Section 5

Ocean Mesoscale Features: Upwelling and Other Phenomena

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2015 Spring Semester
Guess what?
Outline

- 5.1 Upwelling
- 5.2 Wind-driven, offshore, dynamic features
- 5.3 Large rive plumes
- 5.4 Island wakes
- 5.5 Ice edge phytoplankton blooms
- 5.6 Remote sensing in iron limitation studies
- 5.7 Making the most of satellite data for mesoscale studies: conclusions from chapters 3-5
5.1 Upwelling
- The causes and consequences of upwelling

![Diagram of Coastal Upwelling]

*Figure 5.1. Coastal upwelling.*
Figure 5.2. Equatorial upwelling.
Aspects of upwelling detected by satellites

Figure 5.3. SST in the Benguela upwelling region of the southwest Atlantic Ocean, centered on 31°S, 17°W, retrieved from a single MODIS (Aqua) overpass on March 3, 2005, at the same time as Figure 5.4.

were occurring then. Although clouds prevent a clear view of the previous few days, this one example demonstrates the richness of information and insight that can be gained from multiparameter remote sensing of upwelling. Put simply, we may consider that image datasets of wind, SST, and chlorophyll tell us, respectively, about the forcing, the immediate response, and the longer term integrated result of an upwelling event.

There remain problems for detailed monitoring of upwelling processes from space, the foremost of which is the presence of cloud that restricts the use of infrared
and ocean color sensors. In some parts of the world low cloud or sea fog may be associated with the cool SST found in the upwelling zone. One way of ameliorating this is to build up daily SST composite maps from infrared sensors on geostationary satellites, provided cloud does not persist throughout the day (Castelao et al., 2006). This is feasible because most of the important upwelling regions are found at the same latitude as subtropical gyres and within the view of a satellite parked over the

Figure 5.4.
Chlorophyll-α concentration in the Benguela upwelling region of the southwest Atlantic Ocean, centered on 31°S, 17°W, retrieved from a single MODIS (Aqua) overpass on March 3, 2005, at the same time as Figure 5.3.
Equator. If cloud is very persistent then microwave radiometry can be tried, but only for very large regions of upwelling that extend a long way offshore. Because their spatial resolution is no better than 50 km and their accuracy is compromised within up to 100 km of the coast by stray radiation from the land, microwave radiometers are not able to define the spatial structure of upwelling in detail and would not detect any of the cool water found within 20 km of the shore throughout the whole coastline shown in Figure 5.3.

In principle the sea surface height signature at the frontal edge of major upwelling regions should be measurable by altimetry. When upwelling is established it pushes the warm, surface, mixed layer away from the coast, replacing it with colder, denser water. When this happens the sea level lowers over the upwelling region, sloping down steeply at the front where cold, upwelled water meets warm, offshore, surface water (as shown in Figure 5.6). This surface slope is maintained in
geostrophic balance by an equatorward jet that is an essential element of the upwelling system. Therefore the upwelling zone does have a sea surface height signature. As shown in the figure, this moves offshore when there are upwelling-favorable winds, and disappears or moves inshore when the upwelling ceases. If altimetry could resolve SSH at short length scales with sufficient accuracy then it would play a useful role in monitoring the position of the upwelling frontal edge, but so far this has not been achieved. Current research activity (Madsen et al., 2007; Bouffard et al., 2008) is attempting new analyses of existing altimeter data to improve accuracy close to the coast in semi-closed seas, and these techniques may eventually be applied so that altimetry can monitor upwelling and meandering of the upwelling front. Wide-swath altimeters (see section 11.5.5 of MTOFS), if they are ever developed and deployed, would also be valuable for detecting the upwelling frontal edge. Meanwhile, altimetry already provides very good evidence for the changes in sea level associated with upwelling in the eastern equatorial Pacific, and its reduction during an El Niño (as discussed in Section 11.2), although that occurs on a larger spatial scale than most upwelling zones around the world. Altimetry is also applied to studies of eastern boundary currents which, although distinct from the actual upwelling, are closely associated with the fate of the upwelled water. Altimetry identifies the variability of coastal currents out to 500 km from the coast (Strub et al., 1987; Strub and James, 2000) and the occurrence of offshore jets that carry productive water towards the open ocean.

SAR images also have potential for detecting fronts present in upwelling systems, but this approach has not so far given oceanographers any information that they cannot obtain more easily from other sensors. It remains to be seen whether new developments in SAR measurement of currents, using the Doppler centroid method mentioned in Chapter 4, will bring something new to the study of upwelling.
5.1.3 Upwelling regions of the world seen from space

The main upwelling regions of the world are shown in Figure 5.7, mapped onto a 6-year, average annual mean, SST map from MODIS Aqua. Although a long-term average map tends to smooth out the mesoscale detail of instantaneous snapshot images such as Figures 5.3 and 5.4, and also weakens any features that are strongly seasonal, it is used deliberately here because any small-scale features that it does reveal must be those that are strong most of the time and whose location is rather constant. Hence the narrow ribbon of cold water along certain coasts, between 3°C to 6°C cooler than the adjacent ocean, provides strong evidence of persistent upwelling.

In fact these correspond to places where prevailing winds are known to be upwelling-favorable throughout the year. They are found at the eastern margins of the Pacific and Atlantic Oceans at the latitudes of subtropical gyres, in both the northern and southern hemisphere. The four regions of the world where upwelling occurs persistently are the Canary coast off northwest Africa, the Benguela coast off southwest Africa, the Peru coast, and the Oregon coast. Beyond these are regions where upwelling is strong during part of the year (normally the summer months) but not for all of the year, and their signatures in the annual SST map are somewhat more diffuse. Thus, the wider coastline of Oregon and California, the Chile coast, and the Iberian coast are labeled as seasonal.

Figure 5.7. The major upwelling zones around the world. The background image is the 6-year average annual mean SST 9km map produced from MODIS data.
Figure 5.8. Evidence of equatorial upwelling in the 6-year cumulative (January 1, 2002–February 29, 2008) average map of chlorophyll concentration as measured by the MODIS sensor on Aqua, showing the Equatorial Pacific (above) and the Equatorial Atlantic (below), both between 10°N and 10°S. The color scale for this map is the same as for the chlorophyll-a maps of Figures 5.9–5.12 (MODIS data downloaded from the NASA Ocean Color website at http://oceancolor.gsfc.nasa.gov).
Figure 5.9. Benguela upwelling monthly average for February 2004 of SST (left) and chlorophyll (right) both from the MODIS datasets (produced using extracts from level 3 mapped images downloaded from the NASA Ocean Color website at http://oceancolor.gsfc.nasa.gov).
Figure 5.10. The Canary upwelling along the coast of northwest Africa. Monthly average for February 2004 of SST (left) and chlorophyll (right) both from the MODIS datasets (produced using extracts from level 3 mapped images downloaded from the NASA Ocean Color website at http://oceancolor.gsfc.nasa.gov).
Figure 5.11. Upwelling along the coasts of Peru and Chile. Monthly average for April, 2004 of SST (left) and chlorophyll (right) both from MODIS datasets (produced using extracts from level 3 mapped images downloaded from the NASA Ocean Color website at http://oceancolor.gsfc.nasa.gov).

water well away from the coast (Strub et al., 1991; Barth et al., 2000) and studies concerned with the effect of local topography on this process (Barth et al., 2005). Marin et al. (2003) use satellite data to study the occurrence of upwelling shadows, locations where upwelling is inhibited by the relation between wind direction and coastline orientation. Castelao and Barth (2006) explored the role of wind stress
Using satellite data in upwelling research

Figure 5.12. Upwelling along the Oregon and California coasts. Monthly average for July 2004 of SST (left) and chlorophyll (right) both from MODIS datasets (produced using extracts from level 3 mapped images downloaded from the NASA Ocean Color website at http://oceancolor.gsfc.nasa.gov).
5.2 Wind-driven, offshore, dynamical features

Figure 5.13. Weekly average wind speed and direction from QuikScat over Central America for week ending February 18, 2006. The white parallel bars show the three gaps in the mountain chains through which the wind is steered. QuikScat data are produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team (adapted from a graphic image map acquired from www.remss.com).
Figure 5.14. Upwelling during a “Norte” event in the Gulf of Tehuantepec off the Pacific coast of Mexico. Upper panel is the SST measured by Aqua-MODIS on November 15, 2004. Lower panel is the chlorophyll concentration derived from the ocean color channels of the same sensor at the same time. The inset panel shows the average wind field for the week ending November 13, 2004, derived from QuikScat. The color scale for wind speed is the same as that defined in Figure 5.14. The MODIS images were obtained from the NASA Ocean Color website (QuikScat data acquired from Remote Sensing Systems).
5.3 Large river plumes

Figure 5.15. Chlorophyll map of west Equatorial Atlantic Ocean derived from Aqua MODIS on September 30, 2006 showing the track of nutrient-rich water from the River Amazon.
sometimes be seen in satellite images to have attached to them a signature over the adjacent ocean, typically streaming away in a dominant direction giving the appearance of a wake. There are three ways in which this may occur. The first is a purely atmospheric effect. Islands that have fairly high mountains, typically of volcanic origin, produce disturbances in the wind flow that have a satellite signature (e.g., as cloud streets trailing downwind in visible wavelength radiometer images, or as wind shadow zones visible in SAR images as low backscatter regions where the wind stress is reduced behind the island—see also Chapter 9). Typically the disturbance extends a few hundred kilometers at most beyond the island in the prevailing wind flow direction, but occasionally a high mountain can influence the wind flow much farther over the ocean. This is the case in Hawaii where the presence of the islands is credited with reducing the westward wind flow of easterly trade winds in a shadow behind the mountains that stretches for 3,000 km, resulting in the formation of a narrow, easterly, ocean surface current (Xie et al., 2001), apparently far removed from the island whose presence caused it.

The second mechanism is where the wind shadow wake behind high mountains on an island creates a response locally in the ocean. This may be superficial, as when a diurnal thermocline develops in the wind shadow area so that warm patches of SST are clearly seen in thermal infrared imagery. However, in the case of steady winds creating a persistent wind shadow region the shear between shadow and nonshadow regions produces Ekman convergence and divergence (as shown in Figure 5.16). This leads to upwelling and downwelling zones, the former appearing cooler on SST images. Upwelling also brings increased nutrients that may lead to enhanced primary production with an ocean color signature. This can account for the patterns of temperature and color that appear on the downwind side of island chains such as the Hawaiian and Canary Islands (Aristegui et al., 1997; Burton, 2001). Barton et al. (2001) show how the combination of SAR images revealing wind shadow and wind

![Figure 5.16. Schematic cross-section through the sea showing wind shadow, shear lines, and upwelling driven by Ekman transport downwind of an isolated oceanic island.](image-url)
5.5 Ice edge phytoplankton blooms

Figure 5.17. Three maps of chlorophyll-a concentration over the Galapagos region, derived from SeaWiFS ocean color data, spanning 13 days in May/June 2003, illustrating the "island wake" effect.
Figure 5.18. Aqua MODIS view of the Ross Ice Shelf on February 24, 2008. (a) Level 1 real-color composite. (b) Level 2 chlorophyll distribution. This shows plankton blooms associated with the melting ice edge (MODIS data from which this image was created were acquired from NASA’s Ocean Color website at http://oceancolor.gsfc.nasa.gov).
5.6 Remote sensing in iron limitation studies

two of these experiments, but they serve as pointers towards how, more generally, satellite observations can not only be used to provide background climatological knowledge about mesoscale variability, but also have the capacity to supply near real-time data as an integral part of an experimental program.

One way to test the iron limitation hypothesis has used experiments to artificially enrich a region by depositing iron in a suitable form and monitoring the response of the phytoplankton bloom (Boyd et al., 2007). The scale of the resulting bloom is large enough to be detected in level 2 ocean color data products. In some experiments, satellite data have been used explicitly to monitor the long-term fate of the bloom for several weeks after the experiment when prohibitive costs have not allowed in situ sampling to continue beyond the initial stages. For example, in the SOIREE experiment (Abraham et al., 2000), the fertilized patch was detected several times in the few weeks following the iron release on February 9, 1999. Figure 5.19 shows the clearest view acquired on March 23. By this time the bloom, which started as a small circular region, had been drawn into a ribbon shape some 150 km long and then advected by mesoscale turbulent motion into this semicircular shape with a diameter of about 50 km. Maximum chlorophyll concentration is estimated to be 3 mg/m³. Further analysis of typical SeaWiFS data for the previous 2 years confirmed that such magnitudes had not been detected previously in this region where the mean value was 0.20 ± 0.06 mg/m³. Although frequent cloud cover prevents a full dynamic description of the growth and evolution of the bloom, occasional clear views like this provide an overall perspective that assists enormously in interpretation of biogeochemical field measurements. Since then similar use has been made of SeaWiFS and MODIS data during the SERIES and SOFeX experiments (Coale et al., 2004).

![Chlorophyll concentration image](image_url)

**Figure 5.19.** SeaWiFS-derived chlorophyll image of the bloom resulting from the SOIREE iron enrichment experiment. This image was acquired on March 23, 1999, several weeks after the initial release. The bloom is centered at about 141°E, 60.5°S. The diameter of the semicircular feature is about 50 km (original image obtained from NASA Ocean Color website).
5.7 Making the most of satellite data for mesocale studies

• Conclusions from chapters 3-5
into tools used in mainstream oceanography. It is encouraging to find examples, as in the previous subsection, where the creative use of satellite data applied in conjunction with conventional in situ hydrography is providing the extra insight that leads to innovative results and better understanding of complex features. The availability of ocean color data that can be compared with SST and SSH is also opening up new understanding of how biological and chemical processes are steered by water circulation.

These chapters have not probed all aspects of the subject. For example, no mention has been made of the technique of maximum cross-correlation (MCC) in which large-scale flow is detected from the movement of small-scale structures of SST or color between one overpass to the next (see, e.g., Domingues et al., 2000; Barton, 2002; Bowen et al., 2002; Emery et al., 2003). Although the promise of ADT from altimetry is very exciting, in practice these two methods for defining the details of ocean circulation in an eddy-infested ocean are likely to go well together as complementary tools.

We have not entirely left mesoscale processes behind, since the same or similar phenomena crop up in later chapters, but from a different perspective. A field which now seems ripe for more research is to proceed beyond simple analysis and basic
Figure 5.22. 
Contours of the ADT field, equivalent to streamlines of the surface absolute velocity field, overplotted onto the satellite-derived chlorophyll-a field surrounding the Crozet Plateau, for the weeks of (a) October 24-31, 2002, (b) November 1-8, 2005, and (c) October 24-31, 2006 to show how chlorophyll varies consistently with the varying flow field from one year to another (image provided by Hugh Venables, British Antarctic Survey).
understanding of individual mesoscale processes to mapping their climatological variability. The climatology of frontal occurrence already mentioned in Chapter 4 shows that this is possible once a long time series of image data is available. We should expect to construct similar climatologies in relation to eddy statistics or the strength of upwelling. The increasing availability of well-processed datasets, often using carefully specified analyses that blend data from different sensors in order to improve SST, ocean color, or SSH products, should pave the way for generating climatologies of variability. These should contribute to developing our understanding of how climate change affects the detailed behavior of the ocean at local scales.

5.8 REFERENCES


Upwelling System
Ekman pumping

- Upwelling: http://www.youtube.com/watch?v=gE0617WH0IU
- Ekman: http://www.youtube.com/watch?v=COWTm95Gcck