Possible causes of increasing low frequency ocean noise

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Possible causes of increasing low frequency ocean noise

- Growing evidence of 35-year increase at 16-40 Hz (1965-2000)
  - 4 sites N. Pacific (~ 6-9 dB) [Andrew et al, 2011*]
- Speculation about cause
  - Increased shipping?
  - Decreasing pH?
- Global average shipping noise model
  - Derivation (overview)
  - Sensitivity to model inputs
- Model predictions
  - Short term: 1965-2000
  - (Long term: 1900-2200)
- Proposal: Global average source level measurement

**Chapman & Price, JASA EL161 129(5) 2011
Ambient noise spectra: 2000s cf 1960s

2000s

Point Sur

1994-2001

1963-1965

Andrew et al (2002)*

1960s (Wenz)

San Nicolas

2003-2004

2000s

1964-1966

McDonald et al (2006)**


Global average shipping noise model: Derivation I

Global average mean square pressure (MSP):

\[ P_{\text{RMS}}^2 = \rho c^2 H_V \]
\[ \rightarrow \]
\[ \langle P_{\text{RMS}}^2 \rangle = \rho c^2 \langle H_V \rangle \]

\[ H_V = \frac{1}{V} \sum_i H_i \]
\[ H_i = \frac{\Delta W_i}{2\alpha c} \]
\[ \rightarrow \]
\[ \langle P_{\text{RMS}}^2 \rangle = \frac{\rho c M}{2\alpha V} \langle \Delta W \rangle \]

\( P_{\text{RMS}} \) = RMS acoustic pressure
\( \rho \) = density
\( c \) = sound speed
\( \alpha \) = attenuation coefficient
\( H_V \) = energy density
\( H_i \) = free-field source energy*
\( W_i \) = contributing source power (i.e., trapped in water column)
\( M \) = total no. sources
\( V \) = total ocean volume = 1.7 Mm³

*M A Ainslie & R P A Dekeling, The environmental cost of marine sound sources, Underwater Acoustic Measurements 2011, Kos (Greece), June 2011
Global average shipping noise model: Derivation II

Global average “contributing” source power:

\[
\Delta W_i = \frac{2\pi S^{mp}}{\rho c} \left[1 - \text{sinc}\left(\frac{4\pi f}{c} d \sin \psi\right)\right] \sin \psi
\]

\[
\langle \Delta W \rangle = \frac{4\pi \langle S^{mp} \rangle}{\rho c} \left[1 - \text{sinc}\left(\frac{4\pi f}{c} d_{\text{eff}} \sin \psi\right)\right] \sin \psi
\]

\[
d_{\text{eff}} = \frac{c}{4\pi f \sin \psi} \text{sinc}^{-1} \left(\frac{\langle S^{mp} \rangle}{S^{mp}} \text{sinc} \left(\frac{4\pi f}{c} d \sin \psi\right)\right)
\]

\(S^{mp} = \) monopole source factor := \(10^{\text{SL}/10}\)

SL = source level

\(f = \) frequency

\(d = \) monopole depth

\(\psi = \) critical angle
Global average shipping noise model

\[ \left\langle p_{\text{RMS}}^2 \right\rangle = 2\pi \frac{M \sin \psi}{V} \left\{ \frac{\left\langle S^{mp} \right\rangle}{\alpha} \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c d_{\text{eff}} \sin \psi} \right) \right] \right\} \]

Model inputs
- Ship properties:
  - Number of ships: \( M \)
  - Source level: \( \text{SL} = 10 \log_{10} S^{mp} \)
  - Tonnage: \( T \sim \rho^3 \)

- Medium properties:
  - Temperature (critical angle \( \psi \))
  - Temperature, salinity, acidity, (absorption \( \alpha \))
Global average shipping noise model

\[
\left\langle p_{\text{RMS}}^2 \rightangle = 2\pi \frac{M \sin \psi}{V} \left\{ \frac{\left\langle S_{\text{mp}} \right\rangle}{\alpha} \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right] \right\}
\]

- **Model inputs**

  - **Ship properties:**
    - Number of ships: \( M \)
    - Source level: \( SL = 10 \log_{10} S_{\text{mp}} \)
    - Tonnage: \( T \sim \alpha^3 \)

  - **Medium properties:**
    - Temperature (critical angle \( \psi \))
    - Temperature, salinity, acidity, (absorption \( \alpha \))
Global average shipping noise model

\[
\left\langle P_{\text{RMS}}^2 \right\rangle = 2\pi \frac{M \sin \psi}{V} \left\langle S_{\text{mp}} \right\rangle \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right]
\]

▷ Model inputs
  
  ▷ **Ship properties:**
    
    ▶ Number of ships: \( M \)
    
    ▶ Source level: \( \text{SL} = 10 \log_{10} S_{\text{mp}} \)
    
    ▶ Tonnage: \( T \sim a^3 \)

  
  ▷ **Medium properties:**
    
    ▶ Temperature (critical angle \( \psi \))
    
    ▶ Temperature, salinity, acidity, (absorption \( \alpha \))
Global average shipping noise model

\[
\left\langle p_{\text{RMS}}^2 \right\rangle = 2\pi \frac{M \sin \psi}{V} \left\langle S^{mp} \right\rangle \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right] \]

> Model inputs

> **Ship properties:**

> - Number of ships: \( M \)
> - Source level: \( SL = 10 \log_{10} S^{mp} \)
> - Tonnage: \( T \sim \alpha^6 \)

> **Medium properties:**

> - Temperature (critical angle \( \psi \))
> - Temperature, salinity, acidity, (absorption \( \alpha \))
Global average shipping noise model

\[
\langle p_{\text{RMS}}^2 \rangle = 2\pi \frac{M \sin \psi}{V} \left\{ \frac{\langle S^{\text{mp}} \rangle}{\alpha} \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right] \right\}
\]

Model inputs

Ship properties:
- Number of ships: \( M \)
- Source level: \( \text{SL} = 10 \log_{10} S^{\text{mp}} \)
- Tonnage: \( T \sim \alpha^3 \)

Medium properties:
- Temperature (critical angle \( \psi \))
- Temperature, salinity, acidity, (absorption \( \alpha \))
Global average shipping noise model

\[
\left\langle p_{\text{RMS}}^2 \right\rangle = 2\pi \frac{M \sin \psi}{V} \left\langle S_{\text{mp}}^{\text{mp}} \right\rangle \left[ 1 - \text{sinc}\left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right]
\]

- **Model inputs**
- **Ship properties:**
  - Number of ships: \( M \)
  - Source level: \( \text{SL} = 10 \log_{10} S_{\text{mp}} \)
  - Tonnage: \( T \sim d^3 \)
- **Medium properties:**
  - **Temperature** (critical angle \( \psi \))
  - Temperature, salinity, **acidity**, (absorption \( \alpha \))
Model predictions

- Short term (1965-2000)
  - Assumptions (shipping, climate)
  - Predictions

- Long term (1900-2200)
  - Climate only
  - Sensitivity to acidity and temperature
Assumptions (1965-2000)

Shipping

- No. of ships*: 44000 → 88000
- Av. tonnage*: 3700 → 6200
- Av. source level: no change [Wales & Heitmeyer**]

Climate

- pH (SWS scale)***: 8.0 → 7.9
- Temperature: no change


Model predictions (1965-2000)

- Effect of:
  - No. of ships ($M$)
  - Monopole depth ($d$)
  - pH

[Andrew et al (2002)]
Sensitivity to long-term climate change

- Expected change*
  - pH: up to -0.5 (1900-2200)
  - Temperature: +1.7 to 4.4 °C by 2100
  - Wind: increasing with time (1991-2008)**

- Effect on noise
  - pH (200 Hz to 2 kHz):
    - Sensitivity 7.6 dB per pH unit (averaged over sound channel)
    - Example: $\Delta$ pH = -0.3 $\rightarrow$ $\Delta$NL = +2.3 dB
  - Temperature:
    - Competing effects: absorption (+) vs refraction (-)
    - Mainly refraction (-)
    - Strong seasonal fluctuations

Global average source level measurement?

- Noise model:
  \[ \left\langle P_{\text{RMS}}^2 \right\rangle = 2\pi \frac{M \sin \psi}{V} \frac{S_{\text{mp}}}{\alpha} \left[ 1 - \text{sinc} \left( \frac{4\pi f}{c} d_{\text{eff}} \sin \psi \right) \right] \]

- Rearrange for source factor:
  \[ \left\langle S_{\text{mp}} \right\rangle = \frac{V}{2\pi M \sin \psi} \frac{\left\langle P_{\text{RMS}}^2 \right\rangle \alpha_j}{1 - \text{sinc} \left( \frac{4\pi f_j}{c} d_{\text{eff}} \sin \psi \right)} \]

- Global average MSP:
  - Archive data available from CTBTO since 2001

50 Hz – 200 Hz: No change in inferred SL

*M. K. Prior, Underwater Acoustic Measurements 2009, and
*M. K. Prior et al, Underwater Acoustic Measurements 2011, Kos (Greece), June 2011
Fly in the ointment

- Measurements: median of short term (ca. 3 min) samples
- Prediction: global average mean square pressure
- Estimated difference:
  - Assume log-normal distribution: $\sigma \sim 5$ dB *
  - Mean – median = $\sigma^2/(20 \log_{10} e) \sim 3$ dB

Conclusions I

- Noise level measurements 1965-2000 (Point Sur)
  - 16 Hz – 40 Hz:  ~ +9 dB
  - 50 Hz – 100 Hz:  ~ +5 dB

- Increase of 5 dB can be explained by
  - Number of ships → + 3 dB
  - Av. tonnage per ship → + 1.5 dB
  - No need for change in source level
  - No need for climate change (pH, T)
Conclusions II

- Long term effect of increasing acidity
  - +0.8 dB per 0.1 decrease in pH
- Long term effect of increasing temperature
  - Uncertain (competing effects)
  - Possibly in opposite direction to pH
  - Probably strong seasonal fluctuations
- Proposed measurement of global average source level
  - Global average mean square pressure
  - Requires re-processing existing data
Acknowledgements

- R. Andrew
- D. Browning
- W. Carey
- R. Chapman
- R. Dekeling
- C. de Jong
- M. Prior
Questions & answers ...
Where were the measurements made?

Point Sur (receiver ‘d’)

San Nicolas (receiver ‘f’)

Andrew et al, JASA 129, 642-651 (2011)

Chapman & Price, JASA EL161 129(5) 2011
What source level was used?

- Assumed (global average) source level spectrum
  - Measurements 1986 to 1992
  - 272 ships (Mediterranean, E. Atlantic)
  - Assume unchanged 1965-2000

S. C. Wales & R. M. Heitmeyer
JASA 111, 1211-1231 (2002)
How does the tonnage affect the radiated sound power?

- A ship’s tonnage is a measure of its volume ($V$)
- Assume no change over time to the shape or density of average ship
- $d \sim V^{1/3}$
- Deep source radiates more power than shallow source of same source level (surface decoupling)
- Large ships therefore radiated more power than small ones of the same (monopole) source level
How was the monopole depth chosen?

- Two parameters were chosen to match the 1965 Wenz data
  - Monopole depth $d_{\text{eff}}$: 1.5 m
  - Low frequency absorption coefficient $\alpha_{\text{min}}$: 1 dB/Mm ($= 0.001$ dB/km)
What is the significance of $\alpha_{\text{min}}$?

- There are two effects that limit propagation of low frequency sound:
  - Low frequency attenuation $\sim O(0.001 \text{ dB/km})$
  - Physical size of ocean basins $\sim 5000 \text{ km}$

- The $\alpha_{\text{min}}$ term represents the combined action of these two mechanisms
How do temperature and pH affect noise level?

- Refraction (temperature only)
  - Increasing sea surface temperature
  - Increasing sea surface sound speed
  - Decreasing critical angle (lower proportion of total radiated power trapped in sofar channel)

- Absorption:

\[ \alpha(f) \]
\[ \alpha_{\text{min}} = 0 \]
What causes the rapid rise in level at 50 Hz and below?

- Cause unknown; possible explanation:
  - Low frequency (LF) sound does not propagate in shallow water
  - Only ocean going vessels contribute to LF ocean noise
  - Increasing proportion of ocean-going ships (cf coastal shipping) \(ightarrow\)
faster increase than expected from the number of ships alone
How does the measured source level compare with the measurements of Arveson & Vendittis?

- Arveson & Vendittis (AV 2000*) measured radiated noise level
- Keel-aspect value equivalent to dipole source level if no absorption
- Convert inverted monopole source level to dipole source level
- 50-200 Hz
  - consistent with 14 kn ship speed from AV 2000