Oceans

Carbon

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Noble Lectures, Toronto 2019

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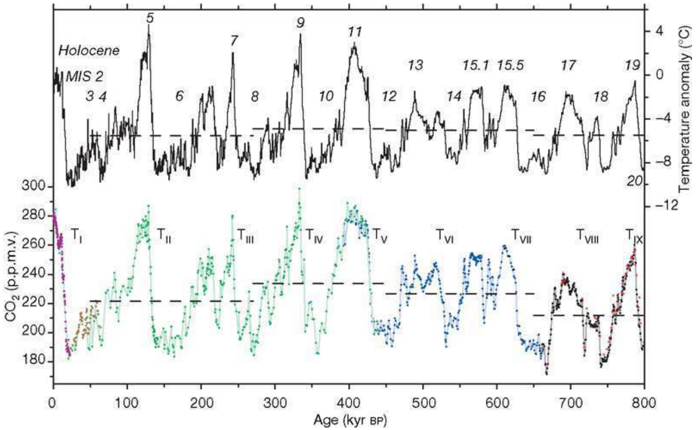
Temperature and CO_2

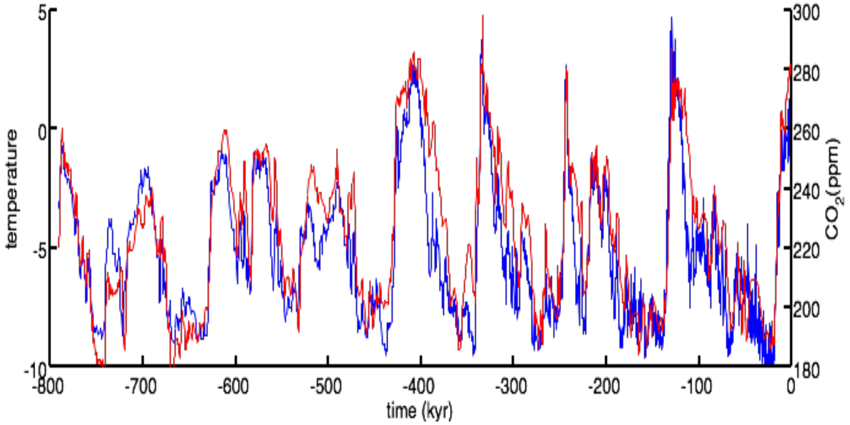


- Temperature is reconstructed by proxy:
  Isotopic fractions of $^{18}\delta O$ and deuterium (^{2}H) in snowfall are temperature-dependent.
- CO_2 lags temperature, especially during the cooling phase.
- CO_2 at LGM about 190 ppm, a major contributor to cool glacial climate.

From DOME (Antarctica). Luthi et al (2008).

Temperature and CO_2

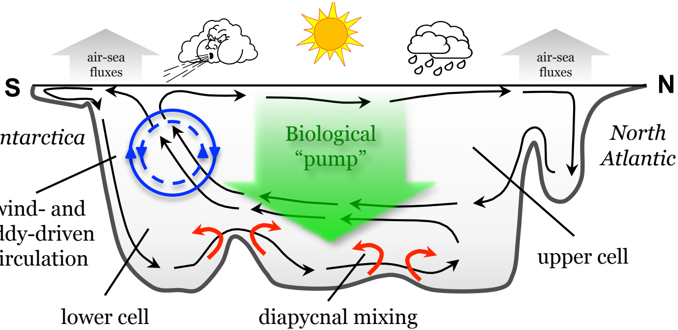
From EPICA (European Project for Ice Coring in Antarctica) www.climatedatainfo



Temperature blue, CO_2 red

CO_2 lags temperature, especially during the cooling phase.

Carbon Cycle and Ocean Circulation



Reference?

- High surface carbon levels in equatorial regions.
  - (a) Carbon flux into atmosphere.
  - (b) Carbon sinking in biological pump.
- ‘Remineralization’ at depth
- Advection and upwelling into Southern Ocean.
- Low surface carbon levels at higher latitudes.
  - (a) Carbon flux from atmosphere.
  - (b) Transport into abyssal ocean.

- In glacial climate more drawdown in Southern Ocean.
- More carbon transport and sequestration in deep ocean.
- Atmospheric CO_2 levels lower.

The Biological Pump

Biological production removes carbon from surface waters to form organic material. As organisms die and sink to the ocean interior, they decompose, releasing the carbon once again to the water, where it may be advected back to the surface.

Photosynthesis in upper ocean takes up carbon:

$$\boxed{H_2O + CO_2 + Nutrients \Longrightarrow CH_2O + O_2}$$

Needs light, and in reality more complicated. Nutrients are phosphates, nitrates, iron, silica

Organic matter sinks, and decomposes and respires (remineraliation):

$$\boxed{CH_2O + O_2 + Nutrients \Longrightarrow H_2O + CO_2}$$

Carbon then advected back to the upper ocean by the circulation.

The Biological Pump

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Photosynthesis

Ingredients | *Product*

Sunlight +
$H_2O + CO_2 +$ Nutrients → "CH_2O" + O_2

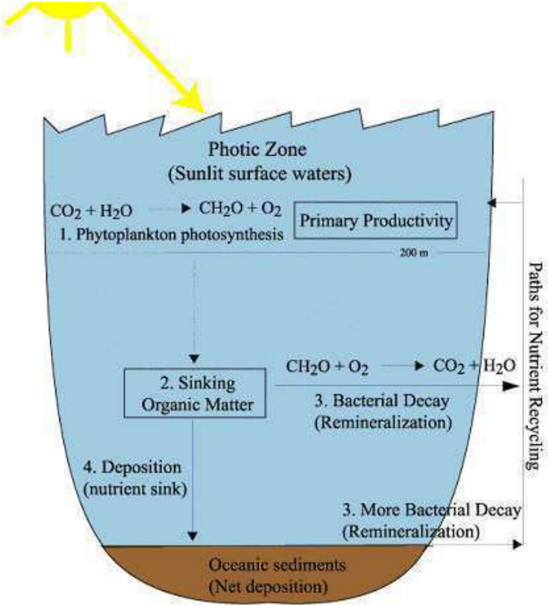
Water — Carbon dioxide — Nitrate NO_3, Phosphate PO_4, Iron, Silica, *among others* — "Organic matter" — Oxygen

Decomposition (and respiration)

Products | *Ingredients*

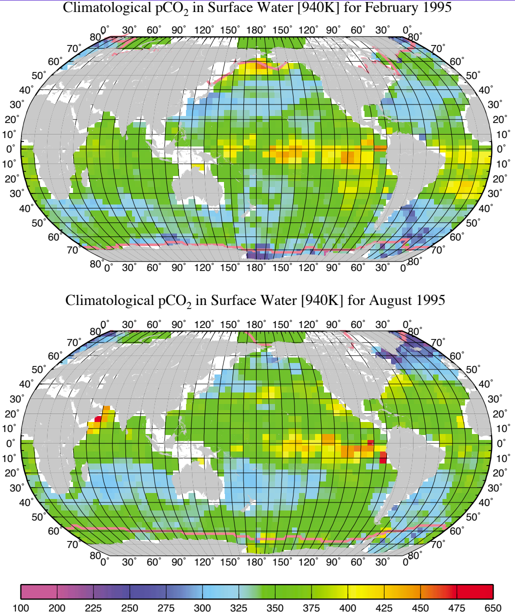
Chemical energy +
$H_2O + CO_2 +$ Nutrients ← "CH_2O" + O_2

Water — Carbon dioxide — Nitrate, Phosphate, Iron, Silica — Organic matter (dead or alive) — Oxygen



Surface Carbon (PCO_2)

Takahashi et al 2002



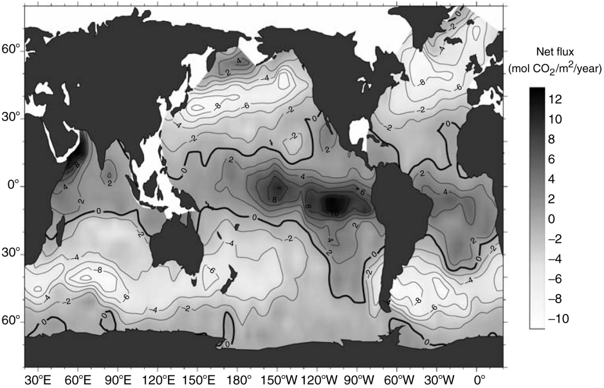
High values (red) in equatorial Pacific — flux to the atmosphere

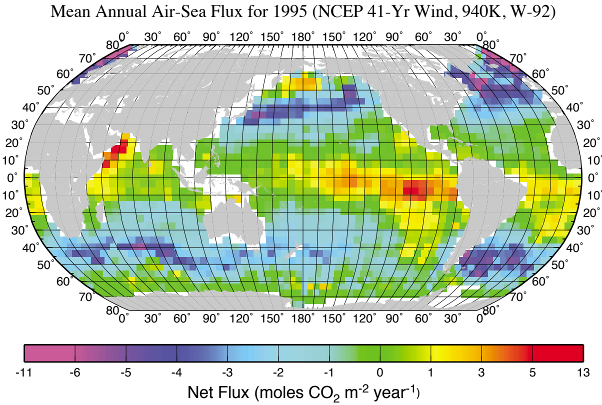
Low values (green → blue → purple) — flux to ocean.

Atmosphere-Ocean Carbon Fluxes

From ocean to atmosphere at low latitudes (dark or red shading).

From atmosphere to ocean at high latitudes (light or blue shading).





Sabine and Feely (2007), Takahashi et al (2002).

Simplified Carbon in for a Model

after Ito and Follows (2005).

Dissolved Inorganic Carbon (C) and Phosphate (P) only. Advected, diffused, and sedimented.

Phosphate:

$$\frac{\mathrm{D}P}{\mathrm{D}t} = \kappa \frac{\partial^2 P}{\partial z^2} + \frac{\partial}{\partial z} F_{\mathrm{bio}}$$

Carbon:

$$\frac{\mathrm{D}C}{\mathrm{D}t} = \kappa \frac{\partial^2 C}{\partial z^2} + R_{ed} \frac{\partial}{\partial z} F_{\mathrm{bio}}$$

F_{bio} is the downward flux of sinking organic material due to biological flux and remineralization. We take:

$$F_{\mathrm{bio}} = -C_P \exp(-z/H_{\mathrm{bio}}).$$

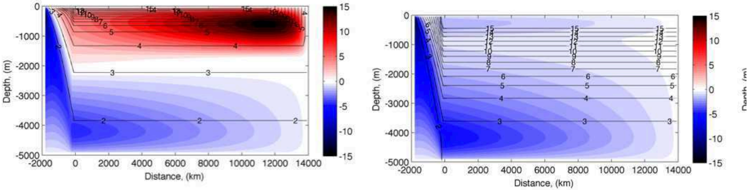
where C_P is proportional to phosphate content: $C_P = P\Delta z_1/\tau_{\mathrm{bio}}$.

Model Results for 'Atlantic' and 'Pacific'

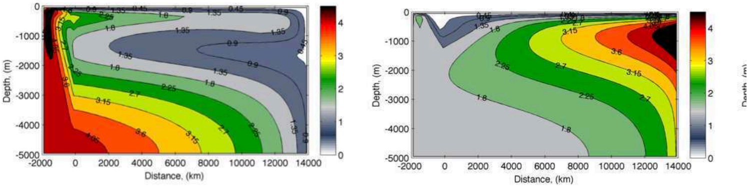
Sambuca

Atlantic | Pacific

Circulation



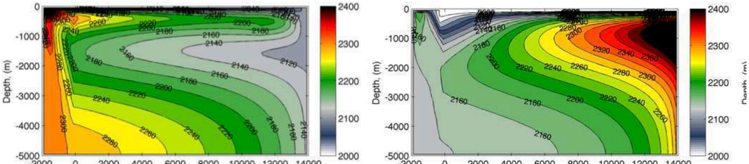
Phosphate



Carbon

gray is low

red is high



Observations for Atlantic and Pacific

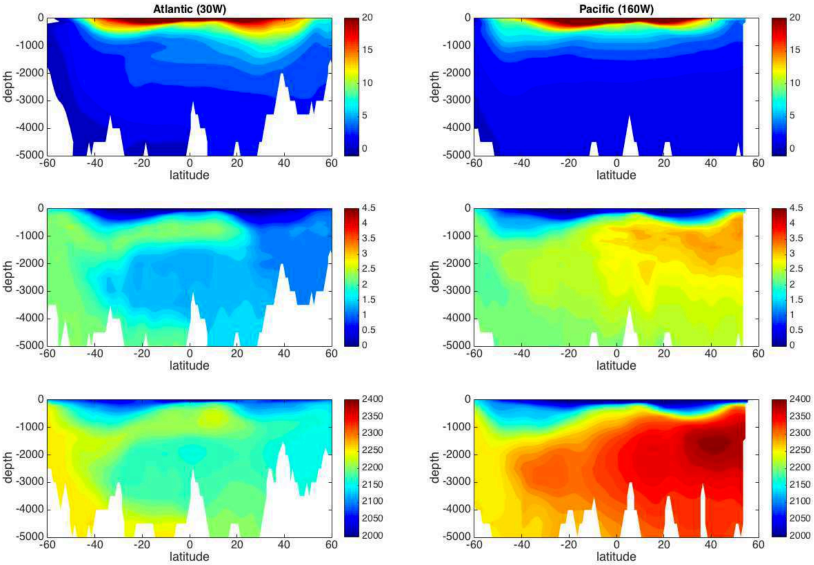
Temperature

Phosphate

Carbon

blue is low

red is high



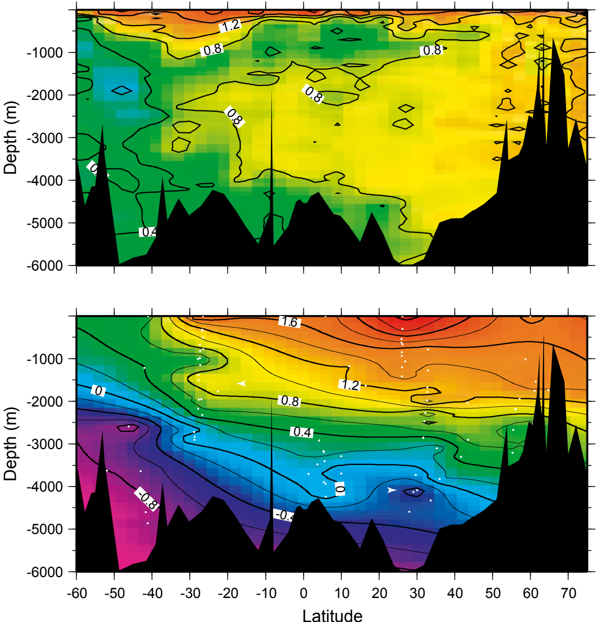
5 World Ocean Atlas (Garcia et al 2010); GLODAP (Key et al 2004).

Glacial and Modern Circulations

δ^{13}C in the Western Atlantic.

Modern

Glacial



Shoaling (thinning) of NADW to about 1,500 m. Expansion of AABW.

Curry and Oppo (2005) as reproduced by Ferrari et al (2014)

Glacial and Modern Circulations

Modern

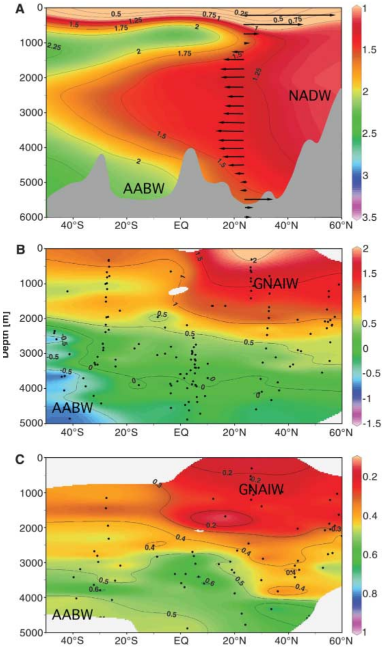
Dissolved Phosphate

Glacial

$\delta^{13}C$

Glacial

Cd (nmol/kg) in LGM



Shoaling (thinning) of NADW to about 1,500 m.

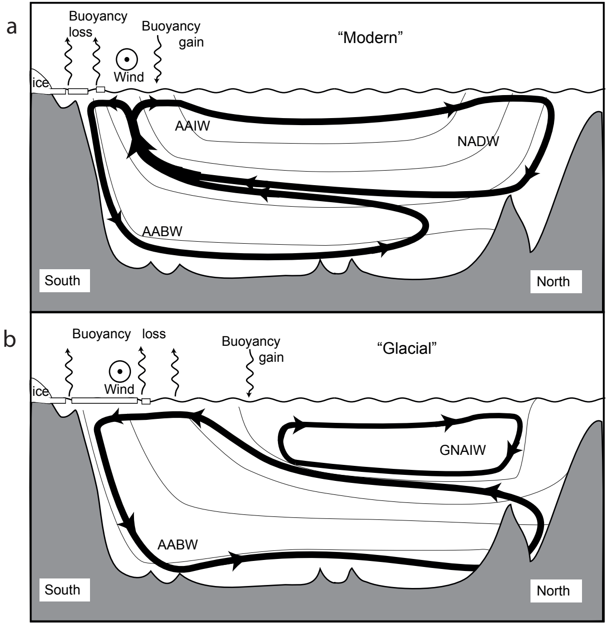
Expansion of AABW.

Stieglitz et al (2007)

Glacial and Modern Circulations

Modern

Glacial

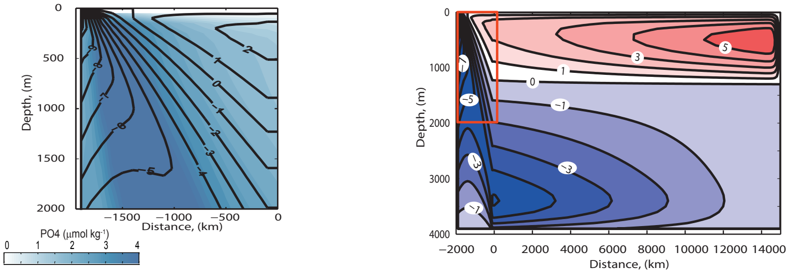


Watson, Vallis, Nikurashin (2014)

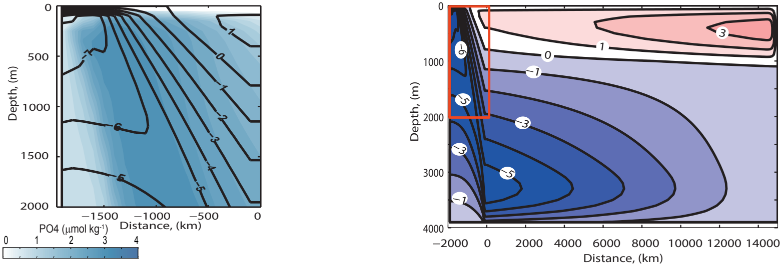
show movie!

Results

a) "Modern"

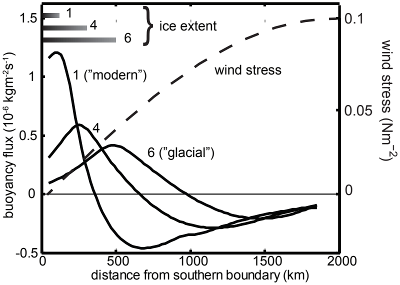


b) "Glacial"

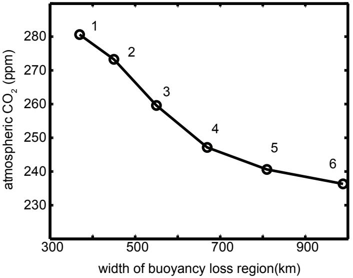


Results

Buoyancy forcing



Atmospheric CO_2



What's going on?

- Upwelling is moved north and there is a greater reach of the southwards flowing surface water.
- Longer residence time of surface water in Southern Ocean.
- More time for biota to remove carbon.
- Carbon levels in surface water is reduced, drawing more down from atmosphere.
- This carbon is then sequestered in the abyss.
- Is not returned by the circulation.

Conclusions and Speculations

A re-arrangement of the ocean circulation in glacial times draws down CO_2 and reduces global temperature.

- Proposed mechanism::
  - Enhanced bottom cell.
  - Longer residence time at surface in high latitudes gives time for biota to photo-synthesize, and draw-down carbon.
  - That carbon is the sequestered in the abyssal ocean, and not returned to the surface.
  - Lower atmospheric CO_2.
- Results are found in SAMBUCA (our theoretical model) and reproduced by a full OGCM with carbon cycle with two basins — stay tuned...

Convective Aggregation and Propagation in the Moist Shallow Water Equations

Application to the Madden-Julian Oscillation (MJO)

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AOFD 2019

http://tiny.cc/Vallis

Two Classic Problems to Solve

1. Convective organization.
2. Madden–Julian Oscillation

How far can we get with the shallow water equations?

Shallow water equations have been used to good effect for dry problems, but not so much for moist problems.

cf Raymond and Fuchs (2012), Sobel and Maloney (2015), Zeitlin and collaborators (c. 2018)

Madden–Julian Oscillation

What is it?

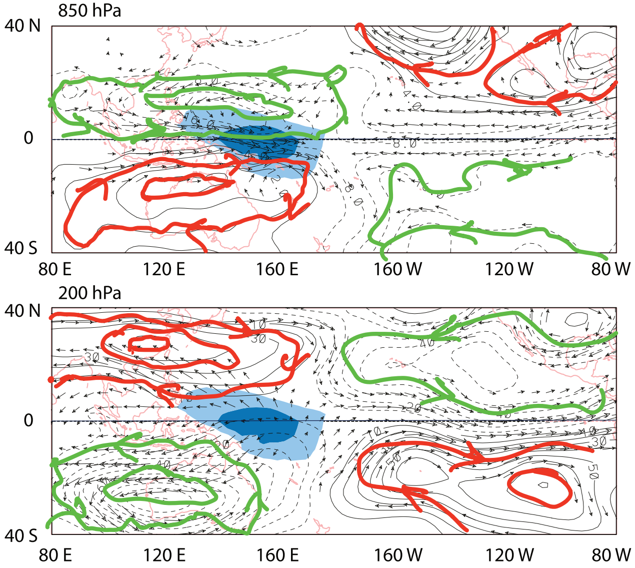
- Not an oscillation (IMHO).
- An eastward moving precipitating disturbance in the tropics, speed about 3–5 m/s.
- Horizontal scale of the effect of a few thousand kilometers (although heavy precipitation region is of much smaller scale.)
- Dipole/quadrupole structure.
- Timescale of reforming 40–60 days (hence the '40-day oscillation'.
- Many other detailed properties that other people will tell you about.

The two key aspects:

1. Eastward moving band of precipitation.
2. Concentrated at equator.

Observations

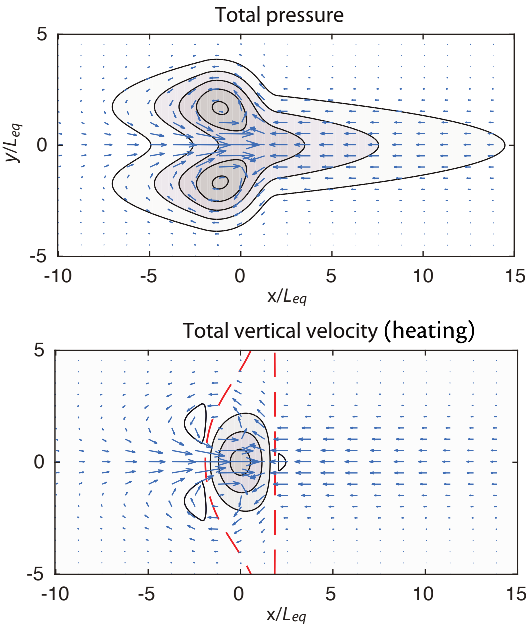
Composite MJO structure

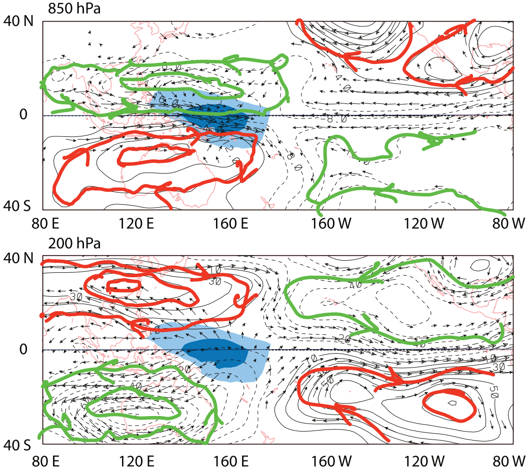


1. Dipole structure slightly west of rainfall.
2. First baroclinic mode in vertical.
3. Pattern moves slowly eastward at a few meters/sec.
4. Instantaneous picture (snapshot) is a mess — lots of isolated convection etc.

Kiladis

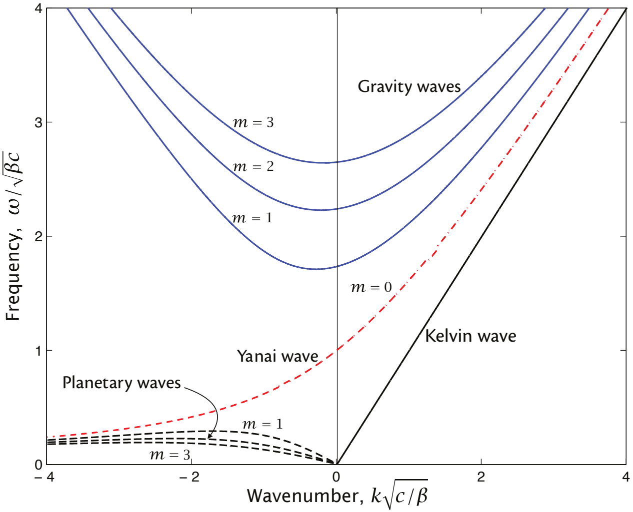
Matsuno–Gill Pattern





Suggests that the MJO is similar to a propagating Matsuno–Gill pattern!

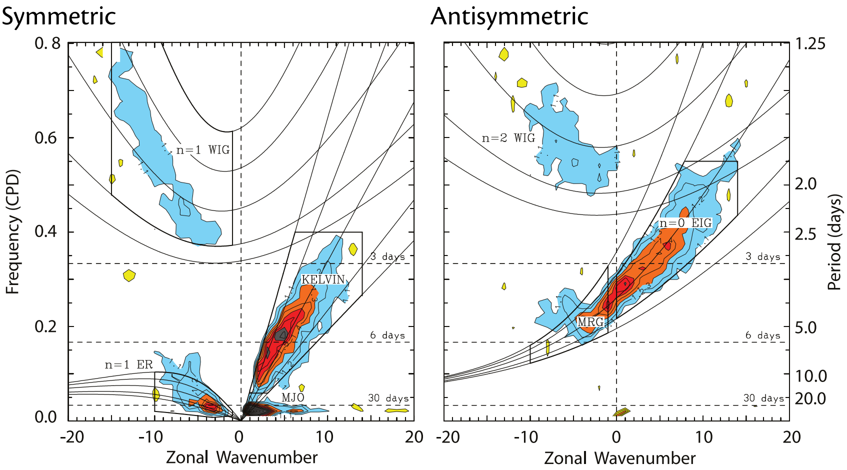
Equatorial Waves



1. Gravity waves at high frequency
2. Rossby waves at low frequency
3. Eastward moving Kelvin waves.

Observed Spectra

Wheeler-Kiladis diagram



(i) Usual gravity, Kelvin and Rossby waves.

(ii) Additional signal at low frequency and large scale.

Hypothesis

1. Convergence of moisture leads to condensation and a heat source.
   (Convective self-aggregation, induced by beta-plane.)
2. A Matsuno–Gill-like pattern spontaneously self-organizes.
3. The convection may lead to a self-maintained M-G pattern, or
4. Spawns Kelvin waves that propagate East, triggering convection east of initial site of convection.
5. Leads to convergence, and more convection. Pattern slowly propagates east.

Convection $\longrightarrow$ eastward gravity waves $\longrightarrow$ triggers convection $\longrightarrow$ eastward gravity waves . . . . . .

Why at the Equator?

Convection efficiently causes convergence at the equator.
Off-equatorial convection will also generate rotational motion.

Why Eastward

Kelvin waves triggered at low frequency. Propagate east *and* decay away from the equator.

Moist Shallow Water Equations

Represent the first baroclinic mode of the primitive equations

$$\text{momentum:} \qquad \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} + \boldsymbol{f} \times \boldsymbol{u} = -g\nabla h - r\boldsymbol{u}, \tag{1}$$

$$\text{mass continuity:} \qquad \frac{\partial h}{\partial t} + \nabla \cdot (h\boldsymbol{u}) = L \times C, \tag{2}$$

Add a moist tracer

$$\frac{\partial q}{\partial t} + \nabla \cdot (q\boldsymbol{u}) = E - C,$$

where E = evaporation, C = condensation, L = latent heat.

$$E = \frac{(q_{\text{surf}} - q)}{\tau_1}$$

$$C = \mathcal{H}(q - q_{\text{sat}})\frac{(q - q_{\text{sat}})}{\tau_2} \qquad q_{\text{sat}} = q_0 \exp(\alpha h)$$

Fast condensation on saturation determined by a Clausius–Clapeyron relation.

The Good and the Bad

Features

- Very austere model. Simplest possible model of moist convection.
- Explicit – no convective parameterization.
- First baroclinic mode represents vertical structure of tropical atmosphere.
- A moisture variable and release of latent heat. Condensation via fast condensation at saturation.
- Contains a Clausius–Clapeyron equation.

Unrealistic Aspects

Too many to list…

- Shallow water equations.
- No lapse rate criteria
- No good convective parameterization
- etc

Convection in a Real Model

Show movies!

The MJO

Why Eastward?

(i) Convection at the equator gives rise gravity waves that preferentially propagate eastward (Kelvin waves).

(ii) Waves trigger more convection. GIves rise to more Kelvin waves, and so on.

(iii) Disturbance moves more slowly than Kelvin waves because of the need to trigger convection.

Why at the Equator?

(i) A disturbance at the equator leads to convergence and self-maintained convection. (See also Matsuno–Gill pattern.)

(ii) A disturbance off the equator generates rotational motion with less convergence.

Why don't GCMs reproduce it well?

(i) GCMs are not good at generating gravity waves — resolution too low and convective parameterizations smooth the effects (cf QBO).

(ii) Need the small scales and/or stochasticity.

(iii) High resolution (cloud resolving) models are beginning now to obtain an MJO.

Thank you all for listening!