SUPPLEMENT

EXPERIMENTAL EQUIPMENT

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The experimental strategy for the meteorological program in the Arctic Ocean Experiment 2001 (AOE-2001) was to continuously monitor the structure of the lower troposphere while also carrying out more detailed, but also often more labor-intensive, boundary layer measurements.

The expedition was divided into several parts. During the 3-week ice drift (2–21 August 2001) the atmospheric program (AOE-2001) had priority and all atmospheric measurement systems were used in an intensive effort with several instrument systems deployed on the ice. The rest of the cruise was shared with other programs, and only short-lived (12–48 h) research stations were possible, precluding a full-scale instrument deployment on the ice. The remote sensing monitoring measurements and the *Oden* weather station were run continuously.

The weather station on *Oden*'s seventh (top) deck, ~ 30 m above the ocean surface, continuously logged 1-min averages of atmospheric variables and some navigational information (see Table S1). Soundings were released from *Oden*'s helipad every 6 h during the whole ice drift and during all of the shorter research stations. In total, 118 successful soundings were carried out during 2 months; 80 of these were launched during the ice drift.

TABLE S1: Summary of direct measurements on board *Oden*.

Instrument	Variable	Height (m)	Sampling	Time period
Ceilometer	Cloud base	~ 30	Four per minute	Whole expedition
Backscatter instrument	Visibility	~ 30	Two per minute	
Eppley pyrgeometer	Incoming longwave radiation	~ 30	1-min average	
Eppley pyranometer	Incoming shortwave radiation	~ 30		
Sonic anemometer	Wind speed and direction	~ 35		
Vaisala Pt100	Temperature	~ 30		
Vaisala humicap	Relative humidity	~ 30		
GPS	Heading and position	Not available		
Vaisala rawinsondes	Temperature, humidity, pressure, wind speed, and direction	15 m (helipad) to 10–12 km	Every 6 h	Research stations and entire ice drift

To monitor the Arctic boundary layer (ABL) structure a suite of remote sensors was deployed on *Oden* (Table S2) and on the pack ice during the 3-week ice drift. The remote sensing array consisted of two sodar systems (one two-beam sodar for vertical wind profiles, and one monostatic sodar for boundary layer structure), a 915-MHz wind profiler, a scanning 5-mm radiometer, and an S-band Doppler cloud and precipitation radar. These sensors provided observations of the thermal, kinematic, and turbulent structure in the lowest 400 m–4 km of the troposphere with temporal resolution from minutes to 1 h. The cloud and precipitation radar provided measurements through most of the troposphere. When used together, these instruments continuously monitor the structure of the lowest troposphere at a temporal and vertical resolution sufficient to resolve many transient features of the ABL. The remote sensing array also enhanced the 6-hourly rawinsonde observations, giving complementary and to some extent redundant measurements of temperature, wind speed, and direction, and indications of turbulence up to 1–2 km at 60–100-m resolution every 6–60 min.

The 915-MHz wind profiler (Ecklund et al. 1988) was deployed on the bow of the *Oden* during the entire cruise; it also contained a motion pack to make it possible to correct the measured winds for the ship's motion. This radar detects backscatter of the emitted radiation from fluctuations in the refractive index, caused primarily by moisture fluctuations and large hydrometeors. Thus, the vertical range of the data is much greater during periods of precipitation, while it is also sensitive to the absolute humidity in the atmosphere. The wind speed is determined from the Doppler frequency shift in the backscattered radiation emitted at different angles to the vertical. Two different modes of operation provide 55- and 97-m resolution, respectively, with a typical range of 1–4 km.

The S-band cloud radar is a vertically pointing Doppler radar, emitting radiation at the S band (Moran et al. 1998; White et al. 2000). Deployed on the bow of the *Oden* for the duration of the expedition, it measured radar reflectivity and vertical velocity within clouds and precipitation. Alternating between two modes, with vertical resolutions of 45 and 105 m, respectively, and a temporal resolution of 30 s, its maximum range was ~ 8.5 km. It provided reflectivity from clouds and precipitation (related to condensed water content), and the mean and spectrum of the fall speeds of cloud and precipitation particles. Taken together, this can yield information on particle phase and size.

The 5-mm (60 GHz) scanning radiometer (Westwater et al. 1999) was mounted on the railing of the seventh deck of *Oden* on the starboard (right) side at about 30 m above the ice with a 270° free view in the vertical plane. The radiometer provided temperature profiles up to ~ 1 km at time resolutions of 0.5 s; postprocessing produced 5-min averages. It utilizes emissions in the oxygen band of the longwave radiation spectrum, making it relatively independent of changes in the meteorological conditions. Theoretical estimates of vertical resolution are 7.5 m near the surface, degrading gradually to 300 m near a 400-m height, though comparisons to soundings and a tall tower suggested better resolution than this. Field tests carried out during winter conditions in Boulder, Colorado, showed root-mean-square errors of less than 1 K when compared to temperature sensors on the 300-m Boulder Atmospheric Observation

Table S2: Summary of remote sensing instruments.

Instrument	Variable	Time resolution	Location
Two-beam Doppler sodar	Wind speed and direction	20-s sampling, 1–10-min averages	On the ice during the ice drift, otherwise on the bow of *Oden*
Monostatic sodar	Boundary layer echo structure	1–3-s sampling	On the ice during the ice drift only
915-MHz wind profiler	Wind speed and direction, turbulence intensity	1-h averages	On the bow of *Oden*
5-mm scanning radiometer	Temperature profiles up to 1 km	1-s sampling, 5-min averages	Seventh (top) deck of *Oden,* starboard side
S-band Doppler radar	Radar reflectivity, and vertical velocity and its spectral width (in clouds and precipitation)	30 s	On the bow of *Oden*

(BAO) tower and to rawinsonde data (Westwater et al. 1999).

Two sodar systems were operated during AOE-2001. One was a vertically directed monostatic sodar recording the boundary layer structure, and the other a two-beam Doppler sodar providing vertical profiles of wind speed and direction. The sodar sends an audible sound pulse and detects its backscatter due to fluctuations in temperature and, to some degree, wind speed. The wind speed is taken from the Doppler-shifted frequency in the return signal as compared with the transmitted frequency emitted at angles to the vertical, assuming a zero mean vertical wind speed. Because the sodar systems rely on acoustic pulses, they are sensitive to contamination from ambient noise. Both sodar systems were, therefore, operated on the ice ~ 150 m away from *Oden* during the ice drift. The two-beam Doppler sodar was additionally operated on the bow of *Oden* during the shorter research stations before 2 August. The transmitted frequency as well as the pulse-repetition frequency of both sodar systems were adjustable, in order to be optimized according to the ambient conditions, giving a variable resolution and range. The vertically directed monostatic sodar provided backscatter intensity every 1–3 s, while the two-beam Doppler sodar provided vertical profiles of the horizontal wind speed every ~ 20 s, averaged in postprocessing to 1- and 10-min averages.

In addition to the sodar systems and the tethered sounding system (see below), the ice camp consisted of an 18-m meteorological telescoping mast, erected about 300 m from *Oden,* near a hut for electronics and data acquisition computers. All instruments were powered by batteries, charged by an alternating current (AC) cable from *Oden.* This proved useful when the main power had to be cut, such as when *Oden*'s position was changed to keep the chemistry measurements directed into the wind. A 2 m × 2 m white-painted ablation shield served as base for the mast, which was stabilized by a system of guy lines. These were attached to T-shaped metallic bars that were introduced through holes in and secured at the bottom of the ice. This proved to be a stable configuration for the duration of the ice drift, and only small daily adjustment of the guy lines was necessary to keep the mast instruments level. Some melt ponds were located near the mast but the ice under and around it was free from open water. The ice surface was snow-covered and the transition from snow to ice was gradual at 5–15 cm. Instruments were deployed on 3-m booms mounted on the mast. Antitorsion bars were also mounted on the mast and guyed to the ice to keep the structure from twisting due to wind forcing on the instrument booms. The mast was extended and retracted by means of a manual winch. To mount and service the instruments, a small scaffold was temporarily raised close to the mast. The scaffold was removed after each use.

Low-frequency profile instruments (see Table S3) at five levels and high-frequency turbulence measurements at two additional levels (see Table S4) were mounted on the mast. The low-frequency data include profiles of wind speed, temperature, and direction at the top level. Also included were absolute temperature and relative humidity at the two turbulence lev-

Table S3: Summary of profile instruments on the meteorological mast. All instruments were sampled at 0.2 Hz and the results were averaged and logged as 1-min averages.

Instrument	Variable	Height (m)	Sampling
Vaisala WAA151 shaft-heated cup anemometer	Wind speed	1.8, 3.4, 7.1, 12.8, 17.3	3–19 Aug
Vaisala WAV151 heated wind vane	Wind direction	18.0	
In Situ thermocouple system	Air temperature profile	1.3, 2.9, 6.6, 12.4, 16.8	
Vaisala humitter 50Y	Air temperature and humidity	3.6, 14.5	
Vaisala	Pressure	0.1	
In Situ thermocouple system	Ice temperature	–0.05, –0.1, –0.2, –0.5, –1.0	6–19 Aug
Eppley pyranometers (PSP) (0.295–2.80-μm wavelength)	Incoming and reflected shortwave radiation	1.5	5–19 Aug
Eppley pyrgeometers (PIR) (4.0–50.0-μm wavelength)	Incoming and outgoing longwave radiation	1.5	

Table S4: Turbulence instruments on the meteorological mast. All turbulence data were sampled at 100 Hz and logged as 20-Hz averages.

Instrument	Variable	Height (m)	Time period
Gill R3 ultrasonic anemometer	3D wind speed	4.7, 15.4	3–19 Aug
Krypton hygrometer CSI KH-20	Water vapor	3.6, 14.5	

els, a temperature profile into the ice, and radiation and atmospheric pressure measurements at the surface. The wind speed profile was measured with shaft-heated cup anemometers, and the temperature profile was obtained from a chain of thermocouples. A single wind vane was mounted at the top of the mast. Independent temperature and relative humidity measurements were made at two levels, on the same booms as the turbulence instruments (see below), to provide a low-frequency reference for the turbulence sensors. Temperature and humidity sensors were mounted inside fan-aspirated radiation shields. A thermocouple string measuring the ice temperature was also installed at the base of the mast, with two sensors placed immediately below the snow surface, and the remaining sensors at 0.1-, 0.2-, 0.5-, and 1.0-m depths. The 1.0-m sensor was encrusted in a 1-m ice core, which was extracted and then replaced with the sensor in it. Additionally, a low structure was deployed ~ 20 m from the mast to hold two pyrgeometers and two pyranometers, measuring downward and upward long- and shortwave radiation at ~ 1.5 m above the surface. All the data were collected at 5-s intervals on a datalogger that calculated and stored the 1-min averages.

The high-frequency instruments included two ultrasonic anemometers to measure the 3D wind components and sonic "speed of sound" temperature, and two Krypton hygrometers to measure water vapor fluctuations (Table S4). The voltage signal from each Krypton hygrometer was ingested by the ultrasonic anemometer electronics, using a built-in converter to digitize the signal. The digitized signals from the Krypton hygrometers were, thus, merged with the wind speed information, and a combined message was sent to the serial port of a personal computer. This provided a convenient method for synchronizing the sampling of the two instruments. The anemometers were installed on the 3-m booms with the Krypton sensors mounted right below the sonic anemometer.

An array of microbarographs was also operated around the ice camp with three pressure sensors deployed in a rough equilateral triangular pattern, about 200 m on each side, and a reference sensor in the center.

The Cooperative Institute for Research in Environmental Sciences (CIRES) Tethered Lifting System (TLS; Balsley et al. 1998) was deployed on the ice next to the sodar system. The TLS incorporated both parafoil kites and aerodynamic balloons as complementary lifting platforms to enable operations in winds from 0 to ~ 20 m s^{-1}. Two sizes of kites were used—7.4 or 13 m^2, the smaller being used when the winds exceeded 12 m s^{-1}. A 21 m^3 aerodynamically shaped tethered balloon was used during calm-to-moderate wind conditions. The balloon is seen to the far right in Tjernström et al.'s (2004) Fig. 1. A combination of three scientific payloads was flown on the TLS, attached to the tethering line. A basic meteorological payload (BMP), a high-resolution 3D wind payload, and an aerosol payload were employed (see Table S5). The BMP provided basic profiles of wind speed and direction, temperature, and humidity. The 3D wind payload was based on an ultrasonic anemometer and a motion-sensing package to provide in situ turbulence measurements at higher altitudes than were possible on the mast. The aerosol payload consisted of a condensation particle counter (CPC) with an automatic switch between different inlets. Four inlets were used with varying numbers of diffusion screens to provide a rough estimate of particle size distribution. Two payloads were often combined during a sounding.

To address horizontal homogeneity issues in the ABL and to account for variability in the surface conditions two National Center for Atmospheric Research (NCAR) Integrated Surface Flux Facility (ISFF) stations were deployed from 5 to 18 August on ice floes ~ 7–10 km away from *Oden*. They were deployed in a roughly equilateral triangular pattern with the main meteorological mast located near *Oden*. These stations had been configured for use in the Arctic during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment (Uttal et al. 2002; Perovich et al. 1999), and were further modified for AOE-2001. The station infrastructure was assembled on *Oden*'s helideck and then was sling-lifted by a helicopter out to the locations on the ice, after which the sensors were mounted. These stations were self-contained, using local solar panels and wind turbines to charge the batteries and using radio modems for transmitting data back to *Oden* in real time. The ISFF stations measured all three wind components, temperature, and humidity at turbulence time scales, as

Table S5: Summary of the Tethered Lifting System (TLS). The TLS was deployed during the ice drift and also at a few shorter research stations. It operated between the surface and 2 km.

Payload	Instrument	Variable	Sampling (Hz)
Basic meteorological payload	Vaisala humitter 50Y	Temperature and humidity	1
	Motorola MPX4115A	Pressure	
	CIRES pitot tube	Wind speed	
	Precision Navigation Vector 2XG	Wind direction	
Turbulence payload	Spectron SpectroTilt II SSY0091C and Analog Devices ADXL202	Tilt and acceleration	20
	GPS Garmin GPS35	Position, acceleration	1
	R. M. Young 81000 sonic anemometer	3D wind speed fluctuations	20
	Krypton hygrometer CSI KH-20	Water vapor fluctuations	
Aerosol payload	TSI PortaCount + CPC with four inlets using TSI particle size selectors to obtain a rough size distribution.	Aerosol particle number concentration	0.05

Table S6: ISFF stations.

Instrument	Variable	Height (m)	Sampling rate (Hz)	Time period
CSI ultrasonic anemometer	3D wind speed	3	20	5–19 Aug
Krypton hygrometer	Water vapor	3	20	
Vaisala humicap	Air temperature	2	1	
	Relative humidity	2	1	
Vaisala PTB220	Pressure	2	1	
Eppley pyrgeometer	Longwave radiation	2	1	

well as temperature, humidity, pressure, and incoming longwave radiation at longer time scales (see Table S6).

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