Environmental correlates of pack ice noise

Nicholas C. Makris and Ira Dyer
Department of Ocean Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 20 September 1985; accepted for publication 13 January 1986)

Low-frequency ambient noise under pack ice of the central Arctic Ocean has long-term variations (periods greater than 1 h) which correlate highly with composite measures of stress applied to the ice by wind, current, and drift. These composites are the horizontal ice stress and the stress moment, and are derived from meteorological and oceanographic data observed simultaneously with the noise. Atmospheric cooling, a known high correlate of midfrequency noise under the ice, is not important at low frequencies.

PACS numbers: 43.30.Nb, 43.30.Bp, 92.10.Rw, 93.30.Li

INTRODUCTION

In April 1982, M.I.T. acquired ambient noise data from a camp situated on pack ice in the Arctic Ocean. Known as the Fram IV expedition,[1] the camp drifted with the pack ice in the general vicinity of 83 °N, 20 °E. Our purpose in acquiring the ambient noise data is to better understand the physical mechanisms associated with Arctic Ocean underwater noise. In this paper we compare the variation of low-frequency ambient noise with various environmental ice-forcing functions, including temperature and wind. We find that low-frequency pack ice noise cross correlates best with the moment due to opposing wind and current stresses acting on the ice, and worst with air temperature.

Milne[2] first described the close connection between midfrequency under-ice noise and air temperature. His observations were made under shore-fast ice in the Canadian Archipelago, and show that noise centered at about 300 Hz

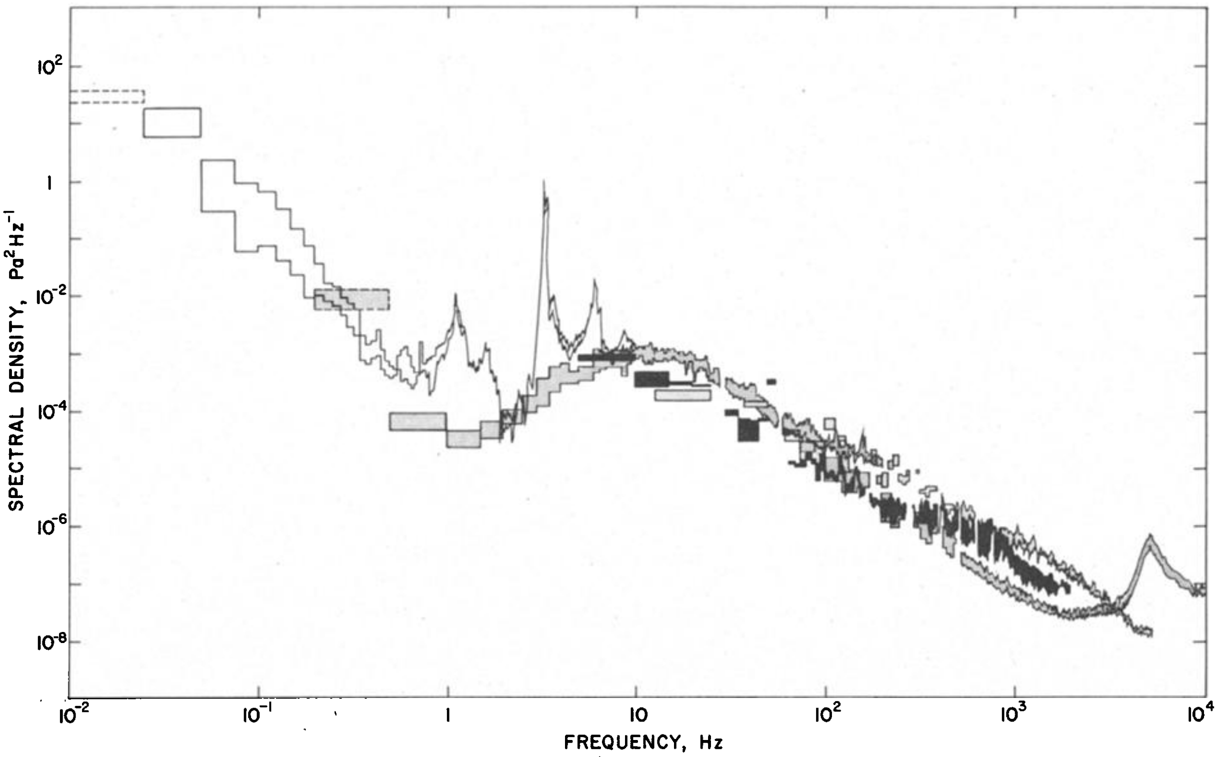

FIG. 1. Composite of ambient noise observed in April 1982 at the Fram IV ice camp (Ref. 3). Data were taken at various times and were selected to represent noise of intermediate spectral level. Averages in spectral density ranged over as few as 8 to as many as 1024 samples over various frequency bandwidths. The data form a reasonably compatible composite which illustrates general characteristics of central Arctic pack ice noise. The 4th power falloff in spectral level below 1 Hz is not yet explained, but hypotheses include nonlinear surface wave noise from the open ocean or pseudosound from turbulence in the OBL interacting with the hydrophone. Peaks from 1–10 Hz are caused by hydrophone cable strum, which is as yet unexplained as to its variability in time and space. (Strum was observed to be stochastic: For 24 identical hydrophone cables deployed over an area of 1×1 km, and simultaneously observed, strum was noted to appear and disappear without causal relation to the observed current or other deterministic parameters.) Broad peaks centered at about 15 and 300 Hz, and a somewhat narrower one at 6 kHz, are associated with ice cracking events in response to various environmental forces. Noise associated with the 15-Hz peak is an ever-present feature of central Arctic ambient noise, that associated with the 300-Hz peak occurs only during periods of atmospheric cooling (Ref. 2), and that associated with the 6-kHz peak is hypothesized to occur only upon floe–floe bumping (Ref. 22).

 0001-4966/86/051434-07$00.80

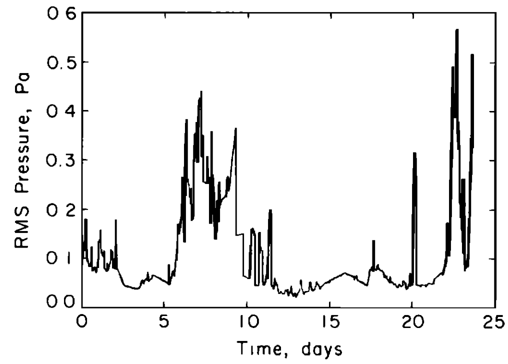

FIG. 2. The rms pressure versus time, for noise in the 10- to 20-Hz band. The record starts on Julian day 89, 30 March 1982, 0600 Z, and terminates on Julian day 112, 22 April, 2200 Z. Portions of the record contain linearly interpolated values; see the text. The mean is 0.11 Pa and the standard deviation is 0.098 Pa.

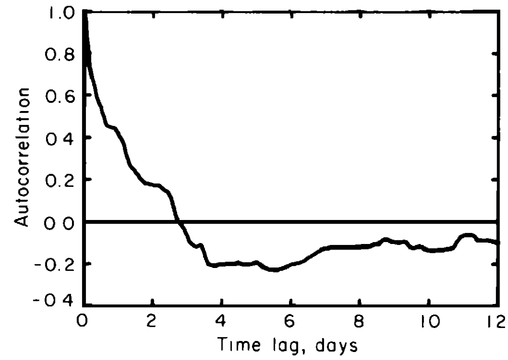

FIG. 3. Time-lagged normalized autocorrelation of the 10- to 20-Hz noise.

and distributed broadly in frequency follows atmospheric cooling (decreases in air temperature). He ascribed the noise to thermally induced tensile stresses in the ice which in turn cause acoustic transients from ice fractures. Such noise was absent during periods of heating, during which Milne observed another noise described by him as "residual."

It is Milne's residual noise which is addressed in this paper. Actually, it is a noise which is always important at low frequencies, with a distinctly different set of environmental correlates. We take it to be centered at about 15 Hz, and also broadly distributed in frequency, as shown in Fig. 1.[3] In the absence of hydrophone strum, such noise dominates the spectrum from about 1 to 100 Hz, at least under pack ice of the central Arctic. [Pack ice consists of first- and multiyear floes, 2–3 m thick, in near continuous contact over large areas of the central Arctic, with joints between floes often consisting of refrozen ice blocks (pressure ridges) heaped and weathered to a height of several meters and to a depth of three to five times the height.]

Temperature, wind, and ice drift data were collected for all, and current for part of the time during which ambient noise data were collected. Time series of the noise and the environmental data were then compared via cross correlation for time periods as long as about 24 days. Buck[4] and Ganton and Milne[5] noted two decades ago that Arctic ambient noise may be related to wind as well as temperature, but they did not have as complete a meteorological and oceanographic data set as we do. More recently, Pritchard[6] compared low-frequency ambient noise with ice drift velocity. Via mesoscale ice models and assumed ice constitutive laws, he converted measured ice drifts to pressure ridging and shearing energy. Pritchard concluded that pressure ridging activity may be important in low-frequency ambient noise, with a cross-correlation coefficient of about 0.68 between noise spectral density and estimated ridging energy. Our study goes beyond these, principally because we investigate a wider range of measured environmental correlates.

I. AMBIENT NOISE DATA

We take the octave band from 10–20 Hz as a surrogate for the broad distribution of low-frequency ambient noise between 1 and 100 Hz. Its time series over a 23.7-day period at the Fram IV ice camp in April 1982 is given in Fig. 2. These data were acquired with an omnidirectional hydrophone 93 m below the ice, amplified and symmetrically filtered with a 48-dB/oct rolloff cornered respectively at 10 and 20 Hz, squared and averaged over 5 min, square rooted, and graphically recorded. For purposes of Fig. 2, the data were sampled at and averaged over hourly intervals, principally because some of the environmental data were available only at these intervals. Our choice of rms pressure to represent the noise, rather than say sound-pressure level, will become clear later.

Because other experiments, some of which interfered with ambient noise observations, were going on as this graphic record was being made, portions of the record had to be edited. It was possible, however, to fill gaps with recorded data acquired digitally.[7] The latter provided data averaged over 1.7 min and we could, via later playback, discriminate between interfering sounds such as made by periodic airgun shots and the desired ambient noise. The digitally recorded data, however, were not always available, so remaining edited gaps in the time series were filled by linear interpolation. The longest such gap is 24 h, the mean gap is 3.8 h, and 36% of the time series has interpolations.

Figure 3 is the autocorrelation of the rms pressure. Its

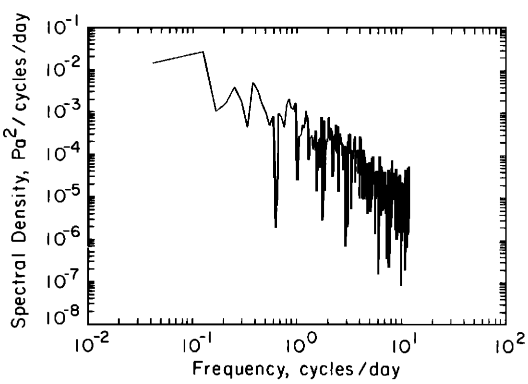

FIG. 4. Spectral density of the zero-mean noise time series in the 10- to 20-Hz band. The density is double-sided; i.e., the ordinate should be multiplied by two and integrated in frequency from zero to infinity to obtain the variance. [The spectrum has no remarkable energy above the general trend at the meteorologically important frequency of 1 cycle/day (diurnal cooling) or at the oceanographically important frequency of 2 cycles/day (inertial oscillations).]

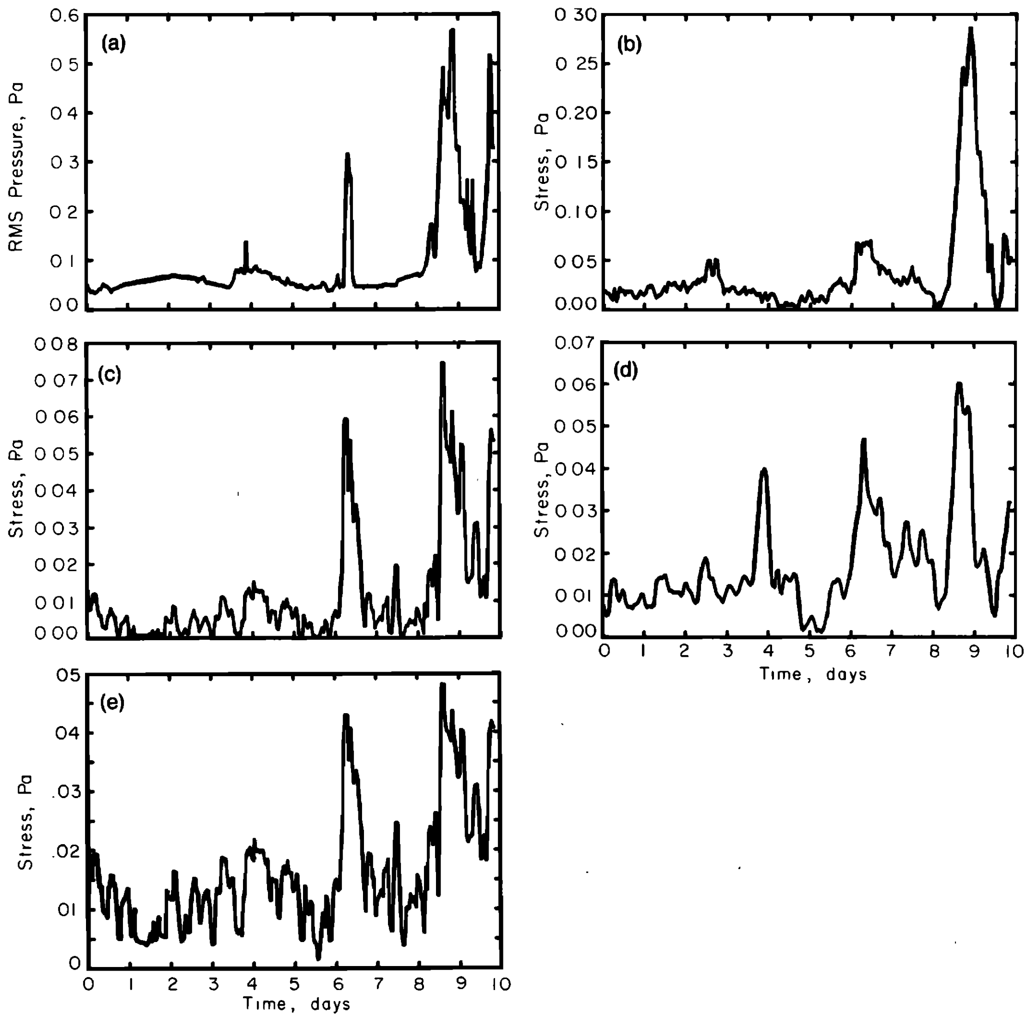

FIG. 5. Noise and various applied stress magnitudes versus time. The records start on Julian day 103, 13 April 1982, 0100 Z, and terminate on Julian day 112, 22 April, 2200 Z: (a) rms pressure, (b) wind shear stress $|\tau_a|$, (c) current shear stress $|\tau_w|$, (d) normal stress associated with the Coriolis force $|\sigma_c|$, and (e) normal stress associated with the pressure gradient force $|\sigma_p|$. See the text for parameter values used to convert measured wind, current, and drift to stress magnitudes. The applied stress values are not considered reliable below about 0.02 Pa, at which inaccuracies in measured data and their translation via assumed stress models [Eqs. (1)–(4)] come into play.

square-integral scale is about 1.4 days and its *e*-folding time is about 1.2 days, either one of which indicates that the noise evolves fairly slowly in time. Mean gap lengths of 3.8 h as well as hourly averages of the rms pressure are therefore not detrimental in use of the time series. There are slight humps in the autocorrelation at about 0.8, 2.0, and 3.3 days but no physical explanation for these is known to us; they may be nothing more than fluctuations also seen in the remainder of the autocorrelation.

The spectral density of the de-meaned rms pressure time series is given in Fig. 4. Its spectral falloff is about (frequency)$^{-1.5}$. There is a slight low-frequency maximum corresponding to a period of about 8 days, not unreasonable in view of the periodicity of the major peaks in Fig. 2.

Figure 5(a) also gives a portion of Fig. 2, covering about 9.9 days of the noise time series. This particular period coincides with the most complete set of environmental data, as will be discussed in Sec. II. Of course, Fig. 5(a) also contains gaps which have been linearly interpolated. The longest gap is 24 h, the mean gap is 5.8 h, and 38% of the record has interpolations.

II. CROSS CORRELATION WITH DYNAMICAL FORCING FUNCTIONS

Also shown in Fig. 5 are (b) 9.9-day records of horizontal wind shear stress which acts on the ice top, (c) current shear stress which acts on the ice bottom, (d) normal stress applied by the Coriolis force which acts uniformly on the ice floe's vertical section, and (e) normal stress applied by the ocean pressure gradient or sea height tilt which acts uniformly on the floe's submerged vertical section. Meteorological data were acquired during Fram IV by Andersen,[8] averaged over and sampled at 10-min intervals, and accumulated and averaged by us over 1-h periods. Wind data at a 9.8-m height above the snow surface (about 10 m above the ice surface) were converted to shear stress data via

$$\tau_a = C_{10}\rho_a|\mathbf{v}_{10}|\mathbf{v}_{10}, \qquad (1)$$

where $\mathbf{v}_{10}$ is the wind vector at 10 m relative to the ice drift vector $\mathbf{v}_d$, C_{10} the 10-m drag coefficient, and ρ_a the air density. From previous measurements of ice/atmosphere boundary layers (ABL) over Arctic ice,[9] $C_{10}\approx 1.6\times 10^{-3}$, corresponding to stable Fram IV conditions. Figure 5(b) displays $|\tau_a|$, which has many of the temporal features seen in the noise. Our choice of rms pressure to describe the noise, and shear stress to describe the wind, reflects an underlying hypothesis: *Noise is created by ice fracture mechanisms proportional to the state of stress in the ice as induced by environmental loads.*

Current data were acquired and processed by Tiemann[10] and Hunkins.[11] Current data at a depth of about 29 m below the ice top (about 27 m below the ice underside) were converted to shear stress magnitude via

$$|\tau_w| = C_w \rho_w |\mathbf{v}_g|^2, \quad (2)$$

where $\mathbf{v}_g$ is the current vector in the geostrophic flow (estimated by Hunkins[11,12] to occur at depths of about 30 m or more below the ice), where C_w is the drag coefficient and ρ_w the sea water density. The current vector is also relative to the ice drift $\mathbf{v}_d$. We take the measured current to be closely geostrophic. For the ice/ocean boundary layer (OBL) corresponding to Fram IV conditions, $C_w \approx 3.2 \times 10^{-3}$,[12,13] typically about $2C_{10}$.[14] Currents were averaged and sampled at 10-min intervals, and accumulated and averaged by us over 1-h periods. Figure 5(c) shows $|\tau_w|$, which contains many temporal features seen in the noise, as does $|\tau_a|$.

Coriolis normal stress is derived from[15]

$$\sigma_c = -2\rho_i h \sin\phi \boldsymbol{\Omega} \times \mathbf{v}_d, \quad (3)$$

where $\mathbf{v}_d$ is the drift velocity, ρ_i the ice density, h the ice sheet thickness, ϕ the latitude, and $\boldsymbol{\Omega}$ the Earth's angular velocity. Ice positions and drift velocities were obtained at hourly intervals via Kalman filtering of satellite navigation data.[16] We take $h \approx 2.5$ m and plot $|\sigma_c|$ in Fig. 5(d). While less satisfactory than $|\tau_a|$ or $|\tau_w|$ as a visual match to the noise, one can still say that $|\sigma_c|$ shows many temporal features suggestive of the noise.

The normal stress applied by the pressure gradient is given by[12,15]

$$\sigma_p = 2\rho_w h_s \sin\phi \boldsymbol{\Omega} \times \mathbf{v}_g, \quad (4)$$

where the submerged thickness of the ice is $h_s = \rho_i h / \rho_w$. This term represents the balance in geostrophic flow between Coriolis and pressure gradient forces, the latter being transferred unabated through the OBL to the ice.[12,15] Figure 5(e) shows $|\sigma_p|$, which also has temporal features similar to the noise.

A normal stress can be induced by lineal acceleration ($\rho_i h \, d\mathbf{v}_d/dt$) but, as is typical for geophysical flows, can be neglected.[15] Its maximum value from the derivative of the ice drift data is about 0.02 Pa, which is at about the level of uncertainty in the other stress values [see Fig. 5(b)–(e)]. Consequently, we neglect lineal acceleration and thus characterize the ice motion as steady-state drift.

A quantitative comparison among the four applied dynamical stresses as correlates of the noise is obtained via cross correlation; results are summarized in Table I. These depend upon the measured data $\mathbf{v}_{10}$, $\mathbf{v}_g$, and $\mathbf{v}_d$; all other parameters are presumed time invariant and do not affect the normalized results. All cross correlations have fairly high maximum correlation as Fig. 5 indicates visually, and one could assert with some justification that any one would

TABLE I. Cross correlation between noise and applied stress components, 9.9-day records.

Stress	Maximum normalized correlation coefficient	Time lag to maximum (h)
$\lvert\tau_a\rvert$	0.84	−1
$\lvert\tau_w\rvert$	0.84	0
$\lvert\sigma_c\rvert$	0.70	0
$\lvert\sigma_p\rvert$	0.76	0

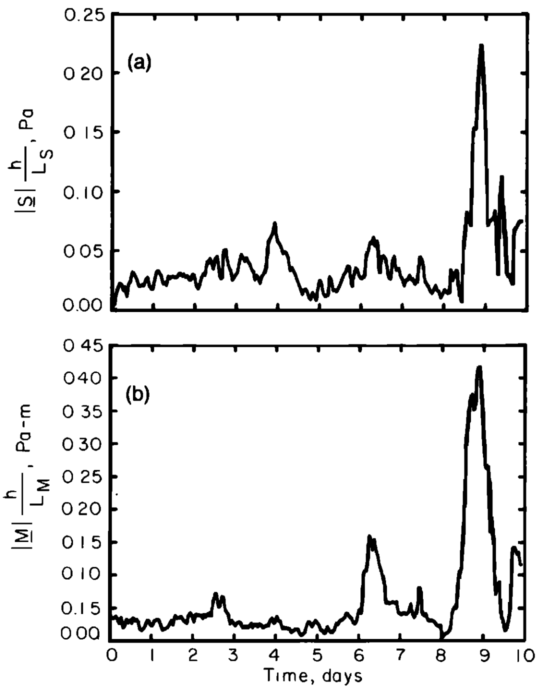

FIG. 6. Composite environmental measures versus time, with the time base as in Fig. 5: (a) horizontal ice stress scaled by h/L_s, (b) stress moment scaled by h/L_M.

suffice as a good correlate. This is so at least because the four applied stresses are not independent: $\mathbf{v}_d$ is related via ice conditions to $\mathbf{v}_{10}$ and $\mathbf{v}_g$ and, aside from numerical factors, τ_w is the square of σ_p. But because of their larger maximum correlations, some preference might be given to wind shear and current shear stresses over normal stresses applied by Coriolis forces and pressure gradients.

Whatever preferences might be advanced on one applied stress over another as a correlate of noise, it is clear that ice responds not to one but to the presence of all. Thus we form two composite measures, the ice stress $\mathbf{S}$ as an equivalent horizontal load on the ice sheet's vertical section

$$\mathbf{S} = (\tau_a + \tau_w + \sigma_c + \sigma_p) L_S / h, \quad (5)$$

and the stress moment $\mathbf{M}$ acting about the ice sheet's central horizontal plane

$$\mathbf{M} = \mathbf{i} \times [\tau_a - \tau_w - \sigma_p (1 - h_s/h)] L_M / 2, \quad (6)$$

where $\mathbf{i}$ is a unit vector in the vertical and where L_S and L_M are lengths parallel to $\mathbf{S}$ and normal to $\mathbf{M}$, respectively, through which a horizontal load or bending moment can be accumulated by the ice. (For central Arctic pack ice we estimate $L_S/h \gtrsim 10^4$ and $L_M/h \lesssim 10^3$, but these values do not enter our study.)

The ice stress $\mathbf{S}$ can be interpreted as that equivalent stress which when multiplied by bh gives the total horizontal force acting on an aggregate ice element of length L_S and width b. Similarly, $\mathbf{M}$ can be interpreted as that stress moment which when multiplied by bh gives the total turning moment (around the central plane) acting on an element L_M, b. It can be seen from Eq. (6) and the smallness of the moment applied by σ_p that $\mathbf{M}$ is dominated by the opposing wind and current stresses.

Because derivatives of our ice drift data show lineal ac-

TABLE II. Cross correlation between noise and composite environmental loads, 9.9-day records.

Measure	Maximum normalized correlation coefficient	Time lag to maximum (h)
$\lvert\mathbf{S}\rvert$	0.81	-1
$\lvert\mathbf{M}\rvert$	0.87	0

TABLE III. Cross correlation between noise and applied stress components, 23.7 day records.

Stress	Maximum normalized correlation coefficient	Time lag to maximum (h)
$\lvert\boldsymbol{\tau}_a\rvert$	0.71	2
$\lvert\boldsymbol{\sigma}_c\rvert$	0.74	2
Cooling tensile	0.15	50

celeration to be negligible, we can say that the horizontal stress $\mathbf{S}$ must be balanced by an equal and opposite stress $\mathbf{S}_i = -\mathbf{S}$. Called the internal ice stress,[12] $\mathbf{S}_i$ (or $-\mathbf{S}$) is an attractive potential correlate under our hypothesis that the noise is related to the state of stress in the ice. Similarly, we assume the ice to be in angular steady state about its central plane (no data were taken to confirm this, but is is quite reasonable), which then must be balanced by $\mathbf{M}_i + \mathbf{M}_b = -\mathbf{M}$, where $\mathbf{M}_i$ is an internal ice stress moment and $\mathbf{M}_b$ a stress moment caused by buoyant forcing of water upon the floating ice. In work too detailed to be included, it can be shown for pack ice conditions that $\mathbf{M}_i \gg \mathbf{M}_b$; lacking this demonstration here, we merely assume $\mathbf{M}_i \approx -M$. Then $\mathbf{M}_i$ (or $-\mathbf{M}$) is also an attractive potential correlate of the noise.

Figure 6 gives the time series of $\lvert\mathbf{S}\rvert$ and $\lvert\mathbf{M}\rvert$ and Table II the correlation coefficients between $\lvert\mathbf{S}\rvert$ and $\lvert\mathbf{M}\rvert$ and the noise. Note that correlations involving Eqs. (5) and (6) do not depend on L_S or L_M, but do depend on values assigned to parameters C_{10}, C_w, h and on others that can be taken with more precision ($\rho_a, \rho_w, \rho_i, \phi, \boldsymbol{\Omega}$), as well as on the directly measured data ($\mathbf{v}_{10}, \mathbf{v}_g, \mathbf{v}_d$). Also, in order to get Fig. 6 and Table II, we need to bolster Eq. (2) with the direction of $\boldsymbol{\tau}_w$ [12,15]:

$$\boldsymbol{\tau}_w \cdot \mathbf{v}_g = \lvert\boldsymbol{\tau}_w\rvert \lvert\mathbf{v}_g\rvert \cos\alpha, \quad \alpha \leqslant 0. \tag{7}$$

That is, the ice/ocean shear stress is rotated counterclockwise through the Ekman spiral of the OBL, and we have taken $\alpha \approx -40°$ to produce Fig. 6 and Table II.

A range of values for C_{10}, C_w, h, and α relevant to central Arctic pack ice can be found in the literature,[12–14] but the values are generally within a factor of two of those selected here. This range can change the results in Table II by no more than about 0.05 in maximum correlation coefficient. Thus we conclude that the shear stress moment $\mathbf{M}$ is an important if not the major correlate of noise, with internal stress $\mathbf{S}$ or wind or current components close seconds if not of equal importance. For comparative purposes, the four cross correlations are graphed in Fig. 7.

We regard the time lags to maximum correlation in Tables I and II and Fig. 7 as zero or essentially so, given uncertainties related to the mean gap in the noise of 5.8 h over 38% of the record and the 1-h averaging periods in both the noise and environmental time series.

III. CROSS CORRELATIONS OF THE 23.7-DAY RECORDS

Further insight may be gained by cross correlating the noise with wind shear stress and Coriolis normal stress over the full 23.7-day noise period, and these results are in Table III. (The geostrophic current $\mathbf{v}_g$ and thus current shear and pressure gradient were not available until the last 9.9-day portion of the noise record.) Wind shear and Coriolis normal stresses again correlate highly with the noise, but have maximum correlation coefficients different by as much as about 0.1 from those of the shorter record.

We interpret the differences in correlation between the longer and shorter record in terms of several factors: (1) Our noise records have gaps which could cause stochastic behavior of the cross-correlation coefficient; (2) quite possibly C_{10} was not a constant over 23.7 days, since it was a period of generally increasing temperature and consequent modification of the ABL; (3) since noise is hypothesized to

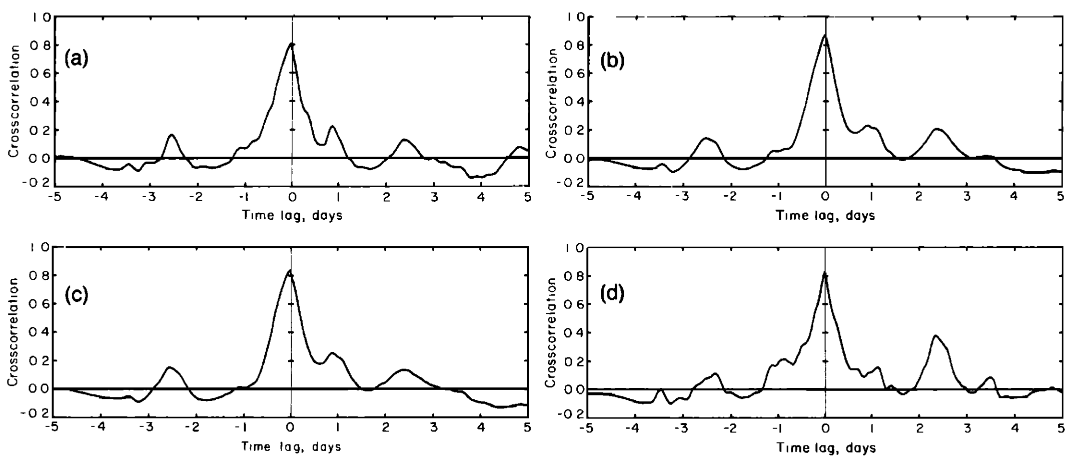

FIG. 7. Time-lagged normalized cross correlation between noise and (a) ice stress $\lvert\mathbf{S}\rvert$, (b) stress moment $\lvert\mathbf{M}\rvert$, (c) wind shear stress $\lvert\boldsymbol{\tau}_a\rvert$, (d) current stress $\lvert\boldsymbol{\tau}_w\rvert$.

be related to the total state of ice stress, any one applied stress component would then have a time-varying correlation as other components wax and wane. In connection with the latter, Pritchard's study[6] entailed 120-day records which, when divided into six 20-day records, yielded cross correlations between noise spectral density and estimated ridging energy averaging 0.65, with a standard deviation of 0.25. Thus we regard the third factor as the most important in our single component data (as well as in Pritchard's), and as evidence that any one applied stress component such as wind shear is an incomplete correlate. Unfortunately, we do not have more than one 9.9-day record to test the cross-correlation stability of one or both of our stress composites; further, dividing the 9.9-day record into shorter ones to test this would run afoul of the 8-day or so period in our data.

Table III also shows the cross correlation with tensile stress applied to the ice during cooling of the atmosphere. As stated earlier, it is well established that such cooling is an important correlate of midfrequency noise,[2] but we see that low-frequency noise is poorly related to atmospheric cooling. Further evidence on the lack of importance of atmospheric cooling in low-frequency noise comes from Fig. 4. The spectral density of the rms pressure at 1 cycle/day does not differ from the general spectral trend, yet the temperature during Fram IV had strong daily cycles (superimposed on a general upward trend). We regard this, plus the low correlation, as a firm negative finding.

IV. SUMMARY AND CONCLUSIONS

We have studied low-frequency ambient noise records obtained under pack ice of the central Arctic Ocean, with short-term noise fluctuations ($\leqslant 1$ h) averaged out. We find that longer-term variations relate largely to stresses applied to the ice by a combination of wind, current, and drift. Stresses applied by temperature are not important at low frequencies.

Our noise records are far from perfect renditions of nature. It is probably true that most field observation programs have blemishes, but this one had to contend as well with competing scientific interests which one of the authors (Dyer) ironically had under his control along with ambient noise. Fortunately the noise evolves slowly in time, so that imperfections in our noise records seem not to be crucial.

Indeed, the noise evolves with a scale on the order of 1 day which, in itself, supports the notion that ponderous environmental forces are at work. More particularly, we are inclined to accept the idea that the stress moment **M** and the ice stress **S** are the two best correlates of low-frequency ambient noise. We do so less because of their cross-correlation coefficients (although they are high enough) and more because they are composites of individual stress-inducing environmental loads. As a matter of physical concept, to accept any one environmental component, say wind, as a noise correlate begs the necessity of accepting a composite.

At least one disagreeable point remains. Why are the correlation coefficients of **M** and **S** about 0.8 and not 1.0? Here are some factors to consider.

(1) With the same argument used previously, neither **M** nor **S** can stand alone. For example, in one possible ice fracture model, **S** can induce bending stresses indirectly via ice overthrusting[17] while **M** does so directly. We stop short of introducing such models in this paper (the M.I.T. Arctic research team is actively pursuing them) and so must stop short of relevant combinations of **M** and **S**.

(2) Ice is known to be a rheological material, especially in response to slowly evolving forces.[17,18] We have not tried correlations with both stress and stress rate as, for example, in Pritchard's[6] estimation of ridging energy from drift velocity.

(3) In a forthcoming paper,[19] Dyer shows that low-frequency ambient noise entails an integral of noise events distributed over an entire Arctic basin. The idea is a familiar one: With a given number of ice fracture events per unit area per unit time, contributions at an observation point grow linearly with range but shrink in intensity inversely with range. Consequently, basin semiaxes (or sound absorption) set the total level which, for the eastern Arctic Ocean at low frequencies, are on the order of 500 by 1000 km. We have used locally measured environmental data which are thought to have spatial scales about 500–1500 km for geostrophic wind and current, and 200–1000 km for drift.[20,21] Thus local wind and current data have reasonable relevance to basin-wide effects, but our cross correlations might be contaminated somewhat by unmeasured spatial variations of the drift.

(4) Aside from noise gaps, the records may be affected by ambient noise from other sources. For example, the ice edge and the connection to the open ocean via Fram Strait were about 400 km from the observation site, and could have made a small contribution which we estimate to be no more than about 20 dB down from the desired central Arctic noise. This translates to a possible reduction in correlation coefficient of no more than 0.1 and, dependent upon noise statistics, likely less than 0.05, but nonetheless of relevance to the question posed.

ACKNOWLEDGMENTS

We thank Prof. Arthur Baggeroer of M.I.T., who shared with Dyer the overall scientific leadership of Fram IV. Also, Prof. Gregory Duckworth and graduate students Josko Catipovic and Peter Stein, all of M.I.T., participated in various ways in Fram IV ambient noise instrumentation and data collection. Keith von der Heydt of the Woods Hole Oceanographic Institution also helped with ambient noise instrumentation. Roger Anderson of the University of Washington helped generously in interpreting for us his meteorological records. Jay Ardai of Lamont–Doherty Geological Observatory was reponsible for acquisition of the drift and current data, and Dr. Werner Tiemann and Dr. Kenneth Hunkins of the same institution were always repsonsive to our many questions on processing of these data. Dr. Hunkins also provided us with many insights on ice stress estimation. We have also benefited from discussions on wind stress with Dr. Kenneth Davidson of the Naval Postgraduate School, and on ice motion and its relationship to noise with Dr. James Lewis and Dr. Warren Denner of Science Applications International Corp. The research reported here is sponsored by the Arctic Program of the Office of Naval Research. Dr. Leonard Johnson and Robert Obrochta have continously encouraged us with interest and enthusiasm as well as with financial support.

[1] A. B. Baggeroer, F. R. diNapoli, and T. O. Manley, "The science program of the Fram experiments," in *Proceedings of IEEE Oceans 85* (IEEE, New York, 1985).

[2] A. R. Milne, "Thermal tension cracking in sea ice: A source of underwater noise," J. Geophys. Res. 77, 2177–2192 (1972).

[3] I. Dyer, "The song of sea ice and other Arctic Ocean melodies," in *Artic Technology and Policy*, edited by I. Dyer and C. Chryssostomidis (McGraw-Hill, New York, 1984), pp. 11–37.

[4] B. M. Buck, "Arctic acoustic transmission loss and ambient noise," in *Arctic Drifting Stations*, edited by J. E. Sater (Arctic Institute of North America, Calgary, Canada, 1968), pp. 427–438.

[5] J. H. Ganton and A. R. Milne, "Temperature and wind dependent ambient noise under midwinter pack ice," J. Acoust. Soc. Am. **38**, 406–411 (1965).

[6] R. S. Pritchard, "Arctic Ocean background noise caused by ridging of sea ice," J. Acoust. Soc. Am. **75**, 419–427 (1984).

[7] K. E. Prada, K. von der Hedydt, and T. F. O'Brien, "A versatile multichannel data acquisition system for seismic and acoustic applications," in *Proceedings of IEEE Oceans 81* (IEEE, New York, 1981), pp. 43–47.

[8] R. Andersen, Polar Science Center, Appl. Phys. Lab., Univ. of Washington at Seattle (private communication).

[9] E. G. Banke, S. D. Smith, and R. J. Anderson, "Drag coefficients at AIDJEX from sonic anemometer measurements," in *Sea Ice Processes and Models*, edited by R. S. Pritchard (Univ. of Washington, Seattle, 1980), pp. 430–442.

[10] W. Tiemann, Lamont–Doherty Geological Observatory, Columbia Univ., Palisades, NY (private communication).

[11] K. Hunkins, Lamont–Doherty Geological Observatory, Columbia Univ., Palisades, NY (private communication).

[12] K. Hunkins, "The oceanic boundary layer and stress beneath a drifting ice floe," J. Geophys. Res. **80**, 3425–3433 (1975).

[13] K. Hunkins, "Geostrophic drag coefficients for resistance between pack ice and ocean," AIDJEX Bull. **38**, 61–67 (1975).

[14] M. G. McPhee, "An analysis of pack ice drift in summer," in *Sea Ice Processes and Models*, edited by R. S. Pritchard (Univ. of Washington, Seattle, 1980), pp. 62–75.

[15] S. Pond and G. L. Pickard, *Introductory Dynamical Oceanography*, 2nd ed. (Pergamon, Oxford, 1983).

[16] W. Tiemann, J. Ardai, B. Allen, T. O. Manley, Y. Kristoffersen, and K. Hunkins, "Geophysical data from drifting ice stations: Fram IV and Tristen," Tech. Rep. LDGO-82-3, Lamont–Doherty Geological Observatory, Columbia Univ., Palisades, NY (1982).

[17] M. Mellor, "Mechanical behavior of sea ice," Monogr. 83-1, Cold Regions Research and Engineering Laboratory, Hanover, NH (1983).

[18] J. Schwarz and W. F. Weeks, "Engineering properties of sea ice," J. Glaciol. **19**, 499–531 (1977).

[19] I. Dyer, "An ambient noise model for the central Arctic Ocean," J. Acoust. Soc. Am. (to be submitted).

[20] R. Colony and A. S. Thorndike, "An estimate of the mean field of Arctic sea ice motion," J. Geophys. Res. **89**, 10 623–10 629 (1984).

[21] R. Colony and A. S. Thorndike, "Sea ice motion as a drunkard's walk," J. Geophys. Res. **90**, 965–974 (1985).

[22] I. Dyer, C-F. Chen, and P. J. Stein, "Acoustic signatures of ice cracking events in the Marginal Ice Zone," EOS **65**, 935 (1984).