



CECIL H. AND IDA M. GREEN
INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS
SCRIPPS INSTITUTION OF OCEANOGRAPHY (0225)

LA JOLLA, CALIFORNIA 92093-0225

20 July 2009

RADM Carr
Chief of Naval Research
800 North Quincy
Arlington, Virginia 22217-5000

Dear Admiral Carr:

I wish to report my activities as Secretary of the Navy Chair of Oceanography for the five year period from March 2003 to March 2009. I have had the honor of holding this Chair beginning with the appointment 1985 – 1990 and will follow the informal letter format designed by Admiral Brad Mooney and continued under Admirals Wilson, Miller, Gaffney Paleaz, Cohen and Landay. This consists of annual reports plus a summary report at the end of the five year period.

The principal emphasis has been on Ocean Acoustic Tomography, starting in 1980 with Carl Wunsch in response to the discovery of "ocean weather" during the MODE expeditions. For the past century oceanographer had believed that most of the kinetic energy of ocean currents was adequately described by some climatic averages (such as 10 ± 1 cm/sec); we now know that more than 90% of the energy is contained in the ocean weather (1 ± 10 cm/sec) with "mesoscale" variability of order 100 days and 100 km. The traditional methods of research vessels chasing independently across the oceans at 12 knots was not adequate to resolve ocean weather variability. Carl and I suggested using sound transmissions to map the oceans, with time series of travel time from a source A to receiver B being a good measure of temperature $T(t)$ variability between A and B, and the difference $A \rightarrow B$ minus $B \rightarrow A$ a measure of the mean velocity $U(t)$. By separately measuring the travel times of the many SOFAR arrivals one can invert for $T(t,z)$ and $U(t,z)$ depth profiles. Tomography takes advantage of the transparency of ocean to sound, and the high speed of sound (3000 knots) which exceeds the speed of research vessels.

We started out in 1981 with typical ranges of 100 km mostly in the North Atlantic, followed in 1983 by 3000 km transmissions between Hawaii and the mainland. In 1991 we transmitted from Heard Island in the Indian Ocean to stations at 18,000 km ranges, half way around the globe. We have worked on a multitude of oceanographic problems, among them the formation of deep water in the Atlantic sector of the Arctic, the flow through Gibraltar, and the decadal climate change in the northeast Pacific, and others. Last year saw a successful experiment in the Philippine Sea.

Nearly all of this work was done by collaboration of Woods Hole, University of Washington, Scripps and others with the support of ONR, for the last twenty years under the leadership of Peter Worcester of Scripps.

Coming now to the 2003 to 2009 period, I have participated in papers marked (A1) to (A19) in the attached bibliography. Unfortunately I have not been able to go to sea for the last five years, and my contributions are minor, with two exceptions: (i) work on the penetration of sound into the sound shadow zone (A16, A17, A18), dealing with a riddle since the earliest days of SOFAR transmissions. We proposed that scattering from internal waves could account for the penetration, and this has now been confirmed by Laura Van Uffelen in her 2009 dissertation. (ii) Scattering from a "spicy" ocean with hot and salty intrusions which are density neutral but not sound neutral (A3).

To summarize my work with the support of the Navy Chair:

- A. Ocean Acoustics as discussed above, publication A1 to A19.
- B. Sea Level Rise and its relation to Ocean Freshening (B1, B2)
- C. Global Warming and Ocean Tides. Colosi and I have examined the Honolulu tide gauge record, which goes back to 1872 (before the end of the monarchy). We found a significant contribution to the published tidal constants from internal tides (this has not previously been recognized). The Honolulu M2 tidal amplitude of 16.9 cm is 16.1 cm from surface (barotropic) tides and 0.8 cm from internal (baroclinic) tides. The later has undergone a 28-degree phase rotation in 100 years, which we attribute to ocean warming. (C1). Further, tidal mixing may be a significant cause of the 40,000 year climate (ice age) variability, which has been attributed entirely to change in solar radiation related to change in obliquity (C2).
- D. Acoustic Noise generated by Ocean Waves. Farrell and I have found that the acoustic noise background in the deep ocean down to 5 km is associated with short surface waves. There is some evidence for a noise minimum centered at 27 Hz (D1, D2). This might be of some interest in ASW detection. The work is continuing.

I do appreciate the support of the Navy Chair.

Sincerely yours,



Walter Munk

cc: F. Herr, T. Paluszkiwicz, E. Livingston, N. Losoya, Defense Technical Information Center, Naval Research Laboratory, T. Haymet, C. Constable, J. Orcutt, W. Farquharson, N. Wilson, L. Eyer

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 140 Sylvester Road Bldg. 140, Room 218 San Diego, CA 92106-3521				10. SPONSOR/MONITOR'S ACRONYM(S)	
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13. SUPPLEMENTARY NOTES					
14. ABSTRACT Continuing experiments in Ocean Acoustic Tomography include ten years of monitoring temperature in the North East Pacific. Scattering of sound by internal waves accounts for the penetration of sound into the geometric sound shadow zone; this has been a puzzle since the earliest days of SOFAR transmission. We have found a barely significant correlation of global sea level rise with a global decrease in salinity. Very low frequency acoustic noise (1 to 40 Hz) in the deep sea can be related to high frequency surface waves, with a possible noise "gap" centered at 25 to 35 Hz.					
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BIBLIOGRAPHY

Research Published within Period of the Award 2003 – 2009

2003

- Munk, W. and D. Day (2003) Harald U. Sverdrup. in *Coming of Age: Scripps Institution of Oceanography*, ed. R.L. Fisher, E.D. Goldberg, and C.S. Cox, pp. 177-201, Scripps Institution of Oceanography, University of California, San Diego.
- (B1) Munk, W. (2003) Ocean Freshening, Sea Level Rising. *Science* **300**: 2041-2043.
- (A1) Munk, W.H., P.F. Worcester, and R.C. Spindel (2003) Acoustic Thermometry of Ocean Climate. Preface to *Collected Papers, Acoustic Thermometry of Ocean Climate (ATOC)*.
- Munk, W., F. Gilbert, J. Orcutt, M. Zumberge, and R. Parker (2003) The Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP). *Oceanography* **16** (3): 34-44.
- Maxwell, A.E., W.H. Munk, F. Gilbert, and C.S. Cox (2003) Sir Edward Bullard. in *Coming of Age: Scripps Institution of Oceanography*, ed. R.L. Fisher, E.D. Goldberg, and C.S. Cox, pp. 13-20, Scripps Institution of Oceanography, University of California, San Diego.

2004

- (A2) Worcester, P.W., and W. Munk (2004) Human-generated Ocean Noise and the Effects on Marine Life: Commentary on Ocean Acoustic Tomography. *MTS Journal* **37**(4): 78-82.
- Munk, W., N. Oreskes, and R. Muller (2004) Gordon James Fraser MacDonald. *Biographical Memoirs: National Academy of Science* **84**: 2-26.
- (B2) Wadhams, P., and W. Munk (2004) Ocean Freshening, Sea Level Rising, Sea Ice Melting. *Geophysical Research Letters* **31**(No. 11): L11311, 10.1029/2004GL020039.
- Munk, W. and D. Day (2004) IVY-MIKE. *Oceanography* **17**(2): 96-105.
- (A3) Dzieciuch, M., W. Munk, and D.L. Rudnick (2004) The propagation of sound through a spicy ocean; the SOFAR overture. *J. Acoust. Soc. Am.* **116**(3): 1447-1462.
- Kennel, C.F., R.S. Lindzen and W. Munk (2004) William Aaron Nierenberg. *Biographical Memoirs: National Academy of Science* **85**: 1-20.
- (A4) Roux, P., W. A. Kuperman and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. Munk, R. C. Spindel, and P. F. Worcester) (2004) Extracting coherent wave fronts from acoustic ambient noise in the ocean. *J. Acoust. Soc. Am.* **116**: 1995-2003.
- (A5) Howe, B. M., B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, D. Menemenlis, J. A. Mercer, W. H. Munk, R. C. Spindel, D. Stammer, P. F. Worcester, and M. Zarnetske (2004) Acoustic remote sensing of large-scale temperature variability in the North Pacific Ocean. *OCEANS'04, MTS/IEEE Techno-Ocean '04*, Kobe, Japan, 1504-1506 [DOI: 10.1109/OCEANS.2004.1406343].

2005

- (A6) Colosi, J. A., A. B. Baggeroer, B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, P. F. Worcester, B. D. Dushaw, B. M. Howe, J. A. Mercer, R. C. Spindel, T. G. Birdsall, K. Metzger and A. M. G. Forbes (2005) Analysis of multipath acoustic field variability

and coherence in the finale of broadband basin-scale transmissions in the North Pacific Ocean. *J. Acoust. Soc. Am.* **117**: 1538-1564.

- (A7) Andrew, R. K., B. M. Howe, J. A. Mercer and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester) (2005) Transverse horizontal spatial coherence of deep arrivals at megameter ranges. *J. Acoust. Soc. Am.* **117**: 1511-1526.
- (A8) Voronovich, A. G., V. E. Ostashev and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester) (2005) Horizontal refraction of acoustic signals retrieved from the North Pacific Acoustic Laboratory billboard array data. *J. Acoust. Soc. Am.* **117**: 1527-1537.
- (A9) Vera, M. D., K. D. Heaney and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester) (2005) The effect of bottom interaction on transmissions from the North Pacific Acoustic Laboratory Kauai source. *J. Acoust. Soc. Am.* **117**: 1624-1634.
- (A10) Baggeroer, A. B., E. K. Scheer and The NPAL Group (J. A. Colosi, B. D. Cornuelle, B. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, W. H. Munk, R. C. Spindel, and P. F. Worcester) (2005) Statistics and vertical directionality of low-frequency ambient noise at the North Pacific Acoustic Laboratory site. *J. Acoust. Soc. Am.* **117**: 1643-1665.
- Munk, W. (2005) Let Roger speak for himself. *Chronicles* (UCSD Emeriti Association) **March 2005**: 3-4.
- Munk, W., F. Spiess, F. Seible (2005) Keeping Lindbergh Afloat: Another View on San Diego's Airport Dilemma. *Voice of San Diego*. July 5, 2005, <http://www.voiceofsandiego.org/site/apps/s/content.asp?c=euLTJbMUKvH&b=291837&ct=1146381>.
- (A11) Worcester, P.F., W.H. Munk, and R.C. Spindel (2005) Acoustic remote sensing of ocean gyres. *Acoustics Today* **1**: 11-17.
- Munk, W. (2005) WHOI. *WHOI 75th Anniversary Symposium*. 21 September 2005.
- Munk, W. (2005) Tides and the Climate. *Keeling Forum*, 07 October 2005.
- (A12) Munk, W. (2005) Foreward. In: *HYDRO TO NAVOCEANO: 175 Years Of Ocean Survey and Prediction by the U.S. Navy, 1830-2005*, C.C. Bates, pp. xv-xvi, Rockton, IL: Corn Field Press.

2006

- (A13) Munk, W. (2006) Ocean Acoustic Tomography: From a stomy start to an uncertain future. In *History of Oceanography*. ed. M. Jochum and R. Murtugudde, pp. 119-138, New York, NY: Springer.
- (A14) Munk, W. (2006) *Sounds in the Sea* Review. *Oceanography* **19**(1): 192-194.
- (A15) Munk, W. (2006) From Ocean Acoustics to Acoustic Oceanography. *EOS Transactions AGU* **87**: Ocean Sciences Meeting Supplement, Abstract OS51A-02.
- (A16) Munk, W. and D. Rudnick (2006) Penetrating the Deep Sound Channel; A Geometric Measure. *EOS Transactions AGU* **87**: Ocean Sciences Meeting Supplement, Abstract OS52J-02.
- (A17) Dzieciuch, M. A., P. F. Worcester, W. H. Munk, D. L. Rudnick, and L. J. Van Uffelen (2006) Propagation of sound through a spicy ocean. *EOS Transactions AGU* **87**: Ocean Sciences Meeting Supplement, Abstract OS52J-03.

- (A18) Rudnick, D.L. and W. Munk (2006) Scattering from the mixed layer base into the sound shadow. *J. Acous. Soc. Am.* **120**(5): 2580-2594.
- (C1) Colosi, J.A., and W. Munk (2006) Tales of the Venerable Honolulu Tide Gauge. *J. Phys. Oceanogr.*, **36**(6): 967-996.

2007

- (C2) Munk, W. and B. Bills (2007) Tides and the climate; some speculations. *J. Phys. Ocean.*, **37**(2): 135-147.
- (A19) Brenner, M.P. and contributors (G. Chandler, P. Dimotakis, F. Dyson, J. Goodman, D. Hammer, J. Katz, D. Meiron, A. Mulliken, W. Munk, W. Press, and J. Sullivan) (2007) *Navy Ship Underwater Shock Prediction and Testing Capability Study*. Mc Lean, Virginia: JASON (JSR-07-200).
- Day, D. and W. Munk (2007) Revelle, Roger Randall Dougan. In *New Dictionary of Scientific Biography*. 8 vols. Scribner's. 4400p. ISBN 978-0-684-31320-7.

2008

- Munk, W. and C. Pendarvis (2008) Where the Swell Begins. *Groundswell Publication*, submitted.
- (D1) Farrell W. E., W. Munk (2008) What do deep sea pressure fluctuations tell about short surface waves?. *Geophys. Res. Lett.*, **35**, L19605, doi:10.1029/2008GL035008.
- Munk, W. and D. Day (2008) Glimpses of Oceanography in the Postwar Period. *Oceanography*, **21**(3): 16-23.
- (D2) Munk, W. (2009) An Inconvenient Sea-Truth: Spread, Steepness and Skewness of Surface Slopes. *Annual Review of Marine Science*, **1**: 377-415, 10.1146/annurev.marine.010908.163940, in press.
- Munk, W. (2009) The William Leighton Jordon, Esq. Award, submitted.
- Munk, W., H. von Storch, and K. Hasselman (2009) Munk Interview, in progress.
- (A19) Worcester, P.F. and W.H. Munk, (2009) Sound Transmission Through a Fluctuating Ocean (1979) and Ocean Acoustic Tomography (1995): An intertwined history. *J. Acoustical Soc. Am.*, submitted.

MEETINGS AND INVITED TALKS

March 2003 – March 2009

Science at Scripps: Historical Precedents and Future Directions

Invited Speaker

University of California, San Diego

La Jolla, California

04 April 2003

Fleet Anti-Submarine Warfare Training Center

Invited Speaker

San Diego, California

16 April 2003

Invited Speaker: *The Rising Sea Level*

Mikaho Elementary School, Sapporo, Japan

01 July 2003

Prince Albert I Medal Lecture

International Union of Geodesy and Geophysics 2003 Conference

Invited Speaker: *Tales of the Venerable Honolulu Tide Gauge*

Sapporo, Japan

02 July 2003

International Union of Geodesy and Geophysics 2003 Conference

Invited Speaker: *Acoustic Thermometry of Ocean Climate*

Sapporo, Japan

03 July 2003

International Union of Geodesy and Geophysics 2003 Conference

Invited Speaker: *Twentieth Century Sea Level; an enigma*

Sapporo, Japan

03 July 2003

An Evening with Walter Munk

Invited Speaker

Birch Aquarium at Scripps, La Jolla, California

18 July 2003

HOME Farfield Experiment: Timberline Meeting

Invited Speaker: *Tales of the Venerable Honolulu Tide Gauge*

Timberline, Oregon

25-29 August 2003

Oceans 2003/SIO Centennial

Invited Speaker: *Sea Level*

San Diego, California

24 September 2003

Oceans 2003/SIO Centennial

Invited Speaker: *1980's: Ocean Acoustic Tomography: Birth of a Technique*

San Diego, California

24 September 2003

Board on Physics and Astronomy Meeting, National Academy of Sciences

Invited Speaker: *Oceans, Mixing, and the Moon*

Irvine, California

01 November 2003

Birch Aquarium Lecture Series

Invited Speaker: *Global Sea Level; an Enigma*

San Diego, California

11 February 2004

North Pacific Acoustic Laboratory (NPAL) Annual Workshop

Invited Speaker: *Abyssal recording of upper-ocean processes*

Borrego Springs, California

29-31 March 2004

ICL Committee Forum

Invited Speaker: *IVY-MIKE: Scripps participation in a thermo-nuclear test in Eniwetak in 1952*

San Diego, California

09 April 2004

Attended: JASON Spring General Membership Meeting

MITRE, McLean, Virginia

15-19 April 2004

Attended: National Academy of Sciences Annual Meeting

Washington, D.C.

18-19 April 2004

Attended: American Philosophical Society General Meeting

Philadelphia, Pennsylvania

21-24 April 2004

Attended: JASON Navy Meetings

La Jolla, California

28-30 June 2004

Attended: JASON Summer General Membership Meeting/Wrap-Up

La Jolla, California
26-28 July 2004

HOME Workshop
Invited Speaker: Tides and Climate
Kona, Hawaii
16-19 August 2004

IAPSO / SCOR Ocean Mixing Conference
Invited Speaker: *Tides and the Climate*
Victoria, British Columbia
13 October 2004

Marine Research Institute
Invited Speaker: *Tides and the Climate*
Reykjavik, Iceland
15 October 2004

Nansen Environmental and Remote Sensing Center
Invited Speaker: *Tides and the Climate*
Bergen, Norway
18 October 2004

Opening of Mohn-Sverdrup Center for Global Ocean Studies and Operational Oceanography
Invited Speaker: *The Science of Harald Sverdrup*
Bergen, Norway
20 October 2004

148th Meeting of the Acoustical Society of America
Invited Speaker: *Abyssal monitoring of upper ocean processes*
San Diego, California
18 November 2004

148th Meeting of the Acoustical Society of America, Fellows Luncheon
Invited Speaker: *IVY-MIKE*
San Diego, California
18 November 2004

Attended: American Philosophical Society General Meeting
Philadelphia, Pennsylvania
27 April – 01 May 2005

Attended: 8th Annual NPAL Workshop
Semiahmoo, WA
12 – 14 May 2005

Attended: Woods Hole Oceanographic Institution 75th Anniversary Science Symposium
Woods Hole, MA
20 – 22 September 2005

Attended: Chief of Naval Research Change of Command Ceremony
Department of the Navy, Office of Naval Research, Washington, DC
20 January 2006

AGU Ocean Sciences Meeting
Invited Speaker: *From Ocean Acoustics to Acoustic Oceanography*
Honolulu, HI
20 – 24 February 2006

AGU Ocean Sciences Meeting
Invited Speaker: *Penetrating the Deep Sound Channel*
Honolulu, HI
20 – 24 February 2006

Attended: HOME “Abyssal Recipes” Working Group Meeting
Honolulu, HI
27 – 28 February 2006

Naval Research Advisory Committee (NRAC), Study on Research Vessel Support for Ocean Sciences
Invited Speaker
Washington, DC
22 March 2006

Ninth North Pacific Acoustic Laboratory (NPAL) Workshop
Invited Speaker: *Scattering from the mixed layer base into the sound shadow*
La Casa del Zorro, Borrego Springs, CA
18 – 20 April 2006

Attended: American Philosophical Society General Meeting
Philadelphia, Pennsylvania
26 – 29 April 2006

Dept. of Earth, Atmospheric & Planetary Sciences Seminar Series
Invited Speaker: *Abyssal Monitoring of Upper Ocean Processes*
Massachusetts Institute of Technology (MIT), Cambridge, MA
03 May 2006

Wunsch Symposium
Invited Speaker: *Keynote Address – Ocean Acoustic Tomography and Other Answers*
Massachusetts Institute of Technology (MIT), Cambridge, MA
05 May 2006

Attended: 10th Annual NPAL Workshop, ONR Deep Water Acoustics
Sleeping Lady, WA
14-17 May 2007

Geoscience Seminar, The Pennsylvania State University
Invited Speaker: *Acoustic Tomography*
State College, PA
21 May 2007

The 26th International Conference on Offshore Mechanics and Arctic Engineering, The American Society of Mechanical Engineers (ASME International), Ocean, Offshore and Arctic Engineering (OOAE) Division
Invited Speaker: The Fred Noel Spiess Memorial Lecture, *Waves*
San Diego, CA
11 June 2007

The XXIV International Union of Geodesy and Geophysics (IUGG) General Assembly
Invited Speaker: *Wind Drag on Waves*
Perugia, Italy
04 July 2007

The 2007 Fluids Engineering Division of the American Society of Mechanical Engineering Summer Meeting
Special Guest Speaker: *Wind Drag on Waves*
San Diego, CA
31 July 2007
Canceled for medical reasons

Attended: Annual Meeting of the American Philosophical Society
Philadelphia, PA
08 – 10 November 2007

University of British Columbia
Invited Speaker
Victoria, BC, Canada
06 February 2008

Revelle Commemorative Lecture
Invited Speaker: *The contributions of Roger Revelle and Introduction of Mike Freilich*
Smithsonian National Museum, Washington, DC
25 February 2008

Attended: Meeting of the Navy Chairs of Oceanography and Admiral Landay
Arlington, VA
10 March 2008

Attended: 11th Annual NPAL (North Pacific Acoustic Laboratory) Workshop
Borrego Springs, CA
14 – 17 April 2008

Garrett 65th Symposium
Invited Speaker: *From 2 cm to 20 cm: Where the Action Is*
Victoria, BC, Canada
29 – 30 July 2008

Attended: Joe Pedlosky Symposium
Falmouth, MA
04 August 2008

Attended: Geophysical Fluid Dynamics Program (GFD): Perspectives and Challenges in GFD
Woods Hole Oceanographic Institute, Woods Hole, MA
6 – 14 August 2008

Baggeroer Festival and Symposium
Invited Speaker: *Listening to Climate Change*
Boston, MA
24 – 26 October 2008

Attended: MEDEA Ocean Panel
Herndon, VA
02 December 2008

Attended: National Academies' Ocean Studies Board
Irvine, CA
7 – 8 January 2009

Attended: MEDEA ETF Meeting
Herndon, VA
19 – 20 February 2009

Attended: Meeting of the Navy Chairs of Oceanography and RADM Carr
Arlington, VA
26 February 2009

Attended: Roger Revelle 100th Birthday Celebration
La Jolla, CA
05 – 07 March 2009

HONORS

2002 Reischauer Laureate, Japan Society of San Diego & Tijuana
San Diego, California, 09 October 2002

Honorary Fellow, Acoustical Society of America
Received at the 148th meeting of the Acoustical Society of America in San Diego, CA on 17 November 2004.

Elected Member, the European Academy of Science
December 2004

Lifetime Achievement Award, The American Society of Mechanical Engineers (ASME International), Ocean, Offshore and Arctic Engineering (OOAE) Division
Received at the 26th International Conference on Offshore Mechanics and Arctic Engineering in San Diego, CA on 11 June 2007.

Spirit of Surfing Award, The Groundswell Society in San Diego, CA in May 2007