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The North Equatorial Countercurrent and heat storage in the western Pacific Ocean during 1982–83

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A sequence of extreme climate anomalies known as an El Niño Southern Oscillation episode was observed in the tropical Pacific Ocean during 1982–83[1,2]. Models suggest that oceanic circulation has an important role in the formation of such anomalies[1,3,4] by altering the pattern of sea-surface temperature through advection. The baroclinic structure of the upper 500 m of the ocean has been monitored routinely in the western Pacific since 1979, providing indirect current measurements by the geostrophic method. These observations, reported here, show large changes in the near-equatorial currents during 1982–83 which are consistent with currents observed in the central and eastern Pacific[5,6]. In particular, the North Equatorial Countercurrent (NECC) flowed with 25–50% increased strength during the early phase, then weakened almost to zero flow. The West Pacific heat pool cooled by more than 1 °C. Observed changes in circulation were large enough to alter surface heat storage by advection, although other potentially important processes may not be negligible.

Baroclinic currents in the tropical ocean are largely determined by the topography of the thermocline (that is, the temperature field), in the same way that wind is determined by a map of pressure. Temperature structure has been monitored using expendable bathythermographs (XBTs) launched from volunteer observing (merchant) ships in a programme operated jointly by France and the United States since 1979[7]. The programme involves soundings to 450 m depth at intervals of ~60 nautical miles along the shipping route between New Caledonia and Japan, the time between cruises being typically 2-4 weeks. After careful quality control, the observations are plotted as a sequence of meridional temperature sections. Four sections chosen to show the essential features of time variability during the last El Niño episode are shown in Fig. 1.

The tropical thermocline has a series of ridges and troughs, the most persistent of which appear (Fig. 1) near 20° N, 20° S and 9° N. In the following discussion, deep levels of the thermocline are called ridges, and shallow levels troughs, in order to maintain their correspondence to ridges and troughs in sea level elevation. The major zonal equatorial currents flow parallel to the ridges and troughs over great distances across the Pacific. The ridge/trough structure varies with monthly and longer-period changes in the field of the trade winds[8]. The NECC near 3-9° N and the South Equatorial Current (SEC) near 2-20° S showed large changes during 1982-83.

The trough near 9° N on the northern side of the NECC began at a nearly normal level[7] during January 1982 (Fig. 1*a*); it intensified by August 1982 (Fig. 1*b*), persisted until January 1983 (Fig. 1*c*), then relaxed almost completely by June 1983 (Fig. 1*d*). The slope of the 20 °C isotherm between the trough near 9° N and the ridge near 3° N is a frequently used index of NECC strength at the surface[9,10]. A time series of monthly values (Fig. 2*a*) was prepared by averaging the depth of the 20 °C isotherm within ±1.5° latitude of the ridge or trough, then taking the difference (ΔD_{20}). We used this isotherm for the index because it is near the depth of maximum vertical temperature gradient in the NECC.

The index of relative geostrophic current strength derived in this way is a rather smooth variable, dominated by low-frequency seasonal and interannual fluctuations. The eastward surface flow of the NECC was stronger than normal during June to December 1982; at approximately the same time, enhanced eastward flow was observed in the central[5] and eastern[6] Pacific. Thereafter, the NECC diminished to an extremely weak level by March 1983 and remained weak until the end of our record (June 1983). The signal during 1982-83 suggests an annual oscillation; however, earlier studies[11,12] have shown that seasonal oscillations are very irregular in amplitude and phase in this region. In association with the changing strength of the current, the ridge on the southern side varies in latitude between the Equator (Fig. 1*b*) and 5° N (Fig. 1*d*) during the episode. Variability in the strength of the NECC during earlier episodes has been inferred from sea level[11]; however, continuous spatial sampling by XBTs is needed to locate the latitude of ridges and troughs and to determine the strength of the full current. The ΔD_{20} index (Fig. 2*a*) shows that the surface current was 25-50% stronger than normal during the early part of the El Niño episode.

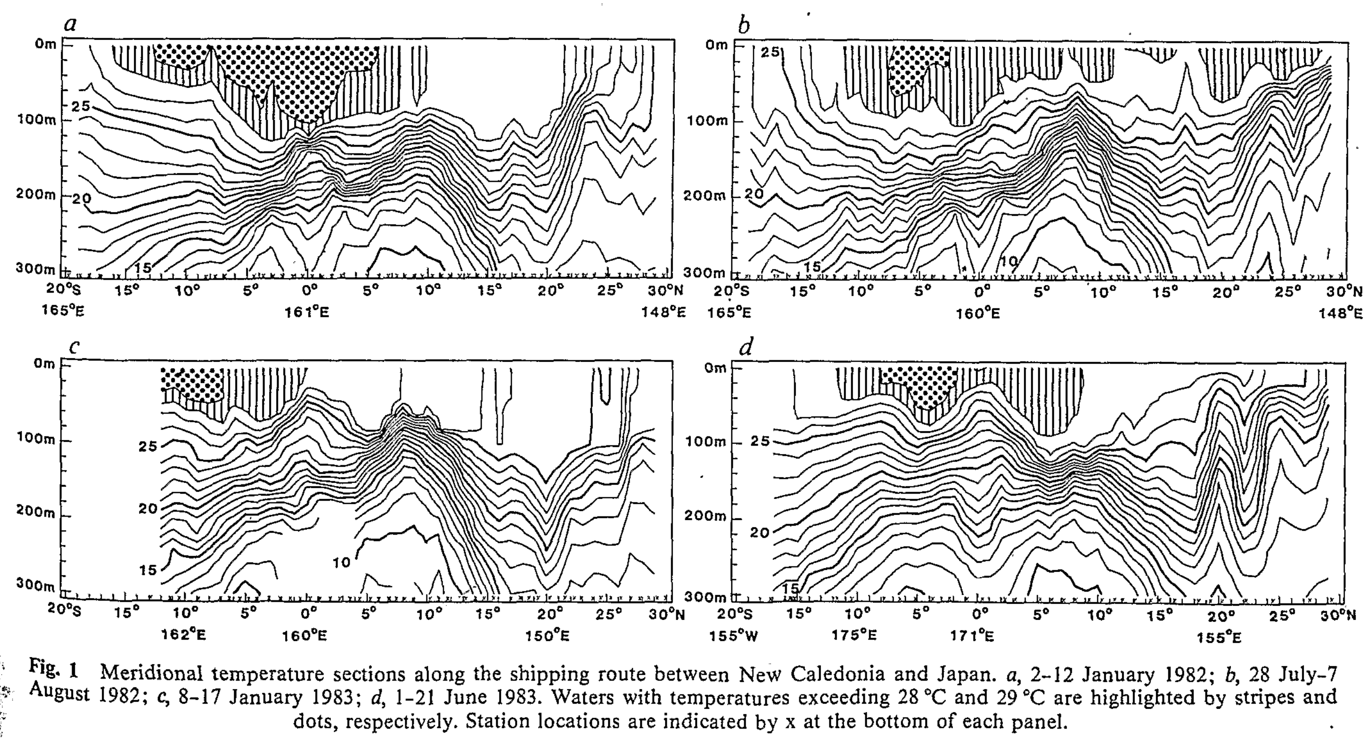

Fig. 1 Meridional temperature sections along the shipping route between New Caledonia and Japan. *a*, 2-12 January 1982; *b*, 28 July-7 August 1982; *c*, 8-17 January 1983; *d*, 1-21 June 1983. Waters with temperatures exceeding 28 °C and 29 °C are highlighted by stripes and dots, respectively. Station locations are indicated by x at the bottom of each panel.

Change in the SEC was also observed on the temperature sections. The SEC was a very stable feature from 1979 until mid-1982[7]. Its strongest surface flow usually appeared between the Equator and 10° S, as shown by the downward slope of all isotherms in this latitude band (Fig. 1*a*). The current shifted southward to 10–20° S (Fig. 1*d*) during the 1982–83 episode, as reported in more detail elsewhere[7].

Another aspect of the temperature field in the western Pacific is a pool of very warm water near the Equator. Its normal structure is seen in January 1982 (Fig. 1*a*) as a pool of 28–29 °C water reaching more than 100 m deep in places. Typically, the near-equatorial (5° N to 5° S) portion of the 29 °C pool extends eastward a short distance beyond the New Caledonia–Japan section (160° E) and westward to Papua New Guinea[13] (about 140° E). The heat pool shifted into the central Pacific during 1982–83 and during an earlier El Niño episode[14,15], while surface temperatures in the west decreased. The recently recognized potential importance of western Pacific temperature in controlling the Southern Oscillation[1,16] suggests that it is essential to document its variability and to understand the processes that control it.

The sequence of temperature sections (Fig. 1) shows changes in the heat pool very clearly. After the normal conditions observed in January 1982 (Fig. 1*a*), the 29 °C pool was depleted in the near-equatorial band by August 1982 (Fig. 1*b*). The cooler 28 °C pool was almost depleted by January 1983 (Fig. 1*c*). Near the end of the episode, in June 1983 (Fig. 1*d*), the heat pool is being re-established in the near-equatorial band, but its volume is still substantially below normal. The heat loss is not restricted to the near-equatorial band, but in fact appears in the complete sequence of sections (not presented) as a prominent interannual signal throughout the latitude band 20° N–15° S, superimposed on the usual seasonal cycle. A monthly index of near-equatorial heat content was derived from the complete sequence of temperature sections by averaging the temperature between the sea surface and the depth of the 26 °C isotherm in the latitude band 1° S–5° N (Fig. 2*b*). Documenting heat storage in this way reduces noise associated with adiabatic vertical motion due to variability of currents[17]. The index (T_a) shows that heat storage during the second half of 1982 and early 1983 was very abnormal compared with the previous 3 yr in that the western Pacific heat pool had cooled by 1.3 °C from June 1982 to March 1983. The cooling occurred relatively rapidly during two stages, June–August 1982 and January–March 1983. Note that the cooling stages correspond to the winter months of either hemisphere. The average cooling over the 9-month period implies a local heat flux of $-20\ \mathrm{W\,m^{-2}}$, taking into account that the average depth of 26 °C was 90 m during that time.

Theoretically, the processes which control heat storage in the surface layer are heat fluxes through the sea surface, entrainment of cold water from the thermocline and advection. Methods of assessing the magnitude of these processes from existing data have errors of the order of $20\ \mathrm{W\,m^{-2}}$, which prevents the determination of a heat budget to account for the observed cooling. Nevertheless, the plausibility of the three processes can be discussed. Surface fluxes and the possibility of colder water from deeper layers replacing displaced warm surface waters through upwelling and mixing will be discussed in a subsequent letter. Advection is discussed here.

The observed increase in eastward surface current (Fig. 2*a*) during the early part of the 1982–83 episode is qualitatively consistent with a model of warm pool migration into the central Pacific[1]. The model attributes increasing temperature in the central Pacific to anomalous eastward advection. By assuming an advective model, we can estimate the rate of this process from the XBT observations. A volume transport of $10\times10^6\ \mathrm{m^3\,s^{-1}}$ is required to remove the 110-m thick (Fig. 1*a*) layer of 28 and 29 °C water from the region 1° S–5° N, 140°–160° E over 6 months (June–December 1982). This volume transport could be largely accommodated by the 25–50% increase in strength of the NECC (Fig. 2*a*), and possibly other eastward currents

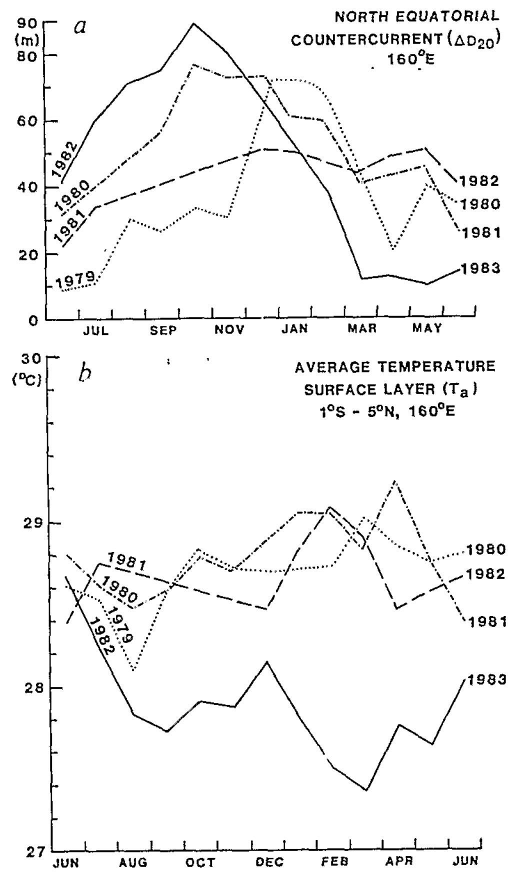

Fig. 2 *a*, Index of surface current speed in the North Equatorial Countercurrent estimated by the difference in depth of the 20 °C isotherm from the southern to the northern side of the current. *b*, Index of temperature in the mixed layer estimated by the vertically averaged temperature between the surface and the depth of the 26 °C isotherm. In *a* and *b* the values for August to November 1981 were interpolated.

at the Equator. In this sense, our observations are consistent with the model of temperature increase in the central Pacific.

But can the western Pacific cool down by advection? Mass continuity is partly maintained by the 50-m rise in the thermocline, which leaves approximately half of the volume transport ($5\times10^6\ \mathrm{m^3\,s^{-1}}$) to accomplish the $-20\ \mathrm{W\,m^{-2}}$ cooling (Fig. 2*b*) by horizontal advection. This cooling rate can be achieved by invoking a temperature gradient of 1.1 °C over a distance of 2,000 km along the trajectory of the current (assuming the width of the current is 5° of latitude). However, what is the source of the cooler water? Waters entering the heat pool in the North and South Equatorial Currents are a few degrees cooler during the winter months of either hemisphere than water leaving in the NECC. The cooler waters of the NEC and SEC flow to the NECC by way of a complex system of meridional currents near the western boundary, so that the temperature gradient of 1.1 °C per 2,000 km often exists along the trajectory. In support of a purely advective model, climatological maps of surface temperature[13] for winter of either hemisphere show an abundance of relatively cool waters near the head waters of the meridional currents. Furthermore, documentation of basinwide surface temperature anomalies during 1982–83[18] using a comprehensive XBT data set shows a dominant spatial pattern of western Pacific cooling extended eastward along the NECC axis. Thus, the purely advective model is possible for the western Pacific, as it is for the central Pacific[1], despite small horizontal temperature gradients in the region.

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