HEXOS—Humidity Exchange Over the Sea
A Program for Research on Water-Vapor and Droplet Fluxes from Sea to Air at Moderate to High Wind Speeds

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Abstract

HEXOS is an international program for the study of evaporation and spray-droplet flux from sea to air. The program includes measurements in the field at moderate-to-high wind speeds, wind-tunnel studies, instrument development, boundary-layer modeling, and subsequent development of parameterization for use in synoptic and climatic models of the atmosphere and the ocean. Present accomplishments of the program are 1) a wind-tunnel study of the flow distortion around the Dutch research platform, Meetpost Noordwijk, 2) a pilot experiment at this platform in November 1984, and 3) an investigation of processes near the air-sea interface in a wind-wave simulation tunnel. The main field experiment, taking place in the autumn of 1986 at and around the Noordwijk platform, includes measurements of the fluxes of water vapor, spray droplets, sensible heat, and momentum, as well as the structure of the planetary boundary layer and the state of the sea. This multidisciplinary effort involves direct measurements from the platform, a mast, a ship, a tethered balloon, moorings, and an aircraft, plus measurements obtained remotely by laser scintillometer, lidar, and radar.

1. Introduction

The HEXOS (Humidity Exchange Over the Sea) program is motivated by an increasing awareness of the importance of the water flux between sea and air, and the need to improve our knowledge of the transfer processes. The latent heat of evaporation is often the largest loss term in the heat balance of the upper ocean. This heat, when released in clouds, fuels the atmospheric engine (e.g. Malkus, 1962). The latent heat of evaporation and condensation is therefore of great importance to synoptic- and climatic-model calculations of both atmospheric and oceanic circulations. Direct measurements of latent-heat flux over the sea have seldom been successful. A widely used bulk-exchange coefficient for evaporation (Friehe and Schmitt, 1976), depends mainly on measurements made at wind speeds less than 8 m \( \cdot \) s\(^{-1}\) and is a weak link in any climate analysis (e.g. Bunker et al., 1982; Taylor, 1984). Does this coefficient remain a constant as high winds churn the sea into breakers and whitecaps? The drag coefficient for momentum transfer is a function of wind speed and stratification (e.g. Smith, 1980; Large and Pond, 1981; Liu et al., 1979) and of sea state (Kitaigorodskii and Zaslavsky, 1974; Geernaert et al., 1986). One might expect the evaporation coefficient also to vary with wind speed and sea state. As whitecap bubbles burst, how much water enters the atmosphere as spray droplets that evaporate in the atmospheric planetary boundary layer (APBL) and cool the air instead of the water? The resultant sea-salt aerosols constitute a major component in the global salt budget, serve as cloud condensation nuclei, and are an important factor in determining optical properties of the marine-atmospheric boundary layer. A maximum vertical flux of water vapor has been observed at levels well above the surface from airborne flux measurements over the Puerto Rico area (LeMone and Penne, 1976) and over the English Channel (Readings, 1980). The droplets may also adversely influence temperature, humidity, and wind sensors (Schmitt et al., 1978).

A rigorous treatment of the effects of sea spray involves consideration of processes affecting the droplet-source function; turbulent transport of droplets, vapor and sensible heat; and the evaporation characteristics of the droplets. There is also evidence that characteristics of the flow over ocean waves must be considered. Modeling efforts have only begun to integrate these processes (e.g. Ling and Kao, 1976). While some aspects of this problem have been investigated through measurements over the ocean (e.g. Blanchard, 1963; Toba, 1965; Monahan, 1968; Chae, 1973; Fairall et al., 1983; Koga, 1984; Monahan, et al., 1983), the complex interactions involved require either very complete measurements or the use of simplifying assumptions.

2. Development of a program of research

In view of the importance of evaporation and latent-heat transfer for both atmospheric and oceanic circulations, it seems almost negligent that so little research has been carried out on the problem. This is, however, not due to a lack of attempts, but rather to the difficulties encountered when making humidity flux and related measurements over the sea. The problem has long been recognized among experimentalists in the air-sea-interaction field. A NATO (North Atlantic Treaty Organization)-sponsored workshop at the Bedford Institute of Oceanography in 1981 assessed the status of knowledge and measurement techniques in this field (Smith and Katsaros, 1981).
The two conflicting conditions that necessitated considerable discussion at that workshop and eventual compromise in the program plan are 1) that present instruments for measuring humidity require frequent attention; thus, the experimental work must be carried out from an occupied research platform; and, 2) any such platform is of such a size that it causes distortion of both the mean flow and of the turbulent fluxes in the atmospheric surface layer, and will be standing in fairly shallow water. The program plan evolved through discussion with experts in the field at several scientific meetings. The Scientific Plan (Smith et al., 1983), endorsed by Working Group A (Boundary Layers and Air-Sea Interaction) of the International Association of Meteorology and Atmospheric Physics poses the following questions:

1) How does the evaporation coefficient depend on wind speed, sea state, and stability?
2) Can surface-layer bulk formulations be applied at high wind speeds, and, if so, at what height should humidity be measured?
3) Can we demonstrate experimentally an expected dependence of evaporation on wind stress, stability, wave breaking, and spray-droplet distribution?
4) How well do “dissipation” measurements from a ship and from a fixed platform estimate evaporation?
5) Can eddy-correlation measurements be satisfactorily corrected for flow distortion by a fixed platform?
6) Can fast-response humidity sensors be made to operate in marine conditions for extended periods of time? Could they be adapted for longer-term operation on unmanned platforms?

The program (Fig. 1), which will result in major progress toward answering these questions, includes development of temperature- and humidity-sensing devices that can operate near the sea surface during conditions of flying sea spray. It started with a wind-tunnel study of flow distortion around the Dutch research platform Meetpost Noordwijk (MPN), (See Fig. 2), which is the main field site, an in situ pilot experiment in November 1984 (HEXPILOT), and wind-tunnel studies of the microscale physical processes involved in evaporation and droplet flux (HEXIST) in June–July 1985. A theoretical component consists of modeling of the coupled fluxes of water vapor, spray droplets, sensible heat, and momentum. Another major component involves exploration of the potential of inertial-dissipation flux methods in the sea-spray environment (Fairall and Larsen, 1986). These components of the program give support to, and are preparatory to, a comprehensive field measurement program, HEXMAX, in the fall of 1986, consisting of point measurements of fluxes, droplet concentrations, and profiles in the whole of the APBL, as well as measurements in the sea (temperature, waves, currents, surfactants). The activities will be centered on the MPN, with measurements from aircraft, ship, buoys, moorings, a mast, a tethered balloon or a kite, and shore stations, as well as from the platform itself. The principal investigators, their affiliations, and primary contributions to the program are listed in Table 1.

3. The program components

a. Study of flow distortion around the MPN

The eddy-correlation method for determining turbulent fluxes is the most direct and fundamental one, but in order to use this method, we must know the effects of flow distortion by the platform on measurements of mean quantities (wind speed, temperature and humidity) and on turbulent fluctuations. An existing 1:25-scale model of the platform was used in a wind-tunnel study of both mean velocities and Reynolds stresses for the west side of this model with a simulated marine-surface boundary layer. The velocity field was measured in two places 10 m and 16 m from the rail of the main deck on the west face of the platform. The study was encouraging for the HEXOS experiment plan since Wills (1984) found that at a distance of 16 m from the west face for most wind directions from 180° to 360°, the Reynolds stresses measured in the tunnel with the platform differed by less than 10 percent from the stress measured in the empty tunnel. Typical results for mean wind speed fluctuating horizontal velocity and Reynolds stress are illustrated in Figures 3a, b, and c. Scalar properties such as humidity, temperature, and droplet concentration, which were not simulated, are less influenced by flow distortion than the velocity vector.

b. Instrument development

Two methods to eliminate spray droplets from the airstream, while allowing measurements of the true atmospheric-humidity fluctuations, have been tested during the pilot experiment. The Bedford Institute group used a reverse-flow trap to catch the drops before the air passes by the sensing gap of a Lyman-α hygrometer. The University of Washington group used a rapidly rotating mesh in front of a thermocouple psychrometer (Katsaros, 1986). Drops caught by the screen...
are flung away by centrifugal force. Fans draw the air through both devices.

An independent instrument package for measuring the high-frequency turbulent fluctuations of humidity, temperature, velocity, and droplet spectra from the MPN boom during HEXMAX is being developed by the HEXIT group (see following section). It will include hot-wire wind sensors, a miniature Lyman-α humidiometer and "cool" films for temperature measurements.

Development of new techniques for measuring humidity is an important part of the HEXOS program. One instrument under development (Table 1) employs an absorption line of water vapor in the near infrared, where liquid water is "transparent." This instrument, using single-mode continuous-wave semiconductor lasers (1.35 micrometers), would permit measurement of humidity near the sea surface (and in clouds) without mechanical devices to remove the drops. Such lasers are extremely small, and are being developed for long-distance fiber-optics communications.

c. Humidity experiment in a simulation tunnel (HEXIST)

The primary goal of HEXIT was to measure the interaction of spray droplets with temperature and humidity under a variety of conditions in the simulation tunnel of the Institut Mécanique Statistique de la Turbulence (IMST) near Mar-

seille, France. Even though the natural production of spray by breaking waves cannot be completely modeled in a tunnel, the HEXIT experiment is of great interest since it allows investigation of the effects of droplets in a systematic manner.
in a controlled environment. The measurements were carried out at IMST during June–July 1985; a preliminary test of measurement systems was carried out the previous March (for participants in HEXIST see Table 1).

Because the Knollenberg spectrometers for measuring drop-size spectra are too bulky to allow undisturbed measurements of humidity and temperature fluctuations simultaneously, separate measurement periods were scheduled for droplets and for vapor fluxes. The droplets were produced by three different processes: high-wind-speed breaking waves, breaking waves generated by a wave generator, and bursting bubbles generated by aeration in the water (Mestayer and LeFauconnier, 1986). The effects of turbulent transport were studied by measuring spray-droplet–concentration spectra as a function of height above the surface, horizontal distance from the bubbler, and wind speed (Fig. 4a) in the range 0.15 to 300 μm at a relative humidity near 100 percent. The drop-size measurements were also taken at relative humidities as low as 50 percent to study the effects of evaporation on the droplet spectra (Fig. 4b) and on the profiles and fluctuations of temperature and water vapor. The conditions of the first set of experiments were then reproduced for turbulence mea-

### Table 1. Principal investigators in the HEXOS program. Affiliations and primary contributions.

<table>
<thead>
<tr>
<th>Name and institution</th>
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measurements of velocity, temperature, and humidity to study effects of droplets on the sensors themselves, on fluxes, and on the inertial subrange of turbulence. Effects of spray on evaporation and turbulent transport were clearly identified. An intense intercomparison of humidity probes was also carried out.

d. The HEXOS pilot experiment

Part of the preparation for the main field program was a pilot experiment on the MPN, which included a flight by a research aircraft. The experiment, from 29 October until 23 November 1984, was scheduled two years ahead of the main field work to allow for analysis of the data and for adjustments in measuring techniques and data collection.

1. Boom measurements. The three groups responsible for obtaining direct measurements of the evaporation rate and other turbulent fluxes intercompared their sensor systems and recording devices by placing the sensors at the tip of a 20-m boom (Fig. 5). The devices mounted on the boom were, a sonic anemometer, an aspirated Lyman-α hygrometer, a microbead thermistor, a pressure anemometer, a wire wave gauge, a whitecap-detecting optical system, a K-Gill anemometer, and aspirated dry and wet-bulb thermocouples. Results from turbulence measurements during the pilot experiment were

1) Flux measurements were obtained at moderate-to-high wind speeds
2) Mean vertical velocities were observed, which indicate flow distortion by about ±3° of tilt angle. They were negative at the sonic anemometer and at the pressure anemometer 0.7 m and 1.2 m respectively below the boom and positive at the center of the K-Gill unit 1.3 m above the boom (Fig. 6). We attribute this in part to flow distortion by the boom itself, and plan to mount the sensors further away from the boom in the future. However, the trend of increasing mean vertical velocity with height above mean water level, indicates effects due to blockage by the platform
3) The water-vapor flux became very small during the highest wind conditions when the atmospheric humidity was high and sea spray was flying. We speculate that moisture was carried principally by spray to elevations above our eddy-flux sensors, whence evaporation of the spray would supply vapor flux to higher levels

In Figures 7 a, b, and c the turbulent-exchange coefficients for momentum, heat, and water vapor, \( C_D \), \( C_H \), and \( C_E \) from the measurements obtained by BIO and UW are presented. The drag coefficients obtained by BIO are higher than those calculated by Anderson and Smith (1981) for data obtained near Sable Island, but are in general agreement with those observed by Geernaert et al. (1986) for another North Sea station, also in 15 m of water. The UW values are lower by about 20 percent. About 10 percent of this difference is due to the use of a 20-minute averaging time by UW versus the 60 minutes used by BIO; noise pick-up from radio-telephones by the UW systems limited the duration of clean traces. The K-Gill also loses the contribution to stress beyond 1 HZ, while the BIO sonic reaches 10 HZ. The remaining difference must be attributed to measurement uncertainties in both systems. The exchange coefficients for heat and water vapor measured by BIO are also higher than some previous observations (Anderson and Smith, 1981), and higher than the values obtained by UW. The discrepancy between the esti-
mates of $C_D$, $C_H$, and $C_E$ by the two groups is larger than what is desirable and that can be achieved. The pilot experiment was not optimal because BIO had to use their second line of equipment (due to shipping delays from another experiment), and UW had a calibration uncertainty in the thermocouple unit, at least in part caused by radiointerference.

FIG. 5. The two prongs of the boom on the Noordwijk research tower with instruments for turbulence measurements. Photo was taken on 21 November 1984 during a measurement period with winds of 13 m $\cdot$ s$^{-1}$. The instruments seen in the picture are at A) Bedford Institute of Oceanography—Sonic anemometer; B) Bedford Institute of Oceanography—Aspirated Lyman-α; C) University of Washington—K-Gill wind-velocity sensor; D) University of Washington—Aspirated thermocouple psychrometer; E) Royal Dutch Meteorology Institute—Pressure anemometer.

FIG. 6. Vertical velocities observed by the K-Gill-anemometer unit during three days of the HEXOS Pilot experiment.

FIG. 7. The exchange coefficients as a function of the neutral wind speed at 10-m height, deduced from measurements 4 to 9 m above the sea surface during near neutral stratification calculated from measurements by Bedford Institute of Oceanography (BIO) and University of Washington (UW). Corrections for measurement height and stratification have been made. a) Drag coefficient, $C_D$. b) Exchange coefficient for heat, $C_H$. c) Exchange coefficient for water vapor, $C_E$. 

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aerosols were observed. Flux-to-concentration ratios, as a function of particle size, are shown in Fig. 9b, with ratios calculated by Fairall et al. (1983) from data obtained under similar conditions during the JASIN experiment.

Aerosol measurements were made with an optical particle counter and a Rotorod inertial impactor. The most important contribution from the sea to the atmospheric particle content is in the size range larger than 1 μm. A particle spectrometer was used to measure particles in the 0.5–32 μm diameter range. The particle spectra, measured during a period of offshore winds, had a primarily continental character with a small marine mode. The height dependence of the particle-size distributions (diameter >10 μm) was investigated with a Rotorod inertial impactor mounted on a float for measurements at 0.12 m and 2 m above the instantaneous sea level. In addition, measurements were made at fixed heights from 1 to 20 m above mean sea level. Eight determinations were made of the height dependence of particle concentrations, each consisting of 18–20 samples at different heights. The variation of particle concentrations in the lower few meters can be explained by particle production and transport mechanisms in relation to the flow patterns close to the surface (de Leeuw, 1986a).

4. Aircraft measurements.

To study the possible contribution of droplets to the distribution of turbulent humidity flux with
height in the lower mixed layer, the British Meteorological Research Flight’s C-130 Hercules aircraft was flown during the pilot experiment on 21 November 1984. Operational and technical feasibility of participation in HEXOS were demonstrated, but although weather conditions were favorable, instrumental problems limited the amount of useful data collected.

**5. Remote sensing.** Measurements of refractive index were obtained from observations of the scintillation of a carbon dioxide laser beam over a 10-km path between the platform and a lighthouse on shore. Water-vapor flux over the path is maintained on three days. On the last day (21 November) the wind speed was greater than 10 m·s⁻¹. Eight runs of approximately 45-minutes duration have been analyzed, coinciding with measuring periods on the boom. Moisture fluxes obtained from the scintillation measurements showed good agreement with fluxes calculated by the bulk-aerodynamic method (Fig. 10) (Kohsiek, 1986).

LIDAR profiles of extinction and backscatter due to aerosols were measured up to a height of about 1 km (de Leeuw, 1986b). From a series of backscatter profiles obtained at six-minute intervals between 19 and 22 November, variations of mixed-layer height and optical density of the mixed layer, as well as the formation, development, and disappearance of layers were clearly revealed. For instance, during the night between 19 and 20 November a reduction in small-particle concentration was associated with the passing of a front and a change from continental to maritime air mass. The visibilities were high on 20 and 21 November, but backscatter in the 1-μm wavelength region of the lidar increased somewhat due to the sea spray created by the high westerly winds.

Other measurements during the pilot experiment included shortwave and longwave radiation, and wave-height measurements from a buoy approximately 100 m from the platform.

e. **The HEXOS main experiment (HEXMAX)**

**1. Measurement plan.** The HEXOS main experiment will combine measurements of evaporation rates from the sea surface at MPN with a comprehensive set of related measurements at MPN and from a ship, an aircraft, a bottom-mounted mast, buoys, moorings, and a shore-based tethered sonde, and radiosonde station. The coordinated measurements include wind stress, heat flux; profiles of wind, temperature and humidity throughout the atmospheric boundary layer; aerosol profiles and drop-size spectra; ocean currents, sea state and wave breaking. Many of these will be measured in duplicate or by several different methods, since an important part of the plan is to intercompare measurement techniques in use by the many participating research groups. Special meteorological analyses such as air-mass transformation modeling will be carried out. No one experimental group has the expertise, equipment, and personnel to carry out the many specialized experiments. HEXMAX will be a unique experiment because it will bring together a number of experts to obtain measurements that will complement and reinforce each other.

The experiment will take place from 6 October to 28 November 1986, a period long enough that several changes in the weather pattern can be expected. The highest priority will be assigned to days with strong westerly winds, when aircraft flights will be scheduled, and platform-based measurements will be made on an intensive 24-hour schedule.

Eddy-correlation measurements of evaporation, heat flux, aerosol flux, and wind stress will be made by sensors of turbulent wind, temperature, aerosol, and humidity fluctuations on the 20-m boom attached to MPN, as during the HEXPilot experiment. A “dissipation” package will be added to the boom for evaluation of the high-frequency portion of the spectra. A Rotorod will collect aerosol-droplet data at the boom, and several instruments will collect aerosol spectra and distributions with height. Droplet spectra will be measured by the UKMO (United Kingdom Meteorological Office) Hercules aircraft flying low-level passes (30 m) parallel to the shore by the MPN. The aircraft will also investigate horizontal and vertical variations of fluxes, aerosols, and mean meteorological parameters. In addition, eddy fluxes will be measured at a telemetering tripod to be installed in 14 m of water, about 5 km from shore. The less-direct “dissipation” formulas will be used to estimate turbulent fluxes from spectra of humidity, temperature, and wind fluctuations measured from a ship. These formulas will be checked by applying them to the turbulence data from the MPN boom and comparing them with eddy-correlation analysis. The influence of flow distortion by the measuring platform will be corrected using the results of the wind-tunnel study of the flow around the model of the MPN.

One to six radiosondes will be launched daily from the ship and from a shore station 10 km from MPN, depending on the mode of operation. A tethered sonde will provide profiles of wind, temperature, and humidity through the atmospheric
boundary layer up to 450 m, during daylight hours, on intensive-mode days and often on regular-mode days.

Oceanographic data will be obtained from moored current meters (which also record water temperature) and from two wave buoys and from the research ship. Bubbles in the water will be observed from the ship, and surface-tension measurements will be made regularly from the MPN platform.

The very extensive data on the structure and development of the atmospheric-and-oceanic boundary layers will provide a unique framework for the evaluation and parameterization of evaporation, heat flux, and wind stress. Because the mean measurements are as important as the direct-flux measurements for parameterizations, measurements of mean humidity and temperature by several devices will be compared.

The HEXIST group will measure fluctuations of temperature, humidity and three velocity components to estimate the turbulent fluxes of water vapor, sensible heat, and momentum from the values of the inertial subrange of the turbulence spectra. They will also examine the isotropy of the velocity components and will study the use of the third moment (skewness) of temperature fluctuations and humidity fluctuations, as an indicator of the fluxes and stratification. A Rotorod sampler for particles with a diameter larger than 10 \( \mu m \) will be mounted from the boom and a second Rotorod sampler, a humidimeter, and a scatterometer for the detection of small particles will obtain profiles near the sea surface. Additionally, profiles of sea salt concentration (3 m, 11 m, 20 m) will be determined by isokinetic air filtration and subsequent chemical analysis for sodium. Information about the sea salt mass size distribution at a height of 11 m will be obtained by the use of a five-stage cascade impactor.

Concentrations of atmospheric trace metals and organic trace compounds will be determined at the MPN. On the basis of new techniques it is now possible to use short enough sampling times (a few minutes to some hours) that relationships between the concentration data and meteorological conditions can be sought.

Several devices that obtain information remotely using visible, infrared, and microwave radiation will be operated from the platform. A LIDAR system measuring vertical profiles of extinction and backscatter will obtain profiles of the atmospheric-boundary layer and inversion height to a distance of 1 km from the platform continuously. A laser scintillator will measure the refractive-index structure function over a 10-km path from the MPN to shore; this structure function is related to the heat-flux and evaporation rate integrated over the path. A frequency modulated carrier wave radar will operate from MPN to calibrate backscatter from the surface as a function of wind speed and direction, or of friction velocity.

Photographic measurements of the whitecap coverage of an area of the sea just upwind of the boom will relate the whitecap coverage to the spray-droplet population and will determine the relative contributions of whitecaps and wave-crest shearing to this population. The dependence of whitecap coverage on wind speed, atmospheric stability (or alternatively on friction velocity), and sea-surface temperature will be investigated.

A 7-m tower mounted on the western edge of the helicopter deck will be instrumented with devices for measuring turbulent quantities, similar to the dissipation package on the boom. This includes a sonic anemometer, dew-point and Lyman-\( \alpha \) hygrometers, hot-wire instruments, and temperature sensors. Results from the tower will be compared with the boom measurements to examine the effects of flow distortion on turbulent quantities, especially in view of the application of the dissipation method, and will be compared with predictions on an older wind-tunnel study of flow distortion.

In order to measure the complete energy balance at the sea surface, shortwave and longwave irradiances will be measured by hemispheric sensors.

2. Bottom-mounted mast. A bottom-mounted tripod will support a mast with minimal-flow distortion in water depths of about 14 m at a position about halfway between MPN and the Dutch coast. The mast will be instrumented with a three-dimensional propeller system and a fast psychrometer for eddy-flux measurements, as well as standard instruments. Data will be telemetered to shore.

3. Ship-based operations. The British ship Frederick Russel will participate throughout HEXMAX. At the time of writing, the planned operations of the Poseidon are limited to CTD sampling and servicing the German tripod-mast. The Frederick Russel belongs to the Voluntary Observing Fleet and as such will make its usual meteorological observations during HEXMAX.

A meteorological package will be installed on a 10-m mast at the bow of the ship. This package consists of two aspirated psychrometers, a Humicap-humidity sensor, and four sets of cup-anemometers with vanes. In addition, a Gill propeller vane, an infrared radiometer, a sea-surface-temperature "fish" with a trailing thermistor, a thermosalinograph, a shipborne wave recorder, shortwave and longwave, upward- and downward-pointing radiometers, and a rain gauge of new design will be operated on the ship. Radiosondes will be released at a rate of one per day at the time of overpass of the Advanced Vidicon High Resolution Radiometer (AVHRR) instrument aboard National Oceanic and Atmospheric Administration (NOAA) satellites.

Mean wind speed, direction, wet and dry bulb temperatures, and various-size ranges of aerosols will be measured, together with mean humidity from a dew-point hygrometer. A newly developed device for measuring relative humidity or total water content in clouds, based upon the warming of the air prior to humidity measurement by a carbon-film hygristor, will be evaluated; it should be capable of measuring relative humidities with a resolution of about 1 percent. It has a frequency response of a few hertz, and will be utilized for dissipation calculations of humidity fluxes.

Velocity fluctuations measured at the bow mast using hot-film sensors will be used to obtain the turbulent kinetic-energy dissipation; humidity fluctuations with a Lyman-\( \alpha \) humidity sensor will be used to determine humidity dissipation. Wind, temperature, and humidity profiles in the atmospheric boundary layer will be obtained from radiosondes.

4. Shore-based measurements. The laser of the scintillometer will be based on shore, as will telemetry systems for the bottom-mounted mast. Vertical profiles of wind, temperature, and humidity in the planetary-boundary layer will be obtained by radiosonde, and by tethered-balloon soundings to a height of 450 m. A 15-m tower will be erected at the water
line to measure near-surface profiles of wind speed, temperature, and humidity.

5. Airborne instrumentation. Boundary-layer flights with the British C-130 Hercules of the Meteorological Research Facility will sample the higher part of the atmospheric boundary layer. This aircraft, based at Farnborough, England, within easy range of MPN, is a complete atmospheric laboratory (Readings, 1985). The aircraft will combine profile ascents and descents, intended to reveal the mean structure of the APBL, with horizontal traverses (both across and along wind) at various levels lying between the minimum operational height (about 30 m above sea level) and the top of the boundary layer.

6. Background information. Background information provided by KNMI will include surface-weather reports and radiosonde data from stations in the surrounding area; air-mass trajectories on selected days; weather maps; currents; wave height and direction from a buoy moored near MPN.

f. Future plans

1. Simulation studies. In 1987–88 the HEXIST group has planned for a new program, coupling numerical modeling and physical simulation in the IMST tunnel, to determine and parameterize the “local” effects of turbulence on droplet generation, transport, and evaporation. The program will take advantage of the possibility to produce a one-dimensional, stationary, turbulent boundary layer over a nonperturbed water surface, with homogeneous transfers of sensible heat, water vapor, and droplets. In order to avoid dynamic perturbations generated by breaking waves, the droplets will be produced by a random, homogeneous grid of bubble generators.

2. The HEXOS stable platform experiments. These would follow the 1986 experiment and make use of sensors (developed for HEXOS or elsewhere) for eddy-correlation measurements of evaporation from a slender, stable, unmanned structure where flow-distortion errors are less than at a manned platform. A depth of 50 m or more will be required for a deepwater wave regime. Radio telemetry of data to shore, and the need for regular maintenance trips will limit the site to about 30 km from a shore-based receiving station.

Data will be limited to measurements of humidity flux and of necessary parameters (to be defined by the previous HEXOS experiments), such as wind speed, air and water temperature, humidity, sea state, and possibly aerosols. The experiment should run through a full year, with increased data collection during storms. A ship may stand by during occasional periods (perhaps 10 days, four times during the year) to make additional measurements as in the 1986 HEXMAX experiment, and aircraft measurements may also be proposed.

3. Low latitude experiments. Since many properties of sea water change dramatically with temperature, and the structure of the atmospheric boundary layer depends on latitude, it is not a straightforward matter to extrapolate midlatitude results to low latitudes. A future series of HEXOS experiments carried out in water temperatures greater than 20°C is envisioned.

g. Modeling of the planetary boundary-layer fluxes during moderate-to-high wind speeds

A model of the coupled fluxes of humidity, temperature, and droplets is being developed, based on the knowledge gained in the HEXOS program and the pioneering efforts of Ling and Kao (1976). We were delighted to find that a similar approach was being taken by a Polish colleague (Stramska, 1986). The source term for the droplet flux from the sea can be related to wave breaking, which can be parameterized in terms of wind speed (e.g. Monahan and O’Muircheartaigh, 1980). However, the subsequent fate of the spray droplets is not well understood at present. A workshop to review the state of knowledge and to coordinate the HEXOS groups’ efforts was held at Pennsylvania State University in April 1986. Separate models deal with the evolution of the droplet spectrum as a function of wind speed, temperature and humidity, the microscale flow of air over the wavy water surface and the turbulent diffusion of vapor, droplets, and heat in the surface layer and in the whole PBL. The latter model at present employs an eddy-diffusion coefficient for the atmosphere that is dependent on height above the interface, atmospheric stratification, and a surface-roughness length $z_0$, which in turn is a function of the wave field.

4. Summary

The HEXOS program addresses an important problem in air-sea interaction: the parameterization of water flux from sea to air. It is a collaborative international effort to study all the processes occurring at the air-sea interface and in the adjacent planetary-boundary layers of sea and atmosphere that may influence this flux. The program described here is only a step on the long road to full understanding of this complex system. Much work will be required to extend the relationships to low-latitude conditions and to obtain long records valid for climate analysis.

Acknowledgments. The following have contributed to the writing of the article: G. de Leeuw, J. H. Duyzer, C. W. Fairall, W. Kohsiek, S. E. Larsen, P. Mestayer, E. Monahan, M. H. Smith, J. E. Tillman, and J. A. B. Wills. Technical support by R. J. Lind, G. Vassiliou, and D. Hendsbee of the University of Washington, R. J. Anderson of BIO, and R. Kraan, E. H. W. Worrell, J. Schaap and others at KNMI are gratefully acknowledged. We are grateful to S. Lavin and J. Meadows who produced the manuscript and to K. Moore who executed the present versions of the figures. The following organizations have provided support: North Atlantic Treaty Organization (NATO) has supported workshops, travel and shipping; the Marine Technology Committee of the U.K. Department of Industry and Trade supported the flow-distortion study; the HEXIST project received support from I.M.S.T. and the Institut National des Sciences de l’Univers (INSU, France); KNMI supported the HEXPILOT experiment; and Rijkswaterstaat made the Meetpost Noordwijk available; K. B. Katsaros received initial HEXOS support from a National Science Foundation visiting professorship for women at the Naval Postgraduate School (NSF grant R11-8310351); the Office of Naval Research, U.S.A., Marine Meteorology Program, directed by Dr. Robert Abbey has supported two planning workshops and travel support to HEXIST and the present HEXOS Pilot Experiment. K. B. Katsaros receives her present HEXOS research support from this program under grant N00014-85-K-0123. This is HEXOS Contribution Number 2.


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