Measurements made during Jasmine

Jasmine featured an ensemble of instruments to make measurements in the ocean and atmosphere with a combination of *in situ* and remote sensing methods. A summary is given in Table 1. On the atmospheric and near-surface ocean side, measurements included gps rawinsondes, bulk near-surface meteorology, air-sea turbulent fluxes, radiative fluxes, numerous raingages, three profiling Doppler radars, microwave and IR radiometers, a cloud ceilometer, and a scanning C-band Doppler precipitation radar. On the ocean side, blah blah blah....

The ETL ship-based air-sea interaction system was used for bulk meteorology, radiative, and turbulent fluxes with additional measurements provided by the ship's operational instruments and CSIRO. The majority of the sensors were mounted on a scaffold unit just aft of the bow (see figure ??); the turbulence sensors were mounted on a forward-facing boom on the ship's jackstaff at the most forward and best exposed location on the ship. The ETL measurement system is described in detail by Fairall *et al.* (1997), so only a brief sketch will be given here. A sonic anemometer/thermometer is used to make turbulent measurements of stress and buoyancy flux; a high-speed infrared hygrometer is used with the sonic velocity data to obtain latent heat flux. A an inertial navigation system is used to correct for ship motions (Edson *et al.*, 1998). Fluxes are computed using covariance, inertial-dissipation, and bulk techniques (Fairall et al., 1996a). Sea-surface temperature is derived from bulk water measurements at a depth of 5 cm with a floating thermistor; corrections are applied for the cool skin effect (Fairall *et al.*, 1996b). Mean air temperature and humidity are derived from a conventional aspirated T/RH sensor; the infrared hygrometer provided redundant information. Wind velocity was derived from the sonic anemometer after appropriate corrections for ship motion; the winds can be referenced to the sea surface using the ship's Doppler speed log or they may be referenced to fixed earth using the ship's pcode GPS. Error estimates are given in Fairall *et al.* (1997).

CSIRO provided a pair of aspirated thermocouple wet/dry bulb psychrometers, a dual (upward and downward facing) IR thermal radiometer (for ocean skin temperature), and two STI Mini-ORG raingages that have been calibrated in the CSIRO rain tower (Bradley and Weller, 1997). The CSIRO psychrometers and raingages served as standard for mean air temperature and humidity and for rain rate. The IR radiometer system provided an estimate of true ocean skin temperature to complement the floating sensor (5 cm depth), the ship's thermosalinograph (about 5 m depth), and CTD ocean temperature profiles.

Through a cooperation of WHOI, CSIRO, NOAA/AOML, and ETL, the flux system was also complemented with bulk air/ocean and high-speed atmospheric CO_2 concentration measurements for investigations of air-sea transfer of CO_2. AOML has an operational underway bulk CO_2 measurement system (Feely et al., 1998) that provides air and oceanic concentrations of CO_2 and the air-ocean concentration difference (ΔpCO_2). Both open-path and closed-path IR-absorption fast CO_2 concentration instruments were used (Fairall et al. 1999; McGillis et al. 1999); these sensors provided fast water vapor measurements to complement the standard fast IR hygrometer..

Three profiling Doppler radars and a microwave radiometer system were used to define a variety of PBL and precipitating system diagnostics. Seagoing versions of the 915 MHz wind profiler (Ecklund et al., 1988) have been used at sea since their development for the TOGA COARE program. The system uses two tilted (15 °) and one vertical beam from a switchable phased array antenna on a mechanical stabilizer to keep it level. For Jasmine, wind profiles were obtained at 60-m and 100-m resolution; with reliable winds to about 2 km and 5 km, respectively, in clear-air conditions. Reliable winds were usually obtained in precipitation up to about 15 km. A 3 GHz (S-band) profiling Doppler radar was used for precipitation measurements (Ecklund et al., 1999). This system uses one vertical beam from a fixed parabolic dish antenna; no stabilization was used. Compared to the 915 MHz wind profiler, the S-band system is much less sensitive to clear-air returns but more sensitive to precipitation. Reliable returns were usually obtained in precipitation up to about 15 km. These two radars have seen extensive use in diagnosing properties of convective systems (Gage et al., 1996; Gage et al., 1999). A 35 GHz (K-band) profiling Doppler cloud radar (Moran et al., 1998) was deployed in combination with a dual frequency microwave radiometer (Hogg et al., 1983) for cloud property measurements. The short wavelength (8 mm) make this radar sufficiently sensitive to observe cloud droplets (thus, it is often referred to as a 'cloud radar'). Cloud radars have had only limited application to marine clouds (Frisch et al., 1995; White et al., 1996; Post et al., 1997) and Jasmine is only the second deployment of such a system on a ship. The microwave radiometer provides retrievals of total integrated water (vapor and liquid separately) and has been used extensively for marine investigations (Snider and Hazen, 1998). The microwave radiometer is an essential complement to the cloud radar for retrievals of cloud droplet size information (Frisch et al., 1998). Additional cloud information is obtained from a commercial lidar ceilometer, which is not 'blinded' by precipitation so it is better able to detect cloud base than the cloud radar, with a vertical resolution of 35 m and a maximum range of 7.8 km.

Table 1. Instruments and measurements for air-sea interaction, cloud, and precipitation studies in JASMINE. Wave hatching denotes ship system.

ITEM	SYSTEM	MEASUREMENT
1	Air-sea flux system	Motion corrected turbulent fluxes
2	Pyranometer & Pyrgeometer	Downward solar radiative, IR flux
3	Bulk meteorology	SST, Tair, RH, wind speed & direction
4	Ceilometer	Cloud-base height
5	0.92 & 3 GHz Doppler radar profiler	Wind & Precipitation Profiles
6	Raingauges	Rainrate
7	Rawinsonde	Wind, temperature, humidity prof.
8	35 GHz Doppler cloud radar	Cloud microphysical properties
9	20, 31 GHz μwave radiometer	Integrated cloud liquid water, total vapor
10	WHOI LICOR 6262 system	Fast CO2 air concentrations
11	Upward pointed IR thermometer	Cloud-base radiative temperature
12	BNL Portable Radiation	Direct/diffuse solar, IR fluxes
13	Scanning C-band Doppler radar	Precipitation 3-D structure
14	CTD	Ocean T, S profiles
15	ADCP	Ocean current profiles
16	Satellite/SCS	NOAA, GMS data
17	IMET/SCS	Meteorology
18	Navigation/SCS	Position, course, speed, heading, etc
19	Thermosalinograph	Near-surface T, S
20	AOML underway CO2 system	Water-air CO2 concentrations
21	Autosal	Water salinity calibrations

Bradley, E. F., and R. A. Weller, 1997: Fourth workshop of the ToGA_COARE Air-Sea Interaction (Flux) Working Group and GEWEX Cloud Systems Study WG-4. NCAR 14-16 May 1997, Boulder, CO. NCAR/MMM, University Corporation for Atmospheric Research, Boulder, CO, pp54.

Ecklund, W.L., D. A. Carter, and B. B. Balsley, 1988: A UHF profiler for the boundary layer: Brief description and initial results. *J. Atmos. and Oceanic Tech.*, **5**, 432-441.

Ecklund, W.L., C.R. Williams, P.E. Johnston and K. S. Gage, 1999: A 3 GHz profiler for precipitating cloud studies. *J. Atmos. and Oceanic Tech.*, **16**, 309-322.

Edson, J.B., A. A. Hinton, K. E. Prada, J.E. Hare, and C.W. Fairall, 1997: Direct covariance flux estimates from moving platforms at sea. *J. Atmos. Oceanic Tech.*, **15**, 547-562.

Fairall, C. W., E. F. Bradley, D.P. Rogers, J. B. Edson, and G. S Young, 1996a: Bulk parameterization of air-sea fluxes in TOGA COARE. *J. Geophys. Res.*, **101**, 3747-3767.

Fairall, C. W., E. F. Bradley, J. S. Godfrey, G.A. Wick, J. B. Edson, and G. S. Young, 1996b: Cool skin and warm layer effects on the sea surface temperature. *J. Geophys. Res.*, **101**, 1295-1308.

Fairall, C.W., A.B. White, J.B. Edson, and J.E. Hare, 1997: Integrated shipboard measurements of the marine boundary layer. *J. Atmos. Oceanic Tech.*, **14**, 338-359.

Fairall, C. W., J. E. Hare, J. B. Edson, and W. McGillis, 1999: Parameterization and micrometeorological measurement of air-sea gas transfer. *Bound.-Layer Meteorol.*, to appear.

Feely, R. A., R. Wanninkhof, H. B. Milburn, C. E. Cosca, M. Stapp, and P. P. Murphy, 1998: A new automated underway system for making high precision pCO2 measurements onboard research ships. *Analytica Chim. Acta*, **377**, 185-191.

Frisch, A. S, C. W. Fairall, and J. B. Snider, 1995: On the measurement of stratus cloud and drizzle parameters with a K-band Doppler radar and a microwave radiometer. *J. Atmos. Sci.*, **52**, 2788-2799.

Frisch, A.S., G. Feingold, C. W. Fairall, and J .B. Snider, 1998:. On stratus cloud liquid water profiles from a cloud radar and microwave radiometer. *J. Geophys. Res.*, **103**, 23195-23197.

Gage, K.S., C.R. Williams and W.L. Ecklund, 1996: Application of the 915 MHz profiler for diagnosing and classifying tropical precipitating cloud systems. *Meteorol. Atmos. Phys.*, **59**, 141-151.

Gage, K.S., C.R. Williams, W.L. Ecklund, and P.E. Johnston, 1999: Use of two profilers during MCTEX for unambiguous identification of Bragg scattering and Rayleigh scattering. *J. Atmos. Sci*., in press.

Hogg, D. C., F. O. Guiraud, J. B. Snider, M. T. Decker, and E. R. Westwater, 1983: A steerable dual-channel microwave radiometer for measurement of water vapor and liquid in the atmosphere. *J. Clim. Appl. Meteor*., **22**, 789-806.

Moran, K. P., B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Welsh, and K. B. Widner, 1998: An unattended cloud-profiling radar for use in climate research. *Bull. Am. Met. Soc*., **79**, 443-455.

McGillis, W. R., J. B. Edson, J. D. Ware, J. E. Hare, and C. W. Fairall, 1999b: Direct covariance CO_2 fluxes across the air-sea interface. *J. Geophy. Res.*, submitted.

Post, M. J., C. W. Fairall, J. B. Snider, Y. Han, A. B. White, W. L. Ecklund, K. M. Weickmann, P. K. Quinn, D. I. Cooper, S. M. Sekelsky, R. E. MacIntosh, P. Minnett, and R. O. Knuteson, 1997: The Combined Sensor Program: An air-sea interaction science mission in the central and western Pacific Ocean. *Bull. Am. Met. Soc*., **78**, 2797-2815.

Snider, J.B. and D.A. Hazen, 1998: Surface-based observations of water vapor and cloud liquid in the temperate zone and in the tropics. *Radio Science*, **33**, 421-432.

White, A.B., C. W. Fairall, A.S. Frisch, B. W. Orr, and J. B. Snider, 1996: Recent radar measurements of turbulence and microphysical parameters in marine boundary layer clouds. *Atmos. Res.*, **40**, 177-221.