Arctic Upper Ocean Studies

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LONG-TERM GOALS

My goals are to investigate and understand the turbulent transfer of momentum, heat, salt, and other scalar contaminants in naturally occurring boundary layers of the ocean, and to apply this knowledge to understanding air-ice-ocean interaction in polar regions.

OBJECTIVES

Objectives include interpreting a substantial body of turbulence data from the ocean boundary layer (OBL) under sea ice to better understand (i) the impact of ice-ocean interaction on the heat and mass balance of sea ice; and (ii) general characteristics of ocean boundary layers in response to surface stress, buoyancy flux, and existing temperature/salinity structure. An important element is developing realistic parameterizations of surface (ice/ocean) fluxes in terms of prognostic variables typically carried in large scale models of ocean circulation. An additional important objective is continued development of techniques for measuring turbulence in ocean boundary layers.

APPROACH

I have developed systems for measuring vertical turbulent fluxes of momentum, heat, and salt in the ocean boundary layer under drifting sea ice by direct covariance of the respective quantities with vertical velocity. Three axis current meters are mounted near Sea-Bird temperature and conductivity sensors in turbulence instrument clusters mounted at several levels on rigid masts. The masts may then be lowered to any level within the upper 120 m of the ocean. The turbulence measurements, nearly unique for ocean boundary layer environments, are then used to determine properties and scales of OBL turbulence.

I have also developed a relatively simple theoretical approach to describing ocean boundary layer mixing based on similarity theory utilizing preferred turbulence scales. This technique, which I call *local turbulence closure*, has been applied to many different ice/ocean scenarios ranging from rapid melting conditions under Arctic sea ice to speculations on heat transfer at the interface between a Europan ice cover and a postulated underlying saline ocean. As described below, recent analysis from the year-long SHEBA project in the Arctic has provided significant additional observational evidence that the scaling approach is appropriate, and illustrated a relatively direct way of estimating eddy exchange coefficients for the rotating ocean boundary layer.

WORK COMPLETED

Work completed in FY 2002 includes:

1. SHEBA turbulence mast data interpretation. The data organization combining oceanographic, ice and surface meteorological data from diverse sources during the year-long SHEBA project, described in the FY 2001 report, has been refined and utilized to estimate important parameters for numerical modeling of ice/ocean exchange. The analysis included a comprehensive look at spectral characteristics of vertical velocity, temperature, and salinity fluctuations, with important implications for understanding scales of turbulence in the boundary layer.

2. SHEBA special events. As identified in the July, 2001, SHEBA meeting in Boulder CO, several events during the SHEBA year were of special interest. Data from some of these times have been organized and used to drive/verify horizontally homogeneous models, in order to understand response of vertical exchange to varied forcing. By specifying different surface boundary conditions, one study, for example, showed that energetic inertial oscillations observed in late summer had relatively little impact on turbulent exchange in the OBL In addition, a particular event in March indicated large response in the upper ocean to a zone of concentrated ice velocity shear (vorticity) passing through the SHEBA site, as inferred from SAR image analysis. The observations have opened a new line of inquiry into a unique aspect of ice/ocean interaction; namely, the concentration of synoptic system differential ice motion into narrow zones of intense vorticity, sometimes extending for several hundred kilometers. I am working with M. Coon and R. Kwok to extend these concepts, with funding under a separate NASA grant.

*3. Scalar fluxes at the ice/ocean interface.*_ The false bottom modeling project begun in 2001 has culminated in a manuscript accepted for publication by JGR (Notz et al., 2002). It shows that during melting, the ratio of exchange coefficients for heat and salt in the laminar sublayers near the interface must be much greater than unity (i.e., that double diffusion is important) in order to explain the migration of false bottoms. Conversely, the fjord studies (below), have shown that during freezing, any double diffusive tendencies are relieved very near the interface, so that the exchange coefficients are more nearly equal. These concepts may be important for understanding how deep convection occurs in the ice-covered Weddell Sea, since the rate at which heat is transferred at the ice/ocean interface may play a critical role in overcoming the so-called thermal barrier.

4. Boundary-Layer Modeling. During 2002, I continued research on OBL modeling, working with scientists from several institutions including the Naval Postgraduate School, University of Washington, Oregon State University, and the Courant Institute (NYU). The LTC model code has been implemented in MatLab, with documentation, and is available with examples on a public FTP site. The MatLab implementation makes it easily accessible across multiple platforms.

5. Fjord Studies. I continued our study of fluxes in the boundary layer under fast ice in Svalbard fjords with scientists from U. Bergen, Cambridge University, Yale University and the University of Washington. In 2002, we deployed instruments in Kongsfjord near Ny Aalesund, and later in VanMijen Fjord during a UNIS student exercise. Quite different conditions were encountered, with very thin ice and high heat flux in Kongsfjord vs. relatively thick ice and water near freezing in VanMijen Fjord. For the first time, the turbulence mast utilized only acoustic Doppler velocimeter (ADV) current measuring technology with very good results. We had consistently large signal-to-noise ratios for both instruments, with capability of measuring covariance statistics down to very small energy levels. In addition, a productive comparison between the ADVs and a nearby travel time current meter was performed.

RESULTS

A primary result from the SHEBA turbulence mast data organization is a final estimate of the appropriate bulk heat exchange coefficient for the SHEBA site. Modern numerical models of ice/ocean interaction often describe the heat and salinity flux at the interface using either the “2-equation” or “3-equation” approach (Holland and Jenkins, 1999). The former expresses the heat flux in terms of a “bulk” relation $H_w = \rho c_p u_{*0} c_H \delta T$ where δT is the elevation of mixed layer temperature above freezing , u_{*0} is the interface friction velocity, and c_H is the bulk heat exchange coefficient (McPhee, 1992). The turbulent heat flux is then combined with the conductive heat flux in the ice to estimate the heat balance at the interface, from which the melt (or freeze) rate, hence salinity flux, is estimated. The more sophisticated, 3-equation approach considers that the salinity at the interface is depressed by rapid melting, which becomes a third unknown, that can be combined with the freezing condition at the interface to provide a quadratic equation for the interface vertical velocity. Unless ice melt is exceptionally rapid, the 2-equation approach is generally acceptable (McPhee, op. cit.), and the main observational challenge is determining c_H.

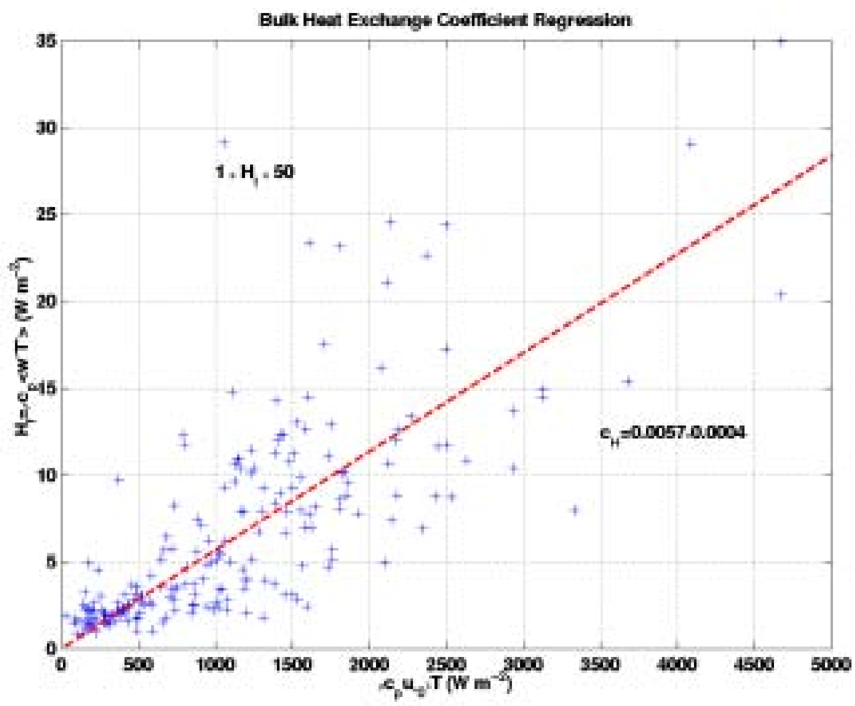

Figure 1. Interface heat flux determined from meausured covariance values at the two upper turbulence clusters on the SHEBA ocean turbulence mast are plotted as a scatter diagram against the product of surface friction velocity and elevation of mixed layer temperature above freezing. The slope of the regression line furnishes an estimate of the bulk heat exchange coefficient. The value is 0.0057 with a 95% confidence interval of ±0.0004.

Three-hour averages of turbulent heat flux from the entire project, with the exception of the summer months (Jun-Aug), were combined for the upper two clusters (nominally 4 and 8 m below the interface) to estimate the ocean interface heat flux, which was compared with corresponding values of $u_{*0}\delta T$. A linear regression then provides the bulk coefficient (Fig. 1) which corresponds closely with values found during previous projects, including first year ice in the Weddell Sea (0.0056, McPhee et al., 1999.

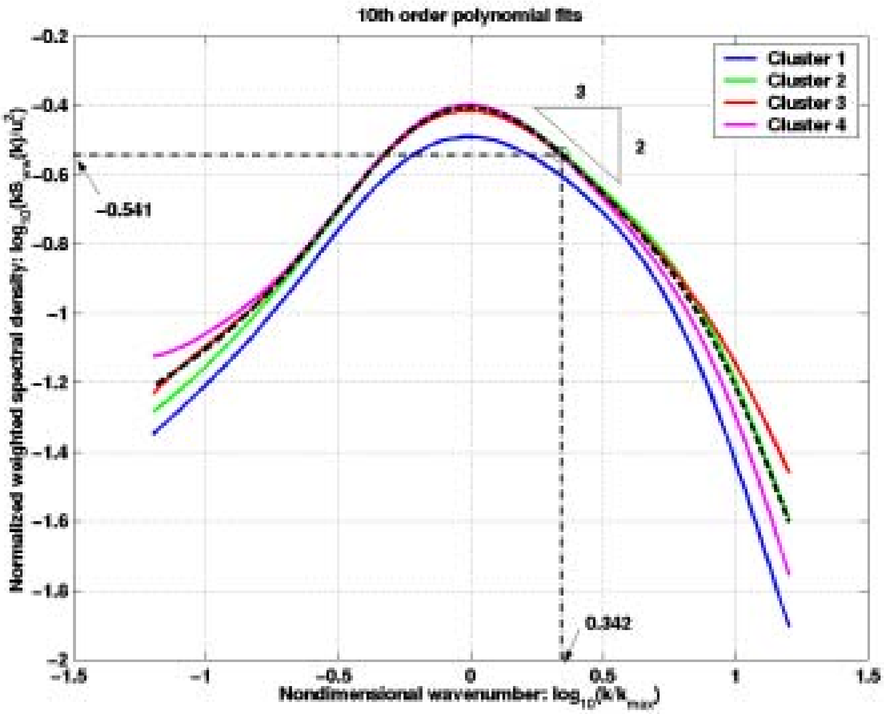

Figure 2 Normalized vertical velocity spectra for each cluster from all 3-hr averages, SHEBA Site 1. For the interior of the OBL (clusters 2-4 at 4, 8, 12 m from the interface), the nondimensional spectra are nearly identical over the wavenumber ranges corresponding to most of the turbulent energy.The special abscissa and ordinate values mark the point where the normalized spectral slope is –2/3, as in the inertial subrange.

Figure 2 illustrates one of the most significant findings from the SHEBA turbulence mast analysis. All of the spectra from beyond the near surface layer (where horizontal variation was significant [McPhee, 2002]), collapse to a near universal, nondimensional form, providing strong evidence that the fundamental turbulence scale is proportional to k_{max}, the wavenumber at the peak in the w spectrum. From this, friction velocity and eddy viscosity may be computed directly from the vertical velocity spectrum. An example comparing the local eddy viscosity at the nominal 12 m below the ice level, where K_m=0.85u_*/k_{max}, with a bulk similarity estimate, K_{sim}=0.02u_{*0}^2/f (McPhee and Martinson, 1994) is shown in Fig. 3. Note that the local estimates are obtained solely from the w spectra. Scalar flux magnitudes are similarly successfully estmated using the T and S variance spectra in combination with the w spectrum. A manuscript is in preparation.

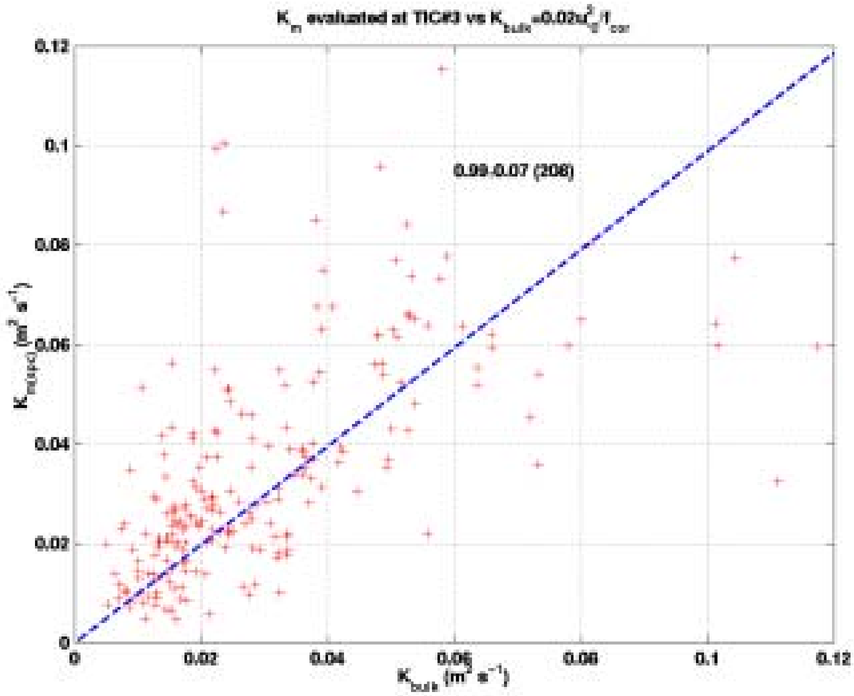

Figure 3. Local eddy viscosity 12 m below the ice/ocean interface is plotted against a bulk eddy viscosity based on similarity theory. The regression slope, 0.99±0.07, is statistically indistinguishable from unity. **K_m** ***is derived from the*** **w** ***spectrum.***

IMPACT/APPLICATION

Research into basic questions of how the ocean boundary layer works has wide application ranging from detailed studies of ice/ocean interaction to bottom boundary layer flow in estuarine environments to ocean parameterization in global circulation models. A new application emerged this year, when I was invited to speculate on extra-terrestrial ice/ocean interaction at a meeting of the Europa Focus Group in Flagstaff , AZ.

TRANSITIONS

An important issue emerging from the large turbulence data set collected during SHEBA is verification of the energy containing scales in rotational boundary layer turbulence. The spectra not only provide an alternative way of measuring fluxes, but also make concrete concepts of eddy viscosity and scalar diffusivities for the OBL: a necessary target for numerical modeling verification.

RELATED PROJECTS

I am working with T. Stanton (NPS) on SHEBA analysis and thermobaricity; with B. Garwood and R. Harcourt on thermobaricity; with J. Morison and D. Hayes (UWAPL) on the SHEBA summer leads; G. Maykut (UW), D. Holland and A. Romanou (Courant Institute), and W. Maslowski (NPS) on incorporating SHEBA results into ice/ocean models; with C. Bitz, R. Moritz, and M. Holland on incorporating ice-albedo feedback into large scale models; with H. Eicken and R. Gradinger (UAF) on shelf-basin interaction problems; with F. Nilsen (UNIS), P. Haugan and A. Siravaag (U. Bergen) on fjord dynamics problems, with E. Skyllingstad (OSU) on LES model formulation and verification.

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