Answer to referee #1

We thank the reviewer for their comment and suggestions on the manuscript „Transient tracer application in the Southern Ocean“. The detailed review clearly points out necessary improvements and corrections.
The focus of the manuscript was reshaped in favor of the theoretical part. Sections corresponding to changes in ventilation were removed. Additional data sets were included and contributions of an additional co-author (John L. Bullister) were added. Some of the described new concepts were improved and extended. New and already existing concepts are now clearly separated.

The manuscript is now structured as follows:

1. Introduction

The introduction was rewritten according to the added and removed parts of the manuscript.

2. Transit Time Distribution

This section was restructured and now only includes the scientific background of the manuscript. New concepts are presented in section 3 in order to clearly distinguish between new and already known concepts.

2.1. Ventilation concept

This section was moved to the beginning of section 2 since it includes information which are used in 2.2.

2.2. Transient Tracers

2.2.1. SF_6

2.2.2. CFCs

This subsection was extended to CFCs in general and also carbon tetrachloride.

2.2.3. Tritium

2.2.4. Argon-39

Text was shortened

2.2.5 Carbon-14

Text was shortened

2.3. Limit of detection

Discussion now focus on detection limit only.

2.4. Tracer age

2.5. Time ranges

Discussion about transient tracer time ranges was extended and a new figure about the tracer order was added.

2.6. Mean age

Section was rewritten for a better understanding.

2.7. Constraining the IG-TTD

New section was added which clearly describes the method of constraining the IG-TTD.

3. The concept of validity areas

This method was completely revised. The tracer age difference is no longer used. Instead we present an enhanced method using the tracer age relationship of the tracers.

3.1. Tracer saturation and TTD sensitivity

In this additional section we discuss in detail saturation effects on transient tracers and the corresponding sensitivities on constraining the IG-TTD.

4. Field data application

The application of field data is now focused on the new concept of validity areas and the limits and characteristics of the IG-TTD in this particular region. Hence, the manuscript now only focuses on the theoretical part rather than switching to another topic such as the ventilation of the Southern Ocean. The area in the South Atlantic is now used as an example for the new tracer concepts that we presented.

4.1. Transient tracer data

The field data was extended using more data sets, e.g. the CLIVAR A13.5 cruise in 2010 and the ANT-X/4 cruise in 1992. Accordingly, the overview map was renewed.

4.2. Validity areas

Here we demonstrate the new concept of validity areas using the transient tracer field data.

4.3. Saturation effects

Here we discuss saturation effects based on available field data and the model output of Shao et al. 2013.

4.4. Application range of the IG-TTD

This section includes new findings about characteristics and limits of the IG-TTD.

4.5. Argon-39 investigations

This approach was renewed by using the CLIVAR A13.5 data set of 2010 and the ANT-X/4 data set of 1992. The results are still similar.

5. Conclusion

Changed accordingly to the new structure of the manuscript.

“Referee’s Comment for os---2014---51:
This manuscript by Stöven et al. needs a major revision before it can be published. It lacks a coherent thread that links two disparate small studies together. In the first part, the authors describe the use of TTDs for several different tracers with a few figures, and discuss their method for determining whether various pairs of these tracers are complementary. Relating tracer age differences to the parameters of the TTDs may not have appeared in the published literature previously, but it has certainly been discussed.
In the second part of the manuscript, the authors use two of these tracer pairs to discuss ventilation of two relatively short hydrographic sections in the southeastern Atlantic Ocean. Their discussions are limited by the quality and quantity of available data, and to some extent by their presentation of their understanding of circulation in the Southern Ocean.
After the discussion of utilizing tracer pairs, the authors should have chosen to interpret data from a hydrographic section where all or most of these tracers were measured and reported. Aside from SF6, all of these transient tracers were measured during the South Atlantic Ventilation Experiment. Aside from 39Ar, all of these tracers are measured on the Repeat Hydrography cruises over the past 6 years.

I'd rate the paper as 2.5 in the category of Scientific Significance and 3 in Scientific Quality. The writing and presentation within the paper is poor. There are many instances where the writing is difficult to follow. I've listed many of my comments on writing and discussion of the science below. This is by no means complete."

Title: rather grandiose for a limited study of tracers in the southeastern Atlantic Ocean

- **Title changed to "Perspectives of transient tracer applications and limiting cases"**

Abstract:
--- There must be a better term than chronological transient tracers, since most of these tracers supply information on elapsed time. I'd prefer trace gas transient tracers.

- **The term "chronological tracers" was introduced by Waugh et al. 2002 and we would like to stick to this known term.**

--- Which classification? Define highly---ventilated? CFC---12 was useful for studying recently ventilated waters during the WOCE era – not so much now. However, I wouldn't group it with argon---39 and carbon---14.

- **A definition of highly ventilated water masses was added.**
- **CFCs fill the gap between tracers of the lower and upper time range. The concerned part was rewritten for a better understanding**

"**Intro:**
--- Ocean ventilation is often defined as the penetration and sinking of waters from the ocean surface into the interior – so it is the transport process!

- **text passage rewritten**

--- Other researchers (e.g. Waugh et al. , 2003) previously demonstrated that IG---TTD can be constrained with tracer pairs before Stoeven and Tanhua in 2014.

- **citations added**

--- Poor English = lines 21---26 – I think it means that the age range for which IG---TTD can be constrained by tracer pairs depends upon the specific tracer pair. In addition the assumptions behind the IG---TTD approach are not true everywhere in the ocean. Finally, the use of IG---TTD for field data requires significant amounts of trial and error (essentially generating lookup tables and matching the data to the values in the table).

- **text passage rewritten**

--- There are no matrices in Section 3"

- **text passage rewritten**

2.1

--- Ppt = parts per trillion

- **text added**

--- What is meant by a stable emission rate? Wouldn't that result in a linear increase in atm. Concentrations?

- **Yes, indeed, the SF_6 emission rate is relatively stable since 2006 which corresponds to a linear atm. increase.**

--- Bullister reports much lower LOD for SF6 – less than 0.05 fmol kg---1

- **The LODs stated in Table 1 were changed for CFCs and SF_6 to a specific range in spite of single values.**

--- "such areas" = study locations

- **text added**

2.2

---CFC---12 was originally produced as a refrigerant. The propellant use was developed later. Production was phased out beginning in the late 1980s.

- **text rewritten**

--- The upcoming problem is only for interpreting its ocean distribution – it is not a problem for the environment.

- **text rewritten**

--- This saturation correction comes out of nowhere in the manuscript. The undersaturation is a result of more than just the emission rate. (Should SF6 have a similar undersaturation?) It will also vary based upon the location of the outcrop of the isopycnals of interest (see also Shao et al. , 2013, 10.1002/jgrc.20370)

- **An extra section was added with information about tracer saturation. This section now also includes the findings of Shao et al., 2013.**

2.3

--- Note that the use of Helium---3 reduces the need for a TIF.

- **text rewritten**

2.4

--- "In spite of" not "despite of"

- **corrected**

---The discussion of a new analytical method for 39Ar seems like a sales pitch in the middle of the paper. I'm not sure why it is here.

- **As described in the text, the new analytical method provides the basis for ^{39}Ar tracer surveys in the near future which implies an upcoming strong potential of this transient tracer. However, the text was shortened and the "sales pitch" removed.**

2.5

--- Nuclear power plants did not release 14C directly, but it is released when nuclear fuel rods are reprocessed

- **specified in text**

--- How did Libby know the LOD for AMS analysis?

- **wrong citation, corrected**

--- Too much detail on 14C for a tracer that is not used in this study

- **The text was shortened but still includes application issues of ^{14}C, which are a relevant contribution to the manuscript.**

2.6

--- I am not sure of what the authors want to emphasize with the discussion of increasing the sample size. If the goal is to achieve a certain LOD, then that might be one step assuming the calibration of the blank is independent of the size of the sample.

--- Why the discussion of LOQ?

--- Precision and accuracy can be unrelated in analytical systems.

- **section rewritten**

3.1

--- “versatile” = various?

--- “Underlying influencing”?

- **corrected**

--- The TTD is a type of Greens function that propagates the surface boundary condition of a tracer into the interior. The particular form of the Green’s function, the Inverse Gaussian, is the TTD of a one---D flow with constant velocity and diffusivity.

- **text rewritten**

--- By constraining the Peclet number to less than 1.8, the authors are artificially reducing the possible solutions. Are there areas where Pe=3 might be reasonable? Pe=1 is the standard choice and makes it easy to convolute the boundary condition into the interior. It appears to work well for the thermocline. There is no reason to expect it to be valid below the thermocline.

- **Note that we used the Δ/Γ–ratio instead of the Peclet number. The PE of the IG-TTD equates to Δ^2/Γ^2 which corresponds to Δ/Γ=1.8 ~ PE=3.24. Higher Δ/Γ– ratios than 1.8 lead to high uncertainties in mean age calculations and are therefore not used in this study.**

3.2

--- The use of the trace gas transient tracers depends on a monotonic increase in the tracer concentrations. The emission rate needs to remain higher than the rate of destruction.

- **text rewritten**

--- In the past the interhemispheric difference was important. It is now about 2 ppt or less than 1%) – certainly less than other sources of error.

- **This is true for water being in contact with the atmosphere during the last decade but the significant interhemispheric difference of the past is still "carried" by deeper water layers, e.g. NADW / AABW.**

--- Shao et al. (2013) found that heating/cooling of the surface water was also important. I assume the authors here mean entrainment of water from below the mixed layer when they state "fast replenishment of surface waters"
--- By definition, possible states of undersaturation can range from 0.1% to 100%. I think the authors need to be clearer here.
--- The only natural isotope considered in this manuscript is Argon---39. Both carbon---14 and tritium are affected by the anthropogenic inputs.

- **section rewritten**

3.3
--- Explain what is meant by "TTD based concentration matrices"
--- Shouldn't it be the hemisphere in which the isopycnal is ventilated (or water mass formed"?

- **text rewritten**

--- It is not the tritium itself that has been used as a transient tracer, but the tracer pair with its daughter isotope. It is commonly referred to as tritium – 3He dating.

- **There are two different applications of tritium. The application of tritium in combination with a tritium input function and the application of tritium in combination with ^{3}He. Both combinations can be found in the literature.**

--- The authors are interpreting Fig. 1 to extract information on specific time ranges without explaining how they find this information. For example I see no similarities between the tritium and SF6 curves.

- **An additional figure was added which clearly shows the tracer order.**

---This comment may be related to the writing by someone whose native language is not English. It is not CFC---12 that is restricted, but the application of CFC---12.
--- This paragraph (1st paragraph, p. 2301) is describing the time range for each tracer, then begins to address combinations of tracers in a general way without clearly explaining how this works.

- **text rewritten**

3.4
--- There are several other studies that look at or suggest the use of tracer pairs that should be cited here. Waugh et al. (2003) explain tracer pairs in a slightly different manner. Other studies include Hall et al. (2002, Global Biogeochem Cycles) and Sonnerup et al. (2013, DSR). The use of the tracer age differences is an attempt to formalize the use of tracer pairs, but the authors need to make the case that this is a significant new finding.
--- What is Co?
--- "belonging TAD matrix" = "corresponding TAD matrix"
--- Waugh et al. (2003) point out that the more orthogonal the source functions, the better the constraints.

- **The method of TADs was replaced by another (new) method using tracer age relationships. Differences and similarities to existing literature is highlighted**

4.1

--- Leave out “identical as”. The sampling … is the same as that described by Stoeven and Tanhua (2014).

--- “attributed” not “contributed”

--- Revise Fig. 3 to include the locations of the argon---39 measurements and remove the bloom area and eddy structure station locations.

- **done**

--- The detailed description of the analytical difficulties should be in a data report.

- **text removed**

--- The transition to a description of the storm---induced effect on surface saturations seems to merit its own paragraph. The authors should do a back of the envelope calculation to convince themselves (and the reader) that bubble injection could have such a large effect on SF6 and barely any on CFC---12, rather than just make an unsupported attribution.

- **text rewritten**

--- I find the discussion about the relative precisions between the two cruises to be confusing and extraneous. Just report the precisions without the details.

- **done**

--- What is meant by carryovers? From the previous station? Do the authors mean that there were leaky Niskins that were likely contaminated by waters from different depths? It sounds as though no one was in charge of ensuring good samples were collected? On all Repeat Hydrography cruises, leaky Niskins are detected by the first sampler (usually the CFC/SF6 person) who would then not sample that Niskin. In any case, a simple statement about number of samples collected vs number loss due to problems with the Niskin samplers would suffice.

- **text partly removed**

--- Gerard---Ewing barrels

--- Note that the Ar was extracted from all four 250---l samples into one cylinder. It is an integrated sample (and a mean if the amount of Ar in each 250---l sample was identical).

- **unclear description rewritten**

4.2

--- How were the frontal positions determined?

--- Fig. 5 shows the partial pressures of these tracers, not the concentrations.

--- How does mixing change the elevation of NADW (I assume the authors mean the shoaling of the core). What role does isopycnal mixing play in increasing the CFC concentrations to the south?

--- Fig. 6 has no info on the near---bottom concentrations of CFC---12

--- Note that once NADW enters the ACC, it does not continue due south crossing this strong current.

--- How does AAIW delimit the transition between UCDW and NADW? It is less dense
than these water masses.
--- Since the authors previous distinguish UCDWand LCDW, the discussion of the elevated CFC---12 at Stations 78---84 should identify this as LCDW.
--- Typo: Antarctic
--- Note: water masses are defined by their T and S (and density). It either is or is not WSDW.
--- The Deacon Cell is not what these authors are describing. I would refer to this as the Southern Ocean Meridional Overturning Circulation. Note that this shoaling is along an isopycnal surface. I'm not sure how the stability of the halocline relates to the SOMOC.
--- What is meant by "enhanced distances"?
--- There are very sparse SF6 data with which to draw any similarities with CFC---12.
--- The authors first point out that the depth to which they can detect SF6 has increased by 200---500 m between 1998 and 2012, and then they state that the only change is an increase in the vertical gradient.
--- What is meant by the "outer branches of AABW"?
--- Instead of averaging vs. depth, the tracers should be averaged along isopycnals and then projected onto a mean depth profile.
--- Since the SAF indicates the northern boundary of the ACC, the northern stations (north of 46°S) are outside of the ACC system.
--- The vertical profiles are smooth for both the northern and southern stations. The vertical gradient is much stronger and nearer the surface in the south.
--- "attributed" not "contributed"
--- The authors need to consider saturations when calculating the TAD – especially in the Southern Ocean.
--- The dashed blue line in Fig. 7c appears to be on the valid side of the TADmin. TAD of 6---12 yrs appear valid in Fig. 8a, and the pSF6 appear to be valid. S(p 2308, line 10)
--- Since SAMW and AAIW are formed via convective processes, would the authors expect their Peclet number to be near 1.? Would undersaturation need to taken into account?
--- A description of the time lag analysis should be included earlier in the manuscript. It is only valid when the individual pCFC---2 corresponds to apparent equilibrium with the atmosphere during the nearly---linear period from approx.. 1970---1990.
--- Argon---39 should be in steady---state (unless there are significant variations in its production or in ocean ventilation). There is no need to correct it to 2012. It is probably not valid to average bottom water concentrations from different basins.

- **Section removed. See remarks in the header.**

5 Conclusions
--- The various age ranges for which these tracers are appropriate have been discussed in many previous studies.
--- Typo: 6 E and 10 E
--- There are many, many papers on ventilation of the Southern Ocean. If the authors wish to cite a 2004 manuscript, at least cite it as e.g.

- **Conclusions rewritten according to the new findings and paper structure.**

Fig. 1
--- Why are panels a and c labeled for the Northern Hemisphere in 2012 and panel d for the Mediterranean Sea in 2011?
--- The caption should also note the date for which all of these panels are valid.

- **done**

Fig. 2
--- Similar comments to those for Fig. 1. Titles of panels need adjusted.

- **done**

Fig. 4
--- use wind speed in m/s rather than force 10

- **corrected**

Fig. 5
--- It is unclear whether all of the white areas are due to bad data or data with concentrations below the detection limit. If the latter is true, then these samples should still be indicated on the panels.

- **figures changed accordingly**

--- As a general comment, in order to make sense of the small print on many of these figures, it was necessary to zoom the figure size by 200%

- **Size of labels and data changed**

Fig. 6
--- Present the CTD data rather than the bottle data

- **figure removed**

Fig. 7
--- typo in the caption – the red line is defined in panel d twice

- **figure removed**