ENSO key concepts

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ENSO is an acronym for **"El Niño / Southern Oscillation"**. It is the Earth's **strongest** year-to-year climate fluctuation, and has global impacts. ENSO is a fundamentally coupled ocean-atmosphere phenomenon, involving the troposphere and the upper ocean of the tropical Pacific, and also interacts with climate variations outside the tropical Pacific.

The tropical Pacific has pronounced zonal & meridional **asymmetries**:

1) A **"warm pool"** in the west
2) A **"cold tongue"** in the east (both on & south of equator) & along S. America
3) A rainy Intertropical Convergence Zone (**ITCZ**) that is mostly north of the equator (esp. in the east)
4) Easterly (i.e. westward) **trade winds**, which drive **Ekman upwelling** of cold water along the equator, especially in the central/eastern Pacific.
5) **Sea level** that slopes up toward the west
6) An ocean **thermocline** that slopes down toward the west

"El Niño" (EN) was named by Peruvian fishermen who noticed the arrival of warm coastal currents around Christmas (the time of the "little boy" or Christ child). El Niño eventually lent its name to the exceptional, large-scale tropical Pacific SST warming that occurs (irregularly) every **2 to 8 years**. The **"Southern Oscillation"** (SO) refers to a basin-scale fluctuation in atmospheric surface pressures between the central tropical Pacific (Tahiti) and western tropical Pacific (Darwin, Australia). The weaker this large-scale pressure gradient, the weaker the easterly (i.e. westward) tropical Pacific trade winds. El Niño and the Southern Oscillation are tightly coupled, and usually occur together; hence the name **ENSO**. **La Niña**, the opposite phase of ENSO, has mostly the opposite impacts of El Niño.

Most strong ENSO SST anomalies (SSTAs) peak in the eastern equatorial Pacific (EEqPac), though some events peak as far west as the dateline (180W). **El Niño's SSTAs peak around Nov-Dec, last about a year, and are usually followed by La Niña.** The strongest well-observed El Niños occurred in 1982-83, 1997-98, and 2015-16. There also appears to have been a strong El Nino in 1877-78, that likely contributed to widespread drought and starvation in India, China, Africa, and South America.

ENSO's amplitude and behavior vary from decade to decade. Much of this long-term variation may be random, perturbed by noisy "westerly wind events" in the western equatorial Pacific. On longer timescales, ENSO serves as a major "noisemaker" that complicates detection of decadal-to-centennial climate variations and changes. Paleo proxy records (corals, tree rings, lake sediments, Andes ice cores, cave deposits) suggest that ENSO has existed for thousands (and probably millions) of years. There is proxy evidence of both interdecadal and intercentennial modulation of ENSO, as well as a radiatively-forced trend toward an apparently stronger ENSO since 1980.

Impacts of a strong El Niño:

1) Drier west Pacific → droughts, fires, crop failures
2) Rainier east Pacific → floods, landslides, crop failures, disease
3) Fewer hurricanes in Atlantic, more in Pacific
4) Strengthened Aleutian Low → warmer winters in northern US
5) Extended Pacific jet stream & storm track → cooler/wetter US Gulf states
6) Weaker upwelling of nutrients near equator & S. America → altered food web
7) Changes in Pacific currents → displaced fisheries
8) (After the event) → warmer tropical Indian & Atlantic oceans → further impacts

Key physical concepts:

1) Equatorial ocean **thermocline** (warm layer above cold deep)
2) Rainfall follows **warmest SST**
3) **Winds converge** on warm/rainy/low-pressure zones
4) Equatorial **easterly trade winds** are seeded by Hadley Cell
   - Coriolis force deflects equatorward surface winds toward the west
5) These equatorial easterlies produce **zonal asymmetry**:
   a) **Upwelling** of cold deep water (time scale of days)
   b) Sea surface tilts up to west; **thermocline tilts** down to west (~2 months)
   c) Westward upper-ocean **currents** (within about 2 months)
   d) Poleward off-equatorial **Sverdrup transport** (within about 6 months)
      - Discharges surface heat poleward
      - Driven by cyclonic wind stress curl (easterly trade winds weakest near equator)
      - Wind vorticity input balances poleward planetary vorticity advection
6) Upper-ocean **"internal waves"** (Kelvin, Rossby) alter thermocline depth
   - Thermocline displacement is opposite & much larger than for sea level
7) Upper-ocean equatorial **Kelvin wave**:
   a) Equatorially confined (2S-2N), eastward-propagating
   b) “Geostrophic” in y (slope balances Coriolis); “gravity wave” in x
      - Surface bump, thermocline depression on equator → eastward eqPac currents
   c) Fast (70 days to cross basin)
8) Upper-ocean equatorial long **Rossby waves**:
   a) All latitudes, westward-propagating
   b) Geostrophic balance
      - Surface dip, thermocline elevation off-equator → eastward eqPac currents
   c) Moves at most 1/3 the speed of equatorial Kelvin wave
      - Waves farther from the equator move slower
9) **Waves reflect** at eastern/western boundaries
   a) Western boundary (Indonesia): off-eq RW bump → eq KW bump
   b) Eastern boundary (S. America): eq KW bump → off-eq RW bump
10) Waves gradually adjust thermocline, establish Sverdrup balance

- **Disequilibrium** induced by mismatch of “fast tilt” & “slow Sverdrup” time scales

11) Warm SSTA produces eastward equatorial wind anomaly, slightly to the **west**
    a) Downwelling/eastward current anoms (**zonal-advection & Ekman feedbacks**)
       → in west: more warm water from west, less cold water from below
       → drags warm SSTA westward
    b) Thermocline depth anomaly slopes down to east (**thermocline feedback**)
       → in east: anomalously warm water at depth, upwells toward surface
       → drags warm SSTA eastward

Harbingers of El Niño:

1) Excess heat content available in W Pacific & off-equator
2) Warm SSTA in WEqPac → shifts atmos convection eastward
3) Strong/frequent westerly wind events in WEqPac

El Niño amplifiers ("Bjerknes positive feedbacks")

1) Weaker westward trade winds →
   weaker upwelling of subsurface cold water, weaker thermocline tilt
   → warmer/weaker upwelling in EEqPac
   → warmer EEqPac → weakens trade winds further
2) Warm pool also sloshes eastward (warm zonal advection)
3) Weaker winds → reduced evaporative cooling of SST in central Pacific

El Niño dampers ("negative feedbacks")

Warmer SST in EEqPac →
- Enhanced cooling due to cloud shading in the EEqPac
- Enhanced evaporative cooling in the EEqPac
- Background upwelling "flushes SSTAs poleward"
  (replaced with "unperturbed" water from below)
- Tropical instability waves (TIWs) near equator
  laterally “stir in” unperturbed off-equatorial SST

El Niño transitioners

1) Poleward Sverdrup discharge of equatorial surface heat →
   - gradual elevation (cooling) of equatorial thermocline
     → eventually cools SST through upwelling
2) DJF southward shift of westerly wind anomalies out of equatorial waveguide →
   - helps re-establish thermocline slope & cold tongue

Present-day statistical and dynamical models, when initialized using observations of tropical Pacific SST, sea level, ocean heat content, and winds, can **forecast ENSO 1-2 years in advance**.

Models suggest that **future tropical Pacific climate** may be "loosely" more El Niño-like:

1) Equatorial SST warms more than off-equator

- but thermodynamically from above, not dynamically from below → *enhanced* dT/dz!
2) Weaker trade winds
   - from atmospheric moistening, coupled to dSST/dx
3) West Pacific rainfall expands eastward

But these model-projected trends have yet to emerge in observations.

Model projections differ on future of ENSO, due to competing feedback changes:
1) Tropical upper ocean more thermally stratified →
   zonal/vertical advection has stronger effect on SST
2) But weaker upwelling →
   subsurface thermal anomalies have weaker effect on SST
3) Changes in cloud feedbacks are less clear

Model projections mostly agree that **ENSO's future rainfall anomalies will strengthen** in most places.

Research frontiers:
1) Improved models (resolution, parameterizations, ensembles)
2) Improved understanding (conceptual models, metrics, machine learning, AI)
3) Enhanced observations (autonomous & moored buoys, satellites)