



iAtlantic Deliverable 1.1

Atlantic circulation variability in the past 50 years

Project acronym:	iAtlantic
Grant Agreement:	818123
Deliverable number:	1.1
Deliverable title:	Atlantic circulation variability in the past 50 years
Work Package:	1
Date of completion:	10/09/2021
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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818123 (iAtlantic). This output reflects only the author's view and the European Union cannot be held responsible for any use that may be made of the information contained therein.

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1 Executive Summary

In a peer-reviewed paper, Biastoch et al. (2021) describe a hierarchy of global $1/4^\circ$ (ORCA025) and Atlantic Ocean $1/20^\circ$ nested (VIKING20X) ocean-sea-ice models. They show that the eddy-rich VIKING20X configuration performed in hindcasts of the past 50-60 years under CORE and JRA55-do atmospheric forcing realistically simulate the large-scale horizontal circulation, the distribution of the mesoscale, overflow and convective processes, and the representation of regional current systems in the North and South Atlantic. The representation of the AMOC, and in particular the long-term temporal evolution, strongly depends on numerical choices for the application of freshwater fluxes. The interannual variability of the AMOC instead is highly correlated among the model experiments and also with observations, including the 2010 minimum observed by RAPID at 26.5° N. This points to a dominant role of the wind forcing. The ability of the model to represent regional observations in western boundary current (WBC) systems at 53° N, 26.5° N and 11° S is explored. The question is whether WBC systems are able to represent the AMOC, and in particular whether these WBC systems exhibit similar temporal evolution to the one of the zonally integrated AMOC. Apart from the basin-scale measurements at 26.5° N, it is shown that the outflow of North Atlantic Deepwater at 53° N is a good indicator of the subpolar AMOC trend during the recent decades, once provided in density coordinates. The good reproduction of observed AMOC and WBC trends in the most reasonable simulations indicate that the eddy-rich VIKING20X is capable of representing realistic forcing-related and ocean-intrinsic trends.

2 Introduction

The Atlantic Ocean circulation influences the above lying atmosphere and plays a key role for climate and climate change. It also shapes the distribution of biogeochemistry in the ocean and determines the connectivity of marine ecosystems. The Atlantic Meridional Overturning Circulation (AMOC) summarizes the four-dimensional ocean circulation and provides an integral metric for the state of the ocean circulation and its impacts. It is one of the most important variables evaluated in ocean and climate models.

Circulation changes in the Atlantic Ocean occur in a range of temporal scales. Owing to the dominance of the mesoscale (Chelton et al., 2011), a snapshot view gives the impression that the ocean is a sea of eddies, without an existence of coherent current systems. While this mesoscale is important for the dispersal of quantities and organisms over large distances, averages over longer time periods offer views on the large-scale circulation variability. On interannual to decadal timescales, the ocean currents and hydrography are strongly determined by the atmospheric forcing, the mechanistic forcing of the wind, and the thermohaline forcing through heat and freshwater fluxes.

Ocean general circulation models (OGCMs) in realistic settings and forced by observed atmospheric data of the past decades simulate the full range of spatio-temporal scales of circulation changes, from the mesoscale to the decadal variability. OGCMs provide important tools for the description of the Atlantic circulation. They expand and guide the interpretation of naturally limited observations and provide physically consistent answers of the mechanistic understanding of the evolution and the interplay of oceanic current systems. In iAtlantic, the simulated velocities, temperatures, and salinities of OGCMs provide the input for Lagrangian dispersal studies to trace the spreading of marine organisms.

The AMOC is characterised by the northward transport of warm waters in the upper layers of the Atlantic and the southward flow of cooler water in deeper layers. As it is linked to the amount of heat transported northward, it shapes the climate in those nations whose coastlines are warmed by its influence (e.g. mild temperatures in Europe). The AMOC also determines the amount of anthropogenic trace gases (Chlorofluorocarbons (CFC), CO₂) taken up and stored in the ocean, thus buffering global warming.

The AMOC is in the focus of WP1, connects the individual tasks that consider the large-scale circulation and its influences of specific regions, guides the setup of ocean observations, and is an important driver for ecosystem connectivity. Within WP1, Task 1.1 provides the framework by setting up, verifying and analysing ocean models and by providing output of the past decades for further analyses and studies of ecosystem connectivity. GEOMAR performs two models to fulfil this goal: VIKING20X covering the full Atlantic, and INALT20 (Schwarzkopf et al., 2019) with a specific focus on the South Atlantic and Agulhas region.

This report is an introduction and summary of a larger report on the Atlantic circulation variability of the last 50 years as simulated by the state-of-the-art high-resolution model VIKING20X that has been accepted to the international peer-reviewed literature (Biajoch et al., 2021). Last 50 years is the timescale that is of interest for most studies in iAtlantic and the best known in respect to ocean observations.

3 Methodology

In this study a nested configuration, VIKING20X, with nominal horizontal 1/20° resolution in the Atlantic Ocean between 33.5°S to ~70°N, is used (Figure 1). It is based on the Nucleus for European Modelling of the Ocean nemo (NEMO, Madec, 2016) code version 3.6, combined with the Louvain la Neuve sea-ice model (LIM2, Fichefet & Morales Maqueda, 1997). NEMO is based on the primitive equations describing the dynamic-thermodynamic state of the ocean discretised on a staggered Arakawa-C grid while the two-layer sea-ice model simulating one ice class with a

viscous-plastic rheology is solved on a B grid. The global configuration (ORCA025) serves as a host for the eddy-rich configuration VIKING20X using Adaptive Grid Refinement in Fortran (AGRIF, Debreu et al., 2008) to regionally increase the resolution by embedding a so-called nest.

VIKING20X is based on the success of VIKING20 (Erik Behrens, 2013; Erik Behrens et al., 2017; Böning et al., 2016; Breckenfelder et al., 2017; Gary et al., 2018, 2020; Handmann et al., 2018) and has been demonstrated to realistically simulate the AMOC (Hirschi et al., 2020) and Labrador Sea (Rieck et al., 2019). All full verification is given in Biastoch et al. (2021).

VIKING20X provides the physically consistent spatial and temporal framework of the ocean observations in the North and South Atlantic (Task 1.2) and for the determination of basin-scale modes (Task 1.4). The ultra-high resolution models, e.g. of the Walvis Ridge (Task 1.3), are embedded into the basin-scale circulation and hydrography through VIKING20X. Output from the VIKING20X hindcasts is also used to advect virtual biological organisms such as mussel or sponges larvae to be combined with the genomic analyses (Task 1.5).

Several model hindcasts are performed under the two different atmospheric forcing sets: CORE (version 2) (Large & Yeager, 2009) and JRA55-do (Tsujino et al., 2018).

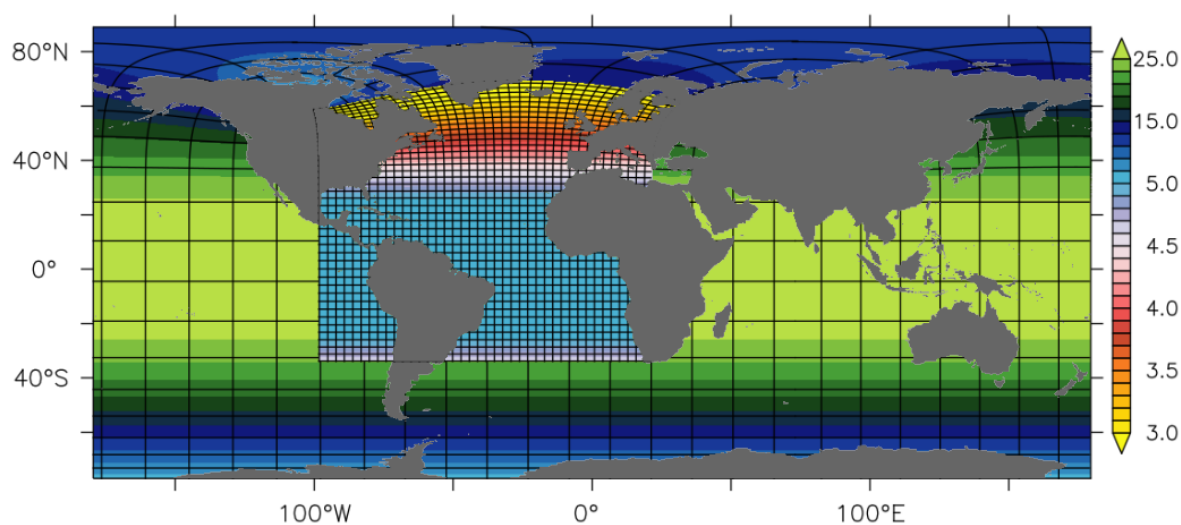


Figure 1. Domain and resolution (in km) of the VIKING20X nest within the global ORCA025 model.

4 Basin-wide Circulation

The structure of the mean sea surface height (SSH; [Figure 2](#)) is robust among the different hindcast experiments and forcing, which confirms the existence of the North Atlantic subtropical and subpolar gyres, the equatorial circulation, and the South Atlantic-Indian Ocean supergyre.

Compared to a coarser resolved version (ORCA025), VIKING20X shows an enhanced level of the mesoscale, as well as an improved structure of western boundary currents. A prominent difference is the realistic separation of the North Atlantic current and its subsequent northward turn into the Northwest Corner in VIKING20X.

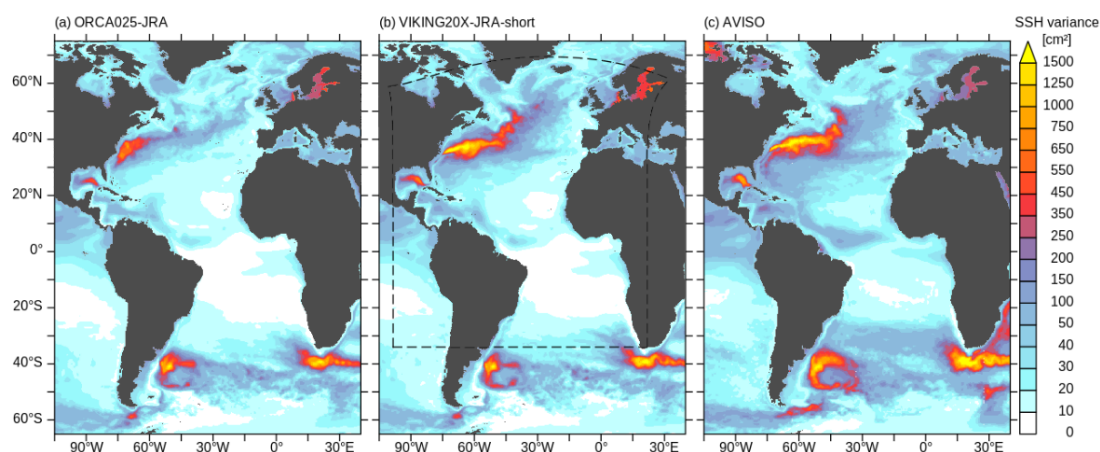


Figure 2. Standard deviation of sea surface height (in cm^2) in (a) ORCA025-JRA, (b) VIKING20X-JRA-short, and (c) satellite altimetry (AVISO), calculated over the period 1993-2019.

While the horizontal circulation is strongly determined by the grid resolution and the wind field, the AMOC strongly depends on both wind and thermohaline driving mechanisms. This involves the applied atmospheric forcing itself, but is also impacted and determined by the sea surface salinity restoring timescales and other details of the atmospheric forcing (Behrens et al., 2013). Notably, the AMOC differs not only in the mean circulation (Figure 3). The general structure with North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW) cells is visible in all experiments but differ in strength. In consequence, different experiments also show different trends over the hindcast lengths (Figure 4).

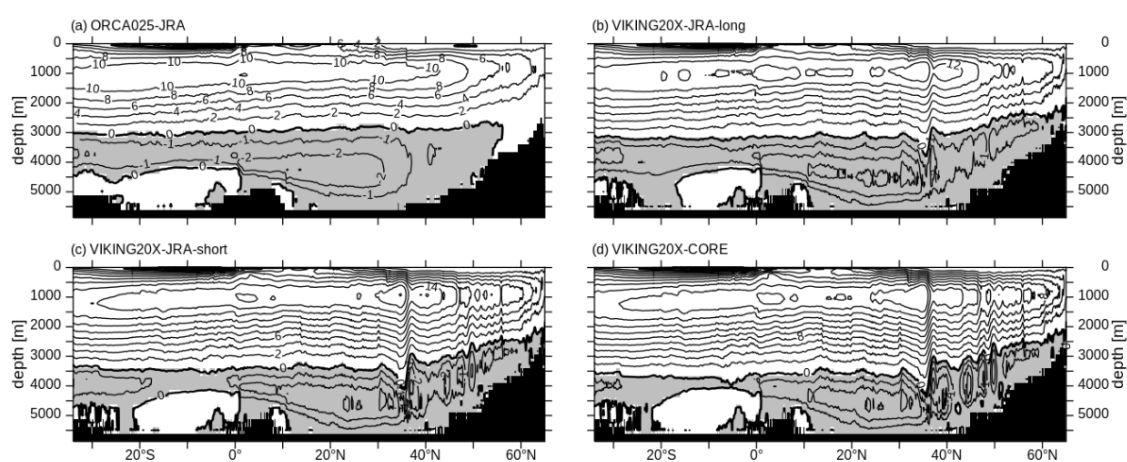


Figure 3. Mean AMOC (1990-2009, in Sv) in (a) ORCA025-JR, (b) VIKING20X-JRA-long, (c) VIKING20X-JRA-short, and (d) VIKING20X-CORE.

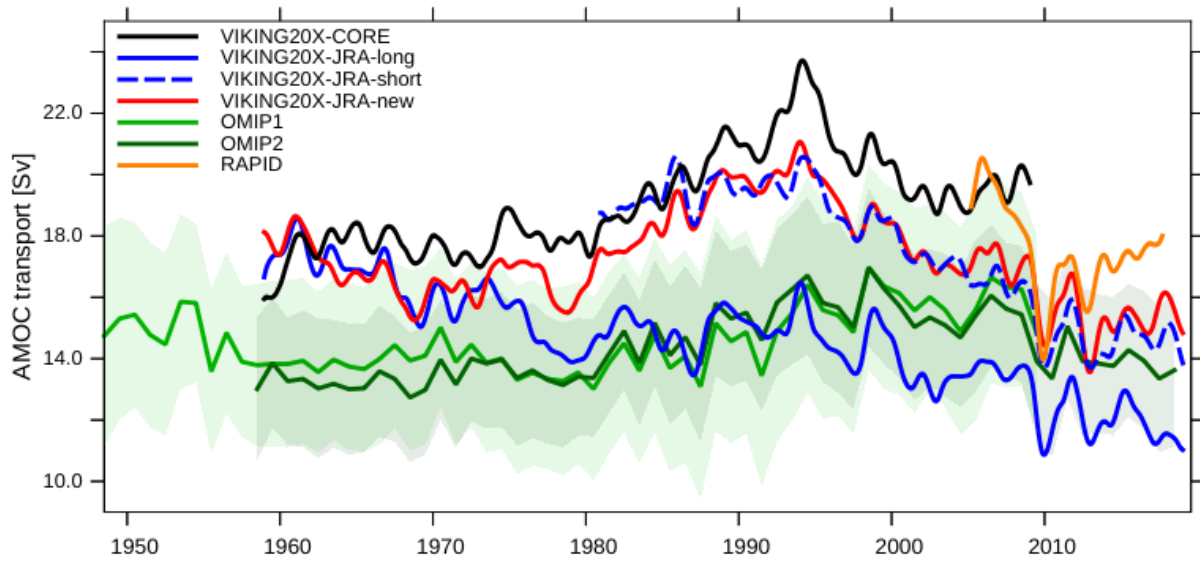


Figure 4. AMOC strength at 26.5°N in experiments at 1/20° (VIKING20X) resolution compared to OMIP1 (Danabasoglu et al., 2016) and -2 (Tsujino et al., 2020) and RAPID observations.

5 Regional Changes

The evolution of the basin-scale horizontal circulation and the AMOC is reflected in many regional current systems. The circulation in the subpolar North Atlantic is represented by an index based on sea surface height (Figure 5). It is highly correlated with the upper ocean density in the centre of the subpolar gyre, the upper ocean salinity in the eastern North Atlantic, and the North Atlantic Oscillation (NAO) index. The decadal variability of the gyre strength is a response to wind stress curl variability over the subpolar North Atlantic (hence NAO).

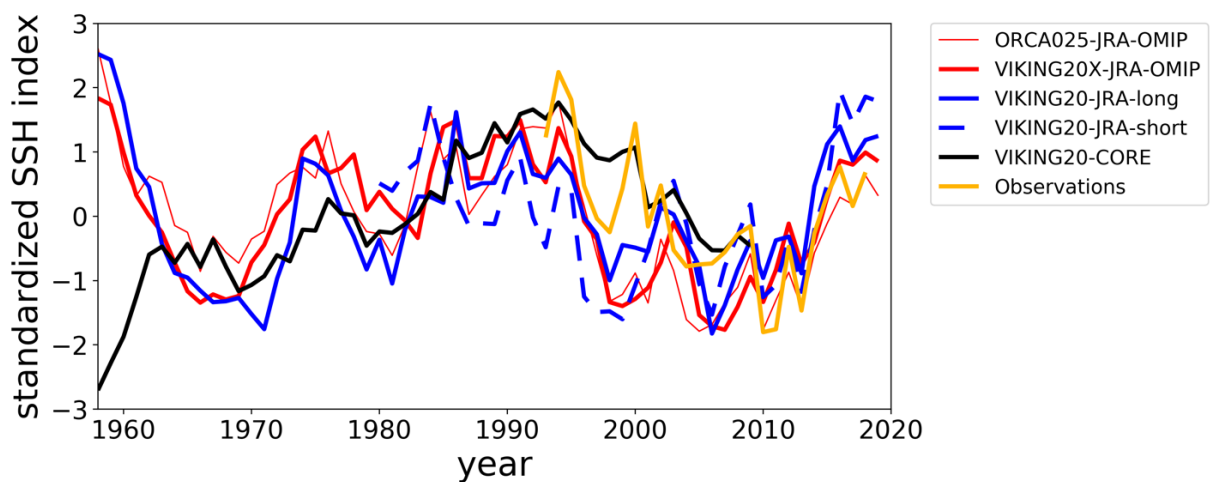


Figure 5. Time series of the annual mean subpolar gyre index in the experiments and based on observations (orange). Here, the index is defined as the second PC of an EOF-analysis for non-

detrended sea surface height in the North Atlantic between 20 and 70°N.

In the subtropical North Atlantic, the transport through the Florida Strait is an important quantity that can be well compared to telephone cable-based observations (Meinen et al., 2010). In contrast to the strength of the subpolar gyre, the strength of this individual component of the western boundary current is less robust among the different experiments, which may be reflected by the different strength of the AMOC component of the Florida Current (Figure 6).

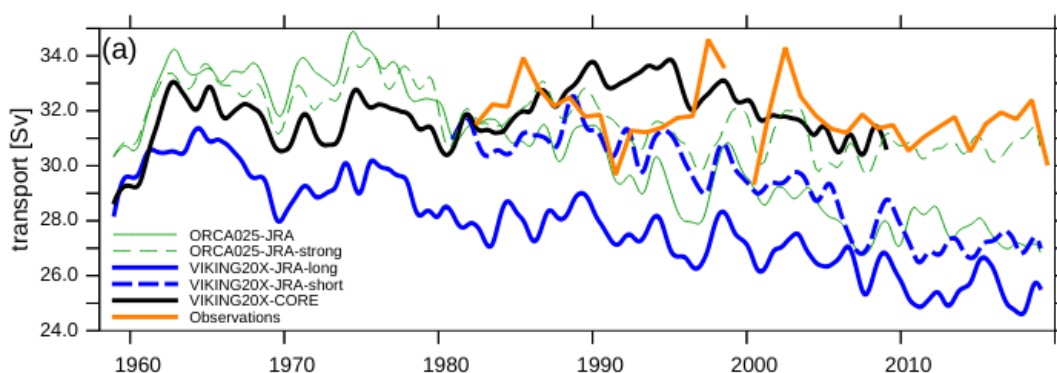


Figure 6. Time series of the transport (Sv) through Florida Strait for different experiments and from cable observations.

In the Southern Hemisphere, the large-scale signal of the AMOC is largely reflected in the transport of the North Brazil Undercurrent (Rühs et al., 2015). As demonstrated in Figure 7, the individual experiments robustly reproduce the observations estimates by the ship-based sections and the moorings off Brazil (Hummels et al., 2015).

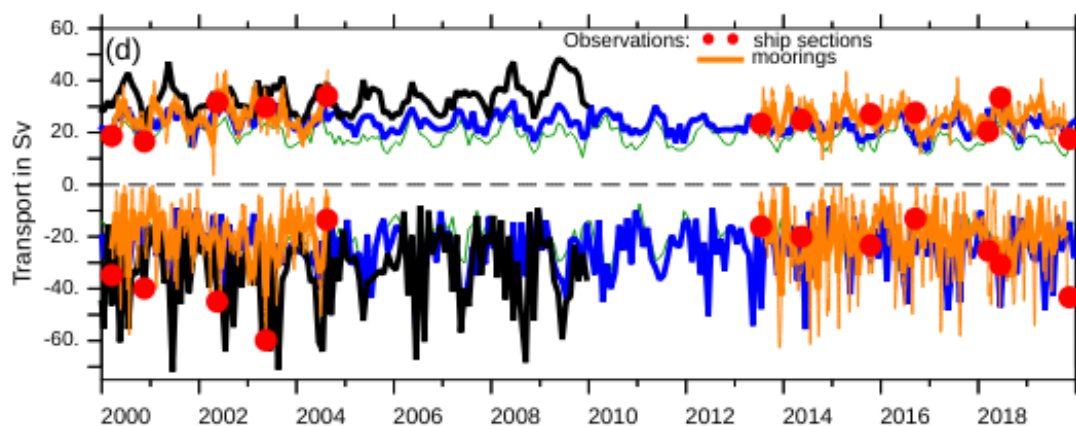


Figure 7. Time series of transport (Sv) from the VIKING20X experiments compared (colours as in Figure 6) to ship-based sections (red dots) and mooring time series (orange).

Although many aspects of the wind-driven circulation are robust among individual experiments,

detailed views of regional current systems (such as the subpolar gyre or the western boundary currents) may substantially differ among individual hindcasts. For a solid expansion of the limited set of observations, careful comparisons need to be made. For more details see Biastoch et al. (2021).

6 Conclusion

The results described in Biastoch et al. (2021) demonstrate that a “realistically” configured ocean hindcast in a configuration like VIKING20X is well suited for simulating the large-scale circulation dynamics in the Atlantic Ocean. Once the mesoscale is resolved by an adequate resolution over the full model domain and the model is driven by a realistic and balanced atmospheric forcing, many aspects of the simulated wind-driven and thermohaline circulation compare very well with observations. These include the large-scale structure of the mean flow, the distribution and strength of mesoscale eddies, WBC structures, and individual current systems. There is good agreement between model and observations in terms of velocity structures and integral transports, even of their temporal variability and trends. Because of the strong impact of the wind forcing, the role of the atmospheric forcing dataset cannot be underestimated for such an ocean-only model.

The simulated interannual variability of the individual western boundary current systems and the large-scale circulation are quite robust among the model experiments, demonstrating the dominance of the atmospheric forcing for these periodicities. Specific details of the decadal variability, in particular those that are caused by the thermohaline forcing (in contrast to the wind-driven changes) also depend on model-related details. This is also true for the long-term trends. The most promising and “realistic” experiments that are used in iAtlantic for comparison with observations, for downscaling using regional model and for studies on the biological connectivity are VIKING20X-JRA-short and VIKING20-JRA-OMIP.

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8 Document Information

EU Project N°	818123	Acronym	iAtlantic
Full Title	Integrated Assessment of Atlantic Marine Ecosystems in Space and Time		
Project website	www.iatlantic.eu		

Deliverable	N°	1.1	Title	Atlantic circulation variability in the past 50 years
Work Package	N°	1	Title	Atlantic Oceanography and Ecosystem Connectivity

Date of delivery	Contractual	31/08/2019	Actual	10/09/2021
Dissemination level	X	PU Public, fully open, e.g. web		
		CO Confidential restricted under conditions set out in Model Grant Agreement		
		CI Classified, information as referred to in Commission Decision 2001/844/EC		

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