“The Origin and Pathway of Nino3 Water Estimated using Products of the ECCO Data Assimilation System”

I.Fukumori, T.Lee, D.Menemenlis, L.-L. Fu, and the ECCO Group
Jet Propulsion Laboratory, California Institute of Technology
Consortium for Estimating the Circulation and Climate of the Ocean (ECCO/JPL-MIT-SIO)

ABSTRACT

The origin and pathway of water occupying the surface layer of the eastern Equatorial Pacific (“Nino3”) are investigated using circulation estimates of the ECCO Ocean Data Assimilation System ("ECCO-2"). The water mass is tracked by a passive tracer and its adjoint that describe where the water goes and where the water came from, respectively. 30% more originate from the southern hemisphere than the north. 80% of the water originating from the subtropics passes the western boundary current. Intra-seasonal variability significantly alters the pathway by stirring the water masses.

Introduction

Subtropical-tropical exchange has been identified as a possible mechanism underlying prolonged El Niño conditions in the early 1990s and other interdecadal fluctuations of the tropical Pacific Ocean [2]. In this scenario, anomalous water subducted in the subtropics is advected over a decade to low latitudes changing the equatorial thermal structure and thereby affecting sea surface temperature and consequently El Niño. The nature of this exchange has been a subject of many investigations. Here, we examine this problem focusing on the origin and pathway of the water mass occupying the surface layer within “Nino3” (150°W~90°W, 5°N~5°S), a region central to El Niño. The water mass is tracked over time using a passive tracer and its adjoint using circulation estimates of the ECCO-2 ocean data assimilation system [1].

ECCO-2 Assimilation System [1]

A prototype, routine, global-ocean, data assimilation system has been established so as to monitor ocean circulation and to better understand processes underlying the seasonal-to-interannual changes. The system, “ECCO-2”, is a product of the consortium, "Estimating the Circulation and Climate of the Ocean" (ECCO; http://www.ecco-group.org), and employs a general circulation model (MITgcm) in a near-global domain (78ºS~78ºN) with high resolution (1º × 0.3º in the tropics, 46 levels with 10m-resolution near the surface, total grid=360×224×46 ≈ 4×10⁶.) The GM isentropic mixing scheme and the KPP mixed-layer formulation are employed. The model is forced by NCEP reanalysis products (time-mean replaced with those of COADS) with relaxation of temperature and salinity at the sea surface towards observed values. Satellite sea surface height and in situ hydrographic data are assimilated using a hierarchy of methods (Table 1). ECCO-2 products are regularly updated (e.g., Fig 1) and are available via the Live Access Server at http://www.ecco-group.org/las.

	Control	d.o.f.	Data Assimilated	period
GF	mixing coefficients, initial TS, forcing	17	temperature (XBT, PALACE, WOCE, TAO, HOTS, BATS)	1993-2000
PKF/PS	time-varying wind	10^7	TOPEX/Poseidon, Jason-1, XBT	1993-present
Adjoint	forcing (wind and heat flux), initial TS	10^7	TOPEX/Poseidon, Levitus TS	1997-2001

Table 1: ECCO-2 Assimilation System
The hierarchy of data assimilation methods allows estimation of different elements of the model uncertainties in a computationally efficient manner. (GF: Green’s function, PKF/PS: partitioned Kalman filter and smoother.)

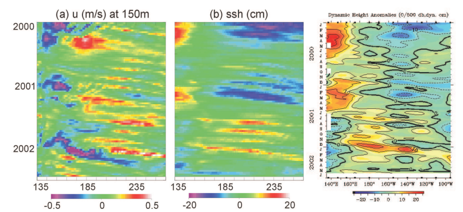

Fig 1: Zonal Velocity and Sea Level Anomalies along 0°N
The regular routine updates of ECCO-2 (left two) provide near real-time analyses of the complete state of the ocean that complement observations (e.g., TAO on right).

Passive Tracer and Its Adjoint

A passive tracer can be utilized to track the circulation of a body of water;

$$\partial c/\partial t = -\vec{\mathbf{u}}\cdot\nabla c + \nabla\cdot(\kappa\nabla c) \qquad (1)$$

By using the same numerical algorithm, velocity field $\vec{\mathbf{u}}$, and mixing tensor κ that operate on temperature and salinity, the tracer ***c*** uniquely follows the advection and mixing of the water mass that the tracer occupies (Fig 2). In particular, the evolution of tracer ***c*** describes ***where the water goes***.

The adjoint of the tracer ***c’*** describes ***where the water came from***. This can be understood by considering the sensitivity of a passive tracer content within the water volume to tracer distribution in the past. A sensitivity would exist only for locations where some of its water made its way to the target volume. This sensitivity can be associated with the adjoint of the tracer. For instance, consider the sensitivity of tracer content at a particular location *i* at a particular time *T;*

$$J = \sum_x e_i^T c(T) \qquad (2)$$

where $e_i = 0$ except $e_i = 1$ at location *i*. The sensitivity of *J* to tracer distribution *N* time-steps in the past $c'(T-N)$ is,

$$c'(T-N) \equiv \frac{\partial J}{\partial c(T-N)} = \frac{\partial c(T-N+1)^T}{\partial c(T-N)} \frac{\partial c(T-N+2)^T}{\partial c(T-N+1)} \cdots \frac{\partial c(T)^T}{\partial c(T-1)} \frac{\partial J}{\partial c(T)} \qquad (3)$$

where $\partial J/\partial c(T) \equiv c'(T) = e_i$. Eq (1) in finite difference form may be written as $c(t) = \mathbf{A}(t-1)c(t-1)$ Then, $\partial c(t)^T/\partial c(t-1) = \mathbf{A}^T(t-1)$ etc and (3) may be written as,

$$c'(T-N) \equiv \partial J/\partial c(T-N) = \mathbf{A}^T(T-N)\mathbf{A}^T(T-N+1)\cdots\mathbf{A}^T(T-1)e_i \qquad (4)$$

The operations conducted from right to left $c'(t-1) = \mathbf{A}^T(t-1)c'(t)$ etc define the adjoint, and in continuous form can be written as

$$-\partial c'/\partial t = +\vec{\mathbf{u}}\cdot\nabla c' + \nabla\cdot(\kappa\nabla c') \qquad (5)$$

The sensitivity, Eq (3), is obtained by integrating (5) backwards in time from time *T*, with end condition $c'(T) = e_i$.

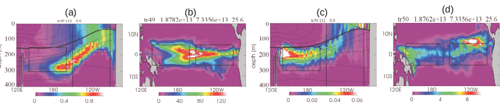

Fig 2: Testing Passive Tracer (a, b) and Its Adjoint (c, d)
The origin of water in Nino3 (top 10m) on 31 Dec. 2000 is examined using a passive tracer (left) and adjoint tracer (right), respectively integrated by the ECCO-2 circulation estimates. The passive tracer is released 1 Jan 2000 in the thermocline in the western equatorial Pacific (140°E~160°W, 5°N~5°S, 150~300m). The adjoint tracer is initialized in Nino3 on 31 Dec 2000. Both tracers are initialized to unity (in arbitrary tracer unit; ATU). Figures show zonal sections (a, c) and depth-integrated plan views (b, d) for the respective results after 1-year integration. Both results show that 25.6% of the Nino3 water originated from the western equatorial thermocline 1-year prior.

Origin and Pathway of Nino3 Water

The adjoint (5) and the forward (1) passive tracer equations are integrated backwards and forward in time, respectively, to deduce where Nino3 water came from and where it went. The two equations are initialized with uniform tracer distributions in Nino3 and are integrated using ECCO-2 circulation estimates. To estimate the climatological mean circulation and pathway, tracer distributions described below are averages among separate 10-year integrations initialized at the end of each year from 1991 to 2000 for the adjoint, and from 1981 to 1990 for the forward passive tracer, unless otherwise noted. Circulation estimates of the ECCO-2 control run (unassimilated) are utilized in the discussions below to achieve the 10-year averaging. Individual integrations using results of the TOPEX-Poseidon assimilation are similar to the those based on the control run.

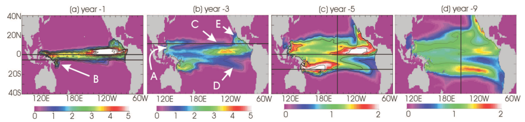

Fig 3: Column Integrated Nino3 Adjoint Tracer (ATU/m²)

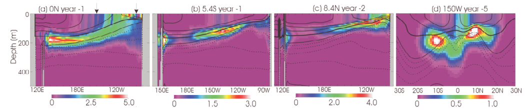

Fig 4: Vertical Sections of Adjoint Tracer (ATU/m³)
Contours are potential density (C.I.=1 kg/m³; thick curve is σ=25 kg/m³).

Discussion

Most of the Nino3 water originate to the west of the eastern equatorial Pacific and away from the Equator along distinct pathways (Fig 3). These routes include the low latitude western boundary currents (LLWBCs) and interior pathways of the northern and southern hemispheres (A, B, C, D). A coastal pathway east of Nino3 is also evident along Central and North America (E). The circulation in the interior and LLWBCs is largely confined to within the thermocline (Fig 4), whereas the coastal pathway mostly resides in the surface layers. In each hemisphere, the LLWBCs carry 70~80% of the meridional transport (Table 2). The coastal transport in the northern hemisphere is relatively small. On average, nearly 30% more of the Nino3 water originate from the southern hemisphere than the northern hemisphere.

Mean transit times (mode) between the subtropics and Nino3 is about 10-years (Fig 5). Approximately 16% of the Nino3 water are found in the surface mixed-layer 10-years prior in nearly equal amount in the eastern basin of each hemisphere (Fig 5). The outcropped water in the northern hemisphere is slightly less dense and extend further westward than those found in the southern hemisphere.

The intra-seasonal variability play a significant role in stirring the water mass, resulting in a much larger interior meridional transport than the pathway inferred from either seasonally averaged or time-mean circulation (Fig 6, Table 2).

The adjoint tracer elucidates the “sloshing” of the thermocline associated with the ‘97-’98 El Niño (Fig 7). In particular, the western end of the water mass coincides with the movement of the 28°C isotherm [3].

The forward passive tracer (Fig 8) illustrates where Nino3 water goes after reaching Nino3. The water circulates westward away from the equator in the upper ocean to the subtropics, above the subtropical-tropical pathway identified by the adjoint tracer (Fig 4).

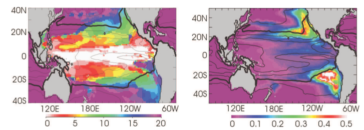

Fig 5: Mode Transit Time of Column Integrated Adjoint Tracer (years) (left) and Adjoint Tracer within the Mixed Layer at Year -10 (ATU/m²) (right).
Contours are potential density (C.I.=1 kg/m³; thick curve is σ=25 kg/m³).

Latitude	Experiment	Total	LLWBC	Interior	CRD
5.7ºS	Average	-29.0 [-38%]	-23.0 (79%)	-6.0 (21%)	
	Steady	-30.0 [-39%]	-27.9 (93%)	-2.2 (7%)	
	Seasonal	-30.1 [-39%]	-27.0 (90%)	-3.1 (10%)	
8.4ºN	Average	21.9 [29%]	15.8 (72%)	4.0 (18%)	2.1 (10%)
	Steady	16.7 [22%]	17.3 (104%)	-0.1 (0%)	-0.6 (-3%)
	Seasonal	20.3 [26%]	19.5 (96%)	1.4 (7%)	-0.6 (-3%)

Table 2: Net 10-year Meridional Transport of Nino3 Adjoint Tracer (10^{12} ATU)
Positive value indicate northward transport backwards in time. Percentages in parentheses are those of each total transport across the section. Percentages in brackets in the total column are percentages of the global net adjoint tracer.

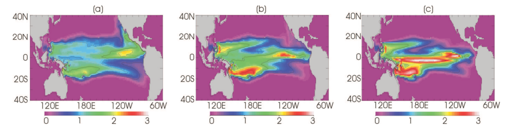

Fig 6: Column Integrated Nino3 Adjoint Tracer (ATU/m²) at Year -5.
Mean distribution (a), seasonal circulation (b), time-mean circulation (c).

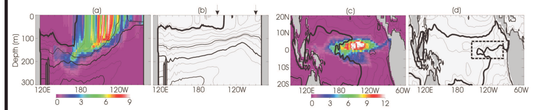

Fig 7: Zonal Section (a) (ATU/m³) and Column Integrated Nino3 Adjoint Tracer (c) (ATU/m²) 1-year Prior Starting from 31 Dec 1997. *Contours are temperature (c.i.=1°C, thick curve is 28 °C). Contours in right panel are SST. Also shown are temperature section (b) and SST (d) of 31 Dec 1997.*

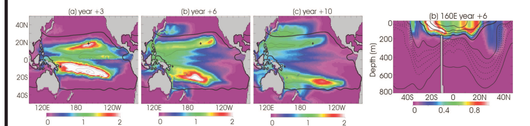

Fig 8: Column Integrated Nino3 Passive Tracer (ATU/m²) and Meridional Section (ATU/m³)

Conclusion

Subtropical-tropical mass exchange is investigated using a passive tracer and its adjoint based on circulation estimates of an ocean data assimilation system. In the absence of sources and sinks, the evolution of passive tracers describes *where the water goes*. In comparison, evolution of the adjoint tracer can be identified as describing *where the water came from*. The tracers reflect effects of both advection and mixing.

Nearly 80% of the subtropical water mass reaching Nino3 travel via the low latitude western boundary currents. The remaining 20% directly reaches the tropics by the interior pathway. Mean transit times are approximately 10-years.

Intra-seasonal variability of the tropical ocean significantly alters the mean pathway that reaches Nino3. In particular, inferences made by seasonal and/or time-mean circulation significantly underestimates the magnitude of the interior pathways.

References

[1] Fukumori, I., *et al.,* A prototype GODAE routine global ocean data assimilation system: ECCO-2, *“En route to GODAE”, Biarritz, France, 2002.*
[2] Gu, D. F., and S. G. H. Philander, Interdecadal climate fluctuations that depend on exchanges between the tropics and extratropics, *Science*, **275**, 805-807, 1997.
[3] Picaut, J., *et al.,* Mechanism of the zonal displacements of the Pacific warm pool: Implications for ENSO, *Science*, **274**, 1486-1489, 1996.