# Vertical structure of the upper ocean in the high–latitude north Atlantic

## FINAL REPORT

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## Background

The subarctic North Atlantic is a region with strong seasonal signals in both physical and bio–optical properties [Marra, 1989]. The site chosen for the Marine Light–Mixed Layers (MLML) field programs (Figure 1) is characterized by a deep (600 to 800 m) winter mixed layer as a result of substantial surface heat loss and strong wind forcing from September to March. Of particular interest at this site is the spring restratification process, wherein the deep mixed layer shoals dramatically as a result of increased surface heating during periods of weak wind forcing. The seasonal changes in mixed layer depth result in immense changes in plankton biomass observed as the spring bloom [e.g. Ducklow, 1989].

The overall MLML program was interdisciplinary, combining physics, biology, and optics in order to determine the extent to which bio-optical properties could be predicted given knowledge of the physical forcing [Marra, 1995]. Our intent was to investigate the restratification process at this unique site, as well as to provide the physical context for the extensive bio–optical measurements. The MLML experiments took place during the spring of 1989 and the spring and summer of 1991. Our contribution to the 1989 experiment was a surface mooring deployed at approximately 59° N, 21° W from April to June. The mooring was outfitted with instrumentation for determination of the air–sea fluxes of heat and momentum, and the vertical structure of temperature, velocity, and bio-optical properties in the upper ocean. During the 1991 field program a more heavily instrumented mooring was deployed at the same site from April to September.

Remote sensing of temperature and ocean color in the subarctic North Atlantic show significant mesoscale variability, particularly in summer. As a result, the role of fronts and eddies in modulating biological variability at the MLML site was of interest. Indeed our results indicate that non-local processes are important to the evolution of upper ocean stratification during summer. However, local one-dimensional processes dominated during the spring transition and the onset of restratification was predictable to first order from knowledge of the local surface forcing.

## Results

The severe environment at the MLML site (high winds, large waves, and strong currents) represented a challenge to our ability to make detailed measurements of atmospheric forcing and the variability of the upper ocean. The process of meeting this challenge began in 1989 with the design and deployment of the MLML pilot mooring. The pilot mooring was deployed in April of 1989 in anticipation of a 5 month deployment, but the experiment was curtailed when a component in the mooring line failed after 10 weeks (both buoy and mooring line were later recovered). Despite the short record, the pilot mooring provided a unique high–latitude data set during restratification of the upper–ocean and initiation of the spring bloom [Dickey *et al.*, 1994a, 1994b; Stramska and Dickey, 1992, 1993, 1994].

Extensive evaluation of the performance of the 1989 pilot mooring was undertaken in cooperation with the Applied Ocean Physics and Engineering Department at WHOI [e.g. Grosenbaugh, 1995, 1996]. The result was a revised 1991 mooring, designed both to minimize the static tension along the mooring line and to survive peak tensions in excess of those observed in 1989. The critical design elements of the 1991 mooring are described by Plueddemann *et al.*, [1993]. The new mooring design resulted in a reliable platform from which 129 days of surface and sub–surface data were collected, and represented a milestone in our efforts to increase the range of severe–environment sites at which long–term meteorological and oceanographic measurements can be made.

The 1991 deployment period included both the spring transition, when upper ocean restratification was initiated after deep winter mixing, and the fall transition, when mixed layer deepening began again. The dominant signal in temperature was seasonal variation, with a 6°C increase observed at the sea surface from May to August. Prior to development of the seasonal stratification, a period dominated by near–surface temperature variability was observed in association with a with a 15 day mean flux of only 20 W $m^{-2}$ into the ocean (Figure 2). Pronounced day/night oscillations of heat flux during this period resulted in alternating development and destruction of stratification and intense diurnal cycling of the mixed layer depth (Figure 3). Interestingly, the principal increase in phytoplankton biomass, i.e. the most intense bloom, occurred not after development of the seasonal stratification, but during the period when the mixed layer was relatively deep and showed substantial diurnal variability Stramska *et al.* [1995].

A qualitative comparison of the observed temperature structure to the prediction of a one–dimensional mixed layer model [Price *et al.* 1986] showed that local processes dominated during the initiation of restratification. The model reproduced the initial "thermal cap", the period of mixed layer depth variability, and the onset of seasonal stratification seen in the observations. This is encouraging for investigators attempting to use one–dimensional bio–physical models to study the spring bloom in the subarctic North Atlantic (e.g. Stramska and Dickey, [1994]; Stramska *et al.* [1995]). After the fall transition, however, neither the magnitude nor the slope of the SST variations were well predicted by the model. It was presumed that this was principally the result of non–local processes such as horizontal and vertical advection.

Our work on the MLML project resulted in four journal articles and two technical reports authored or co–authored by one of us. In addition, another six journal articles, although not authored by us, benefited from our participation in the project. The principal results relating to physical processes and bio–physical interaction appear in Dickey *et al.* [1994a], Plueddemann *et al.* [1995], Stramska and Dickey [1992, 1993, 1994], and Stramska *et al.* [1995]. Tension measurements made from the MLML moorings were important to the mooring dynamics studies of Grosenbaugh [1995, 1996]. Current measurements from MLML were used in a comparative study of current meters by Irish *et al.* [1995]. Observations from the 1989 mooring were used by Dickey *et al.* [1994b] for the determination of net longwave heat flux. Meteorological sensor performance for the 1991 buoy was evaluated by Plueddemann *et al.* [1993]. Acoustic backscatter measurements from the 1991 mooring were used in the investigation of zooplankton biomass variability by Batchelder *et al.* [1995]. Ongoing work includes a quantitative study of the upper ocean heat and momentum balances at the MLML site (with a WHOI Postdoctoral Scholar) and investigation of the spatial structure of physical and bio–optical parameters during the 1991 experiment (with L. Washburn at UCSB).

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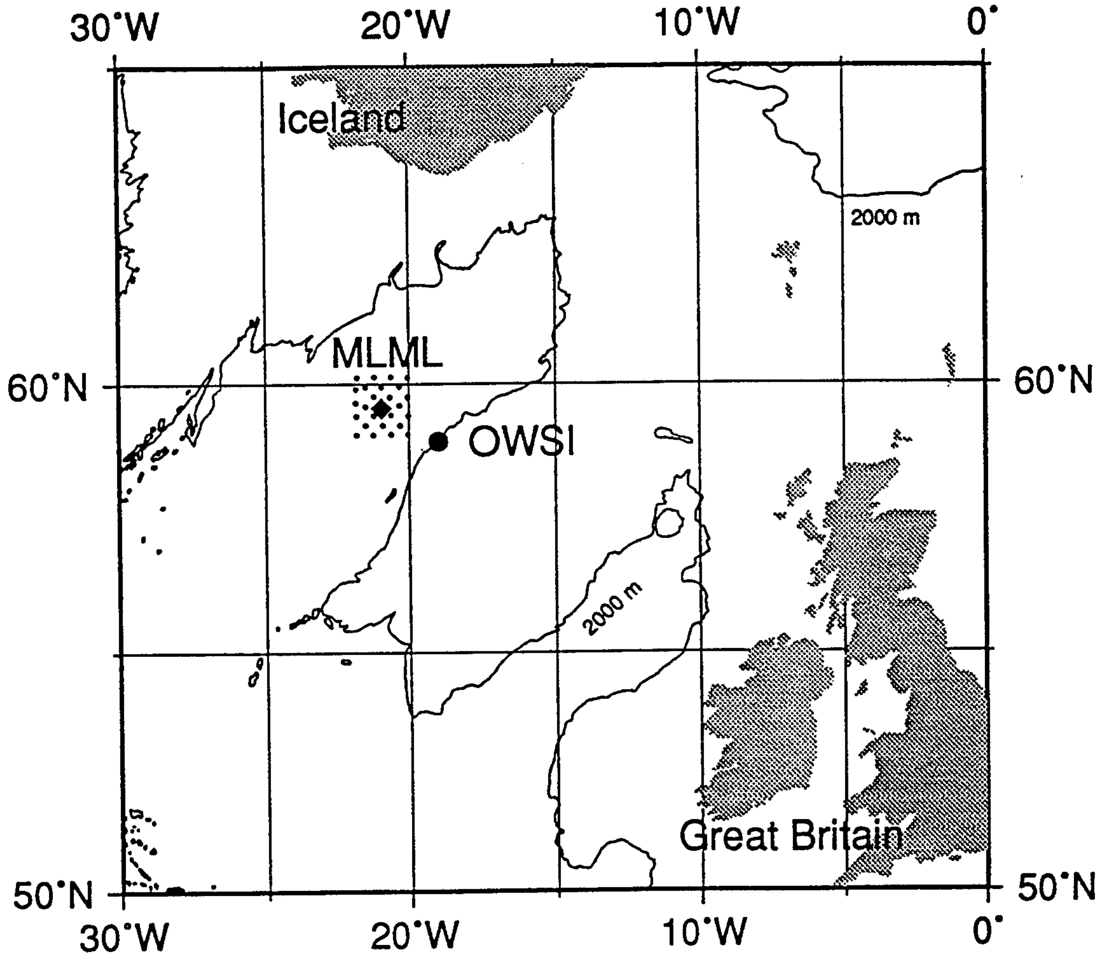

Figure 1: The MLML mooring site is shown along with a grid representing the shipboard survey region. The mooring was deployed at 59° 35.61′ N, 20° 57.85′ W in 2822 m of water about 275 miles south of Reykjavik, Iceland. The site at 59°N, 19°W is Ocean Weather Station India (OWSI) were the data of Lambert and Hebenstreit [1985] were collected.

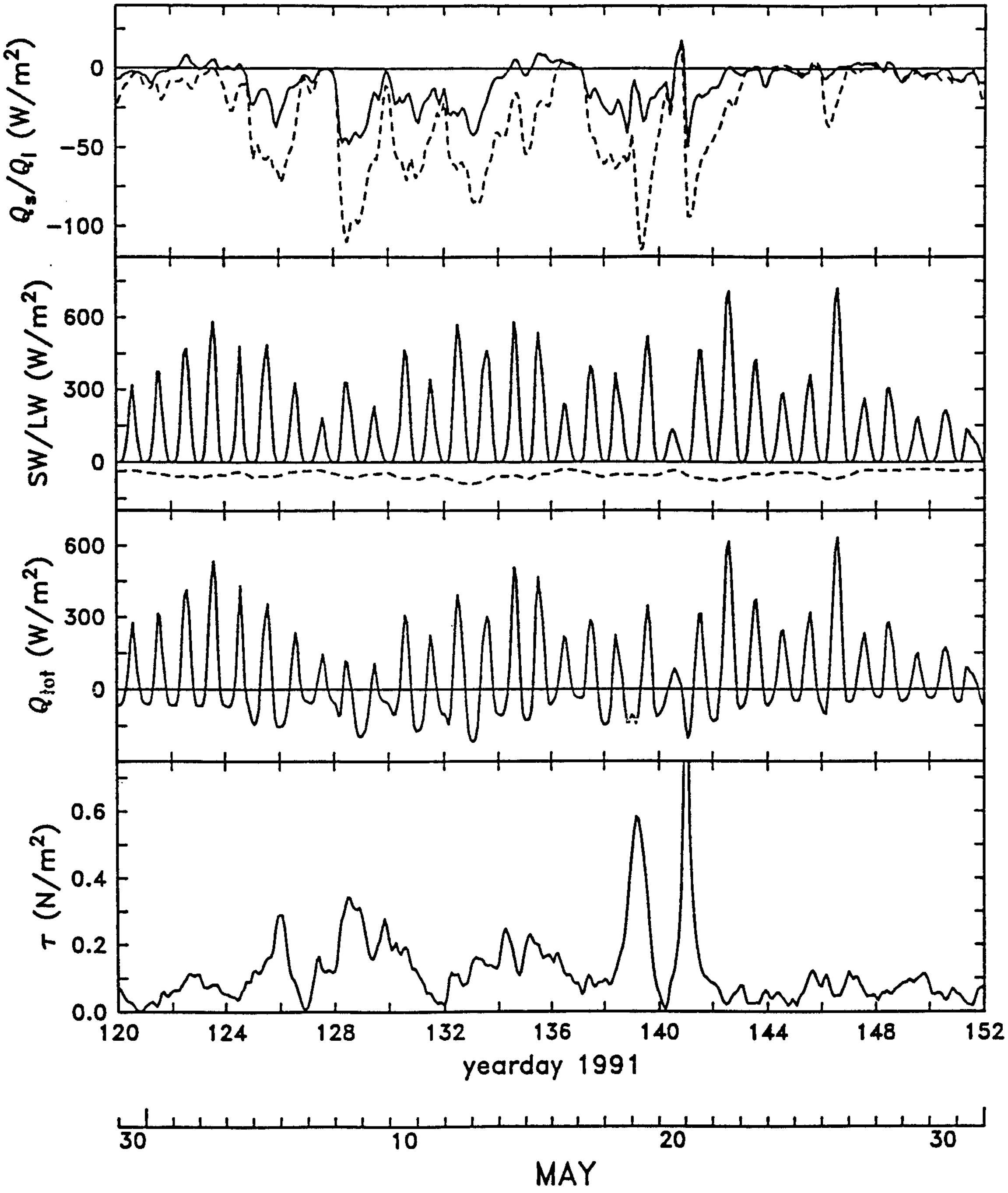

Figure 2: Time series of air–sea fluxes during May. The four panels show (top to bottom) sensible (solid) and latent (dashed) heat flux, net shortwave (solid) and net longwave (dashed) radiation, total heat flux, and wind stress magnitude. The period from 5–21 May is characterized by substantial sensible and latent heat losses due to strong winds and cold, dry air at the sea surface (a negative flux represents a heat loss from the ocean). The total heat flux has pronounced positive to negative oscillations and a mean of only 20 W m$^{-2}$ into the ocean during this period.

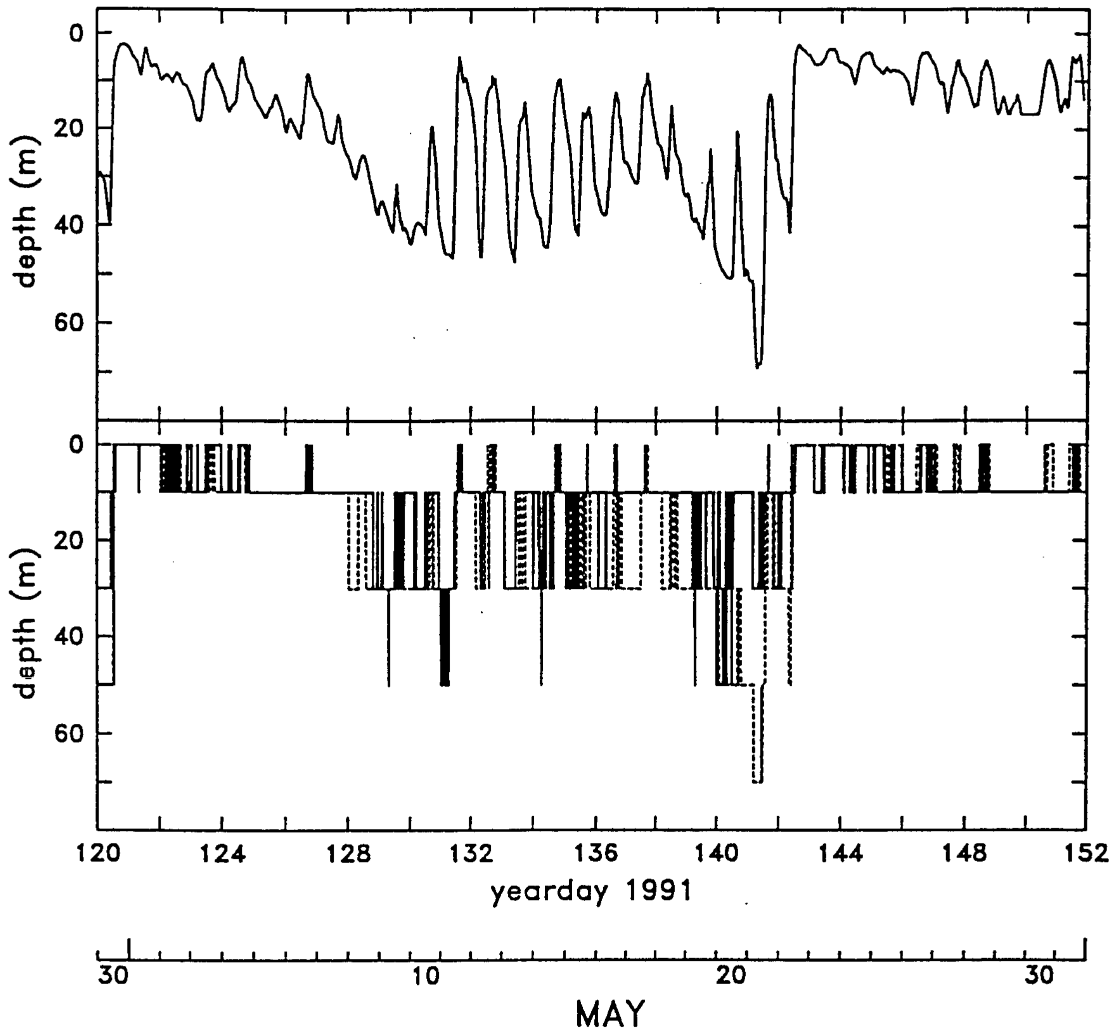

Figure 3: Mixed layer depth, defined as the depth where temperature is 0.01 colder than the surface, from observations and from the Price *et al.* [1996] model. The model had a vertical resolution of 1 m, resulting in a smooth time series (upper panel). Observations were available only at 10, 30, 50, 70 and 80 m, resulting in a "stepped" time series (lower panel, solid line). The model shows similar behavior when subsampled at the same depths as the observations (lower panel, dashed line). Episodic vertical mixing prior to the onset of seasonal restratification, indicated by the intense diurnal cycling of the mixed layer depth during 10–21 May, appears to play an important role in controlling the evolution of bio-optical properties.