Arctic Mixed Layer Dynamics
and
Graduate Student Support

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LONG-TERM GOAL

Our long-term goal is to understand the dynamic and thermodynamic processes causing changes in the velocity and density structure of the upper Arctic Ocean. For example we seek to understand the heat and mass balance of the mixed layer. In light of recent changes in the upper ocean structure, our long-term goals are shifting toward processes important to larger-scale changes.

OBJECTIVES

Our immediate objectives are to understand the effect of horizontal inhomogeneity on the surface boundary layer, and the response of the Arctic shelves to recent changes in the Arctic environment.

APPROACH

In studying horizontal inhomogeneity in the upper ocean we have developed a technique to measure vertical water velocity and the turbulent fluxes of heat and salt with Autonomous Underwater Vehicles (AUV), and constructed the Autonomous Micro-conductivity and Temperature Vehicle (AMTV) to fully test and exploit the technique. AMTV data was gathered at the Surface Heat Balance of the Arctic (SHEBA) station in 1998 and shows the effects of horizontal inhomogeneity on mixed layer fluxes around a summer lead. We are modeling these effects with a modified time-varying 1-D model and a more sophisticated time-varying 2-D model. Also under this grant, the PI and Jinlun Zhang have been examining the response of the Arctic Ocean, particularly the shelves, to large-scale atmospheric changes using a coupled ice-ocean model.

WORK COMPLETED

During the past year working with our graduate student Dan Hayes, (Hayes' support is under ONR Grant N00014-96-1-5033) we have been analyzing data gathered during the SHEBA experiment with the AMTV. This year we completed development of the Kalman smoothing method for determining turbulent vertical water velocity. We were able to improve the accuracy and extend the frequency response of the velocity estimates well beyond what we had achieved earlier by accounting for the vehicle pitching moment caused by the variation in vertical water velocity along the length of the hull. This was done by approximating the effect of differences in vertical velocity along the vehicle hull with an additional first order lag response in the vehicle equation of state. The Kalman smoother method now produces turbulent vertical velocity spectra from the AMTV that agree with spectra from

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14. ABSTRACT
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fixed velocity sensors up to wave numbers of 0.5 cpm or a wavelength of 2 meters. This is nearly the theoretical limit associated with the 1.6-meter vehicle hull length. We have completed and revised a paper (Hayes and Morison, 2001) on the Kalman smoother submitted to *the Journal of Atmospheric and Oceanic Technology*.

To understand the observed summer lead phenomena we have first simulated steady, two-dimensional (x and z), forced convection using a simple advective transformation ($x=V_{ice}\ t$) from Mellor et al. (1986). This converts the problem to a one-dimensional (z) time-dependent problem. The method accounts for spatial variability due to growing boundary layers, but because it is not truly two-dimensional, it does not take into account the effects of horizontal pressure variation or allow for the propagation of horizontally inhomogeneous initial conditions. The one-dimensional, time-dependent model is based on one by McPhee (personal communication) and uses the McPhee (1994) turbulent closure method.

Also under this grant, the PI and Jinlun Zhang have been examining the response of the Arctic Ocean, particularly the shelves, to large-scale atmospheric changes. This work is related to the PI's efforts to develop the Study of Environmental Arctic Change (SEARCH), an interagency (including ONR) program, that aims to understand recent large-scale changes affecting the high-latitude environment (Morison et al., 2000). The shelves are source regions for important water masses, they are commercially and militarily important seasonal sea-ice zones, and they are the sites of relatively rich long-term measurement records. For example, Pavlov et al. (1999), under a previous grant, analyzed 50-year records of near-shore surface salinity and sea surface elevation and showed a positive long-term trend in Russian Arctic sea level. Our effort has focused on modeling the response of such parameters to changing atmospheric conditions using the multi-level, coupled ice-ocean, model of Zhang et al. (1998).

RESULTS

Effects of Horizontal Inhomogeneity

A total of 50 AMTV runs were made at SHEBA in the summer of 1998. Most of our efforts have focused on explaining results obtained under and around a large lead on August 7, 1998 during a storm. The data from this period is central to one of the key questions of the SHEBA oceanography program, the effects of horizontal variability on the boundary layer. Figure 1 illustrates the boundary layer response to spatially varying surface heat and buoyancy flux as measured with the AMTV. The top two panels show temperature and salinity fluctuations measured at 5-m depth on legs of a vehicle run from 600 m out under the 1-km wide lead to the ice edge and 300 m back under the ice. The actual ice draft measured with the AMTV upward looking sonar is shown at the top of the upper panel. The middle panel shows vertical water velocity along the path calculated using the Kalman smoothing technique (here z, vertical velocity w', and fluxes are positive downward). The bottom two panels show instantaneous turbulent heat and salt fluxes from products ($\langle w'T' \rangle$, $\langle w'S' \rangle$) of vertical velocity with temperature and salinity fluctuations respectively. The direction of the wind and ice motion relative to the water was right to left. The variations in temperature and salinity were greatest under the lead and in a region under the ice about 100 m downstream of the lead edge. Downstream of this point the fluctuations decreased dramatically. The situation was nearly the opposite for vertical velocity; vertical motion was suppressed under the lead and up to 100 m downstream. The average heat flux was 87 W m^{-2} downward under the lead and 16 W m^{-2} beyond 100 m downstream of the lead edge. The average salt flux pattern was similar, $4x10^{-5}$ kg m^{-2} s^{-1} upward under the lead and $2x10^{-6}$ kg

m^{-2} s^{-1} downward (essentially negligible) beyond 100 m downstream. Average fluxes in the region within 100 m downstream of the lead edge were between the lead and under-ice values.

As described in Hayes and Morison (2001), the high downward heat flux in the lead agrees with fixed sensor measurements at the lead edge and corresponds roughly to the input of radiative heat at the lead surface. We hypothesize that the heat flux remains elevated at 5 m depth for another 100 m under the ice, because the internal boundary layer associated with drastically reduced heat input, takes 100 m to grow to a depth of 5 m. The salt flux follows a similar pattern supplied by the flux of fresh melt water accumulated near the lead surface from the surrounding ice. The turbulent velocity fluctuations not only increase in magnitude, but also increase in length scale beyond 100 m of the lead edge, probably due to a combination of the rough ice surface and absence of stabilizing buoyancy flux under the ice. These observations also lead us to speculate that unstable stratification may occur, even under nominally stabilizing buoyancy flux, by the interaction of vertical shear and horizontally inhomogeneous salinity. McPhee (personal communication) has suggested such an "overrunning" phenomena, whereby velocity shear drags dense water over an adjacent fresh water patch, as a possible reason for observed rates of mixing at SHEBA that occasionally were greater than would be predicted.

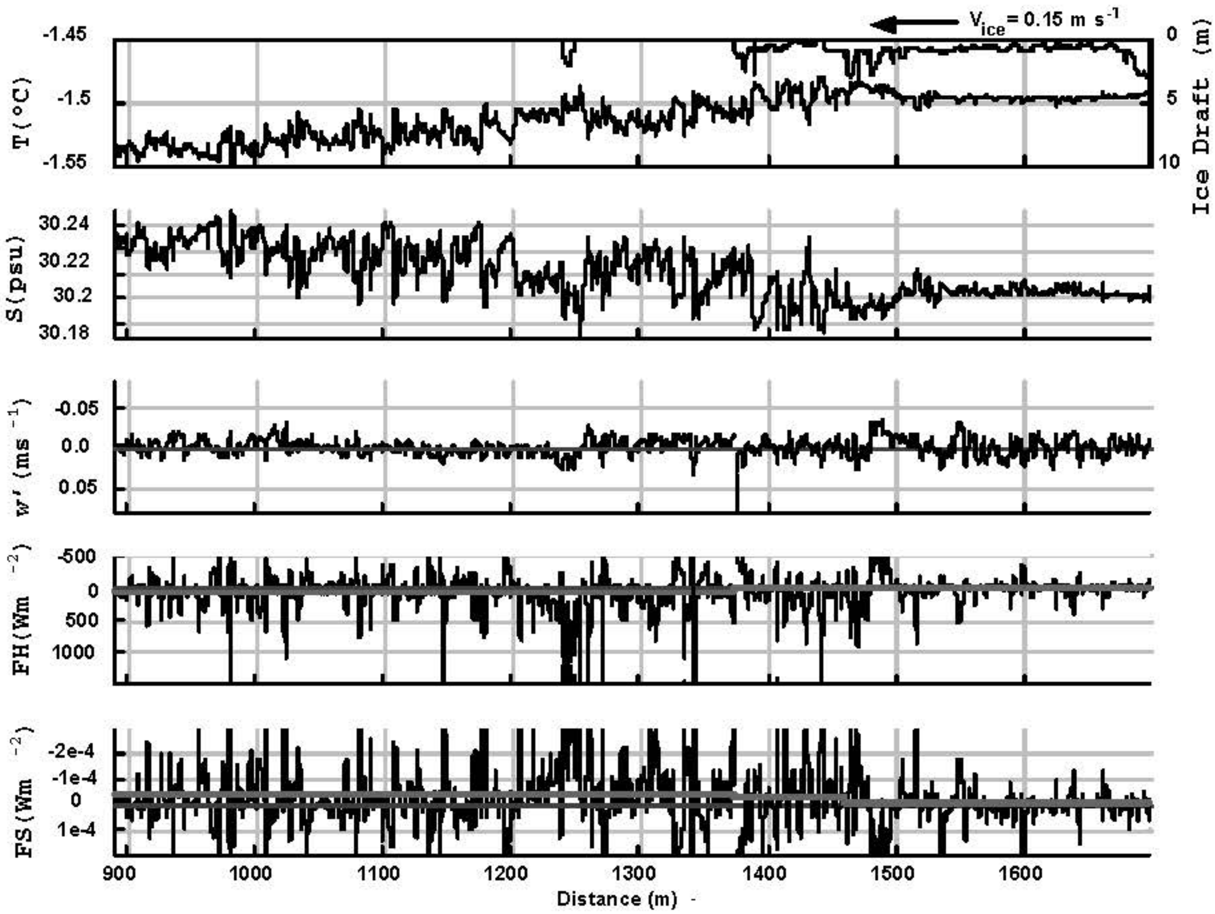

Figure 1. Temperature, salinity, vertical water velocity, heat flux, and salt flux as measured under and beyond a lead with the AMTV at SHEBA on August 7, 1998.

Figure 2 shows initial results simulating conditions as they were for the observations of Figure 1. The top two panels show temperature and salinity. The simulated temperature and salinity changes across the lead are similar to the measured changes. The major difference is that the average simulated salinity gradient across the lead is a tenth the average measured gradient. This may be an instrumental error related to micro-conductivity sensor drift. This does not hurt the salt flux measurements, which involve higher frequency components of conductivity.

The simulated changes downstream of the lead edge are similar to the measurements except that the simulated 5-m temperature begins to decrease immediately at the edge. The 10-m simulated temperature continues to increase for a few hundred meters downstream before leveling off. The measured temperature continues to increase for 100 m downstream of the lead edge, a response intermediate between the simulated 5 and 10-m responses.

The simulated heat fluxes are shown in the third panel of Figure 2. The 5-m heat flux shows values in the lead comparable to the measurements, and as with the measurements, remain high up to 100 m downstream of the lead edge. They remain large downward farther downstream than the measured fluxes, but finally turn upward beyond 1200 m. This pattern explains why the measured heat flux at 5 m does not reverse and become positive upward immediately downstream of the lead. The simulations show that the heat put into the lead continues to be mixed downward into the mixed layer for a considerable distance downstream of the lead. At 10- m depth the transition to upward flux requires even more downstream distance. The simulated turbulent velocity scale and mixing length shown in the fourth and fifth panels are consistent with the appearance of the measured w'. The energy and mixing length both increase under the ice. The increase begins immediately at the lead edge because the turbulent closure scheme makes them strongly dependent on the surface boundary conditions, which are rougher and less stable under the ice.

The boundary layer adjustment model explains many of the observed characteristics of summer lead flux at least for steady conditions. In this it is a useful tool for estimating the partition between lateral and bottom melt, one of the key SHEBA issues.

In other related highlights this past year, Dan Hayes passed his General Exam in late May 2000. His graduate committee approved his Ph.D. thesis proposal to use the SHEBA AMTV results in conjunction with boundary layer modeling to understand the effect of horizontal variability in stably stratified boundary layers.

Also, the PI co-authored two chapters in the *Encyclopedia of Ocean Sciences* to be published by Academic Press. McPhee and Morison (2001) describe basic planetary boundary layer physics in the context of the under-ice boundary layer, and Morison and McPhee (2001) describe the unique elements of ocean-ice interaction that control the exchange of heat, salt, and momentum between the ocean and sea ice.

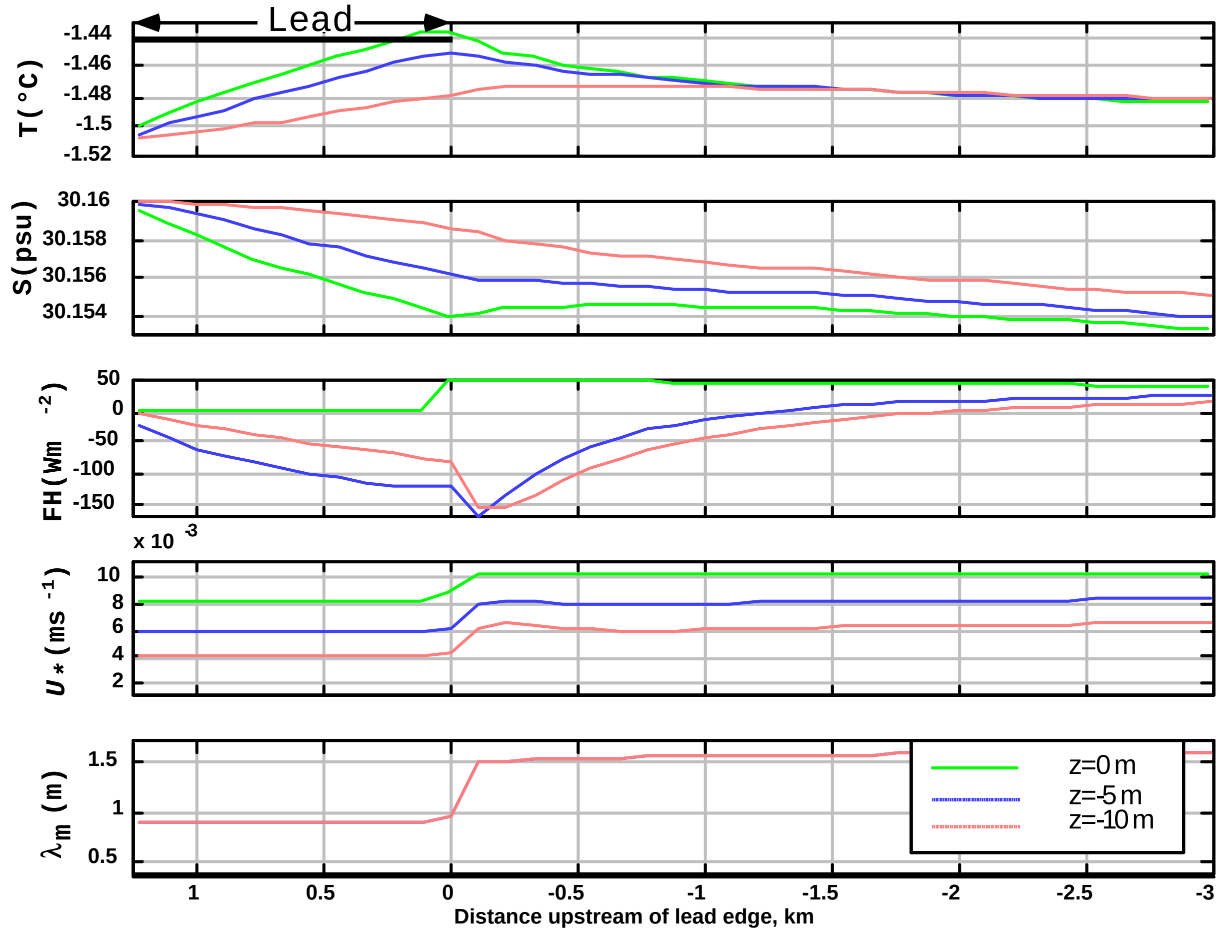

Figure 2. Temperature, salinity, heat flux, turbulent velocity scale, and mixing length as simulated for the lead of Figure 1.

Preparation of these articles has in part motivated us to propose the study of momentum flux to a rough boundary.

Response of the Russian Shelves to a Changing Arctic

As discussed in two publications supported in part by this grant (Morison et al., 2000; Morison, 2001), one of the key hypotheses about the changes in the Arctic environment is that they are related to the rise in the Arctic Oscillation (AO) index (Thompson and Wallace, 1998). The rising AO involves a drop in surface atmospheric pressure over the Arctic Ocean and a cyclonic spin up of the polar vortex. This cyclonic atmospheric circulation is thought to drive a more cyclonic ocean circulation with decreased sea surface elevation in the center of the basin and increased sea level at the ocean margins. Using the model of Zhang et al. (1998) we find that the sea surface is on average lower in the central basin and higher along the Russian coast during periods of positive AO. The implications for the fate of Russian river water and the formation of the cold halocline are important. Increased coastal sea level will tend to move river water eastward toward the Beaufort Sea instead of allowing it to mix across the shelves to produce cold halocline water. Such a pattern would contribute to the observed decrease in Beaufort Sea salinity (McPhee et al. 1998) and reduced cold halocline thickness (Steele and Boyd, 1998).

The Zhang et al. (1998) model shows correlation between the AO index and a several other important parameters on the Russian shelf. There is a correlation (~ 0.5) between AO and sea level at coastal stations in the Kara Sea and near the New Siberian Islands. Historical sea levels in these regions should be useful proxies for the ocean response to the AO. Correlations with surface salinity are not high. The flows into the Barents Sea and off-shelf between Severnaya Zemlya and Franz Josef Land are important to the fate of Atlantic water, shelf-basin exchange and the maintenance of the cold halocline. These show a correlation (~0.6) with AO that suggests these exchanges should be enhanced during periods of high AO. A positive correlation of AO with the eastward flow out of the Kara Sea through Vilkitskogo Strait supports the idea of Steele and Boyd (1998) that enhanced AO should drive more Russian river water (Ob and Yenisey) eastward before mixing it into the Arctic Ocean halocline.

IMPACT/APPLICATION

Impacts of this research include providing a technique whereby nearly any AUV can provide turbulence data as a side benefit to other sampling it carries out. Used with simple vehicles, the technique will yield spatial maps of turbulent energy. Used with sophisticated AUVs, the technique will also yield spatial maps of vertical fluxes of the other variables being measured. Such maps will be the keys to identifying dynamically critical areas and determining the budgets of heat, salt, biomass and pollutants. Modeling the effects of horizontal inhomogeneity will produce fundamental knowledge needed to model the dispersion of moisture, heat, and chemical agents from point sources in the atmosphere as well as the ocean. Our studies of the shelf response to the AO have application to predicting Naval operations in an Arctic with reduced ice extent.

TRANSITIONS

Vehicles like the AMTV and the Kalman smoothing technique could be used militarily. Such AUVs could make clandestine surveys of littoral areas. The method of extracting information on water motion from vehicle motion would have application in determining the wave energy in areas of planned amphibious assault. The technique may also find application as a non-acoustic detection and tracking tool. This would find application in "smart" and acoustically quiet weapons that could detect the wakes of vessels and follow them. Torpedoes using the technique in real time could conceivably follow turbulent ship wakes to their targets.

RELATED PROJECTS

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