

# The Surface Ocean CO<sub>2</sub> Atlas (SOCAT) enables detection of changes in the ocean carbon sink

**D. C. E. Bakker**, B. Pfeil, K. Smith, S. Hankin, A. Olsen, S. R. Alin, C. Cosca, S. Harasawa, A. Kozyr, Y. Nojiri, K. M. O'Brien, U. Schuster, M. Telszewski, B. Tilbrook, C. Wada, J. Akl, L. Barbero, N. R. Bates, J. Boutin, Y. Bozec, W.-J. Cai, R. D. Castle, F. P. Chavez, L. Chen, M. Chierici, K. Currie, H. J. W. de Baar, W. Evans, R. A. Feely, A. Fransson, Z. Gao, B. Hales, N. J. Hardman-Mountford, M. Hoppema, W.-J. Huang, C. W. Hunt, B. Huss, T. Ichikawa, T. Johannessen, E. M. Jones, S. D. Jones, S. Jutterström, V. Kitidis, A. Körtzinger, P. Landschützer, S. K. Lauvset, N. Lefèvre, A. B. Manke, J. T. Mathis, L. Merlivat, N. Metzl, A. Murata, T. Newberger, A. M. Omar, T. Ono, G.-H. Park, K. Paterson, D. Pierrot, A. F. Ríos, C.L. Sabine, S. Saito, J. Salisbury, V. V. S. S. Sarma, R. Schlitzer, R. Sieger, I. Skjelvan, T. Steinhoff, K. F. Sullivan, H. Sun, A. J. Sutton, T. Suzuki, C. Sweeney, T. Takahashi, J. Tjiputra, N. Tsurushima, S. M. A. C. van Heuven, D. Vandemark, P. Vlahos, D. W. R. Wallace, R. Wanninkhof and A. J. Watson

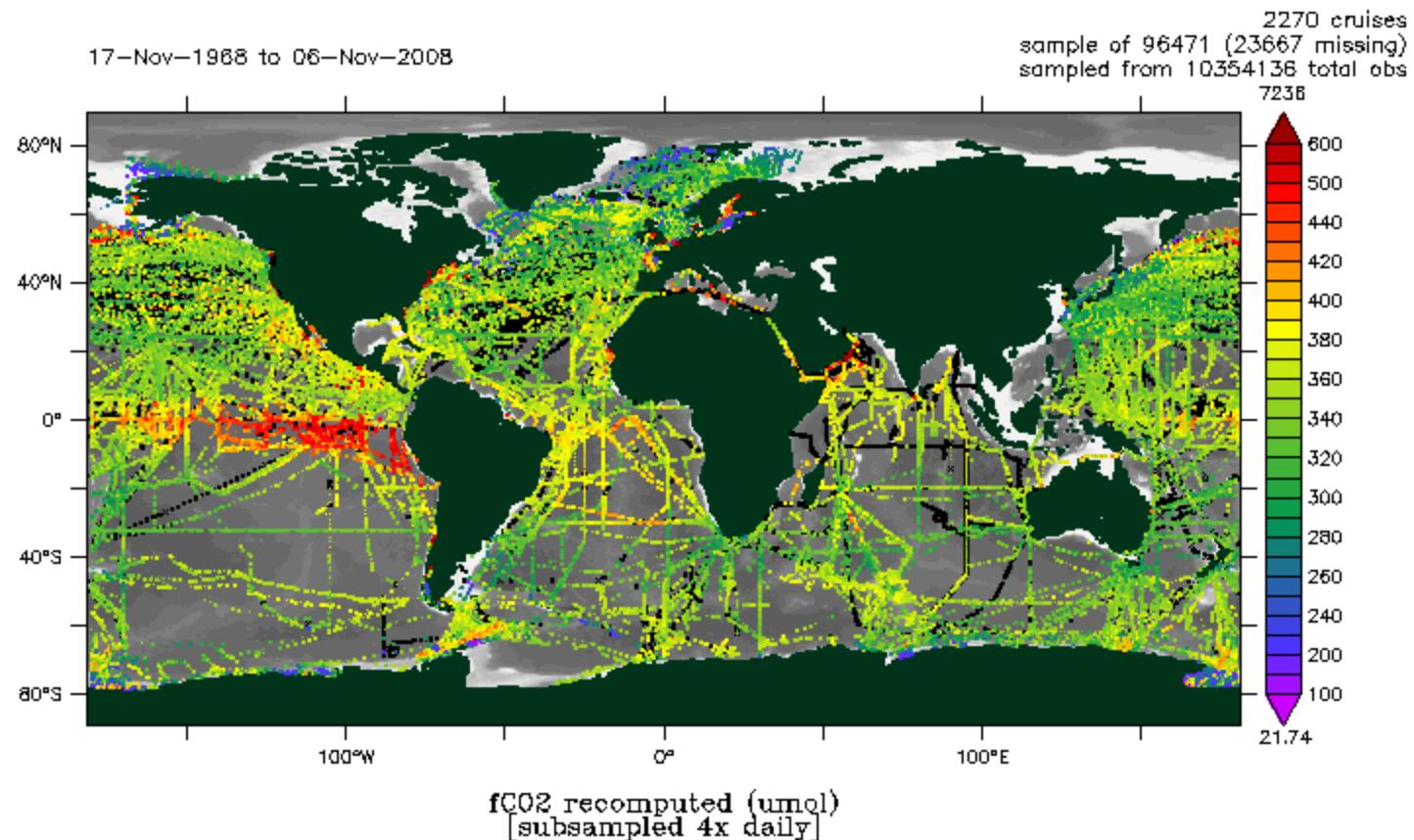
Version 2: 81 contributors from 51 organisations in 17 countries on 5 continents

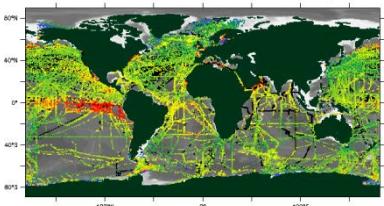


# In 2011:

CarboChange kick-off meeting, Neptun Hotel, Bergen,  
Norway, 9 March 2011

# Surface Ocean CO<sub>2</sub> Atlas (SOCAT)



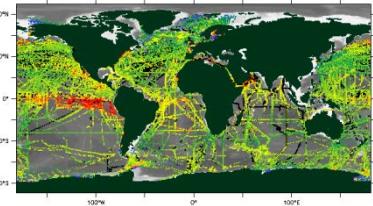


# SOCAT scientists 2007-2011



Meetings in Paris, Delmenhorst, Bremen, Kiel, Tsukuba, Norwich, Hobart, .... & by Skype.

Support by IOCCP, SOLAS, IMBER, SCOR, CSIRO, SFB754, IFM-Geomar, NIES, EU COST 735, CarboOcean, CarboChange, ....



# SOCAT articles

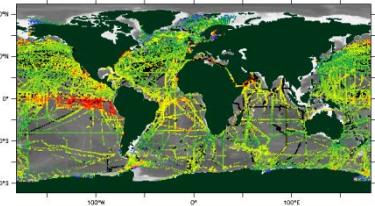
**SOCAT highlight – Science News or EOS, .. (Bakker et al.)**

**ESSD technical article(s) - The more the better!**

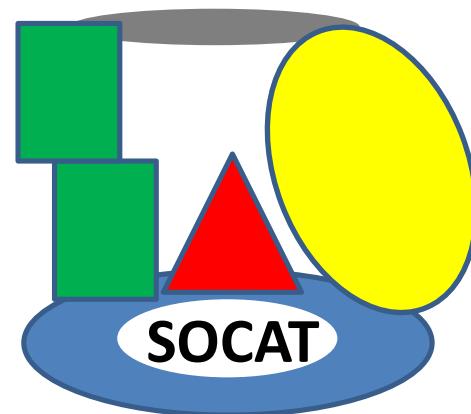
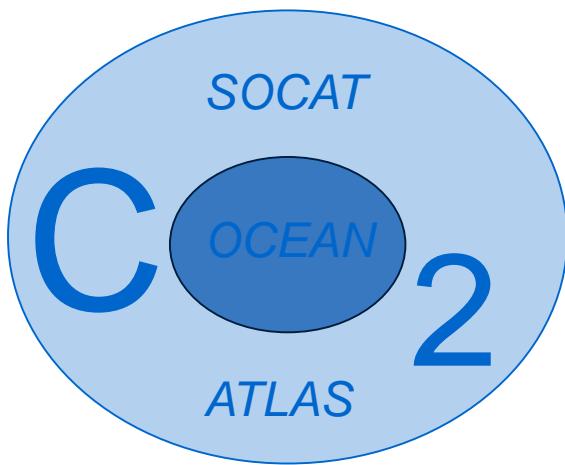
- Technical global paper on the uniform data and QC (Olsen, Pfeil, Bakker et al.), draft available at public release, main reference for SOCAT data set;
- Technical paper on LAS (Hankin, Koyuk, Malczyk?);
- Technical paper on the gridding (Chris?);
- Regional technical papers ?

**Scientific articles – THINK articles!**

- At least 1 high flying paper;
- Special Issue?
- Some papers in time for IPCC AR5.



# SOCAT logo.....



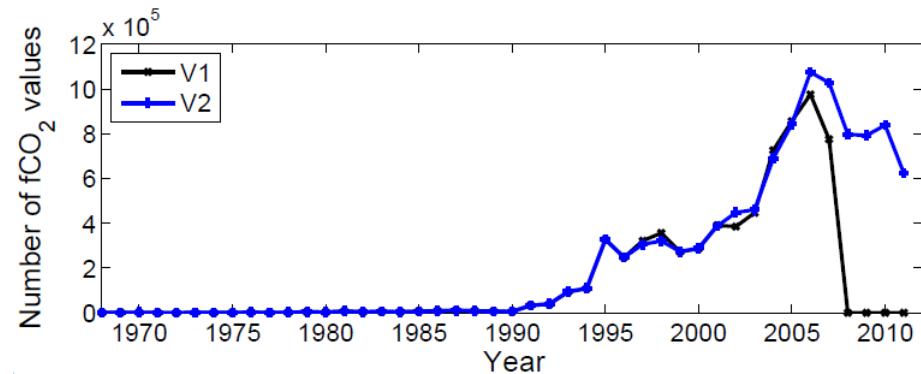
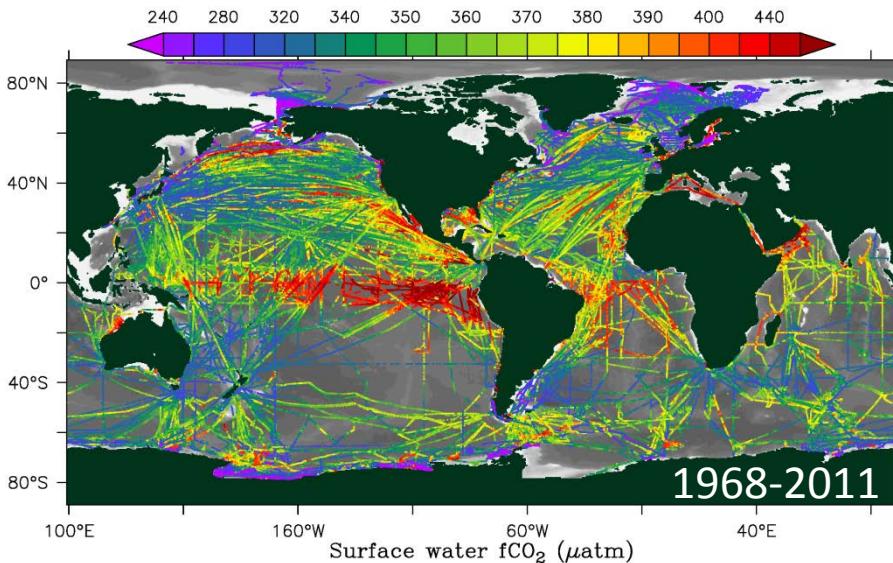
- Comments and suggestions for a logo are much appreciated.

# In 2015:

CarboChange final meeting, Radisson Blue Norge  
Hotel, Bergen, Norway, 19-22 February 2015

# Surface Ocean CO<sub>2</sub> Atlas

[www.socat.info](http://www.socat.info)



SOCAT: Surface ocean fCO<sub>2</sub> (fugacity of CO<sub>2</sub>) in uniform format with quality control;  
2011: Version 1: 1968-2007, 6.3 million fCO<sub>2</sub>, 1851 cruises;  
2013: Version 2: 1968-2011, 10.1 million fCO<sub>2</sub>, 2660 data sets;

Individual data set files / Global synthesis product / Global gridded products;  
Public access to regular releases via <http://www.socat.info/>;  
Interactive online viewers (LAS); Downloadable (text, NetCDF, ODV, Matlab);  
Documented in 3 ESSD articles (68 citations in peer-reviewed publications);

Earth Syst. Sci. Data, 5, 125–143, 2013  
[www.earth-syst-sci-data.net/5/125/2013/](http://www.earth-syst-sci-data.net/5/125/2013/)  
doi:10.5194/essd-5-125-2013  
© Author(s) 2013. CC Attribution 3.0 License.



## 40 citations

### A uniform, quality controlled Surface Ocean CO<sub>2</sub> Atlas (SOCAT)

- B. Pfeil<sup>1,2,3</sup>, A. Olsen<sup>1,2,4,5</sup>, D. C. E. Bakker<sup>3</sup>, S. Hankin<sup>7</sup>, H. Koyuk<sup>9</sup>, A. Kozyr<sup>10</sup>, J. Malczyk<sup>10</sup>, A. Manke<sup>7</sup>, N. Metz<sup>11</sup>, C. L. Sabine<sup>1</sup>, J. Akl<sup>12,13</sup>, S. R. Alin<sup>1</sup>, N. Bates<sup>14</sup>, R. G. J. Bellerby<sup>15,16,2</sup>, A. Borges<sup>15</sup>, J. Boutin<sup>15</sup>, P. J. Brown<sup>6,18</sup>, W. J. Cai<sup>19</sup>, F. P. Chavez<sup>20</sup>, A. Chen<sup>21</sup>, C. Cosca<sup>7</sup>, A. J. Fassbender<sup>22</sup>, R. A. Feely<sup>9</sup>, M. Gonzalez-Davila<sup>23</sup>, C. Goyet<sup>24</sup>, B. Haley<sup>25</sup>, N. Hardman-Mountford<sup>26,27</sup>, C. Heinze<sup>1,2,5,16</sup>, M. Hood<sup>27</sup>, M. Hoppema<sup>28</sup>, C. W. Hunt<sup>2</sup>, D. Hydes<sup>30</sup>, M. Ishii<sup>31</sup>, T. Johannessen<sup>1,2</sup>, S. D. Jones<sup>32</sup>, M. Key<sup>33</sup>, A. Körtzinger<sup>24</sup>, P. Landschützer<sup>2</sup>, S. K. Lauvset<sup>1,2</sup>, N. LeFeuvre<sup>21</sup>, A. Lenten<sup>12</sup>, A. Lourantou<sup>11</sup>, L. Merlinval<sup>11</sup>, T. Midorikawa<sup>33</sup>, L. Mintrop<sup>36</sup>, C. Miyazaki<sup>37</sup>, A. Murata<sup>38</sup>, A. Nakadate<sup>39</sup>, Y. Nakano<sup>38</sup>, S. Nakao<sup>38</sup>, Y. Nojiri<sup>40</sup>, A. M. Omar<sup>5,31</sup>, X. A. Padin<sup>34</sup>, G.-H. Park<sup>42</sup>, K. Paterson<sup>12,13</sup>, F. E. Perez<sup>41</sup>, D. Pierrot<sup>42</sup>, A. Polson<sup>43</sup>, A. F. Rios<sup>31</sup>, J. M. Santana-Casiano<sup>23</sup>, J. Salisbury<sup>29</sup>, V. V. S. S. Sarma<sup>43</sup>, R. Schlitzer<sup>28</sup>, B. Schneider<sup>44</sup>, U. Schuster<sup>1</sup>, R. Sieger<sup>28</sup>, I. Skjelvan<sup>1,2,16</sup>, I. Steinhoff<sup>34</sup>, T. Suzuki<sup>45</sup>, T. Takahashi<sup>46</sup>, K. Tedesco<sup>47,48</sup>, M. Telczewski<sup>48,\*\*</sup>, H. Thomas<sup>40</sup>, B. Tilbrook<sup>12,13,30</sup>, J. Tijputra<sup>42</sup>, D. Vandemark<sup>25</sup>, T. Venes<sup>12,13</sup>, R. Wanninkhof<sup>1</sup>, A. J. Watson<sup>1</sup>, R. Weiss<sup>32</sup>, C. S. Wong<sup>33</sup>, and H. Yoshikawa-Inoue<sup>33</sup>

## 13 citations

### Surface Ocean CO<sub>2</sub> Atlas (SOCAT) gridded data products

- C. L. Sabine<sup>1</sup>, S. Hankin<sup>1</sup>, H. Koyuk<sup>1,2</sup>, D. C. E. Bakker<sup>3</sup>, B. Pfeil<sup>4,5,6</sup>, A. Olsen<sup>7,8</sup>, N. Metz<sup>9</sup>, A. Kozyr<sup>10</sup>, A. Fassbender<sup>1,20</sup>, A. Manke<sup>1,2</sup>, J. Malczyk<sup>11</sup>, J. Akl<sup>12,13</sup>, S. R. Alin<sup>1</sup>, R. G. J. Bellerby<sup>14,4,7</sup>, A. Borges<sup>15</sup>, J. Boutin<sup>9</sup>, P. J. Brown<sup>6,16</sup>, W. J. Cai<sup>17</sup>, F. P. Chavez<sup>18</sup>, A. Chen<sup>19</sup>, C. Cosca<sup>7</sup>, R. A. Feely<sup>9</sup>, M. Gonzalez-Davila<sup>21</sup>, C. Goyet<sup>22</sup>, N. Hardman-Mountford<sup>23,24</sup>, C. Heinze<sup>1,2,5,14</sup>, M. Hoppema<sup>24</sup>, C. W. Hunt<sup>2</sup>, D. Hydes<sup>26</sup>, M. Ishii<sup>31</sup>, T. Johannessen<sup>1,5</sup>, R. M. Key<sup>33</sup>, A. Körtzinger<sup>24</sup>, P. Landschützer<sup>2</sup>, S. K. Lauvset<sup>1,2</sup>, N. LeFeuvre<sup>21</sup>, A. Lenten<sup>12</sup>, A. Lourantou<sup>11</sup>, L. Merlinval<sup>11</sup>, T. Midorikawa<sup>33</sup>, L. Mintrop<sup>36</sup>, C. Miyazaki<sup>37</sup>, A. Murata<sup>38</sup>, A. Nakadate<sup>39</sup>, Y. Nakano<sup>38</sup>, S. Nakao<sup>38</sup>, Y. Nojiri<sup>40</sup>, A. M. Omar<sup>5,31</sup>, X. A. Padin<sup>34</sup>, G.-H. Park<sup>42</sup>, J. Salisbury<sup>29</sup>, V. V. S. S. Sarma<sup>43</sup>, R. Schlitzer<sup>28</sup>, B. Schneider<sup>44</sup>, U. Schuster<sup>1</sup>, R. Sieger<sup>28</sup>, I. Skjelvan<sup>1,2,16</sup>, I. Steinhoff<sup>34</sup>, T. Suzuki<sup>45</sup>, T. Takahashi<sup>46</sup>, K. Tedesco<sup>47,48</sup>, M. Telczewski<sup>48,\*\*</sup>, H. Thomas<sup>40</sup>, B. Tilbrook<sup>12,13,30</sup>, J. Tijputra<sup>42</sup>, D. Vandemark<sup>25</sup>, T. Venes<sup>12,13</sup>, A. J. Watson<sup>1</sup>, R. Weiss<sup>32</sup>, C. S. Wong<sup>33</sup>, and H. Yoshikawa-Inoue<sup>33</sup>

## 15 citations

### An update to the Surface Ocean CO<sub>2</sub> Atlas (SOCAT version 2)

- D. C. E. Bakker<sup>1</sup>, B. Pfeil<sup>2,3</sup>, K. Smith<sup>4,5</sup>, S. Hankin<sup>4</sup>, A. Olsen<sup>2,3,6</sup>, S. R. Alin<sup>1</sup>, C. Cosca<sup>7</sup>, S. Harasawa<sup>7</sup>, A. Kozyr<sup>9</sup>, Y. Nojiri<sup>1</sup>, K. M. O'Brien<sup>4,5</sup>, U. Schuster<sup>9,7</sup>, M. Telczewski<sup>10</sup>, B. Tilbrook<sup>11,12</sup>, C. Wada<sup>7</sup>, J. Akl<sup>11</sup>, L. Barbero<sup>13</sup>, N. R. Bates<sup>14</sup>, J. Boutin<sup>15</sup>, Y. Boze<sup>16,17</sup>, W.-J. Cai<sup>18</sup>, R. D. Castle<sup>19</sup>, F. P. Chavez<sup>20</sup>, L. Chen<sup>1,2,2</sup>, M. Chierici<sup>2,28</sup>, K. Currie<sup>28</sup>, H. J. W. Baar<sup>20</sup>, W. Evans<sup>4,27</sup>, R. A. Feely<sup>9</sup>, A. Fransson<sup>28</sup>, Z. Gao<sup>21</sup>, B. Hales<sup>29</sup>, N. Hardman-Mountford<sup>20</sup>, M. Hoppema<sup>21</sup>, W.-J. Huang<sup>18</sup>, C. W. Hunt<sup>32</sup>, B. Huss<sup>10</sup>, T. Ichikawa<sup>13</sup>, T. Johannessen<sup>3,6</sup>, E. M. Jones<sup>31</sup>, S. D. Jones<sup>34</sup>, S. Jutterström<sup>35</sup>, V. Kitidis<sup>36</sup>, A. Körtzinger<sup>27</sup>, P. Landschützer<sup>1</sup>, S. K. Lauvset<sup>2,3</sup>, N. LeFeuvre<sup>38,39</sup>, A. B. Manke<sup>1</sup>, J. T. Mathis<sup>4</sup>, L. Merlinval<sup>11</sup>, N. Metz<sup>11</sup>, A. Murata<sup>40</sup>, T. Newberger<sup>41</sup>, A. M. Omar<sup>6,32</sup>, T. Ono<sup>33</sup>, G.-H. Park<sup>42</sup>, K. Paterson<sup>11</sup>, D. Pierrot<sup>11</sup>, A. F. Rios<sup>32</sup>, C. L. Sabine<sup>1</sup>, J. Salisbury<sup>29</sup>, V. V. S. S. Sarma<sup>43</sup>, R. Schlitzer<sup>28</sup>, R. Sieger<sup>28</sup>, I. Skjelvan<sup>6,32</sup>, T. Steinhoff<sup>27</sup>, K. E. Sullivan<sup>13</sup>, H. Sun<sup>1</sup>, A. J. Sutton<sup>4,3</sup>, T. Suzuki<sup>46</sup>, C. Sweeney<sup>42</sup>, T. Takahashi<sup>41</sup>, J. Tijputra<sup>6,3</sup>, N. Tsurushima<sup>48</sup>, S. M. A. C. van Heuven<sup>49</sup>, D. Vandemark<sup>22</sup>, P. Vlahos<sup>50</sup>, D. W. R. Wallace<sup>51</sup>, R. Wanninkhof<sup>19</sup>, and A. J. Watson<sup>9</sup>\*

# Documentation and data policy

### Global Data Products Help Assess Changes to Ocean Carbon Sink

PAGES 125–126

Net oceanic uptake of the greenhouse gas carbon dioxide (CO<sub>2</sub>) reduces global warming but also leads to ocean acidification.

Managers have generously donated their time and expertise to SOCAT. These participants were organized into seven regional groups and a global coordination

oceans and coastal seas. The data originate from 1851 voyages by research vessels, commercial ships, and measured water drogues. From these SOCAT products have been created: (1) a global data set of surface ocean CO<sub>2</sub> from 1968 to 2007 (Figure 1) recalculated using a uniform procedure and subject to QC checks; and (2) a global monthly mean surface water CO<sub>2</sub> data product.

## SOCAT data policy:

Recognise the contribution of SOCAT data contributors and quality controllers by invitation to co-authorship or citation of articles. Regional studies: Invite data contributors as co-authors.

## Cite the relevant SOCAT ESSD publication:

V1: Pfeil et al. (2013) ESSD 5: 125–143;

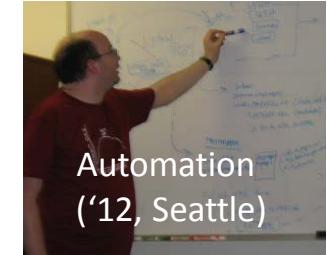
V1: Sabine et al. (2013) ESSD 5: 145–153;

V2: Bakker et al. (2014) ESSD 6: 69–90.



# SOCAT scientists 2011-2015

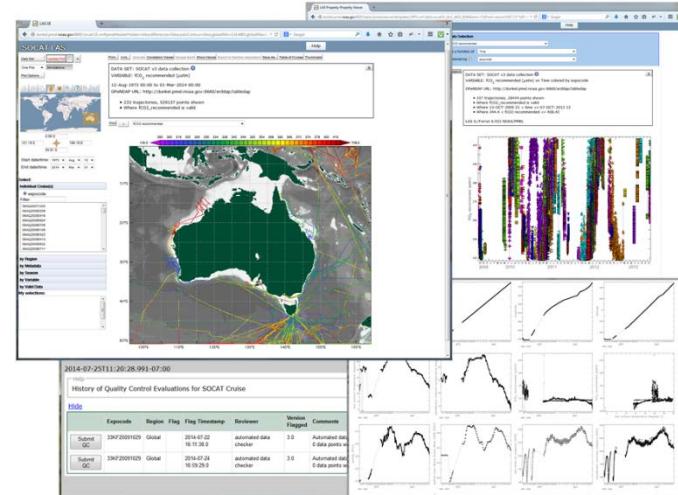
[www.socat.info](http://www.socat.info)



**Movie of v3 QC Webinar:** <http://youtu.be/DJXZxoThkdU>

An activity by the marine carbon community;  
Meetings in Paris, Seattle (3x), Tsukuba, Beijing, Bergen, by Skype.  
Reports at <http://www.socat.info/>;  
Meeting support by IOCCP, IMBER, SOLAS, SCOR, Carbochange, NOAA, NIES, ....

# Version 3 quality control in progress



- **Version 3 needs QC-ers!** (Contact [d.bakker@uea.ac.uk](mailto:d.bakker@uea.ac.uk))
- **Quality control by ~~10 January~~ 15 March 2015;**
- 1200 of 1850 new/updated data sets (1957-2013) need QC;
- Update of QC flags for sensor data with documented in situ calibration;
- Update of quality control system and QC cookbook;
- Movie of QC webinar: <http://youtu.be/DJXZxoThkdU>;
- Early release (Summer 2015);
- Public release (7 September 2015, SOLAS OSC)

# Revision of QC flags (version 3)

- Inclusion of sensor data;
- Encourage in situ calibration of sensors;
- Update metadata forms for sensors (calibration) (v4);
- Identification of platform type (v4);

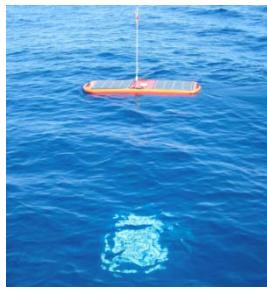
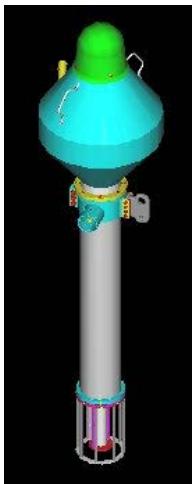
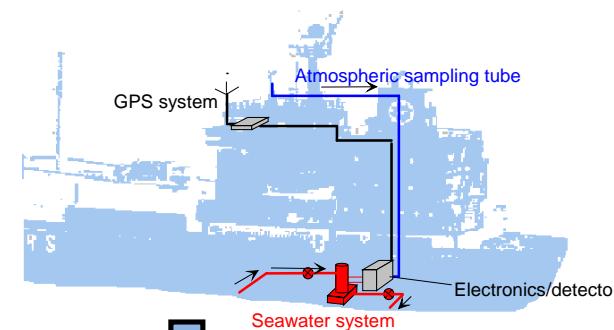


Table 3. Proposed criteria for dataset quality control flags of the SOCAT database version 3.0

Flag	Criteria <sup>a</sup>
A (11)	(1) Accuracy of calculated fCO <sub>2w</sub> (at SST) is better than 2 µatm (2) A high-quality cross-over with another dataset is available (3) Followed approved methods/SOP <sup>b</sup> criteria (4) Metadata documentation complete (5) Dataset QC was deemed acceptable
B (12)	(1) Accuracy of calculated fCO <sub>2w</sub> (at SST) is better than 2 µatm (2) Followed approved methods/SOP criteria (3) Metadata documentation complete (4) Dataset QC was deemed acceptable
C (13)	(1) Accuracy of calculated fCO <sub>2w</sub> (at SST) is better than 5 µatm <del>(2) Followed approved methods/SOP criteria</del> (3) Metadata documentation complete (4) Dataset QC was deemed acceptable
D (14)	(1) Accuracy of calculated fCO <sub>2w</sub> (at SST) is better than 5 µatm (2) Did or did not follow approved methods/SOP criteria (3) Metadata documentation incomplete (4) Dataset QC was deemed acceptable
E (17) <b>NEW</b>	(Primarily for alternative sensors) (1) Accuracy of calculated fCO <sub>2w</sub> (at SST) is better than 10 µatm (2) Did not follow approved methods/SOP criteria (3) Metadata documentation complete (4) Dataset QC was deemed acceptable
NA...NF (version 4)	Submitted data to SOCAT that has not undergone independent dataset quality control as indicated by the "N". The NA though NF are the flags provided by the submitting group

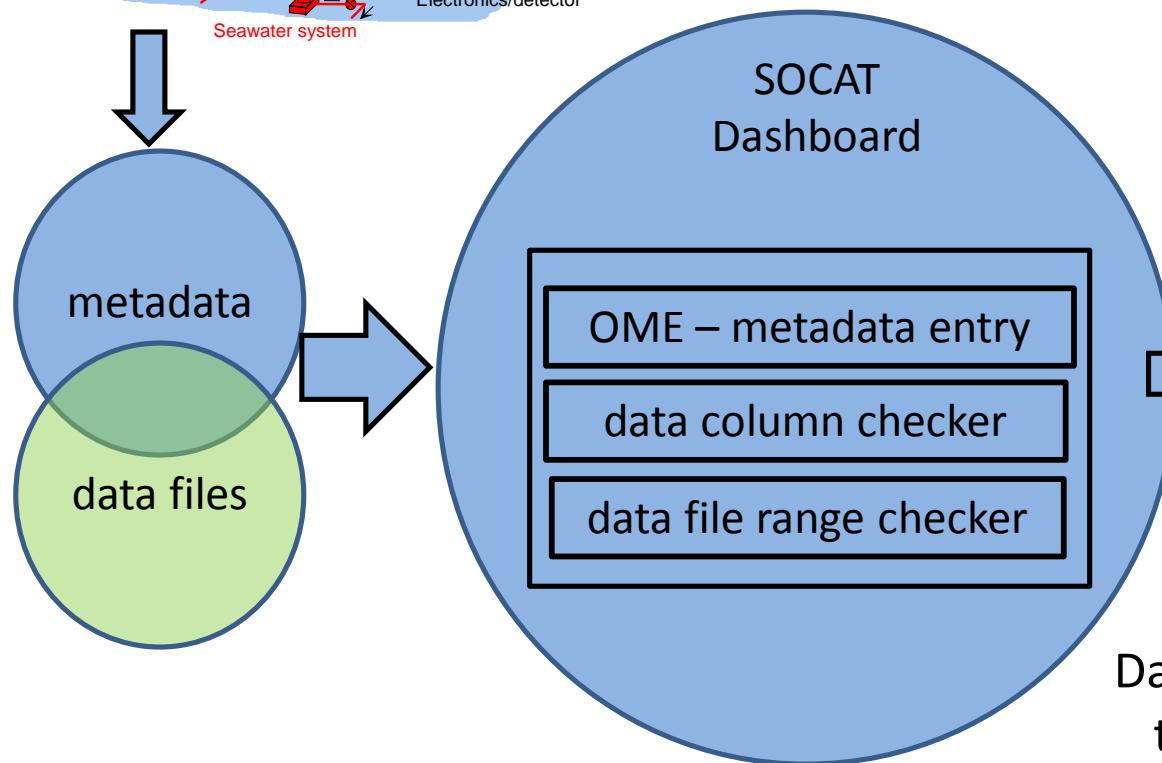
# Automated data upload, version 4

Collect data set

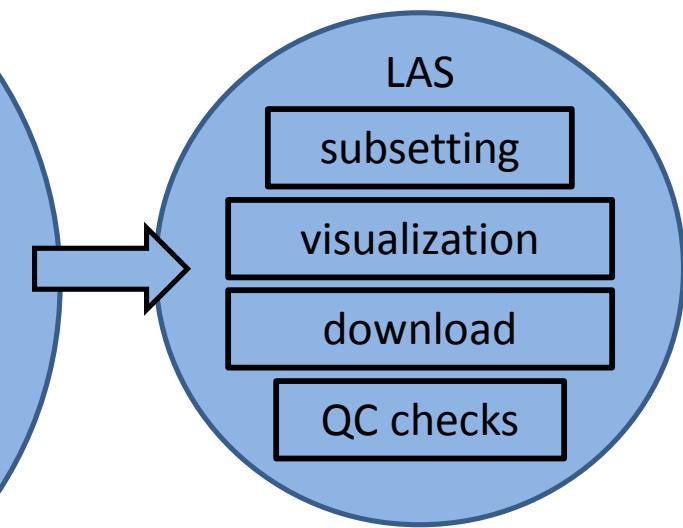


Automation meeting (Seattle, 21-23 Oct. '14)  
Data upload system live (16 March 2015)

Upload data set



Preview data set



Data submission  
to SOCAT QC

# Towards annual SOCAT releases

- V3 schedule
  - QC ends: **15 March 2015**
  - Release: **7 September 2015** (SOLAS OSC, Kiel)
- V4 schedule
  - Data upload and QC begin: **16 March 2015**
  - Data upload ends: 31 Jan 2016
  - QC ends: 31 March 2016
  - Release: 30 June 2016
- V5 schedule
  - Data upload and QC ongoing
  - Data upload ends: 31 Jan 2017
  - QC ends: 31 March 2017
  - Release: 30 June 2017

Starting with version 4, data upload and QC can be done simultaneously.

# Additional parameters and other news

**Salinity and sea surface temperature** in SOCAT are not quality controlled.

SOCAT encourages data providers to submit high-quality salinity and temperature.

SOCAT will accept **additional surface water parameters**, accompanying fCO<sub>2</sub> data (e.g. CH<sub>4</sub>, N<sub>2</sub>O, DIC, TA, pH, nutrients) from version 4 onwards. These additional parameters will **not be quality controlled** and will be reported in separate files.

**SOCAT Community Event on 7 September 2015** at the SOLAS OSC, Kiel.

SOCAT Community Event,  
Bergen, Norway,  
23 June 2014





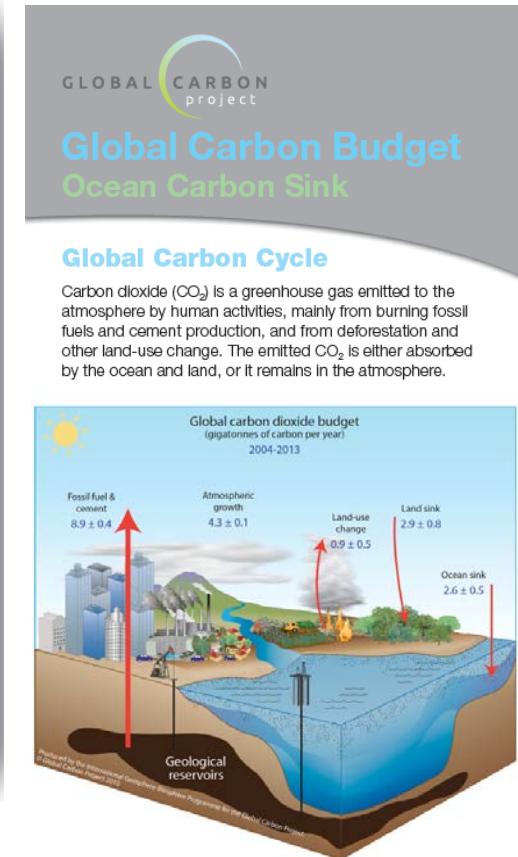
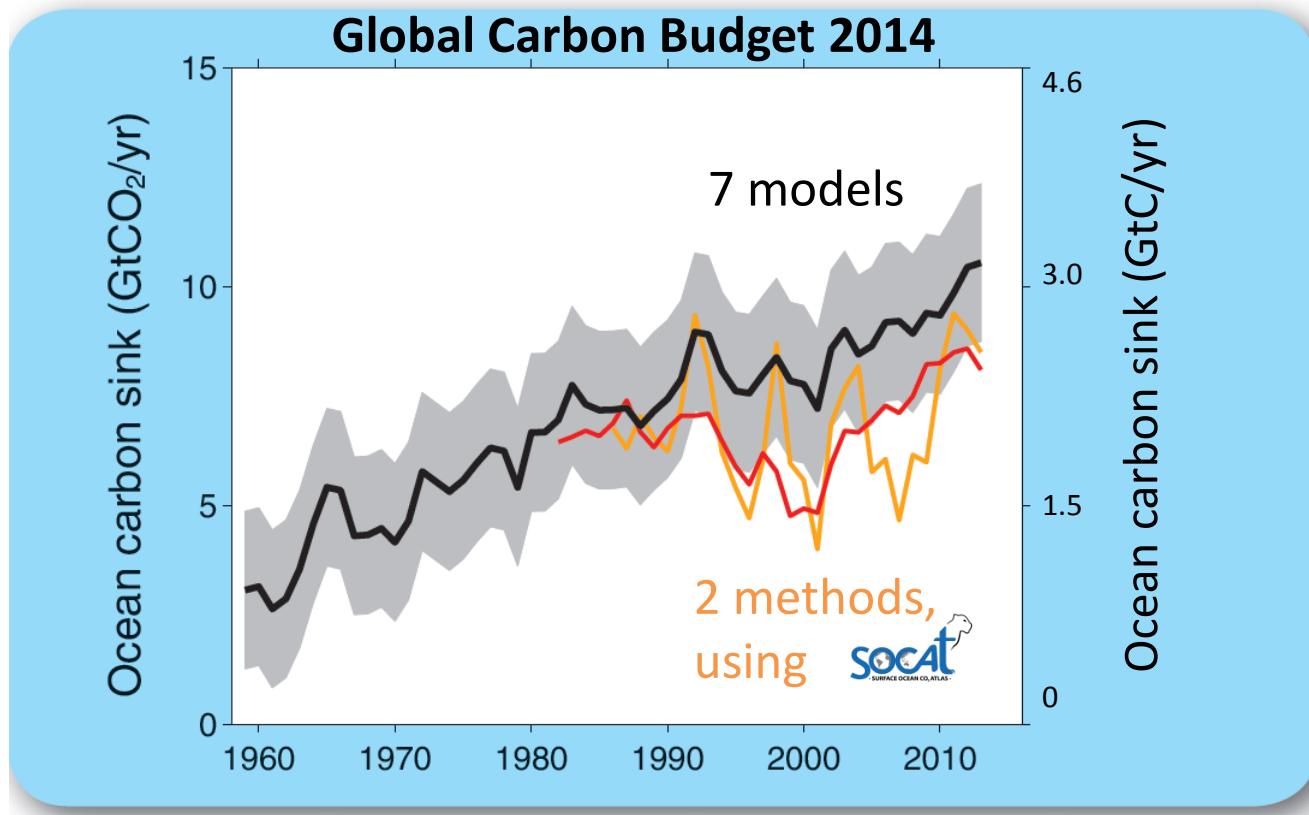
# Impact of SOCAT

Citations by ≥ 68 peer-reviewed, scientific publications  
(2015–1; 2014–29; 2013–21; 2012–5; 2011–3; 2010–8; 2009–1),  
2014 CBD and 2013 IPCC reports, 4 book chapters, ≥ 1 PhD thesis;  
Used by 2013, 2014 Global Carbon Budgets,  
≥ 2 data-products, SOCOM, NASA and ESA projects

Scientific application	Number (of 59)
Reference to SOCAT and/or fCO <sub>2</sub> data	<b>30</b>
Use of SOCAT tools	<b>1</b>
Figure of fCO <sub>2</sub> data distribution	<b>5</b>
fCO <sub>2</sub> in process studies, e.g. ocean acidification and genomics	<b>4</b>
Coastal and ocean CO <sub>2</sub> sink estimates	<b>12</b>
Model validation	<b>6</b>
Regional pH trends	<b>1</b>

# Ocean carbon sink estimates

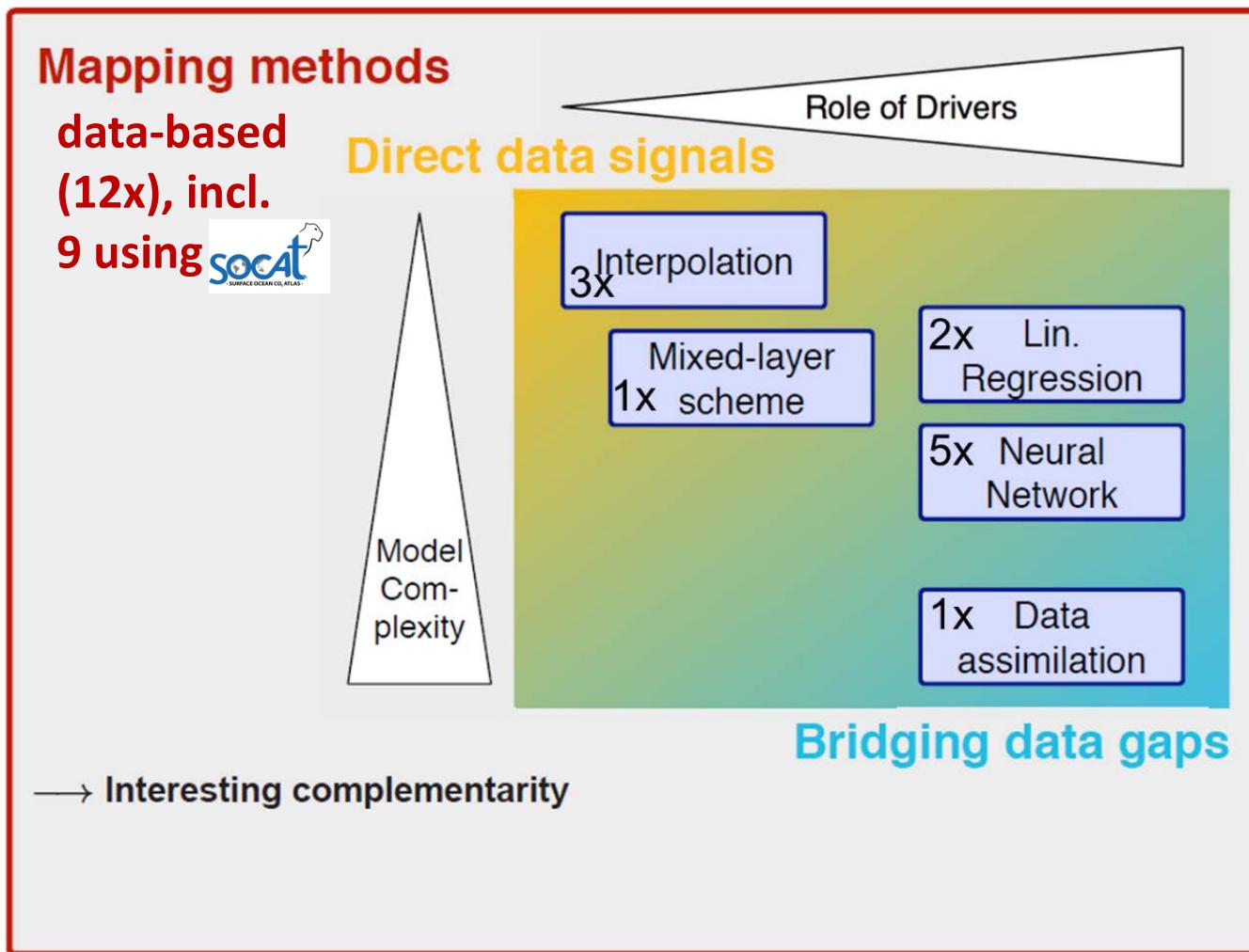
[www.socat.info](http://www.socat.info)



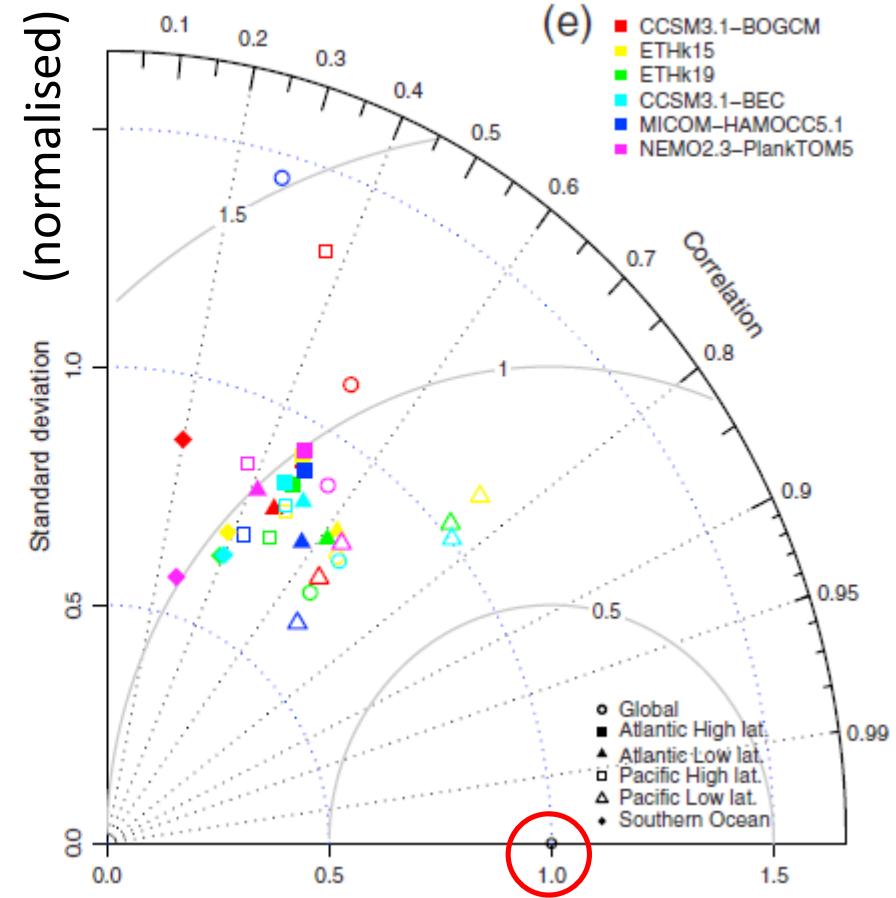
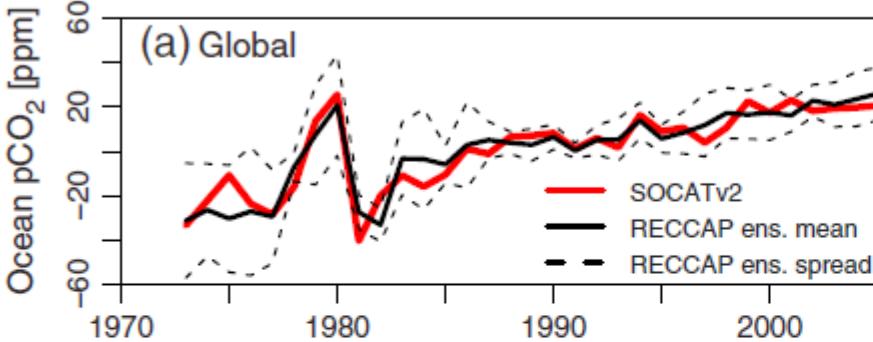
Data-based methods estimate different year-to-year and long term variation in the ocean carbon sink.

(Figures: Le Quéré et al., 2014; Landschützer et al., 2014; Rödenbeck et al., 2014)

# Surface Ocean pCO<sub>2</sub> Mapping Intercomparison (SOCOM) (Christian Rödenbeck)



# Model-data comparison



- Comparison of annual mean anomalies;
- Subsampling of 6 RECCAP models to SOCAT v2 data;
- Global ocean biogeochemical models underestimate spatial and temporal variation in  $f\text{CO}_2$ .

# Conclusions

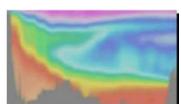
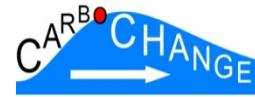
SOCAT is a powerful data synthesis product documenting the ocean carbon cycle.

Applications include:

- Quantification of the ocean CO<sub>2</sub> sink (e.g. Global Carbon Budget, SOCOM);
- Assessments of ocean acidification;
- Validation of ocean biogeochemical models.

SOCAT has >> 100 contributors. Contribute to and/or use SOCAT. Acknowledge the contribution of the data providers, e.g. by invitation to co-authorship, notably in regional studies. [d.bakker@uea.ac.uk](mailto:d.bakker@uea.ac.uk).





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