RESPONSE TO REVIEWER 2

October 4, 2018

The authors selectively review parameterizations of drag coefficient over the open ocean and evaluate the differences in stress that result. The methodology used is to take a satellite-derived data set of wind speed and use these as observations for bulk formulae evaluations of the momentum flux. Seven algorithms are compared. Differences in the momentum flux are (globally) about 14% and are comparable for different geographic regions, with some differences. This is a rather limited study. It uses scatterometer-derived neutral winds, which means the bulk flux algorithms can be directly compared without stability differences being a factor. This is fine, but it does mean that the study does not yield much that is not already known or can be inferred from the equations themselves. Essentially the differences in momentum flux come straight out of the differences in the equations (illustrated in Fig. 1). The results are statistically-based, i.e. averages and mean differences, so there is not any link to at- mosphere or ocean physics or dynamics. The choice of bulk flux algorithms to focus on is rather limited. There are a few well-known 'early' equations and then a couple of well-known later ones, but there are many very popular algorithms which are not evaluated, e.g. Smith (1988), the COARE algorithm (probably the most popular now), and others covered by other inter-comparisons. The study covers similar ground to that of Brunke et al. in a series of papers in the 2000s – see below for references. There is nothing wrong with this study, so I don't have any objections to it being published. However I am afraid I don't think it adds enough new to merit publication, so I cannot recommend it is published.

Minor comments There abstract is too long and there are numerous English errors.

References

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Smith, S. D. (1988). Coefficients for sea surface wind stress, heat flux, and wind pro- files as a function of wind speed and temperature. Journal of Geophysical Research: Oceans, 93(C12), 15467-15472.

Thank you for the reviews. We would ask you to reconsider our article for publication, because we have introduced a number of significant changes, following suggestion from reviewer no. 1, thanks to which the article is now better consulted, more understandable. You are right that Brunke et al., have done a lot of study in air-sea interaction, but their research are more extensive and concern a larger area. We have done our research by following among one of their conclusion, which is: *Finally, a further investigation of the differences in the parameterization of the exchange coefficients in the various algorithms would help in understanding some of the differences between the computed fluxes seen here*.

The aim of the manuscript is to evaluate how much the average monthly and annually momentum transfer values depend on the choice of C_D parameterizations, in other words how the selected parameterization affects the total value of momentum fluxes for large reservoirs. This allows constraining the uncertainty caused by the parameterization choice. In order to achieve this, we used observed wind field for the regions of interest, namely the North Atlantic and the European Arctic, areas where European and Americans oceanographers, including us, operate. This is where most of studies that were basis of the parameterizations we use were performed. We did some comparisons to sub-tropical basins to see the difference in uncertainty caused by the formula choice between the main study regions and less studied subtopics. In our calculations, we do not clearly indicate which formula should be used in the future (impossible without new data) in the NA and the EU, but the simple fact that none of the parameterizations used now is final. We don't want to suggest end users any conclusions, because the differences in the parameterizations used are small, and our goal was to help them make an intelligent and deliberate decision about which parameterizations to use. We have chosen those 7 parameterizations as, in our opinion, they are the most commonly used in the literature during the last decade.

Some of the major changes:

We do our best to improve the manuscript, organize it better than it was, clearly state the objective and conclusion, also mark what new it adds to our knowledge. As the original title could cause confusion and did not clearly define the paper purpose. Therefore we change it in the revised version. The new title now is:
Effect of drag coefficient formula choice on wind stress climatology in the North Atlantic and the European Arctic

The reviewer no 1. pointed out that the purpose of the manuscript was not clearly formulated, so we corrected it and added properly information and corrections inside the text:

L23-32 *Confirming and explaining the nature and consequence of the interaction between the atmosphere and ocean is one of the great challenge in climate and sea research. These two sphere are coupled which lead to variations covering time scales from minutes to even millennia. The purpose of this article is to examine, using a modern set of software processing tools called the FluxEngine, the nature of the fluxes of momentum across the sea surface over the North Atlantic and the European Arctic. These fluxes are important to determine of current system and sea state conditions. Our goal is to evaluate how much the average monthly and annually momentum transfer values depend on the choice of* C_D*, using the actual wind field from the North Atlantic and the European Arctic, and demonstrate existing differences as a result of the formula used.*

L134-145 In this paper we investigate how the relevant or most commonly used parameterizations for drag coefficient (C_D*) affect to value of momentum transfer values, especially in the North Atlantic (NA) and the European Arctic (EA). Our task was to demonstrate existing differences as a result of the formula used how big they can be. As is widely known, the exact equation that describes the connection between the drag coefficient and wind speed depends on the author (Geernaert, 1990). Our intention here is not to re-invent or formulate a new drag parameterization for the NA or the EA, but to revisit the existing definition of drag parameterization, and, using satellite data, to investigate how existing formulas represent the environment in the North. We concentrated on wind speed parameterizations, because wind speed is a parameter that is available in every atmospheric circulation model. Therefore, it is used in all air-sea flux parameterizations, and presently it is used even when sea state provides a closer physical coupling to the drag coefficient (for review see Geernaert et al., 1986).*

Effect of drag coefficient formula choice on wind stress climatology in the North Atlantic and the European Arctic

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Key points: drag coefficient, European Arctic, North Atlantic, parameterizations

Abstract

In this paper we have chosen to check the differences between the relevant or most commonly used parameterizations for drag coefficient (C_D) for the momentum transfer values, especially in the North Atlantic (NA) and the European Arctic (EA). We studied monthly values of air-sea momentum flux resulting from the choice of different drag coefficient parameterizations, adapted them to momentum flux (wind stress) calculations using SAR wind fields, sea-ice masks, as well as integrating procedures. We compared the resulting spreads in momentum flux to global values and values in the tropics, an area of prevailing low winds. We show that the choice of drag coefficient parameterization can lead to significant differences in resultant momentum flux (or wind stress) values. We found that the spread of results stemming from the choice of drag coefficient parameterization was 14 % in the Arctic, the North Atlantic and globally, but it was higher (19 %) in the tropics. On monthly time scales, the differences were larger at up to 29 % in the North Atlantic and 36 % in the European Arctic (in months of low winds) and even 50 % locally (the area west of Spitsbergen). When we choose the parameterizations which increased linearly with wind speed (7-9) momentum flux were largest for all months, in compare to values from the two parameterizations which increase with wind speed sinusoidal (12 and 13), in both regions with high and low winds and C_D values were consistently higher for all wind speeds. As the one of power law parameterization (13) behaves so distinctly differently with low winds, we showed seasonal results for the tropical ocean, which were subdued for the whole region, with monthly averages in the range of 0.2 to 0.3 N m^2.

1. Introduction

Confirming and explaining the nature and consequence of the interaction between the atmosphere and ocean is one of the great challenge in climate and sea research. These two sphere are coupled which lead to variations covering time scales from minutes to even millennia. The purpose of this article is to examine, using a modern set of software processing tools called the FluxEngine, the nature of the fluxes of momentum across the sea surface over the North Atlantic and the European Arctic. These fluxes are important to determine of current system and sea state conditions. Our goal is to evaluate how much the average monthly and annually momentum transfer values depend on the choice of C_D, using the actual wind field from the North Atlantic and the European Arctic, and demonstrate existing differences as a result of the formula used.

The ocean surface mixed layer is a region where kinematic forcing affects the exchange of horizontal momentum and controls transport from the surface to depths (Gerbi et al., 2008, Bigdeli et al., 2017). Any attempt to properly model the momentum flux from one fluid to another as the drag force per unit area at the sea surface (surface shear stress, τ) take into account other physical processes responsible for generating turbulence such as boundary stress, boundary buoyancy flux, and wave breaking (Rieder et al., 1994, Jones and Toba, 2001). Fluxes across the sea surface usually depend nonlinearly on the relevant atmospheric or oceanic parameters. Over the past fifty years, as the collection of flux data has increased, many empirical formulas have been developed to express the ocean surface momentum flux as a relationship between non-dimensional drag coefficient (C_D), wind speed (U_{10}), and surface roughness (z_0) (Wu 1969, 1982; Bunker, 1976; Garratt, 1977; Large and Pond, 1981; Trenberth et al., 1989; Yelland and Taylor, 1996, Donelan et al., 1997; Kukulka et al., 2007; Andreas et al., 2012). These formulas can be divided into two groups. One group of theories gives the C_D at level z in terms of wind speed and possibly one or more sea-state parameters (for example, Geernaert et al., 1987, Yelland and Taylor, 1996, Enriquez and Friehe, 1997), while the second group provides formulas for roughness length z_0 in terms of atmospheric and sea-state parameters (for example, Wu, 1969, Donelan et al., 1997, Andreas et al., 2012 (further referred to as A12)).

As the exchange of air-sea momentum is difficult to measure directly over the ocean meteorologist and oceanographers often rely on bulk formulas parameterized by Taylor (1916), that relate the fluxes to averaged wind speed through transfer coefficients:

$$\tau = \rho C_{Dz} U_z^2 \tag{1}$$

where τ is the momentum flux of surface stress, ρ is air density, C_{Dz} is the non-dimensional drag coefficient appropriate for z height, and U_z is the average wind speed at some reference height z above the sea. C_{Dz} is commonly parameterized as a function of mean wind speed (m s^{-1}) for neutral-stability at a 10 m reference height above mean sea level (Jones and Toba, 2001), which is identified as C_{DN10} or C_{D10} (this permits avoiding deviation for the vertical flow from the logarithmic law):

$$C_{DN10} = \frac{\tau}{\rho U_{10}^2} = (\frac{u_*}{U_{10}})^2 \tag{2}$$

where u_* is friction velocity. Alternatively, the neutrally stratified momentum flux can be determined from the logarithmic profile, thus Eq. 1 can be express as:

$$C_{DN10} = [\kappa / ln\,(10/z_0)]^2 \tag{3}$$

where z_0 (m) is the aerodynamic roughness length, which is the height, above the surface to define the measure of drag at which wind speed extrapolates to 0 on the logarithmic wind profile (Andreas et al., 2012), and κ is von Kármán constant (κ=0.4).

At the same time, we can define the value of friction velocity by the following equation:

$$\tau = \rho\, u_*^2 \tag{4}$$

Comparison with bulk formula (1) leads to the equation:

$$u_*^2 = C_{D10} U_{10}^2 \tag{5}$$

Some of the first studies (Wu, 1969, 1982, Garrat, 1977) focused on the relationship between wind stress and sea surface roughness, as proposed by Charnock (1955), and they formulated (for winds below 15 m s^{-1}) the logarithmic dependence of the stress coefficient on wind velocity (measured at a certain height) and the von Kármán constant. Currently common parameterizations of the drag coefficient are a linear function of 10 m wind speed (U_{10}), and the parameters in the equation are determined empirically by fitting observational data to a curve. The general form is expressed as (Guan and Xie, 2004):

$$C_D 10^3 = (a + bU_{10}) \quad (6)$$

In this work our focus is on the fluxes of average values using seven different drag coefficient parameterizations (C_D), chosen for their importance for the history of the field out of many published within the last half century (Bryant and Akbar, 2016).

$$10^3 \cdot C_{D10} = 0.5U_{10}^{0.5} \qquad \text{for } 1 \text{ m s}^{-1} < U_{10} < 15 \text{ m s}^{-1} \quad (7)$$

(Wu, 1969)

$$10^3 \cdot C_{DN10} = 0.75 + 0.067U_{10} \qquad \text{for } 4 \text{ m s}^{-1} < U < 21 \text{ m s}^{-1} \quad (8)$$

(Garratt, 1977)

$$10^3 \cdot C_{D10} = (0.8 + 0.065U_{10}) \qquad \text{for } U_{10} > 1 \text{ m s}^{-1} \quad (9)$$

(Wu, 1982)

$$10^3 \cdot C_{DN10} = 0.29 + \frac{3.1}{U_{10N}} + \frac{7.7}{U_{10N}^2} \qquad \text{for } 3 \text{ m s}^{-1} < U_{10N} < 6 \text{ m s}^{-1} \quad (10)$$

$$10^3 \cdot C_{DN10} = 0.60 + 0.070U_{10N} \qquad \text{for } 6 \text{ m s}^{-1} < U_{10N} < 26 \text{ m s}^{-1}$$

(Yelland and Taylor, 1996)

$$10^3 \cdot C_D = 1.3 \qquad \text{everywhere} \quad (11)$$

(NCEP/NCAR)

$$10^3 \cdot C_{DN10} = \frac{2.7}{U_{10N}} + 0.142 + 0.076U_{10N} \qquad \text{everywhere} \quad (12)$$

(Large and Yeager, 2004)

$$C_{DN10} = \left(\frac{u*}{U_{10N}}\right)^2 = a^2 \left(1 + \frac{b}{a} U_{10N}\right)^2 \qquad \text{everywhere} \quad (13)$$

where $a = 0.0583$, $b = -0.243$ (Andreas et al., 2012)

where C_{DN10} is the expression of neutral-stability (10-m drag coefficient), C_{D10} is the drag coefficient dependent on surface roughness, U_{10} is the mean wind speed measured at 10 m above the mean sea surface, U_{10N} is the 10-m, neutral-stability wind speed. All of them are generated from the vertical wind profile, but they differ in the formulas used. Two of the parameterization which we chosen are formulated as power-law of the relationship between C_D and U_{10} (eq. 7 and 13), three are formulated as linear-law (eq. 8, 9 10 for light winds, and 12), and one as constant value of the relationship (eq. 11). All the above studies propose different parameterizations (see **Fig. 1**) of the drag coefficient and the function of wind speed, which reflects the difficulties in simultaneously measuring at high sea stress (or friction velocity) and wind speed.

Wu (1969), based on data compiled from 12 laboratory studies and 30 oceanic observations, formulated power-law (for breezes and light winds) and linear-law (for strong winds) relationships between the wind-stress coefficient (C_y) and wind velocity (U_{10}) at a certain height y at various sea states. In his study, he used roughness Reynolds numbers to characterize the boundary layer flow conditions, and he assumed that the sea surface is aerodynamically smooth in the range of $U_{10} < 3$ m s^{-1}, transient at wind speed 3 m $s^{-1} < U_{10} < 7$ m s^{-1}, and aerodynamically rough at strong winds $U_{10} > 7$ m s^{-1}. He also showed that the wind-stress coefficient and surface roughness increase with wind speed at light winds ($U_{10} < 15$ m s^{-1}) and is constant at high winds ($U_{10} > 15$ m s^{-1}) with aerodynamically rough flow. Garratt (1977), who assessed the 10 m neutral drag coefficient (C_{DN10}) based on 17 publications, confirmed the previous relationship and simultaneously suggested a linear form of this relationship for light wind. Wu (1980) proposed the linear-law formula for all wind velocities and later (Wu, 1982) extended this even to hurricane wind speeds. Yelland and Taylor (1996) presented results obtained from three cruises using the inertial dissipation method in the Southern Ocean and indicate that using the linear-law relationship between the drag coefficient and wind speed (for $U_{10} > 6$ m s^{-1}) is better than using u_* with U_{10}. The NCEP/ NCAR reanalysis (Kalnay et al., 1996) uses a constant drag coefficient of 1.3 x 10^{-3} while, for example, the Community Climate System Model version 3 (Collins et al., 2006) uses a single mathematical formula proposed by Large and Yeager (2004) for all wind speeds. Andreas et al. (2012) based on available datasets, friction velocity coefficient versus neutral-stability wind speed at 10 m, and sea surface roughness tested the approach proposed by Foreman and Emeis (2010) for friction velocity in order to find the best fit for parameters $a = 0.0583$ and $b = -0.243$. They justify their choice by demonstrating that u_* vs. U_{10N} has smaller experimental uncertainty than C_{DN10}, and that one expression of C_{DN10} for all wind speeds overstates and overestimates results in low and high winds (**Figs. 7** and **8** in A12).

In this paper we investigate how the relevant or most commonly used parameterizations for drag coefficient (C_D) affect to value of momentum transfer values, especially in the North Atlantic (NA) and the European Arctic (EA). Our task was to demonstrate how existing differences as a result of the formula used how big they can be. As is widely known, the exact equation that describes the connection between the drag coefficient and wind speed depends on the author (Geernaert, 1990). Our intention here is not to re-invent or formulate a new drag parameterization for the NA or the EA, but to revisit the existing definition of drag parameterization, and, using satellite data, to investigate how existing formulas represent the environment in the North. We concentrated on wind speed parameterizations, because wind speed is a parameter that is available in every atmospheric circulation model. Therefore, it is used in all air-sea flux parameterizations, and presently it is used even when sea state provides a closer physical coupling to the drag coefficient (for review see Geernaert et al., 1986).

2. Materials and Methods

We calculated monthly and annual mean momentum fluxes using a set of software processing tools called the FluxEngine (Shutler et al., 2016), which was created as part of the OceanFlux Greenhouse Gases project funded by the European Space Agency (ESA). Since the toolbox, for now, is designed to calculate only air-sea gas fluxes but it does contain the necessary datasets for other fluxes, we made minor changes in the source code by adding parameterizations for the air-sea drag relationship. For the calculations, we used Earth Observation (EO) U_{10} for 1992-2010 from the GlobWave project (http://globwave.ifremer.fr/). GlobWave produced a 20-year time series of global coverage multi-sensor cross-calibrated wave and wind data, which are publicly available at the Ifremer/CERSAT cloud. Satellite scatterometer derived wind fields are at present believed to be at least equally as good as wind products from reanalyses (see, for example, Dukhovskoy et al. 2017) for the area of our interest in the present study. The scatterometer derived wind values are calibrated to the U_{10N}, and, therefore, are fit for use with the neutral-stability drag coefficient (Chelton and Freilich, 2005). All data came in netCDF-4 format. The output data is a compilation file that contains data layers, and process indicator layers. The data layers within each output file, which are details part of the FluxEngine, include statistics of the input datasets (e.g., variance of wind speed, percentage of ice cover), while the process indicator layers include fixed masks as land, open ocean, coastal classification, and ice.

All analyses using the global data contained in the FluxEngine software produced a gridded (1° x 1°) product. The NA was defined as all sea areas in the Atlantic sector north of 30º N, and the EA subset was those sea areas north of 64° N (**Fig. 2**). We also defined the subset of the EA east of Svalbard ("West Svalbard" between 76º and 80º N and 10º to 16º E), because it is a region that is studied intensively by multiple, annual oceanographic ship deployments (including that of the R/V Oceania, the ship of the institution the authors are affiliated with). FluxEngine treats areas with sea-ice presence in a way that is compatible with Lüpkes et al. (2012) multiplying the water drag coefficient by the ice-free fraction of each grid element. We also define "tropical ocean" as all areas within the Tropics (23º S to 23º N, not show) in order to test the hypothesis that the new A12 parameterization will produce significantly lower wind stress values in the region.

3. Results and Discussion

Using the FluxEngine software, we produced global gridded monthly air-sea momentum fluxes and from these we have extracted the values for the study region, the global ocean, the NA Ocean, and its subsets: the Arctic sector of the NA and the West Spitsbergen area (WS). Some of the parameterizations used were limited to a restricted wind speed domain. We used them for all the global wind speed data to avoid data gaps for winds that were too high or too low for a given parameterization (**Fig. 1**). However, circulation models have the very same constraint and, therefore, the procedure we used emulated using the parameterization in oceanographic and climate modeling.

Since wind velocity was used to estimate C_D, **Fig. 1** shows a wide range of empirical formulas and **Fig. 2** shows annual mean wind speed U_{10} (m s^{-1}) in the NA and the EA. The differences between the parameterizations are distinct (**Fig. 1**). The C_D values from the parameterizations 7 - 9 increased linearly with wind speed since the results from the parameterizations 10,12,13 are characterized by sinusoidal distribution and indicating decreases for winds in the range of 0 - 10 m s^{-1}, after which they began increase. Despite many measurements, the drag coefficient still has wide variability at low and moderate wind speeds. Our research has showed that al lower wind values (<10 m s^{-1}) the differences between the drag coefficient parameterizations are greater than at higher speeds (> 10 m s^{-1}) and the most outlier results are those obtained from the power law parameterization of Andreas et al., (2012). The lower the wind speed, the higher uncertainty are, and at low winds it is uncertainty by a factor of 0.5-1.5 depending on the formula used, while at moderate winds it is uncertainty by a factor of 1.5-2.0 **(Fig. 1).** At a wind value of about 15 m s^{-1}, the results from eq. 8, 9, and 13 overlapped providing the same values for the drag coefficient parameterizations. Additionally, we compared directly the results of the two parameterizations for the drag air-sea relation that uses different dependencies (**Fig. 1**). For this estimation we chose the two most-recent parameterizations (eq. 12 and 13) that showed the lowest values and change seasonally depending on the area used. As a result, these months with weak winds have significantly lower momentum flux values, which could be the effect of statistically weaker wind in ocean areas having stable winds with waves traveling in the same direction as the wind at similar speeds. Comparison showed that the A12 parameterization demonstrates almost zero sea surface drag for winds in the range of 3 - 5 m s^{-1}, which is compensated for by a certain surplus value for strong winds. The small drag coefficient values facilitate what Grachev and Fairall (2001) describe as the transfer of momentum from the ocean to the atmosphere at wind speeds of 2 - 4 m s^{-1}, which correspond to the negative drag coefficient value. Such events require specific meteorologist conditions, but this strongly suggests that the average C_D value for similar wind speeds could be close to zero. The annual mean wind speed in the NA is 10 m s^{-1}, and in the EA it is 8.5 m s^{-1} (**Fig. 2**).

Figure 3 presents maps of the mean boreal winter DJF and summer JJA momentum fluxes for the chosen C_D parameterizations (Wu, 1969 and A12 – the ones with the largest and smallest C_D values). The supplementary materials contain complete maps of annual and seasonal means for all the parameterizations. The zones of the strongest winds are in the extra-tropics in the winter hemisphere (southern for JJA and northern for DJF). The older Wu (1969) parameterization produces higher wind stress values than A12 in both regions with high and low winds and C_D values are consistently higher for all wind speeds except the lowest ones (which, after multiplying by U^2, produced negligible differences in wind stress for the lowest winds). The average monthly values for each of the studied areas are shown in **Fig. 4**. Generally, this illustrates that the sinusoidal the drag coefficient parameterization is, the smaller the calculated momentum flux is. For global data (**Fig. 4a**), not much seasonal change is noted, because the strongest winds are in fall and winter, but these seasons are the opposite in the northern and southern hemispheres. The parameterization with the largest momentum flux values for all months is that of Wu (1969), the linear one, while the two parameterizations with the lowest values are the sinusoidal ones (Large and Yeager, 2004 and A12). For the NA (**Fig. 4b**), with is much more pronounced seasonal wind changes, the situation is more complicated. With high winter winds, the A12 parameterization is no longer the one that produces the smallest wind stress (it is actually in the middle of the seven). However, for low summer winds, it is the lowermost outlier. Actually, in summer, the constant C_D value used by the NCEP/NCAR reanalysis produces the highest wind stress values in the NA. The situation is similar for the EA (a subset of the NA), the wind stress values of which are shown in **Fig. 4c**, and for the WS area (not show). In the Arctic summer, A12 produces the least wind stresses, while all the other parameterizations look very similar qualitatively (even more so in the Arctic than in the whole NA). Because the A12 parameterization behaves so distinctly differently with low winds, we also show seasonal results for the tropical ocean (**Fig. 4d**). The seasonal changes are subdued for the whole tropical ocean with the slight domination of the Southern Hemisphere (the strongest winds are during the boreal summer) with generally lower momentum transfer values (monthly averages in the range of 0.2 to 0.3 N m^{-2} compared to 0.2 to 0.4 N m^{-2} for the NA and 0.2 to 0.5 N m^{-2} for the Arctic). The sequence of values for the parameterization is similar to that of the global ocean, but there are differences. Here the NCEP/NCAR constant parameterization is the second highest (instead of Wu, 1982 for the global ocean) while, unlike in the case of the global ocean, A12 produces visibly lower values than does the Large and Yeager (2004) parameterization.

Table 1 and **Fig. 5** present the annual average air-sea momentum flux values (in N m^{-2}) for all the all regions studied and all the parameterizations. The results show that the annual North Atlantic momentum fluxes, depending on the formula used, varies from -0.0.290 N m^{-2} for A12 to 0.333 N m^{-2} for Wu (1969). In the case of global annual average, the values are -0.283 and 0.322, respectively. Table 1 shows also the same data "normalized" to the A12 data (presented as percentages of A12, which produced the lowest values for each region), which allows us to visualize the relative differences. A surprising result is the annual ratios of the parameterizations values for the global, the NA, and the Arctic regions (**Fig. 4** shows that this is not true on monthly scales). The spread of the momentum flux results is 14 % in all three regions, and even flux values themselves are larger in the NA than globally and larger in the Arctic than in the whole of the NA basin. In the NA region with winds stronger than average for world ocean, the formula giving highest momentum transfer results are the ones with highest values for strong winds, with exception of Andreas et al. (2012) which is lower due to its low values for lower winds speeds. The smaller WS region, with winds that are, on average, weaker than those of the whole Arctic (but stronger than those of the whole NA), had slightly different ratios of the resultant fluxes. For the tropical ocean, which is included for comparison because of its weaker winds, the spread in momentum flux values on an annual scale is 19 %. The spreads are even larger on monthly scales (not shown). The difference between A12 and Wu (1969) and NCEP/NCAR (the two parameterizations producing the largest fluxes on monthly scales) are 27 % and 29 % for the NA (in July), 31 % and 36 % for the Arctic (in June), 42 % and 51 % for the WS region (in July) and 23 % and 22 % for the tropical ocean (in April), respectively. Seasonality in the tropics is weak, therefore, the smallest monthly difference of 16 % (July) is larger than the difference for the global data in any month (the global differences between the parameterizations have practically no seasonality). On the other hand, the smallest monthly differences between the parameterizations in the NA, the Arctic, and the WS regions are all 7 %, in the month of the strongest winds (January).

Because the value of momentum flux is important for ocean circulation, its correct calculation in coupled models is very important, especially in the Arctic, where cold halocline stratification depends on the amount of mixing (Fer, 2009). We show that with the parameterization used in modelling, such as the NCEP/NCAR constant parameterization and Large and Yeager (2004), production stress results differ by about 5 %, on average (both in the Arctic and globally), and the whole range of parameterizations leads to results that differ, on average, by 14 % (more in low wind areas) and much more on monthly scales. One aspect that needs more research is the fact that the newest parameterization, A12, produces less momentum flux than all the previous ones, especially in lower winds (which, by the way, continues the trend of decreasing values throughout the history of the formulas discussed). The A12 parameterization is based on the largest set of measurements of friction velocity as a function of wind speed and utilizes the recently discovered fact that b in equation (7) is not negligible. It also fits the observations that developed swell at low wind velocity has celerity which leads to zero or even negative momentum transfer (Grachev and Fairall, 2001). Therefore, the significantly lower A12 results for the tropical ocean (the trade wind region) and months of low winds elsewhere could mean that most momentum transfer calculations are overestimated. This matter needs further study, preferably with new empirical datasets.

4. Conclusions

In the present work the evaluation of how the selected parameterization affects the total value of momentum fluxes for large reservoirs was assessed. This allows constraining the uncertainty caused by the parameterization choice. In order to achieve this we calculated monthly and annually average momentum fluxes using a set of software processing tools called the FluxEngine in the North Atlantic (NA) and the European Artic (EA). The NA was defined as all sea surface areas in the Atlantic sector north of 30° N, and the EA was sea areas north of 64° N. Based on our results, we still do not know which one of the parameterizations can be reccomend as the most suitable for the NA and the EU study. Further investigation of the differences in the parameterization of the exchange coefficient in the various algorithm would help in resolving this problem.

Despite many measurements, the drag coefficient still has wide variability at low and moderate wind speeds. The lower the wind speed, the higher uncertainty are, and at low winds it is uncertainty by a factor of 0.5-1.5 depending on the formula used, while at moderate winds it is uncertainty by a factor of 1.5-2.0 (Fig. 1). The annual mean wind speed in the NA is 10 m s^{-1}, and in the EU it is 8.5 m s^{-1}.

We show that the choice of drag coefficient parameterization can lead to significant differences in resultant momentum flux (or wind stress) values. Comparing the values of momentum flux across the sea surface from the power law parameterization, it showed that in both regions, with low and high winds, the parameterizations specified for all winds speeds (eq. 13) has lower values of wind stress than the parameterizations specified for light winds (eq. 7). In the Arctic, the NA, and globally the differences between the wind stress, depend on formula used, are 14 % and they are higher in low winds areas. The parameterizations generally have a decreasing trend in the resultant momentum flux values, with the most recent (Andreas et al., 2012) producing the lowest wind stress values, especially at low winds, resulting in almost 20

% differences in the tropics (Table1). The differences can be much larger on monthly scales, up to 29 % in the NA and 36 % in the EA (in months of low winds) and even 50 % locally in the area west of Spitsbergen. For months that have the highest average winds, the percentage differences are smaller (about 7 % everywhere), but because absolute value of the flux are largest for high winds, this 7% discrepancy is also important for air-sea momentum flux values. Since momentum flux is an important parameter in ocean circulation modeling, we believe more research is needed (one aspects that needs more research is the fact that the newest power law parameterization, A12, produces less momentum flux than all the previous ones, especially in lower winds), and the parameterizations used in the models possibly need further development.

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Table 1. Area average annual mean values of momentum flux (wind stress) [N m^{-2}] for all the studied regions and parameterizations. In each column the percentage values are normalized to A12, the parameterization that produced the smallest average flux values.

Figure 1. The drag coefficient parameterization used in the study (Eqs. 7-13) as a function of wind speed U_{10} (m s^{-1}).

Figure 2. Annual mean wind speed U_{10} (m s^{-1}) in the study area—the North Atlantic and the European Arctic (north of the red line).

Figure 3. Maps of momentum flux [N m^{-2}] across the sea surface (wind stress) for boreal winters ((**a**) and (c)) and summers ((**b**) and (**d**)) for Wu (1969) and A12 drag coefficient parameterizations (the two parameterizations with the highest and lowest average values, respectively).

Figure 4. Monthly average momentum flux values [N m^{-2}] for (**a**) global ocean, (**b**) North Atlantic, (**c**) European Arctic, and (**d**) tropical ocean. The regions are defined in the text.

Figure 5. Area annual average momentum flux values for (**a**) European Arctic and (b) Tropical ocean. The vertical solid line is the average of all seven parameterization and the dashed lines are standard deviations for the presented values. Global and the North Atlantic results are not shown because the relative values for different parameterizations are very similar (see Table 1), scaling almost identically between the basins.

Table 1. Area average annual mean values of momentum flux (wind stress) [N m^{-2}] for all the studied regions and parameterizations. In each column the percentage values are normalized to A12, the parameterization that produced the smallest average flux values.

	Global	North Atlantic	Arctic	W. Spitsbergen	Tropics
Wu (1969)	0.322 (114 %)	0.330 (114 %)	0.375 (114 %)	0.360 (114 %)	0.261 (119 %)
Garratt (1977)	0.307 (109 %)	0.316 (109 %)	0.358 (109 %)	0.344 (110 %)	0.251 (115 %)
Wu (1982)	0.311 (110 %)	0.320 (110 %)	0.363 (110 %)	0.349 (111 %)	0.255 (117 %)
NCEP/NCAR	0.303 (107 %)	0.312 (107 %)	0.353 (107 %)	0.341 (108 %)	0.258 (118 %)
Yelland & Taylor (1996)	0.297 (105 %)	0.306 (105 %)	0.348 (106 %)	0.335 (107 %)	0.245 (112 %)
Large & Yeager (2004)	0.285 (101 %)	0.293 (101 %)	0.333 (101 %)	0.320 (102 %)	0.236 (108 %)
Andreas et al., (2012)	0.283 (100 %)	0.290 (100 %)	0.329 (100 %)	0.314 (100 %)	0.219 (100 %)

Figure 1. The drag coefficient parameterization used in the study (Eqs. 7-13) as a function of wind speed U_{10} (m s^{-1}).

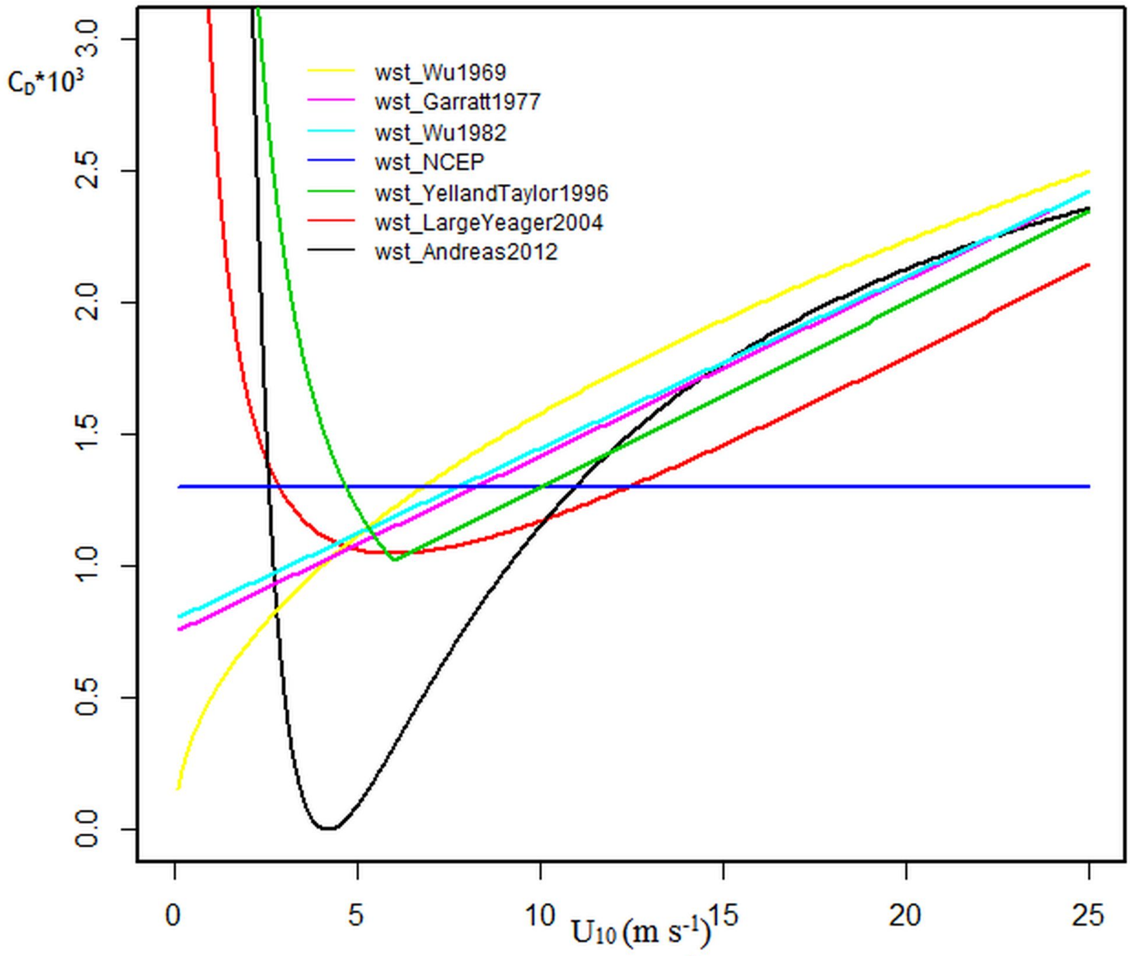


Figure 2. Annual mean wind speed U_{10} (m s^{-1}) in the study area—the North Atlantic and the European Arctic (north of the red line).

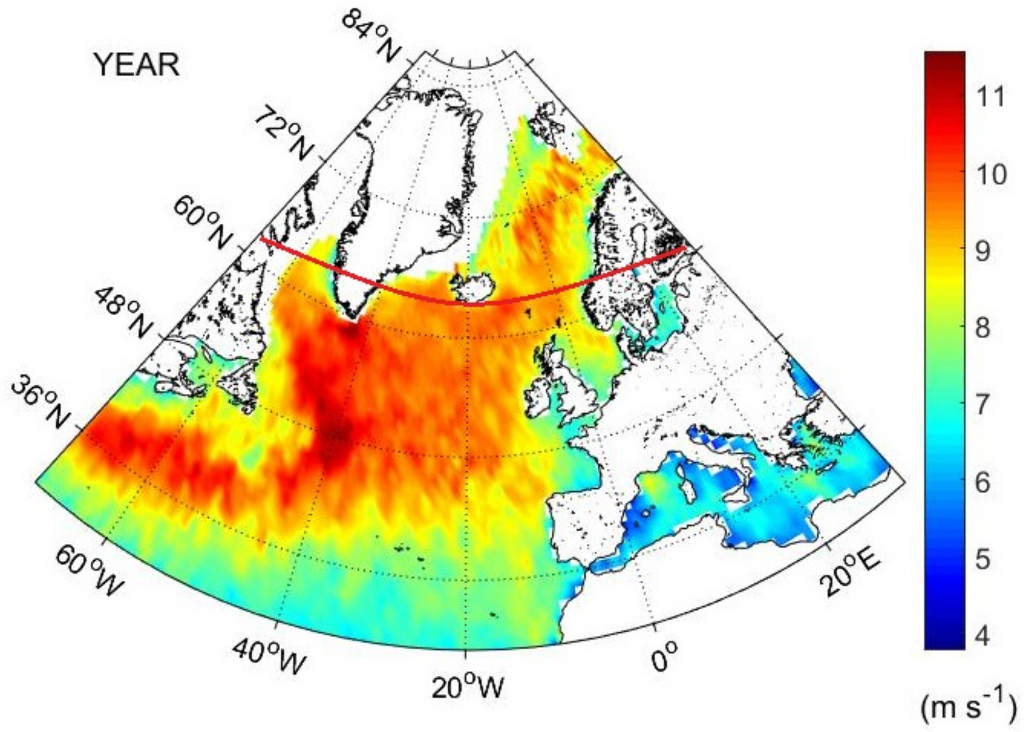
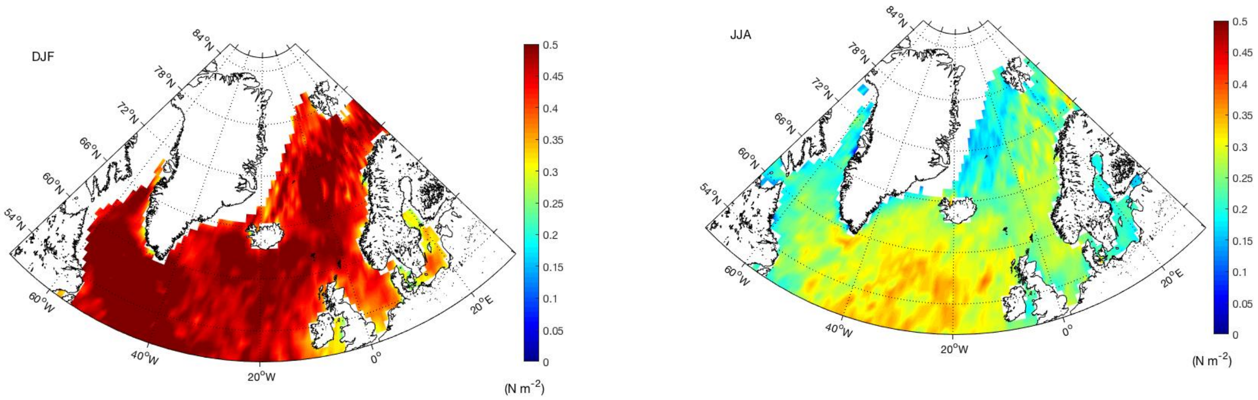


Figure 3. Maps of momentum flux [N m^{-2}] across the sea surface (wind stress) for boreal winters ((**a**) and (**c**)) and summers ((b) and (**d**)) for Wu (1969) and A12 drag coefficient parameterizations (the two parameterizations with the highest and lowest average values, respectively).

(**a**) Wu, (1969) (**b**) Wu (1969)



(**c**) Andreas, et al., (2012)

(**d**) Andreas, et al., (2012)

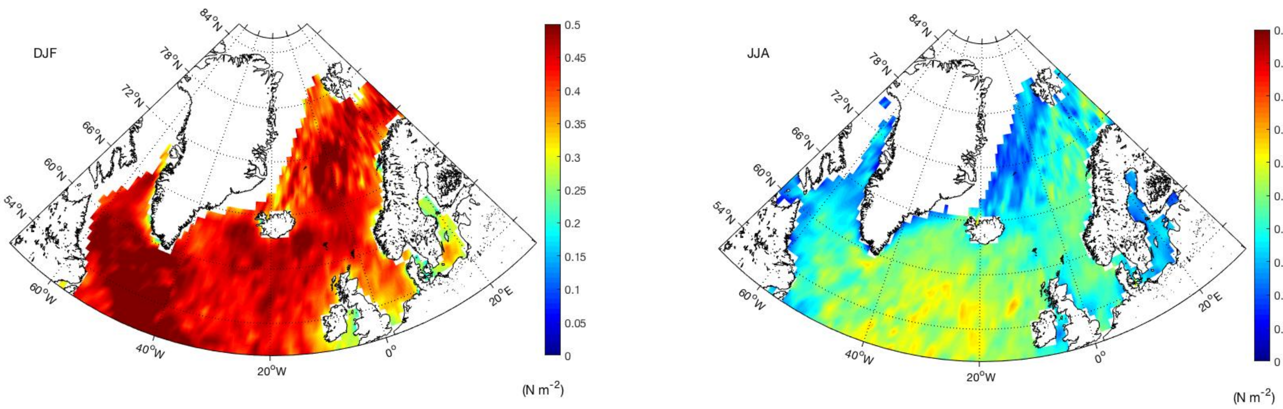
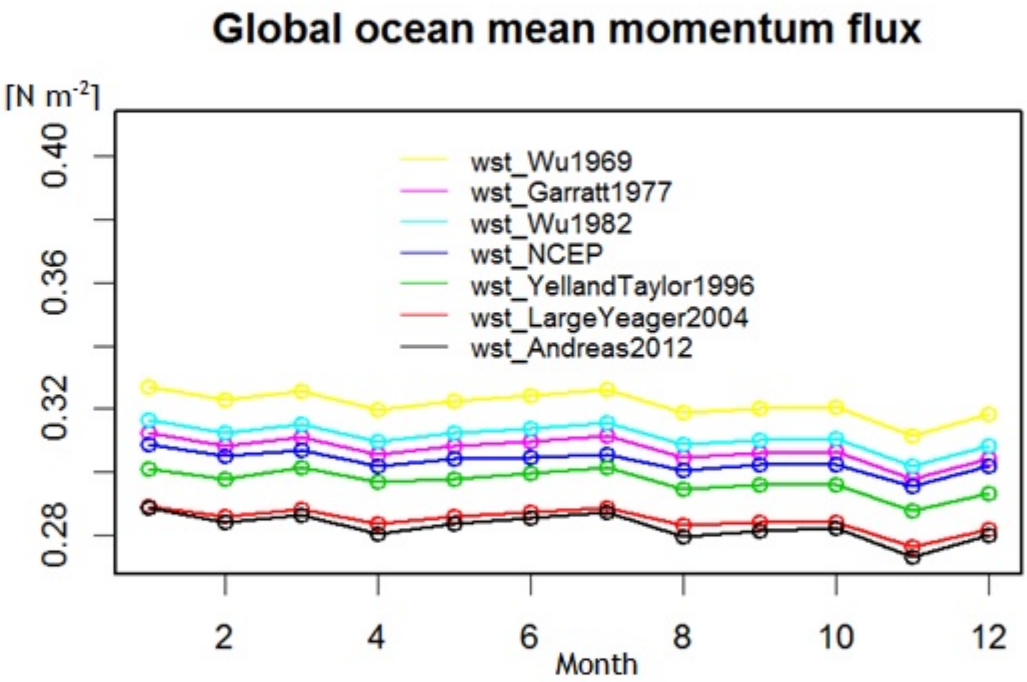


Figure 4. Monthly average momentum flux values [N m^{-2}] for (**a**) global ocean, (**b**) North Atlantic, (**c**) European Arctic, and (**d**) Tropical ocean. The regions are defined in the text.

(**a**)



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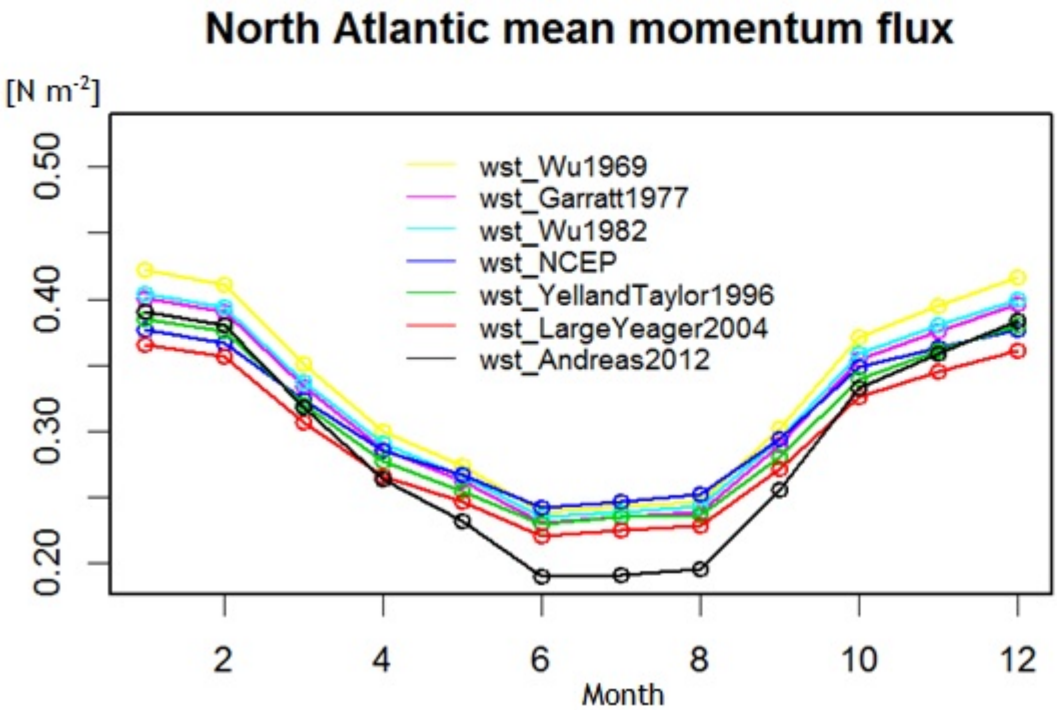
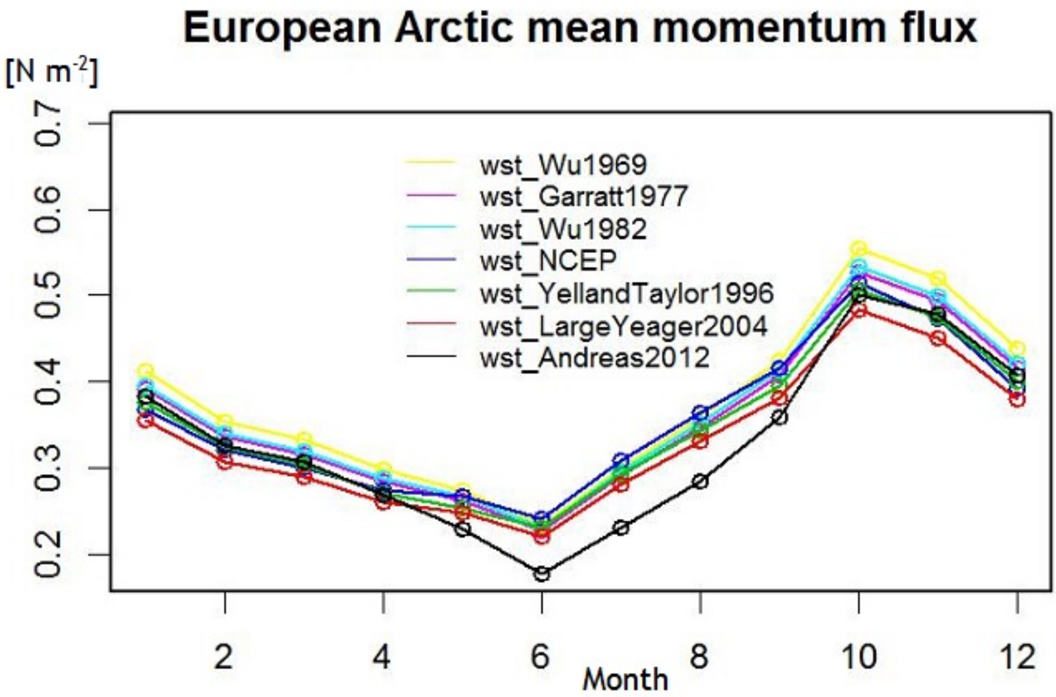


(**c**)


European Arctic mean momentum flux
[N m-2]
0.2
0.3
0.4
0.5
0.6
0.7
wst_Wu1969
wst_Garratt1977
wst_Wu1982
wst_NCEP
wst_YellandTaylor1996
wst_LargeYeager2004
wst_Andreas2012
2
4
6
8
10
12
Month

(**d**)

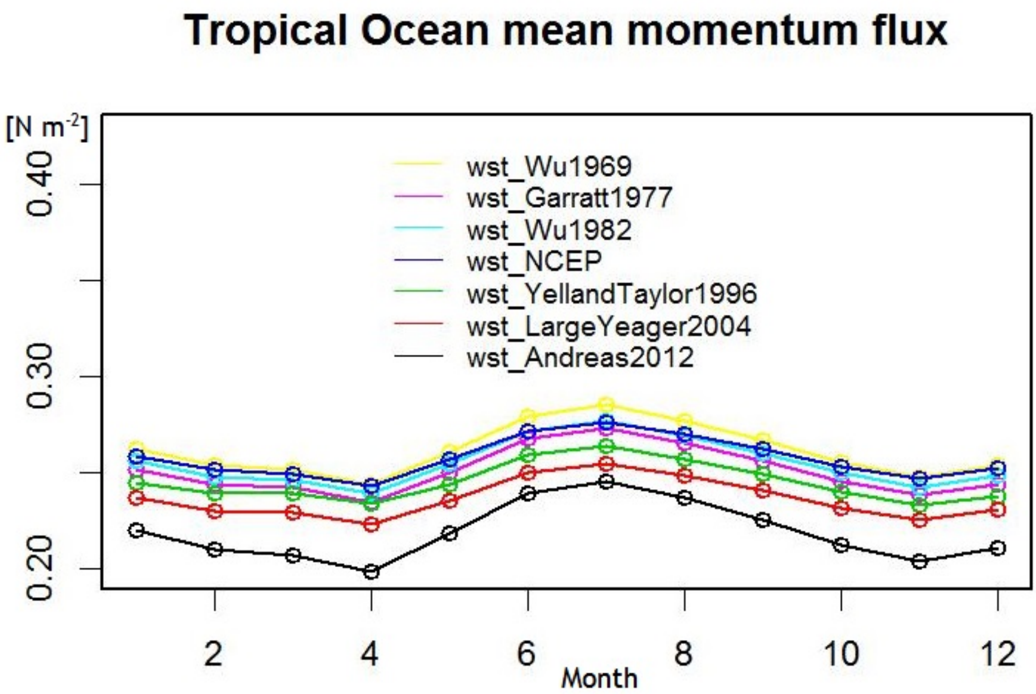
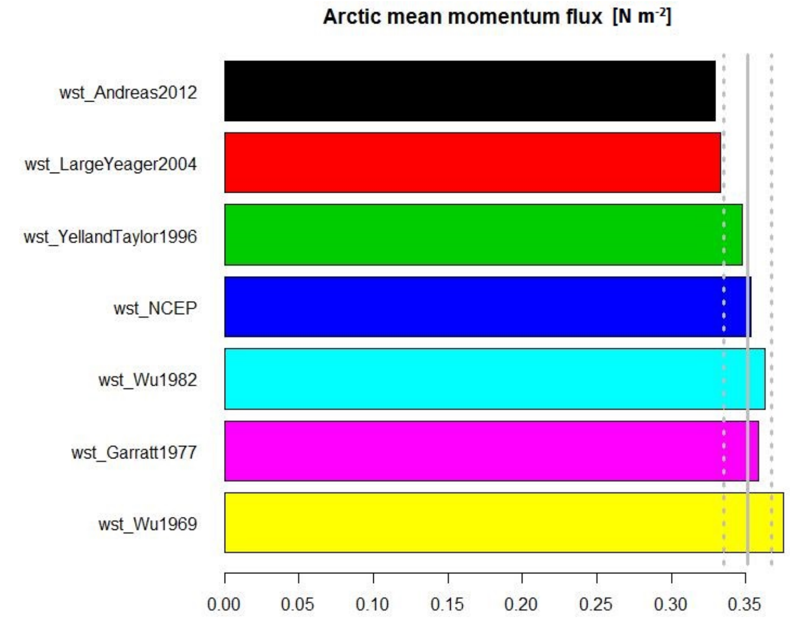

Tropical Ocean mean momentum flux
[N m-2]
0.20
0.30
0.40
wst_Wu1969
wst_Garratt1977
wst_Wu1982
wst_NCEP
wst_YellandTaylor1996
wst_LargeYeager2004
wst_Andreas2012
2
4
6
8
10
12
Month

Figure 5. Area annual average momentum flux values for (**a**) European Arctic and (**b**) Tropical ocean. The vertical solid line is the average of all seven parameterizations and the dashed lines are standard deviations for the presented values. Global and the North Atlantic results are not shown because the relative values for different parameterizations are very similar (see Table 1), scaling almost identically between the basins.

(**a**)



(**b**)