Sea ice concentrations in the Weddell Sea: A comparison of SSM/I, ULS, and GCM data

W. M. Connolley

British Antarctic Survey, Cambridge, UK

[1]   The sea ice fraction in the interior of the pack, especially in winter, is important for climate studies and for validation of sea ice models. When ice concentration is high, a difference of only a few percent in ice fraction can have a major effect on the ocean-air fluxes. Satellite estimates of the ice fraction in the Antarctic winter based on microwave emissions are typically 90–95%, with values from the "Bootstrap" algorithm higher than the "NASA team". However coupled ocean-atmosphere models usually show higher concentrations. A recent evaluation for the Arctic has shown that the true winter ice fractions can be very high, above 99%. Upward looking sonar data from the Weddell Sea is used to show that Antarctic concentrations are higher than previously estimated, and to reevaluate climate model results in this light. The bootstrap algorithm is found to provide a better fit to the sonar data. **Citation:** Connolley, W. M. (2005), Sea ice concentrations in the Weddell Sea: A comparison of SSM/I, ULS, and GCM data, *Geophys. Res. Lett.*, *32*, L07501, doi:10.1029/2004GL021898.

1.   Introduction

[2]   Sea ice fractions are routinely available from the Scanning Multichannel Microwave Radiometer (SMMR) and its successor the Special Scanning Microwave Imager (SSM/I). Studies based on these data of the interior of the winter pack show open-water fractions up to 10%, with variations according to which algorithm is used. However it is acknowledged that while the derivation of ice edge from SSM/I is fairly reliable, the determination of the fraction within the winter pack is difficult. An early study by *Steffen and Schweiger* [1991], by comparing SSM/I with Landsat imagery, suggests that SSM/I underestimated Arctic winter ice fractions by 4% ± 7%. Unfortunately only one Antarctic winter scene was available, for the Weddell Sea in August. This Landsat image showed homogeneous ice with low open water fraction ("less than 5%") whereas the SSM/I showed only 65–75% ice fraction. Because they were unable to interpret this difference, the scene was not included in the study. *Burns* [1993] compared four algorithms over 6 days in September 1989 in the Weddell Sea and found wide variations. *Comiso and Steffen* [2002] review NASA Team and Bootstrap algorithm performance in the Antarctic by comparison with Landsat and Operational Line Scan derived concentrations. This could not be done systematically because the comparison required rare cloud free images. Winter scenes in the Bellingshausen and Ross Seas, and elsewhere, showed high ice concentrations in better agreement with the Bootstrap than Team algorithm.

[3]   *Meier et al.* [2001] show extensive areas of 100% cover for the Arctic in winter for the CalVal algorithm, but they regard this as implausible (perhaps incorrectly, in view of the *Kwok* [2002] results cited below) and modify the algorithm to National Ice Center Hybrid, which still produces concentrations higher than the NASA Team values. However, they did not compare the different algorithms to observations in the central Arctic so determining which is more physically realistic remained unanswered.

[4]   *Kwok* [2002] notes that only very limited "ground truth" is available for the winter pack, but by use of a Synthetic Aperture Radar (SAR) derived product found that the open water fraction in the Arctic, between January and April 1998, was only 0.3% within the perennial ice zone. The Bootstrap algorithm underestimated the ice fraction by 0.7%, and the NASA Team by 1.4%.

[5]   In this paper I compare SSM/I-derived sea ice concentrations from the NASA Team and Bootstrap algorithms with ground truth from Upward Looking Sonar (ULS) data, and use this to reevaluate the performance of the UK Met Office/Hadley Centre coupled atmosphere-ocean model HadCM3 in the Antarctic, specifically in the Weddell Sea where the ULSs are located.

2.   Data: ULS, SSM/I and HadCM3

[6]   I use information about sea ice concentrations from three sources. Firstly, SSM/I-derived sea ice concentrations from the NASA Team and Bootstrap algorithms. These have the advantage of global spatial coverage and a twenty-year time series of daily data. Their disadvantage is that different algorithms give different results for the interior of the pack, because of uncertainties as to the best method of combining the various satellite channels to produce concentration values. However, the different algorithms agree well on the location of the ice edge. Secondly, ULS data, which gives point measurements with high temporal resolution. Thirdly, I consider output from the UKMO Hadley Centre coupled atmosphere-ocean GCM HadCM3 in the Antarctic, specifically in the Weddell Sea where the ULSs are located. This, of course, is model data.

[7]   The ULS dataset [*Harms et al.*, 2001] was retrieved from NSIDC at URL http://nsidc.org/data/g01359.html; processing of the raw return data is described by [*Strass*, 1998]. I have processed the dataset to average the data (available at 720 or 900 second intervals, according to ULS) into daily averages which could be compared to satellite data, and the daily averages were then used to create monthly averages. The raw ULS data provides a signal for the presence or absence of ice (together with ice draft, if ice is present) and the averaging of this signal is then taken
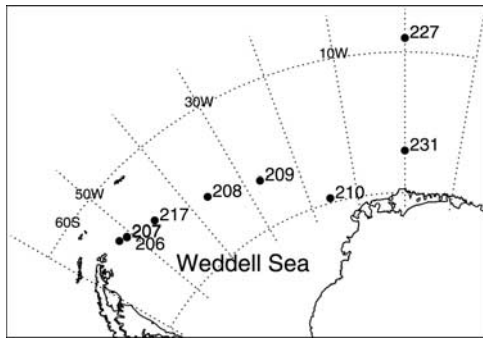
Figure 1. ULS locations in the Weddell Sea.

to be a daily average ice fraction. The ULS "footprint" at the surface is approximately 10m diameter. Most papers on the ULS have concentrated on the key variable - ice draft - that they uniquely provide. The ice concentration information is comparatively unverified. *Harms et al.* [2001, Figure 8] provide a visual comparison of three ULS derived concentrations against SSM/I which appears to show reasonable agreement, with the ULS concentrations perhaps slightly lower. *Strass and Fahrbach* [1998] estimate that the uncertainty in average ice coverage is 1.5%.

[8] Figure 1 shows the ULS locations in the Weddell Sea used in this study, following the numbering of Harms et al.. Three further ULSs (212, 232 and 233) were judged too close to the coast, since there were problems with interpolating the SSM/I products this close to the coast, and hence were not used. One more ULS (229) has a very short record and was not used. This leaves eight ULSs, mostly across the continental shelf break of the Weddell sea, but with two along 0E. The ULSs were operated for two distinct periods, the first 1990–2, the second 1996–8. When comparing to SSM/I, I use the satellite data for the appropriate period, interpolated to the ULS locations.

[9] The SSM/I data come from two sources using different algorithms. Data derived using the NASA Team algorithm [*Grumbine*, 1996] were retrieved via http://polar.
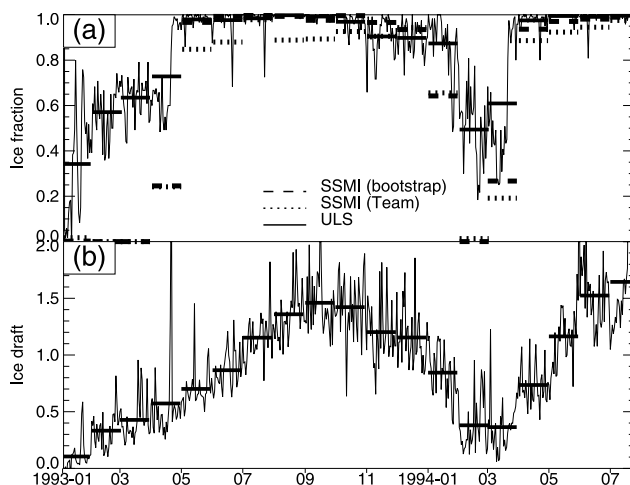
ncep.noaa.gov/seaice/icegroup.html. Bootstrap algorithm data [*Comiso*, 1999] were retrieved from NSIDC via http://www.nsidc.org/data/nsidc-0079.html. *Comiso and Steffen* [2001, and references therein] compare Team and Bootstrap concentrations in the Antarctic.

[10] The climate model used is the Hadley Centre coupled ocean atmosphere sea ice model, HadCM3. This has a horizontal resolution of 2.5° latitude by 3.75° longitude for the atmospheric component and 1.25° by 1.25° in the oceans. There are 19 levels in the atmosphere and 20 vertical levels in the ocean. Further details are given by *Gordon et al.* [2000]; the sea ice in particular is described by *Turner et al.* [2001]; and the Antarctic climate is described by *Turner et al.* [2005]. For use in this study the model has been modified to include elastic-viscous-plastic (EVP) sea ice rheology [*Hunke and Dukowizc*, 1997] and this version is referred to as HadCM3 + EVP.

[11] The SSM/I and ULS data are clearly different in their spatial and temporal sampling. The ULS footprint is approximately 10 m whereas the SSM/I data is provided on a 25 km grid, averaged up to one-degree square (approx 100 km) for this study. The ULS fractional concentration represents an average of 1 (ice) and 0 (no ice) with measurements spaced about 10 minutes apart whereas the SSM/I fraction is derived once per day. To alleviate the problems with intercomparing these datasets I use only the monthly averages. On this scale, the SSM/I estimates for the interior of the pack are quite smooth and (if this reflects the physical nature of the sea ice field) the SSM/I and ULS estimates should be comparable. Although the instantaneous ice cover is not a homogeneous ice sheet but consists of many ice types with various thicknesses and snow cover, the time-averaged state is more uniform; problems with emissivity variations are minimized by focusing on the winter period. The SSM/I and ULS will have different statistics (in terms of scatter) but there is no reason to believe that the difference in sampling causes a bias
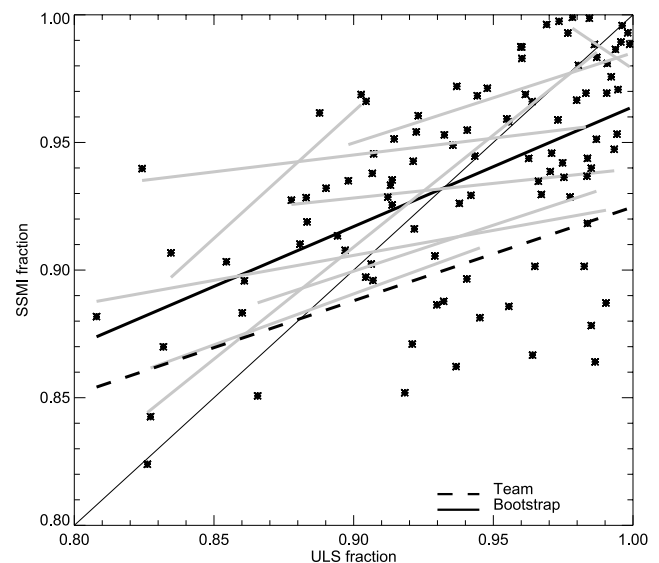

Figure 2. Daily sea ice fraction from ULS 208 (thin solid line), together with horizontal bars representing monthly means. Solid: monthly average of the ULS data; dotted: Team; dashed: Bootstrap. ULS data from *Harms et al.* [2001].

Figure 3. Scatter plot of ULS and SSM/I (Bootstrap) concentrations together with the regression line (thick solid line; slope = 0.47; r2 = 0.3). Also plotted is the ULS-Team regression (dashed; slope = 0.37; r2 = 0.1), but not the individual points; and the regression lines for individual ULSs against Bootstrap (grey).
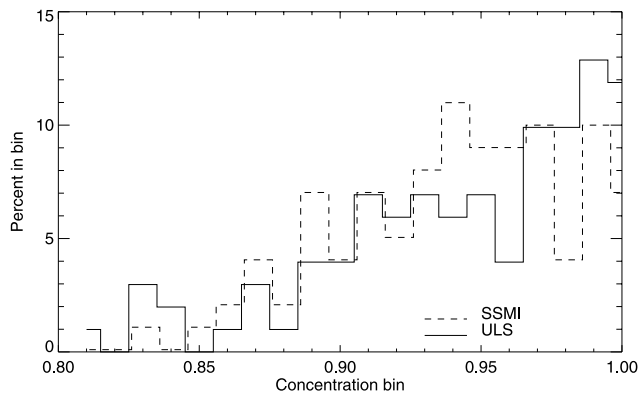
Figure 4. Histogram of sea ice concentration. X axis: ice fraction (0.8–1.0). Y axis: percentage in each bin. Solid line: ULS. Dashed: SSM/I (Bootstrap).

between the two methods. *Strass and Fahrbach* [1998] state that under homogeneity assumptions, the ULS cover should equal the SSMI cover.

3. Results—Comparison Against a Typical ULS

[12] Figure 2 shows a plot of two years of daily sea ice fraction from a typical ULS (number 208), together with bars representing monthly means. In general during the winter periods of high ice fraction the ULS and Bootstrap are within about 5%. During the first winter Bootstrap tends to be higher than the ULS; during the second winter this reverses. Both ULS and Bootstrap are considerably (usually about 10%) higher than Team. There are exceptions though: in December 1993 Team is very slightly higher than Bootstrap which is a few percent higher than ULS.

[13] At the start of the record, in January, February and March 1993; and also for one month in 1994, the ULS returns non-zero fractions but the SSM/I shows no ice. Inspection of the daily ice fields shows that the SSM/I ice edge is distinctly south of the ULS location at all times. The ice drafts from the ULS for these months show a steady increase with irregular fluctuations and is consistent with the fraction data. It is thus something of a mystery as to why ULS and satellite disagree. *Ackley et al.* [2003] report a disagreement of 1 to 1.5 degrees between satellite and ship-derived ice edges in summer, with the satellite-derived edge south of the ship-derived estimate, which they attribute to physical causes such as the diffuse ice conditions and surface flooding or snow melt. Ackley et al. found no such

biases in winter, when ice and ocean are much easier to discriminate by satellite; and I find no obvious disparities in winter (although since all the ULS are well within the winter pack limits these would not be expected). In the remainder of the paper I shall concentrate on high-fraction ice where I do not expect these problems.

4. Results—All ULSs

[14] To investigate the relationship between ULS and SSM/I fractions in the interior of the pack I select only those occasions where both sources reported concentrations greater than 0.8. Figure 3 shows a scatter plot of ULS and SSM/I (Bootstrap) monthly average fractions. The slope of the regression against Team is lower than Bootstrap, though both are less than unity. The fit is worse to Team (r-squared of 0.1 as opposed to 0.3 for Bootstrap) but even the fit for Bootstrap is poor in terms of total variance explained. The intercept of the Bootstrap regression line at a ULS value of 100% is 96%, suggesting that Bootstrap is on average underestimating dense ice extents by about 4%. However, many of the SSM/I monthly means are above 96% so it is not possible to simply rescale the SSM/I values - though they could be rescaled and then cut off at 100%. The r-squared value of 0.3 is highly statistically significant so the data are certainly related, but are biased. The slope of the Bootstrap regression line in Figure 3 is 0.47, and the 95% confidence limits for this are [0.33, 0.61], which excludes 1 by a considerable margin. Hence, the data are judged to be statistically significantly different. From the above I conclude that the Bootstrap provides a better fit to the ULS data and use it preferentially for the rest of this paper.

[15] Figure 4 shows the distribution of observations into different ice fraction bins. The shape of the graph for the SSM/I and ULS are broadly similar: there is a general increase towards high concentrations. SSM/I percentages-in-bin are roughly constant above ice fraction 0.93, whereas the ULS maximum is in the highest bins. This is consistent with Figure 3, showing that ULS estimates tend to be higher.

5. Results—HadCM3+EVP Against Bootstrap

[16] Because HadCM3 is a coupled atmosphere-ocean GCM the model data do not apply to any particular year, so I can only compare climatologies. Hence I cannot directly use the ULS data since the time series from these are too short to form a good climatology. Previous studies [*Turner et al.*, 2001] comparing this model to SSM/I (Team) have
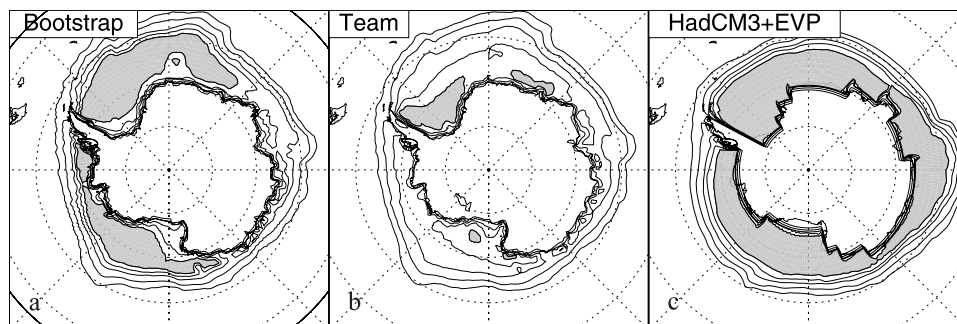

Figure 5. Plot of September mean sea ice concentration from (a) SSM/I (Bootstrap); (b) SSM/I (Team) and (c) HadCM3+EVP. Contours at 0.15, 0.5, 0.8, 0.9, 0.95 fraction; filled above 0.95.
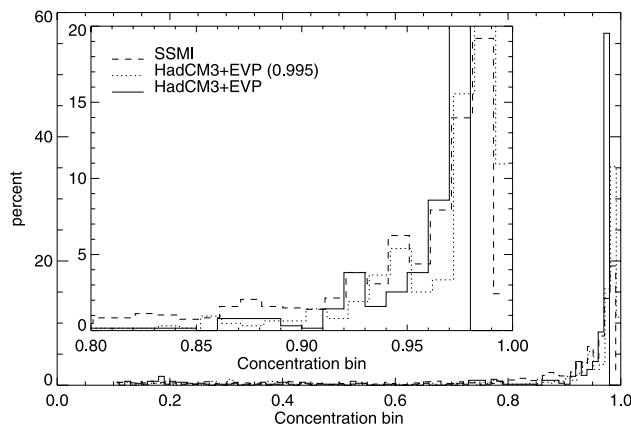
Figure 6. Histogram of sea ice concentration for the Weddell Sea sector (0E–60W). X axis: ice fraction (main plot: 0–1; inset plot: 0.8–1.0). Y axis: percentage in each bin. Solid line: HadCM3+EVP. Dotted: HadCM3 with upper ice fraction limit raised to 0.995. Dashed: SSM/I (Bootstrap).

concluded that the model ice concentrations are too high by perhaps 10%. This is seen in Figure 5b comparing the Team results which show only limited areas where the concentration exceeds 95%, to the model where concentrations are above 95% in most of the interior of the pack (Figure 5c). There is less disparity comparing against Bootstrap (Figure 5a), where concentrations exceed 95% except around the East Antarctic coast from approx 45E to 135E

[17] Figure 6 shows histograms comparing model and SSM/I for the whole Weddell Sea area (0–60W). The solid black line is the standard version of the model, in which a maximum ice fraction of 0.98 is imposed in the southern hemisphere. This limit was imposed in earlier versions of the GCM and inherited by HadCM3 because it was believed to be physically realistic. The dotted black line shows the results of a run in which the limit is 0.995, the same as for the northern hemisphere. The higher limit fits the SSM/I better: the maximum of the histogram is now in the 98–99% bin. However the maximum for the model is still too high: 35% of the model ice is in the 98–99% bin compared with less than 20% for the SSM/I; but this is better than the standard run. Both versions of the model show very little ice in the 80–90% categories, where SSM/I shows a few percent. Note that the model uses a single ice category and a primitive ridging scheme.

6. Conclusions

[18] I have compared satellite-based sea ice concentrations derived from Bootstrap and NASA Team algorithms and ULS estimates of sea ice fraction in the Weddell sea. Bootstrap fits the ULS data much better than Team, but there are still discrepancies between Bootstrap and ULS data, particularly at very high concentrations. It seems likely that the ULS data are more reliable, though this is hard to verify. If so, I suggest that even Bootstrap may be underestimating the proportion of very high fraction ice.

[19] I have compared sea ice concentrations from a climate model (HadCM3 with EVP ice dynamics) to the SSM/I data. There is a generally good fit when comparing

histograms. The model overestimates very high fraction ice categories compared to Bootstrap, although the ULS-SSM/I comparison suggests the SSM/I may be underestimating the concentrations. Allowing the model to produce very high fraction ice, by raising an artificial limit of the maximum ice fraction, improves the fit to SSM/I.

[20] This paper suggests that present-day sea ice fractions are higher than obtained from SSMI data and some models. This might lead to a reconsideration of values for glacial fractions derived from models too. Consequently the statement of *Morales Maqueda and Rahmstorf* [2002] that the mechanism for CO2-draw down during the glacial cycle proposed by *Stephens and Keeling* [2000] could only explain a fraction of the effect, because the sea ice fractions would be too low, might be reconsidered as well.

References

Ackley, S., P. Wadhams, J. C. Comiso, and A. P. Worby (2003), Decadal decrease Of Antarctic sea ice extent inferred from whaling records revisited on the basis of historical and modern sea ice records, *Polar Res.*, *22*, 19–25.

Burns, B. (1993), Comparison of SSM/I ice concentration algorithms for the Weddell Sea, *Ann. Glaciol.*, *17*, 344–350.

Comiso, J. (1999), June to September 2001, in *Bootstrap Sea Ice Concentrations for NIMBUS-7 SMMR and DMSP SSM/I*, http://nsidc.org/data/nsidc-0079.html, Natl. Snow and Ice Data Cent. Digital Media, Boulder, Colo. (Updated 2002.)

Comiso, J. C., and K. Steffen (2001), Studies of Antarctic sea ice concentrations from satellite data and their applications, *J. Geophys. Res.*, *106*, 31,361–31,385.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood (2000), The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, *16*, 147–168.

Grumbine, R. W. (1996), Automated passive microwave sea ice concentration analysis at NCEP, *Ocean Model. Branch Tech. Note 120*, 13 pp., Natl. Oceanic and Atmos. Admin., Silver Spring, Md. (Available at http://polar.ncep.noaa.gov/seaice/docs/ssmi.auto/ssmi120.html.)

Harms, S., E. Fahrbach, and V. H. Strass (2001), Sea ice transports in the Weddell Sea, *J. Geophys. Res.*, *106*, 9057–9073.

Hunke, E. C., and J. K. Dukowicz (1997), An elastic-viscous-plastic model for sea ice dynamics, *J. Phys. Oceangr.*, *27*, 1849–1867.

Kwok, R. (2002), Sea ice concentration estimates from satellite passive microwave radiometry and openings from SAR ice motion, *Geophys. Res. Lett.*, *29*(9), 1311, doi:10.1029/2002GL014787.

Meier, W. N., M. van Woert, and C. Bertoia (2001), Evaluation of operational SSM/I ice-concentration algorithms, *Ann. Glaciol.*, *33*, 102–108.

Morales Maqueda, M. A., and S. Rahmstorf (2002), Did Antarctic sea-ice expansion cause glacial CO$_2$ decline?, *Geophys. Res. Lett.*, *29*(1), 1011, doi:10.1029/2001GL013240.

Steffen, K., and A. J. Schweiger (1991), NASA team algorithm for sea ice concentration retrieval from Defense Meteorological Satellite Program special sensor microwave imager: Comparison with Landsat satellite imagery, *J. Geophys. Res.*, *96*, 21,971–21,987.

Stephens, B. B., and R. F. Keeling (2000), The influence of Antarctic sea ice on glacial-interglacial CO$_2$ variations, *Nature*, *404*, 171–174.

Strass, V. H. (1998), Measuring sea ice draft and coverage with moored upward looking sonars, *Deep Sea Res., Part I*, *45*, 795–818.

Strass, V. H., and E. Fahrbach (1998), Temporal and regional variation of sea ice draft and coverage in the Weddell Sea obtained from Upward Looking Sonars, in *Antarctic Sea Ice: Physical Processes, Interactions, and Variability*, *Antarct. Res. Ser.*, vol. 74, edited by M. O. Jeffries, pp. 123–139, AGU, Washington, D. C.

Turner, J., W. M. Connolley, D. Cresswell, and S. A. Harangozo (2001), The simulation of Antarctic sea ice in the Hadley Centre Climate Model (HadCM3), *Ann. Glaciol.*, *33*, 585–591.

Turner, J., W. M. Connolley, T. A. Lachlan-Cope, and G. J. Marshall (2005), The performance of the Hadley Centre Climate Model (HadCM3) in high southern latitudes, *Int. J. Climatol.*, in press.

————————————
W. M. Connolley, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. (wmc@bas.ac.uk)