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Spatial Variations in Sea-Ice Formation-Onset in the Laptev Sea as a Consequence of the Vertical Heat Fluxes Caused by Internal Waves Overturning

by Sergey Kirillov[1]

Abstract: The Laptev Sea shelf is an area that is strongly affected by the continental runoff in the summer. Huge amount of freshwater flows into the eastern Laptev Sea via the Lena River and forms a density interface that strongly affects the water column dynamics and the thermal processes. Delay in ice formation might be one of the consequences caused by both density stratification and the solar heat accumulated in the deeper layer. The internal waves seem to be one of the possible mechanisms that cause the mixing and explain the observed variations in ice-formation dates. Data of several ADCP records deployed in the Laptev Sea in 1998/1999 and 2000 were processed in an attempt to evaluate the heat exchange rate due to the internal wave acting. It was found that vertical heat flux could result in an additional delay of ice-formation up to 5-6 days depending on the local bottom topography. It was also revealed that the storm events in fall increase the average energy of internal wave spectrum by 2-3 times over its calm state. This can also enhance the efficiency of exchange through the pycnocline by the factor of 5-10.

Zusammenfassung: Das Gebiet des Laptewsee-Schelfs wird im Sommer stark durch kontinentalen Eintrag geprägt. Gewaltige Süßwassermengen werden durch die Lena in die östliche Laptewsee eingetragen und bilden eine Dichtegrenze, die stark auf Dynamik und thermische Prozesse in der Wassersäule einwirkt. Verzögerte Eisbildung kann ein Effekt sein, verursacht sowohl durch die Dichteschichtung wie durch Akkumulation eingestrahlter Wärme in tieferen Schichten. Interne Wellen scheinen einen möglichen Mechanismus darzustellen, der die beobachteten Schwankungen der Eisbildung erklären könnte. Verschiedene ADCP Datenserien aus Verankerungen der Jahre 1988/1989 und 2000 wurden bearbeitet, um den Wärmeaustausch durch Interne Wellen abzuschätzen. Es zeigte sich, dass der vertikale Wärmefluss eine zusätzliche Verzögerung der Eisbildung von 5-6 Tagen in Abhängigkeit von der lokalen Bodentopographie zur Folge haben kann. Es zeigte sich ebenfalls, dass Sturm-Ereignisse im Herbst die durchschnittliche Energie des internen Wellenspektrums um das 2-3fache im Vergleich zum Ruhezustand steigern können. Dies kann ebenso die Austausch-Effizienz durch die Pyknokline um einen Faktor 5-10 erhöhen.

INTRODUCTION

In the Laptev Sea, one of the largest Siberian shelf seas, pronounced non-uniform physical properties of the water column are the result of vertical and horizontal density gradients that are caused by the huge freshwater input. In this respect dynamic processes that occur at the pycnocline play a vital role and have a distinct effect on the hydrological regime of this arctic shelf sea (KIRILLOV et al. 2001, DMITRENKO et al. 2001). The freshwaters of the Lena River forms the extended frontal areas in the surface layer of the Laptev Sea. Being combined with the solar heating in summer time it results in warming below the pycnocline due to frontal convergence. It allows accumulating up to 20-30 kJ m^{-2} in intermediate water depths (DMITRENKO et al. 1999). A striking consequence for this effect might be a delay of sea-ice formation onset in fall. Until recently it was hypothesised that the onset of ice formation in the Laptev Sea occurs almost simultaneously in all areas (VANDA & YULIN 1993). This hypothesis was not supported by satellite observations during the freeze-up period. As soon as oceanographic and remote sensing information concerning the ice-formation onset were collected on a regular basis, our view on these processes changed dramatically. It was observed that the freeze-up in the Laptev Sea showed a spatial pattern that consists of distinct zones with different times of the freeze-up onset (KIRILLOV et al. 2002). The dimensions of these zones exceed tenths of kilometres and the onset of the freeze-up differed by weeks. A possible reason for this observed difference is a variable heat exchange through the pycnocline.

In 1972 GARRETT & MUNK (GM) presented an overview of the historical data on internal waves in the ocean. They assumed that internal waves occupy the frequency-band from local inertial to buoyancy frequencies. As a result of this work they formulated a model with an internal wave background, which is steady in time and space regardless of the vertical and horizontal boundaries of the ocean basin. This model was modified by different authors (GARRETT & MUNK 1975, CAIRNS & WILLIAMS 1976, MUNK 1981), which revised some details of the frequency spectrum, but did not change the general assumptions of the model. The universal GM spectrum is in good agreement with observations and within the framework of the GM model several models of dissipation rate were formulated in (MCCOMAS et al. 1977, 1981, HENYEY 1986, GREGG 1989). Despite the universal character of the GM model the shape of the horizontal kinetic energy (HKE) spectrum is consistent with observations of internal wave dynamics in different areas of the World Ocean although the spectral energy level may vary in space. In particular, the Arctic Ocean is a region with a HKE that is one order of magnitude below the predicted HKE for mid-latitude level (LEVINE 1985, PADMAN & DILON 1989). On the other hand there is evidence that the GM model also works within shallow water conditions near the shore (PRINGLE 1999, D'ASARO 2000, LEVINE 2002). In this respect the current velocity measurements gathered with Acoustic Doppler Current Profiler (ADCP) in the shallow Laptev Sea are of special interest. The extremely shallow water depths make these measurements a unique data set for estimating the vertical heat exchange due to internal wave breaking according to the GM model. According to the above statements in this article we consider the distinctive features of the internal waves back-

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ground on the Laptev Sea shelf and their potential role in the variability of the ice formation onset.

MATERIAL

The short-term current velocities measured with WH 300 kHz ADCP at several hydrographic stations carried out during German-Russian TRANSDRIFT VII expedition in 1999 (YS99 stations #17, 19, 20, 23 and 24) as well as the daily records during TRANSDRIFT VIII expedition in 2000 (YS00 stations #11, 24 and 48) in the frame of the “Laptev Sea System” project were used to analyze the internal wave properties in the Laptev Sea shelf area (Fig. 1). Vertical profiles of current velocities in YS99 data set were gathered every second during time intervals varied from 2 to 3.5 hours. Further, it was averaging every minute with 1 m vertical bin-size. The records with same technical characteristics were obtained in 2000. The only difference is the applying the five minutes time-averaging interval at station YS0011. Duration of all these records varies from 1 day at station #48 to 4 and 7 days at stations #24 and #11 respectively.

Two additional ADCP records started in August 1998 until September 1999 (mooring stations YANA and LENA, deployed during TRANSDRIFT V) were also examined to investigate the storm impact to the vertical heat exchange intensity. These moorings were deployed in the central and southern parts of the Laptev Sea to record water dynamics twice per hour every 1.5-2 m in depth. The NCEP winds Reanalysis data provided by the NOAA-CIRES ESRL/PSD Climate Diagnostics branch, Boulder, Colorado, USA (website http://www.cdc.noaa.gov/) were analyzed to recognize the storm events during YANA and LENA moorings deployments.

RESULTS

The internal waves background at the Laptev Sea shelf

Time series of the horizontal velocities on the Laptev Sea shelf were analyzed to compare the HKE spectrum with the GM79 model of internal-wave spectrum. As already stated in the previous publications, it was found that the energy level of the spectrum is two orders of magnitude lower than that predicted

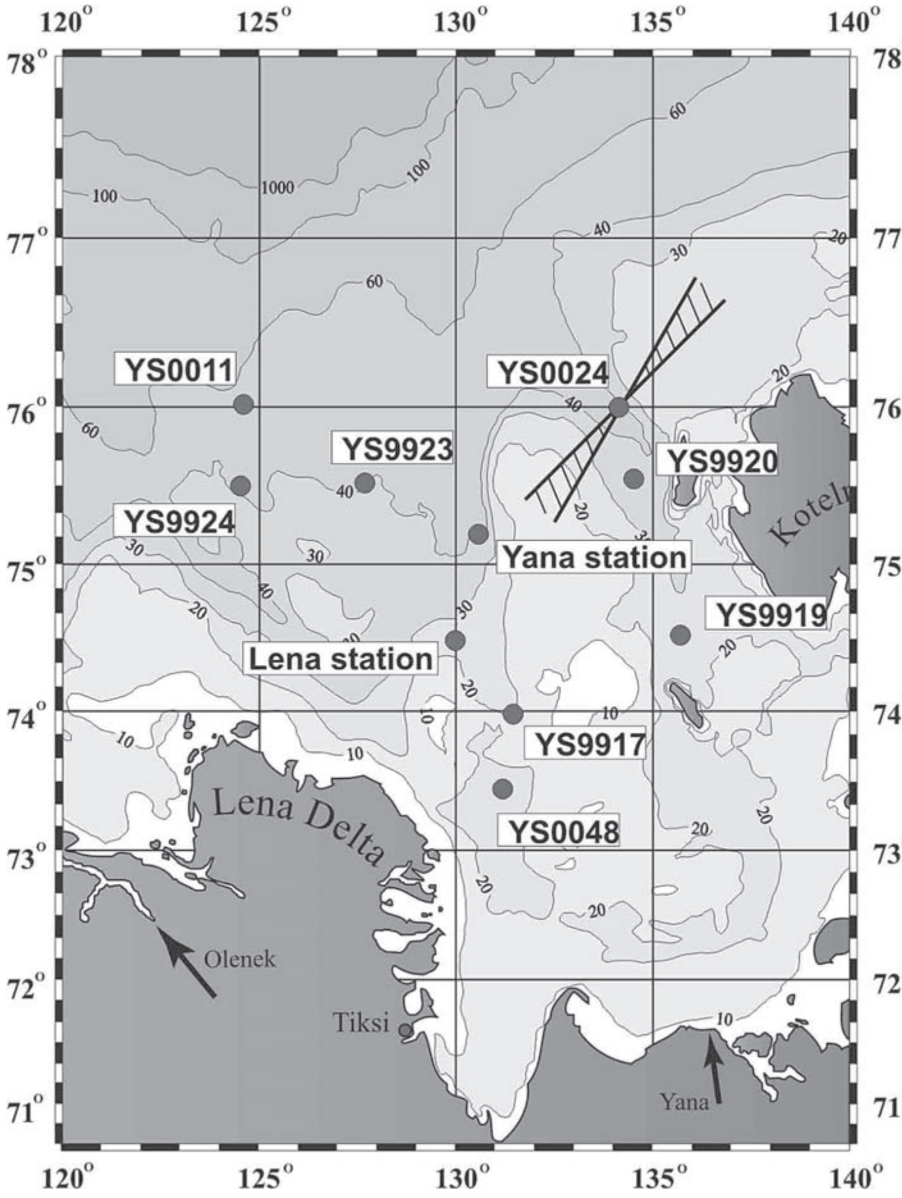

Fig. 1: The Laptev Sea region and location of long-term ADCP moorings deployed in 1998 (YANA and LENA moorings) and short-term ADCP stations carried out in September, 1999 (YS99 #17, 19, 20, 23 & 24) and in September, 2000 (YS00 #11, 24 & 48).

Abb. 1: Südöstliche Laptewsee und Lage der ADCP-Langzeit-Verankerungen YANA und LENA, ausgelegt 1998 und der ADCP-Kurzzeit-Verankerungen YS99 #17, 19, 20, 23 & 24, ausgelegt im September 1999 und YS00 #11, 24 & 48, ausgelegt im Septeember 2000.

by the GM model. It was assumed to be a result of the sea-ice cover that insulates the ocean interior from atmospheric forcing and due to the low level of inherent tidal energy in the Arctic (Levine 1985, Padman & Dilon 1989). Despite the lower energy the HKE is mostly in good agreement with -2 slope predicted by GM (Fig. 2). The traditional exceptions in the shape of the spectra are the maximum at the near-inertial frequency (approximately 12.4 hours) and the spectral "shoulder" at the high frequencies. These discrepancies were noted by different authors in the observations of the internal-wave pattern throughout the world (Levine 1999), but our results are especially interesting because the "shoulders" starts far away from local buoyancy level (more then 50 cph anywhere).

The GM spectrum was evaluated initially as isotropic in different directions, but near the shore this assumption is rather disputable. Sufficient polarization of horizontal velocity found in numerous regions far away from the open ocean tends to focus the wave energy towards the coast (McKee 1973). ADCP observations were analyzed in the light of this issue to find out the wave orientation and ellipticity of the current ellipses. Like the GM model our spectrum was considered as an isotropic one with the only exception at station YS0024. Here the strongly polarized currents were found within the frequency band from local inertial frequency to the "shoulders" (Fig. 2). Wave-ellipse orientation varies a little within the 40°- 65° range in the counterclockwise direction from the east (Fig. 1, station YS0024). In terms of topography it means that energy of the waves focused across topography irregularities predominates the other directions. The specific topography at station YS0024 position allows us to assume bottom reflection to be the reason for energy focusing.

Following Osborn (1980), Henyey (1986) and Gregg (1989), we define mixing intensity through the relation between observed shear variance of the horizontal current velocities (S^2) and the expected shear variance according to the GM79 model (S^2_{GM}). The GM spectrum deals with the 0.1 cpm vertical wave-number cutoff as a critical value for shear ($Ri = 1/4$). Nevertheless, in non-GM internal wave model this parameter can be much higher, especially if the HKE level is less then GM one at rather higher buoyancy. We chose a vertical cutoff value arbitrary as the start of white slope in vertical wave-number spectrum. It is approximately 0.7 cpm instead of GM's 0.1 cpm. In addition we used 1.39 as a multiplier for S^2 to make it comparable to S^2_{GM} as a correction for the attenuation of the first-difference filter (Gregg & Sanford 1988) and 0.6 multiplier for ADCP-beam separation correction (Alford & Pinkel 2000).

The mixing efficiency and vertical heat exchange due to internal waves

The vertical mixing diffusivities were defined using of Gregg's (1989) approach with modification in the critical wave-number cut-off value. To estimate the shear we used the frequencies below the "shoulder" for a better comparison with the GM model as the latter was evaluated without taking into consideration such irregularities as "shoulders". The background level of mixing intensity was found to be quite moderate: in term of diffusivities the intensity of mixing varies from molecular and up to maximum values $5\text{-}30 \cdot 10^{-5}$ m^2 s^{-1} within the pycnocline layer at station YS0024. Considering the typical vertical gradient of temperature at the upper part of intermediate water layer gives the potential vertical heat flux up to 33 W m^{-2} (Kirillov et al. 2003). We applied a simple 1-D model with the heat fluxes at the surface in form presented in (Dethleff et al. 1998) to examine the evolution of temperature profiles observed in TRANSDRIFT VIII cruise. The aim of these calculations was to find out the moment when mixed layer water temperature drops below the freezing point. And it was revealed that the additional heating of the surface mixed layer from pycnocline might result in sea-ice formation onset delay up to maximum 5-6 days over the different areas in the

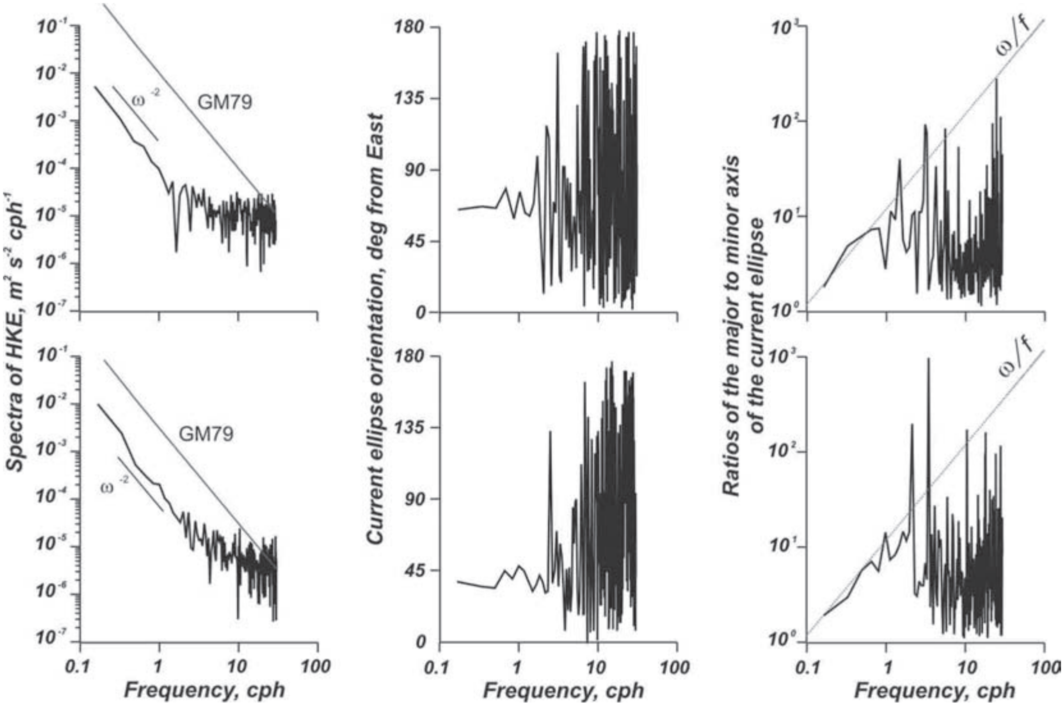

Fig. 2: Spectral characteristics of HKE, ellipse orientation and major/minor axis ratio at 17 m depth (top panel) and 38 m depth (bottom panel) at mooring station YS0024. Solid lines indicate the HKE level according to GM79 model and dotted lines represent the major/minor axis ratio from theory of internal waves.

Abb. 2: Charakteristika der horizontalen kinetischen Energie (HKE) in 17 m Wassertiefe (oben) und 38 m (unten) an der Verankerung YS0024. Schwarze Linien zeigen HKE-Niveau entsprechend GM79-Model. Gepunktete Linien zeigen Achsenverhältnisse nach der Theorie der Internen Wellen.

eastern part of the Laptev Sea (KRILLOV et al. 2002). Nevertheless, these results do not correspond to two-three weeks' delay in ice formation onset in different areas according SSM/I images analysis. But the values mentioned above are based on the short time-series observed during relatively calm (not windy) period although the shallow water dynamic is very sensitive to atmospheric forcing and the energy level can dramatically change under these conditions (LEVINE 1985). Long-term mooring records allow us to estimate the mixing efficiency increase and, hence, additional heat flux from the intermediate warmer layer during enhanced atmospheric forcing in fall. To recognize the storm events both NCEP Reanalysis wind data at 75N 130E and the sea-level pressure records at YANA mooring were analyzed. Three well pronounced increases of wind speed accompanying by strong sea-level deformations were chosen to estimate the spectral HKE changes. All these events were observed between relatively calm periods (Fig. 3). And after having eliminated wind forcing, the HKE spectra level sinks rapidly to its level in "calm state". According HENYEY et al. (1986) the rate of internal-waves energy dissipation is proportional to the squared total energy per unit area. In the term of Henyey, the relation "mixing efficiency" $\sim \varepsilon \sim E^2$ is appropriate if spectral HKE energy corresponds to that of the GM model with -2 spectral energy slope. Despite the spectral slope changes dramatically at the higher frequencies during the storms (Fig. 3) we might estimate at least an order of HKE increase. And under the strong atmospheric forcing the enhancement of the energy as matching the factor of 2-3 was revealed. The total energy increase is by 2.87, 1.88 and 3.09 times higher than the pre-storm HKE level in the band from inertial frequency to 1 cph. Follow HENYEY, it would potentially increase the heat fluxes from warm intermediate layer up to 3.5-9 times above that during the calm period and explain the higher variability of sea-ice formation onset. So we can speculate that enhanced atmospheric forcing over the shelf region would dramatically increase the sea-ice formation onset up to several weeks revealed via satellite images analysis. Our selective estimations agree this suggestion.

CONCLUSION

Through their instability and breaking internal-waves seem to play a significant role in vertical mixing through pycnocline. Under the strong density interface due to the huge amount of river runoff in the Laptev Sea, the water interior is a favourable environment for the occurrence of internal waves. This research was aimed at answering the question whether the internal wave breaking results in delay of ice formation onset and at evaluating the time scale of the delay. We have found that this process could result in ice formation delay up to maximum 5-6 days over the eastern part of the Laptev Sea. This, however, does not correspond to the two-week delays in

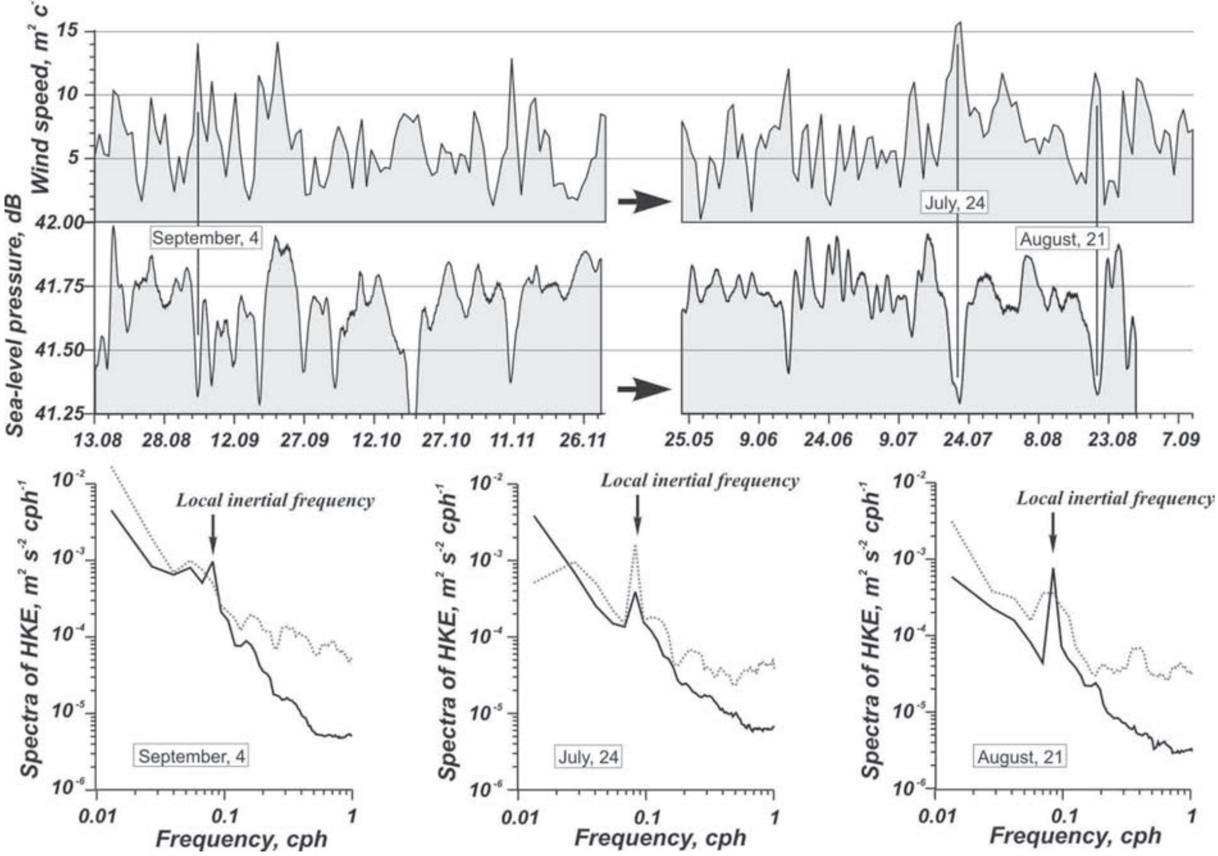

Fig. 3: HKE spectral level evolution during several events of strong atmospheric forcing evaluated from NCEP Reanalyse wind data and pressure sensor records at YANA mooring station. The dotted lines at lower panels indicate the maximum level of HKE during the storm and solid lines indicate the HKE level just before the storm.

Abb. 3: Entwicklung des HKE Spektral-Niveaus während verschiedener Ereignisse mit starkem atmosphärischen Antrieb abgeleitet aus der NCEP-Analyse von Wind- und Druckdaten der YANA-Verankerung. Gepunktete Linien (unten) zeigen max. Niveau des HKE bei Sturm; schwarze Linien beschreiben HKE-Niveau unmittelbar vor dem Sturm.

ice-formation observed in the Laptev Sea region. Another possible mechanism was analyzed in order to answer this discrepancy. Storm events during fall are thought to be responsible for the further delay of sea-ice formation.

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