Determination of Boundary-Layer Fluxes With an Integrated Sounding System

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Abstract

An important atmospheric goal of TOGA COARE is to determine the exchange of momentum, and sensible and latent heat in the western Pacific over the time scales of convective storms, westerly bursts and lower frequency events. TOGA COARE will also require detailed moisture budget studies in support of improved understanding of sub-gridscale processes and the evaluation of model parameterization schemes. Present field-deployable measurement systems do not provide observations on the temporal and spatial scales necessary to properly address these and other issues. We present the concept of the so-called Boundary-Layer Integrated Sounding System (BLISS) as a means to provide these measurements. The BLISS consists of a suite of demonstrated in situ and remote sensing subsystems which together provide the measurements to sense directly or retrieve high-resolution profiles of winds, temperature and moisture and associated fluxes. Individual subsystems under consideration include: surface meteorological station; UHF Doppler wind profiling radar; radio acoustic sounder; infrared interferometer-spectrometer; microwave radiometer; and an Omega-VLF radiosonde system for in situ but low frequency profiles to ~20mb. Other features of the integral system include a central data acquisition and processing counter, real-time satellite telemetry link, and rugged, easily transported base station. We estimate the cost of to be sufficiently modest to enable deployment of a network of order 10-15 systems in support of TOGA COARE.

1. Background

The scientific requirements that have motivated the concept of a Boundary-Layer Integrated Sounding System (BLISS) are summarized in the early planning for the TOGA Coupled Ocean Atmosphere Response Experiment (e.g., see Lukas and Webster, 1988) as well as other major mesoscale and stormscale experiments such as the U.S. national Stormscale Operational and Research Meteorology program, STORM (NCAR, 1989). We summarize below some of the major objectives and scientific issues of TOGA COARE and the observational requirements provided by a network of integrated sounding systems.

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The warm waters of the Western Pacific play a major role in the dynamics of the coupled ocean-atmosphere El Niño/Southern Oscillation (ENSO) phenomena. ENSO forcing and response events are a major cause of low frequency atmospheric variability, especially in the tropics. A major objective of TOGA is to develop sufficient scientific understanding of ENSO phenomena to permit the eventual prediction of these events through the application of coupled ocean-atmosphere models. As recognized by TOGA scientists, the key to understanding the Southern Oscillation appears to lie in detailed knowledge of the physical processes that couple the tropical ocean and atmosphere.

It is widely recognized that the current observational effort of TOGA is insufficient to resolve certain key scientific issues that must be understood to make further progress. As identified by the 1987 Western Pacific Air-Sea Interaction Workshop (Lukas and Webster, 1988), and recently refined, these issues include the need to understand:

- Principal processes responsible for coupling of ocean and atmosphere in the Western Pacific warm pool system.

- Principal atmospheric processes that organize convection in the warm pool region.

- Tropical oceanic response to combined buoyancy and wind stress forcing in the Western Pacific.

- Multiple scale interactions that extend the oceanic and atmospheric influence of the Western Pacific warm pool region to other regions, including the role and significance of the westerly burst phenomenon.

One important and illustrative research goal of TOGA COARE will be to examine the dynamical interaction of the ocean and the atmosphere during westerly wind bursts. The occurrence of episodic westerly wind bursts over the Western Equatorial Pacific is thought to play an important role in the genesis of the El Niño. As discussed in Lukas (1988), the westerly wind bursts can provide the needed trigger to generate Kelvin waves in the Western Pacific Ocean. Furthermore, a series of westerly wind bursts could also provide the mechanism for moving the warm pool of water that normally resides in the Western Pacific eastward toward the dateline.

A complete understanding of the evolution of these bursts requires a better understanding of the dynamics of atmospheric circulation systems over the Western Pacific Ocean. The westerly wind bursts may be associated with surges of cold air originating from higher latitudes. Unfortunately, the Western Pacific Region is largely void of upper-air observations that are needed to answer some of the questions now being raised. For example, the vertical structure of the westerly wind bursts is largely unknown. Also, their relationship to convection and the recurring 30-60 day oscillation need to be explored.

Another important part of the TOGA COARE will be detailed moisture budget studies. Historically, budget studies have been done for the Atlantic as part of the GATE Experiment. The few budget studies that have been done for the tropical Pacific have shown a different heating profile. The heating profile is largely determined by latent heat release in convective storms. Climate models have been shown to be very sensitive to the detailed heating profile.

Rasmusson (1988) has recently pointed out that TOGA process studies aimed at addressing deficiencies in modelling the coupled ocean-atmosphere system must address both a proper physical understanding of sub-gridscale processes and the "calibration" of simplified parameterization schemes. The latter goal can be achieved through careful budget studies.

Moisture budget studies require accurate high vertical resolution soundings of humidity and wind. The BLISS is designed to provide this information. The continuous lower troposphere wind profiling capability of the 915 MHz Doppler radar will be ideally suited for determining the perimeter vapor flux. Moisture profiling is also very important. The IR interferometer and microwave radiometer will provide this information together with periodic balloon soundings.

2. Boundary Layer Integrated Sounding System (BLISS)

2.1 Overview

The objective of the BLISS is to develop a sounding system that will provide the research community with a transportable facility which can satisfy the observational/scientific requirements of TOGA COARE and other programs by routinely measuring all important thermodynamic variables (and some radiative variables) through the lower troposphere. It is important that the BLISS function as an integrated system rather than as independent measurement systems. In this regard, an important aspect of the development is to mechanically engineer the facility within a common transportable housing, and to provide a central data acquisition, processing, display and communications capability.

The profiling requirements of the boundary-layer segment of the atmospheric science community were surveyed by Dabberdt *et al.* (1986). About 25 scientists participated in a survey and subsequent workshop to establish consensus priorities for the most important atmospheric variables and the performance specifications of the requisite profiling system(s). First-priority variables were identified to be: horizontal winds, temperature, and humidity; other variables and their relative priority (in parentheses) included: boundary-layer height (2), turbulence (3), cloud base height (3), aerosols (3), and trace gases (3) such as ozone, sulfur dioxide and nitrogen dioxide. Table 1 summarizes what the authors refer to as consensus requirements for profiling systems that will meet the needs of atmospheric scientists concerned with boundary-layer processes.

The performance of the UHF boundary-layer wind profiler reported by May *et al.* (1989) is virtually consistent with the needs summarized in Table 1. Significant progress has been made over the last few years in the measurement of temperature, another first-priority variable. The technology used to achieve this progress is the so-called radio acoustic sounding system, or RASS. The RASS approach measures the vertical profile of the speed of sound using a Doppler wind profiler to track the propagation of the refractive index gradient established by an acoustic wave. After corrections for humidity and atmospheric motion, the speed of sound is uniquely related to the square root of temperature. Whereas RASS is a straightforward extension of wind profiler technology, there presently is no comparable demonstrated application for humidity profiling. And even with RASS, there is a height limitation of a few kilometers. Although these heights meet the needs of the boundary-layer community, they do not satisfy the upper-level requirements of the mesoscale, synoptic and climate communities. As an attempt to achieve these requirements, we have proposed a suite of complementary active and passive remote and in situ sensors. Figure 1 is a conceptual illustration of the integrated sounding system. Candidate component sensors include: UHF wind profiler, RASS, navaid rawinsonde system, high resolution infrared interferometer-spectrometer (HIS), microwave radiometer, and surface meteorological system. The objective of

Table 1

Consensus Requirements for Boundary-Layer Profilers

Requirement	Horizontal Wind ($m\ s^{-1}$)					Temperature (K)					Specific Humidity ($g\ kg^{-1}$)				
	mean	s.d.	min	max	mode	mean	s.d.	min	max	mode	mean	s.d.	min	max	mode
Height coverage, km	3.4	1.1	1.5	5.0	3.0	3.7	1.4	1.0	6.0	5.0	3.6	1.4	1.0	6.0	3.0* 5.0*
Height resolution, km	82	53	10	200	100	58	39	10	100	100	72	34	10	100	100
Time resolution, min	15	14	1	60	15	15	15	1	60	1* 30*	16	16	1	60	30
Threshold	0.7	0.4	0.1	1.0	1.0	-	-	-	-	-	1.2	1.6	0.01	5.0	1.0
Accuracy	0.8	0.5	2.0	0.1	0.5	0.7	0.3	0.05	1.0	1.0* 0.5*	0.7	0.3	0.1	1.0	1.0
Precision	0.5	0.3	1.0	0.1	0.5	0.3	0.3	0.02	1.0	0.1* 0.2*	0.4	0.4	0.01	1.0	1.0

Source: Dabberdt *et al.* (1986)

* bi-modal response

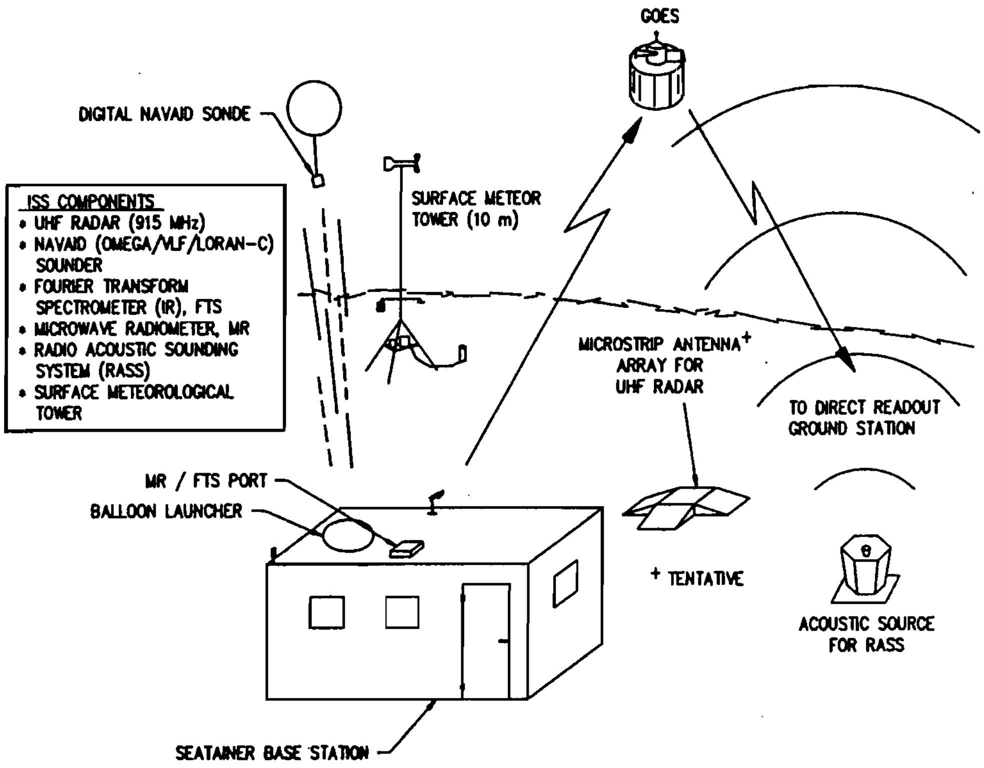

FIG.1. Conceptual design of the Boundary-Layer Integrated Sounding System.

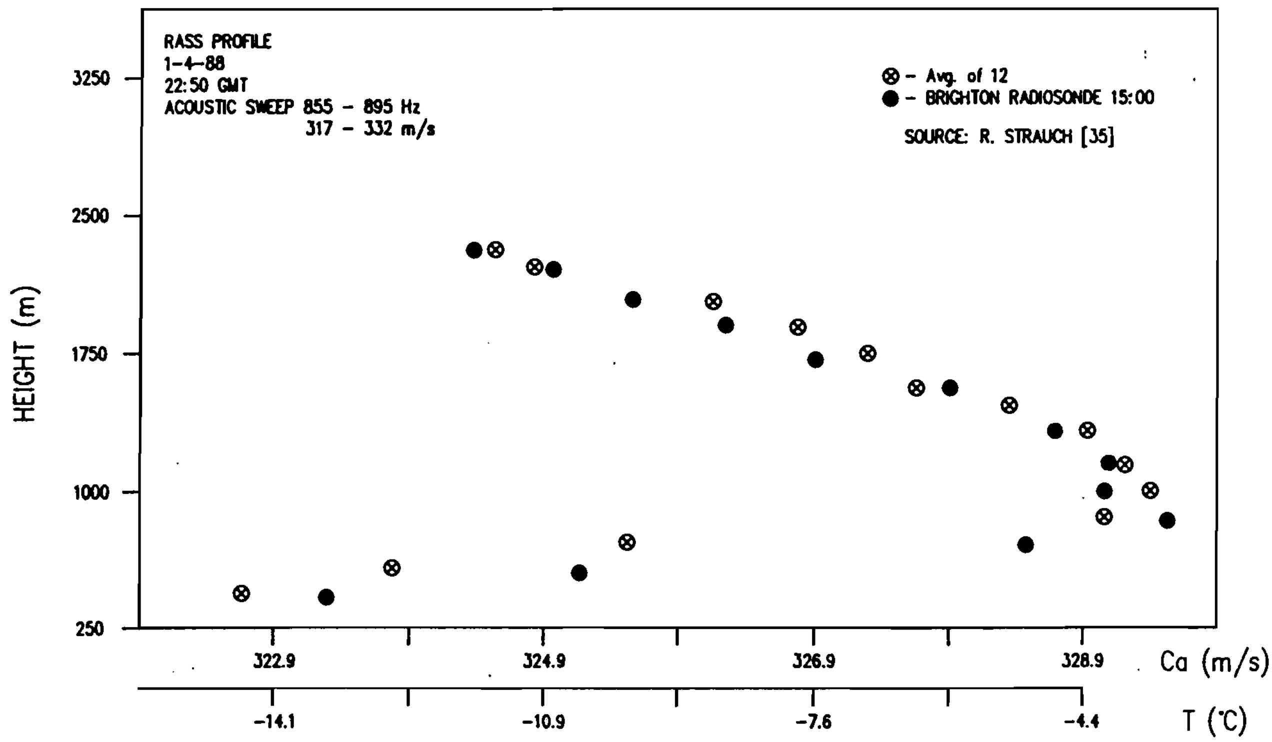

FIG.2. Comparison of near-coincident temperature profiles by RASS and radiosonde near Brighton, Colorado (USA).

the system is to provide comprehensive, continuous high-resolution thermodynamic profiling of the lower troposphere and lower resolution profiling of the upper troposphere and stratosphere. The integrated sounding system would be easily transported and deployed in coordinated networks for application in a wide range of research studies.

2.2 *Clear-Air UHF Radar*

Ecklund et al. (1988a) have developed a clear-air boundary layer radar using a microstrip antenna and a UHF frequency of 915 MHz to obtain three-component wind profiles with 150-m height resolution from a minimum height of 100m to a maximum height of several kilometers. In a recent test at Christmas Island with a 0.9 x 0.9m antenna area and an average transmitted power of only 1W, they were able to consistently obtain one-minute averaged profiles to a height of 1.8km. Using a larger antenna and a higher power output, we plan to incorporate a similar radar design into the BLISS that will yield maximum ranges (i.e. heights) of 3-4km; this should be possible with a tenfold increase in the radar sensitivity. The height resolution will be enhanced to 100m and possibly to 30m. Estimates of the measurement uncertainty of the current radar is estimated at about 1 m/s. Table 2 provides system specifications for the present NOAA prototype system as given by Ecklund et al. (1988b), as well as proposed specifications for the BLISS.

Table 2

BOUNDARY LAYER RADAR SPECIFICATIONS

	Present System	Proposed System
FREQUENCY (MHz)	915	915
WAVELENGTH (m)	0.33	0.33
ANTENNA AREA (m^2)	1 - 2	2 - 9
BEAMWIDTH (1 way, deg)	18 - 9	9 - 6
AVERAGE POWER (W)	1	10 - 30
RANGE RESOLUTION (m)	150	100
LOWEST HEIGHT (m)	150	100
AVERAGING TIME (s)	30 - 120	30 - 120
TYPICAL COVERAGE (km)	1 - 2 (clear air)	3+

2.3 *Radio Acoustic Sounding System*

Temperature profiles have been obtained by augmenting the clear-air wind profiling radar with an acoustic source that is swept across an acoustic band at approximately 1/2 the radar wavelength. The Bragg scattering condition is satisfied at the acoustic frequency where the maximum UHF backscattered return is obtained. By using the radar to measure the propagation of the acoustic wavefront, the profile of the speed of sound is obtained from which the temperature profile is derived by applying corrections for atmospheric humidity (obtained in the BLISS from the navaid sounding system or the passive sensors) and the wind speed (measured by the clear-air radar). The RASS technique has successfully been tested by Currier et al. (1988) and Strauch (1988).

Strauch *et al.* (1989) evaluated three RASS systems using 50, 404 and 915 MHz wind profilers and 5, 5 and 50 W acoustic transmitters, respectively. The maximum altitudes achieved by the three systems were 5-9, 1.5-2.5, and 0.6-1.5 km, respectively. The lower maximum altitude at the higher frequencies is partially the result of the increased rate of acoustic absorption: 45 dB km^{-1} for a 2 kHz acoustic source and 915 MHz radar vs. 10 dB km^{-1} for a 900 Hz source and 404 MHz radar. Horizontal wind apparently has little effect on temperature retrieval for winds up to 10 ms^{-1}. The RMS difference between RASS temperatures (both 50 and 404 MHz systems) and co-located radiosonde measurements averaged 0.5K over a variety of weather conditions; Figure 2 is a comparison of RASS and radiosonde temperature profiles from some earlier work by Strauch (1988).

2.4 NAVAID Radiosonde System

The sounding component of the BLISS will follow the design of the TOGA sounding system now deployed on Kanton Island to support TOGA/ENSO studies. Many features of the system follow from earlier NCAR developments, such as the Automated Shipboard Aerological Program and the Cross-chain Loran Atmospheric Sounding System (CLASS). Figure 3 illustrates the Kanton Island System which consists of six components:

- A 3.7 x 3.7 m insulated plastic modular environmental shelter,
- A primary 1200-Watt solar panel/battery system and a secondary 1,000-Watt wind turbine/battery system,
- An Omega/VLF navaid upper-air sounding system,
- A nylon bag balloon launcher,
- A surface meteorological system, and
- A satellite communications system (GOES).

The upper-air sounding system in the Kanton Island station uses world-wide Omega navigation signals and the U.S. Navy VLF communications signals to compute upper-level winds. A commercial lightweight (200 gm) radiosonde contains an Omega/VLF receiver for receiving the navaid signals and a telemetry transmitter for retransmitting these signals to a ground receiving station (base station). The radiosonde also makes measurements of pressure, temperature and humidity (P,T,H) and telemeters this data to the base station. The radiosonde is transported vertically by a 200 gm balloon at an ascent rate of about 300 m/min; the state measurements (P,T,H) are obtained at a 1.2-s rate and smoothed over 20-s intervals (i.e. least squares fit), the Loran Time-Of-Arrival (TOA) measurements are made every 4-s and smoothed over a 30-s interval; the Omega/VLF Phase measurements are made every 10-s and smoothed over a 2-min interval. All data (P,T,H and winds) are output every 10-s. BLISS will have the capability to compute winds by using either the Omega/VLF navaid signals or by using multi-chain Loran-C signals. This added capability will provide improved wind accuracy and height resolution of the computed winds in areas where Loran-C coverage exists. We also will explore using the Global Positioning System for increased accuracy and better height resolution.

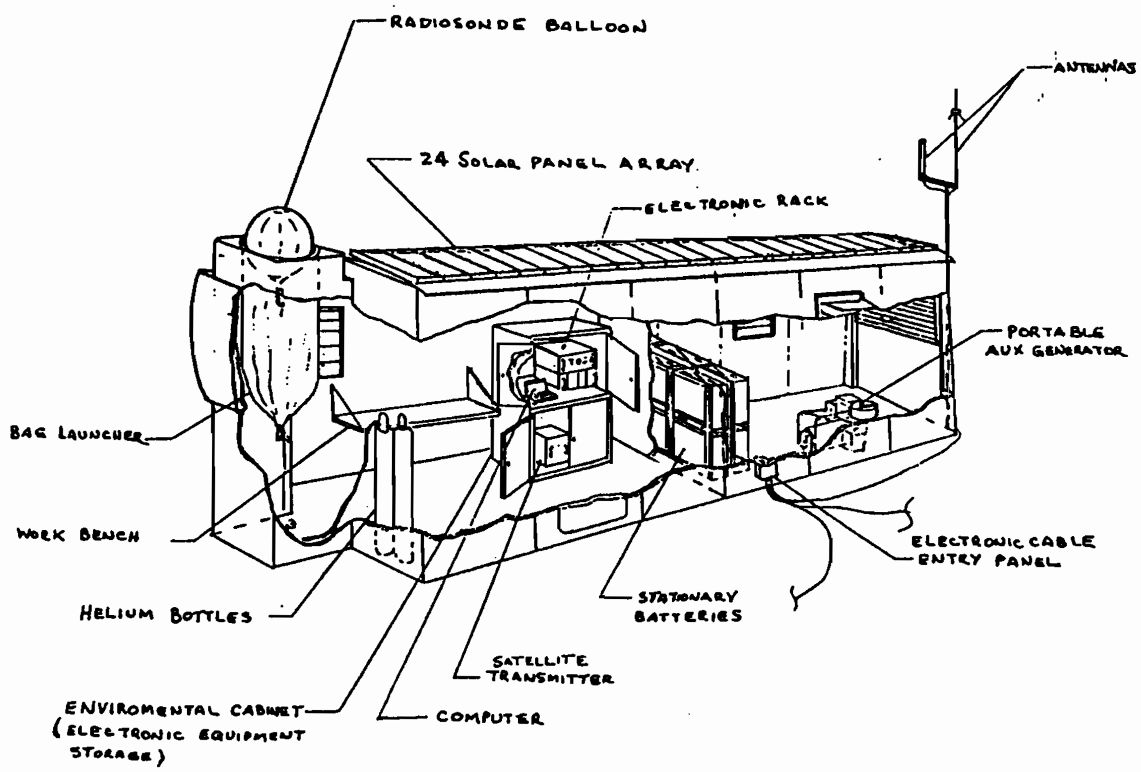

FIG.3. Layout of Kanton Island System.

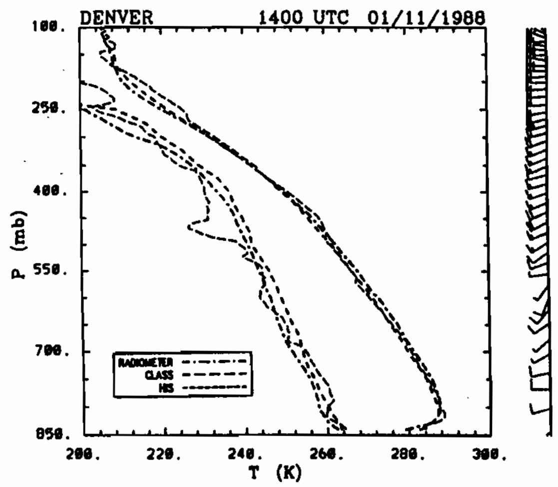

FIG.4. Coincident temperature and dewpoint profiles by radiosonde (CLASS), interferometer spectrometer, and microwave radiometer at Denver, Colorado - U.S.A. (source: Smith et al., 1989).

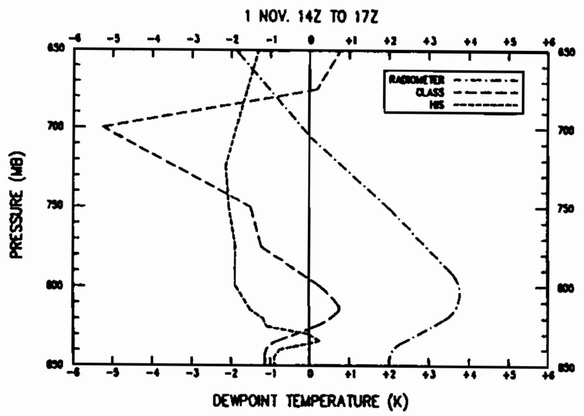

FIG.5. Three-hourly changes of dewpoint profiles obtained by radiosonde (CLASS), interferometer spectrometer, and microwave radiometer at Denver, Colorado - U.S.A. (source: Smith et al., 1989).

2.5 *High Resolution Interferometer Spectrometer (HIS)*

Fourier transform spectrometry (FTS) provides observations of high resolution continuous spectra of atmospheric emissions with relatively simple and inexpensive instrumentation. In the short and intermediate infrared region (3-20um), the 0.5cm^{-1} spectral resolution enables isolation of emission due to atmospheric H_2O, CO_2, N_2O, O_3, CH_4, and CO. A ground-based system looking upwards and observing downwelling radiation can be used to profile temperature and water vapor with high vertical resolution (≈200m near the surface, but diminishing with height); the other trace gases might also be profiled in a similar manner. The present high-resolution FTS system has successfully been used on high-altitude aircraft. Several lower spectral resolution FTS sounding systems have flown on earth-orbiting and planetary-mission satellites. A simplified ground-based system recently has been tested through comparisons with in situ tower-mounted sensors and radiosondes, and remote profiles obtained by radio acoustic sounding and microwave radiometers; these comparisons were made late in 1988 at Denver Stapleton Airport in conjunction with the NOAA/ERL/Wave Propagation Laboratory and NCAR.

Examples of temperature and dew-point profiles are given in Figure 4 from the recent Denver intercomparison experiment (Smith el al., 1989). The experiment compared coincident profile measurements obtained by HIS, microwave radiometer and the CLASS cross-chain LORAN radiosonde system, respectively. Data retrieval with the two passive sensors utilized seasonal climatology. Temperature profiles compare well up to 300 mb (surface pressure is about 840 mb) except for a smoothing of the inversion top around 815 mb and a failure to detect fine-scale structure in the upper levels (e.g. 575 and 450 mb). The remote moisture profiles are only representative in the broad sense, failing to sense significant features throughout most of the profile; e.g. note the dry layer between 450 and 500 mb. Another application is the detection of temporal changes in moisture. Figure 5 illustrates 3-h changes in the vertical profiles of dew point temperature corresponding to the period of the profiles of Figure 4. There is generally good agreement in the actual profiles of dew-point change resulting from CLASS and HIS, and very good agreement in a relative sense between CLASS and radiometer profiles. These early results suggest applications for hybrid systems that use periodic radiosonde profiles to obtain absolute measurements and continuous remotely sensed profiles to obtain temporal changes.

2.6 *Microwave Radiometer*

The microwave radiometer is a passive sensor that measures incident energy at various frequency bands; the candidate sensor for the BLISS operates at 21, 31, and 60 GHz to provide estimates of the vertical profiles of temperature and humidity, as well as the integrated precipitable water vapor and cloud liquid water content. The 21 GHz and 31 GHz channels are fixed frequency channels, whereas the 60 GHz channel is tunable over a 6 GHz bandwidth with measurements available at 11 frequencies. The humidity is determined by simultaneous measurements at two frequencies: the integrated precipitable water vapor is measured by the absorption at 22.2 GHz, and the cloud liquid water content is determined from absorption at 35 GHz. Temperature profiles are determined by measurements on oxygen absorption lines at 60 GHz, with corrections for cloud liquid water. Thermodynamic profile data from the navaid sounding system are used to initialize the profile inversion of the radiometric data, although climatological profiles can also be used (with lesser accuracy). Figures 4 and 5 illustrate the temperature and humidity profiles and temporal profile changes obtained with a similar radiometer in Denver, Colorado.

2.7. *Meteorological Surface Station*

The surface meteorological station will be patterned after the remote stations presently in use with the NCAR portable automated mesonet (PAM); see Brock et al. (1985). PAM remote stations measure pressure, temperature, humidity, winds, and liquid precipitation. So-called integrated sensors provide calibrated measurements in engineering units for pressure, temperature and humidity; an integrated wind sensor is nearing completion at present. Recent enhancements to the PAM remote station include a capability to measure the surface radiation budget through use of a radiation stand and a general purpose interface; this capability will be included in the BLISS.

3. Boundary-Layer Flux Estimates

3.1 Momentum Flux

The vertical flux of horizontal momentum is an important dynamical quantity that can be determined from measurements of the covariance of horizontal and vertical velocities. The technique of determining momentum flux from velocity measurements by a single Doppler radar using VAD analysis dates from early work by Lhermitte (1968) and Wilson (1970). The technique has been used by Kropfli (1986) to obtain measurements of turbulent fluxes in the planetary boundary layer. His measurements were confirmed using independent measurements of momentum flux obtained from the tower at the Boulder Atmospheric Observatory.

Momentum flux measurements have recently been made in the free atmosphere at several locations using wind profiling Doppler radar. The technique utilized is similar to the VAD analysis but typically involves velocity measurements in only a few (usually four) azimuthal directions. This adaptation was developed by Vincent and Reid (1983) for middle atmosphere research. In the middle atmosphere, momentum flux is primarily due to internal gravity waves but the principle of measurement remains the same.

According to the method (Vincent and Reid, 1986) momentum flux is measured by two radar beams symmetric with respect to the vertical direction. If beam 1 measures the radial component v_1

$$v_{R1} = -u_1 \sin\theta - w_1 \cos\theta \tag{1}$$

and beam 2 measures the radial component v_2

$$v_{R2} = +u_2 \sin\theta - w_2 \cos\theta \tag{2}$$

then with a few assumptions concerning horizontal homogeneity of the velocity field

$$\overline{u'w'} = (\overline{v_{R2}^2} - \overline{v_{R1}^2})/2 \sin 2\theta \tag{3}$$

where θ is the off-vertical beam angle.

Recent determinations of momentum flux utilizing wind-profiling Doppler radar and the technique of Vincent and Reid (1983) have been reported by Fukao *et al.* (1988), Fritts and Vincent (1987), Reid and Vincent (1987), and McAffee *et al.* (1989).

3.2 Scalar Fluxes

There are at least four methods of estimating vertical profiles of fluxes of scalar variables such as sensible and latent heat; these methods include eddy correlation; similarity theory; budget analyses; and conditional sampling. The authors are unaware at this time of any definitive tests and evaluations of any of the methods; with the very recent demonstration of the viability of RASS temperature profiling, we expect there will be significant research efforts in this area.

Eddy correlation is perhaps the candidate methodology that comes first into consideration, primarily because it is the only first-principle method of the group. The vertical flux of any scalar **c** is determined simply by the time average of the product of its fluctuation (**c'**) with that of the vertical wind component (**w'**), where flux = $\overline{c'w'}$. There are however several limitations in the sampling that may preclude rigorous application of eddy correlation. At lower levels the sampling rate is too slow (seconds) and the height resolution (30-50m, min.) too coarse. At higher levels these limitations may not be severe, but the low signal-to-noise ratio of the measurements may limit application in view of the (normally) smaller values of the fluxes aloft.

Similarity theory offers an alternative method. When the vertical profile of momentum flux and horizontal wind is known, the profile of the eddy diffusivity for momentum (K_u) is calculated from the ratio of the shear stress (or momentum flux) to the vertical gradient of the horizontal wind. Applying similarity implies that one can specify *a priori* the relationship between the eddy diffusivity for momentum and those for sensible heat and latent heat. In the simplest case, one may assume a ratio of unity; one also may estimate the profile of the ratio based on the profile of the gradient Richardson number (**Ri**). With independent estimates of the fluxes at the surface, the ratio can be calculated at the surface and assumed constant with height or the surface ratio used as an anchor point. Lacking definitive studies, one may assume a scaling approach based on a stability parameter such as **Ri** may offer the best chance for success.

The two methods above (and 'conditional sampling' discussed later) provide estimate from profile measurements at a single location; **budget analyses** provide line or area average estimates based on profile measurements at two or three or more locations, respectively. For the simple case of lateral homogeneity with respect to the flow, the vertical profile of the horizontal average (between sampling locations flux derives from knowledge of the flux at either the upper or lower boundary. The usual approach is to define the upper boundary of the budget domain as the first level where the vertical flux is assumed zero (typically where the scalar gradient goes to zero). The longitudinal fluxes are given by the average of the horizontal wind and the scalar, and the horizontal divergence of the longitudinal fluxes is balanced by a mean vertical flux. Although the authors are unaware of any budget analyses using remotely sensed profiles, there have been other similar applications. Johnson *et al.* (1971) and Ludwig and Dabberdt (1972) successfully applied the method using wind profiles from theodolites and carbon monoxide profiles obtained from an instrumented helicopter to estimate traffic emissions of CO from downtown San Jose and St. Louis.

Conditional sampling is a new concept recently introduced by Businger and Oncley (1989) that offers significant promise on the basis of preliminary evaluations using *in situ* measurements in both the surface layer and planetary boundary layer. The method is a simplification and extension of the eddy accumulation technique (Desjardins, 1977), but seems to overcome some of the sampling constraints of the latter. The conditional sampling approach is based on the empirical relationship between the scalar flux and the difference between the mean upward (+) and downward (-) scalar concentration, where

$$\overline{w'c'} = b(\zeta)\sigma_w[\overline{c^+} - \overline{c^-}] \quad (4)$$

and $b(\zeta)$ is an empirical coefficient that is a slight function of stability, where $\zeta = z/L$ (z is height, and L the Monin-Obukhov length). Sensitivity tests by Businger and Oncley demonstrate that the method is relatively insensitive to stability, and vertical velocity threshold and bias. The insensitivity to w-threshold suggests the method may be applicable to the types of data available from disparate profiling systems (with similarly disparate sensitivities and sampling frequencies).

4. Concluding Comments

TOGA COARE and other mesoscale experiments require networks of sounding systems to estimate profiles of momentum and heat (sensible and latent) and their fluxes, as well as kinematic quantities. While no single technology can address all these requirements, an integrated sounding system consisting of active and passive profilers and in situ methods offers significant promise. Candidate sensing technologies have been reviewed, and a number of potentially applicable flux estimating methods described.

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PROCEEDINGS

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