Atmospheric Forcing as a D~~d~~river for Ocean Forecasting

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Abstract. The connection of the ocean component with the Earth system is subject to the way the atmosphere interacts with it. The paper illustrates the state of the art in the way atmospheric fields are used in ocean models as boundary conditions for the provisioning of the exchanges of heat, freshwater and momentum fluxes. Such fluxes are typically based on Numerical Weather Prediction systems which ingest observations from~~can be based on~~ remote-sensing and in situ instruments~~, like SAR, or provided directly by Numerical Weather Prediction systems~~. This study also discusses how the ocean-atmosphere fluxes are numerically ingested in ocean models from global to regional to coastal scales. Today's research frontiers on this topic are opening challenging opportunities for developing more sophisticated coupled ocean-atmosphere systems and improved ocean-atmosphere flux datasets.

1 ~~Air-Sea Flux Data Sets~~Introduction

The exchanges of heat, freshwater and momentum between the oceans and the atmosphere play a critical role as boundary conditions in global, regional and coastal Operational Ocean Forecasting Systems (OOFS). ~~A brief overview, including uncertainties, of air-sea flux data sets of heat, freshwater and momentum (which is equivalent to wind stress) is presented in Section 2 with applications in OOFS in mind.~~ Nowadays, the two primary sources of information regarding air-sea fluxes used in OOFS are satellite-based observations and atmospheric model forecasts which assimilate various data types. More specifically, using observation-based surface flux products is, by definition, a way to drive an ocean monitoring system or to produce an ocean reanalysis. Using an atmospheric forecast appears mandatory to produce an ocean forecast. In section 2 we discuss the atmospheric forcing for ocean forecasts, for ocean analyses/monitoring systems, and for ocean reanalyses. Some basic aspects of air-sea flux data sets of heat, freshwater and momentum (which is equivalent to wind stress), including their uncertainties, are also presented in section 2. For further information about the challenges associated with the closure of ocean-atmosphere energy and water budgets we refer to reader to Yu (2019) and literature quoted therein. Section 3 discusses options for the implementation of ocean-atmosphere fluxes in OOFS and section 4 discusses applications of air-sea flux data sets in OOFS.

In recent years, several new flux products have become available which contain fields at sub-daily and hourly timescales. This tendency has been driven, in part, by the high time resolution possible with atmospheric forecasts and the need to include high frequency variability in forcing fields for OOFS. A complete survey of the wide range of flux datasets and their technical details is beyond the scope of this document. Instead, an overview of the main flux datasets is presented in Section 4~~2~~ with ~~the most~~frequently used data sets in OOFS being highlighted.

~~For information about sea-ice boundary conditions we refer the reader to Section 2, noting that~~ Sea-ice boundary conditions depend on the formulation of sea-ice models and how they are implemented in an OOFS. For example, sea-ice models can be part of an OOFS, of a Numerical Weather Prediction (NWP) system or be coupled to both. Consequently, respective input sourced from external data sets depend on the exact model architecture. Sea-ice boundary conditions are not discussed any further in this study.

2 Atmospheric Forcing for different applications in ocean models

2.1 ~~Remotely-sensed fluxes~~Atmospheric forcing for ocean forecasts

Currently, all OOFS in forecast mode rely on forcing parameters provided by NWP systems. This is primarily due to the ubiquity and low latency of these systems, as well as the convenience of receiving gridded outputs. Although NWP products may not always be perfectly accurate, their self-consistency is a key factor when considering the forcing for OOFS. ~~All OOFS known to us today use air-sea fluxes provided by NWP systems, mostly because of low latency required for OOFS and the convenience of NWP outputs being gridded products.~~ These NWP systems often assimilate relevant satellite observations, noting that surface heat fluxes are not directly observed by remote sensors but are computed by the NWP systems by using a mixture of different observed geophysical variables and parameterisations. These derived surface fluxes are then being used by OOFS~~to obtain improved estimates of air-sea fluxes~~, hence we briefly describe some of the remotely sensed observations in the subsequent paragraphs. ~~Furthermore, remotely sensed estimates of air-sea fluxes can be used to validate the surface fluxes in an OOFS.~~

The net air-sea heat flux is the sum of four components: two turbulent heat flux terms (the latent and sensible heat fluxes) and two radiative terms (the shortwave and longwave fluxes). ~~Bulk formulae are employed to estimate the latent and sensible heat fluxes whereas radiative fluxes are determined either from empirical formulae or from radiative transfer models (Josey, 2011).~~ Satellite-based estimates of air-sea heat flux terms suffer because it is not yet possible to reliably measure near surface air temperature and humidity directly from space. For example, satellites measure radiances in various wavelength bands which must then be inverted to obtain temperature. Bulk formulae are employed to estimate the latent and sensible heat fluxes whereas radiative fluxes are determined either from empirical formulae or from radiative transfer models (Josey, 2011). These indirect techniques lead to a source of uncertainty in the turbulent heat flux terms which are critically dependent on the sea-air temperature and humidity difference near the interface (Hooker et al., 2018; Tomita et al., 2018). Estimates of the radiative flux terms are available from various sources, e.g. Pinker et al. (2018), and can be combined with indirect estimates of the turbulent fluxes to form net heat flux products.

In contrast, ~~the~~ wind stress is well determined from scatterometers since SEASAT-A (1978), ERS-1 (1991) and QuikSCAT (1999) ~~since the launch of QuikSCAT in 1999~~ (Jones et al., 1982; Portabella and Stoffelen, 2009; Hoffman and Leidner, 2005) and subsequent satellite missions. Global wind measurements by Synthetic Aperture Radar (SAR) go all the way up to the coast due to its high resolution, filling critical gaps in ocean wind speed and direction observations in coastal areas (Khan et al., 2023). However, despite quite some efforts having been devoted to SAR wind retrievals over the past two decades (e.g. Horstmann and Koch, 2005), there is currently no SAR wind processor that can provide a coastal wind stress product of sufficient quality and/or coverage for use in operations, while its use for OOFS development purposes must be done with caution and on a test-case basis.

Precipitation is also remotely-sensed using various techniques including infrared measurements of cloud top brightness temperature, which acts as a proxy for rain rate, and passive microwave measurements. Launched in 2014, the US-Japanese led Global Precipitation Measurement Mission (GPM) is an international network of satellites that provides global observations of rain and snow at different times of the day (Hou et al., 2014). However, validation of these fields over the ocean is challenging due to the lack of high quality measurements from rain sensors and the difficulty with making this measurement (Weller et al., 2008). As a consequence, uncertainty remains in the precipitation fields with follow-on effects for estimating the associated air-sea freshwater flux (evaporation minus precipitation) (Josey, 2011).

~~**1.2 Numerical weather prediction**~~

Satellite-based fluxes are observations that lack a forecast range, whereas OOFS need forecasts -- this is a significant reason for using NWP models in forecast mode. Consequently, NWP models have become a major source of complete sets of air-sea flux fields for OOFS at high resolution (3-hourly or better) with global spatial coverage. ~~NWP models assimilate a wide range of observations including surface meteorological reports, radiosonde profiles and remote sensing measurements. These models have become a major source of providing to OOFS complete sets of air-sea flux fields at high resolution (3 hourly or better) with global spatial coverage~~ Furthermore, a~~A~~ir-sea fluxes from NWP systems are an attractive option for OOFS because of their operational reliability and timely release of forcing fields akin to the operational cycles of OOFS. NWP models assimilate a wide range of observations including surface meteorological reports, radiosonde profiles and remote sensing measurements. The turbulent flux terms are estimated from the model's surface meteorology fields while the shortwave and longwave flux are output from the radiative transfer component of the atmospheric model. ~~Air-sea fluxes from NWP systems are an attractive option for OOFS because of their operational reliability and timely release of forcing fields akin to the operational cycles of OOFS.~~ However, NWP systems are of course dependent on the model physics which, although constrained to some extent by the assimilated observations, has the potential to produce biases, particularly in the radiative flux fields and precipitation

(Trenberth et al., 2009; Weller et al., 2022) and in the wind stress vector components (Belmonte and Stoffelen, 2019; Trindade et al., 2020).

2.2 Atmospheric forcing for ocean analysis/monitoring systems

An analysis is a snapshot of the state of the ocean or atmosphere at any given time. It is created by using a model and observations to provide a best fit. An ocean or atmosphere analysis is generally used as a starting point for forecasts to make them as close to reality as possible (i.e. with all the data available). Consequently, surface forcing derived from the analysis of an atmospheric forecasting system can be used to calculate an ocean analysis, together with ocean in-situ and remotely sensed observations. Ocean analyses are a common by-product of an OOFS, especially when run with data assimilation. An example is the Copernicus Marine Service operated by Mercator Ocean International which provides global Near Real Time (NRT) analysis datasets and forecasts of the 3D ocean regularly every day, forced by ECMWF IFS atmospheric forecasting product (Drillet et al., 2024).

2.3 Atmospheric forcing for ocean reanalyses

An ocean reanalysis consists of modelling the state of the ocean over a long period of time (several years) while correcting it with the best available past observations. Ocean reanalyses can be used for validating OOFS and enable past case studies. For these purposes, using atmospheric reanalyses or any best fit of observed atmospheric data is recommended. Fixed versions of NWP models run over multidecadal periods are commonly referred to as atmospheric reanalyses - two examples are those from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) and ECMWF (Table 1). Although not suitable for near real-time OOFS due to their delayed-mode operation, air-sea fluxes derived from atmospheric reanalyses have proven to be a valuable tool for testing OOFS during their development stages as well as scenario simulations and analyses of past extreme events. In essence, atmospheric reanalyses are often used in OOFS development and in ocean reanalyses for the following reasons: they are typically of higher quality than output from operational NWP systems (where there is less time for quality control); they are available over an extended period of time, often covering multiple years to decades which allows to explore various weather and climate phenomena in the ocean model in response to the atmospheric forcing; and model parameters in an atmospheric reanalysis are being kept constant over the integration period, thus producing a consistent data set.

~~1.3 Other flux products~~

In addition to the ~~two~~ primary classes of flux datasets described above, flux fields for OOFS are available from several other types of products. An example are surface fluxes available from various ocean synthesis efforts, that is ocean models with data assimilation such as the Estimating the Circulation and Climate of the Ocean (ECCO) model (Stammer et al., 2004). These systems are typically forced by global atmospheric reanalysis fields which are then adjusted as a result of the assimilation and optimisation process. Similar to atmospheric reanalyses, air-sea datasets based on delayed-mode synthesis efforts are suitable for testing OOFS during their development stages.

3 Implementation of Atmospheric Forcing Fields in OOFS

This section briefly lists methods for implementing ocean-atmosphere fluxes applicable in ocean forecasts, monitoring and reanalyses. The four most common approaches are:

- using directly the atmospheric fluxes produced by NWP systems of national meteorological services. Typically, NWP systems produced by national meteorological services provide atmospheric surface forcing fields to OOFS in order to compute water, heat, and momentum fluxes. Such fields may also be supplemented by real-time or near real-time observations, e.g. satellite data, and other averaged datasets including climatology. For example, Trindade et al. (2020) show how scatterometer-derived wind stress can be used to remove NWP model output local biases. Relevant points to consider when using NWP products in OOFS are data availability, space-time resolution and domains for regional/coastal OOFS (see next section). Table 1 provides examples of widely used global atmospheric NWP and reanalysis products;

- using a so-called "bulk" forcing to simulate the near-surface ocean-atmosphere interactions (Josey, 2011). This method permits the use of sea-surface temperature to compute inline and at each time step the turbulent fluxes and upward radiative fluxes, and so to introduce a pseudo-coupling. The bulk forcing requires some atmospheric data: air temperature, air humidity, downward shortwave radiation, downward longwave radiation, precipitation, wind speed and wind stress. The latter can also be calculated from the wind speed. This method raises the same questions as the previous one, plus, the choice of the surface flux parametrisation and associated choice of coefficients in the bulk formulae;

- using an intermediate simplified atmospheric model (e.g. Lemarié et al., 2021) driven by atmospheric NWP 3D fields and producing ocean-atmosphere fluxes consistent with the ocean evolution and resolution. This method is more complex than the bulk forcing but improves the feedbacks between the upper ocean and lower atmosphere, especially when the intermediate atmospheric and the ocean model have the same horizontal resolution in order to provide high resolution atmospheric fields (Alvarez-Fanjul et al., 2022);

- using a fully coupled ocean-atmosphere modelling system where the surface fluxes are an integral part of the coupled system. Although this is the most advanced physical approach to simulate ocean-atmosphere interactions it comes at a relatively high numerical/computational cost, including the initialisation/assimilation. The advantages of a fully coupled system (compared to the first three methods) are no (or, for regional OOFS, a lower) dependence on the data availability from external sources and a fully coupled system ensures a two-way consistency of the ocean-atmosphere fluxes.

4~~2~~ Applications of Air-Sea Flux Data Sets in OOFS

~~Typically, NWP systems produced by national meteorological services provide atmospheric surface forcing fields to OOFS in order to compute water, heat, and momentum fluxes. Such fields may be also supplemented by real-time or near real-time observations, e.g. satellite data, and other averaged datasets including climatology. Alternatively, in a more complex modelling framework, an ad hoc atmospheric model can be developed at the same resolution of the ocean model in order to provide high resolution atmospheric fields (Alvarez-Fanjul et al., 2022).~~Each of the implementations ~~classes of flux product~~ described above has its own advantages and disadvantages and it is not possible to recommend a best air-sea flux product based on the method for implementing surface fluxes in an ocean model; rather, the choice of flux dataset must be guided by the scientific feasibility and by the application in mind. For example, near real-time NWP products are needed for operational ocean forecasting purposes whereas a reanalysis product might be appropriate and more convenient to use during the development stages of an OOFS and for validation purposes. Hence, w~~W~~e offer some examples of possible air-sea forcing fields in OOFS in Table 1 but are by no means complete or prescriptive.

Table 1: Examples of global atmospheric forcing products and providers. Adapted from Alvarez-Fanjul et al. (2022).

Dataset	Description	Provider
GFS	Global Forecast System, produced by the National Centers for Environmental Prediction (NCEP), provides analysis and forecast atmospheric fields for the global ocean at the resolution of about 28 km	https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs
NAVGEM	Navy Global Environmental Model runs by the United States Navy's Fleet Numerical Meteorology and Oceanography Center (FNMOC)	https://www.usno.navy.mil/FNMOC/meteorology-products-1m
ECMWF IFS and ERA5	European Center for Medium range Weather Forecasting that provides reanalysis, analysis and forecast atmospheric fields at medium, extended, and long range	ECMWF https://www.ecmwf.int/
Met Office UK	United Kingdom Meteorological Office that produces the Unified Model, a numerical model of the atmosphere used for both weather and climate applications	Met Office https://www.metoffice.gov.uk/
GEM	Global Environmental Multiscale model, an integrated forecasting and data assimilation system developed in the Recherche en Prévision Numérique (RPN), Meteorological Research Branch (MRB), and the Canadian Meteorological Centre (CMC)	Environment Canada https://collaboration.cmc.ec.gc.ca/

4~~2~~.1 Applications in g~~G~~lobal OOFS

Global NWP models like those operated by centre~~er~~s listed in Table 1 at present have typical horizontal grid resolutions of 20 km or better (and 60 vertical levels or more). With this kind of horizontal resolution, it is possible to capture large-scale synoptic weather phenomena and associated signals in the air-sea fluxes used to force ocean models.

However, in NWP systems with such grid resolutions it is not possible to accurately simulate smaller-scale ocean-atmosphere interactions such as oceanic fronts, orographic features like land-sea circulation or air-sea interactions associated with mesoscale oceanic eddies, noting that the synoptic (eddy-)scale in the ocean is of the order of ~100 km which is about an order of magnitude smaller than in the atmosphere at about ~1000 km.

Atmospheric forcing fields are typically interpolated onto the respective grid points of the ocean model, e.g. momentum fluxes onto the velocity grid points, air-sea heat fluxes onto the temperature grid points and evaporation minus precipitation onto the salinity grid points of the ocean model (plus volume or mass flux in the continuity equation). This interpolation can be accomplished by either using an internal interpolation routine of the ocean model, by using bulk formulae at the ocean grid to calculate surface fluxes of heat, freshwater and momentum or by using specific coupling software, e.g. Craig et al. (2017), for fully coupled ocean-atmosphere-wave-sea-ice models.

4~~2~~.2 Applications in regional and coastal OOFS

There is a plethora of regional and coastal ocean models with fixed, variable and adaptive grids and with horizontal resolutions often in the 10-100 m range (Kourafalou et al., 2015). It is therefore not possible to provide specific guidance about the appropriate choice of air-sea fluxes required for this type of models.

Regional to basin-scale OOFS are typically forced with air-sea-fluxes from the latest high-resolution global NWP systems, e.g. O'Dea et al. (2012). In contrast, coastal OOFS require a different approach. Coastal air-sea circulation and topographic features like small islands and their interactions with air-sea fluxes are not reproduced by global-scale atmospheric models, hence much higher resolution coastal atmospheric models are needed to provide reliable upper ocean boundary conditions. This can be accomplished by direct coupling of high-resolution atmospheric models to coastal ocean models or by using air-sea fluxes from a stand-alone NWP higher resolution coastal model~~,~~ (Hordoir et al., 2019). Other examples of regional atmospheric models are the UK Met Office Unified Model–JULES Regional Atmosphere and Land configuration (Bush et al., 2023) and the Weather Research & Forecasting Model (WRF) ~~e.g.~~ (Skamarock et al., 2008)~~Hordoir et al. (2019)~~. Either way, these atmospheric models need to be (multiply) nested within coarser-resolution regional and/or global models which provide lateral and upper boundary conditions. This is an active field of R&D where the development of coastal NWP and OOFS often goes hand-in-hand with efforts to develop fully coupled ocean-atmosphere forecasting systems. However, it should be noted that for both components, atmosphere and ocean, not just suitable lateral boundary conditions from coarser component models are required but it is also highly desirable to have an appropriately dense atmospheric and oceanic observing system to constrain these models and improve (coupled) forecasts.

High-resolution air-sea fluxes which are based on remotely sensed fluxes can also be used to evaluate the quality of the forcing fields in coastal ocean models. An example is the Synthetic Aperture Radar (SAR)-based remotely sensed regional ocean wind speed and direction database which has been made available ~~recently~~ by the Australian Integrated Marine Observing System (Khan et al., 2023). The data set is a km-resolution ocean wind speed and direction database over coastal seas of Australia, New Zealand, Western Pacific islands, and the Maritime C~~c~~ontinent. It is obtained from Europe’s Copernicus Sentinel-1 A and B SAR satellites from 2017 up till present. The data set is a first of its kind in the region and captures the spatial variability of coastal ocean winds over a wide swath (250 km). However and as stated above, any SAR-derived wind stress product available to date and its use for OOFS development purposes needs to be treated with caution and should be done on a case-by-case assessment.

5~~3~~ Conclusions

This study ~~chapter about air-sea fluxes has~~ provides~~d~~ some information about the diverse range of air-sea flux datasets that are now available for the community to use as air-sea forcing in OOFS. NWP systems provide the majority of flux products to force today’s OOFS. Generally speaking, the quality and usefulness of these datasets are ~~defined~~ influenced by the~~ir~~ spatial and temporal resolutions of remotely sensed and in situ observations that are assimilated into the NWP systems and are limited by associated biases which should be taken into account when choosing ~~a~~such dataset~~s as surface forcing in an OOFS~~. Consequently, air-sea flux data sets for OOFS should be chosen with the applications and users of the outputs in mind.

References

Alvarez Fanjul, E., Ciliberti, S., Bahurel, P.: Implementing Operational Ocean Monitoring and Forecasting Systems. IOC-UNESCO, GOOS-275. https://doi.org/10.48670/ETOOFS, 2022.

Belmonte Rivas, M., Stoffelen, A.: Characterizing ERA-Interim and ERA5 surface wind biases using ASCAT, Ocean Sci., 15, 831–852. https://doi.org/10.5194/os-15-831-2019, 2019.

Bush, M., Boutle, I., Edwards, J., Finnenkoetter, A., Franklin, C., Hanley, K., Jayakumar, A., Lewis, H., Lock, A., Mittermaier, M., Mohandas, S., North, R., Porson, A., Roux, B., Webster, S., Weeks, M.: The second Met Office Unified Model–JULES Regional Atmosphere and Land configuration, RAL2. Geosci. Model Dev., 16, 1713–1734, https://doi.org/10.5194/gmd-16-1713-2023, 2023.

Craig, A., Valcke, S., Coquart, L.: Development and performance of a new version of the OASIS coupler, OASIS3-MCT_3.0. Geoscientific Model Development, 10, 3297-3308. https://doi.org/10.5194/gmd-10-3297-2017, 2017.

Drillet, Y., Martin, M., Miyazawa, Y., Bell, M., Chassignet, E., Ciliberti, S.: Core Services: An Introduction to Global Ocean, State of the Planet Discuss. [preprint], https://doi.org/10.5194/sp-2024-38, in review, 2024.

Hoffman, R.N., Leidner, S.M.: An Introduction to the Near–Real–Time QuikSCAT Data. Weather and Climate, 20, 476-493. https://doi.org/10.1175/WAF841.1, 2005.

Hooker, J., Duveiller, G., Cescatti, A.: Data Descriptor: A global dataset of air temperature derived from satellite remote sensing and weather stations. Scientific Data, 5, 180246. https://doi.org/10.1038/sdata.2018.246, 2018.

Hordoir, R., Axell, L., Höglund, A., Dieterich, C., Fransner, F., Gröger, M., Liu, Y., Pemberton, P., Schimanke, S., Andersson, H., Ljungemyr, P., Nygren, P., Falahat, S., Nord, A., Jönsson, A., Lake, I., Döös, K., Hieronymus, M., Dietze, H., Löptien, U., Kuznetsov, I., Westerlund, A., Tuomi, L., Haapala, J.: Nemo-Nordic 1.0: A NEMO based ocean model for Baltic & North Seas, research and operational applications. Geosci. Model Dev., 12, 363-386. https://doi.org/10.5194/gmd-12-363-2019, 2019.

Hou, A.Y., Kakar, R.K., Neeck, S., Azarbarzin, A.A., Kummerow, C.D., Kojima, M., Oki, R., Nakamura, K., Iguchi, T.: The Global Precipitation Measurement Mission. Bulletin of the American Meteorological Society, 701-722. https://doi.org/10.1175/BAMS-D-13-00164.1, 2014.

Jones, W. L., Schroeder, L. C., Boggs, D. H., Bracalente, E. M., Brown, R. A., Dome, G. J., Pierson, W. J., Wentz, F. J.: The SEASAT-A satellite scatterometer: the geophysical evaluation of remotely sensed wind vectors over the ocean. Journal of Geophysical Research: Oceans, 87(C5), 3297-3317. https://doi.org/10.1029/jc087ic05p03297, 1982.

Josey, S.A.: Air-sea fluxes of heat, freshwater and momentum. In: Brassington, G.B., (ed.) Operational Oceanography in the 21st Century. Heidelberg, Springer, 155-184, 450pp. https://doi.org/10.1007/978-94-007-0332-2_6, 2011.

Khan, S., Young, I., Ribal, A., Hemer, M.: High-resolution calibrated and validated Synthetic Aperture Radar Ocean surface wind data around Australia. Scientific Data, 10, 163. https://doi.org/10.1038/s41597-023-02046-w, 2023.

Horstmann, J., Koch, W.: Measurement of ocean surface winds using Synthetic Aperture Radars. IEEE Of Oceanic engineering, 30, 508-515, 2005.

Kourafalou, V.H., De Mey, P., Le Hénaff, M., Charria, G., Edwards, C.A., He, R., Herzfeld, M., Pascual, A., Stanev, E.V., Tintoré, J., Usui, N., van der Westhuysen, A.J, Wilkin, J., Zhu, X.: Coastal Ocean Forecasting: system integration and evaluation. Journal of Operational Oceanography, 8:sup1, s127-s146. https://doi.org/10.1080/1755876X.2015.1022336, 2015.

Lemarié, F., Samson, G., Redelsperger, J.-L., Giordani, H., Brivoal, T., Madec, G.: A simplified atmospheric boundary layer model for an improved representation of air-sea interactions in eddying oceanic models: implementation and first evaluation in NEMO (4.0). Geoscientific Model Development, 14(1), 543-572, https://gmd.copernicus.org/articles/14/543/2021/, https://doi.org/10.5194/gmd-14-543-2021, 2021.

O'Dea, E.J., Arnold, A.K., Edwards, K.P., Furner, R. Hyder, P., Martin, M.J., Siddorn, J.R., Storkey D., While, J., Holt, J.T., Liu, H.: An operational ocean forecast system incorporating NEMO and SST data assimilation for the tidally driven European North-West shelf. J. Oper. Oceanogr., 12, 5:1, 3-17. https://doi.org/10.1080/1755876X.2012.11020128, 2012.

Pinker, R.T., Zhang, B., Weller, R.A., Chen, W.: Evaluating surface radiation fluxes observed from satellites in the southeastern Pacific Ocean. Geophysical Research Letters, 45, 2404-2412. https://doi.org/10.1002/2017GL076805, 2018.

Portabella, M., Stoffelen, A.: On scatterometer ocean stress, J. Atm. and Ocean Techn., 26 (2), 368–382 https://doi.org/10.1175/2008JTECHO578.1, 2009.

Skamarock, W. C., Klemp. J. B, Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X.-Y., Wang, W., Powers, J. G.: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp., doi:10.5065/D68S4MVH, 2008.

Stammer, D., Ueyoshi, K., Köhl, A., Large, W.B., Josey, S., Wunsch, C.: Estimating air-sea fluxes of heat, freshwater and momentum through global ocean data assimilation. Journal of Geophysical Research: Oceans., 109, C05023. https://doi.org/10.1029/2003JC002082, 2004.

Tomita, H., Hihara, T., Kubota, M.: Improved satellite estimation of near-surface humidity using vertical water vapor profile information. Geophysical Research Letters, 45, 899-906. https://doi.org/10.1002/2017GL076384, 2018.

Trenberth, K.E., Dole, R., Xue, Y., Onogi, K., Dee, D., Balmaseda, M., Bosilovich, M., Schubert, S., Large, W.: Atmospheric reanalyses: a major resource for ocean product development and modeling. Community White Paper, Oceanobs'09. BAMS, E1968-E1990, 2009.

Trindade, A., Portabella, M., Stoffelen, A., Lin, W., Verhoef, A.: ERAstar: a high resolution ocean forcing product", IEEE Trans. Geosci. Rem. Sens., 58 (2), pp. 1337-1347. https://doi.org/10.1109/TGRS.2019.2946019, 2020.

Weller, R.A., Bradley, E.F., Edson, J.B., Fairall, C.W., Brooks, I., Yelland, M.J., Pascal, R.W.: Sensors for physical fluxes at the sea surface: energy, heat, water, salt. Ocean Sci., 4, 247-263. https://doi.org/10.5194/os-4-247-2008, 2008.

Weller, R.A., Lukas, R., Potemra, J., Plueddemann, A.J., Fairall, C., Bigorre, S.: Ocean Reference Stations - Long-Term, Open-Ocean Observations of Surface Meteorology and Air–Sea Fluxes Are Essential Benchmarks. Bulletin of the American Meteorological Society, 103(8), E1968-E1990. https://doi.org/10.1175/BAMS-D-21-0084, 2022.

Yu, L.: Global Air–Sea Fluxes of Heat, Fresh Water, and Momentum: Energy Budget Closure and Unanswered Questions. Annu. Rev. Mar. Sci., 11, 227–48, 2019.

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

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