**El Niño Southern Oscillation (ENSO); Ocean-Atmosphere Interactions**

**Take away ideas and understandings**

1. Mean climatology of the tropical Pacific ocean-atmosphere system.
2. Changes in equatorial Pacific ocean and atmosphere circulation associated with El Niño and La Niña events.
3. Two dynamic feedback processes which act to intensify El Niño and La Niña events.
4. Why this system oscillates and the time-scale of this oscillation.
5. Effects of El Niño/La Niña on regional and global climate.

**I. General Background**

* The tropical Pacific displays a large zonal gradient in sea surface temperature [SST], with a "warm pool" in the west and cold SST along the Equator in the east.
* At intervals of 3 to 7 years the warm pool surges eastward. El Niño refers to a warming of the central and eastern tropical Pacific, the two largest episodes of the 20th century).
* When the warm pool is pressed against the western boundary of the tropical Pacific Ocean, the eastern tropical Pacific is cooler than normal, this is called La Niña.
* What makes it so notable are the worldwide impacts on climate of El Niño and it's "mirror image", La Nina.

**II. Impacts of 1982/83 El Nino Episode**

* One of the two largest amplitude El Nino of this century.
* Most recent (1997-98) El Niño was comparably large as well.
* Droughts in Australia, India, Southern Africa.
* Floods in Peru, Ecuador, USA Gulf of Mexico states, & Colorado River basin.
* Collapse of coastal fishery in Peru (largest average annual catch of marine fish in world).

**III. Mean Tropical Pacific Ocean-Atmosphere Climatology**

* The Intertropical Convergence Zone (ITCZ; [General Circulation Lecture](http://eesc.columbia.edu/courses/ees/climate/lectures/gen_circ/index.html)) is where the trade winds from the Northern and Southern Hemispheres converge into a narrow belt close to the equator, a result of the general Hadley circulation which dominates the tropics and subtropics.
* The winds have two main effects on the tropical Pacific ocean. They cause a general westward motion of surface waters and warmest waters pile up at the western Pacific.
* Since the winds are from the NE in the northern tropics and from the SE in the southern tropics, these winds also cause the surface waters in the eastern tropical Pacific to diverge as a result of Ekman pumping. This divergence causes cold, nutrient-rich subsurface water to upwell at the equator.
* These two processes cause the tropical Pacific to develop an E-W temperature asymmetry: warm in the west and cold in the east. Deep atmospheric convection and heavy rainfall occurs in the western Pacific over the warm water, whereas there is net atmospheric subsidence over the colder water in the eastern Pacific (see schematic diagram of "normal" conditions in the tropical Pacific. The rising motions in the west and descending motions in the east establish an E-W atmospheric circulation called the Walker circulation.
* Subtropical/tropical circulation in the Pacific could thus be considered as including two orthogonal, but coupled, components: (A) Hadley Cell transport crossing latitude lines; towards the equator at the surface and away from the equator in the upper troposphere); and (B) Walker Cell transport parallel to the equator; westward at the surface and eastward in the upper troposphere). The combined effect of the Hadley Cell, Walker Cell and rotating earth dynamics is to cause intense convergence and vertical circulation at the ITCZ (near 0° latitude), over both the land and the sea.
* Strength of the trade winds varies in phase with the strength of the Walker Cell circulation.
* Strengthening and weakening of the Hadley and Walker circulations play a crucial role in reinforcing El Niño/La Niña perturbations to the mean tropical Pacific ocean-atmosphere climatology.

**IV. End Members of ENSO Circulation**

* Net transport of trade winds in Pacific is nearly always from east to west.
* Stronger than average trade winds tend to push the warm surface layer of the ocean (upper few 100 meters) towards the western end, creating a thick warm layer (La Nina conditions).
* La Nina has higher than average precipitation in Australia, India & Indonesia.
* Weaker trades relax pressure on surface ocean layer & it starts to move back across Pacific from west to east, raising SST in the eastern tropical water, including Peru (El Nino conditions), with the zone of heavy rains shifting out over the central Pacific islands.
* Instrumental records of mean sea level pressure (MSLP) & sea surface temperature (SST) extend only back to the last third of the 19th century, but growth of coral on islands across the low latitudes Pacific have retained signals in their isotopic composition which permit some aspects of the history of ENSO to be reconstructed over at least several centuries.

**V. General History of ENSO Research; Sir Gilbert Walker** 1904, a British mathematician entered the British colonial service as director general of observations for India.

* Arrived shortly after huge famine caused by drought (very weak monsoon rains).
* His goal was to predict the Indian Monsoon, which periodically fails to bring sufficient rain for crops to the Indian subcontinent (modern India, Pakistan and Bangladesh); e.g. 1899 famine.
* The Observatory was founded after the monsoon failure of 1877, the worst famine in Indian history.
* Indian met service collected meteorological data from all over the world and made correlations of that data with Monsoon rainfall, to explore whether it was part of global phenomenon
* Walker found that many global climate variations, including Monsoon rains in India, were correlated with the Southern Oscillation, a large scale see-sawing of atmospheric mass between the eastern and western sides of the tropical Pacific.

**VI. Mean Sea Level Pressure (MSLP) Index of ENSO**

* A widely used index of the strength of the Southern Oscillation, the Southern Oscillation Index (SOI) is given by the normalized difference, SLP at Tahiti - SLP at Darwin. Barometric records at those stations go back to the 1880's .
* Both Darwin & Tahiti have an appreciable seasonal cycle of Mean Sea Level Pressure (1933-1992). The SOI from the early 1880s is shown as Fig. 16.
* Smallest contrast between the two locations occurs in the southern hemisphere autumn, while the highest gradient in MSLP is during the austral summer.
* Higher positive values of SOI indicate stronger trade winds, especially in the southern hemisphere (La Nina conditions).
* For most of the time, mean sea level pressure (MSLP) is relatively high in the south central Pacific (e.g. Tahiti) and MSLP is relatively low over the Indian Ocean and N. Australia (e.g. Darwin), with a net transport of air at low latitude from east to west -- the easterly trade winds.
* Every few years the MSLP difference between east and west weakens; consequently the trades relax and there is often drought in India and Australia. Monsoon rainfall correlations to SO were established by mid 1920s.
* Between 1970 and 1990, there were about four La Nina episodes when high values of SOI persisted for many months, and an equal number of El Nino episodes.
* Note these episodes were NOT spaced uniformly in time with a transition period of constant length from one to the other; thus the oscillator process clearly is complicated
* Over the past century, approximately 25% of the years could be classified as being in each of the two extreme ENSO states, assuming the six month mean value of SOI (June - November) diverged from the long-term mean by more than 0.5 standard deviation units.
* NINO3 is the SST anomaly (departure from normal) averaged over the region 5°N to 5°S and 90°W to 150°W. There is a tight coupling between the SO and eastern equatorial SST -- that is, El Nino is a time series of Darwin SLP plotted in parallel with a widely used El Nino index called NINO3. By chance, the units of Darwin MSLP (millibars) and NINO3 SST (°C) have almost exactly the same range of values. NOTE: The Darwin MSLP data have been smoothed (5-month running mean) to reduce month-to-month fluctuations.

**VII. General History of ENSO Research; Jacob Bjerknes**

Walker, however, failed to make the connection between the SO and El Nino. This link was made convincingly by the Norwegian America meteorologist, Jacob Bjerknes. He made extensive use of data gathered during the 1957 International Geophysical Year, which happened to be a time with a strong warm (El Nino) event.

* Bjerknes realized that unusual events separated by half the circumference of the planet -- El Nino & the Southern Oscillation -- could be linked together as parts of a huge coupled phenomena -- ENSO-- involving both the ocean and atmosphere (Fig. 22 - see powerpoint).

**VIII. General Description of ENSO Processes: Why is There an El Nino State?**

* Bjerknes did more than establish the empirical connection between EN and SO. He also provided an hypothesis about the mechanism of ENSO that underlies our present understanding.
* The key is to appreciate how odd the "normal" state of the Pacific is. shows climatological SSTs in the tropical Pacific for December. Note how cold the eastern equatorial ocean is, despite the strong solar heating. (By contrast, the El Nino state) is more what one would expect from solar heating alone. Note that the anomalies are the difference between the full SST fields in Figs 1 and 2). Cold water is present in the eastern tropical Pacific because:
  + The easterly trades drive westward currents, bringing the cold waters of the Peru Current from the South American coast;
  + The Coriolis force turns westward surface currents poleward in both hemispheres -- this is the Ekman transport. Consequently, surface waters diverge from the equator (Ekman divergence) and the poleward currents must be fed by waters upwelling from below. These waters are denser and colder than the surface waters they replace.
  + The tropical ocean may usefully be viewed as a 2-layer fluid, with an upper warm water layer separated from a lower cold water layer by a sharp thermocline (the temperature change of 10°C between the upper and lower layers may take place in as little as 100m). The trade winds push the warm upper layer waters poleward as well as westward, pulling the thermocline to the surface in the east. As a result the waters upwelled there are even colder than they would be if the upper layer waters were more evenly distributed with longitude.
* All 3 of the above effects contribute, but the upwelling ones are the most important.
* All are due to the easterly winds. Bjerknes realized that the easterly winds are in turn due to the temperature contrast along the equator: the surface air flows from cold (high pressure) to warm (low pressure), the strength of the temperature contrast controlling the strength of the winds. It does this via the pressure gradient force -- the difference in MSLP between the eastern and western Pacific (Note the direct relation to the SO). Higher pressure characterizes colder air over colder water.
* Thus there is a positive feedback: stronger SST gradients across the Pacific tropics lead to stronger easterly winds lead to stronger SST gradients. (Bjerknes termed it a "chain reaction.")
* El Nino is the opposite state: Suppose the waters in the east warm somehow. Then the trades will weaken. The thermocline will relax, so the upwelled water will not be as cold as before. (If the winds in the east are part of the weakening then the strength of the Ekman divergence -- the equatorial upwelling -- will also weaken.) so the east-west SST gradient will weaken further and the trades will weaken further and so on. ANOTHER POSITIVE FEEDBACK.
* Also, when the trades relax and the warm water layer starts to move back across Pacific from west to east, it raises SST in the eastern tropical water, including Peru (El Nino conditions), with the zone of heavy rains shifting out from the western Pacific over the central Pacific islands.
* Bjerknes thus explained the existence of a cold (high SOI) state and a warm (low SOI) state, but could not explain the transition from one to the other. He couldn't explain why one state (e.g. east cold) or the other (east warm) would not just stabilize and remain forever.
* Difference in January SST between the two extreme ENSO episodes of this century (Jan 1983 [El Nino] minus Jan 1956 [La Nina]) illustrates that the eastern tropical Pacific experiences the largest shift in SST for any large area of the ocean, being about 4°C warmer during El Nino conditions.
* Several spatially averaged SST indices for the eastern Pacific have been developed to reflect the state of ENSO as expressed in the surface ocean temperature field
* NINO-3 region is now the most commonly used SST region for ENSO, but other such as the Wright Index have been used historically in the literature.

**IX. Why Does ENSO State Tend to Oscillate?**

* The short answer is "equatorial ocean dynamics"; something that was poorly understood in the late 60s when Bjerknes did his ENSO work.)
* The key observations were made in the 1970s by Klaus Wyrtki, an oceanographer at the University of Hawaii. Wyrtki had a network of tide gauges in the tropical Pacific which gave records of sea level. In the tropics, monthly average sea level is an excellent substitute for the monthly average depth of the thermocline -- that is, for the thickness of the upper ocean warm layer. Wyrtki showed that an El Nino event is associated (preceded, in fact) by a transfer of warm water from west to east. It is this transfer of warm water to the east that is thought to trigger a warm event.
* But what triggers the movement of waters to the east? Think of the tropical Pacific as a huge tub, with the waters sloshing back and forth. In the cold phase the warm waters are low in the east, so they must be high somewhere else. This is because water is conserved and because warm water is very nearly conserved: there is some heat exchange with the atmosphere, but from the ocean's point of view it doesn't amount to much. (From the atmosphere's point of view its quite a lot -- it is just this rearrangement of the atmospheric heating that sets off the worldwide climate anomalies associated with El Nino.)
* The "somewhere else" that the water level is high is primarily the western tropical Pacific. Eventually this water will return to the east and set off the next warm event. Most immediately, it pushes down the thermocline and raises the temperature of the upwelled waters in the eastern Pacific. The Bjerknes positive feedback takes over: the trade winds weaken and still more warm water flows east and SSTs warm. The main center of atmospheric convection shifts eastward, disrupting the world's "normal" weather patterns.
* The eastward sloshing of warm surface waters overshoots equilibrium. Since there is now more warm water in the east, there is less in the west. Eventually this message (the raised thermocline signal ) is transmitted back to the east and the warm event starts to weaken, to be replaced in turn by a normal to cold phase. And so on, forever (or at least thousands of years, judging from the observational record).
* There is one more wrinkle in the story to point out: part of what makes the oscillation possible is an asymmetry between eastward and westward motions in the ocean ([2-D Animation](http://eesc.columbia.edu/courses/ees/slides/climate/coupledrun2.html)). Along the equator there is a relatively fast eastward (and only eastward) motion called an equatorial Kelvin wave. Peaking somewhat off the equator are westward motions called [Rossby waves](http://eesc.columbia.edu/courses/ees/slides/climate/rossby.gif). These carry the message of the high (say) thermocline in the west, westward to the boundary of the ocean (Philippines, New Guinea, Australia) where they are reflected eastward in the equatorial Kelvin wave. This delay is needed for the oscillation -- without it one would have the amplification in place that Bjerknes contemplated.
* Here is a [3-D animation](http://eesc.columbia.edu/courses/ees/slides/climate/animlg1.gif) (Fig. 26 in powerpoint) the tropical Pacific as it cycles through an El Niño then La Niña event. The surface shown is sea-level (in cm) and the surface is colored according to the SST anomalies associated with each event.

**XI. Kelvin Wave / Rossby Wave Oscillations discussed in Wednesday session.**

**Reading:**

* George Philander (1998) "Is the Temperature Rising?: The Uncertain Science of Global Warming" Chapter 9, pp. 143-157.
* Glantz, M.H. (ed.) et al. "Teleconnections Linking Worldwide Climate Anomalies." Chapter 2, pp. 13-42. (more advanced).
* Article by Steve Zebiak, *The Sciences*, March/April 1989.
* Article by Cane et al, (1994) *Science*, 370, 204-205.
* UCAR, NOAA, *El Nino and Climate Prediction Reports to the Nation*, Spring 1994, No. 3.
* Davis, Mike (2001) Late Victorian Holocausts, El Nino Famines and the Making of the Third World. Verso, London & New York.

**Resources**

* Sources of ENSO information, much of it current:
  + [NOAA ENSO Homepage](http://www.ogp.noaa.gov/enso/).
  + [NOAA/NCEP Climate Prediction Center](http://www.cpc.ncep.noaa.gov/).
  + [International Research Institute for climate prediction](http://iri.ldeo.columbia.edu/).
  + [International Research Institute, Experimental Climate Forecast Division](http://iri.ucsd.edu/).
* Zebiak and Cane, diverse papers.
* Chen et al. (1995) *Science*, V269 (Sept 22, 95), 1699-1702.
* [El Nino and California Precipitation](http://twister.sfsu.edu/elnino/elnino.html).
* [CPC - Data: Current Monthly Atmospheric and SST Index Values](http://nic.fb4.noaa.gov/data/cddb/).
* [Impacts of El Niño and Benefits of El Niño Prediction](http://www.pmel.noaa.gov/toga-tao/el-nino/impacts.html).
* *Science*, 251 (Feb 8 '91) 615.
* *Environmental Science and Technology*. v25 (Feb '91) 210-212.
* *Science*, 248 (Apr 6 '90) 33-34.
* *New York Times*. APR 5 '94, pC4.
* *Oceanus*, V34 (Spring 91), 6-8.
* [Hays, J., **Water: the vital fluid**, April 1996](http://eesc.columbia.edu/courses/ees/lithosphere/hays_tutorial_3/water.html).
* EOS.