Re-emergence of anthropogenic carbon and Pacific warm pool acidification

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Science Question

- *Ishii et al.* [2009] evaluated time series of carbon spanning decades in the warm pool region; DIC is increasing by 9 μmol/decade (driving drop in Ω_{arag}), but this cannot be explain by local air-sea CO_2 fluxes
- Mechanism proposed in Discussion section of *Ishii et al.* [2009]: increasing DIC trend in warm pool is entering ocean in extra-tropics, and transported to warm pool
- Here we apply model to identify dynamical and thermodynamical controls on inter-gyre exchange of anthropogenic carbon and equatorial Pacific acidification

Warm pool corals: "biodiversity hot spot"

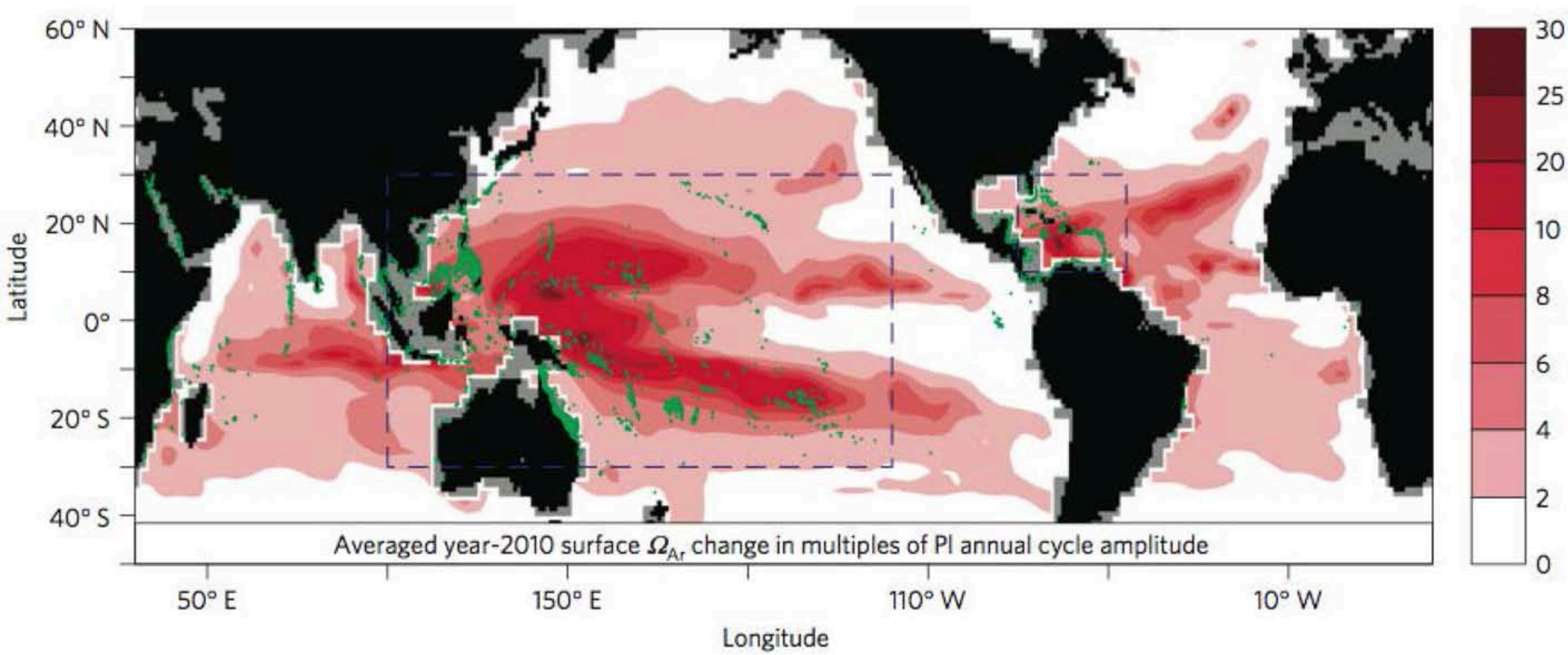


Fig. 1. *Change in surface Ω_{arag} between preindustrial and year 2010, expressed as multiples of the annual Ω_{arag} amplitude in the preindustrial; based on MPI-ESM simulations [from Friedrich et al., 2012]. Note the large degree of variation across the coral reef regions (shown as green dots), from 2–10x the preindustrial amplitude.*

Why might a warm pool acidification trend be important?

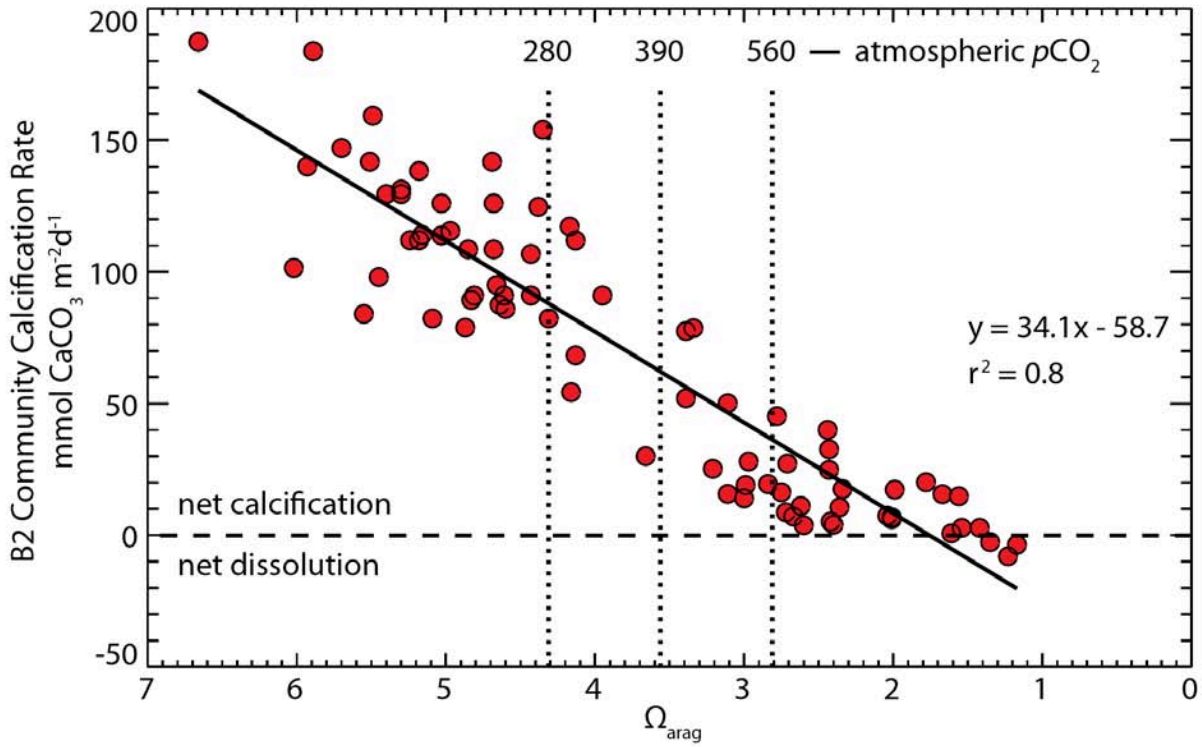
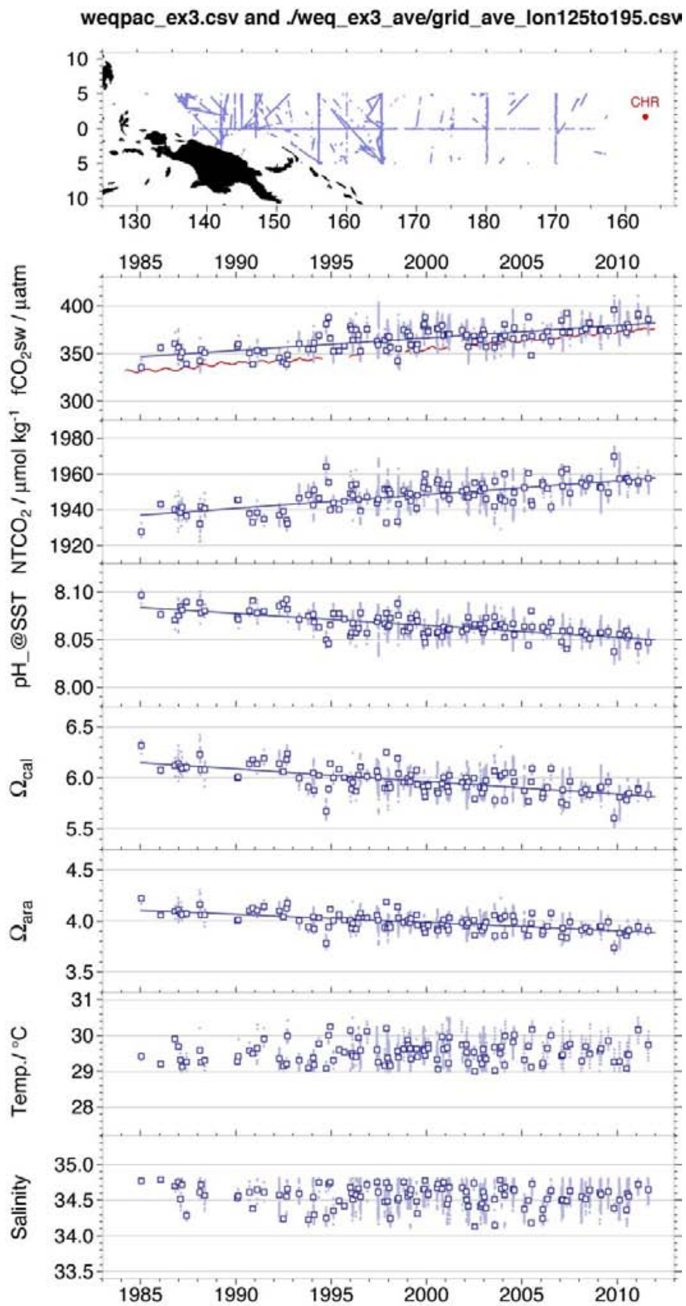


Figure 2. Changes in coral community calcification rate in the Biosphere 2 coral reef mesocosm as a function of decreasing aragonite saturation state (Langdon et al., 2003). Atmospheric pCO_2 levels that roughly correspond with the Ω_{ar} values are shown: 280 ppm = pre-industrial, 390 = present day, and 560 = 2X pre-industrial. Note that once Ω_{ar} reached a value of 1.0–2.0, the coral community shifted from net calcification to net dissolution. *Figure drawn from data provided by Chris Langdon*

Langdon et al. (2004)
Kleypas and Yates (2009)



Observational study of Ishii et al. [2009; 2012]:
Evaluated all available carbon measurements from the warm pool area in order to identify rate of acidification of surface waters there

Table 1: Decadal trends calculated using linear regression and data in Ishii et al. [2009]

Parameter	Unit	1985	2005	Change	Change per year
SST	degrees_C	29.5	29.5	0.0	0
SSS		34.5	34.5	0.0	0
DIC	micro-mol/kg	1906.7	1925.0	18.3	0.91
pCO_2	micro-atm	345.0	375.0	30.0	1.5
TA	micro-mol/kg	2265.9	2265.9	0.0	0
pH@SST		8.0855	8.0570	-0.0285	-0.0014
$\Omega_{calcite}$		6.153	5.865	-0.288	-0.0144
$\Omega_{aragonite}$		4.111	3.918	-0.193	-0.0096

Main result: Acidification is occurring, and is driven by increases in DIC concentrations;

DIC increase: ~9 µmol/decade

However, can't be explained by local air-sea fluxes of CO2 over the warm pool.
Speculation: DIC increase is coming from the subtropical mode water formation regions!

Proposed pathway of anthropogenic DIC delivery to western Pacific warm pool from subtropics:

Step 1: Anthropogenic DIC in extra-tropics subducts and undergoes intergyre exchange to the equatorial region within the thermocline

Step 2: For the Pacific, anthropogenic DIC "re-emerges" within the eastern equatorial Pacific cold tongue; scaling arguments suggest that in the mid-1990s, this was of order ~0.4 PgC/year

Step 3: Westward advection within South Equatorial Current, with simultaneous "lightening" resulting from surface buoyancy fluxes

Apply ocean carbon cycle model:

NEMO-PISCES model of *Aumont and Bopp* [2006]
ORCA2 configuration: 2 degree resolution, with enhanced meridional resolution of 0.5° near the equator
Global model has been widely used in hundreds of publications

Includes representation of anthropogenic carbon transient in ocean (taken as difference between contemporary and natural signals)

Model has been extensively evaluated by *Iudicone et al.* [2012] for global anthropogenic transient in carbon ; was also evaluated for case of Southern Ocean in study of *Iudicone et al.* [2011];

Step 3: Westward transport of EUC water within the South Equatorial Current (SEC), with simultaneous "lightening" through buoyancy gain

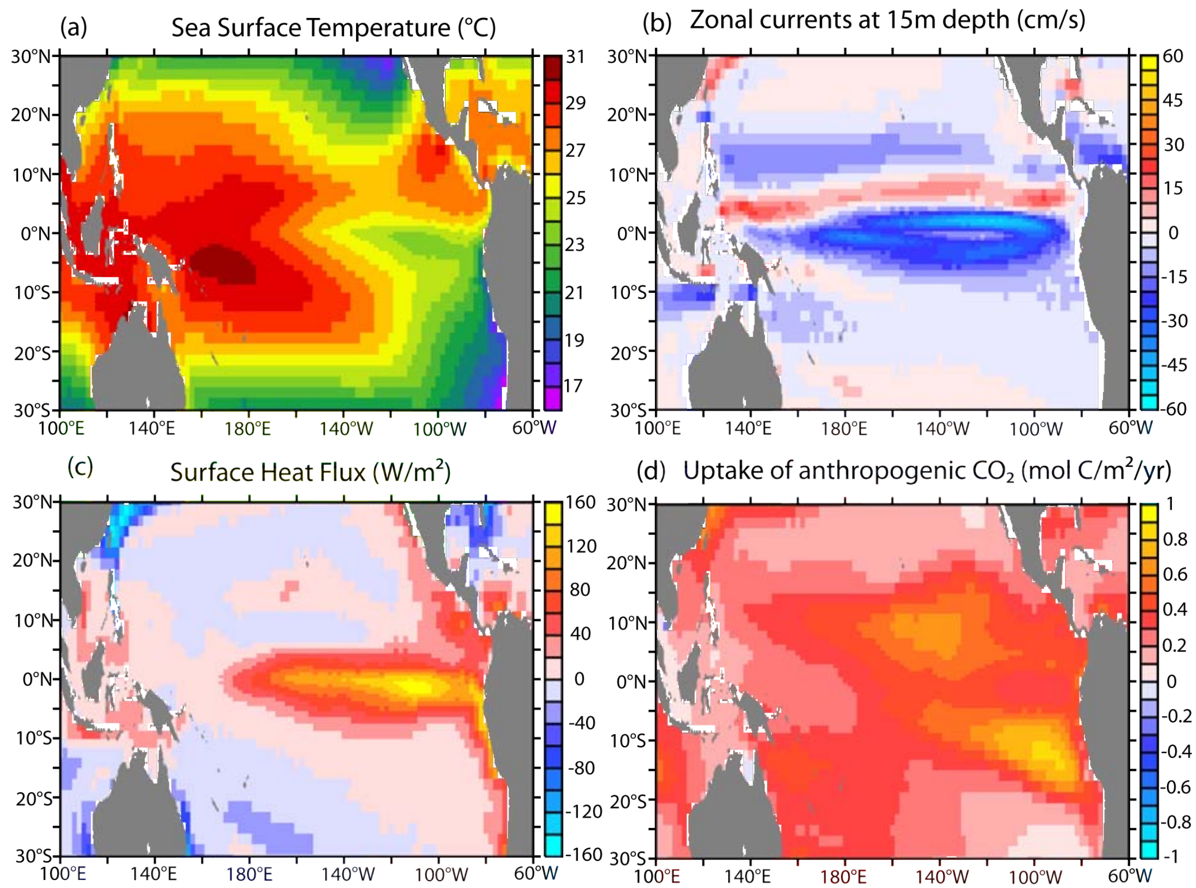
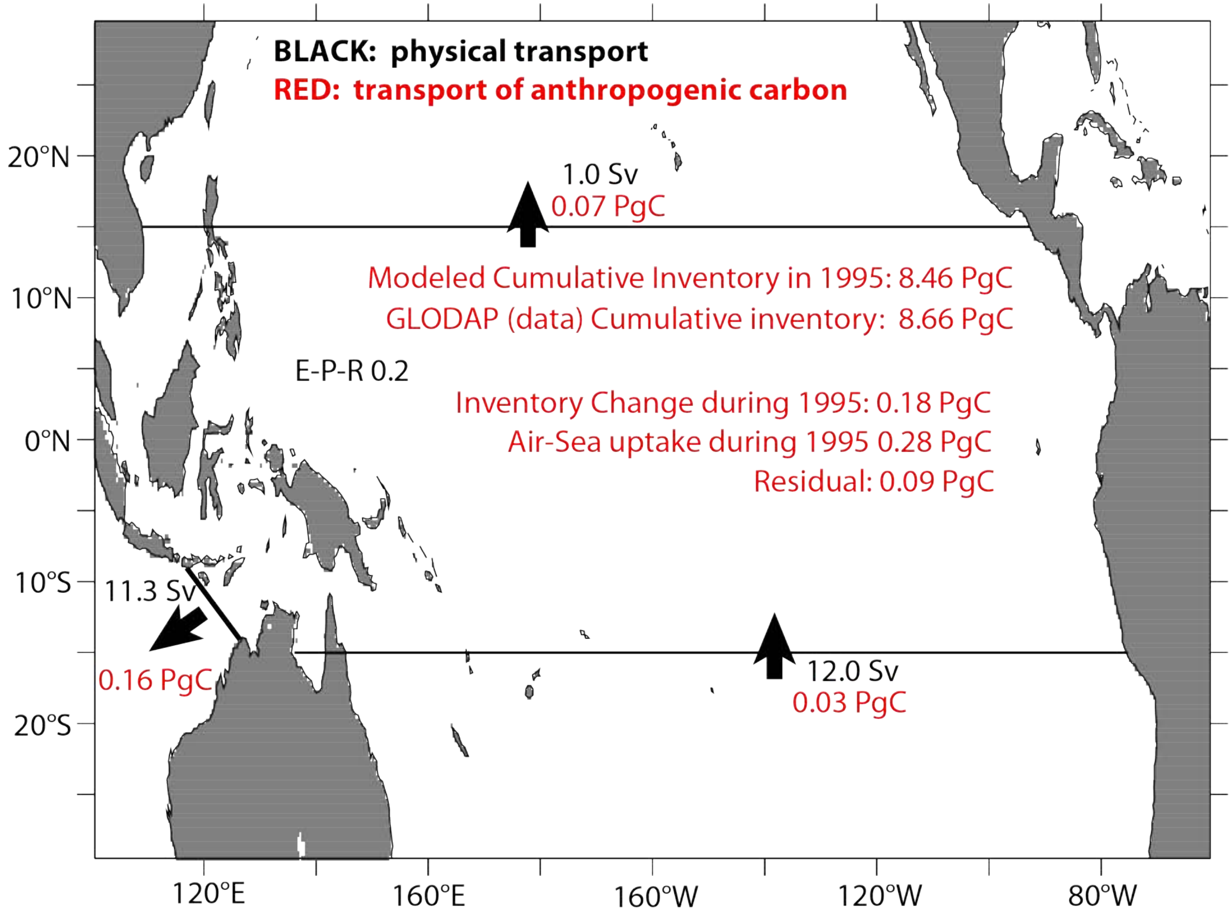


FIGURE 2: annual mean output from NEMO-PISCES model in 1995

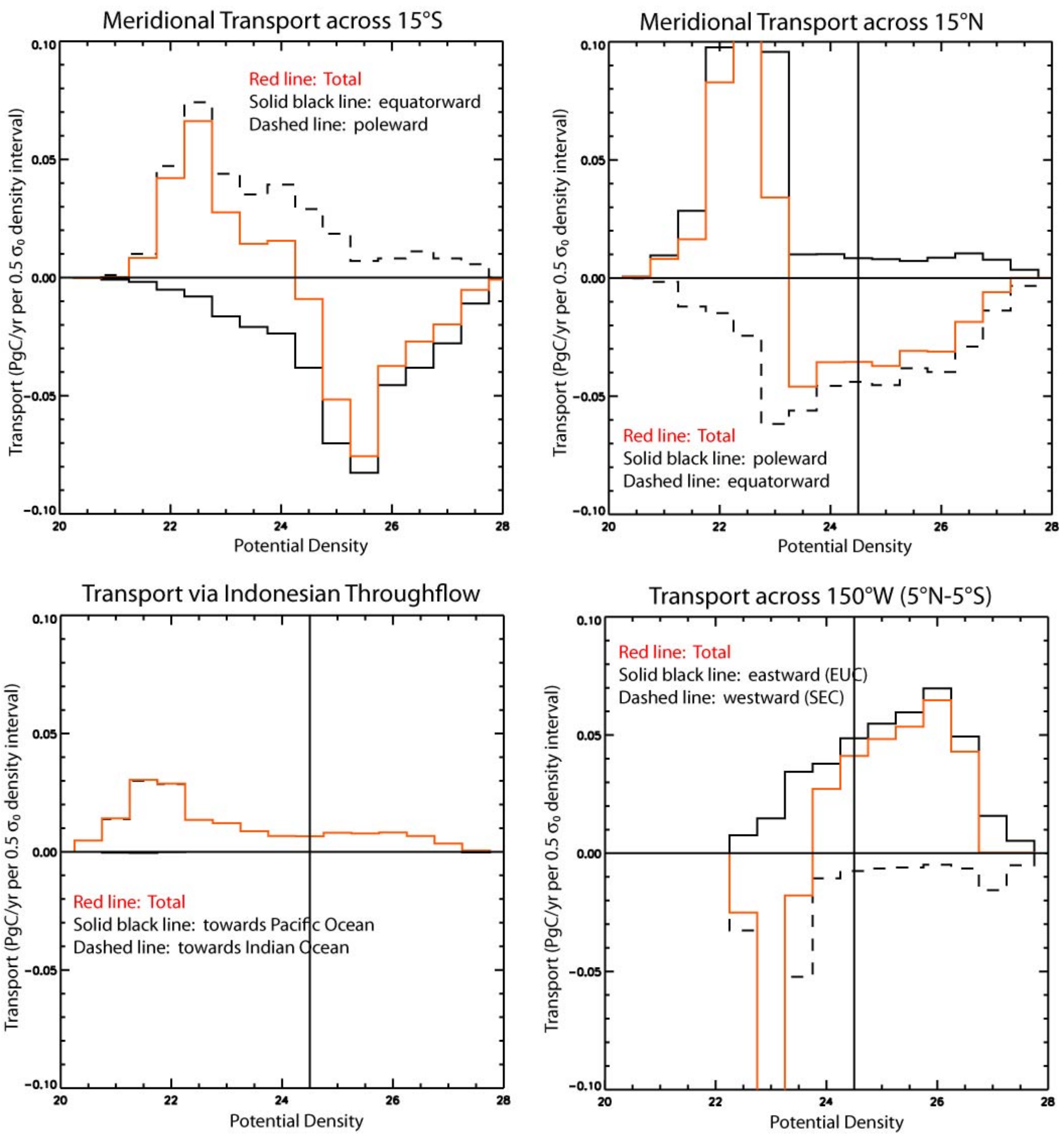
Schematic of depth-integraged horizontal transports into and out of Equatorial Pacific "box" (15°N-15°S)



Given interest in "intergyre exchange" of anthropogenic carbon, will want to define gyre boundaries to be at 15°N and 15°S

For carbon transports integrated across sections at 15°N and 15°S, first impression is of weak transports

Advective Transports of Cant in 1995 for model



Transport of anthropogenic carbon in ORCA2-PISCES, binned by 0.5 σ_0 units

Positive values indicate poleward transport of anthropogenic carbon

Lower right panel shows Eastward (solid black) and Westward (dashed black) transport of anthropogenic carbon across 150°W between 5°N-5°S

"Re-emergence" (eastward transport) is 0.4 PgC/year, and SEC transport westward is ~0.3 PgC/year

Largely confirms Ishii's idea

Important points with first round of model diagnostics:

For both 15°N and 15°S, model reveals importance of STCs
Interior (thermocline) transport of anthropogenic carbon towards the equator, and surface (Ekman) transport of anthropogenic carbon away from equator

Model produces 9 μmol/decade increase in DIC concentrations in the warm pool region, consistent with inference of *Ishii et al*. [2009] from observations

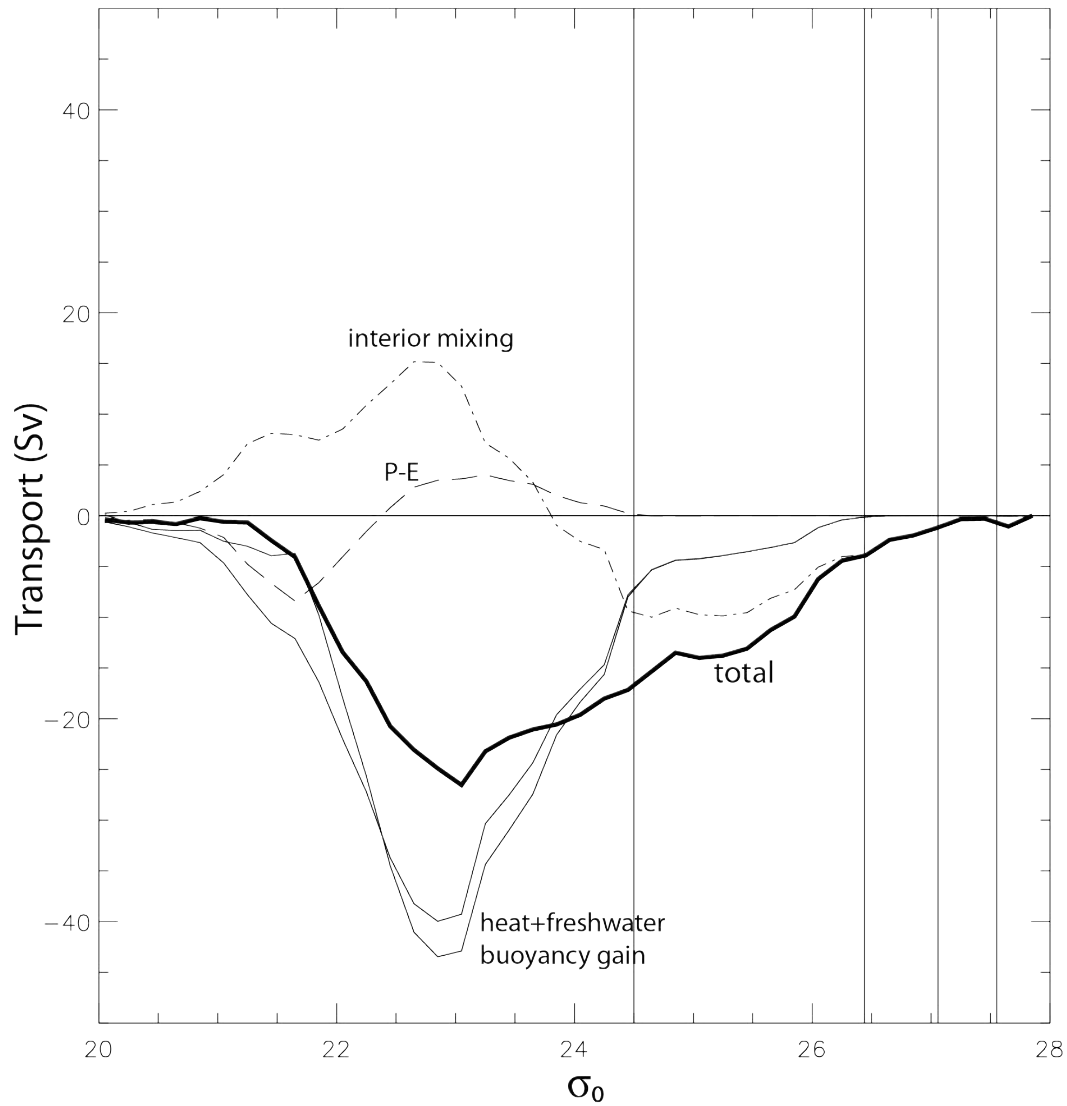
Analysis at 150°W supports (large!!!) re-emergence of anthropogenic carbon of subtropical origin in cold tongue of 0.4 PgC/yr in 1995, with this being of order ~20% of the total uptake rate of anthropogenic carbon by the ocean.

Likewise the model diagnostics at 150°W supports the idea of a westward transport in the South Equatorial Current of order 0.3 PgC/yr in 1995

Watermass transformation diagnostics provide *thermodynamic* view of upwelling in equatorial Pacific

Mixing largely opposes impact of surface buoyancy forcing

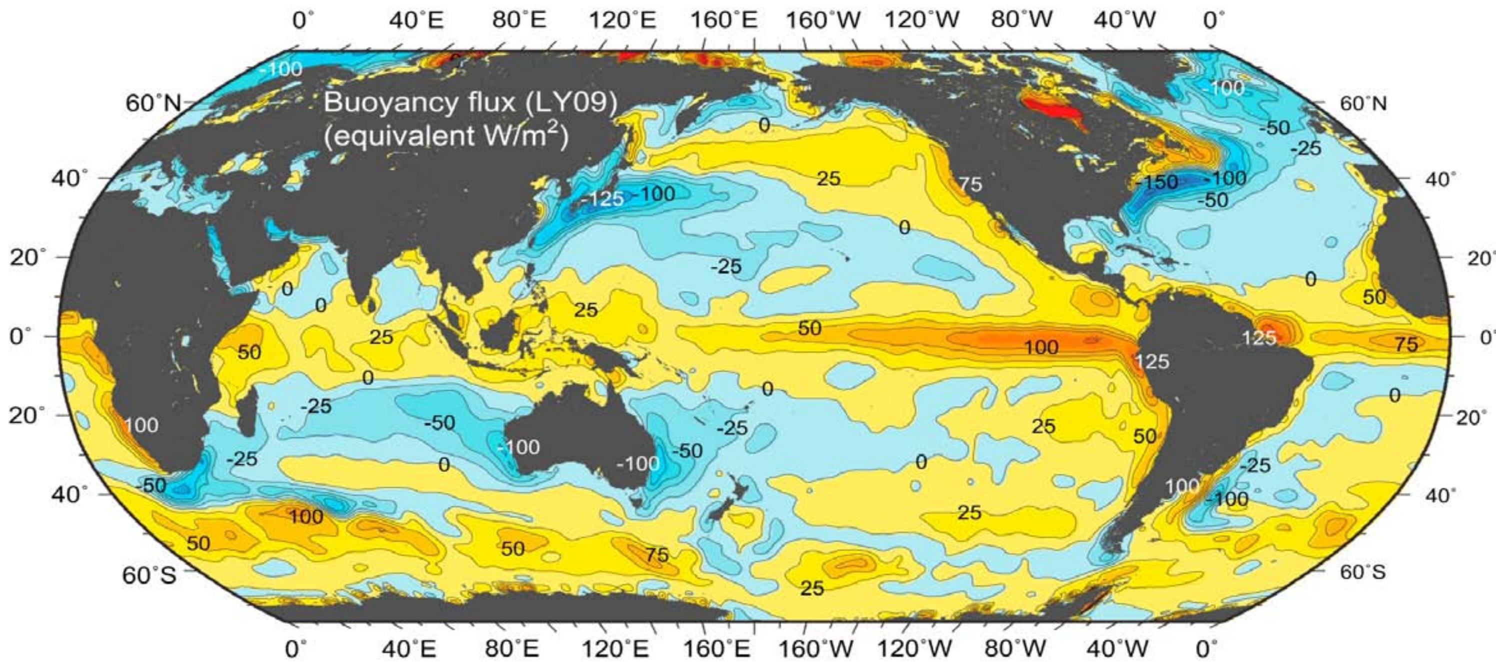
Watermass transformations over 15°S-15°N for EqPac
Interpret as *diapycnal transports of water*



Positive values: water densified

Negative values: water lightened

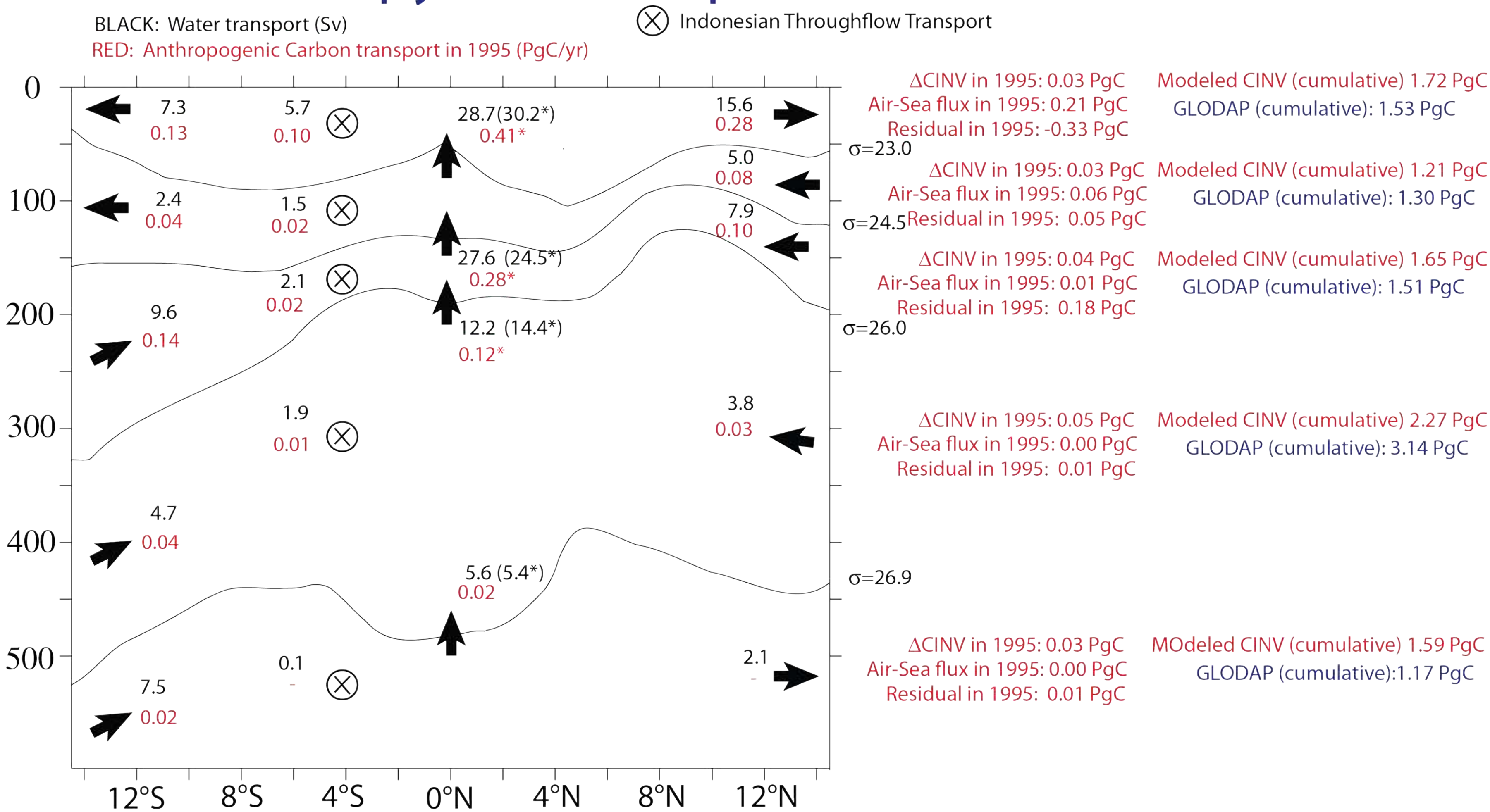
Buoyancy input over large scales, with positive values representing buoyancy gain by the ocean, and negative values buoyancy loss



Annual mean air–sea buoyancy flux converted to equivalent heat fluxes (W/m^2), based on Large and Yeager (2009) air–sea fluxes. Positive values indicate that the ocean is becoming less dense. Contour interval is 25 W/m^2. The heat and freshwater flux maps used to construct this map are in the online supplement to Chapter 5 (Figure S5.8).

TALLEY

Schematic of STC along-isopycnal transports and across-isopycnal transports in 1995 (15°S<Y<15°N)



The residual is computed as: lateral divergence + gain + air-sea.
The missing terms in the residual are: mixing divergence + diapycnal divergence

What have we learned from the model?

Analysis of transport at 150°W (5°N-5°S) supports idea of large "re-emergence" of thermocline anthropogenic carbon to surface waters of equatorial Pacific; acidification from below

"Re-emergent" carbon into surface equatorial waters is larger than uptake of anthropogenic carbon by gas exchange

Large "intergyre" exchange of anthropogenic carbon at 15°N and 15°S, with large degree of compensation between equatorward interior thermocline flow and poleward surface Ekman flow

…but what about extra-tropical dynamical controls on anthropogenic carbon?

What are expected extra-tropical source regions for re-emergence anthropogenic carbon?

Lagrangian view of Pacific circulation: NCEP-forced ORCA2-NEMO model

Rodgers et al. [2003]: EUC source regions identified via reverse Lagrangian trajectories

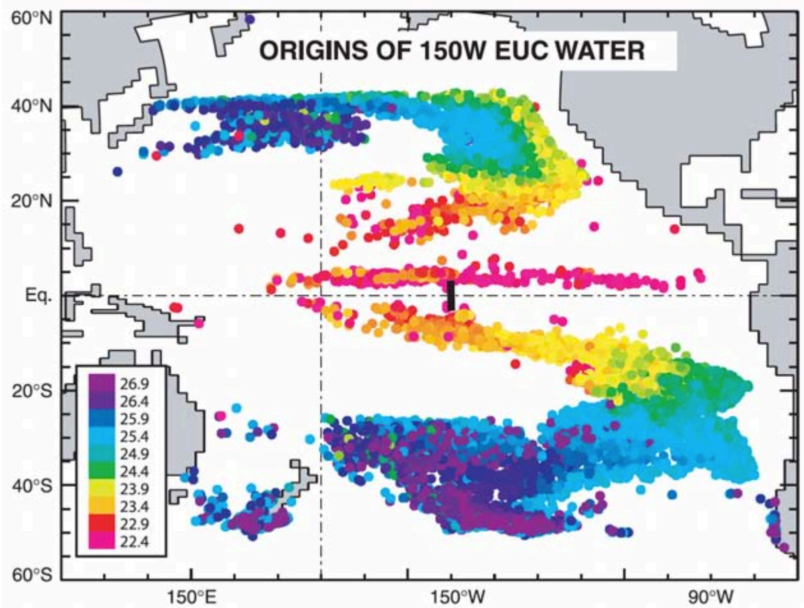


Figure 1. Source regions of the EUC identified with Lagrangian trajectories. The particles were released within the EUC at 151°W (see text for EUC definition; the section at 151°W is marked with a solid black line), and advected with the reverse model circulation fields until they intersected the base of the mixed layer (defined using a 0.01 difference in density in σ_0 units). The densities of the particles within the EUC at 151°W are shown in color.

Through the mid-1990s, a number of papers developed the framework of "re-emergence"

Figure shows where EUC waters (31 Sv transport) crossing 150°W detrained from the mixed layer

Colors show density of water as it enters the mixed layer as a consequence of reverse Lagrangian trajectory analysis

Conclusions

- Model results consistent with idea proposed by *Ishii et al.* (2009) that large-scale intergyre exchange connected to warm pool acidification
- Re-emergence of anthropogenic carbon in cold tongue region is critical part of this process; re-emergence in mid-1990s of order 0.4 PgC/year
- "water mass transformations" and "diapcynal transport of carbon" are important to science understanding of ventilation/emergence pathways
- Future work: will benefit from Lagrangian diagnostics ("connectivity")