The other CO$_2$ problem from a different angle: Studying Ocean Acidification using satellite Earth observation

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Ocean acidification

- Oceans annually absorb ~25% of anthropogenic CO$_2$ emissions.
- This lowers the pH of sea water and can lead to a decrease in calcium carbonate saturation state, with potential implications for marine animals, especially calcifying organisms.
- Measuring SST and salinity and any two of the four “key” parameters ($C_T$, $A_T$, pCO$_2$ and pH) enables the carbonate system to be monitored.
Understanding of Ocean Acidification has been limited by availability of carbonate system data.

In 2012, OA researchers formed the Global OA Observing Network to bring together datasets, research and resources.

Algorithms using in situ hydrographic, Earth observation and/or model data have been developed.

Increase in data, e.g. from the Ship of Opportunity Programme and data buoys provides opportunity to test algorithms.
Many regional OA parameter algorithms exist that use combinations of inputs that could exploit satellite data.

Are the new satellite salinity data of any use?
Ocean acidification

Measuring sea surface salinity from space

- ESA SMOS and NASA-CONAE Aquarius were launched in 2009 and 2011, both measuring global SSS
Highlights that salinity from space enables us to monitor and study alkalinity-salinity relationship.
Review and forward look paper

Salinity from Space Unlocks Satellite-Based Assessment of Ocean Acidification

Highlights that salinity from space enables us to monitor and study alkalinity-salinity relationship.
Case Study Regions

5 regions

- Greater Caribbean
- Amazon Plume
- Barents Sea
- Bay of Bengal

Global, SMOS salinity for October 2010 (blue-red)
Sea ice (green)
European Space Agency
Pathfinders Ocean Acidification

- Evaluate existing empirical algorithms using satellite, climatological and re-analysed in situ data as inputs.
- Evaluation of algorithms in different regions using all possible inputs and compare to an example Earth System model (HadGEM2-ES).
- Determine if satellite observed inputs outperform, equals or deteriorates performance of empirical algorithms.
- Rank performance to determine optimum algorithm and input (termed model).
European Space Agency
Pathfinders Ocean Acidification

- Evaluate existing empirical algorithms using satellite, climatological and in situ data as inputs.
- Evaluation of algorithms in different regions using all possible inputs.
- Determine if satellite observed inputs outperform, equals or deteriorates performance of empirical algorithms.
- Rank performance to determine optimum algorithm and input (termed model).

Massive data collation and quality control effort

> 100 TB of satellite data from >15 satellite sensors

- 14,000,000 in situ data
### Earth observation data

<table>
<thead>
<tr>
<th>No.</th>
<th>Sensor/name (version)</th>
<th>Spatial resolution (temp. resolution)</th>
<th>Temporal period</th>
<th>Geographic coverage</th>
<th>Parameters</th>
<th>References</th>
<th>Data held</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cryosat-2 (GlobWave GDR)</td>
<td>~300 m along track, ~4 km across track (daily, monthly)</td>
<td>2010-present</td>
<td>Global</td>
<td>U10, Ice coverage, Ice thickness</td>
<td>Laxon et al., (2013)</td>
<td>Yes</td>
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<tr>
<td>2.</td>
<td>SMOS (CATDS v2)</td>
<td>0.25° × 0.25° (monthly) 0.5° × 0.5° (daily)</td>
<td>2010-present</td>
<td>Global</td>
<td>SSS, U10</td>
<td>Font et al. (2010)</td>
<td>Yes</td>
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<tr>
<td>3.</td>
<td>MERIS (3rd reprocessing)</td>
<td>RR 1km (daily, monthly)</td>
<td>2002-2012</td>
<td>Global</td>
<td>Rrs, chl</td>
<td>Rast et al. (1999)</td>
<td>Yes</td>
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<tr>
<td>4.</td>
<td>MODIS-Aqua (Seadas 7)</td>
<td>1 km, 4 km, 9 km (daily, monthly)</td>
<td>2002-present</td>
<td>Global</td>
<td>Rrs, chl, SST</td>
<td>NASA Ocean colour website oceancolor.gsfc.nasa.gov</td>
<td>Yes</td>
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<td>5.</td>
<td>AATSR</td>
<td>1 × 1 km (daily, monthly)</td>
<td>2002-2012</td>
<td>Global</td>
<td>SSTskin</td>
<td>-</td>
<td>Yes</td>
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<td>6.</td>
<td>ESA SST CCI (ARC v1.1.1)</td>
<td>0.1° × 0.1° (monthly)</td>
<td>1992-2012</td>
<td>Global</td>
<td>SSTskin, SSTsub</td>
<td>Merchant et al. (2012)</td>
<td>Yes</td>
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<tr>
<td>7.</td>
<td>ESA Ocean Colour CCI (v0.95)</td>
<td>4 × 4 km (daily, monthly)</td>
<td>1997-2012</td>
<td>Global</td>
<td>Rrs, chl</td>
<td>Brewin et al., (2012)</td>
<td></td>
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<tr>
<td>8.</td>
<td>RA2 (GlobWave GDR)</td>
<td>400 m along track, 80 km across track at equator over 35</td>
<td>2002-2012</td>
<td>Global</td>
<td>U10</td>
<td><a href="http://www.gobwave.info">www.gobwave.info</a></td>
<td>Yes</td>
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</table>
Publically available *In situ* data

<table>
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<tr>
<th>No.</th>
<th>Dataset name</th>
<th>Temporal period</th>
<th>Geographic location</th>
<th>Parameters</th>
<th>N</th>
<th>References</th>
<th>Access secured</th>
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</thead>
<tbody>
<tr>
<td>1.</td>
<td>SOCAT v2.0</td>
<td>2005-2011</td>
<td>Global (incl. CS regions *)</td>
<td>(fCO_{2w}), SSS, SST</td>
<td>6,000,000+</td>
<td>Bakker et al. (2013)</td>
<td>Yes</td>
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<td>2.</td>
<td>LDEO v2012</td>
<td>1980-present</td>
<td>Global (incl. CS regions *)</td>
<td>(pCO_{2w}), SSS, SST</td>
<td>6,000,000+</td>
<td>Takahashi et al. (2013)</td>
<td>Yes</td>
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<td>3.</td>
<td>GLODAP</td>
<td>1970-2000</td>
<td>Global</td>
<td>(A_T), DIC, SSS, SST, Nitrate</td>
<td>10,000+</td>
<td>Key et al. (2004)</td>
<td>Yes</td>
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<td>4.</td>
<td>CARINA AMS v1.2, CARINA ATL v1.0, CARINA SO v1.1</td>
<td>1980-2006</td>
<td>Arctic, Atlantic, Southern Ocean</td>
<td>(A_T), DIC, SSS, SST</td>
<td>1500+</td>
<td>CARINA group (2009a)</td>
<td>Yes</td>
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<td></td>
<td></td>
<td>CARINA group (2009b)</td>
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<td>CARINA group (2010)</td>
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<td>AMT</td>
<td>1995-present</td>
<td>Atlantic</td>
<td>(pCO_{2w}), SSS, SST, Chl, pH</td>
<td>1000+</td>
<td>Robinson et al., 2009</td>
<td>Yes</td>
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<td>6.</td>
<td>NIVA Ferrybox</td>
<td>2008-present</td>
<td>Arctic</td>
<td>(pCO_{2w}, A_T), DIC, SSS, SST</td>
<td>1000+</td>
<td>Yakushev and Sørensen (2013)</td>
<td>Yes</td>
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<td>7.</td>
<td>OWS Mike</td>
<td>1948-2009</td>
<td>Arctic</td>
<td>(A_T), DIC, SSS, SST, Chl</td>
<td>1000+</td>
<td>Skjelvan et al. (2008)</td>
<td>Yes</td>
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<td>8.</td>
<td>RAMA Moored buoy array</td>
<td>2007-present</td>
<td>Bay of Bengal</td>
<td>SSS, SST</td>
<td>1000+</td>
<td>McPhaden et al. (2009)</td>
<td>Yes</td>
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<td>9.</td>
<td>ARGO floats</td>
<td>2003-present</td>
<td>Global</td>
<td>SSS, SST</td>
<td>1,000,000+</td>
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<td>Yes</td>
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</table>
### New *in situ* data from collaborators

<table>
<thead>
<tr>
<th>No.</th>
<th>Collection method</th>
<th>Temporal period</th>
<th>Geographic location</th>
<th>Parameters</th>
<th>N</th>
<th>Contact/owner</th>
<th>Access promised</th>
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<tbody>
<tr>
<td>1.</td>
<td>Research cruise</td>
<td>Nov-Dec 2013</td>
<td>Bay of Bengal</td>
<td>SSS, SST, $A_T$, $pCO_{2w}$, DIC, pH</td>
<td>30+</td>
<td>Dr Joe Salisbury (see letter of support)</td>
<td>Yes</td>
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<tr>
<td>2.</td>
<td>RAMA Moored buoy array</td>
<td>2007-present</td>
<td>Bay of Bengal</td>
<td>SSS, SST</td>
<td>100+</td>
<td>Dr Joe Salisbury (see letter of support)</td>
<td>Yes</td>
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<td>2.</td>
<td>Research cruises</td>
<td>Dec 2013-onwards</td>
<td>Bay of Bengal</td>
<td>$A_T$, DIC, SSS, SST, $pCO_{2w}$</td>
<td>100+</td>
<td>Dr Punyasloke Bhadury (See letter of support)</td>
<td>Yes</td>
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<td>3.</td>
<td>Research expedition</td>
<td>Aug 2013, 2014</td>
<td>Arctic</td>
<td>$A_T$, DIC, SSS, SST</td>
<td>50+</td>
<td>Dr Helen Findlay</td>
<td>Yes</td>
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<td>4.</td>
<td>Research expedition</td>
<td>Mar-Sep 2014</td>
<td>Arctic</td>
<td>$A_T$, DIC, SSS, SST</td>
<td>50+</td>
<td>Dr Helen Findlay</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Overview of methods

1. Convert all data (in situ, climatology, model, satellite) binned to daily and monthly 1° x 1°.

1. Identify locations and times where we have in situ carbonate parameters to compare with estimates generated from empirical algorithms.

2. Generate performance statistics for C_T, T_A, pH and pCO_2:
   a. Calculate all statistics for all possible comparisons for each model (optimal characterisation of each model e.g. accuracy assessment).

   b. Calculate all statistics for only common data points for each model to produce an aggregated model performance (rank model performance based on choice of input data).
Overview of methods

1. Convert all data (in situ, climatology, model, satellite) binned to daily and monthly 1° x 1°.

Very few pH data coincident or usable.

Performance of pCO₂ models was very poor.

So here we are presenting Cₜ and Tₐ results (optimal characterisation of each model e.g. accuracy assessment).

b. Calculate all statistics for only common data points for each model (rank model performance based on choice of input data).
Algorithms tested

5 region (Global, Amazon plume, Caribbean, Bay of Bengal, Arctic Barents)

Possible inputs to choose from:

5 sets of SST data  
7 sets of salinity data  
3 sets of nitrate data

Total alkalinity ($T_A$) – the ability for water to neutralise an acid:


Total carbon ($C_T$) – also called Dissolved Inorganic Carbon

- 4 algorithms (HadGEM2-ES,Lefevre2010,Bonou2016,Lee2000)

Results in >?? possible combinations and permutations.
$T_A$ - model accuracy
$T_A$ - best salinity ranking

The diagram compares the aggregated relative RMSE for various regions and models. The x-axis represents different regions: GLOBAL, G CARIB, AMAZON, AMAZON S<35, BARENTS, and BENGAL. The y-axis shows the aggregated relative RMSE. The colors represent different models: HADGEM2-ES CLIM, CORA CLIM, AQUARIUS CLIM, SMOS CLIM, LDEO CLIM, HADGEM2-ES, and CORA.
$C_T$ – model accuracy

RMSE (μmol kg$^{-1}$)
$C_T$ - best salinity ranking

![Graph showing aggregated relative RMSE for different regions and datasets.]
Conclusions

1. Possible to explore the salinity-alkalinity relationship using satellite data.

2. Globally, all models and inputs give the similar accuracy (mean $T_A$ RMSE ~ 59 μmol kg$^{-1}$, mean $C_T$ RMSE ~ 35-50 μmol kg$^{-1}$).

3. Caribbean, all models (except HadGEM2-ES) and inputs give the same accuracy (mean $T_A$ RMSE ~ 20 μmol kg$^{-1}$, mean $C_T$ RMSE ~ 20 μmol kg$^{-1}$).

4. For both $T_A$ and $C_T$ - Remote sensing salinity driven model performance is near identical to that of in situ salinity in the Caribbean (and to a lesser extent in the Bay of Bengal).

5. For both $T_A$ and $C_T$ – Remote sensing salinity (SMOS) out performs all others for low salinity amazon plume region. (mean $T_A$ RMSE ~ 90 μmol kg$^{-1}$, mean $C_T$ RMSE ~ 75 μmol kg$^{-1}$).

6. Now preparing data for public release:
   a. $C_T$, $T_A$ and corresponding Seacarb derived pH and pCO$_2$ spatial data for each region in 2010.
   b. A preliminary remotely-sensed upwelling indicator dataset (global coverage, 2010-present day, daily and monthly temporal resolution, Ekman pumping and Ekman transport components).
Sensitivity of SMOS in Polar waters

- Sensitivity of SMOS brightness temperature to salinity in the Arctic is around 50% of the sensitivity in the tropics.
- Current smallest errors in the tropics are 0.2-0.3 PSU, so errors in Arctic waters are of the order 0.5 PSU.