Dear Editor,

Thank you for allowing us the opportunity to revise the manuscript, “Investigating the relationship between volume transport and sea surface height in a numerical ocean model” by Estee Vermeulen et al. We are grateful to the two anonymous reviewers for their suggestions which have significantly improved the manuscript.

In particular we have condensed much of the text to improve readability of the manuscript and clarified the relevance of the study by clearly stating the aims of validating the Agulhas transport proxy in HYCOM, followed by a concise discussion on the shortfalls of the model transport proxy.

Please find below the detailed responses to the reviewers’ comments and the amended manuscript attached.

Kind regards

Estee Vermeulen,

on behalf of the authors.

Interactive comment on “Investigating the relationship between volume transport and sea surface height in a numerical ocean model” by Estee Vermeulen et al.,

Anonymous Referee #1

Received: 21 Dec 2018

1) The manuscript is very long and would benefit from shortening. There is a lot a duplication between the latter subsections of section 2 and the whole of section 3. Then the authors repeat the results in section 4 again.

Authors- Thank you for this suggestion, the manuscript has been shortened and duplication removed.

Changes in manuscript: Sections 1,2,3 & 4

2) The immediate relevance of the study is unclear. The authors present their results very much as a proof-of-concept for the ACT measuring principle, but the moorings have already been successfully deployed. The motivation therefore feels a bit redundant. Another motivation could be to improve physical understanding of the relationship between SSH and transport, but for that the manuscript is too much focused on the statistics of the relation between the two variables, rather than the hydrodynamics. For example, there are quite a few statements (e.g. line 277 & 279) where a careful analysis of the hydrodynamics would be appropriate

Authors: The goals of the paper were to use the numerical model to test the sensitivity of the transport proxy to i) changes in the vertical structure of the current and how this impacted the linear relationship between SSH slope and transport, and ii) the time period of data needed to build a strong relationship between transport and SSH slope. We appreciate this wasn’t clear and have now clarified our goals in the revision.

Changes in manuscript: Rephrased this in the Abstract (l 24-26), section 1 (l105-109) as well as in the summary and conclusion section (l426-431).

3) The construction of Tjet and Tbox is quite confusing. For e.g. there is a Tx and a Txsw, even though in both cases they are used for the transport in the southwest (sw) direction. Use better terms for these? Might it help to add the equations how all these transport variables are constructed?

Authors- Txsw is the southwestward component of Tx, we have clarified this in the text.

Changes in manuscript: See l 187-191 & l204-207

4) There is no validation of the depth structure of the Agulhas Current in HYCOM. Given that there is quite some mention of the baroclinic nature of the current, this would be good to validate using e.g. the ACT array data themselves.

Authors: Thank you for this suggestion, an important addition to the validation. We have now included a new figure showing the time mean (2010-2013) velocity cross section of the Agulhas Current at the ACT array, for both the ACT in-situ observations and for the HYCOM numerical model.

Changes in manuscript: See Fig 2 and l170-176

5) It is a missed opportunity I feel, that the authors have not also investigated the temperature/heat transport. That is something that was hard to do in the ACT array itself, yet is crucial for its climate monitoring ambition. Here, the authors have all the information to calculate the relation between volume and temperature transports

Authors: Unfortunately, this is beyond the scope of the study. The study is focused on investigating the sensitivity of the transport proxy to the underlying assumptions on which it was based. However, it is something we hope to pursue in future. Please see Bryden and Beal, 2001 & Morris et al., 2017.

Other, more minors comments are

- The abstract is fairly technical and detailed, especially in the second half. I am not sure how relevant this is to most readers. For example, how useful is it to mention the terms Tjet and Tbox if they are not explained?
Authors- Noted, the abstract has now been revised.
Changes in manuscript: See Abstract

- line 110: add 'time' before 'length scale'?
Authors- Noted, however this sentence was removed.

- line 161: It is unclear whether the nesting is one-way or two-way
Authors- One way nesting approach and clarified in the text
Changes in manuscript: l 130

- Is table 1 really relevant? Most, if not all, of the information is also in the text. And since there is only one model setup, why does it need to be in a table?
Authors: We agree and have now removed this table.
Changes in manuscript: removed Table 1

- Figure 1: The altimetry line stops just before reaching the shore. Is this an artefact of the plotting, or does this highlight that nearshore altimetry is not used. If the latter, it would be good to mention that
Authors- This was the first satellite coordinate point from track 96 (of the TOPEX/Poseidon and Jason satellites) overlapping the starting point of the ACT array

- line 272: I don't understand why the 12km product is used, if the 6km product is more accurate. Why not interpolate the 6km product to the actual mooring locations?
Authors- We used the 12km resolution as it more closely matches the 10km resolution of HYCOM. The 6km product also adds more noise/submesoscale processes, which is beyond the resolution of HYCOM to resolve.

- Eq 2: Why not use Tx here, if it is equivalent to Yi?

Authors- Yes, they are equivalent and we have changed Yi to Tx
Changes in manuscript: See l265 & Figure 8

- Table 3 would be much more useful if it also listed the observational ACT results?

Authors: We have now included the ACT observational results in Table 2.
Changes in manuscript: Table 2

- line 490: Is this increase from 86% to 88% is statistically significant?

Authors: This sentence was removed since the objective was not to formally compare the improvement between the fit of the linear models, but rather to assess the current structure of the residual transport events, in order to see why the linear relationship doesn't hold for certain transport events and at different locations of the array (see Fig 9). We essentially fitted a linear relationship to model data at each mooring, assessed the current structure of residual outliers that didn't fit the linear relationship, and refitted the linear relationship excluding the violating events (Figure 4). The linear relationship is suited to a barotropic current structure, however baroclinic variability in the model violates this proportional relationship between SSH slope and transport.
Changes in manuscript: l385-390

- Table 4: I don't understand why all the r-values are essentially the same. What does this tell us about the system? How to interpret this? And how is the correlation with the observations?

Authors: the performance of the proxy did not necessarily improve by calculating the linear relationship over longer time scales, suggesting that the current dynamics in the model system are very consistent.

Changes in manuscript: See Table 3 & l 493

type-os etc:

- line 62: 'area' instead of 'field'?

- line 120: Zhu et al should be ncitep{}

- line127: 'but may also be'

- line 182: remove ’notably’

- Figure 2: use ’dashed’ instead of ’faint’?

- line 641: ’has’ instead of ’have’

Authors: Thank you for highlighting these errors, all have now been corrected

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Anonymous Referee #2

Received: 16 Jan 2019

The manuscript would benefit with a reorder and editing. For example, in the Summary and Conclusion section the authors state (line 534-537) “The HYCOM model provided the means to investigate the validity of the assumptions used to create the proxies, such as the constant relationship between SSH slope and transport per unit distance at each mooring location and the temporal scale of observations needed to build a strong linear relationship between transport and SSH slope.” They then follow with a limited discussion explaining some reasons why the proxy does not capture the model transport, referring to figures to justify this reasoning – this is not a summary or conclusion. It is suggested that much of the information (lines 534-628) should be incorporated into the relevant parts of Section 3.
A reordering of Lines 629-696 would form what may be considered a “Summary and Conclusion” sections.

Authors- Thank you for these suggested changes which were in line with the other reviewer. We have now significantly condensed and clarified the text and flow of the paper.

Section 2.1 should only provide details of the model used in this study. The reader is not interested in the details of the larger regional model that provided the boundary conditions of the higher resolution (1/10o) nested model.
Authors: Noted and changed
Changes in manuscript: see section 2.1

The presentation of section 2 was convoluted and thus difficult for the reader to easily understand the approach taken. It is suggested that the authors revise this section to more clearly and concisely explaining the methods and assumptions.

Authors: Noted and revised

Changes in manuscript: Section 2

Lines 275-290 “The length scales of the slopes ranged from 24 km at mooring A to 12 km at mooring G and 48 km for the offshore CPIES-pairs, indicating an increase in the spatial scale of offshore flow, possibly due to increased offshore variability. Results from the in situ proxy experiment by Beal and Elipot [2016] also showed an increasing length scale with increasing distance offshore, however the results varied considerably in magnitude: 27 km at mooring B to 102 km at mooring G." Can you explain the reason for the difference in length scales between the model and observations (in situ and satellite)? Does this indicate the model doesn't capture the observed variability? What implications does this have for this study?

Authors: The reason why the length scales differ between the model and the observations is because the model does not capture completely and accurately the observed variability. This limitation and its implication is now discussed in this study and clarified in the text.

Changes in manuscript: See l 434 (section 4)

It is suggested that section 2.4.1 be revised to remove any unnecessary information concerning the larger regional model.

Authors: Noted and changed

Changes in manuscript: section 2.4.1

Line 407-408. "The proxies only capture a portion of the transport estimate from the HYCOM model, suggesting it also only captures a portion of the model variability." Is this the only problem with the proxy estimate? A more detailed analysis is really required to understand the impact of the assumptions used in developing the proxy.

Authors: The frequently impinging eddies make it difficult for the proxy to accurately estimate the transport of both Tbox and Tjet because the eddies resulted in the correlation of the regression models decreasing offshore. Therefore, the proxy transport estimates (for both Tbox and Tjet) inshore were more accurate than the ones offshore. We have clarified this in the text

Changes in manuscript: l 436-464

Line 418-420 "In summary, the results indicate that the proxy is generally better suited in HYCOM to estimate the box transport rather than the jet transport. Further analysis in this study therefore only focuses on the box transport." It is not appropriate to simply ignore results that don't agree. You need to fully explore the reasons why the different proxies fail.

Authors: The difference in the performance of the jet transport algorithm in the models and in the observations suggests that the models are unable to resolve all the dynamics associated with meander events, for which the jet algorithm was specifically developed.

The jet transport proxy by Beal and Elipot [2016] was developed to estimate the transport of the Agulhas Current during mesoscale meander events, which generally causes the current to manifest as a full-depth, surface intensified, cyclonic circulation out to 150 km from the coast with anticyclonic circulation farther offshore. The Agulhas meanders in the HYCOM simulation occur in association with large anticyclonic eddies predominantly located at the offshore edge of the current, with a narrow, southwest stream close to the coast. In some instances anticyclonic eddies span the length of the entire array. Therefore, considering that the model is unable to resolve the dynamics associated with meander events, for which the jet transport algorithm was specifically developed, further analysis only focuses on the box transport proxy
In addition, the poorer performance of the Tjet proxy in HYCOM and possibly in the in situ study, may also be because it only represents the southwestward component of the flow, whereas the input sea

surface slope reflects the net flow along the array. Therefore, based on these findings further analysis focussed on the Tbox proxy.
We have explored this in the text.

Changes in manuscript: see l33, l331-340 & l440-455

Lines 485-499 Removing outlier to increase the performance of the proxy is not appropriate. The authors should clearly identify the dynamical reasons for the reduced skill of the proxy. It is only through this in-depth analysis that advantages and disadvantages of the proxy can be fully explored.

Authors- The reason we decided to remove the outliers was because in the case of the offshore linear models, the outliers were often the transport events that violated the linear relationship between SSH slope and transport. Investigation into the current structure of the outlying transport events further showed the baroclinic nature of the eddies that broke down the linear relationship between SSH slope and transport, specifically for the offshore regression models. Thus, removing the transport events that violated the relationship proved to increase the performance of the proxy. Motivating that the offshore variability resulted in the poorer performance of the models offshore.

Changes in manuscript: see l385-l390 & l465-468 & Figure 4

The manuscript is lengthy and the prose overly convoluted and repetitive, when reviewing the manuscript the authors should, where possible, simplify the writing and remove repetition. Below are a few examples:

Authors: Thank you for highlighting this, we have thoroughly revised the manuscript to improve readability.

Line 85-89 "The Agulhas transport proxy of Beal and Elipot [2016] was derived from the physical principle of geostrophy, where along-track sea surface height slope measured by satellite altimeters can ultimately be related to a measure of volume transport across a portion of the current, provided that the surface current represents the flow at depth [Beal and Elipot, 2016]. " can be deleted as lines 89-93 fully explain the major findings of the Beal and Elipot, 2016 study.

Authors: Noted and corrected

Line 151 change ": : : in doing so: : :" to ".. thus : : :"

Authors: Corrected

Line159-161 remove " The horizontal resolution of the parent model ranged from 14 km in the northern Indian Ocean to 45 km in the Southern Ocean, with a resolution ranging from 30 to 40 km in the region of the Agulhas Current." This information is not needed; the reader can refer to George et al., 2010 if they require more information on the model from which the boundary conditions were taken.

Authors: Noted and corrected

Line 154-155 Change “The HYCOM output in this study was made available from a nested 1/10_ model of the greater Agulhas Current System (AGULHAS) [Backeberg et al., 2008; 2009; 2014].” To “This study used output from a nested 1/10_ model of the greater Agulhas Current System (AGULHAS) [Backeberg et al., 2008; 2009; 2014].”

Authors: Noted and corrected

These are a few examples; there are many more instances of repetition and where more concise writing would improve the text.
Minor comments

Line 45 change “As the current continues southwestward the current becomes..” to “As the current continues southwestward it becomes.. “

Authors: Noted and corrected

Line 60-62 poorly constructed sentence “The unique circulation of the Agulhas Current System, in the context of regional and global climates, makes it an important field of research.”

Authors: The unique circulation of the ACS, in the context of regional and global climate variability, makes it an important field of research
Changes to manuscript- l63

Line 67: “However, the close proximity of the current to the coast makes it difficult to monitor using satellite altimetry [Rouault et al., 2010].” Is this statement still true given the development of the AVISO X-track product (https://www.aviso.altimetry.fr/en/data/products/sea-surface-heightproducts/regional/x-track-sla/coastal-along-track-sea-level-anomalies.html)?

Authors: Noted and addressed
Changes in manuscript: in l70-73. The close proximity of the Agulhas Current to the coast has made it difficult to monitor using satellite altimetry, however, newer altimetry products dedicated to coastal areas are promising but are yet to be validated within the Agulhas Current region (Birol et al., 2017).

Line 74-84. It can be shown that the total cost of in situ observing, satellite observations and models are all on similar cost. Singling out in situ observations as the only costly tool is not appropriate or accurate.

Authors: Noted, cost aspect removed.
Changes in manuscript: l80

Change “ In situ observations may accurately measure the dynamics of the Agulhas Current throughout the water column but are expensive and spatially coarse.” To “In situ mooring observations provide high temporal observations of the Agulhas Current throughout the water column but spatially coarse.” Authors: Noted and corrected

Line 106 Change [Beal and Elipot, 2016] to Beal and Elipot [2016] Authors: Noted and corrected

Line 120 Change Zhu et al. [2004] to [Zhu et al., 2004] Authors: Noted and corrected

Line 158-159 Change ".. buffer zone." To ".. sponge layer." Authors: Noted and corrected

Line 166-167 Change "Both models have 30 hybrid layers and targeted densities ranging from 23.6 to 27.6 kg/m3. To "AGULHAS has 30 hybrid layers and targeted densities ranging from 23.6 to 27.6 kg/m3." Authors: Noted and corrected

Line 185 Add " : : : 2010-2013 (Figure 1, Beal et al., 2015) Authors: Noted and corrected

Line 193-195 Change "During the first phase of the ACT experiment, the mooring array was maintained in the Agulhas Current for a period of 34 months, perpendicular to the continental slope at 34_S, south of East London, South Africa (Figure 1)." To " The ACT mooring array was located perpendicular to the continental slope at 34_S, south of East London, South Africa (Figure 1)." Authors: Noted and corrected

Line 200 Change " From the data collected in Beal et al. [2015], two volume transports were estimated:: : : " to "From the data collected, Beal et al. [2015], provided two volume transports estimates: .." Authors: Noted and corrected

Line 202 Change ": : : is a net transport" to ": : : is the net transport .." Authors: noted and corrected

Line 218 Remove "Based on physical principles sea surface slope is proportional to surface geostrophic velocity." Authors: Removed

Line 237 Define Tx and Txsw

Authors: The transport variable in the regression models was defined as transport per unit distance, i.e. the vertically integrated velocity with units in ms2.s-1 where *Tx* represents the net component of the current flow and *Txsw* the southwestward component of the flow.

Changes in manuscript: See l187-191

Line 269 "The coordinates of the along-track altimeter data were obtained from the filtered 12km Jason-2 Aviso satellite product, and not the unfiltered 6 km product which was used for the original ACT proxy [Beal and Elipot, 2016], since the 12 km product matched the _10 km model resolution more closely." Is this difference significant given that the model is interpolated onto the altimetry ground track?

Authors: No, the difference is not significant. However, at the time, we decided to use the 12km resolution as it more closely matches the 10km resolution of HYCOM.

Figure 2 Caption. Change "Figure 2: HYCOM transport per unit distance proxy (m2 s⍰1) for Tx (blue) and Txsw (red) transport at 1 km intervals at the first model time step (solid lines, week of 3rd January 1980) and for the mean reference period (dashed lines). The faint grey lines represent the positions of moorings and offshore CPIES pairs." To Figure 2: HYCOM transport per unit distance proxy (m2 s⍰1) for Tx (blue) and Txsw (red) transport at 1 km intervals at the first model time step (solid lines) and for the ACT reference period (2010-2013, dashed lines). The grey dashed-lines represent the positions of moorings and offshore CPIES pairs.” Authors: Noted and corrected

Changes in manuscript- see Figure 3

Line 303-306 remove “Tx and Txsw are simply shown at the first model time step (week of the 3rd of January 1980) in HYCOM and for the mean of the reference period (2010-2013) to show the difference between the net and southwest transport components used to calculate Tbox and Tjet (Figure 2).” Authors: Removed

Line 411 Remove “Figure 4 shows the correlation between proxy and model transports for each year.” Authors: Removed

Line 413 Add “: : :.insignificant minimum correlation of 0.00 (2003) (Figure 4).” Authors: Noted

Line 413 Change “: : : correlation of 0.82 (2014) and an insignificant minimum correlation of 0.00 (2003).” To “: : : correlation of 0.82 (2014) and a minimum correlation of 0.00 (2003).” Authors: Noted

Lines 428-431 Remove. “Figure 5 shows the surface variability by displaying the eddy kinetic energy and the mean surface geostrophic flow as represented by the overlaying SSH contours over the 3-year reference period, and over the highest (1988) and lowest (1994) correlated years of the box transport proxy.” Authors: Removed

Any important information in this sentence should be included in the figure caption.

Line 431-432. Add “During the reference period the current appears to be stable with low levels of EKE inshore whereas offshore the flow is more variable with higher levels of EKE (Figure 5).” Authors: Noted

Line 445 Remove “Figure 6 shows the mean cross-track velocity profiles during the reference period (2010- 2013), the highest correlated year (1988) and the lowest correlated year (1994) for each mooring and the CPIES-pairs.” Authors: Removed
Any important information in this sentence should be included in the figure caption

Investigating the relationship between volume transport and sea surface height in a numerical ocean model

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Abstract

The Agulhas Current Time-series mooring array (ACT) measured transport of the Agulhas Current at 34°S for a period of 3 years. Using along-track satellite altimetry data directly above the array, a proxy of Agulhas Current transport was developed based on the relationship between cross-current sea surface height (SSH) gradients and the measured transports. In this study, the robustness of the proxy is tested within a numerical modelling framework, using a 34-year long regional-hindcast simulation from the Hybrid Coordinate Ocean Model (HYCOM). Two reference proxies were created using HYCOM data from 2010-2013, extracting model data at the mooring positions and along the satellite altimeter track for; ~~(1)~~ the box-transport ~~(T_{box})~~ and ~~(2)~~ the jet (southwestward) transport ~~(T_{jet})~~. ~~Next,~~ sensitivity tests were performed where the proxy was recalculated from HYCOM for (1) a period where the modelled vertical stratification was different compared to the reference proxy, and (2) different lengths of periods: 1, 3, 6, 12, 18 and 34 years. Compared to the simulated (native) transports, it was found that the HYCOM proxy was more capable of estimating the box transport of the Agulhas Current compared to the jet transport. The HYCOM configuration in this study contained exaggerated levels of offshore variability in the form of frequently-impinging baroclinic anticyclonic eddies. These eddies consequently broke down the linear relationship between SSH slope and vertically-integrated transport, ~~resulting in stronger correlations for the inshore linear regression models compared to the ones offshore. Vertically integrated transport estimates were therefore more accurate inshore than those offshore or when the current was in a meandering state.~~ Results showed that calculating the proxy over shorter or longer time periods in the model did not significantly impact the skill of the Agulhas transport proxy, suggesting that 3-years was a sufficiently long time-period for the observation based transport proxy.

1 Introduction

The Agulhas Current System is the strongest western boundary current in the Southern Hemisphere and transports warm tropical water southward along the east coast of South Africa [Lutjeharms, 2006]. The Agulhas Current, in the northern region, is known for its narrow, fast, flow conditions following the steep continental slope [de Ruijter et al., 1999]. As the current continues southwestward the current becomes increasingly unstable over the widening continental shelf until it eventually retroflects, forming an anticyclonic loop south of Africa and returning to the Indian Ocean as the eastward Agulhas Return Current [Beal et al., 2011; Biastoch and Krauss, 1999; Dijkstra and de Ruijter, 2001; Hermes et al., 2007; Lutjeharms, 2006; Loveday et al., 2014]. The anticyclonic loop, known as the Agulhas retroflection, contains some of the highest levels of mesoscale variability in the global ocean [Gordon, 2003] ~~through the formation of~~ Agulhas rings, eddies and filaments. ~~This, in turn, contributes significantly to the Benguela upwelling system, the Atlantic Ocean and the global overturning circulation system [Gordon et al., 1987; Beal et al., 2011; Durgadoo et al., 2013], thereby impacting the Atlantic Meridional Overturning Circulation (AMOC) by providing a salt advective feedback through a process known as the Agulhas leakage [Biastoch and Krauss, 1999; Beal et al., 2011; Durgadoo et al., 2013; Loveday et al., 2014].~~ In the regional context, the Agulhas Current has a major influence on the local weather systems, due to large latent and sensible heat fluxes, which contributes to rainfall and storm events over the adjacent land [Reason, 2001; Rouault et al., 2002; Rouault and Lutjeharms, 2003]. The unique circulation of the Agulhas Current System, in the context of regional and global climate~~s~~, makes it an important field of research.

To understand the complicated dynamics of the Agulhas Current requires an integrated approach using numerical ocean models, satellite remote sensing measurements and *in situ* observations. Previous studies have suggested that measuring the dynamics of the Agulhas Current in the northern region is easier due to its stable trajectory and its confinement to the continental slope [van Sebille et al., 2010]. However, the close proximity of the current to the coast makes it difficult to monitor using satellite altimetry [Rouault et al., 2010]. In addition, the frequent disturbances of the current in the form of solitary meanders, also known as Natal Pulses, and its interactions with mesoscale features originating upstream and from the east [Elipot and Beal, 2015], remain poorly resolved in many numerical ocean models [Tsugawa and Hasumi, 2010; Braby et al., 2016], highlighting the challenges involved in monitoring and modelling the dynamics in this region.

There is a trade-off between spatial and temporal sampling. *In situ*-observations may accurately measure the dynamics of the Agulhas Current throughout the water column but are expensive and spatially coarse. In contrast, satellite observations can provide high spatial resolution data of the surface ocean but lacks detailed information below the surface. Hence, numerical models are needed to provide a temporally coherent, high resolution representation of the ocean throughout the water column. Numerous studies aiming to monitor long-term changes in global current systems have adopted methods to combine various sampling tools [eg. Maul et al. 1990; Imawaki et al. 2001; Andres et al. 2008; Zhu et al. 2004; Yan and Sun 2015], including the recent development of the Agulhas transport proxy established to monitor the interannual variability and long-term trends in Agulhas Current transport [Beal and Elipot, 2016].

The Agulhas transport proxy of Beal and Elipot [2016] was derived from the physical principle of geostrophy, where along track sea surface height slope measured by satellite altimeters can ultimately be related to a measure of volume transport across a portion of the current, provided that the surface current represents the flow at depth [Beal and Elipot, 2016]. Beal and Elipot [2016] have shown that a strong relationship exists between surface geostrophic velocity and full-depth transport such that sea level anomalies can be used to study the variability and dynamics of the Agulhas Current System as has been demonstrated before [Fu et al., 2010; Rouault et al., 2010; Rouault and Penven, 2011; etc.]. The 22-year transport proxy created by Beal and Elipot [2016] assumed a fixed linear relationship between *in situ* transport and sea surface slope based on *in situ* measurements over the 3-year sampling period of the Agulhas Current Time-series experiment (ACT) [Beal et al., 2015]. Analyses of the Agulhas Current transport proxy time-series concluded that the Agulhas Current has not intensified over the last two decades in response to intensified global winds under anthropogenic climate change [Cai, 2006; Yang et al., 2016], but instead has broadened as a result of increased eddy activity [Beal and Elipot, 2016] in agreement with Backeberg et al. [2012].

This modelling study aimed to recreate the Agulhas transport proxy developed by Beal and Elipot [2016], within a regional HYCOM simulation of the greater Agulhas Current System in order to test the validity of the underlying assumptions on which the satellite altimeter derived proxy was based. Firstly, the Agulhas Current transport proxy was recreated using modelled data from HYCOM following the methodology of Beal et al. [2015] and [Beal and Elipot, 2016] for the data period 2010-2013. This reference proxy allowed for the relationship between Agulhas Current transports and sea surface slope across the Agulhas Current Time-series experiment (ACT) array to be investigated in HYCOM. Following this, the impact of the vertical variability of the current on the accuracy of the transport proxy was assessed. Finally, the optimal length scale of observations needed to build a strong linear relationship between transport and SSH slope was tested by recalculating the proxy using 1, 3, 6, 12, 18 and 34 years of HYCOM data.

Assuming a constant vertical stratification over the 3 year sampling period, and hence ignoring baroclinic changes that could potentially impact the linear relationship between sea surface slope and full depth transport could become problematic when generating a 22 year proxy of Agulhas Current transports. Therefore, key questions for this paper include: (1) How is the linear relationship between transport and sea surface slope affected when recalculating the proxy over longer time periods in HYCOM? (2) How will changes in the vertical structure of the Agulhas Current impact the transport proxy? Theoretically the vertical velocity structure changes during mesoscale meander events Zhu et al. [2004] and thermohaline processes [Beal and Elipot, 2016] since horizontal changes in stratification result in changes in the velocity structure with depth. Perhaps even changes in the strength of the Agulhas Undercurrent may impact the transport proxy. Finally, (3) what would be the ideal sampling period needed to build a strong, linear relationship between transport and SSH slope? Building the linear relationship over periods longer than 3 years could perhaps increase the skill of the transport proxy by averaging out random perturbations, but may be also be affected by the interannual variability of the current system [Elipot and Beal, 2018]. This study aims to test the robustness of using 3 years of *in situ* mooring data to develop a satellite altimetry derived transport proxy for the Agulhas Current at 34°S, by testing the underlying assumptions in a numerical modelling framework. This can assist in planning future deployments of moorings ultimately

~~facilitating the improvement of an integrated ocean observing system for the Agulhas Current.~~

This paper is structured as follows; Section 2 describes the data and methods, it should be noted that this section forms a key part of the paper as the methods of recreating the proxy are an integral component of the study. Section 3 presents the results from the HYCOM transport proxy and lastly Section 4 presents the summary and conclusions.

2 Data and Methods

2.1 The Hybrid Coordinate Ocean Model

The Hybrid Coordinate Ocean Model (HYCOM) is a primitive equation ocean model that was developed from the Miami Isopycnic Coordinate Ocean Model (MICOM) [Smith et al., 1990]. HYCOM combines the optimal features of isopycnic-coordinate and fixed-grid ocean circulation models into one framework [Bleck, 2002] and uses the hybrid layers to change the vertical coordinates depending on the stratification of the water column. The model makes a dynamically smooth transition between the vertical coordinate types via the continuity equation using the hybrid coordinate generator [Chassignet et al., 2007]. Well-mixed surface layers use z-level coordinates, -coordinates are utilized between the surface and bottom layers in a well-stratified ocean, and the bottom layers apply -coordinates following bottom topography. Adjusting the vertical spacing between the hybrid coordinate layers in HYCOM simplifies the numerical implementation of several physical processes without affecting the efficient vertical resolution, and ~~in doing so~~ combines the advantages of the different coordinate types in optimally simulating coastal and open-ocean circulation features [Chassignet et al., 2007].

~~The HYCOM output in this study was made available from a nested 1/10°~~ model of the greater Agulhas Current System (AGULHAS) [Backeberg et al., 2008; 2009; 2014]. The regional nested model, AGULHAS, received boundary conditions from the basin-scale model of the Indian and Southern Ocean (INDIA) [George et al., 2010] every 6-hrs. The boundary conditions were relaxed towards the outer model over a 20 grid cell ~~buffer zone.~~ ~~The horizontal resolution of the parent model ranged from 14 km in the northern Indian Ocean to 45 km in the Southern Ocean, with a resolution ranging from 30 to 40~~

km in the region of the Agulhas Current. The nested model covered the region from the Mozambique Channel to the Agulhas Retroflection region and the Agulhas Return Current, geographically extending from approximately 0°-60° East and from 10°-50° South, with a horizontal resolution of ∼10 km that adequately resolved mesoscale dynamics to the order of the first baroclinic Rossby radius estimated to be about 30 km [Chelton et al., 1998]. Both models have 30 hybrid layers and targeted densities ranging from 23.6 to 27.6 kg/m^3.

The parent model was initialised from Levitus climatology (WOA05) [Antonov and Levitus, 2006] and spun up for 10 years using climatological ERA interim forcing [Dee et al., 2011]. AGULHAS was initialised from a balanced field of the parent model interpolated to the high-resolution grid. Both models were then run from 1980 to 2014 using interannual forcing from ERA40 [Uppala et al., 2005] and ERA-interim [Dee et al., 2011]. Version 2.2 of the HYCOM source code has been used in this model and, together with the second order advection scheme, provides an adequate representation of the Agulhas Current [Backeberg et al., 2014]. However, limitations of the free running model include high levels of SSH variability south of Madagascar and offshore of the Agulhas Current, suggesting that eddy trajectories may be too regular in the model [Backeberg et al., 2014]. The data available for this study was a weekly output of the regional HYCOM model of the Agulhas region from 1980 to 2014. See table 1 for a summary of the model configuration.

2.2 The Agulhas Current Time-series Experiment

The ACT experiment was established to notably obtain a multi-decadal proxy of Agulhas Current transport using satellite altimeter data. The first phase of the experiment was the *in situ* phase where the ACT mooring array was deployed in the Agulhas Current, near 34 S, for a period of three years from 2010-2013 [Beal et al., 2015]. The second phase was the development of the transport proxy, where sea surface height along the ACT section, obtained from along track satellite altimetry, was regressed to the *in situ* transport measurements [van Sebille et al., 2010; Beal and Elipot, 2016]. To optimally facilitate the regression between the transport and altimetry, the ACT array was collocated with the altimeter track number 96 successively occupied by satellites TOPEX/Poseidon

Table 1: HYCOM specifications.

Model	HYCOM (regional)
Configuration	AGULHAS (nested)
Nested domain	0°-60°E; 10°-50°S
Time period	1980-2014
Resolution	1/10°; Weekly (7/8 days)
Grid spacing (km)	~10 km
Vertical discretization	30 hybrid layers Target densities (+1,000 kg/m3) layer 1 - layer 30: 22.30, 22.60, 22.90, 23.20, 23.50, 23.80, 24.10, 24.40, 24.70, 25.00, 25.30, 25.60, 25.90, 26.20, 26.50, 26.80, 26.89, 26.99, 27.08, 27.18, 27.27, 27.37, 27.46, 27.56, 27.65, 27.75, 27.84, 27.94, 28.00, 28.05
Bathymetry	GEBCO 1'
Atmospheric forcing	6-hourly ERA-interim reanalysis data (1/4°) resolution
Boundary forcing	Parent model (INDIA)
Advection scheme	2nd order
Vertical mixing scheme	KPP

(1992-2002), Jason-1 (2002-2008) and currently Jason-2 (since 2008) and Jason-3 (since 2016) [Beal and Elipot, 2016] (Figure 1).

During the first phase of the ACT experiment, the mooring array was maintained in the Agulhas Current for a period of 34 months, perpendicular to the continental slope at 34°S, south of East London, South Africa (Figure 1). The array was made up of 12 sites; site A through G were full depth current meter moorings which were, on average, 26 km apart. Sites P2-P5 were CPIES (Current- and Pressure-recording Inverted Echo Sounders) placed 50 km apart. The CPIES were used to estimate the geostrophic cross-track velocity beyond mooring G so that the Agulhas Current variability was fully captured during

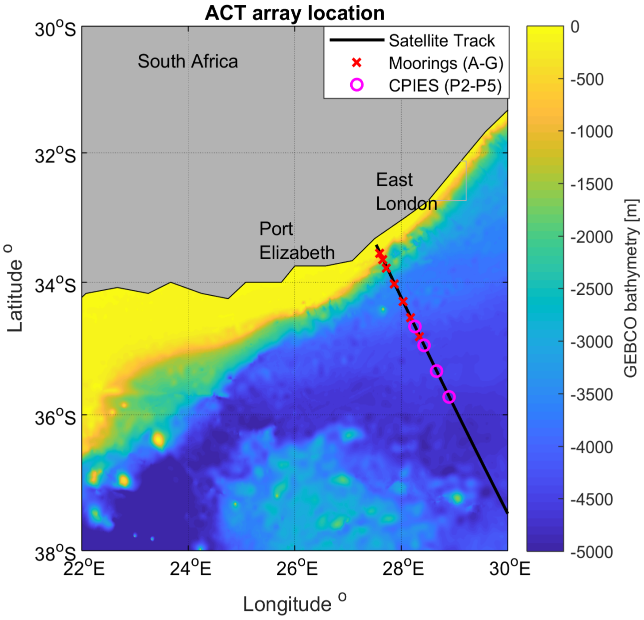


Figure 1: Geographical location of the ACT array with the mooring (red crosses) and CPIES (magenta circles) stations relative to the T/P, Jason-1,2,3 satellite track #96 (black line). Colour shading illustrates the GEBCO bathymetry (m).

meander events [Beal et al., 2015]. From the data collected in Beal et al. [2015], two volume transports were estimated: (1) a box or boundary layer transport (T_{box}) and (2) a western boundary jet transport (T_{jet}). T_{box} is a net transport within a fixed distance from the coast, while T_{jet} is a stream dependent transport that is calculated by changing the boundaries of integration at each time step depending on the strength and cross-sectional area of the southwestward jet. The western boundary jet transport algorithm was developed to specifically exclude the northeastward transport during meander events, occurring inshore of the meander [Beal et al., 2015].

During the second phase of the ACT experiment, Beal and Elipot [2016] built a 22-year transport proxy by regressing the three years of *in situ* transport measurements against along-track satellite altimeter data spanning the years 1993-2015. Beal and Elipot [2016] noted the importance of the relationship between sea surface height and transport when inferring trends in the current structure based on satellite altimetry and remained cautious regarding the assumptions used to validate the proxy. In order to obtain transport estimates using altimetry, it was also important to define accurate boundaries for the Agulhas Current to distinguish whether the current is stable or meandering and to determine the width of the current to calculate T_{box} and T_{jet}.

2.3 Development of the Agulhas transport proxy

Based on physical principles sea surface slope is proportional to surface geostrophic velocity. Previous analyses have shown that the vertical structure of the Agulhas Current is barotropic [Elipot and Beal, 2015], such that the direction of current velocity anomalies does not change significantly with depth. This suggests that the relationship between surface geostrophic velocity and full depth transport should be strong, despite the presence of the Agulhas Undercurrent [Beal and Elipot, 2016]. The relationship between sea surface slope and transport was therefore tested using linear regression models, which explicitly described a relationship between the predictor variable, sea surface slope and the response variable, transport per unit distance [van Sebille et al., 2010; Beal and Elipot, 2016].

The transport proxy created by Beal and Elipot [2016] was initially developed by finding a linear relationship between transport and sea surface slope across the entire length of the ACT array, a common method used in previous studies [Imawaki et al., 2001; van Sebille et al., 2010; Sprintall and Revelard, 2014; Yan and Sun, 2015]. However, this method lead to uncertainty in the linear regression due to the strong, co-varying sea surface height across the current. The preferred method was therefore to build nine individual linear regression models, one for each mooring position and CPIES-pairs along the ACT array, which locally related transport to sea surface slope [Beal and Elipot, 2016]. It is important to note that the regression models assumed a constant, linear relationship between sea surface slope and transport over the three-year *in situ* period. The transport variable in the regression models was defined as transport per unit distance (Tx and $Txsw$), i.e. the vertically integrated velocity with units in m^{2}s^{-1}. The total transports, T_{box} and T_{jet} in m^{3}s^{-1}, were calculated by integrating the Tx and $Txsw$ estimates, predicted from the regression models, to the respective current boundaries.

2.4 Recreating the Agulhas transport proxy in HYCOM

2.4.1 Model Transport

In order to recreate the Agulhas Current proxy in HYCOM, data corresponding to the measurements collected from the ACT mooring array were extracted from the model.

The barotropic velocity -equivalent to an integral of the velocity with depth- from each mooring location (A-G) and CPIES pairs P3-P4 and P4-P5 was extracted for the 34-year model period. Extracting the barotropic velocity component from each mooring avoided interpolation errors that may have occurred if the model velocity was interpolated onto the locations of each current-meter instrument on each mooring [e.g. van Sebille et al., 2010]. Transport per unit distance (Tx) for each mooring was calculated by multiplying the cross-track barotropic velocity by the respective depth at each mooring location and the sea surface slope for each of the locations were obtained from the model (see next section) (hereafter CPIES pairs P3-P4 and P4-P5 were included as mooring positions 8 and 9). The same method was employed to build regression models between sea surface slope and the southwestward component of the flow ($Txsw$), as is required to ultimately calculate the jet transport (T_{jet}) [Beal et al., 2015].

To assess the accuracy of the transport proxy, the HYCOM transport proxy was compared to the simulated (native) transport in HYCOM to quantify the differences between the proxy and modelled transports and hence understand which processes the proxy may fail to represent. The transport across the ACT section in HYCOM was extracted by setting up the grid points between the two coordinates defining the start and end of the section following the great circles of the sphere and calculating the defined transport at each grid point along the section. The transport calculation facilitated a separation of the transports into two components: the box transport (T_{box}) and the jet transport (T_{jet}).

2.4.2 Model SSH

In order to reproduce the "along-track" SSH altimeter data needed to create the proxy as in Beal and Elipot [2016], 34 years of HYCOM SSH was linearly interpolated onto the coordinates of the TOPEX/Jason satellite track number 96 overlapping the model ACT array. The coordinates of the along-track altimeter data were obtained from the filtered 12 km Jason-2 Aviso satellite product, and not the unfiltered 6 km product which was used for the original ACT proxy [Beal and Elipot, 2016], since the 12 km product matched the ~10 km model resolution more closely. To obtain the sea surface slope for each regression model, an optimal pair of SSH data points was chosen such that the horizontal length scale between them allowed for a maximum correlation between the sea surface slope and *Tx*. The length scales of the slopes ranged from 24 km at mooring A to 12 km at mooring G and 48 km for the offshore CPIES-pairs, indicating an increase in the spatial scale of offshore flow, possibly due to increased offshore variability. Results from the *in situ* proxy experiment by Beal and Elipot [2016] also showed an increasing length scale with increasing distance offshore, however the results varied considerably in magnitude: 27 km at mooring B to 102 km at mooring G. In this study the SSH slope was calculated such that a negative SSH slope corresponds to a negative surface velocity (southwest) according to geostrophy, whereas a positive slope would indicate positive northeastward flow.

2.4.3 Building the regression models

Nine linear regression models were ~~first~~ developed to estimate the transport per unit distance *(Tx* and *Txsw*) from the HYCOM sea surface slope during ~~approximately~~ the same three-year period over which the ACT proxy was developed (April 2010- February 2013). The three-year time period ~~will further be referred to as the reference period~~. ~~Further tests were later performed, where the proxy was calculated over a range of different time periods (see section 2.6).~~

To calculate the total transport across the ACT array requires continuous *Tx* estimates across the current. This was achieved as in Beal and Elipot [2016] by fitting a piece-wise cubic Hermite interpolating polynomial function to obtain transport estimates at 1 km intervals from the coast to the end of the array (Figure ~~2)~~. Fitting the transport function to the coast and equating it to zero would be equivalent to implementing a no slip boundary condition in the model. Before calculating the total transport the current boundaries needed to be defined. The box transport (T_{box}) was calculated by integrating *Tx* horizontally to 230 km offshore, the three-year mean width of the current in HYCOM. The jet transport (T_{jet}) was calculated using the algorithm developed by Beal et al., 2015 by integrating *Txsw,* the southwest transport component, to the first maximum of *Tx* beyond the half-width of the current (115 km in HYCOM) at each time step (Figure ~~2)~~. ~~Beal et al. [2015] argued that T_{jet} therefore captured the southwestward transport of the~~

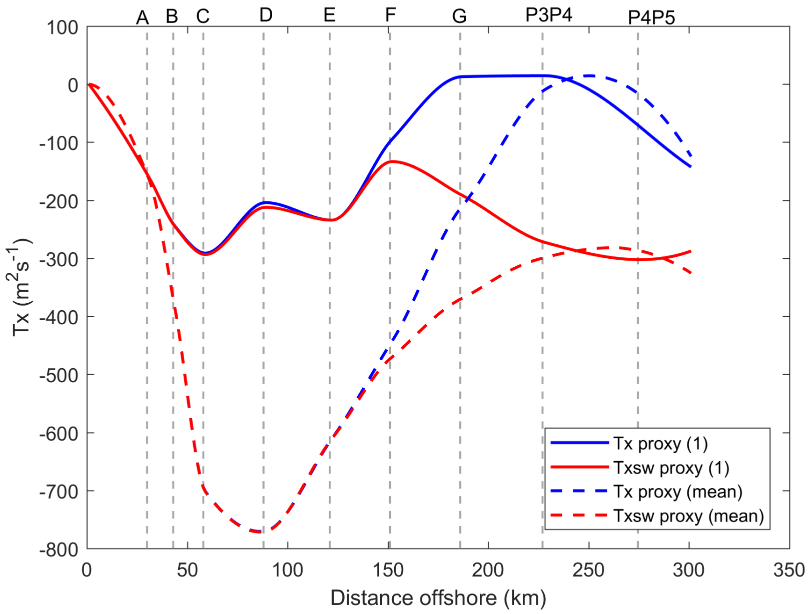


Figure 2: HYCOM transport per unit distance proxy (m^2 s ^{1}) for Tx (blue) and $Txsw$ (red) transport at 1 km intervals at the first model time step (solid lines) and for the mean reference period (dashed lines). The faint grey lines represent the positions of moorings and offshore CPIES pairs.

meandering Agulhas Current. Tx and $Txsw$ are simply shown at the first model time step (week of the 3rd of January 1980) in HYCOM and for the mean of the reference period (2010-2013) to show the difference between the net and southwest transport components used to calculate T_{box} and T_{jet} (Figure 2).

In order to test the accuracy of the transport proxy, it was first compared to the HYCOM transport for the same period over which the proxy was developed (2010-2013). By studying the corresponding model fields we were able to identify dynamic features in the model that the proxy failed to capture. The correlation for the overlapping transports from the model and the model proxy was calculated as well as the 3-year mean and standard deviation (Table 3). Then, assuming that the three-year linear relationship between SSH slope and transport per unit distance (Tx and $Txsw$) from 2010-2013 remains constant, the regression models were applied to the entire 34-year SSH model data. This resulted in transport per unit distance estimates (Tx and $Txsw$) for each mooring position at each time step from 1980 to 2014. Thereafter, the 34-year transports were calculated by applying the same methods that were used to calculate the 3-year transport time-series; firstly, obtaining Tx estimates at 1 km-intervals along the array and secondly integrating horizontally to obtain T_{box} and T_{jet} (Figure 2).

2.5 Comparison of the transport proxy to actual model transports

The simulated model transports were calculated using the full-depth velocity fields across the array. If the relationship between SSH slope and transport is strong, there would be good agreement between the proxy and the actual model transports. To quantify this, correlations and transport statistics for the model and proxy were calculated from the two time series. These provided insight into which processes the proxy may have failed to capture, which were then further investigated in HYCOM. Statistics are deemed significant at the 95% significance level.

Eddy kinetic energy (EKE) was calculated to show the surface variability of the current coincident with averaged SSH contours used to represent the mean surface structure (Figure 5). The eddy kinetic energy was calculated as follows:

$$\mathrm{EKE} = \frac{(u^0)^2 + (v^0)^2}{2} \qquad (1)$$

where u^0 and v^0 are the zonal and meridional geostrophic current anomalies relative to the geostrophic current mean calculated over the 3-year mean reference period, and over the highest and lowest correlated years. In order to evaluate the subsurface current structure along the ACT array, vertical velocity profiles were analysed for each mooring and CPIES-pair over the 3-year mean reference period as well as over the highest and lowest correlated years.

Transport variability in the HYCOM model was analysed by investigating residual transport events in the worst and best performing regression models. In order to examine the impacts of variable mesoscale features, residual transport events were identified as the outlying residual transport values above and below 2 standard deviations of the estimated transport.

$$e = Y_i - \hat{Y}_i \qquad (2)$$

where e is the estimated residuals, Y_i is the HYCOM transport per unit distance value (Tx) and $\hat{Y}_i$ is the estimated transport per unit distance value according to the linear regression models.

To investigate the current structure during these residual events, composite averages of the cross-track velocity structure were analysed. The cross-track velocity at each depth layer in HYCOM was extracted at 12 km intervals from 0 km to 400 km offshore, for the 34-year model period. Although the ACT array only reached 300 km offshore, analysis of the current structure in HYCOM was extended further offshore. Previous analyses have shown increased levels of offshore variability in this HYCOM simulation [Backeberg et al., 2009; 2014], which therefore made it interesting to study the subsurface structure during the offshore current meanders and the influence these could have on the transport proxy. To further investigate the effect of the residual transport values on the ~~box~~ transport proxy, ~~considering it performed better than the jet transport proxy (see section 3.2),~~ all corresponding transport events exceeding plus or minus two standard deviations were removed from each linear regression model during development of the proxy~~, after which the T_{box} proxy was re-calculated as explained in section 2.4.3 and evaluated against the initial box transport proxy~~.

2.6 Sensitivity tests

~~To test the sensitivity of the time span of observations used to create the transport proxy,~~ sensitivity experiments were performed to test how many years of ~~virtual *in situ* observations are~~ needed to create an accurate proxy ~~to monitor the~~ Agulhas Current transport. ~~Using~~ 34 years of model data the linear relationship could be tested over much longer or shorter periods.

Using the method described in section 2.4.3, regression models were built for 1, 6, 12, 18 and 34 years~~,~~ In addition, the models were calculated over two arbitrary 3-year periods, to test the ~~influence that different current dynamics over different years could have on the development of the transport proxy.~~ Lastly, the regression models were calculated over the maximum and minimum annual transport years in HYCOM, as well as during the years the HYCOM transport standard deviation was the largest and the smallest. Table 2 shows the time range over which the sensitivity experiments were performed. ~~The 3 year *in situ* period in the model corresponded to the actual time range over which the *in situ* experiment was conducted, April 2010 - February 2013 [Beal et al., 2015].~~

Table ~~2;~~ Sensitivity experiment time periods.

Time range (years)	Model dates
1	Jan 2011 - Dec 2011
3	Apr 2010 - Feb 2013
6	Jan 2009 - Dec 2014
12	Jan 2003 - Dec 2014
18	Jan 1997 - Dec 2014
34	Jan 1980 - Dec 2014
3*	Jan 1980 - Dec 1982; Jan 2000 - Dec 2002
Max (Min) HYCOM transport.	2003 (1982)
Max (Min) HYCOM transport STD.	2013 (1980)

3* Corresponds to the two additional 3-year periods

3 Results

3.1 HYCOM linear regression models

The coefficient of determination (R^2) from the regression models ~~showed~~ how well the linear relationship predicts the transport ~~per unit distance estimates~~ in HYCOM (Figure ~~3~~). ~~The~~ R^2 ~~statistics from the regression models~~ ranged from 0.86 at mooring A (30 km offshore) to 0.49 at the last CPIES-pair P4P5 (275 km offshore) for *Tx* and 0.86 at mooring A to 0.37 at P4P5 for *Txsw* (P values < 10^{-3}). Results from ~~the *in situ* experiment~~ showed an increase in the R^2 statistics in the regression models ranging from 0.51 at mooring A and 0.81 for CPIES-pair P4P5 for *Tx* ~~[Beal and Elipot, 2016], thus showing that the regression models had poorer skill inshore during the *in situ* experiment, whereas in HYCOM the regression models have poorer skill offshore.~~ The results from the *Txsw* regression models in HYCOM showed similar results ~~f~~for the inshore mooring locations (A, B, C, E) with slightly higher correlations for offshore moorings F, G and CPIES-pair P3P4 but a lower correlation for D and the furthest CPIES-pair P4P5. ~~This shows that the *Txsw* regression models explained more variance for moorings F, G and P3P4 but less variance for D and P4P5 than the *Tx* regression models.~~

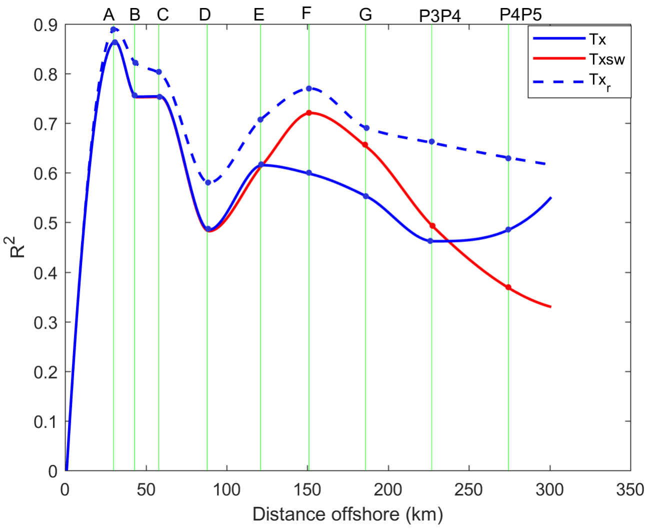


Figure 3: R^2 statistics from the linear regression models showing the relationship between HYCOM SSH slope and HYCOM transport per unit distance for each mooring (A-G) and CPIES-pair (P3P4 & P4P5) over the 3-year reference period (2010-2013). *Tx* is represented by the solid blue line and *Txsw* by the solid red line. The dashed blue line represents the results of *Tx* after the removal of the residual transport events (see section 3.4). Sites A - CPIES pair P4P5 are shown by the faint green lines.

3.2 Proxy validation

In order to test the accuracy of the box and jet HYCOM transport proxies, these were compared to the box and jet transports extracted from HYCOM. This aided the investigation in terms of identifying transport events or features the proxy failed to represent.

Based on the correlation of the 3 year proxy transport (2010-2013) to the model transport over the same period, the box transport proxy explained 57% of the variance while the jet transport proxy only explained 14% of the variance. Assuming a constant three year linear relationship for the nine regression models, the transport proxy was calculated using 34 years of HYCOM SSH slope, after which the 34 year box transport proxy explained 52% of the variance and the jet transport proxy explained 26% of the variance.

Table 3 summarises the transport statistics based on the 3 year and extended 34 year time period. The 34-year mean transport and standard deviation from HYCOM for the box and jet transport was -84 ± 47 Sv and -110 ± 38 Sv respectively. The proxy box transport was -87 ± 34 Sv and the jet transport was -92 ± 31 Sv. A higher jet transport was expected considering it excludes northeast counter-flows that decrease the box transport [Beal et al., 2015]. The differences between the standard deviations between HYCOM and

Table 3: a) Summary of the transport statistics of the HYCOM model transport against the HYCOM proxy transport over the 3-year and extended 34-year time period. Negative values denote transport in the southwest direction. 1 Sv=10^6 m^{3}s ^{1}. b) Correlations between the HYCOM model transport and HYCOM proxy transport, for the box transport and jet transport with the percentage of variance shown in brackets. All correlations were significant.

a)	HYCOM (2010-2013)		Proxy		HYCOM (1980-2014)		Proxy	
Transport	T_{box}	T_{jet}	T_{box}	T_{jet}	T_{box}	T_{jet}	T_{box}	T_{jet}
Mean & Std (Sv)	-81 ± 53	-112 ± 41	-91 ± 35	-92 ± 30	-84 ± 47	-110 ± 38	-87 ± 34	-92 ± 32
Max (Sv)	-223	-244	-196	-185	-236	-245	-213	-219
Min (Sv)	44	-48	-36	-46	87	-30	-20	-27

b)	T_{box}	T_{jet}
2010-2013	0.75 (57%)	0.38 (14%)
1980-2014	0.72 (52%)	0.51 (26%)

the proxy indicate that transport in HYCOM experiences more variability compared to the proxy. The proxies only capture a portion of the transport estimate from the HYCOM model, suggesting it also only captures a portion of the model variability. The positive minimum transport values for T_{box} during both time periods also appear to be peculiar, suggesting a current reversal during those events (Table 3).

Figure 4 shows the correlation between proxy and model transports for each year. The correlation per year for T_{jet} varies greatly from year to year with a significant maximum correlation of 0.82 (2014) and an insignificant minimum correlation of 0.00 (2003). In contrast, the correlations for T_{box} vary much less and are always significant with a maximum correlation of 0.88 (1988) and minimum correlation of 0.50 (1994). The box transport has higher correlations for most of the 34-year time period except during two single years where the jet transport has a higher correlation, 0.78 against 0.70 during 1991 and 0.54 against 0.50 during 1994. In summary, the results indicate that the proxy is generally better suited in HYCOM to estimate the box transport rather than the jet transport. Further analysis in this study therefore only focuses on the box transport.

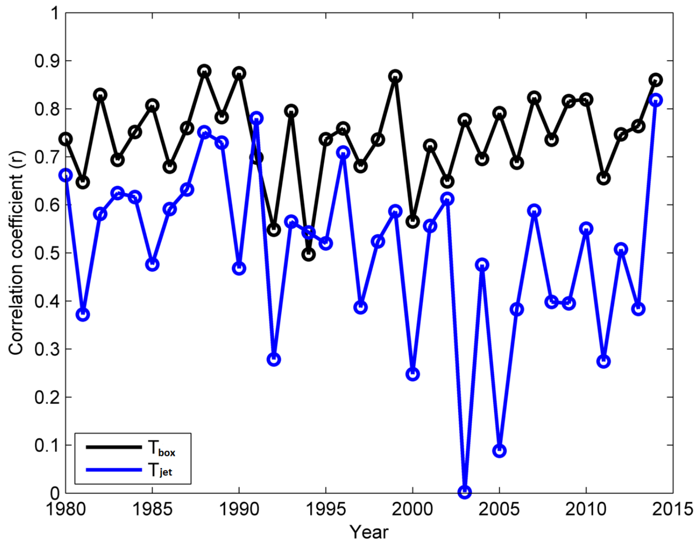


Figure 4: 34-year annual correlations between the box (black) and jet (blue) transport proxies against the box and jet transports extracted from HYCOM.

3.3 Evaluating the net transport proxy

The strengths and weaknesses of the box proxy are further investigated by selecting the highest and lowest correlated years from the 34-year annual correlations (Figure 4), and evaluated by plotting the current structure in the model over the respective years (Figures 5 & 6). Investigating the full depth current structure could emphasize important sub-surface processes which may not have distinct signatures at the surface and may therefore be excluded in the transport proxy.

Figure 5 shows the surface variability by displaying the eddy kinetic energy and the mean surface geostrophic flow as represented by the overlaying SSH contours over the 3 year reference period, and over the highest (1988) and lowest (1994) correlated years of the box transport proxy. During the reference period the current appears to be stable with low levels of EKE inshore whereas offshore the flow is more variable with higher levels of EKE. The flow depicts a similar structure during the lowest correlated year, however, during the highest correlated year the mean EKE is higher along and downstream of the array with a relatively stable current structure in comparison to 1994 and 2010-2013. The narrow spacing of the SSH contours for all three periods indicates a strong gradient inshore and hence a strong mean geostrophic current, however the wide spacing between the SSH contours offshore suggests that the variability in the model is confined to the offshore side of the current. It is assumed that high levels of mesoscale variability in the model could bias the current position and hence the transport estimate~~, however~~, based on the analysis there were ~~approximately five~~ anticyclonic eddies during the highest correlated year (1988) and $\sim$7 anticyclonic eddies during the lowest correlated year~~,~~ which does not ~~greatly differentiate~~ the accuracy of the proxy for those years.

~~Figure 6 shows the mean cross track velocity profiles during the reference period (2010-2013), the highest correlated year (1988) and the lowest correlated year (1994) for each mooring and the CPIES pairs.~~ The model cross-track velocity changes direction with depth, specifically for offshore mooring G and CPIES-pairs P3P4 and P4P5, at the depth of $\sim$2000 m (Figure 6) thereby defining the depth of the Agulhas jet. During the 3-year reference period the velocity changes direction at moorings B and G ($\sim$1200 m and $\sim$2000 m respectively) and at sites P3P4 ($\sim$2000 m) and P4P5 ($\sim$300 m, $\sim$2000 m). During 1988 sites F-P4P5 experience a change in direction ($>\sim$2000 m). Lastly, during 1994 mooring G and sites P3P4 and P4P5 exhibit a change in direction ($>\sim$2000m). ~~This shows that the offshore variability in the model impacts not only the surface variability (Figure 5) but also the subsurface flow, which would directly impact the accuracy of the box transport proxy.~~

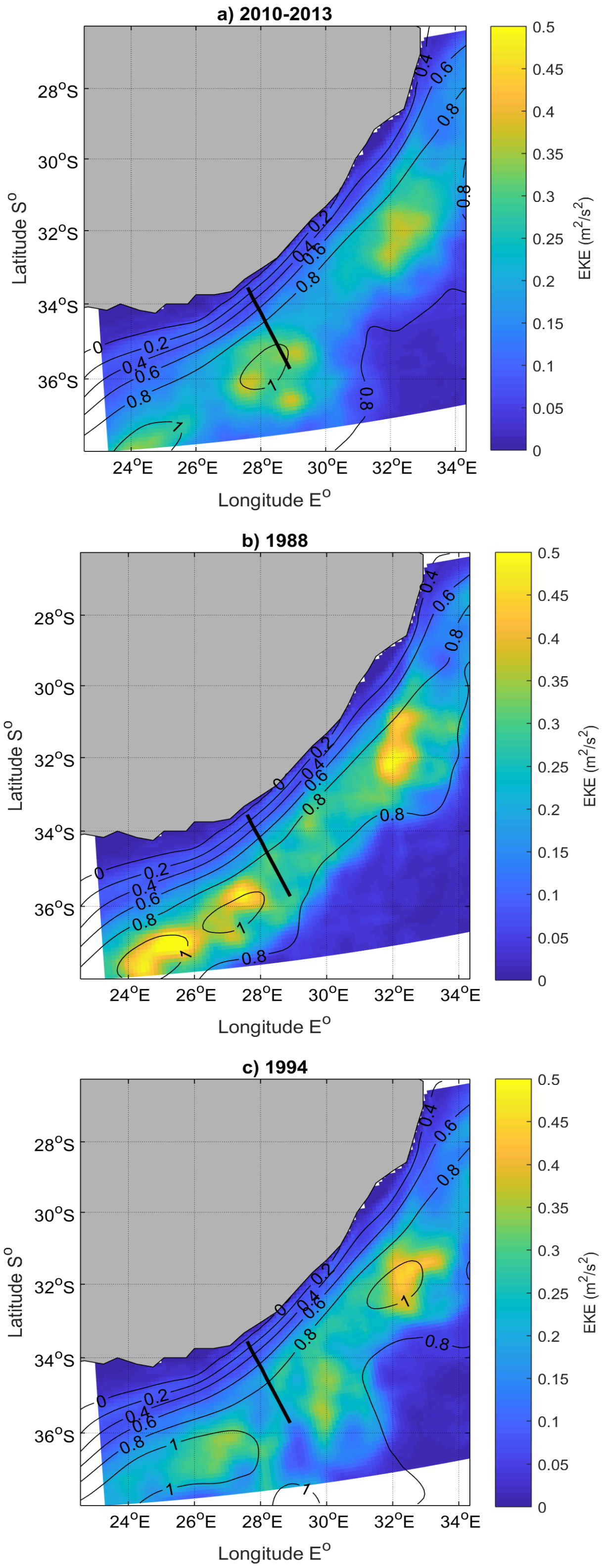
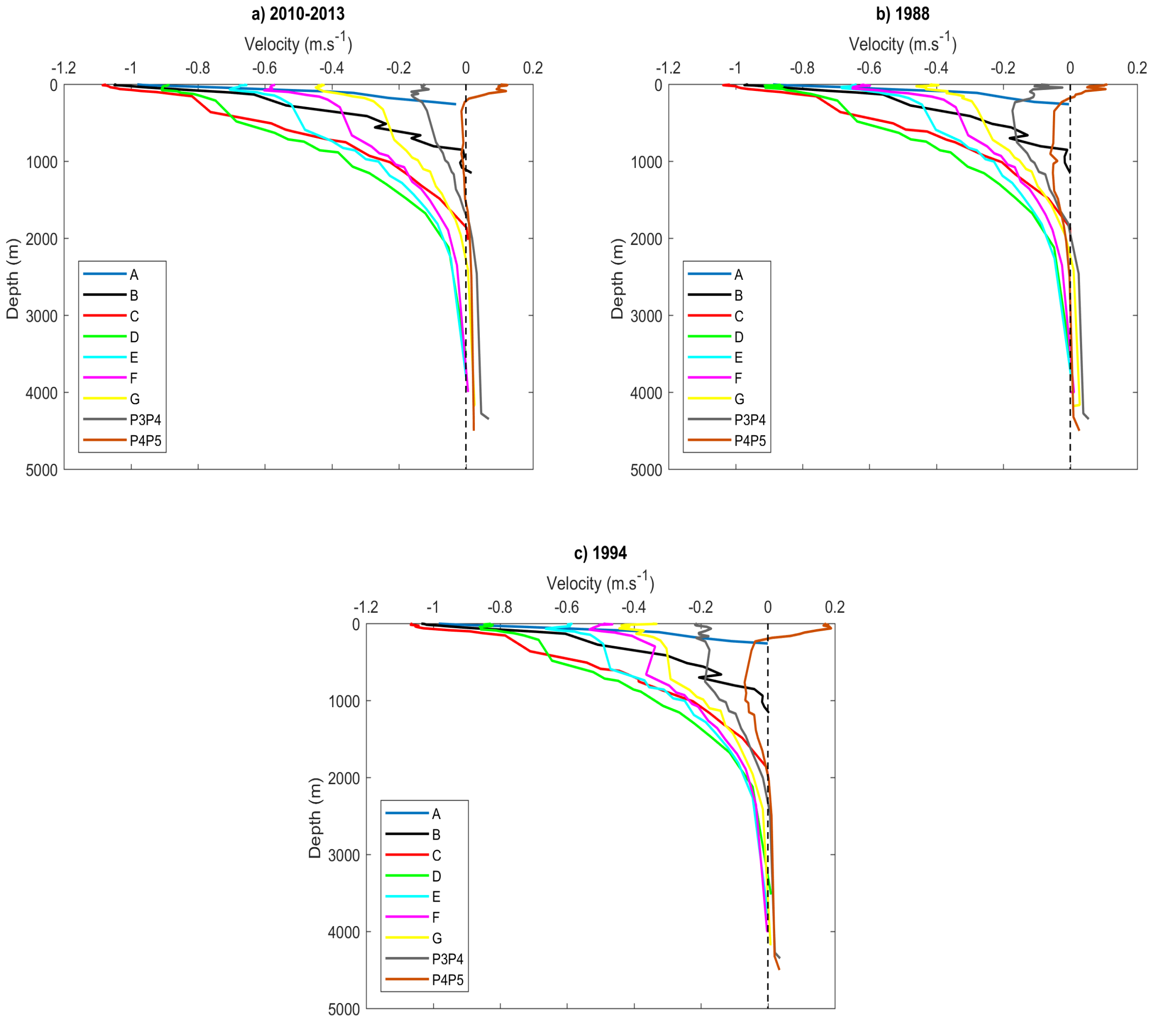


Figure 5: Eddy kinetic energy (EKE in m^{2}s ^{2}) and sea surface height (SSH in m) contours during (a) the reference period (2010-2013) (b) the highest (1988) and (c) lowest (1994) correlated years. The black line representing the ACT array.



Figure~~6~~: Mean cross-track velocity profiles (m s^{-1}) during (a) the 3-year reference period (2010-2013), (b) during the highest correlated year (1988) and (c) the lowest correlated year (1994). Each colour represents the different moorings (A-G) and CPIES-pairs (P3P4 & P4P5) . Negative values indicate southwestward flow.

3.4 Investigating the transport variability

~~This section will investigate factors of transport variability in the HYCOM model which caused the limitations in the HYCOM transport proxy.~~ ~~It was previously shown that the performance of the linear regression models weakened moving offshore because of the decrease in correlation between transport per unit distance and SSH slope.~~ Regression model ~~8,~~ CPIES-pair P3P4 (RM 8, Figure~~7a),~~ captured the least transport variance at 46% and ~~regression model 1,~~ mooring A (~~RM 1,~~ Figure ~~7b~~), explained the most transport variance at 86%. ~~The differences between the magnitudes of the residual transport events between RM 1 and RM 8 emphasize a large difference in transport variability between~~

the inshore and offshore mooring locations in HYCOM.

According to the methods presented above, a negative SSH slope in HYCOM corresponds to a negative (southwest) surface velocity and if the current structure were barotropic, a negative (southwest) transport per unit distance estimate and vice versa. As shown in regression model 1 (Figure 7b), all the data points are clustered such that the negative SSH slope relates to a negative transport per unit distance, in the absence of northeast counterflows. Careful analyses of regression model 8 shows that eight of the nine residual transport events do violate the proportional relationship between SSH slope and Tx (Figure 7a). Some of which have a negative SSH slope relating to a positive transport per unit distance where others show a positive SSH slope with negative transport per unit distance. Therefore the SSH slope does not always reflect the direction of flow at depth, and thus the correct sign for Tx.

Examination of the cross track velocity structure with depth (Figure 8) shows that there is a change in the direction of velocity in the bottom layers at the location of regression model 8 (CPIES-pair P3P4). The cross-track flow in the surface layers (~0-700 m) of the

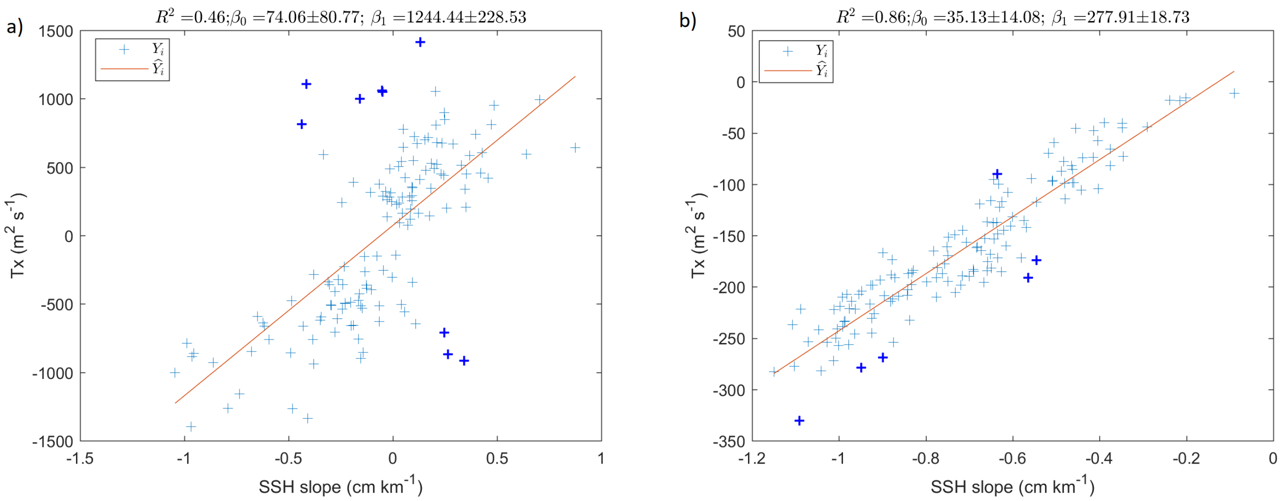


Figure 7: Linear regression models showing the relationship between HYCOM SSH and transport per unit distance (Tx) for a) CPIES-pair P3P4 (RM 8); capturing the least transport variance (46%) and b) Mooring A (RM 1); capturing the most transport variance (86%). Y_i (blue crosses) represent the Tx values from HYCOM and $\hat{Y}_i$ (red line) represents the Tx estimates from the linear regression model. The bold crosses highlight the residual transport events with transport values greater or less than 2 standard deviations of the transport estimate. The coefficient of determination (R^2) quantifies the amount of variance explained by the regression model, $\beta\iota$ is the slope coefficient and βo the intercept with 95% confidence intervals. Note the different scaling on the x & y-axes.

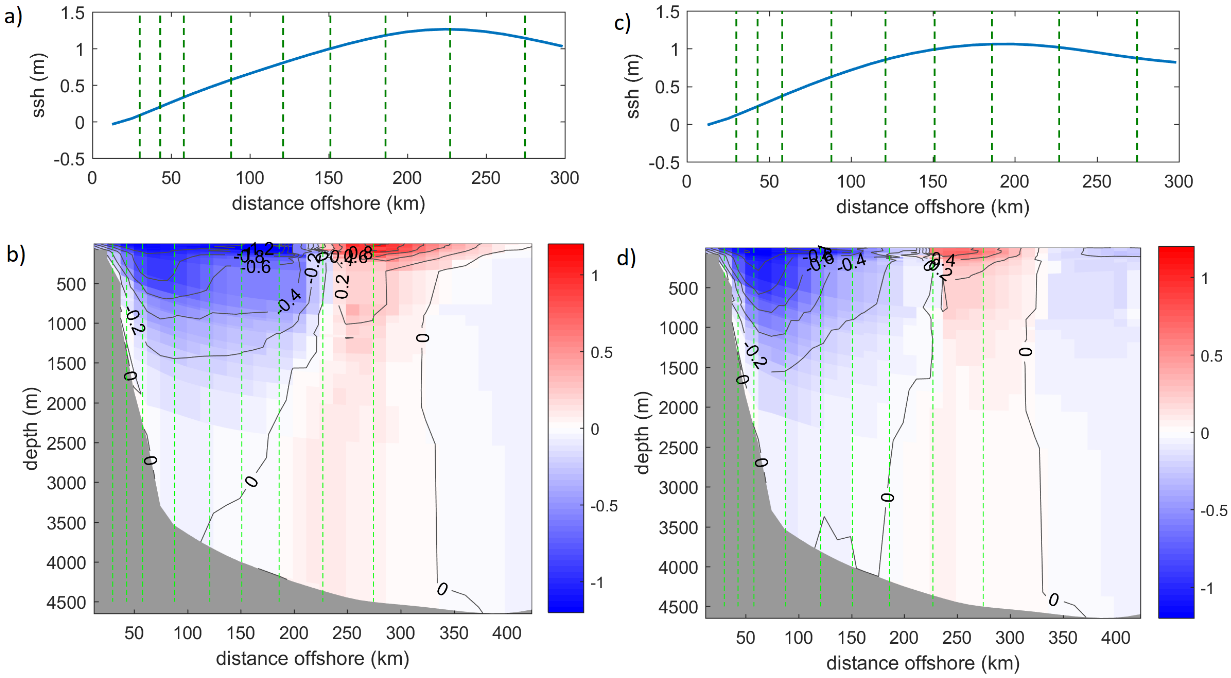


Figure ~~8~~: ~~Composite~~ SSH (m) and cross-track velocity structure (ms^{-1}) of the residual transport events from a & b) regression model 8 and c & d) regression model 1. Blue shading represents the negative, southwest current direction and red represents the positive, northeast current flow. Contours are every 0.2 ms^{-1}. Dashed vertical lines represents the nine locations of the mooring and CPIES-pairs, the first line representing mooring A and CPIES-pair P4P5 furthest offshore.

current is ~~towards southwest~~, whereas below ∼700 m the flow is ~~towards the northeast~~. Therefore, the vertically integrated flow (Tx) is positive, ~~that is towards the northeast,~~ and in the opposite direction implied by the SSH slope. In contrast, at ~~the location of~~ mooring A, the composite velocity field is always ~~towards the southwest~~, ~~that is~~ consistent with the SSH slope.

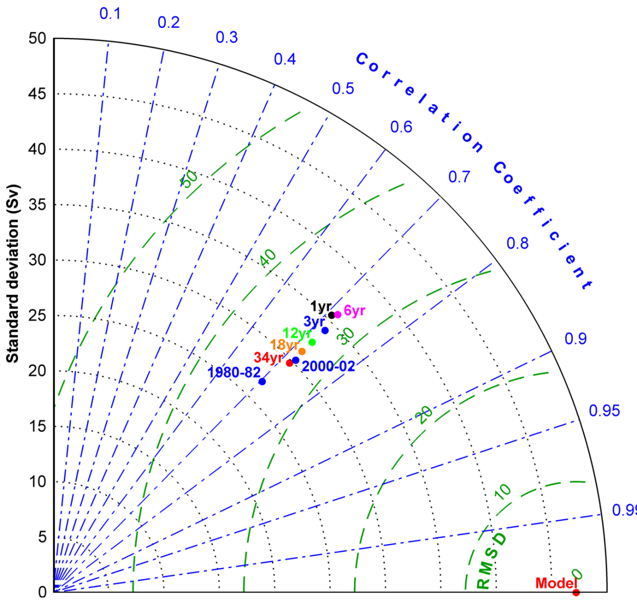
~~The residual investigation (Figures 7 & 8) shows how large outliers decrease the overall performance of the linear regression models, by decreasing the percentage of captured variance. If these transport events were removed the performance of the linear regression models would statistically increase. Removing the outliers larger than ±2 standard deviations from regression model 8, increases the percentage of captured variance from 46% to 66%. For model 1, removing outliers increases the captured variance from 86% to 88%. The improvement is specifically greater for regression model 8 due to the removal of the extreme events that violated the directly proportional relationship between SSH slope~~

and transport. Figure 3 shows the increase in the performance of the linear regression models after the removal of the outlying transport events from all nine regression models. The increase in variance explained is notable for the regression models corresponding to the inshore moorings B and C and offshore moorings F, G and CPIES pairs P3P4 and P4P5. After the removal of the outlying transport events, the box transport proxy was re-calculated and its performance compared to the initial proxy. The "improved" T_{box} proxy captures more variance, 72%, compared to 52% for the original proxy.

3.5 Sensitivity tests

The 34-year Agulhas transport proxy was based on regression models built using only 3 years of HYCOM model data. The statistics in Table 4 and Figure 9 illustrates the results obtained from building the linear regression models and deriving the transport proxy using 1, 3, 6, 12, 18 and 34 years of model data. The Taylor diagram (Figure 9) shows the distribution of the results in terms of standard deviation of the transport, the correlation, and the root mean squared error (RMSE) between the proxies and the HYCOM model transport. We find that the correlation between proxy box transport and model box transport is not improved by using more model data to build the proxy. The correlation is 0.72 when using data from 2010-2013, and changes by no more than 0.01 when extending the number of years of model data. Similarly, building the proxy with one year of model data decreases the correlation by only 0.01 (Figure 9 & Table 4). The only visible difference was the decrease in standard deviation. It was expected that the correlation would increase because using more years of model data may capture more current variability and the RMSE would decrease to correspond to the model transport estimates.

The sensitivity of the box transport proxy was also tested using two arbitrary 3-year periods. In comparison to the correlation obtained during 2010-2013 the correlation decreased by 0.02 during 1980-1982 and remained the same during 2000-2002. The results obtained from calculating the T_{box} proxy during the maximum (minimum) transport and standard deviation years in HYCOM showed no improvement or decrease in the skill of the proxy either.



~~Figure 9: Taylor diagram showing the results of the box transport proxy calculated based on a 1 year linear relationship (black), 3 years (blue), 6 years (magenta), 12 years (green), 18 years (orange), 34 years (red) and during 1980-1982 and 2000-2002 (blue).~~

Table ~~4:~~ Transport statistics and correlation results obtained from calculating the ~~net~~ transport proxy over a range of time periods.

Net transport	**Transport (Sv)**	**STD (Sv)**	**RMSE (Sv)**	**r**
MODEL	-84.32	47.23	0	1.00
1-yr	-87.26	35.47	33.36	0.71
3-yr	-87.21	34.09	32.76	0.72
6-yr	-87.04	35.91	33.04	0.72
12-yr	-86.91	32.51	32.83	0.72
18-yr	-88.71	31.28	32.95	0.72
34-yr	-88.15	29.74	33.14	0.72
1980-1982	-87.86	26.80	34.14	0.70
2000-2002	-94.80	30.31	32.87	0.72

4 Summary and conclusions

The Agulhas Current transport proxies, developed by Beal and Elipot [2016], were based on nine linear regression models, each assuming a constant linear relationship from three years of observations between *in situ* transport and satellite along-track sea surface gradients. Applying constant linear models and assuming a constant vertical current structure, the transport proxies were extended using 22-years of along-track satellite data in order to ~~yield~~ two 22-year time-series of Agulhas Current transports [Beal and Elipot, 2016]. The Agulhas Current transport proxies in the current study replicates the methods used by

Beal and Elipot [2016] but applies these using a regional HYCOM model of the Agulhas Current [Backeberg et al., 2009; 2014]. The HYCOM transport proxies were developed using nine, three-year linear regression models between model transport and model SSH slope, and extended using 34-years of the model SSH data from 1980 to 2014.

The HYCOM model provided the means to investigate the validity of the assumptions used to create the proxies, such as the constant relationship between SSH slope and transport per unit distance at each mooring location and the temporal scale of observations needed to build a strong linear relationship between transport and SSH slope. Two transport types, the box transport and the jet transport, were extracted from HYCOM in order to validate the box transport proxy (T_{box}) and the jet transport proxy (T_{jet}). The T_{box} proxy explained a higher percentage of transport variance (57%) during the three year reference period (2010-2013), in comparison to the T_{jet} proxy that only captured 14% of the variance. Using 34 years of model data (1980-2014), assuming the fixed 3-year relationship between SSH slope and transport, T_{box} explained 52% of the variance in comparison to T_{jet} that only captured 26%. Results from Beal and Elipot [2016] also showed that the box transport proxy (T_{box}) explained a higher percentage of variance (61%) during the ACT period than the jet transport proxy (T_{jet}: 55%).

The poorer performance of the T_{jet} proxy in HYCOM compared to the *in situ* T_{jet} proxy of Beal and Elipot [2016] is partly due to various model discrepancies such as the consistent merging of the anticyclonic eddies with the Agulhas Current in the northern region [Backeberg et al., 2014], in addition to unresolved eddy dissipation in this region [Braby et al., 2016]. It may also possibly be because it only represents the southwestward flow, whereas the input sea surface slope reflects the net flow along the array. Therefore, considering the box transport proxy explains a higher percentage of variance for most of the 34-year period, further analysis on the current structure was based on the T_{box} proxy only.

One of the main assumptions on which the Agulhas transport proxy relies is that the vertical structure of the current does not change outside the 3-year reference period [Beal and Elipot, 2016]. There are limitations to the ability of satellite altimeters to detect sub-surface variability [Robinson, 2004], however, it has been suggested that a strong relationship between SSH and full depth transport exists [Beal and Elipot, 2016].

The surface structure of the current was investigated in terms of the mean EKE and SSH contours (Figure 5), which are ideally equivalent to surface geostrophic flow and hence show the mean horizontal extent of the current [Robinson, 2004]. The vertical variability was investigated by plotting the mean cross track velocity profiles (Figure 6). During the highest correlated year (1988) the current is stable and inshore, whereas during the lowest correlated year (1994) and during the proxy development period (2010-2013) the current is meandering and it appears that a large portion of the energy of the current has been shifted offshore. These results are consistent with Elipot and Beal [2015], who showed that during the passage of a meander event, a large portion of kinetic energy is extracted from the flow through the process of barotropic conversion. Results from the analysis of the vertical profile of the current reveals subsurface counterflows, specifically for the offshore moorings (G, P3P4 and P4P5) and occasionally for inshore mooring B. An explanation for the offshore subsurface counter flows may be due to the impinging baroclinic eddies continuously propagating downstream [Backeberg et al., 2009], which thereby affect the entire water column by changing the direction of flow at certain depths. This will explain why the transport proxy fails to capture current reversals, as implied by the positive minimum transport values in Table 3, because the SSH slope is not reflective of the subsurface counterflows associated with the impinging baroclinic eddies. The occasional current reversal for inshore mooring B (43 km offshore, 1264 m depth) may be due to influence of the simulated Agulhas Undercurrent in HYCOM which flows approximately 40-60 km offshore, 1000-1700 m deep (Figure 8), as opposed to *in situ* estimates of 11-60 km offshore and 1000-2900 m deep [Beal, 2009].

The question still remains as to why most of the transport variance was explained in the year 1988 and the least in 1994? Figure 3 highlighted that the performance of the linear regression models decreased offshore, such that when the current is in a meandering state, the T_{box} proxy fails to accurately estimate the transport. It could be assumed that using the T_{jet} proxy would improve the accuracy, however, the performance of the southwest regression models are only slightly stronger at the offshore end of the array. The jet transport proxy by Beal and Elipot [2016] was developed to effectively estimate the transport of the Agulhas Current in the event of a mesoscale meander, which generally causes the current to manifest as a full depth, surface intensified, cyclonic circulation out to 150km from the coast with anticyclonic circulation farther offshore [Elipot and Beal, 2015]. The Agulhas meanders in the HYCOM simulation occur in association with large anticyclonic eddies predominantly defined to the offshore edge of the current, with a narrow, southwest stream against the coast [Backeberg et al., 2009] or in some instances with an anticyclonic eddy across the entire length of the array. The resolution of HYCOM is able to capture the mesocale dynamics of eddies [Holton et al., 2017] however, it fails to resolve the near-coastal features, such as the inshore, surface intensified cyclonic motion in this simulation. This would require a finer resolution at the coast, in order to reveal smaller offshore displacements, ~50 km, associated with these meander events [Elipot and Beal, 2015]. The high levels of offshore variability in HYCOM is therefore the main limiting factor in the performance of both transport proxies.

The regression model for CPIES pair P3P4 (regression model 8) performed the worst, only explaining 46% of the transport variance (Figure 7a). Evidence from the HYCOM velocity fields showed that the offshore location of CPIES pair P3P4 was highly susceptible to the impinging anticyclonic eddies, which in turn resulted in high levels of variability in the horizontal and vertical velocity current structure (Figures 7a & 8). The presence of the anticyclonic eddies would be included in T_{box}, considering that the eddies produce a strong surface signature (Figure 5), but the SSH slope might not necessarily be reflective of the transport beneath the eddy. It has been observed in a layered ocean that, when assuming geostrophy, the net transport in the uppermost layer (~0-1000 m) is mainly proportional to the SSH slope [Andres et al., 2008]. If this was the case, the performance of regression model 8 would be higher, but the current experiences a baroclinic flow beneath the entire water column which is not reflective of the SSH slope (Figure 8). As the anticyclonic eddy crosses the offshore edge of the ACT array, its baroclinic nature in HYCOM effects the direction of velocity beneath the location of CPIES pair P3P4, which therefore results in a weak correlation between SSH slope and transport. The impinging anticyclonic eddies would have a similar influence on the offshore regression models for mooring G and CPIES pair P4P5 (Figure 8).

The regression model for mooring A (regression model 1) performed the best in terms of the correlation between SSH slope and transport per unit distance (Figure 7b) explaining 86% of the variance. The inshore location of mooring A, 30 km off the coast, experienced

~~low levels of transport variability with a stable southwest current trajectory (Figure 5 & 8) and Figures 6 and 8 illustrate a barotropic current structure in the vicinity of mooring A with no sub surface counterflows. The small, sub surface variability observed inshore of the array, below 2000 m depth do not necessarily have a direct impact on the SSH signal or drastically change the volume transport of the water column, however the further offshore, the closer the interaction of the current with the offshore baroclinic eddies, the weaker the performance of the regression model.~~

~~It is important to consider that the Agulhas Current simulation in HYCOM is not completely realistic, demonstrating much higher levels of mesoscale variability than observed [Backeberg et al., 2008; 2009]. Rouault and Penven [2011] and Elipot and Beal [2015] showed that, on average, 1.6 mesoscale meanders pass through the ACT array at 34°S per year. In the HYCOM simulation an average of 5 anticyclonic eddies passed over the array per year. A study by Braby et al. [2016] investigating eddy activity in the northern Agulhas Current using satellite altimetry, showed that both cyclonic and anticyclonic source eddies dissipate upon approaching the main Agulhas Current. However, the observed eddy interaction and dissipation process is poorly resolved in many numerical ocean models [Tsugawa and Hasumi, 2010; Penven et al., 2011; Durgadoo et al., 2013; Backeberg et al., 2014; Loveday et al., 2014], including the HYCOM model used in this study.~~

The frequently impinging eddies ~~make it~~ difficult to effectively estimate the accurate box transport of the Agulhas Current in the model since the advection of these eddies have previously been found to be responsible for large transport fluctuations [Backeberg et al., 2009]. The transport proxy only includ~~es~~ the transport of the portion of the eddy that ~~is~~ reflected in the SSH signal across the array, whether it ~~is only~~ the southwestward or northeastward portion of the eddy or both~~,~~ and should therefore match the transport peaks from the model. ~~The transport in the model and proxy may fluctuate accordingly, however the transport estimates will not necessarily be equivalent, since it also depends on the strength of the proxy along the ACT array. In other words, the~~ transport proxy may capture the SSH signal of the eddies along the array, ~~however~~ the correlation of the regression models decrease offshore~~,~~ t~~herefore~~ transport estimates inshore would be more accurate than the transport estimates offshore when the current is in a meandering state.

It was shown that removing the residual transport events~~,~~ violating the proportional relationship between SSH slope and transport improved the proxy performance i.e. increased the percentage of transport variance explained. Several studies have researched methods to decrease the levels of EKE in numerical simulations. Backeberg et al. [2009] improved the representation of the southern Agulhas Current by applying a higher-order momentum advection scheme, resulting in a well-defined meandering current rather than a continuous stream of eddies. Anderson et al. [2011] found that the use of relative wind forcing significantly decreased eddy intensities and a study by Renault et al. [2017] focussing on the current stress feedback between the ocean and atmosphere demonstrated a reduction of mesoscale activity by deflecting energy from the geostrophic current to the atmosphere, showing that the indirect current feedback, improved the representation of the Agulhas Current. Improving the mesoscale variability in the HYCOM model could therefore yield better results for the transport proxy, specifically for the offshore regression models, in the future. Furthermore, improving the simulation of coastal, shelf and continental slope features, including the Agulhas Undercurrent could decrease the performance of the inshore regression models. In order to effectively mirror the performance of the *in situ* transport proxy developed by [Beal and Elipot, 2016] would ideally require a numerical model that accurately simulates Agulhas meanders and the vertical variability, including an accurate representation of the Agulhas Undercurrent, which has not yet been achieved in existing regional configurations.

The development of the ACT transport proxy was initially tested using a regional NEMO configuration in order to evaluate the potential of the altimeter proxy to monitor the multi-decadal transport of the Agulhas Current [van Sebille et al., 2010]. Using the numerical model, it was concluded that the correlation between the Agulhas Current transport and gradient in sea surface height was greater than r=0.78 for any three-year measuring period, and is therefore an adequate timescale to build an accurate transport proxy [van Sebille et al., 2010].

The HYCOM output in the current study was used to test the validity of the relationship between transport and SSH slope over a range of time periods. It was hypothesised that building the linear relationship over longer time periods, >3 years, would increase the skill of the transport proxy, since the linear relationship would include more current variability over longer periods of time. The results showed that calculating the transport proxy over longer or shorter time periods did not necessarily improve the performance of the proxy, thereby suggesting that the current dynamics for any 3-year period in the model could be very similar, in agreement with the results obtained in van Sebille et al. [2010], suggesting that the results were consistent despite the model biases. This justifies that 3 years is a sufficient time period to develop the satellite altimeter transport proxy of the Agulhas Current in HYCOM. Lastly, the study showed that the transport proxy is sensitive to subsurface variability in the model, suggesting that caution should be taken regarding the implicit assumption of a fixed vertical current structure. The accuracy of the transport proxy remains sensitive to model bias and implications therein, suggesting that these results should be tested rigorously in other model simulations. Sensitivity studies of this kind, using numerical ocean models, provide useful information into planning *in situ* studies in the future, and understanding the sensitivities and limitations of transport proxies could further improve long term monitoring methods in the global ocean.

**Authors contributions*

E.V. conducted the data analyses and wrote up the final paper. B.B provided the HYCOM model data, supervised the project and provided financial support. J.H. supervised the project and provided financial support and S.E. assisted with the methodology of the transport proxy. All authors helped to conceptualize ideas and contributed to writing the paper.

We have no conflicts of interest to disclose.

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