5. Ocean GCM as a tool for studying ENSO.

5.1. Ocean data reanalyses by means of GCM.

Since the data on the ocean subsurface field are either unavailable or sparse, scientists use realistic (to the extent that we understand ocean today) General Circulation Models (GCM) forced by observed wind stress and observed or estimated heat fluxes at the surface. This gives us a detailed knowledge about subsurface ocean, including current velocities, density field, temperature, and various tracer distribution. Figures 17-19 show such calculations for the temperature field for the period of 1982-1989 when two strong El Niño events (1982 / 1983 and 1987) occurred.

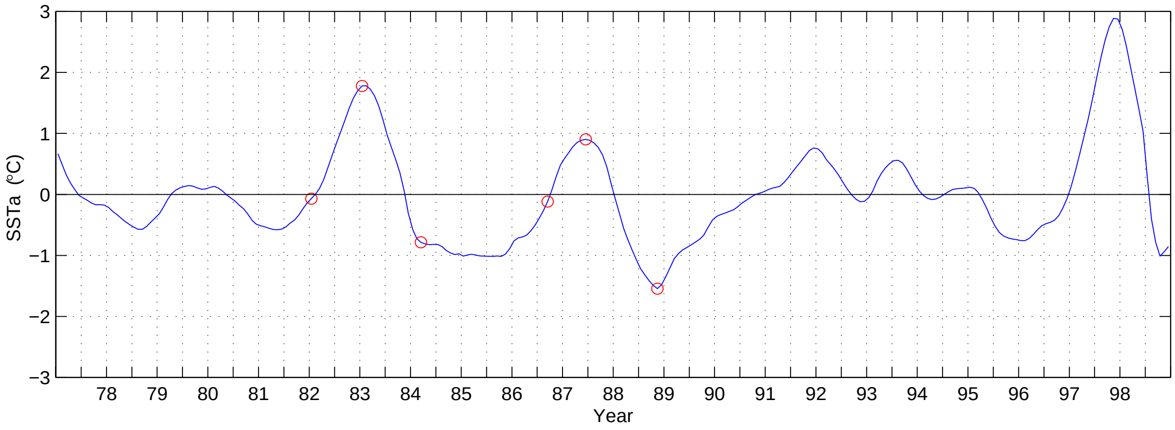


Figure 17. Observed SST anomalies in the eastern Pacific (averaged over the Nino3 region). The circles indicate snapshot times for the next figure.

More elaborate versions of this type of ocean reanalysis incorporate subsurface observations from the TAO array and measurements from satellites into the calculation procedure.

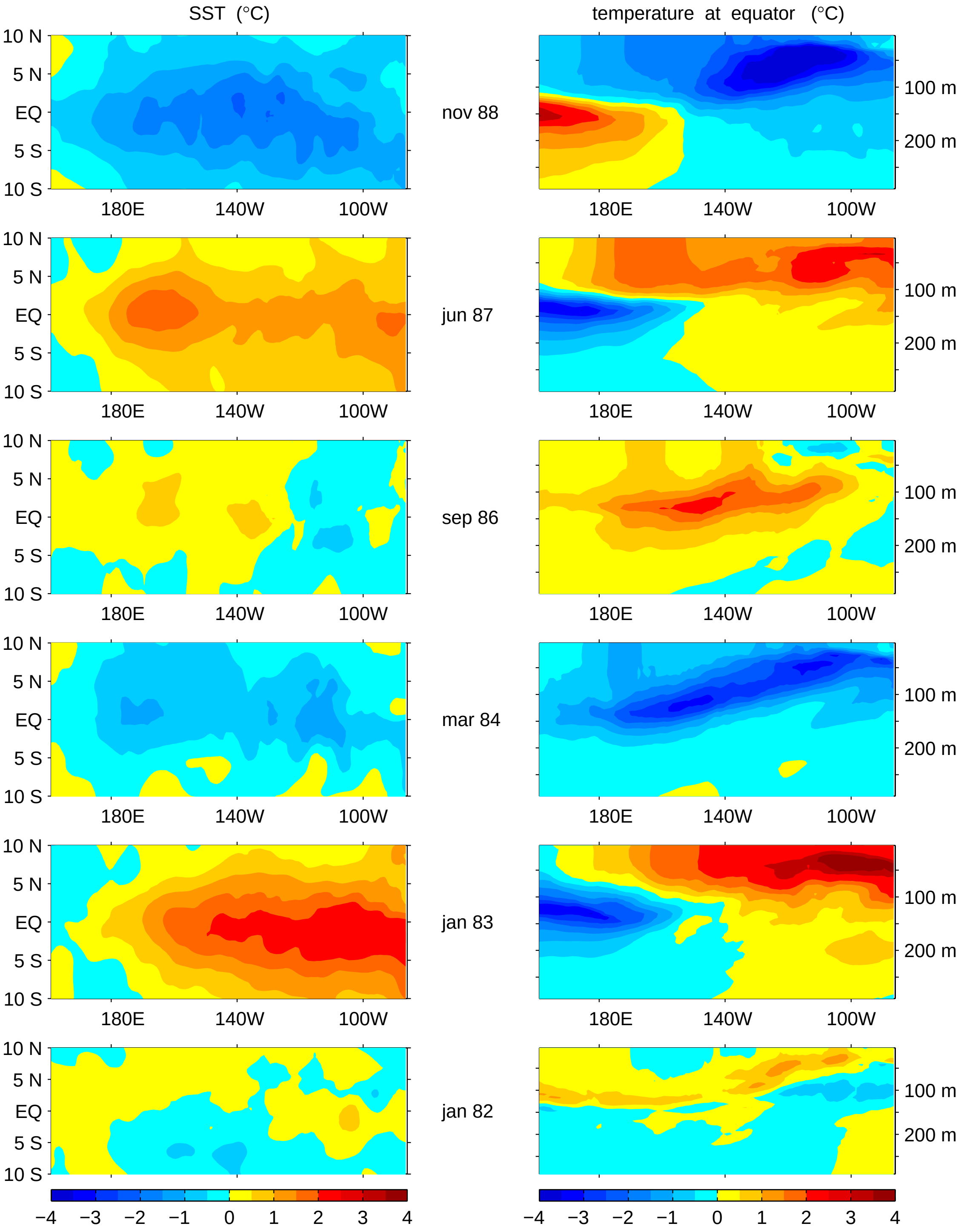


Figure 18. Temperature anomalies at the surface and at depth from GCM calculations for times indicated in the previous figure. The seasonal cycle and high-frequency fluctuations are removed from the data.

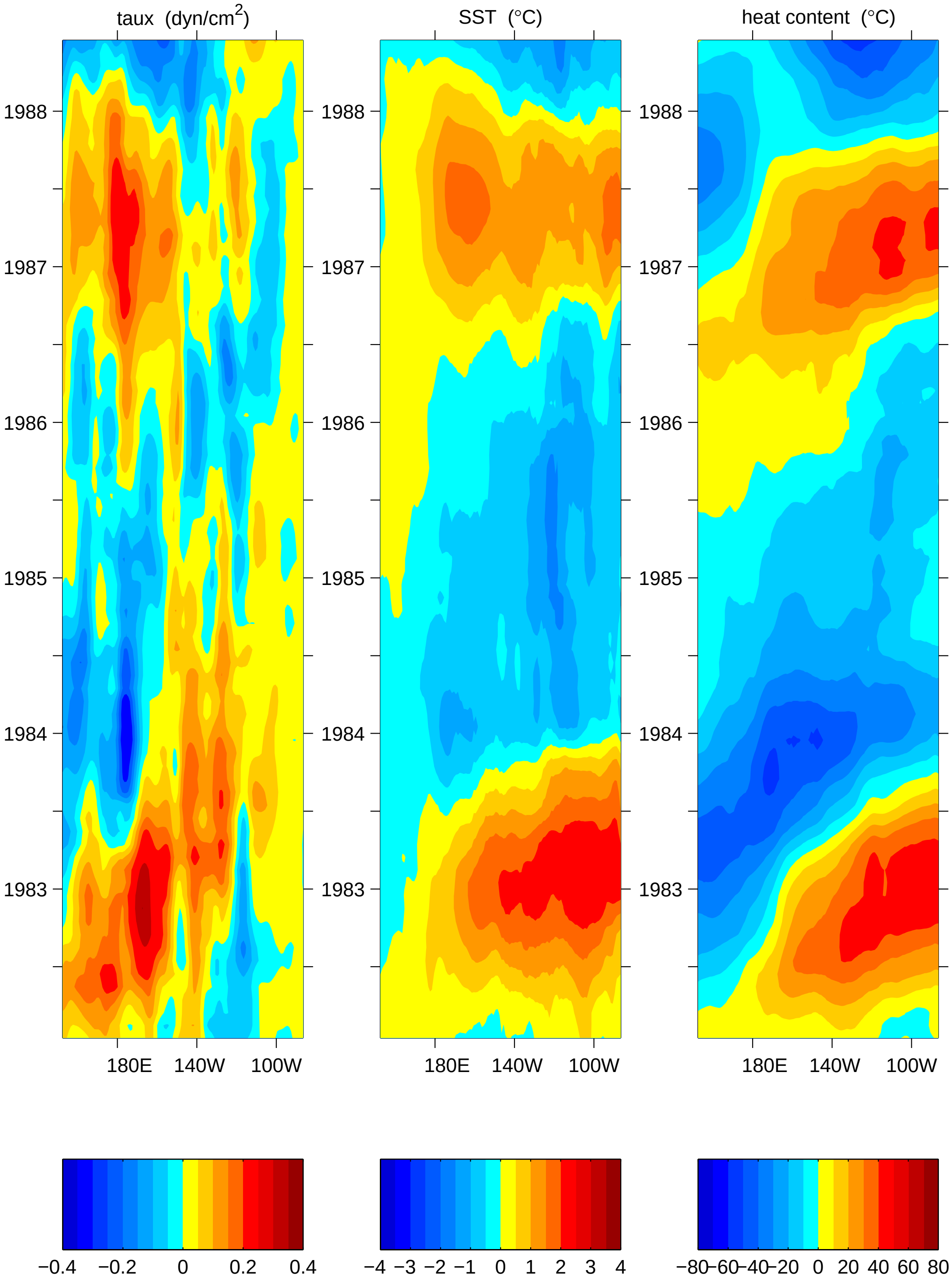


Figure 19. Wind, SST and heat content anomalies from GCM calculations for the period of 1982-1989. The seasonal cycle and high-frequency fluctuations are removed from the data.

5.2. The energetics of the Southern Oscillation.

The energetics of the transformations in the ocean associated with the Southern Oscillation amount to an approximate balance between the terms

$$dE/dt = W + \mathrm{Dissipation} \qquad (5.1)$$

where t is time, E is the available potential energy (APE) of the ocean, and W is the wind power (work done on the ocean by the winds per unit time) averaged over the tropical Pacific Ocean (for a reference see Goddard and Philander 2000). In a continual oscillation, La Niña corresponds to a state of maximum, El Niño to a state of minimum APE. Thus, APE is a measure of the thermocline slope.

One can derive equation (5.1) from the linear shallow-water equations on the equatorial β-plane in the long-wave approximation. Again, for simplicity, symmetry with respect to the equator, and no annual forcing are assumed:

$$u_t + g'h_x - \beta y v = -ru + \tau/\rho H, \qquad (5.2)$$

$$h_t + H(u_x + v_y) = -rh, \qquad (5.3)$$

$$g'h_y + \beta y u = 0. \qquad (5.4)$$

Adding (5.2) multiplied by u, and (5.3) multiplied by h, and using (5.4) with the boundary conditions (Section 2.), one arrives at

$$E_t + 2rE = \iint u\tau\, dx\, dy, \qquad (5.5)$$

where

$$E = \rho \iint \left(\frac{g'h^2}{2} + \frac{Hu^2}{2} \right) dx\, dy, \qquad (5.6)$$

and the integrals are calculated over tropical Pacific ocean (say 130^{o}E-85^{o}W, 15^{o}S-15^{o}N).

Since the perturbation kinetic energy of the motion under consideration is very small (of the order of several percent of the total), Eqs. (5.5) and (5.6) can be rewritten with a good accuracy as

$$E_t = W + (\ldots) \tag{5.7}$$

$$E = \frac{\rho}{2}\int\int g' h^2 dxdy, \tag{5.8}$$

$$W = \int\int u\tau dxdy, \tag{5.9}$$

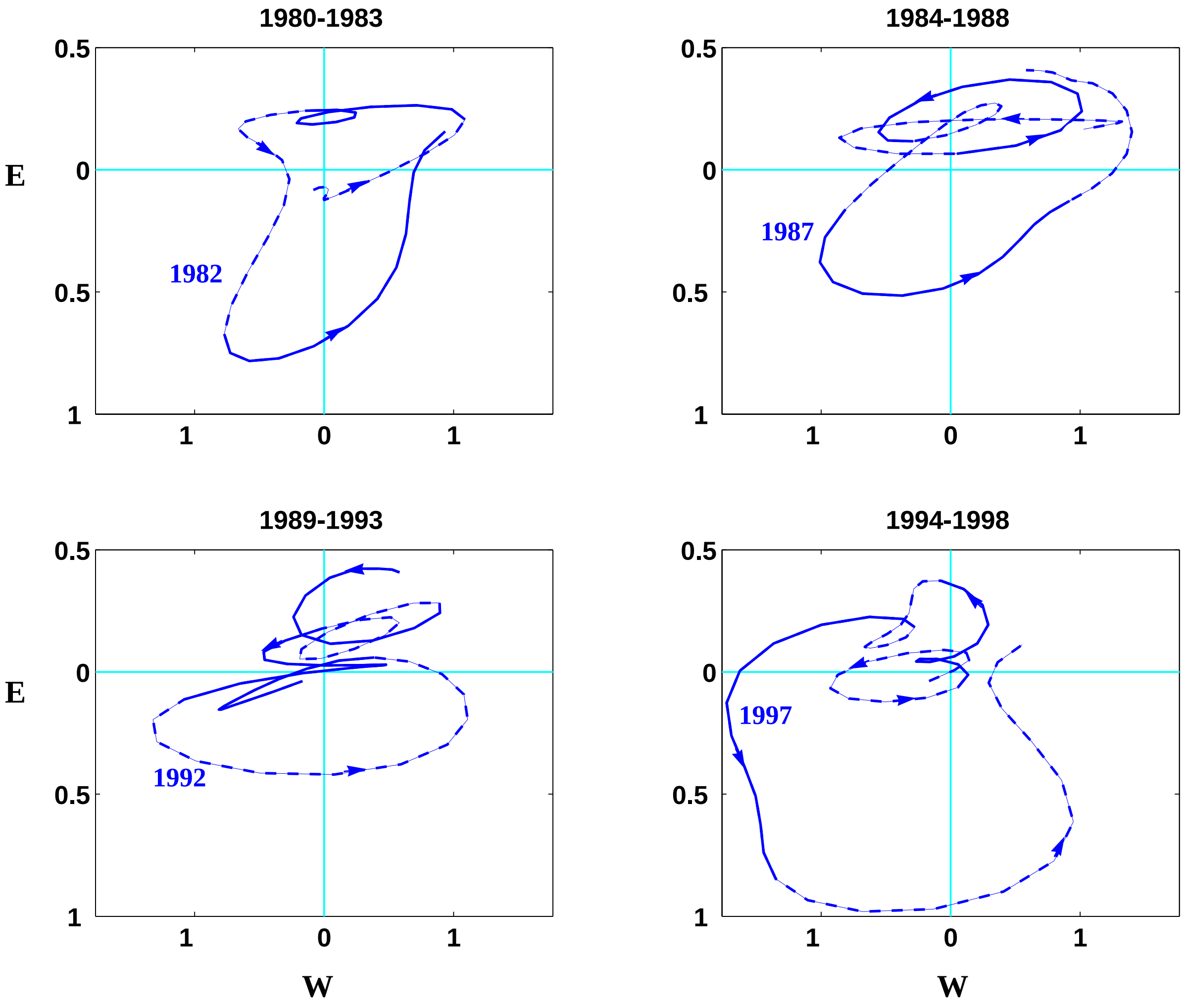
The omitted terms in the brackets describe the higher-order nonlinear terms (negligible for small perturbations), explicit energy dissipation, the energy loss at the western, northern and southern boundaries, and any numerical dissipation after finite-differencing. Equations (5.7) - (5.9) represent the fact that the only way one can change the total available potential energy of the system is through the work of the wind or through dissipation.

If one uses the data from GCM calculations, the energy should be defined as

$$E = -\frac{g}{2}\int\int\int\frac{(\rho - \bar{\rho})^2}{\hat{\rho}_z}dxdydz$$

where $\rho = \rho(x, y, z, t)$ is the density, and $\hat{\rho}(z)$ is the reference density corresponding to the hydrostatically balanced reference state with no zonal and meridional dependences.

A convenient method for studying ENSO is the analysis of phase diagrams that have wind power (W) and oceanic available potential energy (E) as axes. Figure 20 displays an example of such phase diagrams from the calculations described in Section 5.1.



1980-1983

1984-1988

1989-1993

1994-1998

Figure 20. The E-W phase diagrams for the period 1979-1998. Each panel describes 5 years. The perturbation values of E and W are plotted. Alternate years are shown in solid and dashed lines, respectively. The trajectory being at the bottom of the panels corresponds to El Niño. Four major El Niño events are clearly seen (in 1982, 1987, 1992 and 1997). The phase trajectories are counter-clockwise.

Acknowledgements.

Figure produced in these notes are reproduced from several sources, including the TAO web-site (http://www.pmel.noaa.gov/tao/), George Philander's book on El Niño, the June issue of JGR (1998) devoted to El Niño, and several published or unpublished papers by the author. I thank G. Philander, D. Neelin, P. Chang, S. Harper, M. Harrison, M. McPhaden, M. Latif, A. Rosati, E. Tziperman, D. Anderson, J. Slingo, P. Niiler, B. Winter, A. Wittenberg who have greatly contributed to my understanding of El Niño. The Appendix is taken from Eli Tziperman lectures for Woods Hole GFD (2001).

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These are only very few references (from perhaps a thousand) on this subject.

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Problem set 1.

I.

When deriving the shallow-water equations, scientists often use the so-called “rigid-lid” approximation; however, it is known that El Niño causes important changes (although small) of the sea level. How will the shallow-water equations change if the effects of the free surface are taken into account? What is the relation between changes in the thermocline depth and in the sea level height?

II.

The heat content of the upper ocean (i.e. the temperature averaged over upper 300m) is often used as a good proxy for the thermocline depth. Show that the two are indeed related. You can use a simple model for the thermostructure

$T(x,y,z,t)=20+10*\tanh((z-h)/d)$,

where $h=h(x,y,t)$ - the thermocline depth, z - the vertical coordinate, d - a parameter that characterizes the sharpness of the thermocline.

III.

Using the shallow-water equations with the no-net-flow boundary condition at the western boundary show that the total energy of such a system is not conserving even if the explicit damping is set to zero.

Problem set 2.

This problem set introduces several useful web-sites where one can find many helpful information about El Niño etc.

I.

http://www.pmel.noaa.gov/tao/jsdisplay/

Using data from TOGA-TAO array, identify Kelvin waves propagating along the thermocline and calculate their phase speed. Further, estimate the phase speed of the thermocline depth anomaly (also eastward-propagating) associated with El Niño of 1997-1998. Compare the two.

II.

http://iridl.ldeo.columbia.edu/maproom/.ENSO/

Analyzing various data sets of SST, wind, thermocline, etc., describe the state of the tropical Pacific at present. Try to give possible scenarios of climate development that we might expect within the next year.

III.

http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94/figviewer.html?plottype=colors

Using Levitus climatology study the properties of the seasonal cycle in the tropical Pacific. When is the cold tongue most intense? When does the warmest month in the eastern Pacific occur? Estimate the “phase speed” of the seasonal cycle (say, by looking at the motion of the 27 degrees isotherm from April to September).

IV.

http://www.people.virginia.edu/~mem6u/mbh99b.html

Explore Mann et al reconstruction of the NINO3 SST for the last 400 years. If time allows, calculate the spectrum of the time series.

The following Appendix reproduces three pages from Eli Tziperman lectures for Woods Hole GFD (2001) with the detailed derivations of the structure and other characteristics of Kelvin and Rossby waves.