Lecture 8: Coastal Upwelling

- The Physics of coastal upwelling
- Biological responses
Coastal Upwelling

Wind Stress

Coastal Upwelling Jet

Surface Ekman Layer

Bottom Ekman Layer
Processes in Coastal Upwelling

When winds have a component blowing parallel to the coast, Ekman layer transport directed $90^\circ$ to the right.

Offshore surface transport lows sea level near the coastal, produces a pressure gradient which is directed normal to the shore and drives a geostrophic current along the coast.

Flow field related to upwelling is directed at an angle away from the coast near the surface, parallel to the coast at mid-depth (below the Ekman layer but above the bottom boundary layer) and at an angle towards the coast in the frictional boundary layer at the bottom.
colder nutrient-rich waters from the deep ocean are uplifted onto the shelf and coastal upwelling jet is formed.

More than half of the world’s annual commercial fishing occur in the upwelling zone.
Five major coastal currents associate with upwelling area besides numerous coastal region, e.g. North South China Sea, coast off Vietnam
Horizontal distribution of water temperature at 10 m showing strong alongshore variability in upwelling on the shelf off NSCS (Guo, SOA)
Relationships between the wind, Ekman drift and coast, as illustrated below, lead to the formation of **Coastal Upwelling**.
Negative pressure gradient, \( dp/dx < 0 \) \((Pa > Pb)\), formed by the density contrast and sea level difference across the upwelling area, generates southward geostrophic current.
The width of coastal upwelling—the Rossby deformation scale

D: The distance of the upwelling front from shore, which moves offshore as upwelling progresses.

Ri (Rossby internal deformation scale): The width of the region where the interface rises to the sea surface.

\[ Ri = \left( g' H \right)^{1/2} / f \]

\( g' \) is the reduced gravity, \( H \) is depth of the upper layer and \( f \) is Coriolis parameter.

\[ g' = \frac{\rho_2 - \rho_1}{\rho} g \]
Variations in upwelling

- Time dependent
- Space dependent
Spatial variability of upwelling:
Ocean Surface Temperature on Sep. 5, 1994 as measured by satellite.
• By bottom topography:
Vectors of QuickScat wind stress (Pa) and MODIS SST (C) average over the cruise periods in 2000 and 2002
The topography (in meters) in the northern South China Sea
The selected cross-shelf sections (dashed lines) are marked by their grid numbers.

The location where shelf isobaths protrude shoreward is marked by SCI (shoreward convex isobaths).

zoomed area in the region

between Guangdong and Xiamen
Daily mean (a) surface, (b) bottom velocity vectors (m s$^{-1}$); (c) depth-integrated velocity magnitude (m s$^{-1}$) and (d) surface elevation (m).
Daily average surface (left column) and bottom (right column) $\sigma^\theta$ (kg m$^{-3}$) on days 10 and 30, showing the strong shoreward advection near SCI and the subsequently eastward advection of dense bottom waters between Shanwei and Shantou during upwelling.
Across-shore sections of daily-averaged alongshore velocity, $u$ (m s$^{-1}$), cross-shore velocity $v$ (m s$^{-1}$) and density $\rho$ (kg m$^{-3}$) at lines 305 (Shanwei), 338 (Shantou) and 372 (Taiwan Shoals) on day 30.
Figure 5c: Surface elevation (cm) on days 6, 10 and 15. The contour interval is 1 cm with a heavy contour line for -10 cm.
Figure 6: Across-shore sections of daily-averaged alongshore velocity $v$ (m s$^{-1}$) and potential density $\sigma_\theta$ (kg m$^{-3}$) at the location of the CODE C line on days 6, 10, 15 and 20. Negative (positive) values of $v$ are indicated by solid (dashed) contours. The contour interval for velocity is 0.1 m s$^{-1}$ with heavy contour lines for 0 and -0.5 m s$^{-1}$. The contour interval for $\sigma_\theta$ is 0.2 kg m$^{-3}$ with heavy contour lines for 25 and 26 kg m$^{-3}$. 
Figure 7: Across-shore sections of daily-averaged alongshore velocity $v$ (m s$^{-1}$) at the locations of the CODE N and R lines on days 10 and 15. Negative (positive) values of $v$ are indicated by solid (dashed) contours. The contour interval is 0.1 m s$^{-1}$ with heavy contour lines for 0 and -0.5 m s$^{-1}$. 
•By combined effects of time-dependent wind stress and coastline variation--------**upwelling relaxation**

*Figure 1. Map of the CODE region showing the topography and the locations of the current meter moorings (solid circles) in 1982. Stations where meteorological measurements were obtained are shown as open circles [adapted from Limeburner, 1985].*
Figure 2. Time series of the alongshore component of the (middle) wind stress at buoy B13, (top) water temperature, and (bottom) alongshore velocity at depths of 10, 20, 35, and 52 m from the CODE moorings R2, C2, and N2. The time series have been filtered with a 36 hr low-pass filter. The alongshore direction for the wind stress and currents is 317° T. The temperatures and alongshore velocities at 20, 35, and 53 m depths are offset by 3°C, 6°C, and 9°C C and 0.5, 1.0, and 1.5 m s⁻¹, respectively.
Figure 5a: Surface velocity vectors (m s$^{-1}$) on days 6, 10 and 15. The direction of the wind stress is indicated by the arrows on days 6 and 10.
Figure 5b: Surface temperature (C) on days 6, 10 and 15. The contour interval is 0.5 C.
Figure 10: Modeled (left) and observed (right) near surface (10 m depth) velocity vectors (m s⁻¹) from the CODE mooring locations during upwelling (April 19, May 3) and during relaxation (April 22 and 24, May 5 and 7). The modeled surface temperature (C, color contours) and the wind stress vectors \( \tau \) for each day are also shown.
Figure 11: Depth-averaged velocity vectors (m s⁻¹) and surface elevation (cm, color contours) in the vicinity of Pt. Reyes during upwelling (April 19, May 3) and during relaxation (April 22 and 24, May 5 and 7).
Figure 12: Across-shore sections of daily-averaged alongshore velocity $v$ (m s$^{-1}$) and potential density $\sigma_\theta$ (kg m$^{-3}$) at lines 113 and 143 during upwelling on April 19 and during relaxation on April 22. The contour intervals are 0.1 m s$^{-1}$ for $v$, with the 0.5 m s$^{-1}$ and 0 contours bold, and 0.2 kg m$^{-3}$ for $\sigma_\theta$, with the 25 and 26 kg m$^{-3}$ contours bold.
Coastal trapped waves and other oscillations

- The local convergence or divergence along the coast increases or decrease local sea level, which leads to the formation of local pressure gradient.
- The resulting currents from the local pressure gradient lead to the propagation of these local increased or decreased sea level (i.e. wave propagation).
Kelvin Wave

• largest amplitude at the coast, amplitude falls off exponentially towards the open ocean;
• Propagate in the direction with coastline on its right in the NH and on its left in the SH;
• Its existence requires coastline, but not shelf.
Coastal Trapped Waves

• Their existence requires region of shallow ocean between the coast and the deep ocean;
• Offshore and inshore movement of a water column during upwelling or downwelling on a sloping shelf below the Ekman layer is associated with a continuous change of potential vorticity due to the stretching and widening;
Figure 9. (a) depth-averaged velocity with magnitude greater than 0.1 m s\(^{-1}\) (color contours) on days 2 (red), 5 (yellow) and 10 (green) overlapped with velocity vectors on day 15.
Figure 9 (continued) (b) across-shore section of daily averaged alongshore velocity with values less/greater than -0.1/0.1 m s⁻¹ for upwelling/downwelling at the northern open boundary on days 5 (red), 10 (yellow) and 15 (green); (c) time series of daily-averaged transports 60 km offshore across northern (NB) and southern (SB) boundaries for the case with no wind at the NB during upwelling and downwelling, respectively. Winds are turn off after day 15.
• Upwelling and primary production

Fig. 5.09 Patterns of nitrate distribution (μmol L⁻¹): (a) during weak winds, (b) soon after the onset of strong winds, and (c) after persistent strong winds. Ocean floor shaded. Reprinted with permission from Codispoti and Friederich (1978), Pergamon Press.
with river
zooplankton concentration at IM=905 on day90 (millimole m$^{-3}$)

without river

dissolved oxygen concentration at IM=305 on day30 (millimole m$^{-3}$)
Remarks about the upwelling-primary production

- There is a time delay between the onset of the wind and the arrival of nutrient-rich water.

- There has to be a quantity of nutrient-limited phytoplankton cells ready to respond to the availability of nutrients.

- The high productivity results from the alternation of upwelling events. (upwelling brings nutrient, calm period, stratification develops, phytoplankton grows and multiplies)
• Upwelling and zooplankton

- Zooplankton organism, e.g. copepods, require longer time (weeks) to complete life cycle.

- Process is: adult copepods is upwelled to the surface from deep water during upwelling, their offspring thrive on the abundant phytoplankton and tend to be carried offshore. The peak value of zooplankton occurs when upwelling is weakened so that they can stay over the shelf.
Mean

May 23 - August 2, 2001

\( \sigma_0 \)

Chlorophyll-a (log)

Zooplankton

\( \text{lat, } ^\circ \text{N} \)

\( \text{lon, } ^\circ \text{W} \)

\( 0.5 \text{ m/s} \)

24.2 24.6 25 25.4

0 0.5 1 1.5

0 2 4 6
Lower nitrate and chlorophyll-a, and higher zooplankton concentration are found during the periods after upwelling (or relaxation of upwelling and downwelling, e.g. June 22-30)

Figure 6. Time evolution of surface nitrate (mmol N m⁻³), phytoplankton (mmol N m⁻³), and zooplankton (mmol N m⁻³) at three sections (Cascade Head (200), Newport (175), and Heceta Bank (148)). The white line in the left panel represents the north-south component of the wind stress (N m⁻²). The white line in the middle and right panels represents the position of the core of the coastal jet.
•Upwelling and fish

- Upwelling favorable wind
- Upwelling circulation
- Upwelling nutrients
- Bursts of Phytop.
- Relaxing of upwelling winds
- Build up of Zoo.
- Landing of fish
Example of upwelling in California current
Bakun upwelling index:

\[ \tau = \rho_a C_d v^2 \]

\[ M_E = \frac{\tau}{f} \]

\( \rho_a \) is air density 0.00122 g cm\(^{-1}\), \( C_d \) is drag coefficient as 0.0026. The upwelling index is the simply the time average of \( Me \) for different part of coastal zone.

Fig. 5.15 Each plot on the left-hand side of the diagram is the upwelling index for each month of the year, averaged for the 20 years between 1948 and 1967. Each is for a different latitude, as indicated on the map on the right. Note that the strongest upwelling occurs at 34° N. In the southern half of the range the index is positive all year round, but at latitudes 39–45° N the index is negative in winter. Modified from Bakun (1973).
Fig. 5.16 Average coastal temperature anomaly (°C) in summer, calculated as the difference between each location and a smoothed reference temperature for offshore conditions at the same latitude. Positive anomalies hatched, negative anomalies shaded. From Bakun and Parrish (1982).
Fig. 5.17 Temperature and nitrate distributions off Point Sur, California, from satellite and shipboard operations. Note the difference between actual field data and the averaged long-term trends in the previous figure. From Traganza et al. (1983).
Ekman Pumping and Primary Production in a Cyclone

Figure 2. Vectors: QuikSCAT wind vectors at 21:46 UTC 6 July 2000 illustrating Kai-Tak’s wind field, the wind speed is mostly between 20–40 m/s. Colours and contours: contours of the Ekman pumping velocity estimated from QuikSCAT wind vectors showing upwelling (118–120°E, 19–20.5°N) induced by Kai-Tak.

High surface Chl-a