Coarse mode marine aerosol particles
A brief review

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Rationale
ICAP Ensemble Sea Salt AODs

• Despite being one of the oldest areas of aerosol research, there is much divergence in published measurements and model results.

• Despite similarities in source functions and meteorology, there is more spread/mean diversity in sea salt components in the ICAP multi-model ensemble than any other specie.

• “Closure” of sea salt observations with optics is thwarted by large measurement uncertainty on both the microphysical and optical side.
AEROCOM Sea-Salt Emissions
Climate models are in worse shape.
How about field measurements?
The State of Sea Salt Particle Size From my 2002 talk. Not too much has changed. But see Reid et al., 2006 and Jaegle et al, 2011 for latest synopsis.

Gong et al., [1997] Order of magnitude uncertainty in concentration

Porter and Clarke [1997] Factor of 10 uncertainty in size

Andreas [1998] Don’t even think about flux
Sometimes Dilbert is a bit close to home…..

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**Comic Strip:**

1. **Boss:** Do you have those budget numbers from last month?
   - **Dilbert:** They’re totally inaccurate.
2. **Dilbert:** I know, but those are the only numbers we have.
   - **Boss:** Actually, we have infinite inaccurate numbers to choose from.
3. **Boss:** Let’s keep those in our back pocket in case we need them.
   - **Dilbert:** I’ll encrypt them so no one else can use them.
What does it look like at the surface for a large sea salt emissions event???

- Extra tropical cyclones drive global sea salt verification statistics in aerosol models, but maybe not most relevant global sea salt budgets.

- But, these are the most challenging regions to measure, or even define.

NOAA P-3 on landing
Particle Formation
Is it as simple as this?

Regardless, volume and number controlling processes are likely decoupled.

Adapted from Bill Keene

Dry Spume
A Current Challenge: Reconcile microphysical and optical properties

First we must come to grips that coarse mode marine aerosol systems are perhaps the most complex observability problems in aerosol science. Ask yourself what problem are you trying to solve? Because right now one size fits none.

For ICAP’s problems, at the moment we need to reconcile remote sensing and model views of the coarse mode sea salt aerosol system. Questions include:

- What are we measuring? In situ measurements of particle size, chemistry, source/sink.
- What are we seeing? Satellite and surface remote sensing of aerosol properties.

How do we bridge the two? Thermodynamics.

These will be demonstrated through examples from ONR field campaigns. Usually I am not so Navy centric, but this is the stuff you need to know.
### Dust: Reid et al, 2003

<table>
<thead>
<tr>
<th>Reference</th>
<th>Region</th>
<th>MMD VMD (μm)</th>
<th>Geo. St. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerodynamic Methods</strong></td>
<td></td>
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<td></td>
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<tr>
<td>D’Almeida et al., [1987]</td>
<td>Sahara</td>
<td>3+1</td>
<td>2.1</td>
</tr>
<tr>
<td>Almeida et al., [1990]</td>
<td>Algeria</td>
<td>3+0.5</td>
<td>1.8</td>
</tr>
<tr>
<td>Almeida and Gillette, [1993]</td>
<td>Tajikistan</td>
<td>3 – 6</td>
<td>–</td>
</tr>
<tr>
<td>Almeida et al., [1996]</td>
<td>Turkey (from Libya)</td>
<td>7+1</td>
<td>–</td>
</tr>
<tr>
<td>Almeida et al., [1999]</td>
<td>Negev Desert</td>
<td>5+1</td>
<td>–</td>
</tr>
<tr>
<td>Almeida et al., [2000]</td>
<td>Canary Islands</td>
<td>5+1</td>
<td>–</td>
</tr>
<tr>
<td>Almeida et al., [1997]</td>
<td>Texas</td>
<td>6+1</td>
<td>2.2</td>
</tr>
<tr>
<td>Almeida et al., [1994]</td>
<td>Owens (Dry) Lakebed</td>
<td>4+1</td>
<td>2.3</td>
</tr>
<tr>
<td>Almeida et al., [1993]</td>
<td>Tajikistan</td>
<td>5+1</td>
<td>1.9+0.3</td>
</tr>
<tr>
<td>Talbot et al., [1986]</td>
<td>Barbados</td>
<td>3.2+0.8</td>
<td>2.5</td>
</tr>
<tr>
<td>PRIDE Study</td>
<td>Puerto Rico (Saharan)</td>
<td>3.5+1</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td>4.4+1.2</td>
<td>2.1+0.2</td>
</tr>
</tbody>
</table>

### Sea Salt: Reid et al, 2006

<table>
<thead>
<tr>
<th>Location</th>
<th>RH</th>
<th>Height (m)</th>
<th>VMD (μm)</th>
<th>stdg</th>
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<tbody>
<tr>
<td><strong>Aerodynamic Particle Sizers (dry)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maring et al., [2003]</td>
<td></td>
<td>dry</td>
<td>10 m</td>
<td>4/5</td>
</tr>
<tr>
<td>Quinn et al., [1996]</td>
<td>55%</td>
<td>dry</td>
<td>15 m</td>
<td>2.9/4</td>
</tr>
<tr>
<td>Pizza et al.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Maring et al., [2000]</td>
<td></td>
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<tr>
<td>PRIDE Study</td>
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</tr>
<tr>
<td><strong>Mean</strong></td>
<td></td>
<td></td>
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### Cascade Impactors

<table>
<thead>
<tr>
<th>Location</th>
<th>RH</th>
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<th>VMD (μm)</th>
<th>stdg</th>
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</thead>
<tbody>
<tr>
<td>Tenerife</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>9</td>
</tr>
<tr>
<td>ASTEX/Atlantic</td>
<td></td>
<td>Amb</td>
<td>Cliff</td>
<td>7</td>
</tr>
<tr>
<td>Ireland</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~4.5</td>
</tr>
<tr>
<td>Ireland</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~5.0</td>
</tr>
<tr>
<td>SE Pacific</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2.1</td>
</tr>
<tr>
<td>Szigeti</td>
<td></td>
<td>Amb</td>
<td>5.5 m</td>
<td>~2.2</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~4.0</td>
</tr>
</tbody>
</table>

### Optical Particle Counters

<table>
<thead>
<tr>
<th>Location</th>
<th>RH</th>
<th>Height (m)</th>
<th>VMD (μm)</th>
<th>stdg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawaii</td>
<td></td>
<td>dried</td>
<td>5 &amp; 20 m</td>
<td>7/12</td>
</tr>
<tr>
<td>Outer Hebrides</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2.2</td>
</tr>
<tr>
<td>Variable</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2.0</td>
</tr>
<tr>
<td>Cape Grim</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2.0</td>
</tr>
<tr>
<td>Montgomery/ASIN</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2.0</td>
</tr>
<tr>
<td>Azores</td>
<td></td>
<td>Amb</td>
<td>15 m</td>
<td>~2.0</td>
</tr>
<tr>
<td>Bermuda</td>
<td></td>
<td>Amb</td>
<td>250 m</td>
<td>~2.0</td>
</tr>
<tr>
<td>US East Coast</td>
<td></td>
<td>Amb</td>
<td>variable</td>
<td>~2.1</td>
</tr>
<tr>
<td>AST</td>
<td>X</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
</tr>
<tr>
<td>Reider et al., [2001]</td>
<td></td>
<td>Amb</td>
<td>30-100 m</td>
<td>~2.0</td>
</tr>
</tbody>
</table>

### Inversions (ambient)

<table>
<thead>
<tr>
<th>Location</th>
<th>RH</th>
<th>Height (m)</th>
<th>VMD (μm)</th>
<th>stdg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawaii</td>
<td></td>
<td>Amb</td>
<td>variable</td>
<td>8</td>
</tr>
<tr>
<td>Composite</td>
<td></td>
<td>Amb</td>
<td>variable</td>
<td>8</td>
</tr>
<tr>
<td>Bermuda</td>
<td></td>
<td>Amb</td>
<td>variable</td>
<td>5.0</td>
</tr>
<tr>
<td>North Sea</td>
<td></td>
<td>Amb</td>
<td>14 m</td>
<td>~2</td>
</tr>
<tr>
<td>North Sea</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2</td>
</tr>
<tr>
<td>North Sea</td>
<td></td>
<td>Amb</td>
<td>10 m</td>
<td>~2</td>
</tr>
</tbody>
</table>

*Estimated from given surface median diameter and geometric standards deviation using Hatch-Chot equations
RED Aerosol Flux Game Plan

Deploy EC instruments to starboard boom on FLIP
   Campbell Sonic, LICOR $\text{H}_2\text{O}/\text{CO}_2$, FSSP, PCASP

Deploy mean aerosol instruments to upper deck
   Dried inlet, APS 3320, TSI Neph, CSASP DOA

Use CIRPAS Twin Otter for vertical distribution

Use site as receptor for Hoppel and Co.

Advantages: Stable platform, long fetch
Marine Aerosol Size Distribution Issues
Do the sizing biases we found for dust extend to sea salt?
Most OPC data in the literature cannot be trusted at face value.

Particle Sizer Intercomparison Sept. 10 2001

Geometric Diameter, $d_p$ ($\mu$m)

- **Optical Methods**
  - FLIP PCASP
  - FLIP FSSP-Mid Gain
  - FLIP APS
  - TO PCASP
  - TO FSSP-Low Gain
  - TO FSSP-Forward Caps
  - TO APS

- **Aerodynamic Methods**

Persistent systematic errors exist in sea salt size distributions: But why variability?

Closest to Reality:
Response Curve Degeneracy
Channel/Gain Bias
Reporting/Curve Fit Bias
Inlet/Humidity Bias
Sample Volume

Please show me how you can calibrate around this!
Marine Aerosol Measurement Implications:
Extinction/Column Closure Failures for Cleaner Background Environments

**Vertical Profile/Column Closure Bias:**
FSSP: Instrument response to increasing humidity unphysical. We are getting an image of the response function back.

**Hygroscopicity Bias:** Organics need to be accounted for. Current algorithms (such as Gerber or Tang) overestimate hygroscopicity. Crahan’s results from RED make more sense.

Difference in AOT can be a factor of 2
RED: Environmental Conditions

Wind Speed (m s⁻¹)

Significant Wave Height (m)

Day of the Year

Particle Concentration d >1 μm (cm⁻³)

Day of the Year

Eddy Correlation

Sept 11

FSSP Outage
A Word on Wind- Sea Salt Regressions

High winds imply high particle concentrations. But low wind does not imply low concentrations.

High Wind Period

All Data

$r^2 = 0.42$

$r^2 = 0.25$
Why Poor Correlations?
Upwind Source: Sept. 8, 2030 UTC
So how about source fluxes? Lewis and Schwartz
Wind Regressions and Fluxes

Cm versus Wind

Fluxes
Example Methods

- Flavors of lab or field whitecap scaling
- Gradient
- Eddy correlation
- Box method
- Model tuning
Hypothesized Dependencies

- Stability/momentum flux
- Organic component/Chl a
- Wind-wave direction differences
- SST
Bill Keene’s Bubble Maker:
Looking at how ocean properties influences production
Number Production Flux

Time, hh:mm UTC, 2 June 2010

* Diameters at 80% RH.
Number Production Flux vs. Seawater Characteristics
Keene et al., 2010 AGU

- SST (°C); Salinity (psu)
- Chl a (μg L⁻¹)
- SST
- Salinity
- Chl a

- Sub-μm Flux (cm² s⁻¹)
- Super-μm Flux (cm² s⁻¹)

- Sub-μm (R² = 0.63)
- Super-μm (R² = 0.43)
Number Size Distributions in Head Space
Do bubble dynamics converge to stabilize coarse mode size?

![Graphs showing number size distributions](image)
Dry Deposition

• Slinn: “This is an algorithm o be tested, not a parameterization to be used….”

• Need to distinguish between production and net flux.

• Dry deposition is as much as the source problem as the source.

• From a measurement point of view it is seldom considered.

• From a modeling point of view it equally defines MBL concentrations as the source.

• I still do not know what to think about Hoppels source function, but in modeling space his logic seems sound.
Measuring flux: EOPACE Duck is still the only actual measurement of source flux in the literature.

Shore

Sea

$u = 8 \text{ m/s}$

$u = 12 \text{ m/s}$

$u = 8 \text{ ms}^{-1}$

$u = 12 \text{ ms}^{-1}$
The Null Hypothesis. Regional variability
Do different parts of the world create different particles? Are surf zone particles like open ocean particles?

- Differences by “investigator” is consistent between regions of the world.
- Very few measurements at high wind speeds and variable ocean/wave conditions.
- There are physical reasons why open ocean and surf particle fluxes could be different.
- If they are different, then surf would probably be larger.
- Does relative comparability (order of magnitude) of recent fluxes imply everything comes out in the wash? Is this really something we can forward model?
High AODs in the high mid-latitude oceans. Cloud and lower boundary condition biases are a big problem for data assimilation.

- S. ocean aerosol anomaly: Fact or cloud bias?
- N. oceans have same problem, but often attributed to pollution.
- Cloud issues: Masks, 3d radiation effects, pixel sampling, and some reality.
- Model winds helps with lower boundary condition.
- Microphysics? Sampling?

Zhang et al., 2005
Marine AOD- A Satellite Perspective

Who’s satellite obs do you trust?
It is easy to say it is just cloud bias, but there is more to it than that.

December-May

- NOAA AVHRR
- GACP AVHRR
- Col. 5 Terra
- Col. 5 Aqua
- Deep Blue 5.1 Terra
- Deep Blue 5.1 Aqua
- MISR Col 22
- SeaWiFs v5.2
- OMI OMAEROe
- OMI OMAERUVG

June-November

- NOAA AVHRR
- GACP AVHRR
- Col. 5 Terra
- Col. 5 Aqua
- Deep Blue 5.1 Terra
- Deep Blue 5.1 Aqua
- MISR Col 22
- SeaWiFs v5.2
- OMI OMAEROe
- OMI OMAERUVG

2005 Aerosol Optical Depths

AVHRR (670 nm), MODIS Col 5, Deep Blue SeaWiFs (550 nm), OMI (500 nm)
Cruise tracks and daily averages of aerosol optical depth at 500 nm (squares are colored with respect to AOD values, i.e. blue – AOD<0.10, green – 0.1≤AOD<0.2, yellow – 0.2≤AOD<0.3, orange – 0.3≤AOD<0.5, red – 0.5≤AOD<0.7, purple – AOD≥0.7).
Cruise tracks and daily averages of coarse mode aerosol optical depth at 500 nm (squares are colored with respect to coarse AOD values, i.e. grey – AOD<0.05, blue – 0.05< AOD<0.10, green – 0.1≤AOD<0.2, yellow – 0.2≤ AOD<0.3, orange – 0.3≤AOD<0.5, red – 0.5≤AOD<0.7, purple – AOD≥0.7).
Over most of the ocean, the AOD is at the satellite retrieval noise floor.

From Shi et al., 2011, ACP
Relating Mass to Extinction: Odds are in favor of the fine mode than the coase mode.
But there are good relationships between AOD and mass for simple MBL conditions. But, you have to actually measure mass.
Let's look at more extreme events!
This is your lower boundary condition.
Power loss power to three of four engines over the northern Atlantic Ocean at ~800 m altitude in a powerful extra-tropical cyclone.

These failures left insufficient power for sustained flight and crew prepared to perform an in-water emergency landing.

After passing through a minor one-minute long rain band, pilots were able to restart the engines and return home safely.

Preliminary investigation suggested that sea salt aerosol particles generated in the high winds and seas coated the aircraft, leading to severe engine fouling and ultimately compressor stalls.
Salt on a P3 after flying into a North Atlantic bomb...
NOGAPS/IR Image
A classic extra tropical bomb

Feb. 9th Cyclone
F9
45N
Cold Dry Slot
Occluded Front
Cold Front

39N
Warm Sector

F8
Cyclone Sampled on Feb. 8

Warm Front
Aircraft Obs in the Dry Slot

Dropsonde

- Adiabat
- Transition
- Dewpoint
- Temperature

(b) Wind Speed (Kts)
- Direction
- Speed
- Occcluded Front
- Dry Slot

(d) Potential Temperature (°C)
- Humidity
- =>Rapid air exchange
- Potential Temperature
- Occcluded Front
- Dry Slot

Wind Direction (deg)
- Relative Humidity (%)
Cold air over the gulf stream enhanced mixing further
A Two Dimensional View: CALIPSO
Maximum salt altitude 1.5-2 km

February 10, 2007, ~4Z

- Cirrus associated with F8
- Low Center
- Occluded Front
- Dry Slot
- Cold Front
- Cirrus south of storm

Latitude Longitude:
58.95
30.85
53.03
34.09
47.04
36.04
41.01
38.76
34.96
40.59

Altitude (km):
10
5

Despite being one of the oldest fields of aerosol research, uncertainties on many basic sea salt parameters and hence models remains high.

Verification statistics are driven in extreme event where measurement is difficult, and even common definitions break down. In many cases, they may not even be relevant.

Based on field data, we have found that most of these uncertainties can be traced back to specific systematic errors in particle sizing and thermodynamics. The question is how much legacy data is correctable? Can this lead to something that can improve prediction?

Remote sensing is a powerful tool (see Travis Toth’s Poster Friday), but errors are equally large and tend to be positive definite (LBC, Clouds, Microphysics). Lots of good work has been done studying the effects, but the native product may not be appropriate.

But there is hope! Modeling capability and new observations are making headway.
Questions?