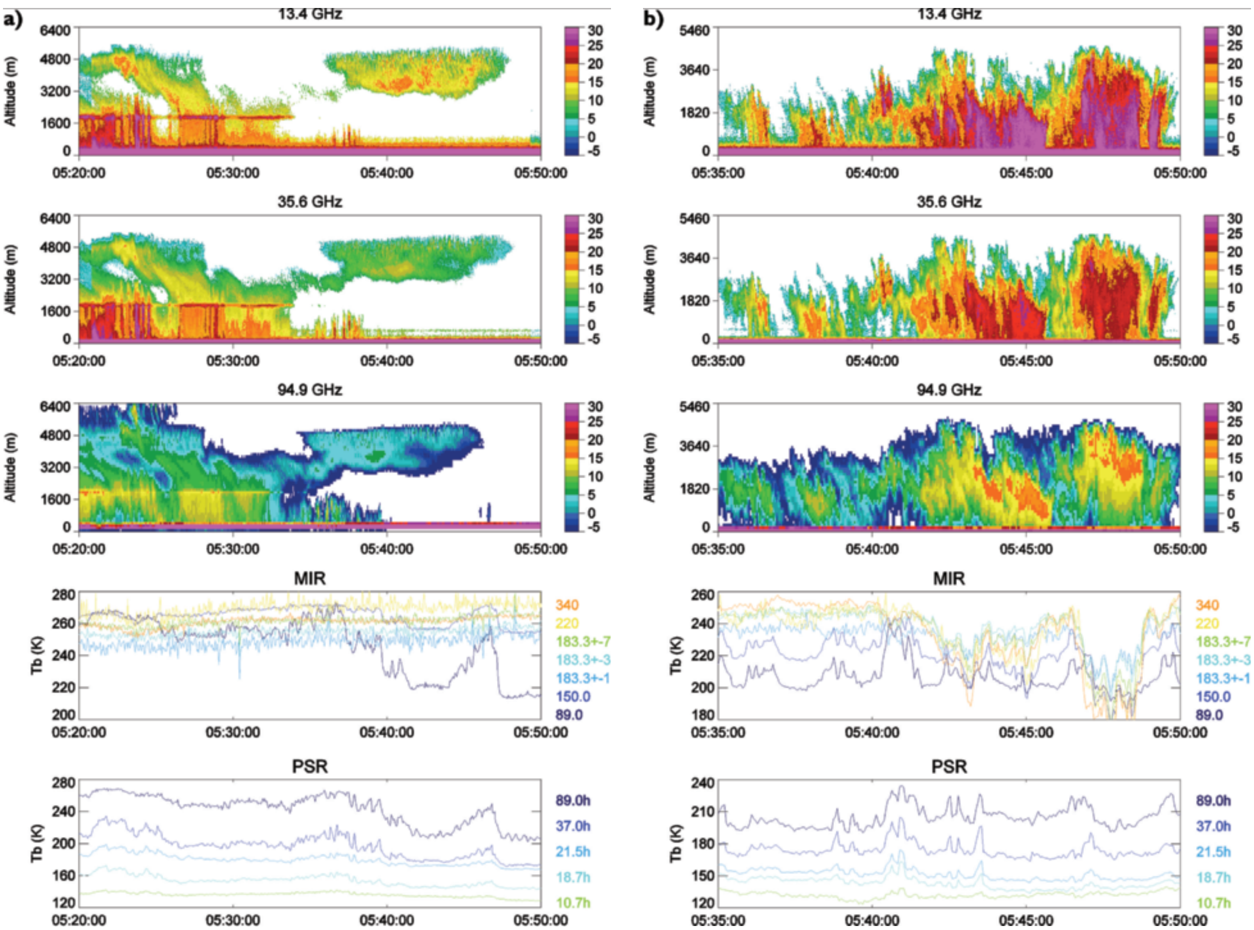


**Fig. 2. (a) 27 Jan 2003 (rain event with bright band over the Sea of Japan) coincident Wakasa Bay data from the NASA P-3, and (b) 29 Jan 2003 (convective snow event over the Sea of Japan) coincident Wakasa Bay data from the NASA P-3. All data are cross-track nadir.**

for a variety of unplanned investigations as well and, to this end, are made freely available to the community.

**ACKNOWLEDGMENTS.** The success of the Wakasa Bay campaign is attributable to many people. The dedication of Willie Dykes, the P-3 captain, to finding ways to fly the needed flight lines under often-challenging circumstances, was key to success. Thanks also go to Dave Easmunt, mission manager, for the many hours he hunted down necessary equipment and information. Thanks go to the instrument principal investigators and their staff for an excellent campaign. Many thanks to Ramesh Kakar and David Starr for their support in obtaining the funding from NASA.

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## A FEW DEFINITIONS

**Beam filling** is the systematic error in retrieved rain rate introduced when the microwave radiometer's field of view is not filled with a constant rain rate.

**Freezing level** (also called the melting level) is the altitude at which the temperature is 0°C.

**Radiative transfer** is the process of transmission of electromagnetic radiation through the atmosphere. The main two elements of radiative transfer are a multiplicative effect (extinction) and an additive effect (emission).

**Bright band** is the layer just below the freezing level where snow with a water coating produces high radar reflectivities.

**Forward modeling** is the process of using a physical model and radiative transfer theory to estimate the remotely sensed brightness temperature of geophysical parameters.