Mini review: Characteristics of upwelling in several coastal areas in the world

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Abstract. This paper provides an overview of the upwelling processes and the controlling factors as an effort to reveal the characteristics and the intensities of upwelling events in several parts of the world. This review aimed at identifying the characteristics of upwelling and how the global climate controlling this physical phenomenon such as ENSO, IOD and Kelvin Wave. Several places in the Southeast Asia experienced high intensities of upwelling when El Nino events such as in South of Java, East Coast of Malaysia Peninsula and in Vietnam Coastal area. The results of this review found that area with the most intensive and productive upwelling in the world is South American waters and Banguela Upwelling System (BUS) in the African Coast. However, several other areas also show intensive and high productivity of upwelling, such as off the southern coast of Java Island in Indonesia and the Banda Sea and its surroundings. It is found that upwelling with stronger intensity can result in increase of mortality of certain organisms such as scallops. Additionally, increase of nutrients in a waters is often accompanied by an increase in several species of toxic algae that are harmful to the local fishery system (harmful algae blooms, HABs).

1. Introduction

Numbers of research have been carried out throughout the world on important role of upwelling phenomenon in marine waters and its impact to ocean productivity. Nevertheless, they did not take into account the specific characteristics and comparisons among those upwelling which occurred in different areas either temporally or spatially. On the other hand, information about this biological aspect of oceanography is truly essential in order to support its marine and fisheries development in these particular zones. Given ecological and socio-economic significance to the coastal area, the assessment and knowledge on these dynamics are extremely important.

Researches on upwelling have been carried out since the 1970s through in situ measurements in the waters of the Baltic Sea. Due to physical and chemical differences, water mass carried by upwelling can be observed through satellite imagery, especially its sea surface temperatures and chlorophyll-a concentrations. Since the 1990s, through the rapid development of remote sensing and analysis of hydrodynamic model, we have been able to reach a qualitatively new insight and understanding of this phenomenon [1].

In general, upwelling is identified by the lifting of water masses from the bottom of water column caused by the work balance among wind (wind stress), Coriolis effect, pressure gradient, and bottom friction. This vertical uplift of the water mass takes several days to several weeks over a distance of
nearly 100 meters or more [2]. This review focuses on the results of research over the last few decades that have been carried out in several places from various parts of the world. From Europe to North America and South America, from Asia Pacific to South and Southeast Asia and some water areas in Africa. This work also studied unique characteristics of each upwelling that occurred in each of the world's waters by displaying special features including the upwelling triggers and how much productivity generated, and how deep the mass of water lifted up to the surface by the upwelling energy. It is certainly discovered various characteristics of each upwelling around the world. Some coastal waters are famous for upwelling which is very closely related to ENSO (El Nino Southern Oscillation) and IOD (Indian Ocean Dipole) such as in the Southeast Asia region including Indonesia, Malaysia, and Vietnam. While in other places such as the southern coastal waters of America which includes Peru, Chile and Venezuela.

![Figure 1](image.png)

**Figure 1.** Location of significant coastal upwelling regions in the world ocean [2]

The area where upwelling occurs is always identically with water productivity because it is rich in nutrients (nitrates, phosphates and silicates) carried by the water mass from the bottom of the water [3], [4]. Therefore, this area is rich in pelagic fishery resources, both small and large. In addition to the positive impact of this upwelling phenomenon, it is not uncommon for negative impacts such as blooming of certain algal species to occur which can cause anoxic conditions and cause massive death of several fish species [5], [6].

Knowledge of the upwelling characteristics of various places from different latitudes with different seasons that characterize the difference in wind direction and speed makes an important contribution to the development of better fisheries management, planning actions, strategies and protection, of fishery resources and the coastal environment. Numbers of studies have been conducted to reveal the mechanism of upwelling and its significance to local waters. However, a review describing the characteristics of upwelling in every places in various parts of the world has never been done.

This review aimed to provide the current information on the development of research on the upwelling phenomenon that occurs in the world as well as the characteristics of each upwelling event that characterizes the differences between one place and others (Figure 1). In addition, this review also aimed to find out which areas could be categorized as the most intensive and productive upwelling areas in the world.

Indonesia itself has a type of coastal upwelling which is strongly influenced by the change of seasons. In the southern hemisphere, upwelling is strongly influenced by the southeast monsoon, on the contrary in the northern hemisphere, such as waters in the Aceh Sea, northern Natuna, northern
Banggai and Sulawesi Sea. In addition, as mentioned above, ENSO, IOD and some long waves such as Kelvin and Rossby waves play an important role in modulating the upwelling phenomenon.

2. Materials and method
This review used data and information that have been published in international journals from various parts of the world from 1990 to 2021 through www.sciencedirect.com. A total of 31 articles were used to discuss the characteristics of upwelling that occurs mainly in coastal waters in several places in the world, including Indonesia and several countries in the Southeast Asian region, South America, Europe, Africa, and Australia. In this paper, we have divided upwelling events along with their mechanisms, triggering factors and their significance to the surrounding waters based on several regional categories, namely, East Asia - Southeast Asia, Europe, Australia, America - South America and Africa.

3. Results and discussion
Research on coastal upwelling in the world have been carried out since the 1970s until now using various methods. In the first time, the researchers conducted their research by measuring directly in the study site. However, along with the development and progress of science and technology in the field of remote sensing, it is increasingly easier for researchers to access image data. The data includes sea surface temperature, chlorophyll-a and sea level anomaly.

Upwelling can be defined as a process of physical dynamics of seawater in which the vertical movement of water masses from the bottom of the water to the surface which is generated by the wind. A mass of heavier, cooler and usually nutrient-rich water towards the sea surface, displacing the warmer, less nutrient-dense surface water that is swept away by the wind towards the open sea. The mass of nutrient-rich water raised to the surface stimulates the growth and reproduction of primary producers (phytoplankton). Due to the phytoplankton-biomass and the presence of cold water, upwelling could be identified from SST and Chlorophyll-a.

Not all of the world's coastal waters experience the upwelling phenomenon, only certain water areas are supported by several factors, including the position of the land to the ocean, wind direction and speed, bottom topography of the waters and the Coriolis effect which are working in the area. In addition, upwelling can occur in the equatorial zone, eddy processes, ridges or sills in the bottom of the sea and the presence of the capes.

![Figure 2. Percentage of upwelling research in the world per region of 31 scientific articles](image)
Our review showed that most of the research were carried out in the Southeast Asian area such as Indonesia, Vietnam, and Malaysia of 35%. Followed by South America of 30% where the regions are the most productive upwelling areas in the world (Figure 2). Only 20% of the 31 studies were located in Europe. Meanwhile Arabian Sea was 15%. It suggested that people were more interested in conducting research on upwelling in the interesting area that had close relationship with fisheries system in the world.

3.1. Asia, Southeast Asia and Australia
In this review, the occurrence of coastal upwelling in the Southeast Asian region was specifically studied in several countries, including Indonesia [7], [8], [9], [10], Malaysia [11], and Vietnam [12], [13] which generally occurs in dry season from July to November. Upwelling events in Southeast Asia were generally triggered by the southeast monsoon winds. These studies covered the northern coastal waters of the Banda Sea and the eastern part of the Arafura Sea. In addition, South Java and West Sumatra had also become the areas where upwelling occurred which was modulated by strong IOD and El-Nino events in 2015. Upwelling in this zone played an important role in terms of productivity of local waters that contributes to local and regional fisheries system [7], [11], [8], [12], [9], [13], [10].

On the east coast of Malaysia Peninsular the upwelling was triggered by the southwest monsoon where a positive wind stress curl with longshore winds caused Ekman's transport to go offshore. However, due to the ENSO wind anomaly, the intensity of upwelling in this water area weakened (Strongest El-Nino 2009/2010 and 2015/2016). Meanwhile on the coast of Vietnam, during the dry season, the south easterly wind got stronger. In this location, ENSO played an important role in increasing the intensity of upwelling which allows an increase in water productivity. Meanwhile, the La-Nina event weakened the upwelling on the other side [11]. Upwelling in this Southeast Asian region had a very significant impact on local fisheries with an abundance of small and large pelagic fish supported by high concentrations of chlorophyll-a, nitrate, phosphate and silicate.

In western of South China Sea, upwelling induced by jet eddy system through the horizontal advection by a northwest ward jet, the divergence/convergence in cyclonic/anticyclonic eddies and upwelling/downwelling in cyclonic/anticyclonic eddies. This phenomenon occurred in August to September. As usually, this upwelling promotes the growth of phytoplankton surrounding the area [14]. It was different in terms of time and trigger compared to that of another side at South China Sea such as at the Vietnam Coastal area, where upwelling triggered by much stronger south-easterly wind during summer season (July). In this site, upwelling modulated by ENSO event as pointed out earlier. While at Zheijiang Coast, uplift of water mass from the bottom to 5 – 10 meter layer caused the bloom of phytoplankton, chlorophyll-a of 10.9 µg.L⁻¹ and nitrate phosphate of 16.9 and 0.90 M. This induced an hypoxia condition due to the decomposition of the bloom. However, it was not reported the fishes death during and post of this upwelling [12].

Another coastal area in the South Asia such as Southwest Coast of India, the southwest monsoon period during April to November caused the substantial increase of water column with high turbidity and inorganic nutrients (ammonium, phosphate and silicate) during and after the peak of Southwestern Monsoon (SWM) period [15]. In coastal waters of Tahiti (France Polynesia), upwelling occurs not because of the wind and the Coriolis effect but due to an internal wave where the amplitude of this wave was able to push water masses from a depth, rich in nutrients to the surface at a layer of 30-40 meters. This upwelling occurs along the coast of the Tahiti Islands [16]. The other side of the world, in Kangooro Island, Australia, the water mas was fertilized by the upwelling which is generated by Flinders Current Systems. It occurs in February to March during summer time where waters from 300 meters lifted up to the surface with the temperature of 10.4°C, salinity of 34.5 ppm, nitrate and phosphate of 13.35 and 0.94 mol.L⁻¹ which supported the ocean productivity [17].

3.2. America and South America
In the coastal areas of South America, upwelling phenomenon were investigated in several places, including in the Ubatuba waters off the coast of Brazil. Upwelling in this place, normally triggered by
northeasterly wind where water from the bottom was lifted up to the surface along with high nutrients from 200 - 400 meters to 35 meters with the salinity of 35.7 PSU [18]. Meanwhile, in the central Chile region, between spring and summer, alongshore equator and wind stress generated the divergence of Ekman current of the coast. In the San Jorge Gulf, Southwestern Atlantic, Argentina, between spring and summer time, upwelling was triggered by westerly and northwesterly wind [19].

In the other side of Chile, namely Tongang Bay, the Austral spring – summer season induced stronger upwelling which caused higher mortality of the Scallop (Argopectea purporatus), while weakened upwelling induced lower mortality. This proved that upwelling not always brings the benefit of the organism around the area but also causes some negative impacts [20]. As the consequence of the subsurface water properties (eg, colder, more acidic, hypoxic and richer nutrients), physiologically A. purporatus was able to cope with stressful environmental conditions imposed by higher upwelling intensities by enhancing its metabolic and calcification rate as well as producing higher concentrations of the shell organic matter [20].

Another investigation in Chilean Coast, mostly during Austral spring – summer season, upwelling occurred when equator wind transport surface waters off-shore replacing them by cold and nutrients rich from subsurface layer. This also enhanced productivity, triggers important changes of higher trophic level, a positive and significant effect of the upwelling over total allowable catch and harvest of benthic gastropod [21]. On the other hand, Humboldt Current System (HCS) in the eastern coast of South America is categorized as the most productive upwelling worldwide. Some locations are yearly upwelling and some are seasonally with the predominant phytoplankton in this location namely from diatom genera [22]. Off the Northern of California, during spring time, the southward wind induced the upwelling system which triggered grazing of mesozooplankton higher during spring time than winter [23].

3.3. Africa

In African Coastal Waters, upwelling generally triggered by southeasterly wind monsoon that occurs during summer season (May to September) at the western edge of Pemba Island, Tanzania has an active upwelling from 80 – 100 meter depth from where, they are lifted up the water mass to the surface which has a significance contribution as the host of large concentrations of small pelagic fishes [24]. However, in the eastern of Arabian Sea, in summer season, southwest monsoon wind has triggered the upwelling from the depth of 80 meter with the temperature of 4 – 5°C. This upwelling brings high dense, low temperature, and high nutrients waters towards the surface layer which leads to the phytoplankton blooming along the sea. In this area, upwelling modulated by Kelvin Wave [25]. In the southeastern of Arabian Sea, the relaxation of upwelling period induced the blooming of Gonyamlax polygramma. The elevation of upwelling intensity, phosphate and salinity during this period likely triggered the bloom of G. polygramma in the study area. Since this species is categorized as Harmful Alga Blooms (HABs), its existence may threaten fish stock such as sardines which have a vital role in the ecosystem [26].

Another side of Africa like in Namibian Coast, part of Banguela Upwelling System (BUS), one of the most productive upwelling area in the world. This upwelling triggered by southeasterly wind during austral-spring as other upwelling occurred in African Coast. Surprisingly, this area was found 129I in the northern of BUS of 1 x 10^7 atom. kg^-1 is mainly due to the impact of nuclear weapons global fall out without any evident impact of nuclear fuel reprocessing. Strong equatorial wind stress induced off-shore transport of surface water which is replaced by cool, nutrients rich from subsurface waters which created the fisheries rich environment [27].

In the North Africa, particularly in the Mediterranean Sea, the Cape of Mazagan and Cape of Juby along the Moroccan Coast, the maximum of the upwelling occurred when the northeast trade wind which are generated off Gibraltar in summer, it decreases when they blow from a more southern area. Photic layer in the area marked phytoplankton growth (the highest concentration of chlorophyll of the whole zone were up to 14 mg.m^-2 [28].
3.4. Europe

Some important area of upwelling in the world that support fisheries system coastal area are in Europe. Several places in this zone such as Ria Formosa, South of Portugal [29], Northern Coast of the Gulf of Finland, Baltic Sea [30], North Estonian Coast – Gulf of Finland, Baltic Sea [1]. The Iberian/Canary Current System (ICCS), Lisbon Bay, Portugal [31]. The upwelling occurred on certain seasons and create a high productivity in terms of fisheries.

In Ria Formosa, South of Portugal, in spring time, the two inlet imported Chlorophyll-a and phosphate, while in the absence of upwelling conditions, due to wind reversals and/or long period of wind relaxation, both inlets exported nitrate and phosphate. This processes fertilized the coastal area. The upwelling in this area predominantly triggered by westerly wind and occurred between May and Octobers which is uncommon upwelling [29]. Another side of Portugal Coast Ocean like in Iberian/Canary Current System (ICCS), Lisbon Bay Portugal. The upwelling occurred between spring and late summer, from spring to autumn. This upwelling associated not only with high diatom abundances but also higher dinoflagellate. The phytoplankton community structure showed significant spatially and seasonally differences. HABs also occurred at higher concentrations and were more persistent [31].

A unique upwelling occurred in the North Estonian Coast, Gulf of Finland, Baltic Sea during winter time (January to March) which lifted up water from 20 – 50-meter depth layer flowed up the coastal slope and replaced previous surface water which was triggered by westerly wind. This upwelling kept the Estonian Coast ice-face longer and water temperature slightly higher than at the Finnish Coast [1]. Winter upwelling as a phenomenon has long been ignored and therefore probably underestimated. Like summer upwelling, winter upwelling affects nutrients transport up to sea surface as well. On the other hand, Northern Coast of the Gulf of Finland, Baltic Sea, the south-westerly wind blowing for 60 h generated a strong upwelling. This lifts up nutrients from 40 – 65 meter to 10 meter upper layer. This upwelling elevated nutrients and increased the biomass of phytoplankton [30].

4. Conclusion

The characteristics of upwelling phenomena are different from one place to another area in the world. In the Southeast Asia, upwelling generally triggered by south-easterly wind during dry season (June to November). Another side of Asia such as South China Sea, the upwelling induced by jet eddy system as occurs at the western of this area during summer period. Upwelling also modulated by ENSO, IOD and Kelvin Wave in several parts in the world particularly in the Southeast Asia and South China Sea. In Europe, some upwelling occurred during the winter time which provided high rich nutrients to the surface waters like in the North Estonian Coast, Gulf of Finland, Baltic Sea. Humboldt Current System (HCS) in South America, Banguela Upwelling System (BUS) in Africa, off the coast of Java Island, and Banda Sea are categorized as the most productive upwelling area in the world. It is uniquely that was found upwelling caused by the amplitude of internal wave that occurred along the coast of the Tahiti Islands, French Polynesian.

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