The Role of the NECC in a Strong El Niño

or

A new/old Theory of the El Niño

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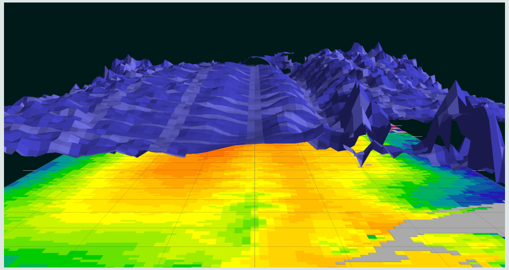
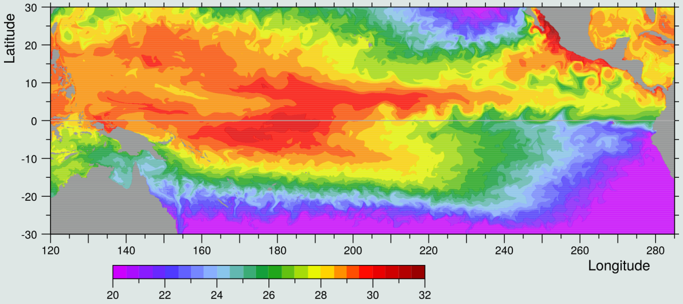
This powerpoint style presentation was prepared for the EGU Assembly 2020.

This expanded file includes (a) notes on each slide, (b) questions asked at EGU2020, (c) expanded answers and (d) my questions.





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Background *(Where are we coming from?)*

1. The study is based on analysis of data from Andrew Coward's high-resolution (1/12°) global run of the Nemo ocean model. The model ran from 1957 to 2016, forced by ECMWF reanalysis fields. There were 66 model levels, 24 in the top 300m of ocean.

* The study reported here looked in detail at the periods 1980-1995 and 1995-2000. These include the strong El Niños of 1982-1983 and 1997-1998.

2. Strong El Niños involve the movement of deep atmospheric convection from Indonesia and the western Pacific to the central and eastern Pacific.

* Evans and Webster (2014) showed that deep atmospheric convection only occurs when sea surface temperatures (SST) are above 28°C.

* The study focuses on ocean processes that may generate such high SST values in the central and eastern Pacific

Atmospheric profile for SST of 25°C and 30°C

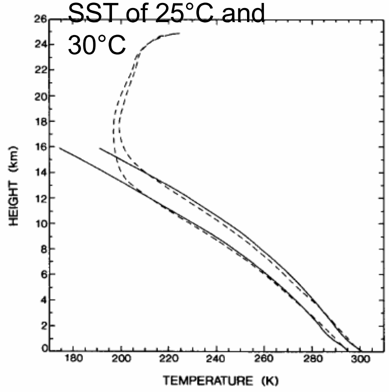

FIG. 10. Temperature as a function of height averaged over time and x, for 25° and 30°C cases (dashed lines). Adiabats computed as described in text are displayed by solid lines.

Held et al 1993

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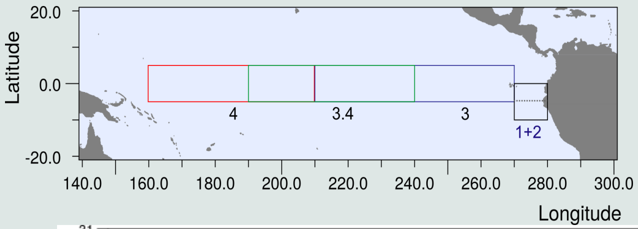
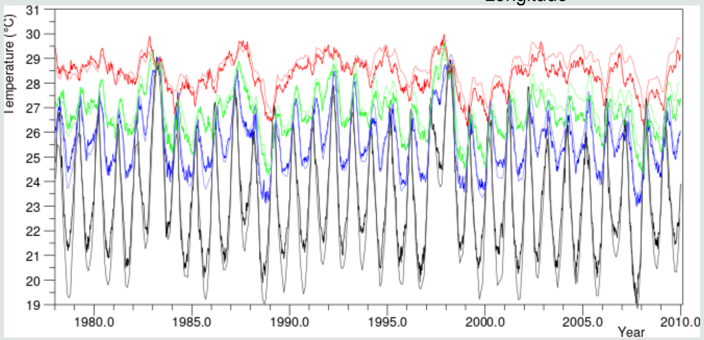
Validation *(Is the model any good?)*

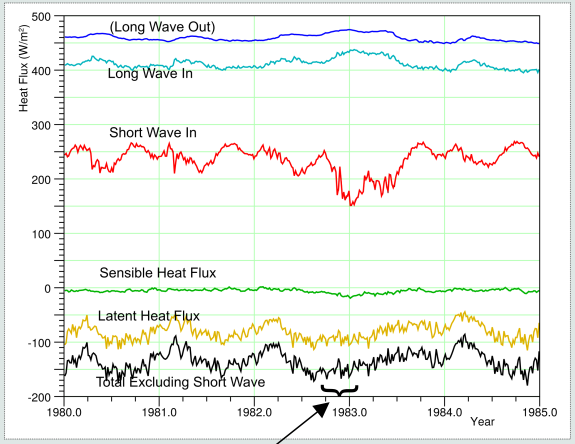


1. The model was first validated (Webb 2016) against observed sea surface temperatures (SST) in the Pacific NINO regions (Top figure)



2. The agreement was good, even during the strong El Niños of 1982-83 and 1997-98 (thick lines model, thin observations).

3. An analysis of the surface fluxes (lower figure) showed that increased temperatures during the strong El Niños were not due to a feedback from the real SST values via the atmospheric boundary layer.



Fluxes in Region 3.4

Heat loss from ocean is slightly larger while El Niño is developing

4. The analysis also showed that the high SST values during the strong El Niños were not due to local heating of the ocean. The alternative was the advection of high SST values by ocean currents.

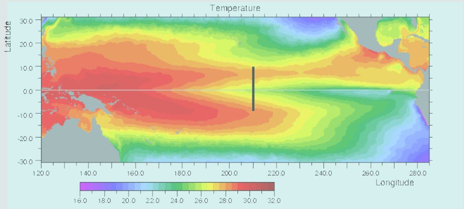
Advection *(Where and when is warm water transported across the ocean?)*

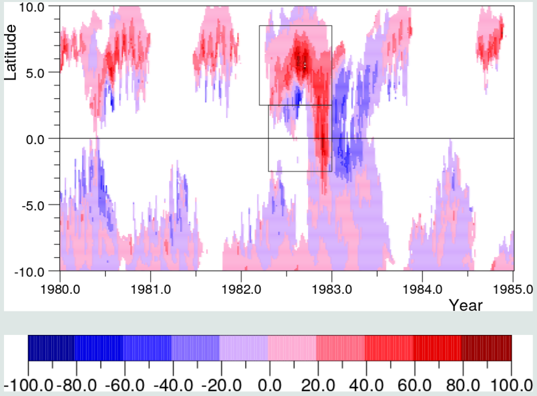
1. Model archive data was used to calculate the transport of water across lines of longitude. The middle figure shows the transport of water with a temperature greater than 28°C across 210°E.

2. It shows that during the growth of the 1983-84 El Niño, the bulk of the transport of warm water occurred at the latitudes of the North Equatorial Counter Current (NECC). This was active during the whole of the second half of 1982. Warm water was only advected near the Equator during the last few weeks of the year.

3. Comparable results were obtained at other longitudes.

4. The total transport figures give a similar picture, at 210°E the NECC transporting almost four times that of the current in the Equatorial Wave Guide (2.5°S-2.5°N).





Vertically integrated flux (m2s-1)
10 m2s-1 ≈ 1.1 Sv / °latitude

Total Transport (m^3)

2.5°N-8.5°N : 310×10^{12} m^3
2.5°S-2.5°N : 79×10^{12} m^3

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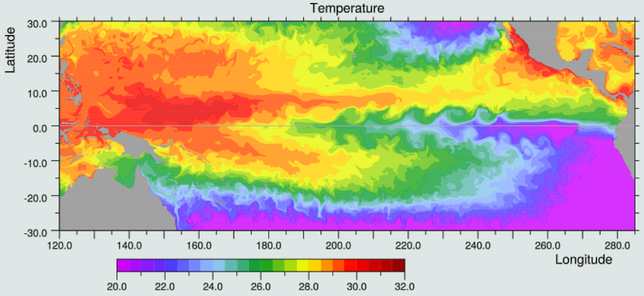
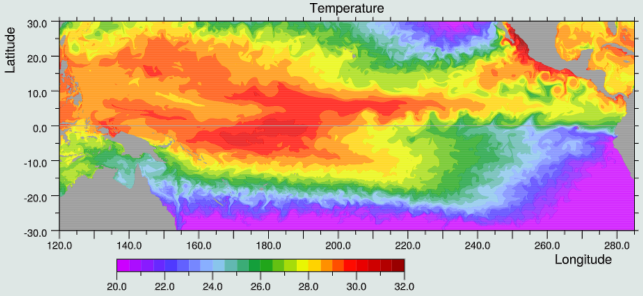
Tropical Instability Eddies *(Why doesn't an El Niño occur every year?)*

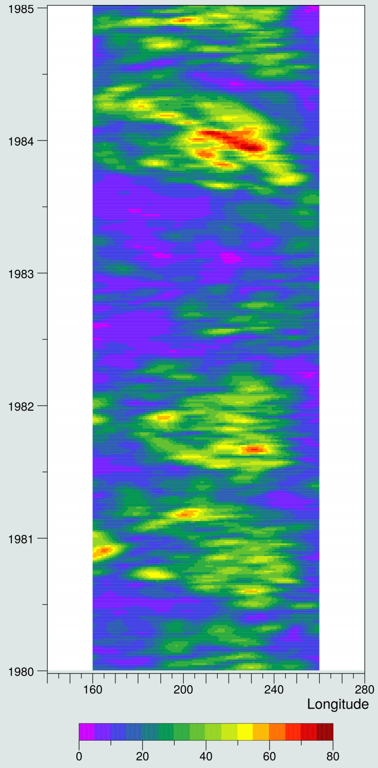
27 September 1981



27 September 1982



Transport Variability (m^2s^{-1}) at 6°N
50 m^2s^{-1} ≈ 5.5 Sv/degree



1. Given that the NECC can carry warm water from the warm pool of the western Pacific right across the ocean, and that is present every year, why isn't there an El Niño every year?

2. The SST values in September 1981 and 1982 give a clue - the Tropical Instability Eddies (or waves) in the central Pacific being much weaker during the growth of the 1982-83 El Niño.

3. This is confirmed by plots of the north-south current variance at the latitudes of the NECC. These show a region of low variance which extends eastwards across the ocean during the growth phase of each strong El Niño.

4. The results imply that in a normal year the core temperature of the NECC is diluted by the turbulence due to the instability eddies, but as an El Niño develops eastward these are reduced in strength, allowing the NECC to transport warm surface water further eastwards.

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Particle Tracking *(Where does the water go?)*

1. Further evidence for the way water is mixed out of the NECC comes from particle tracking.

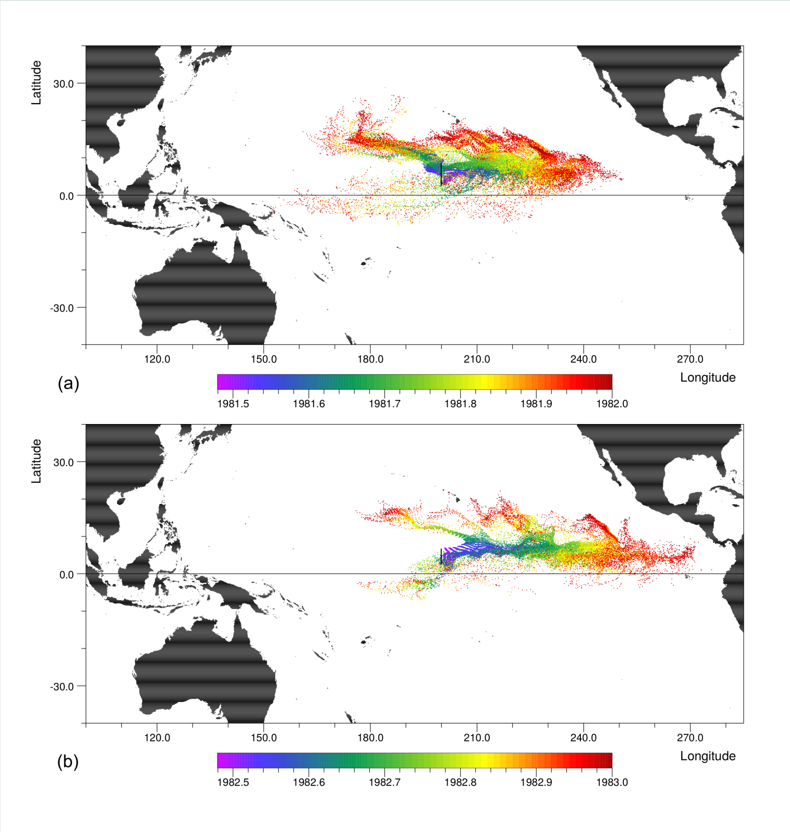
2. In the top figure, particles were seeded in model cells with temperatures above 27.8°C at longitude 200E (black line). The dots show the location of the particles at five day intervals during the rest of the year. Warmer colours occur later in the year.

3. For the lower figure, particles were seeded in 1982, during the growth stage of the strong 1982-83 El Niño. Whereas in 1981 the temperatures at 200°E only reached 28°C, here all the seeded cells had temperatures above 29C.

4. The figures show that while the El Niño was developing, the NECC suffered from less turbulent mixing. As a result much of the warm core of the current reached the far eastern Pacific.

- where it was near the right latitude to stimulate deep atmospheric convection in the atmospheric Inter-Tropical Convergence Zone (ITCZ).

Start from June 1981 : a ‘typical’ year
Seeded cells T>27.8°C



Start from June 1982 : a growing El Niño
Seeded cells T>29°C

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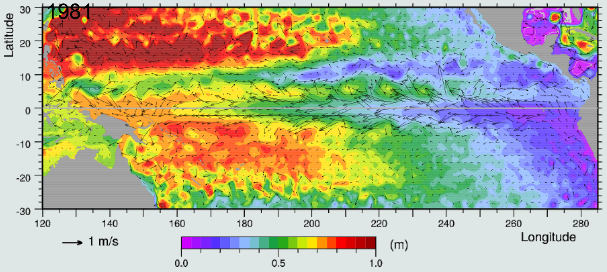
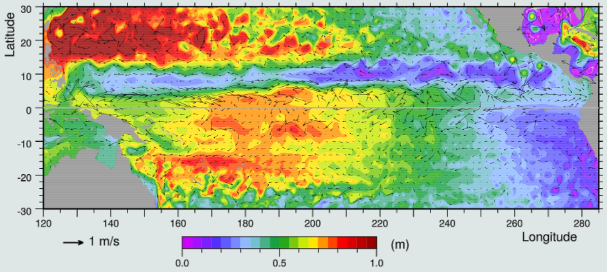
Sea Level *(What controls the strength of the NECC?)*

Model Sea Level : 27 September 1981

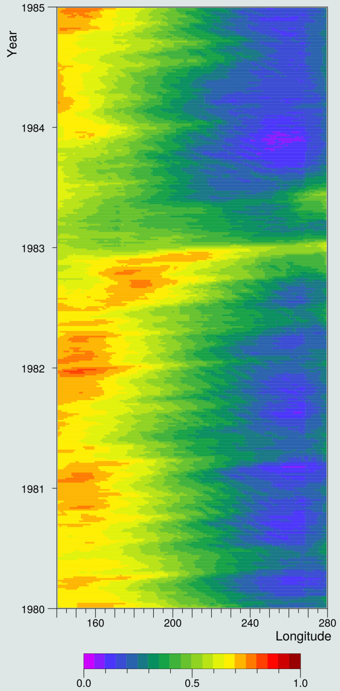


27 September 1982

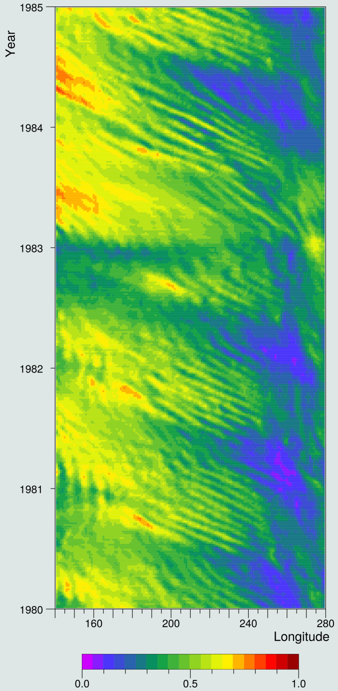


Time series of sea levels (m)

Equator



6°N



1. The NECC is a geostrophic current running along the southern slope of the North Equatorial Trough (6°N-10°N). Its strength depends on the depth of the trough, the height of the ridge lying near the Equator and the latitude of the slope – all of which vary in time. Differences between a normal and a strong El Niño year are shown above.

2. The depth and southern slope of the trough is affected by the annual Rossby wave. This is generated in the east Pacific near the start of each year, the wave at 6°N arriving in the west in mid-summer. The wave travels more slowly at higher latitudes.

3. The figures on the right show that in years when a strong El Niño is growing the sea level in the west at 6°N is lower than normal – just at the time that the annual Rossby wave arrives. They also show that the high sea levels on the Equator move into the central Pacific, between the regions of easterly and westerly winds. These changes are also seen in the (above) sea level plots for September 1981 and 1982.

4. Wyrtki (1978) was the first to report the connection between strong El Niño's and the sea level difference across the NECC in the western Pacific - based on his analysis of sea level at island stations.

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A Growing Strong El Niño *(What should I look out for in the ocean?)*

1. The figure shows sea level and surface currents on the 29 March, 29 June, 27 September and 31 December, during the growth phase of the strong 1982-1983 El Niño.

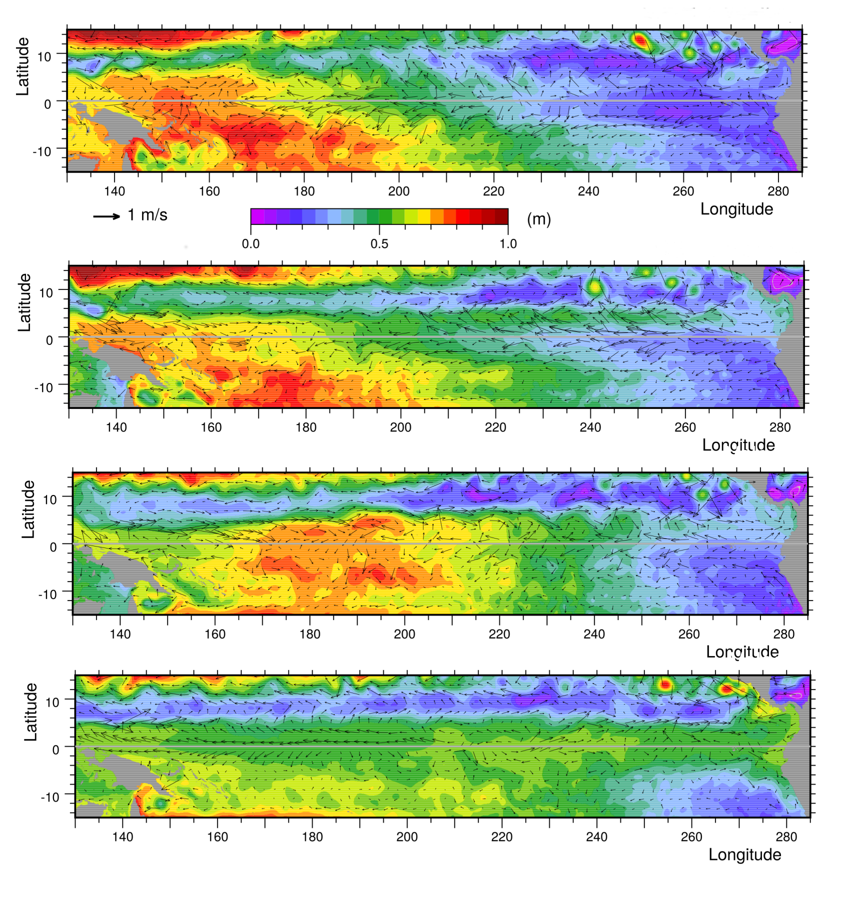
2. They show the development of low sea levels in the western Pacific in mid-year, the movement of high sea levels on the Equator into the central Pacific and the resulting increase in the strength of the NECC at all longitudes during the second half of the year.

3. The increased strength of the NECC in the west coincides with the increased transport of warm pool water, initially into the central Pacific and finally into the far eastern Pacific - the warm water finally arriving around Christmas (El Niño).

4. The movement of the warm pool water is associated with changes in the winds and changes in sea level near the Equator, presumably due to the deep atmospheric convection moving away from Indonesia and the western Pacific towards the central and eastern Pacific.

As the warm water crosses the ocean, the varying speed of the annual Rossby waves takes the NECC and the warm water to the north. Here it is closer to the ITCZ where the atmosphere is most unstable

5. On the equator, the westward flowing Equatorial Current decays, a result of the reduced easterly winds. This results in weaker tropical instability eddies and the increased transport of warm water by the NECC discussed earlier.



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Other Theories

(What about theory X : Isn't the NECC just a side issue?)

1. Most El Niño theories involve the Equatorial Wave Guide.

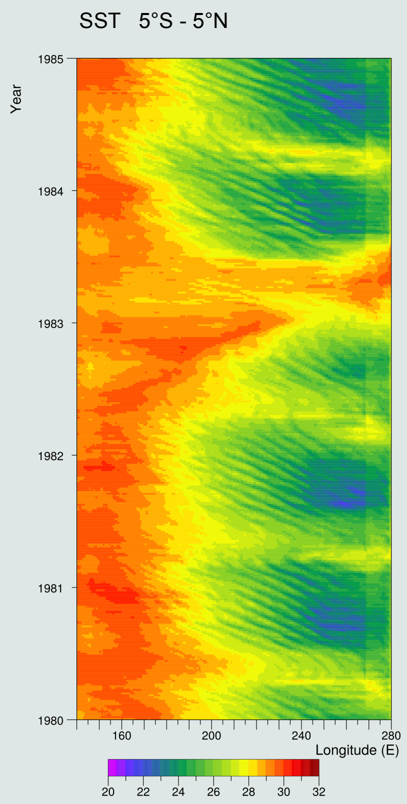
2. In the present study the latitudes of the Equatorial Wave Guide are important for the reduced strength of the Equatorial Current and the movement of high sea levels into the central Pacific. The latitude of the wave guide boundary is also important because of the rapid change in the Coriolis term with latitude, affecting both geostrophic currents and Ekman pumping.

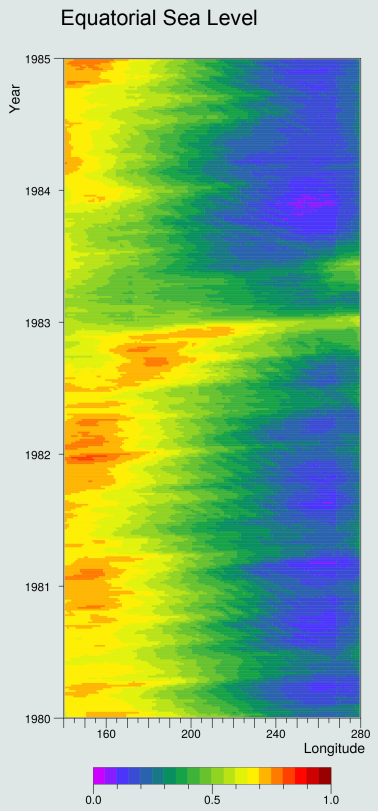
But in other respects the wave guide had no significant effect.

3. As an example, the two figures on the right show the average temperature between 5°S and 5°N (the band to construct the NINO indices) and sea level at the Equator.

The sea level picture shows a series of Equatorial Kelvin Waves during the autumn of 1982. The winds that force them occur at longitudes where the temperature is already near its maximum – so they are a result of the developing El Niño.

Note that as they propagate eastwards, the Kelvin waves have no significant effect on the SST field. Also SST values near South America only increase significantly after the end of 1982. As with the other figures shown, similar results were also found during the strong 1997-1998 El Niño.





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Conclusions *(and some hypotheses)*

1. The NECC is the dominant current responsible for transporting warm ocean waters westwards during the development of a strong El Niño.

2. The initial stage of development is associated with a region of low sea level which develops in the western Pacific in mid-year near 6°N.

3. The further development of the El Niño is aided by the timing of the annual Rossby wave which enhances the strength of the NECC during the autumn months.

4. During this period the Equatorial Current is reduced in strength. This reduces the strength of tropical instability eddies (TIEs).

5. The reduction in the strength of TIEs, reduces horizontal mixing in the core of the NECC, allowing it to transport warm water much further east.

6. The combination of these processes, together with the associated changes in deep atmospheric convection and circulation, cause the El Niño.

References

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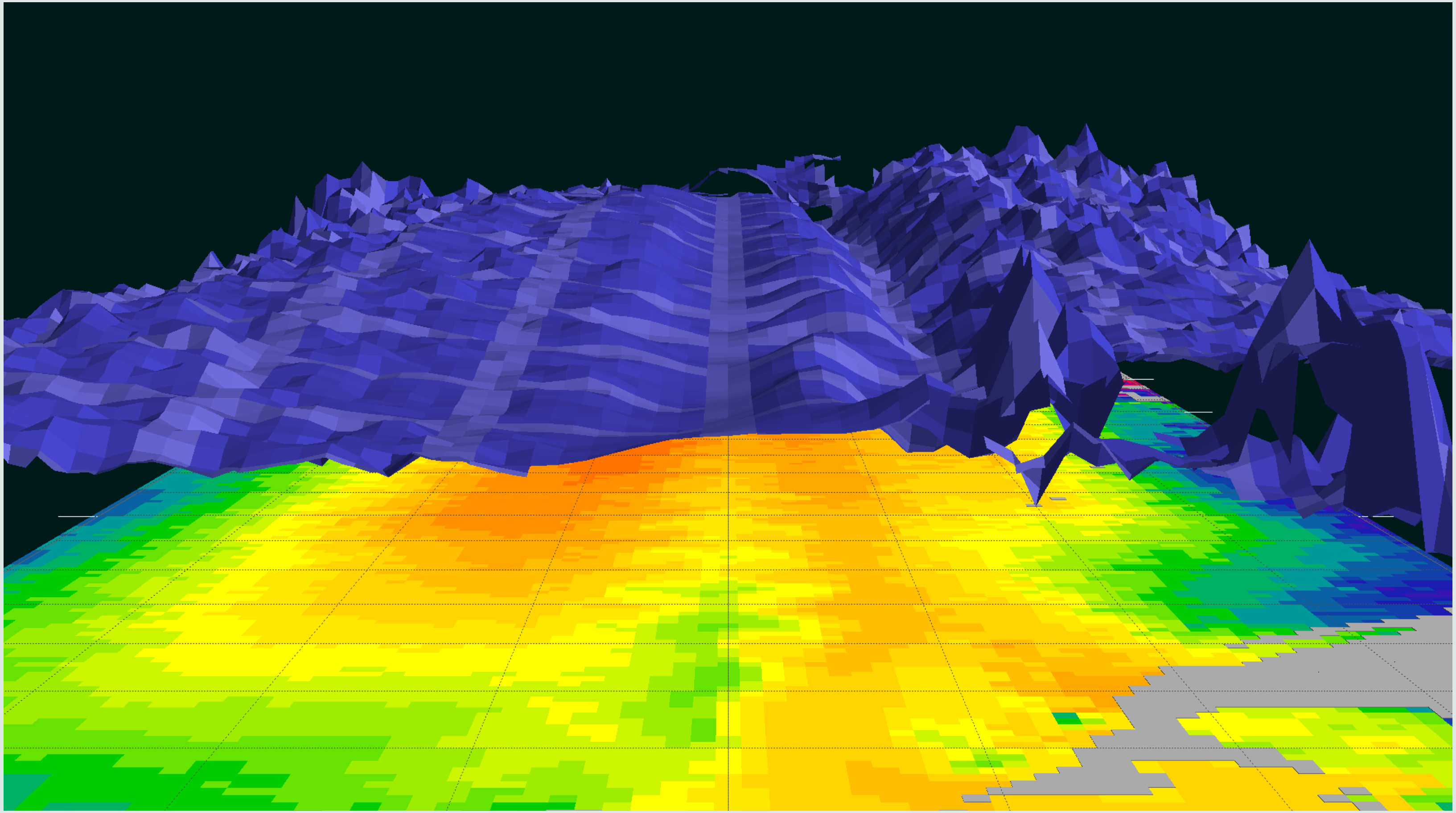
Webb, D.J., Coward, A.C. and Snaith H.M. (2020) A comparison of Ocean Model Data and Satellite Observations of features affecting the growth of the NECC during the strong 1997-98 El Niño. Ocean Science (Accepted for Publication).

Video of a seminar on this study is available:

Title: El Niño : Ocean Mechanisms

Link: https://www.youtube.com/watch?v=EbL44NRBJbY

Pacific SSH and SST



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Questions Asked

Unfortunately I did not take a screenshot at the end of my talk - but four of the questions were related to:

(1) The time taken for the NECC to carry water across the Pacific

(2) The model resolution necessary to accurately represent the NECC in climate models

(3) Non-linearities

(4) How I reconciled the ideas reported here with theories which emphasise the role of processes occurring on and near the Equator?

In the following pages I again answer the questions but this time in the more expanded way appropriate to a proper poster session.

I would have also used a poster session to ask my own questions so:

(5) My question to those who work with coupled models and/or study the atmosphere during an E Niño.

1. The time taken for the NECC to carry water right across the Pacific

I emphasis ‘right across the Pacific’ because with a group of old time oceanographers my strong El Niño would be a ‘Classic El Niño’. It was the fisheries problems off Peru around Christmas which gave the phenomena its name and got them started on the research.

The present work shows that a strong El Niño occurs when (a) something increases the transport of warm water by the NECC in the western Pacific and (b) that the timing is right for the annual Rossby waves, at the different latitudes, to give the NECC an extra impetus right across the Pacific.

The model showed that the Rossby waves are generated in the eastern Pacific early in the year and the fastest waves, at around 6°N, arrive in the western Pacific around mid-year. In most years they tend to decay in amplitude rapidly after passing the dateline but in 1982 and 1997 there was an extra drop in sea level, in the far west, just before mid-year and this gave the NECC the extra impetus to get significant amounts of warm water moving east.

Once this happens, the moving centre of atmospheric convection, the changed winds on the Equator and the resulting reduction in the tropical instability eddies, allow the NECC to transport water >28°C much further to the east – arriving off South America around Christmas. So, sorry for the roundabout answer, but the time required is around six months.

You might ask:

* *If the initial impetus does not occur around mid-year what happens?*

  There is no annual Rossby wave to help – so I guess you get a mid-ocean El Niño.

* *And what gives NECC its initial impetus?*

  I do not know. What is your best bet? *(Madden-Julian Oscillation, …, …)* . I’d like to know – but it needs to do something special around 6°N-8°N in the western Pacific

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2. The model resolution necessary to accurately represent the NECC in climate models

The width of the North Equatorial Trough is around four degrees, so working on the basis of a minimum of ten points per wavelength this means that a one degree ocean grid is too coarse, half a degree would be better. My model with a ¼ degree grid represents the trough well and does a reasonable job with the tropical instability eddies.

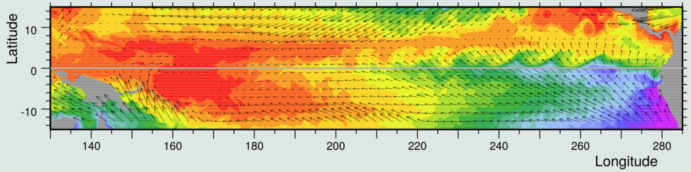
So if you are interested in studying the difference between the different types of El Niño you probably need an ocean model with half a degree resolution or better.

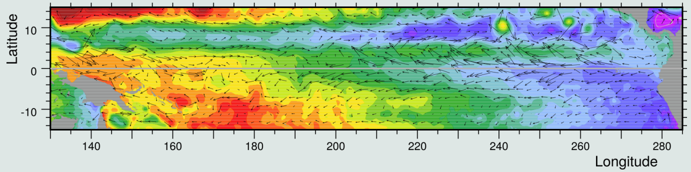
For the atmospheric model you probably need something similar. As I understand it the North Equatorial Trough is generated by the wind shear seen in the bottom figure (surface wind and total cloud water).

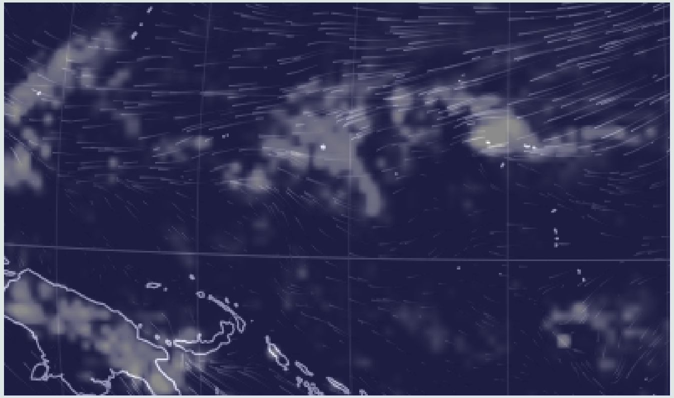
The shear causes Ekman suction and it is this, averaged over a period of years which generates the trough – so to get a reasonable trough the atmospheric model needs to generate similar jumps in the wind stress. So again I suspect that half a degree resolution or better to study the phenomena.

Shorter term changes, like the latitude of strong shear also need to be resolved. The annual Rossby wave is generated in the eastern Pacific. It is possible that some of this is due to flow across the isthmus early each year – so resolving gaps in the mountain ranges may be of concern.

If (today's) figure had shown a significant wind along the Equator, I would have to say that it is the difference from this which is important. A constant easterly at all latitudes generates a sea surface slope from east to west, but no net northward transport – any Ekman transport away from the Equator being balanced by an equal geostrophic flow towards the Equator due to the slope.







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3. Non-linearities

This is a broad subject which could refer to many aspects of strong El Ninos.

(1) The basic generation mechanism of the North Equatorial Trough and NECC, i.e. the processes of Ekman transport, Ekman suction and geostrophy are primarily linear processes.

(2) The tropical instability eddies are nonlinear - the result of barotropic and/or baroclinic instabilities. There are papers by Philander (1978), Cox(1980) and Luther and Johnson (1990) but they disagree on the form of the instability or the currents involved. In the model results I have looked at, the eddies seem to decay as soon as the Equatorial Current fails - although the current shear between the Equator and the core latitude of the NECC may remain high.

(3) Once the ocean surface temperatures rise above 26°C, the evaporative flux into the atmosphere increases rapidly with temperature – although it does depend on wind speed as well. Because of this effect, it may be difficult for the maximum SST temperatures to rise far above 28°C*, say, even with increased CO_2, although there is nothing to stop an increase in the area of ocean with the warmest temperatures or the total flux of heat (especially latent heat) into the atmosphere.

(4) The most non-linear aspect of all appears to be the relationship between the sea surface temperature and the height of atmospheric convection. As pointed out by Evans and Webster (2014) the tropical atmosphere roughly follows the wet adiabatic so it is only fully saturated air at sea level that is above a critical temperature which will be successful. Note however that the critical temperature does depend on sea level pressure, being lower when the sea level pressure is low.

*Note: In September 1988, north of New Guinea, we had a streamlined fish measuring temperature and salinity in the top few centimetres of ocean. During an initial period of low winds, afternoon SST temperatures above 30°C were common. One day it passed 32°C but the wind had dropped to zero and the ocean surface was glassy. During the later windier period temperatures were nearer 29°C, dropping at one point to below 28°C. (King et al, IOSDL Report No 291, Fig 3 : https://noc.ac.uk/publication/115310).

4. How do I reconciled the ideas reported here with theories which emphasise the role of processes occurring on and near the Equator?

As they say – a really good question : and my answer is that I don't – except those that involve believable advection.

The equatorial wave guide theories seem to fall into three camps. These are

1. *Easterly winds result in high sea levels and a large pool of warm water in the western Pacific. When the winds relax this sloshes across to the other side of the ocean – causing the El Niño*.

This suffers from the 'Rubber Duck' problem. When water sloshes from one side (or bath end) to the other, only the wave moves - the warm water (and the ducks) stay in the roughly the same position. So western Pacific warm pool water would never move to the central or eastern Pacific.

2. *Westerly wind bursts generate a series of equatorial Kelvin waves which carry warm water eastwards along the Equator.*

This has the same problem as (1). Equatorial Kelvin waves can only transport mass and heat via the Stokes drift. Near the surface the drift has been calculated to be as high as 34 cm/sec but this is not enough to seriously reverse the westward flowing Equatorial Current (see notes).

3. Westerly wind bursts generate equatorial Kelvin waves which, when they arrive in the eastern Pacific, increase the thermocline thickness and result in a warming the ocean surface layer.

So the warm pool water does not move? It is possible that the stokes drift could thicken the thermocline, but (for example in 1997) the main thickening and warming occurs after the two main waves generated by westerly wind bursts? So where does the later major thickening and warming come from? [Once the cold undercurrent stops in the eastern equatorial Pacific, local water replaces it. Cold water is no longer upwelled. Surface temperatures may jump from 19°C to 26°C, with similar dramatic changes in sea level – but not enough to trigger deep atmospheric convection.]

So when It comes down to it – I only believe in advection. There is some, mainly north-south, advection due to Ekman transport and there may be a small role for stokes drift but the main processes are local advection due to the winds on and along the Equator and geostrophic advection due to the NECC, other currents and eddies like the tropical instability eddies.

My Question?

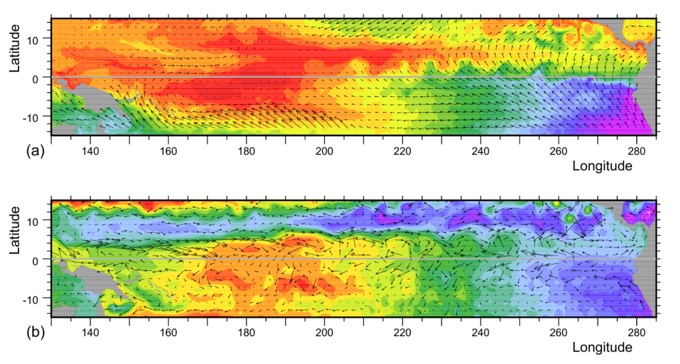
If we were talking during a poster session my question to you would be a variation of "Why are atmospheric El Niño studies so hung up about sea surface temperature (SST) along the Equator?".

I ask this because SST values along the Equator are usually low, a result of the upwelling of cold Equatorial Undercurrent water. At the surface warmer water is usually found to the north, nearer the ITCZ – where deep atmospheric convection does occur – or nearer the SPCZ. So I am surprised that analyses of, say, the CMIP5 runs do not concentrate on the representation of deep convection in the different models, ask where it occurs, the air temperatures, humidity and atmospheric pressure near the sea surface when it occurs and how these change during El Niño type events and/or during global warming?

Now I agree that, once an El Niño has become established, it can generate a region of high temperatures and high sea level on the Equator in the central ocean and this may be a good measure that an El Niño is present. However it says little about the physics.

The problem is that the high SST region is usually an area of low winds with the high sea level supported by westerlies flowing into the region from the west and easterlies from the east.

Now I agree that when a high SST region generates low atmospheric pressure to the north or south, there will be westerly winds on the equator and these bursts will, while the event lasts, move water further east. However as I understand it these are fairly rare short lived events and I cannot see them moving such patches of warm water from New Guinea to the central Pacific (let alone to South America).



SST (above) and SSH (below) from September 1982 (Webb 2018, Fig. 24)

What I can imagine is winds on the equator flowing towards a convection region to the east, situated either in the ITCZ or SPCZ. Such winds will have a westerly component and if they dominate the average over a couple of months they could shift water eastwards along the Equator. So I see the convection regions in models and reality as being the key features to track – not just SST on the Equator.

So is this wrong? - and if so what is the full story?

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or

A new/old Theory of the El Niño

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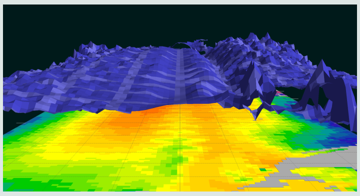
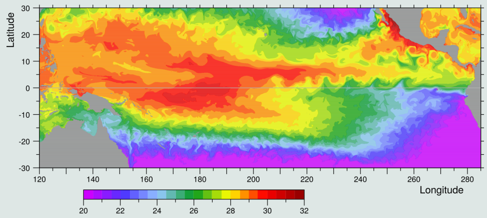
This powerpoint style presentation was prepared for the EGU Assembly 2020.

This expanded file includes (a) notes on each slide, (b) questions asked at EGU2020, (c) expanded answers and (d) my questions.





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Background *(Where are we coming from?)*

1. The study is based on analysis of data from Andrew Coward's high-resolution (1/12°) global run of the Nemo ocean model. The model ran from 1957 to 2016, forced by ECMWF reanalysis fields. There were 66 model levels, 24 in the top 300m of ocean.

* The study reported here looked in detail at the periods 1980-1995 and 1995-2000. These include the strong El Niños of 1982-1983 and 1997-1998.

2. Strong El Niños involve the movement of deep atmospheric convection from Indonesia and the western Pacific to the central and eastern Pacific.

* Evans and Webster (2014) showed that deep atmospheric convection only occurs when sea surface temperatures (SST) are above 28°C.

* The study focuses on ocean processes that may generate such high SST values in the central and eastern Pacific

Atmospheric profile for SST of 25°C and 30°C

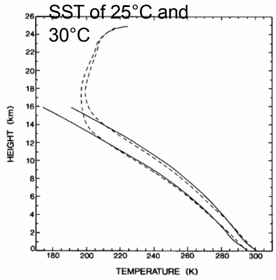


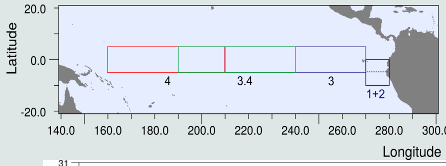
FIG. 10. Temperature as a function of height averaged over time and x, for 25° and 30°C cases (dashed lines). Adiabats computed as described in text are displayed by solid lines.

Held et al 1993

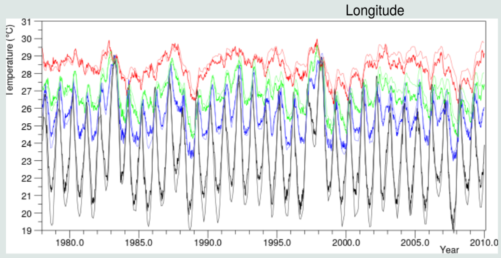
The project started when I became involved in validating Andrew Cowards high resolution NEMO run. As most of the work at NOC concerned the Atlantic I thought it would be useful to work on the Pacific – where I have some history with both modelling and sea-going studies.

It also gave me a chance for me to understand the El Niño from my own point of view - as a theoretical physicist concerned primarily with the ocean but also with a wide interest in other branches of physics and geophysics.

Validation *(Is the model any good?)*



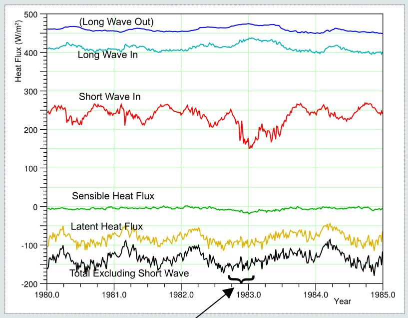
1. The model was first validated (Webb 2016) against observed sea surface temperatures (SST) in the Pacific NINO regions (Top figure)



2. The agreement was good, even during the strong El Niños of 1982-83 and 1997-98 (thick lines model, thin observations).

3. An analysis of the surface fluxes (lower figure) showed that increased temperatures during the strong El Niños were not due to a feedback from the real SST values via the atmospheric boundary layer.

4. The analysis also showed that the high SST values during the strong El Niños were not due to local heating of the ocean. The alternative was the advection of high SST values by ocean currents.



Fluxes in Region 3.4

Heat loss from ocean is slightly larger while El Niño is developing

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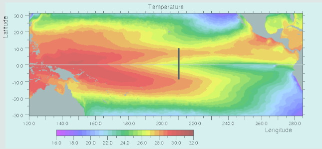
The validation phases was critical to the study. As the lead developer of the OCCAM global ocean model, I had been unhappy about the change to NEMO.

However the French interest in the tropical Pacific has meant that the near surface equatorial current systems are well resolved in the NEMO model and I have been pleasantly surprised by the quality of the results.

It was these results which convinced me to stop validating the model and instead start using it as a research tool to understand the physics involved in the El Niño system.

Advection *(Where and when is warm water transported across the ocean?)*

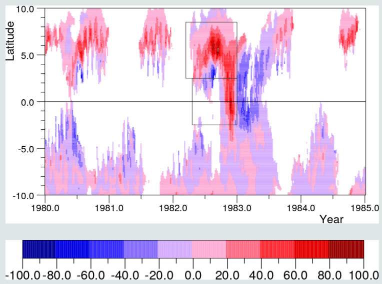


1. Model archive data was used to calculate the transport of water across lines of longitude. The middle figure shows the transport of water with a temperature greater than 28°C across 210°E.

2. It shows that during the growth of the 1983-84 El Niño, the bulk of the transport of warm water occurred at the latitudes of the North Equatorial Counter Current (NECC). This was active during the whole of the second half of 1982. Warm water was only advected near the Equator during the last few weeks of the year.

3. Comparable results were obtained at other longitudes.

4. The total transport figures give a similar picture, at 210°E the NECC transporting almost four times that of the current in the Equatorial Wave Guide (2.5°S-2.5°N).



Vertically integrated flux (m2s-1)
10 m2s-1 ≈ 1.1 Sv / °latitude

Total Transport (m^3)

2.5°N-8.5°N : 310×10^{12} m^3
2.5°S-2.5°N : 79×10^{12} m^3

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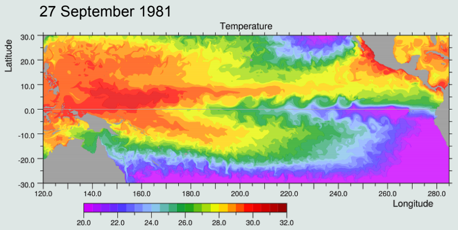
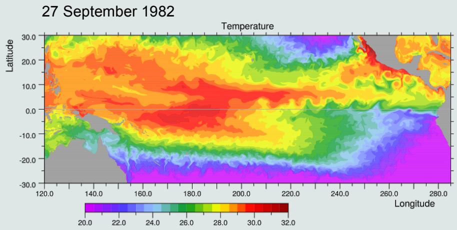
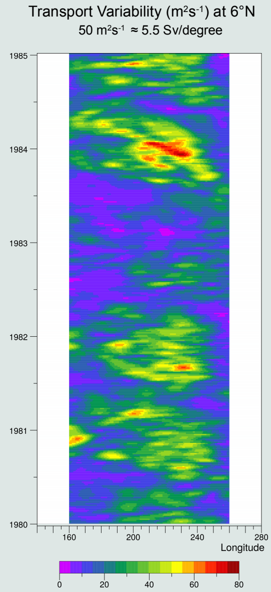
Up to this point I was expecting the Equatorial Wave Guide to dominate the transport of warm water across the Pacific.

The results surprised me and made me start thinking - first could the model really be so wrong? And later - could the standard theories really be so wrong?

Tropical Instability Eddies *(Why doesn't an El Niño occur every year?)*







1. Given that the NECC can carry warm water from the warm pool of the western Pacific right across the ocean, and that is present every year, why isn't there an El Niño every year?

2. The SST values in September 1981 and 1982 give a clue - the Tropical Instability Eddies (or waves) in the central Pacific being much weaker during the growth of the 1982-83 El Niño.

3. This is confirmed by plots of the north-south current variance at the latitudes of the NECC. These show a region of low variance which extends eastwards across the ocean during the growth phase of each strong El Niño.

4. The results imply that in a normal year the core temperature of the NECC is diluted by the turbulence due to the instability eddies, but as an El Niño develops eastward these are reduced in strength, allowing the NECC to transport warm surface water further eastwards.

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The figure on the right finally convinced me that I had a hypothesis which could be quantitatively justified.

Recently with colleagues I repeated a similar analysis using satellite measurements of the Pacific (Webb et al 2020). Most of the comparisons between model and observations showed good agreement. Unfortunately the the variance signal, calculated from the satellite SSH field and assuming geostrophy, is not so clear.

However the model results are so dramatic that I think it is unlikely that the idea is completely wrong.

Particle Tracking *(Where does the water go?)*

1. Further evidence for the way water is mixed out of the NECC comes from particle tracking.

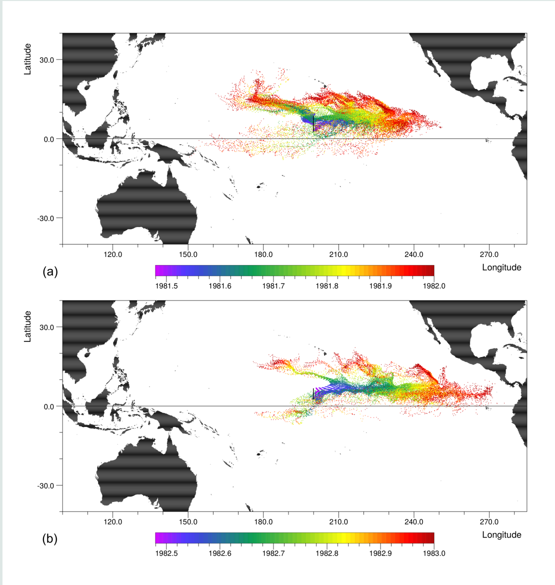
2. In the top figure, particles were seeded in model cells with temperatures above 27.8°C at longitude 200E (black line). The dots show the location of the particles at five day intervals during the rest of the year. Warmer colours occur later in the year.

3. For the lower figure, particles were seeded in 1982, during the growth stage of the strong 1982-83 El Niño. Whereas in 1981 the temperatures at 200°E only reached 28°C, here all the seeded cells had temperatures above 29C.

4. The figures show that while the El Niño was developing, the NECC suffered from less turbulent mixing. As a result much of the warm core of the current reached the far eastern Pacific.

- where it was near the right latitude to stimulate deep atmospheric convection in the atmospheric Inter-Tropical Convergence Zone (ITCZ).

Start from June 1981 : a 'typical' year
Seeded cells T>27.8°C



Start from June 1982 : a growing El Niño
Seeded cells T>29°C

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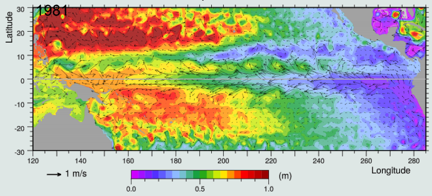
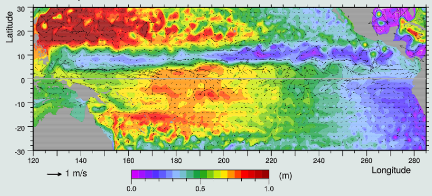
I thought this was a nice test. Fisheries data from Peru indicates that during an El Niño, water near the coast comes from north of the Galapagos – presumably displaced by the NECC water masses tracked here.

Sea Level *(What controls the strength of the NECC?)*

Model Sea Level : 27 September 1981

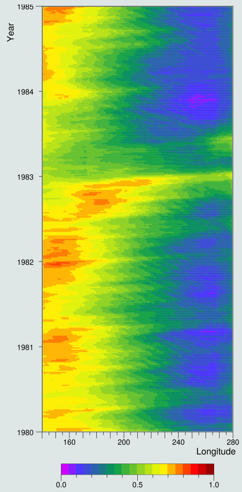


27 September 1982

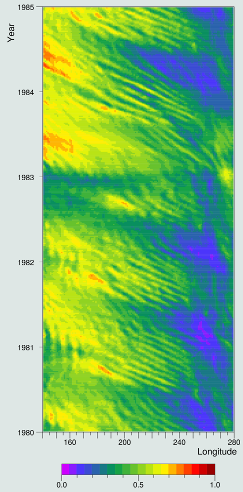


Time series of sea levels (m) at

Equator



6°N



1. The NECC is a geostrophic current running along the southern slope of the North Equatorial Trough (6°N-10°N). Its strength depends on the depth of the trough, the height of the ridge lying near the Equator and the latitude of the slope – all of which vary in time. Differences between a normal and a strong El Niño year are shown above.

2. The depth and southern slope of the trough is affected by the annual Rossby wave. This is generated in the east Pacific near the start of each year, the wave at 6°N arriving in the west in mid-summer. The wave travels more slowly at higher latitudes.

3. The figures on the right show that in years when a strong El Niño is growing the sea level in the west at 6°N is lower than normal – just at the time that the annual Rossby wave arrives. They also show that the high sea levels on the Equator move into the central Pacific, between the regions of easterly and westerly winds. These changes are also seen in the (above) sea level plots for September 1981 and 1982.

4. Wyrtki (1978) was the first to report the connection between strong El Niño's and the sea level difference across the NECC in the western Pacific - based on his analysis of sea level at island stations.

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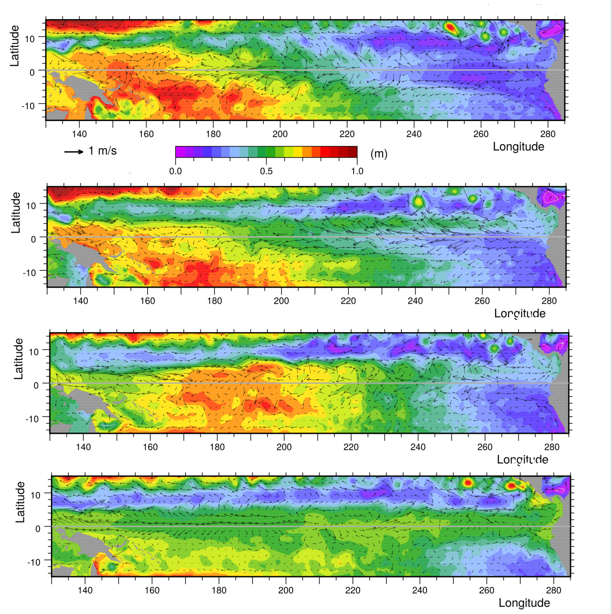
The development of regions of high sea level in the central Pacific during an El Niño has been discussed previously by Kug et al. 2009 (J.Climate.22,1499-1515)

A Growing Strong El Niño *(What should I look out for in the ocean?)*



1. The figure shows sea level and surface currents on the 29 March, 29 June, 27 September and 31 December, during the growth phase of the strong 1982-1983 El Niño.

2. They show the development of low sea levels in the western Pacific in mid-year, the movement of high sea levels on the Equator into the central Pacific and the resulting increase in the strength of the NECC at all longitudes during the second half of the year.

3. The increased strength of the NECC in the west coincides with the increased transport of warm pool water, initially into the central Pacific and finally into the far eastern Pacific - the warm water finally arriving around Christmas (El Niño).

4. The movement of the warm pool water is associated with changes in the winds and changes in sea level near the Equator, presumably due to the deep atmospheric convection moving away from Indonesia and the western Pacific towards the central and eastern Pacific.

As the warm water crosses the ocean, the varying speed of the annual Rossby waves takes the NECC and the warm water to the north. Here it is closer to the ITCZ where the atmosphere is most unstable

5. On the equator, the westward flowing Equatorial Current decays, a result of the reduced easterly winds. This results in weaker tropical instability eddies and the increased transport of warm water by the NECC discussed earlier.

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This figure shows the development of SSH only at the start of the 1982-1983 El Niño. The 2018 paper also includes the SST fields and similar plots of the 1997-1998 El Niño.

Other Theories

(What about theory X : Isn't the NECC just a side issue?)

1. Most El Niño theories involve the Equatorial Wave Guide.

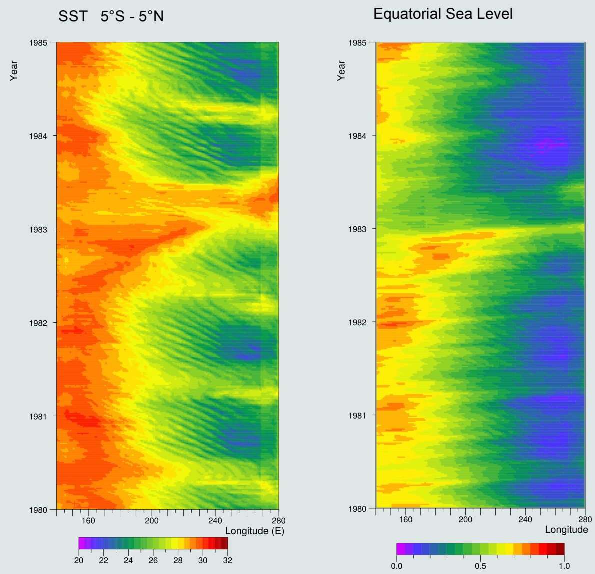
2. In the present study the latitudes of the Equatorial Wave Guide are important for the reduced strength of the Equatorial Current and the movement of high sea levels into the central Pacific. The latitude of the wave guide boundary is also important because of the rapid change in the Coriolis term with latitude, affecting both geostrophic currents and Ekman pumping.

But in other respects the wave guide had no significant effect.

3. As an example, the two figures on the right show the average temperature between 5°S and 5°N (the band to construct the NINO indices) and sea level at the Equator.

The sea level picture shows a series of Equatorial Kelvin Waves during the autumn of 1982. The winds that force them occur at longitudes where the temperature is already near its maximum – so they are a result of the developing El Niño.

Note that as they propagate eastwards, the Kelvin waves have no significant effect on the SST field. Also SST values near South America only increase significantly after the end of 1982. As with the other figures shown, similar results were also found during the strong 1997-1998 El Niño.



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1. There will be some who are unhappy about the role of the NECC describer here. However physical theories can never be proved, only disproved. So … .

2. The reason why the community has become fixated on the Equatorial Wave Guide might be of interest to historians and those who study scientific method.

   One possible reason is that the growth of experimental research into the El Niño occurred at a time when mathematicians became interested in the elegant mathematics of the wave guide. It was also only a few years since the Equatorial Undercurrent had been discovered. Thus it was a no-brainer to look for possible connections between the different systems.

3. One additional area of the Equatorial Wave Guide which may be important is the Cold Pool in the eastern Pacific. This is caused by the upwelling by the easterly winds of water from the cold Equatorial Undercurrent. The latter lies near the surface in the eastern Pacific.

   During an El Niño when the undercurrent fails, any upwelled water is much warmer so the Cold Pool disappears. SST and SSH values both rise by large amounts but the SST still stays well below 28°C.

   However the increased temperature means that winds flowing from the region north towards the ITCZ will be much warmer than in a normal year.

Conclusions *(and some hypotheses)*

1. The NECC is the dominant current responsible for transporting warm ocean waters westwards during the development of a strong El Niño.

2. The initial stage of development is associated with a region of low sea level which develops in the western Pacific in mid-year near 6°N.

3. The further development of the El Niño is aided by the timing of the annual Rossby wave which enhances the strength of the NECC during the autumn months.

4. During this period the Equatorial Current is reduced in strength. This reduces the strength of tropical instability eddies (TIEs).

5. The reduction in the strength of TIEs, reduces horizontal mixing in the core of the NECC, allowing it to transport warm water much further east.

6. The combination of these processes, together with the associated changes in deep atmospheric convection and circulation, cause the El Niño.

A couple of extra points:

1. Unfortunately the TOGA-COARE array does not have current measurements in mid-Pacific away from the equator. Thus the array cannot be used to measure the energetics of the TIEs at the latitude of the NECC.

2. When I wrote the 2018 paper I thought the region of low sea level that developed in the western Pacific was due either to a stronger than normal Rossby wave or some sort of focussing of energy due to stratification in the ocean.

   I now think neither is true and instead that the low sea level near 6°N is probably either a locally wind driven process (most likely) or (possibly) Rossby wave growth due to the winds near the dateline.

References

Wyrtki, K. (1973) Teleconnections in the Equatorial Pacific Ocean, Science, 180, 66–68

Evans, J. L. and Webster, C. C. (2014) A variable sea surface temperature threshold for tropical convection, Aust. Meteorol. Oceanogr. J., 64, S1–S8. https://doi.org/10.22499/2.6401.007

Held, I.M. and Hemler, R.S. (1993) Radiative-Convective Equilibrium with Explicit Two-Dimensional Moist Convection. J. Atmos. Sci., 50(23) 3909-3927.

Webb, D. J. (2016) A comparison of sea surface temperatures in the Equatorial Pacific Nino regions with results from two early runs of the NEMO 1/12° Ocean Model. Research and Consultancy Report No. 55, National Oceanography Centre, Southampton, UK. http://nora.nerc.ac.uk/id/eprint/513264.

Webb, D. J. (2018) On the role of the North Equatorial Current during a strong El Niño, Ocean Science, 14, 633–660. https://www.ocean-sci.net/14/633/2018.

Webb, D.J., Coward, A.C. and Snaith H.M. (2020) A comparison of Ocean Model Data and Satellite Observations of features affecting the growth of the NECC during the strong 1997-98 El Niño. Ocean Science (Accepted for Publication).

Video of a seminar on this study is available:
Title: El Niño : Ocean Mechanisms
Link: https://www.youtube.com/watch?v=EbL44NRBJbY

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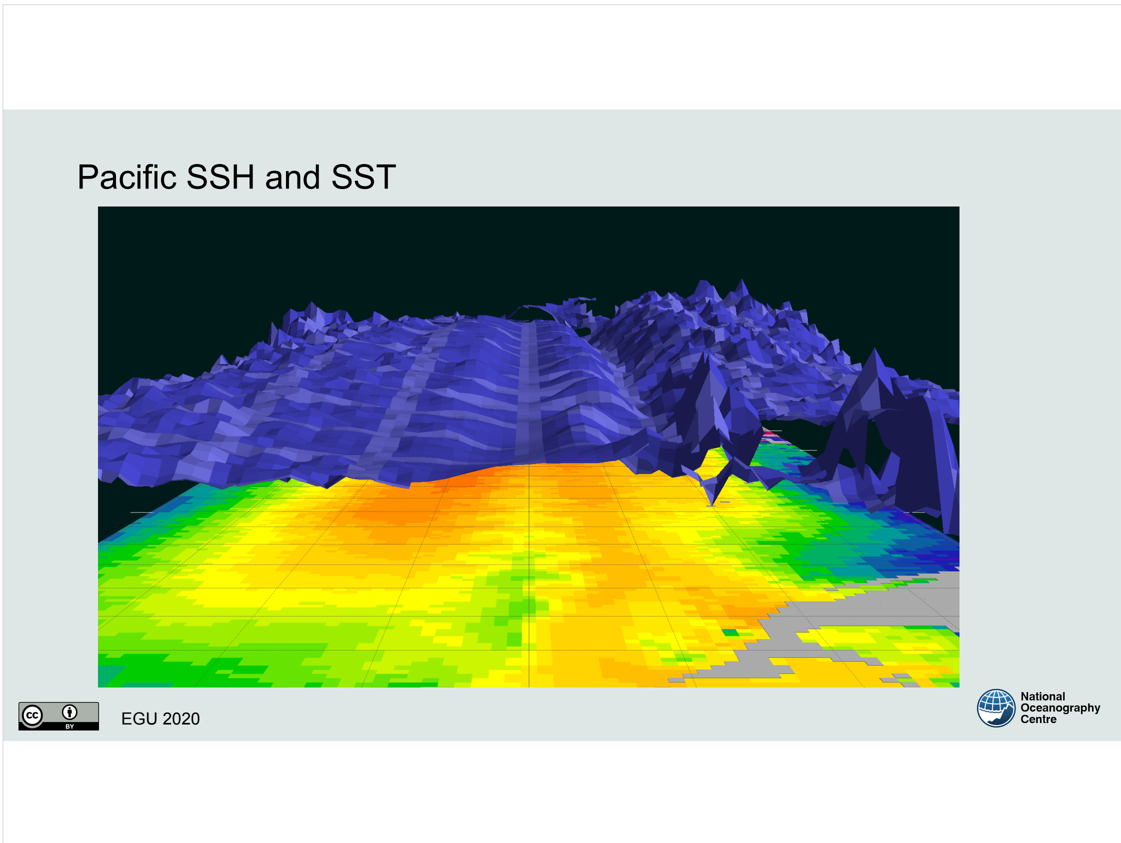


This figure showing SSH and SST was constructed from NEMO archive data averaged onto a 1 degree Pacific grid. It is from the autumn of a non-El Niño year. The grid lines are at intervals of 10 degrees of latitude and longitude.

The SSH field (top) shows the Equatorial Trough (due to the eastward flowing Equatorial Current), the deep North Equatorial Trough and the ridge in between on which lie tropical instability eddies.

Further to the north and south can be seen the peaks due to the meso-scale eddy field.

Although the SSH anomalies due to tropical instability eddies are much smaller than those due to the meso-scale eddies, the low value of the Coriolis term near the Equator means that currents can be similar.

The SST field (bottom) shows the Cold Pool, on the Equator in the eastern Pacific, and the cooler temperatures in the Equatorial Current to the west – both due to the upwelling of cool undercurrent water.

Questions Asked

Unfortunately I did not take a screenshot at the end of my talk - but four of the questions were related to:

(1) The time taken for the NECC to carry water across the Pacific

(2) The model resolution necessary to accurately represent the NECC in climate models

(3) Non-linearities

(4) How I reconciled the ideas reported here with theories which emphasise the role of processes occurring on and near the Equator?

In the following pages I again answer the questions but this time in the more expanded way appropriate to a proper poster session.

I would have also used a poster session to ask my own questions so:

(5) My question to those who work with coupled models and/or study the atmosphere during an E Niño.

1. The time taken for the NECC to carry water right across the Pacific

I emphasis ‘right across the Pacific’ because with a group of old time oceanographers my strong El Niño would be a ‘Classic El Niño’. It was the fisheries problems off Peru around Christmas which gave the phenomena its name and got them started on the research.

The present work shows that a strong El Niño occurs when (a) something increases the transport of warm water by the NECC in the western Pacific and (b) that the timing is right for the annual Rossby waves, at the different latitudes, to give the NECC an extra impetus right across the Pacific.

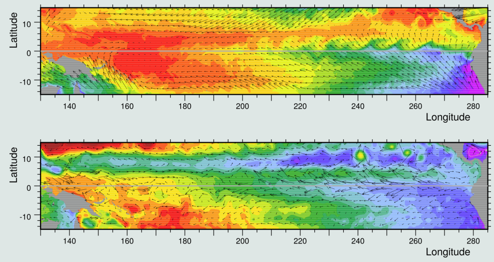
The model showed that the Rossby waves are generated in the eastern Pacific early in the year and the fastest waves, at around 6°N, arrive in the western Pacific around mid-year. In most years they tend to decay in amplitude rapidly after passing the dateline but in 1982 and 1997 there was an extra drop in sea level, in the far west, just before mid-year and this gave the NECC the extra impetus to get significant amounts of warm water moving east.

Once this happens, the moving centre of atmospheric convection, the changed winds on the Equator and the resulting reduction in the tropical instability eddies, allow the NECC to transport water >28°C much further to the east – arriving off South America around Christmas. So, sorry for the roundabout answer, but the time required is around six months.

You might ask:

* *If the initial impetus does not occur around mid-year what happens?*
  There is no annual Rossby wave to help – so I guess you get a mid-ocean El Niño.
* *And what gives NECC its initial impetus?*
  I do not know. What is your best bet? *(Madden-Julian Oscillation, …, …)* . I’d like to know – but it needs to do something special around 6°N-8°N in the western Pacific

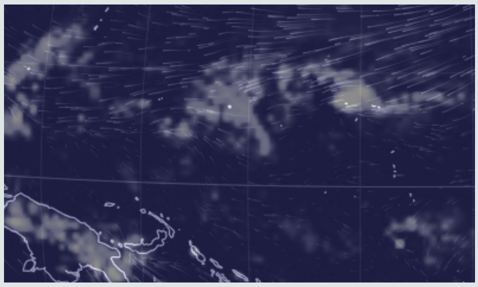
2. The model resolution necessary to accurately represent the NECC in climate models



The width of the North Equatorial Trough is around four degrees, so working on the basis of a minimum of ten points per wavelength this means that a one degree ocean grid is too coarse, half a degree would be better. My model with a ¼ degree grid represents the trough well and does a reasonable job with the tropical instability eddies.

So if you are interested in studying the difference between the different types of El Niño you probably need an ocean model with half a degree resolution or better.

For the atmospheric model you probably need something similar. As I understand it the North Equatorial Trough is generated by the wind shear seen in the bottom figure (surface wind and total cloud water).



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The shear causes Ekman suction and it is this, averaged over a period of years which generates the trough – so to get a reasonable trough the atmospheric model needs to generate similar jumps in the wind stress. So again I suspect that half a degree resolution or better to study the phenomena.

Shorter term changes, like the latitude of strong shear also need to be resolved. The annual Rossby wave is generated in the eastern Pacific. It is possible that some of this is due to flow across the isthmus early each year – so resolving gaps in the mountain ranges may be of concern.

If (today's) figure had shown a significant wind along the Equator, I would have to say that it is the difference from this which is important. A constant easterly at all latitudes generates a sea surface slope from east to west, but no net northward transport – any Ekman transport away from the Equator being balanced by an equal geostrophic flow towards the Equator due to the slope.

3. Non-linearities

This is a broad subject which could refer to many aspects of strong El Ninos.

(1) The basic generation mechanism of the North Equatorial Trough and NECC, i.e. the processes of Ekman transport, Ekman suction and geostrophy are primarily linear processes.

(2) The tropical instability eddies are nonlinear - the result of barotropic and/or baroclinic instabilities. There are papers by Philander (1978), Cox(1980) and Luther and Johnson (1990) but they disagree on the form of the instability or the currents involved. In the model results I have looked at, the eddies seem to decay as soon as the Equatorial Current fails - although the current shear between the Equator and the core latitude of the NECC may remain high.

(3) Once the ocean surface temperatures rise above 26°C, the evaporative flux into the atmosphere increases rapidly with temperature – although it does depend on wind speed as well. Because of this effect, it may be difficult for the maximum SST temperatures to rise far above 28°C*, say, even with increased CO_2, although there is nothing to stop an increase in the area of ocean with the warmest temperatures or the total flux of heat (especially latent heat) into the atmosphere.

(4) The most non-linear aspect of all appears to be the relationship between the sea surface temperature and the height of atmospheric convection. As pointed out by Evans and Webster (2014) the tropical atmosphere roughly follows the wet adiabatic so it is only fully saturated air at sea level that is above a critical temperature which will be successful. Note however that the critical temperature does depend on sea level pressure, being lower when the sea level pressure is low.

*Note: In September 1988, north of New Guinea, we had a streamlined fish measuring temperature and salinity in the top few centimetres of ocean. During an initial period of low winds, afternoon SST temperatures above 30°C were common. One day it passed 32°C but the wind had dropped to zero and the ocean surface was glassy. During the later windier period temperatures were nearer 29°C, dropping at one point to below 28°C. (King et al, IOSDL Report No 291, Fig 3 : https://noc.ac.uk/publication/115310).

4. How do I reconciled the ideas reported here with theories which emphasise the role of processes occurring on and near the Equator?

As they say – a really good question : and my answer is that I don't – except those that involve believable advection.

The equatorial wave guide theories seem to fall into three camps. These are

1. *Easterly winds result in high sea levels and a large pool of warm water in the western Pacific. When the winds relax this sloshes across to the other side of the ocean – causing the El Niño.*

This suffers from the 'Rubber Duck' problem. When water sloshes from one side (or bath end) to the other, only the wave moves - the warm water (and the ducks) stay in the roughly the same position. So western Pacific warm pool water would never move to the central or eastern Pacific.

2. *Westerly wind bursts generate a series of equatorial Kelvin waves which carry warm water eastwards along the Equator.*

This has the same problem as (1). Equatorial Kelvin waves can only transport mass and heat via the Stokes drift. Near the surface the drift has been calculated to be as high as 34 cm/sec but this is not enough to seriously reverse the westward flowing Equatorial Current (see notes).

3. *Westerly wind bursts generate equatorial Kelvin waves which, when they arrive in the eastern Pacific, increase the thermocline thickness and result in a warming the ocean surface layer.*

So the warm pool water does not move? It is possible that the stokes drift could thicken the thermocline, but (for example in 1997) the main thickening and warming occurs after the two main waves generated by westerly wind bursts? So where does the later major thickening and warming come from? [Once the cold undercurrent stops in the eastern equatorial Pacific, local water replaces it. Cold water is no longer upwelled. Surface temperatures may jump from 19°C to 26°C, with similar dramatic changes in sea level – but not enough to trigger deep atmospheric convection.]

So when It comes down to it – I only believe in advection. There is some, mainly north-south, advection due to Ekman transport and there may be a small role for stokes drift but the main processes are local advection due to the winds on and along the Equator and geostrophic advection due to the NECC, other currents and eddies like the tropical instability eddies.

Weber et al (2014) calculated the stokes drift due to internal equatorial Kelvin waves. They estimated that in the central Pacific a large wave would generate a stokes drift of 34 cm/sec near the surface. The current reverses at around 100m with an enhanced return flow below, the maximum current lying near 150m. The net transport, integrating from the surface to anywhere below 300m was essentially zero.

Such a drift would be insufficient to significantly reverse the westward flowing Equatorial current (typical speed 50 – 100 cm/sec), so it would not transport warm water eastwards.

Weber, J.E.H, Christensen, K.H and Brostrom, G. (2014) Stokes drift in Internal Equatorial kelvin Waves: Continuous stratification versus Two-Layer Models. Journal of Physical Oceanography, 44, 591-599.

My Question?

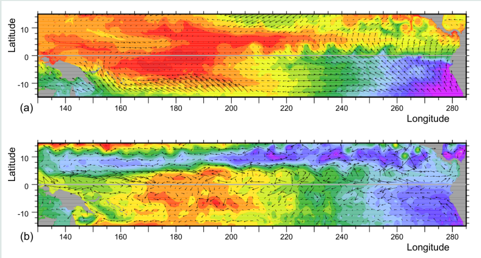
If we were talking during a poster session my question to you would be a variation of "Why are atmospheric El Niño studies so hung up about sea surface temperature (SST) along the Equator?".

I ask this because SST values along the Equator are usually low, a result of the upwelling of cold Equatorial Undercurrent water. At the surface warmer water is usually found to the north, nearer the ITCZ – where deep atmospheric convection does occur – or nearer the SPCZ. So I am surprised that analyses of, say, the CMIP5 runs do not concentrate on the representation of deep convection in the different models, ask where it occurs, the air temperatures, humidity and atmospheric pressure near the sea surface when it occurs and how these change during El Niño type events and/or during global warming?

Now I agree that, once an El Niño has become established, it can generate a region of high temperatures and high sea level on the Equator in the central ocean and this may be a good measure that an El Niño is present. However it says little about the physics.

The problem is that the high SST region is usually an area of low winds with the high sea level supported by westerlies flowing into the region from the west and easterlies from the east.

Now I agree that when a high SST region generates low atmospheric pressure to the north or south, there will be westerly winds on the equator and these bursts will, while the event lasts, move water further east. However as I understand it these are fairly rare short lived events and I cannot see them moving such patches of warm water from New Guinea to the central Pacific (let alone to South America).



SST (above) and SSH (below) from September 1982 (Webb 2018, Fig. 24)

What I can imagine is winds on the equator flowing towards a convection region to the east, situated either in the ITCZ or SPCZ. Such winds will have a westerly component and if they dominate the average over a couple of months they could shift water eastwards along the Equator. So I see the convection regions in models and reality as being the key features to track – not just SST on the Equator.

So is this wrong? - and if so what is the full story?

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