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The Role of Rivers in Ocean Forecasting

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Abstract. The connection between the ocean and the land is made possible thanks to rivers, which are a vital component of the Earth's system. They govern the hydrological and biogeochemical contributions to the coastal ocean and influence local circulation and the distribution of water masses, modulating processes such as upwelling and mixing. This paper provides an overview of recent advancements in river modelling, with a particular focus on estuaries. The methods discussed range from those currently adopted in coarse-resolution ocean forecasting systems, where mixing processes are primarily parameterized, to coupling approaches that are better suited for coastal systems. A review of river data availability is also presented, illustrating various sources, from observational data to climatological datasets, and more precise river modelling approaches that are improving the representation of water discharges in operational systems. Finally, a compendium of current operational systems is provided, with a focus on how river forcing is treated, from global to coastal scales.

1 Introduction

Rivers provide the primary link between land and sea and deliver annually an average of 36 thousand km^3 of freshwater and over 20 billion tons of solid and dissolved material to the world ocean (Milliman and Farnsworth, 2011). River discharge into the ocean is a major component of the global hydrological and biogeochemical cycles, which have undergone significant changes under the influence of climate change and human activities (Shi et al., 2019; Yan et al., 2022; Qin et al., 2022; Chandanpurkar et al., 2022). Mediated through estuaries, freshwater fluxes influence the ocean circulation and salinity, and in particular the upper-ocean stratification, which in turn affects the mixed layer depth, ocean currents, and air-sea interaction (Chandanpurkar et al., 2022; Dzwonkowski et al., 2017; Sprintall and Tomczak, 1992; Sun et al., 2017). Freshwater inputs to the ocean also modulate coastal upwelling events, thus impacting productivity of the coastal marine environment (Sotillo et al., 2021).

Despite rivers' influence on the coastal and basin-wide circulation and dynamics, in global and regional scale models effectively accounting for riverine freshwater discharge into the oceans is a challenging problem (Sun et al., 2017; Verri et al., 2020). The setup of practical open boundary conditions (OBC) is dependent on flow dynamics, model resolution, data availability, and other factors (Blayo and Debreu, 2005). At coarse scales that cannot resolve the estuarine dynamics, river

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outlets are typically represented in a simplistic way, with climatological runoff and zero or constant salinity values, implicitly neglecting estuarine mixing or exchange (Sun et al., 2017; Verri et al., 2020; Verri et al., 2021). Consequently, important natural processes are omitted and, depending on how river forcing is defined, ocean model results may differ significantly from one another, predominantly in the shelf areas (or regions of freshwater influence, ROFI), but also at regional and global scales (Tseng et al., 2016).

The next sections present a review of approaches to treat river forcing in global, regional and coastal ocean models, including dynamic methods to represent the mixing processes in estuaries through parameterization and coupling techniques. A description of data sources used for this purpose is also provided, with examples taken from existing OOFS. While the first sections review the scientific literature and ancillary information, for example, taken from operational centers and data providers websites, the last section summarizes results from a survey sent to the OceanPredict community.

2 River forcing in ocean models

In nature, estuaries transport and transform water properties along their length, due to tidal mixing, deposition and resuspension, and up- and down-estuary advection. Saltwater intrusion driven by tides and other coastal signals (e.g. storm surges) controls the estuarine water exchange and affects the net estuarine outflow and corresponding salinity values (Sun et al., 2017; Verri et al., 2020). However, although water properties at the head differ from those at the mouth, in models too coarse to resolve the estuaries, river discharge observed far from the river outlet is typically inputted at the coast with zero salinity (Verri et al., 2021; Herzfeld, 2015).

2.1 Freshwater input in coarse resolution models: towards a parameterization of estuarine mixing processes

Herzfeld (2015) describes and assesses the performance of various methods for inputting freshwater into regional ocean models. A first approach, referred to as a point source input, adds a term of freshwater flux into one or more layers of the model via the continuity equation, with no associated velocity profile. A second approach, the flow input, considers the inertia of the river flow and prescribes a velocity profile at the boundary whose vertical integral is equal to the inflow flux. These two methods must have a predefined depth at the boundary over which to distribute the volume inflow. A more accurate approach is to add an artificial channel to the coastline to give momentum to the flow and initiate mixing between fresh and salt waters (Lacroix et al., 2004; Sobrinho et al., 2021)

The horizontal distribution of the runoff plays an important role in the regional salinity distribution and in the vertical stratification and mixing (Tseng et al., 2016). In global ocean models, however, freshwater inflow is frequently added at the ocean surface, either as an increased precipitation rate over a specified area or by reducing surface salinity (i.e. a virtual salt flux), rather than being introduced as a lateral inflow at the coastal boundary. This freshwater can be distributed vertically over several layers or diffused horizontally using enhanced mixing (Sun et al., 2017; Tseng et al., 2016; Yin et al., 2010).

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Several plume responses may result from the choice of the horizontal and vertical distribution of freshwater input. However, most model applications produce plumes whose types differ from plumes associated with real river discharges (Tseng et al., 2016; Garvine, 2001; Schiller and Kourafalou, 2010). Larger scale offshore stratification is also expected to be impacted by this choice.

MacCready and Geyer (2010) establish the theoretical foundation for estuarine mixing parameterizations, which underpins some physics-based methods used to simulate unresolved estuarine processes in regional and global ocean models, such as the estuary box model (EBM); see, for example, Figure 1 (Sun et al., 2017). These models attempt to parameterize mixing processes and to account for baroclinic flow, typically using a two-layer formulation, e.g. Verri et al. (2020), Verri et al. (2021), Herzfeld (2015), Rice et al. (2008), Hordoir et al. (2008). From these representations, analytical solutions can be found for the volume fluxes and outflow salinity. Applied globally to the Community Earth System Model (CESM), such an approach revealed substantial localized, regional, and long-range effects when compared to cases without parameterization, highlighting once again the strong sensitivity of ocean models to the treatment of rivers (Sun et al., 2017).

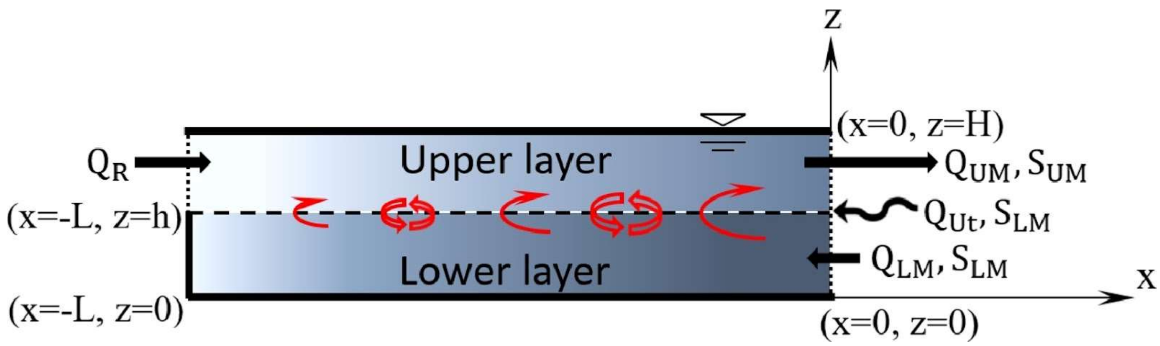

Figure 1: Schematic diagram of the estuary box model (EBM), depicted as a two-layer rectangular box with constant width, uniform local depth (H), and a time-varying length (L). Each layer has a fixed thickness (h for the lower layer and H-h for the upper layer), with vertically uniform but horizontally variable salinity and density. Thick solid lines represent closed boundaries, dotted lines mark open boundaries, and the dashed line shows the interface between layers. Volume fluxes (Q) and salinities (S) are indicated by arrows at open boundaries: riverine freshwater discharge (Q_R) enters at the estuary head, oceanic saltwater flows into the lower layer at the mouth (Q_{LM}), and Q_{Ut} represents the average tidal volume flux during half a tidal cycle, driving net horizontal salt flux into the upper layer at the mouth. Shear-induced turbulent mixing (shown by paired upward and downward open arrows) and upward advection from exchange flow (solid upward arrows) link the upper and lower layers. The color gradient illustrates salinity variation, from fresher (lighter shades) to saltier (darker shades) waters.[1]

2.2 Freshwater input in high resolution models

In contrast, when the model resolution is higher than the estuary width, the latter can be resolved explicitly by extending the grid for some distance inland using either real bathymetry or a straight channel approximation. When extending it beyond the salinity intrusion limit and/or the head of tides, a freshwater flux can be directly specified at the upstream boundary. This is

[1] Reprinted from Ocean Modelling, Vol 112, Sun, Q., Whitney, M. M., Bryan, F. O., and Tseng, Y., A box model for representing estuarine physical processes in Earth system models, Page 140, Copyright Elsevier Ltd. (2017), with permission from Elsevier.

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the preferred option in many east coast US studies (Herzfeld, 2015) (e.g. RISE - Liu et al., 2004; LATTE - Choi and Wilkin, 2007; MerMADE - Hetland and MacDonald, 2008).

2.3 One-way and two-way coupling

Coupling techniques can be used to link two or more models to allow one-way data exchange, for example, between a hydrological model and an ocean model. That way, external forcing is reduced to fewer variables. Limitations of this approach include processes that cannot be resolved at the land-sea interface and the need to extend the ocean domain limits far landward, beyond the limit of tide and storm-surge propagation. In a compound flooding context, two-way coupled models are preferred because both land and ocean processes can be represented along with their interactions (Bao et al., 2022; Cheng et al., 2010). When adding momentum flux between land and ocean processes, the ability to reproduce water levels in the estuary is enhanced (Bao et al., 2022). Moreover, with seamless grid transitions between the different models, flexibility and cross-scale capabilities are augmented (Zhang et al., 2016).

3 Data sources

3.1 Freshwater discharge

An unsolved problem and one of the classical limitations of OOFS with respect to river forcing is the absence of global networks of observed river flows to the oceans. While advances are being made in creating such a network, several challenges remain pertaining to data quality, accessibility, and timeliness, at the required spatial and temporal scales.
In situ river discharge observations are necessary to build climatologies and they represent a key component of the calibration of hydrological models, and thereby of any reanalysis, near-real-time (NRT) analysis and forecast products. The various types of discharge products used in OOFS are described in the following.

3.1.1 Climatologies

Most ocean models use climatologies to introduce river forcing based on multi-decadal averages of observed and/or modeled freshwater discharges, along with zero or constant salinity values. Although use of climatological data is still commonly accepted, even when the estuarine dynamics is not resolved, more realistic and less subjective estimates of freshwater and salinity inputs would produce a more accurate representation of river plumes in ocean models (Verri et al., 2021), especially during nonseasonal (e.g. storm induced) events (Chandanpurkar et al., 2022). Moreover, given the global decline of the hydrometric networks, building climatologies is not always possible, especially for small or less studied rivers (Campuzano et al., 2016; Mishra and Coulibaly, 2009). Furthermore, monthly climatological products are not adequate for high resolution coastal models where temporal variability at daily or even higher frequency is needed (Sotillo et al., 2021).

3.1.2 River databases

River databases and services are progressively becoming available and provide better estimates of coastal runoff and river discharges at the global scale (Sotillo et al., 2021). These databases typically assemble information from multiple data providers into coherent, gap-free and quality-controlled datasets. A few examples are given here:

- The Global Runoff Data Center (GRDC), under the auspices of the WMO, is an international archive of quality controlled historical mean daily and monthly discharge data, from over 10,000 stations distributed in 159 countries, facilitating exchanges between data providers and data users. The most recent published version of the Freshwater Fluxes into the World's Oceans, based on the water balance model WaterGAP contains annual runoff values covering the 1901-2016 period.
- A 35-year daily and monthly global reconstruction of river flows (GRADES), with bias correction from machine-learning derived global runoff characteristics maps, was developed in support of the Surface Water and Ocean Topography (SWOT) satellite mission (Lin et al., 2019).
- A global dataset of monthly streamflow for 925 of the world's largest rivers connecting to the ocean was built by Dai et al. (2009), updated from Dai and Trenberth (2002).
- A dataset of historical river discharge from 1958 to 2016 was created using the CaMa-Flood global river routing model and adjusted runoff from the land component of JRA-55 (Suzuki et al., 2018; Tsujino et al., 2018).
- A global database of monthly mean runoff for 986 rivers was incorporated in the NCOM, now HYCOM, U.S. model (Barron and Smedstad, 2022), that expands on the work of Perry et al. (1996) with corrections and additions derived from monthly mean streamflow from the USGS (Wahl et al., 1995), and extends the basic RivDIS database (Vörösmarty et al., 1998) to make adjustments for missing discharge attributed to small (ungauged) rivers.
- A database of pan-Arctic river discharge (R-Arcticnet).
- A database for Greenland liquid water discharge from 1958 through 2019 (Mankoff et al., 2020).
- The largest known dataset compiles publicly available river gauge data, with satellite-based rating curves used to fill in the temporal gaps (Riggs et al., 2023).

Of particular importance is the fact that some of these databases use model-simulated runoff ratios (e.g. from Community Land Model (CLM) or river routing model) over gauged and ungauged drainage areas to estimate the contribution from the areas not monitored by the hydrometric network and adjust the station flow to represent river mouth outflow, e.g. Dai et al. (2009). This allows more precise derivation of the total discharge into the global oceans, through the sum of both gauged and ungauged discharges.

It is not evident that any of these databases are updated on a regular schedule; some remain static, others are updated irregularly. Such databases are useful in the context of a reanalysis, but less so in an operational context where near-real-time data feeds are required.

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Alternatively, indirect approaches using tidal statistics at the estuarine entrance from tidal stations rather than direct flow measurements have been developed to estimate the net freshwater discharge at the mouth of an estuary, with the advantage of integrating processes at the basin scale, downstream of the last hydrometric station (Moftakhari et al., 2013; Moftakhari et al., 2016). Because tide gauge records at the coasts were often installed well before the onset of systematic river gauging (Talke and Jay, 2013), such inverse techniques make it possible to extend flow records back in time.

3.1.3 Operational river discharge products

The Global Flood Awareness System, GloFAS-ERA5, is an operational global river discharge reanalysis produced consistently with the ECMWF ERA5 atmospheric reanalysis and providing global gridded data products from 1979 to near-real-time (within a 7-day delay) (Harrigan et al., 2020). Figure 2 illustrates the resolution of the river network that emerges in the GloFAS gridded data, and the association of discharge at the coast to point sources in a regional model of the northwest Atlantic Ocean that is in development for future operations.

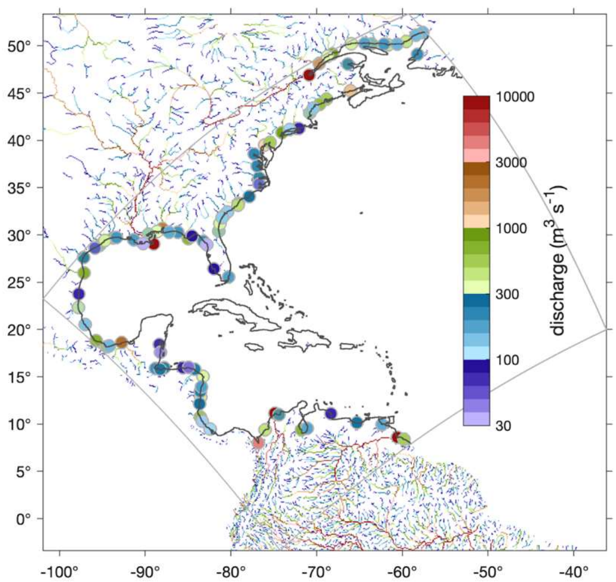

Figure 2: Annual mean surface water discharge (m3 s-1) in 0.1º x 0.1º cells of the GloFAS analysis from Harrigan et al. (2020) for the year 2023. Filled circles show the locations of 93 point sources in the prototype East Coast Community Ocean Forecast System (ECCOFS) ROMS model (domain denoted by the gray perimeter box) associated to GloFAS points near the coast that have long-term mean (2009-2019) discharge exceeding 50 m3 s-1.

Several centers are also producing continental- and global-scale hydrological (ensemble) forecasts operationally: the European Flood Awareness System (EFAS) (Thielen et al., 2009), the European Hydrological Predictions for the Environment (E-HYPE)

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(Donnelly et al., 2015), the Hydrologic Ensemble Forecast Service (HEPS) in the U.S. (Demargne et al., 2014), the Flood Forecasting and Warning Service (FWWS) in Australia, the National Surface and River Prediction System (NSRPS) in Canada (Fortin et al., 2023); and globally, the World-Wide HYPE (WWH) (Arheimer et al., 2020) and GloFAS (Harrigan et al., 2023). Notably, as part of the GloFAS service evolution, global daily ensemble river discharge reforecasts (20-year) and real-time forecast (2020-present) datasets are made free and openly available through the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Harrigan et al., 2023).

Other projects have been supported by the Copernicus Marine Environment Monitoring Service (CMEMS), for example, the LAMBDA project regionally focused on the European Atlantic Façade and the North Sea. The resulting freshwater model estimates and in-situ observations are operationally updated and made available via the project viewer web interface (Sotillo et al., 2021).

3.1.4 Remotely-sensed discharges

With the successful launch of the SWOT satellite in December 2022, new discharge products will become available globally at a nominal resolution of 10 km over river reaches wider than 100 m, thus vastly expanding measurements of global rivers in both gauged and ungauged basins (Durand et al., 2023). Significant improvements on global uncalibrated models are expected (Emery et al., 2018). Furthermore, the temporal variations in SWOT discharge could lead to a better representation of the global hydrological cycle and to enhanced ocean model solutions near the coast when forced by SWOT discharges.

3.2 Salinity and temperature

Estuarine mixing processes affect the salinity distribution and its seasonal variations near river mouths (Sun et al., 2019). Models are particularly sensitive to salinity in shelf areas and ROFI zones, most often due to the diverse treatment of OOFS given to coastal and river freshwater forcing (Sotillo et al., 2021). Therefore, to assess the impact of a chosen formulation and evaluate model performances, sea surface salinity (SSS) and temperature (SST) are typically used. The climatology of the World Ocean Atlas (Locarnini et al., 2013; Zweng et al., 2023) can have a high positive salinity bias nearshore and is not adequate for model evaluation in these areas. As an alternative, Sun et al. (2019) built on the original World Ocean Database and developed an improved salinity and temperature climatology with an enhanced representation of the coastal ocean. In-situ data and satellite observations from SMOS, Aquarius and SMAP (Bao et al., 2019) can also be used to assess the impact of river forcing on sea surface salinity (Feng et al., 2021). However, strong land-sea differences in microwave emissivity make satellite observations unreliable within some 70 km of the coast (Vazquez-Cuervo et al., 2018). Higher resolution coastal satellite products have been demonstrated based on empirical relationships between local salinity and ocean color observations (e.g. Geiger et al, 2011), but these are not globally applicable. Improved and sustained operational monitoring for salinity observations is still needed with enhanced spatial coverage and temporal repetition in order to build confidence in numerical solutions near the coast.

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3.3 Examples of current OOFS

The status of implementation of river forcing in current OOFS is described in this section. The objective is to get a picture of the current landscape of approaches and data sources. The list of systems presented below is not exhaustive and is limited to a compilation of comments received as part of a survey conducted among members of the OceanPredict community in May 2023. It is meant to illustrate the diversity of methods employed for treating freshwater fluxes in OOFS and associated input data sources, in global, regional, coastal and inland systems. The literature review presented in the previous sections provides other examples to complete the picture.

3.3.1 Global systems

Table 1: Examples of river forcing methods and data sources in global OOFS.

System	Domain(s)	Resolution	Circulation Model	Method for river forcing	Data sources
MOVE/ MRI.COM-G3	Global	1/4°	MRI.COM Ver. 4	River discharge is expressed as a part of the surface freshwater	Climatology of JRA-55do river runoff data
NASA Goddard Earth Observing System (GEOS)	Global	25 km – 4 km	MOM6	GEOS-land component run off, routed to catchments	In situ data, land/catchment model
RTOFSv2	Global	0.08°	HYCOMv2.2	Rivers are implemented as virtual salt flux at the ocean surface. River runoff is distributed over several ocean grid points around the river source by applying spatial smoothing to spread out the effect of the river and prevent negative salinities due to	RTOFS uses global climatology of monthly mean river discharge created at NRL (Barron and Smedstad, 2022). It provides monthly runoff for 986 rivers. The dataset is based on the Perry (1996) data with corrections and additions derived from: (1) monthly

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				numerical overshooting. To mimic the river inflow, river freshwater is mixed from the surface down to a depth specified by the user (set to 6 meters in RTOFS). In the grid cells with not-zero river runoff and in the upper layers, river freshwater is mixed within increased vertical diffusivity. Alternatively, rivers can be added directly to the input precipitation fields, which is a better option for a higher (than monthly) frequency river flow data. It is possible to treat rivers (as well as E-P) as a mass exchange (not activated in RTOFS).	mean streamflow over all years, accessible from the USGS (Wahl et al., 1995); (2) the Global River Discharge (RivDIS) database (Vörösmarty et al., 1998); (3) the Regional, Hydrometeorological Data Network (R-Arcticnet) database provides most of the information ultimately used on rivers flowing into the Arctic, primarily rivers in Russia and Canada.
FOAM-CPLNWP	Global	1/4°	NEMO v3.6	Fresh water runoff from land is input in the surface layer of the ocean with the assumption that the runoff is fresh and at the same temperature as the local sea surface temperature. An enhanced vertical mixing of $2x10^{-3}$ m^2s^{-1} is added over the top 10 m of the water column at runoff points to mix the runoff vertically and avoid instabilities associated with very shallow fresh layers at	Climatological river runoff fields were derived by Bourdalle-Badie and Treguier (2006) based on estimates given in Dai and Trenbert (2002) (Blockley et al., 2014)

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				the surface (Storkey et al., 2018).	

3.3.2 Regional systems

Table 2: Examples of river forcing methods and data sources in regional OOFS.

System	Domain(s)	Resolution	Circulation Model	Method for river forcing	Data sources
MOVE/MRI.COM-NP/JPN	North Pacific	2 km - 10 km	MRI.COM Ver. 5	River discharge is expressed as a part of the surface freshwater	Climatology of JRA-55do river runoff data
TOPAZ	Arctic and Nordic Seas	12 km	HYCOM	Removal of salt from the surface (an ellipse around the river mouth) and barotropic water flux. We use nutrients (N, P and Si) from the globalNEWS model and scale them by river discharge.	SMHI (Arctic-HYPE and E-HYPE), GRACE satellite for Greenland mass loss and a home-made climatology for Greenland surface mass balance.
eSAMarine	South Australian Gulfs and Shelf	2.5 km and 0.5 km	ROMS	None, intermittent river input is usually weak to non-existent.	None
DMI_ HYCOM_ CICE	Arctic and Atlantic Oceans	4-10 km: ~5 km throughout Arctic and	HYCOM + CICE fully coupled using ESMF coupler. CICE runs on a subset of	River forcing is converted to monthly means precipitation equivalents [m/s] for ~50,000 river-runoff	River forcing is taken from various sources using a dataset from the Geological Survey of Denmark

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		northern Atlantic	the full HYCOM domain	outlets and distributed to the nearest coastal model grid point(s) (Ponsoni et al., 2023).	and Greenland (Mankoff et al., 2020), converted to monthly means precipitation equivalents [m/s]
Danish Storm Surge System, DKSS	North Sea - Baltic Sea, with multiple nested subdomains	3 nautical miles (coarsest) to 0.1 nautical mile (finest)	HBM, Hiromb-Baltic Model	River forcing is treated as a freshwater flux into coastal grid cells. Water temperature equal to receiving cell (river temperature data not used) with 0°C as lower limit to avoid instantaneous freezing.	European hydrological model E-HYPE3, from which an annual plus a calendar day ~30y climatology has been derived and used as a back-up for a daily forecast. The forecast model is run by the Swedish Hydrological and Meteorological Institute, and the day-to-day service comes with an annual fee.
IBI Near-Real-Time	European Atlantic façade (the Iberia-Biscay-Ireland zone): Lat: from 26N to 56N, Lon:	1/36º, Surface and 3D fields (50 vertical levels)	NEMO v3.6	Freshwater river discharge inputs are implemented as lateral open boundary conditions for the main 33 rivers of the IBI area. The system also incorporates an extra coastal runoff	Data come from different sources, depending on their availability, in the following order: (1) Model data: SMHI hydrologic model; (2) Monthly climatological data

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	from 19W to 5E			rate (derived from the Dai and Trenberth (2002) climatology, on a monthly basis), which makes the IBI forcing consistent with the ones imposed in the parent Copernicus Marine GLOBAL system.	taken from GRDC, French "Banque Hydro" dataset, Copernicus Marine Service and Emodnet.
IBI Multi-Year	European Atlantic facade (the Iberia-Biscay-Ireland zone): Lat: from 26N to 56N, Lon: from 19W to 5E	1/12º, Surface and 3D fields (50 vertical levels)	NEMO v3.6	Same as IBI-NRT, but with an additional river (LAGAN)	Data come from different sources, depending on their availability, in the following order: (1) In-situ data: daily measurements from Copernicus Marine Service, Emodnet or national web sites; (2) Model data: SMHI hydrologic model.
CBEFS (Chesapeake Bay Environmental Forecast System)	Chesapeake Bay	600 m x 600 m	ROMS	Freshwater - Real time USGS river gauge data is scaled to better represent total freshwater inflows over a larger area based on a watershed model. The scaled discharge is then	In situ gauge data. Hindcast watershed model information. Artificial Neural Networks.

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				disaggregated into the main river inflow and smaller streams based on proportions developed from the watershed model. The forecast is a simple autoregressive model based on the past few days. Riverine Biogeochemistry - Inputs are specified using Artificial Neural Network AI models based on the discharge and date, which recreate what the watershed model would have predicted had the current and forecast conditions been simulated by the watershed model. Temperature - Water temperature is specified using a combination of real time gauge data and monthly averages depending on what is available.	

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DREAMS	East Asian marginal seas	0.3 – 22 km	RIAM Ocean Model	Coastal precipitation is directly converted into the amount of river discharges. The integration distance was optimized by using model Green's functions (Hirose, 2011).	GPV precipitation data of JMA
FOAM-AMM15	Northwest European Shelf Seas	1.5 km	NEMO v3.6	For each river input location, a daily freshwater flux is assigned, with depth determined by the average ratio of runoff to tidal range (as per the estuary classifications of Cameron and Pritchard, 1963). The runoff temperature is assumed to align with the local sea surface temperature (SST), as the climatology does not include temperature data (Graham et al., 2018).	River runoff is primarily derived from a daily climatology of gauge measurements averaged for 1980–2014. UK data were processed from raw data provided by the Environment Agency, the Scottish Environment Protection Agency, the Rivers Agency (Northern Ireland), and the National River Flow Archive (gauge data were provided by Sonja M. van Leeuwen, CEFAS, Lowestoft, UK, personal communication,

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					2016). For major rivers that were missing from this data set (e.g. along the French and Norwegian coasts), data have been provided from an earlier climatology (Vörösmarty et al., 2020; Young and Holt, 2007), based on a daily climatology of gauge data averaged for the period 1950–2005 (Tonani et al., 2019).
FOAM-AMM7	Northwest European Shelf Seas	7 km	NEMO v3.6 (coupled to ERSEM 20.10 for biogeochemistry)	For each river input location, a daily freshwater flux is assigned, with depth determined by the average ratio of runoff to tidal range (as per the estuary classifications of Cameron and Pritchard, 1963). The runoff temperature is assumed to align with the local sea surface temperature (SST), as	Daily timeseries of river discharge, nutrient loads (nitrate, phosphate, silicate, ammonia), alkalinity (bioalkalinity, dissolved organic carbon) and oxygen were produced from an updated version of the river dataset used in Lenhart et al. (2010), combined with climatology of daily discharge data

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				the climatology does not include temperature data (Graham et al., 2018).	from the Global River Discharge Database (Vörösmarty et al., 2020) and from data prepared by the Centre for Ecology and Hydrology as used by Young and Holt, 2007. The climatology has an annually-varying component until 2018 to account for historic changes in nutrient loads, values for 2018 are used as a climatology in the operational system (Kay et al., 2020).
DOPPIO Rutgers University and MARACOOS	Northeast USA and Nova Scotia, Canada	7 km	ROMS	Discharge is introduced as volume flux divergence (method LwSrc in ROMS) at 27 point sources in model cells adjacent to the coast.	Daily USGS discharge data are scaled for ungauged portions of the watershed based on the statistics of a 10-year hydrological model analysis.

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Table 3: Examples of river forcing methods and data sources in coastal OOFS.

System	Domain(s)	Resolution	Circulation Model	Method for river forcing	Data sources
DFO's Port Ocean Prediction Systems	Kitimat Fjord, Vancouver Harbour, Lower Fraser River, St Lawrence Estuary, Port of Canso, Saint John harbour	20 – 200 m	NEMO 3.6	NEMO's runoff feature for some rivers, and a SSH open boundary condition for others	Gauge data (from ECCC) where available, climatology elsewhere
CIOPS	East/West + SalishSea500	1/36° + 500m for SS500	NEMO 3.6	Same as DFO port models	Gauge data for Fraser River, climatology elsewhere
FANGAR_ BAY	Ebro Delta	350m / 70m	COAWST (ROMS/ SWAN)	Climatological freshwater from Ebro River	In situ data
NARF (Northern Adriatic Reanalysis and Forecasting system)	Northern Adriatic Sea (Mediterranean Sea)	1/128° (~750 m)	MITgcm-BFM (coupled hydrodynamic-biogeochemical)	The downstream end of the rivers flowing into the basin is simulated as a narrow channel: one or two cells in the horizontal direction and a few vertical levels. Freshwater discharge rates from NRT data or climatologies are converted into horizontal velocities (the section of the riverbed is known) and applied as lateral open	In-situ NRT discharge data for the Po River (main contributor), climatologies for the others (with sinusoidal modulation: maxima in spring/fall, minima in summer/winter). Daily frequency.

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				boundary conditions. Salinity is constant (5 PSU), temperature has a yearly sinusoidal cycle (maxima and minima in summer and winter, respectively) and biogeochemical concentrations are derived from literature/climatologies.	

3.3.4 Inland systems

Table 4: Example of river forcing methods and data sources in inland OOFS.

System	Domain(s)	Resolution	Circulation Model	Method for river forcing	Data sources
WCPS	Great-Lakes+ NWA	1/36° + 1km	NEMO 3.6	Fully coupled hydrologic model for GL, climatology for NWA	Hydrological model uses gauge data

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Competing interests

The contact author has declared that none of the authors has any competing interests.

Data and/or code availability

Data/code availability is not applicable to this article as no new data/code were created or analysed in this study.

Authors contribution

Pascal Matte: Conceptualization, Investigation, Writing – review and editing. John Wilkin: Writing – review and editing. Joanna Staneva: Writing – review and editing.

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