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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "The evolution of shipping emissions and the costs of recent and forthcoming emission regulations in the northern European emission control area" *by* L. Johansson et al.

L. Johansson et al.

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Since the comments of both referees were inter-connected we prepared a common response. The revised manuscript is attached as supplements

NOTE: the content of this response is identical with the response to Referee 1.

Common response to both referees

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Both referees agreed that the auxiliary fuel consumption in the submitted manuscript was not in line with other recent studies and bunker statistics. We have therefore carefully checked in detail, and evaluated again the bottom-up estimation capabilities of the model with respect to reported fuel consumption (both for main and auxiliary engines) . We conducted an extensive re-evaluation of the code and the model, which revealed a programming error in the STEAM code that was associated with the link of vessel attributes to activity data.

We then made the proper corrections to the code and re-computed all the model runs presented in the paper, including the scenarios. In other words, a major re-computation was done. Some of the results expectedly changed – most notably the fraction of auxiliary fuel consumption of IMO-registered vessels decreased from the previously reported value of 38% to the value in the current manuscript of 32%. (As we point out in the more detailed responses below, also our previous results actually did not indicate a 50% fraction of total fuel consumption) Fortunately, the main results concerning the reduction scenarios and fuel costs remained largely unchanged, although we naturally corrected the presented values throughout the whole text of the manuscript.

In addition to the auxiliary fuel consumption, other significant changes in the revised manuscript address the decrease in cargo transport in 2009. Now, there is a more substantial difference of cargo traffic between 2009 and 2011, reflecting the economic downturn in the European Union.

The re-evaluation of the numerical results also addressed the unidentified ships without IMO-identification. As we studied the auxiliary fuel consumption, we found out that most of the modeled fuel consumption of these non-IMO registered vessels originated from harbours, from fairly stationary locations. Although the paper for the most part concentrates on IMO-registered traffic, we felt that the large auxiliary fuel consumption of unidentified ships left an unnecessary bias to the presented flag state distributions and total emission inventories.

We therefore improved the model also in this respect, by adding an empirical limitation function to the auxiliary engine use, specifically for these unknown ships. A description of this model improvement has been added to the revised manuscript as a new section 2.3.5. The arguments for this improvement have also been briefly described in the following. In the model, all ships were added with a so-called berthing timer [on a resolution of a minute] that will start counting, after the ship will decrease its speed below 1 knot. This numerical timer is reset after the ship begins operating again (speed > 1 knot). After two hours of berthing, the instantaneous auxiliary fuel consumption is assumed to decrease linearly from its initial value. We have assumed that after eight hours of berthing, the rate of auxiliary fuel consumption has been decreased to one fifth (1/5) of the initial auxiliary fuel consumption rate.

Although a large margin of error still remains with the use of auxiliary engines for the unidentified vessels, we feel that the model treatment is now more realistic. The more detailed parameterization of this auxiliary consumption limiting feature for unidentified vessels will require a much more thorough study and is outside the scope of this paper.

Detailed responses - anonymous Referee #1 Received and published: 31 July 2013, Second referee response

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Referee - The authors gave an extensive reply on this comment in which several arguments were included. These arguments are all contain valid information to a certain degree. Most of the questions were responded suf?ciently by the authors. Some explanations were added to the manuscript also. Nevertheless it remains hardly conceivable that auxiliary engines can be responsible for more than 50% of the total fuel consumption.

Authors - This (latter) statement was not correct and this has been corrected in the revised manuscript (please see also our response above, in the section 'common response to both referees'). In the revised manuscript, according to the modeling results for 2011, it has been estimated that auxiliary use for the most notable ship types varies between 18% and 35% of the total.

The two contributing factors leading to this behavior have been identified and corrected and model calculations have been updated accordingly.

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Referee - It is stated by the authors that their model uses bottom-up calculation. This means that results cannot be checked very easily. Not by a referee and probably even by the authors themselves.

Authors - The referee is correct in the respect that the amount of data is voluminous, detailed evaluation is costly and not all time series for instantaneous emissions and fuel consumption statistics can be evaluated for every vessel. However, some checks and evaluation can be made and has actually been made.

We have gathered a collection of fuel use reports from more than 30 ships that operated within the ECA region in 2009. For all these ships we have compared the reported auxiliary and main engine fuel consumption on a monthly basis (although these comparisons have not been presented in the manuscript). Based on this evaluation material we can say that the estimated auxiliary fuel consumption in the current, revised STEAM model is generally under-estimated with respect to the reported amounts.
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Referee - Nevertheless in the end the results (the totals) have to obey to some simple math. Somewhere in their response to the ?rst referee comment authors estimate fuel usage in harbours approximately at 25%. This 25% of fuel in harbors is of course completely used by auxiliary engines. As a consequence to reach 50 percent fuel use by auxiliaries (on the total) it is necessary that at sea on average more than 1/3 of all fuel is used by auxiliaries.

Authors - The referee is correct. It is not possible to reach a conclusion pointing towards

50% share for auxiliary fuel consumption. This claim has been corrected in the revised manuscript. We have also presented an improved solution for evaluating the use of auxiliary engines for small vessels, which will improve the accuracy of the model in this respect (details presented in other points above and in the revised manuscript).

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Referee - To my opinion this is a rather extreme average share of fuel used by auxiliaries at sea even when slow speed steaming is applied widely.

Authors - Yes, the referee is correct and this has been revised. The fuel consumption is calculated as Fuel consumed = power used * specific fuel consumption * duration of the operation mode. The values for used power are similar to those used by Starcrest (Port of Long Beach Air Emissions inventory – 2011 (http://www.polb.com/civica/filebank/blobdload.asp?BlobID=10194). Some differences are evident, most notably the inclusion of a fourth operation mode for ships (anchoring). This indicates that once the cargo operations (loading/unloading) are complete, the vessel power usage decreases. This feature is not currently present in STEAM, but should be included in the future work. In practice the duration of this operation mode needs to reflect the size of the vessel. Clearly, loading/unloading a large vessel takes more time than the corresponding operations on a small vessel. We are currently introducing the cargo handling mode in STEAM, but this requires more work and data collection. The approach which will be taken fully exploits the cargo capacity description of the data obtained from classification societies and attempts to identify and assess the primary consumers of electrical components onboard.

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Referee - In another place in their response authors point at the circumstance that only 65% of time is spent at sea. This means that 35 percent of time is spent in harbors. Combined with the fact that the share of fuel in harbors is about 25% this means that fuel rate in harbors is about 0.25/0.35 = 70 percent compared to fuel rate at sea. It is

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very likely that fuel rate in harbors can not be 70 percent of the fuel rate at sea. So two extreme situations seem to occur in the model to explain the high percentage (of more than 50 percent) of fuel spent in auxiliaries: 1. In harbors average fuel rate is 70 percent of average fuel rate at sea 2. At sea at least about 1/3 of total fuel use is consumed by auxiliaries.

I kindly request the authors to check whether these two situations do occur in the model results. When these two situations do not occur other explanations of high fuel usage by auxiliaries are needed. When these two situations in the model results do occur the behavior of the model should be checked with the assumptions and the expectations that are forthcoming.

The reasoning that this model has a complex bottom-up approach does not dismiss the authors from their duty to check whether the model behaves within the boundaries that may be expected.

Authors - The referee is correct, and these statements have been revised in the manuscript. We have also re-computed all the results, using the corrected and improved model version.

These spurious results in the older manuscript version were caused by two reasons. First, there was a programming error, which hampered the linking of vessel particulars to activity data. The second reason concerns the description of small or unknown vessels, which spend most of their time in harbor areas but are still sending AIS position reports. We have corrected the programming error, improved the description of small vessel power usage (this has been described in more detail above) and rerun all the calculations to make results more consistent.

Finally, regarding the fuel consumption rates in different operational modes, the model proposes the following ratios for the most notable ship categories in ECA 2011:

(Fig 1 of response)

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As it can be seen from the figure, there are substantial differences between the predicted average fuel consumption rate and the average fuel consumption rate in cruising mode, as the Referee suggested. The values in the table were calculated from the individual vessel-specific model output from all vessels that operated in ECA region in 2011, using the revised STEAM model.

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Detailed responses - Anonymous Referee #2 Received and published: 3 September 2013

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Referee The general points by the reviewer: The authors present a bottom-up emission inventories for shipping in Baltic Sea and North Sea for years 2009 and 2011 investigating effects of IMO legislation in European ECAs on emissions and on fuel costs. Emissions from shipping have been in focus due to their high contribution to total anthropogenic emissions of SO2, NOX and PM. A thorough investigation of effects of the recent and future IMO legislation is important and within the scope of ACP. The emission model and its application on emission inventory for Baltic Sea and North Sea shipping have been presented by the authors earlier, the study of the effects of IMO legislation and of different mitigation scenarios is novel and the results are important contribution to state of the knowledge both for science and for policy makers. The emission inventories for shipping have been associated with substantial uncertainties and a detailed study like this one can improve understanding of distribution of fuel consumption/emissions between different ship categories and ship operation modes. The specific comments and requests of the reviewer:

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Referee - However, here I would agree with comment of referee 1 that the fuel consumption by auxiliary power generation looks very high in proportion to the consump-

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tion by main engines, both comparing total fuel consumption in port to that at sea (my calculation gave 60%) and comparing fuel consumption by auxiliaries to ME at sea. Since these ?ndings are not in agreement with earlier inventories, I would recommend specifying fuel consumption by auxiliary machinery (&boilers) by the different ship categories along with the ME fuel consumption.

Authors - Both the correction of a programming error in the STEAM source code and the empirical function added for small vessels (as described above in more detail) have evidently improved this behavior in the revised manuscript, regarding auxiliary (aux) power generation.

However, we would also like to point out that in general, there are major uncertainties regarding aux engine usage in all currently available models, as noted e.g. in the second IMO GHG study of Buhag et al. The uncertainty analysis (Table A1.10 "Confidence and uncertainties of calculation of fuel consumption of auxiliary engines", page 149) indicates that the average size of the installed auxiliary engine, average operating days of auxiliary engine and average load of aux engine are very challenging to estimate. In the IHS Fairplay data, on which the second IMO GHG study was based on, the table lists the information regarding the confidence of installed aux engine (AE) power as "High, but with gaps". In the extended Fairplay data, the coverage of AE data in the global fleet is about 35%. This is clearly not an all-inclusive result, which could in the future be improved significantly (up to 85%-90% coverage) by combining data from several sources. Buhaug et al state that the AE fuel consumption assessments are challenging because of the variability of power demands of ships and operational differences. Significant amount of work is still required to identify and model the primary consumers. We are sure that reviewers have recognised this shortcoming in the second IMO study and agree that this part can be improved.

Unfortunately, data of boiler installations of each vessel is scarcely available and large effort is needed to obtain this data from various sources. We are currently in the process of data collection, but data from current sources indicate that classification societies do not provide information of boiler capacity (heating surface area, steam generation capacity, daily boiler consumption) as a part of their commercial data services. It is a reasonable assumption that no aux boiler is used in transit mode, which can be attributed to the existence of waste heat recovery systems in the exhaust line (exhaust boiler). In these cases, vessels use the engine heat for steam/hot water generation. However, on low engine loads, the temperature of the exhaust is not enough to produce sufficient amounts of steam. Some vessel classes (like asphalt and bitumen tankers) require cargo heating or additional power to re-liquify cargo (LNG plants), which usually means that these vessels can have significantly larger need for boilers and aux engine power than any other ship class.

Feed water temperature affects the heat required to vaporize water in order to provide steam for the vessel. This makes boiler use dependent both on latitude and time of the year. One of the reasons for the seasonal dependency of boiler fuel consumption is because of the ambient conditions, but others like capacity utilization changes can also have an impact. During the summer, the energy needed for steam generation is less than during the cold season. Exactly the opposite can be observed with aux engine usage. The maximum of aux engine usage occurs during the summer period, when cooling and ventilation systems are used extensively. These two opposite features are not totally canceled out and on annual level some seasonal variation remains, but the net effect is much more linear than either aux engine or boiler consumption alone.

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Referee - Please, check also consistency of the following 2 statements: p.16115, l.20: ... use of the auxiliary engines may be responsible for more than a half of the total fuel 50 consumption

Authors - This sentence was presented in the Introduction chapter. Since in the results-section we present a more thorough estimation of the role of auxiliary engines in terms of fuel consumption, here we have simply rewritten the statement: “The auxiliary en-

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gines are responsible for a significant portion of the total fuel consumption, and any reduction in cruising speed will inevitably cause an increase in auxiliary fuel consumption."

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Referee - p. 16129, l. 18: Based on the fuel consumption statistics for IMO registered vessels, 38% (#same in both years?) of the total fuel was consumed by auxiliary engines in 2009 and 2011. ... Without shaft generators the predicted fuel consumption of main and auxiliary engines would be almost equal

Authors - The fraction of aux/main engine fuel consumption for IMO-registered vessels has remained fairly constant during the study period. However, to write more accurately, we now refer to the latest dataset for 2011. According to this dataset 32% (previously before re-runs 38%) of fuel consumption was produced in auxiliary engines and the ratio of aux/total varies between ship types. We have added these corrected ratios in the revised text.

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Referee - Does the ?rst statement (more than 50%) mean auxiliary engines if no shaft generation were not used? This is somewhat confusing.

Authors - With the shaft generators, we estimate that auxiliary engines contribute 18% - 35% for tankers, passenger ships, container ships and cargo ships. The statement remains the same: without shaft generators we would see ratios close to 50% with some ship types. The text has been written more clearly.

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Referee - The methodology of emission calculations in STEAM is presented in detail in earlier papers and is only brie?y outlined in this manuscript. Here I would recommend presenting explicitly how PM2.5 emissions change with the different fuels assumed in the study as numerous conclusions about PM emissions are done. Also the effects of

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exhaust cleaning systems should be described more clearly (p. 16120, l.26 – p.16121

Authors - The text describing this matter has been modified in Chapter 2.3.1, so that the changes in predicted PM2.5 emissions in terms of different fuel types and exhaust gas systems are clearer.

In (Jalkanen et al. 2012) we have presented PM2.5 emission coefficients as a function of FSC, engine specific fuel-oil consumption (SFOC) and engine load. The effect of FSC to the emissions of SO4 sulphate particles is linear.

The exhaust cleaning systems directly influence the predicted emission coefficients. An installed sulfur scrubber reduces predicted SOx emissions and has an impact on predicted PM2.5 chemical components. The efficiency of scrubbers seems also to depend on the PM size (Corbett et al, ACP 10 (2010) 9689), but this effect has not been included in STEAM because of lack of measurement data. Instead, PM removal efficiency has been assumed as 75% in STEAM which has been written in Chapter 2.3.2.

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Referee - l.2: 'amount of exhausted SOX and PM is not allowed to exceed the amount that would be exhausted by burning fuel with acceptable FSC' – does this mean that SOX and PM emissions are set to be equal to those from acceptable fuels or that emissions are set to those corresponding to actual EGCS applied?)

Authors - No, SOx and PM2.5 emissions are not set to be equal to the accepted limits, as these depend on whether EGCS has been used or not. As a result of FSC evaluation in the model, the SOx and PM2.5 emission coefficients are always lower or equal to the accepted limits.

We have revised this part of the text to be more clear. One set of equations has been added to the revised manuscript to explain this more explicitly (Eqs. 2 a-b). The modeling of SOx and PM2.5 emissions is based on the FSC requirements and the

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assumption that the ship owners aim to minimize their fuel costs. For instance, if a ship is required to use 0.1% MGO and has a sulphur scrubber installed: Using 0.1% MGO in combination with the installed scrubber would result in lower emission coefficients than is required Thus, the cost minimizing solution for the ship owner, while at the same time conforming with the regulations, would be some fuel mixture with a FSC (0.1 + x)%, where x is the additional fuel sulphur content that can be used, due to the use of the scrubber. Taking into account the EGCS's efficiency to reduce emissions, the model calculates this additional fuel sulphur content x. The equations to calculate x have now been included in the text (Eqs. 2a-b). The evaluation of x will result to the maximum fuel sulphur content that the ship can use utilizing the scrubber, while at the same time complying with the SECA requirements.

Finally, to describe the effects of exhaust gas cleaning systems (and Eqs.2a-b) in the presented scenario runs, the results were further explained by adding the following text: "The estimated PM2.5 emissions in this [2015 with scrubbers] scenario were slightly smaller than in 2015 scenario without scrubbers. The reason for this is that the virtual scrubbers reduced 66% from SOx emissions and 75% from PM2.5 emissions and thus, FSC_A' in Eqs. 2a-b results in a slightly lower FSC than would be required in terms of PM2.5 emission factor in 2015."

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With best regards, Authors

Please also note the supplement to this comment:
http://www.atmos-chem-phys-discuss.net/13/C7978/2013/acpd-13-C7978-2013-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., 13, 16113, 2013.

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Ship type	average fuel consumption, for berthing aux engines, kg/h	average fuel consumption, for cruising & maneuvering aux and main engines, kg/h
RORO	193	2882
Container	482	3165
General cargo	85	416
Tanker, chem.	171	1069
Passenger cruiser	300	3172
Bulk carrier	203	2075
Passenger ship	41	73
Tanker, LPG	149	898
Tanker, product	123	843
ROPAX	182	796
Tanker crude	169	1339
Ref. cargo	236	2216
Vehicle carrier	218	1986
Tanker, LNG	133	3397

Fig. 1. Average fuel consumption rate for different vessel categories. STEAM model estimates (ECA 2011 data)